



Development Possibilities of Environmental Noise Propagation Modelling

Thesis for the Degree of Doctor of Philosophy (PhD)

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Development Possibilities of Environmental Noise Propagation Modelling

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Table of Contents

Abbreviations & Acronyms	
1 Introduction	1
1.1 Overview	1
1.2 Literature Review	7
1.3 Research Questions.....	13
1.4 Research Objectives.....	14
1.5 Research Roadmap	17
2 Influence of Road Surface Types on Noise Levels in the CNOSSOS-EU Method	18
2.1 Introduction	18
2.2 Materials and Methods	18
2.2.1 Methodology	19
2.2.2 Road Surface Types in the Examined Countries.....	23
2.3 Results	26
2.3.1 Comparison of Sound Power Level Differences for the CNOSSOS-EU Road Surfaces	28
2.3.2 Comparison of Sound Power Level Differences for the German Road Surfaces	29
2.3.3 Comparison of Sound Power Level Differences for the Austrian and the Finnish Road Surfaces	31
3 Impact of the ISO 9613-2:2024 Updates on Outdoor Sound Propagation	32
3.1 Introduction	32
3.2 Materials and Methods	32
3.2.1 Ground Effect Correction Factor	33
3.2.2 Cylindrical Surface Reflections	35
3.2.3 Enhanced Screening Calculations	37
3.2.4 Chimney Stack Directivity.....	38
3.2.5 Foliage Attenuation	38

3.3	Results	39
3.3.1	Ground Effect Correction Factor	40
3.3.2	Cylindrical Surface Reflections	41
3.3.3	Chimney Stack Directivity	42
4	Comparison of the CNOSSOS-EU and the ISO 9613-2 Predictions with Field Measurements	44
4.1	Introduction	44
4.2	Materials and Methods	44
4.2.1	Methodology	45
4.2.2	The CNOSSOS-EU Model Setup	52
4.2.3	The ISO 9613-2 Model Setups	54
4.3	Results	57
4.3.1	Modelled Noise Levels without Considering the Fence.	58
4.3.2	Modelled Noise Levels Considering the Fence	60
5	Discussion and Limitations	63
6	Thesis Points and Novelty	72
6.1	Thesis 1: Influence of Asphalt Concrete Surfaces (ACS) on Noise Emissions in the CNOSSOS-EU Method	72
6.1.1	Thesis Point	72
6.1.2	Problem Statement	72
6.1.3	Approach	72
6.1.4	Novelty	73
6.2	Thesis 2: Acoustic Behaviour of Cement Concrete Surfaces (CCS) in the CNOSSOS-EU Method	73
6.2.1	Thesis Point	73
6.2.2	Problem Statement	73
6.2.3	Approach	74
6.2.4	Novelty	74
6.3	Thesis 3: Noise Impact of Paving Block Surfaces (PBS) in the CNOSSOS-EU Method	74

6.3.1	Thesis Point.....	74
6.3.2	Problem Statement	75
6.3.3	Approach	75
6.3.4	Novelty.....	75
6.4	Thesis 4: Impact of the ISO 9613-2:2024 Updates on Outdoor Sound Propagation	75
6.4.1	Thesis Point.....	75
6.4.2	Problem Statement	76
6.4.3	Approach	76
6.4.4	Novelty.....	76
6.5	Thesis 5: Comparative Validation of the CNOSSOS-EU and the ISO 9613-2 Models	76
6.5.1	Thesis Point.....	76
6.5.2	Problem Statement	77
6.5.3	Approach	77
6.5.4	Novelty.....	77
6.6	Thesis 6: Practical Applicability of the CNOSSOS-EU and the ISO 9613-2 for Road Traffic Noise Modelling	77
6.6.1	Thesis Point.....	77
6.6.2	Problem Statement	78
6.6.3	Approach	78
6.6.4	Novelty.....	78
7	Conclusion and Future Work.....	79
8	Acknowledgments.....	83
9	List of Publications.....	84
	Bibliography	85

List of Tables

Table 1: Road Surface Parameters.	22
Table 2: Road Surface Types in the Examined Countries.	24
Table 3: Sound Power Level Difference from the Reference Surface in dB.	27
Table 4: Measurement Data Processing.	47
Table 5: Traffic Counts for the Representative Ten Hours in veh/h.	52
Table 6: Parameters of the CNOSSOS-EU Model.	53
Table 7: α_i, m and βm Coefficients for B217 SMA-11 [90,91].	53
Table 8: Measured Noise Levels, $L_{eq,1h}$, in dB(A).	57
Table 9: Modelled Noise Levels, $L_{eq,1h}$, without the Fence in dB(A).	58
Table 10: Modelled Noise Levels, $L_{eq,1h}$, with the Fence in dB(A).	61
Table 11: Differences in Measured and Modelled Noise Levels Considering the Fence at MP2 in dB(A).	62

List of Figures

Figure 1: Noise Emission Difference Calculation Steps.....	23
Figure 2: Noise Reduction Capabilities of the CNOSSOS-EU Road Surfaces.	29
Figures 3a/b: Noise Reduction Capabilities of the German Road Surfaces.....	30
Figure 4: Noise Reduction Capabilities of Austrian and Finnish Road Surfaces.	31
Figure 5: Sound Ray Reflection at a Cylinder [48].	36
Figure 6: Typical K_{lin} Factors for Different Forestry Parameters [48].	39
Figure 7: A_{gr} Difference between the 1996 and 2024 ISO 9613-2. Source Height: 50 m AGL.	40
Figure 8: A_{gr} Difference between the 1996 and 2024 ISO 9613-2. Source Height: 2 m AGL.	41
Figure 9: Direct Sound and Reflection Difference for 1/1 Octave Bands from 63 Hz to 500 Hz at Polygon and Cylinder Objects.	42
Figure 10. Direct Sound and Reflection Difference for 1/1 Octave Bands from 1 kHz to 8 kHz at Polygon and Cylinder Objects.	42
Figure 11: Sound Propagation of a Chimney Stack with 1 m Radius Implementing Directivity Correction at 125 Hz and 4 kHz.	43
Figure 12: MP1 and MP2 Distances from the Centreline.....	45
Figure 13: Adjustment of MP1 and MP2 In-Situ.	49
Figures 14a/b/c: Site Conditions Observed During the Measurement Campaign.	51
Figure 15: CNOSSOS-EU Model in SoundPLAN 9.1.	54
Figure 16: ISO 9613-2 Point Source Model in SoundPLAN 9.1.....	55
Figure 17: ISO 9613-2 Line Source Model in SoundPLAN 9.1.....	56
Figure 18: Mean Average Error without the Fence in dB(A).....	60
Figure 19: Cross-Section Noise Map – No Fence Scenario: CNOSSOS-EU....	69
Figure 20: Cross-Section Noise Map – Fence Scenario: CNOSSOS-EU.....	69
Figure 21: Cross-Section Noise Map – No Fence Scenario: ISO 9613-2:1996 and 2024 Line Source.	70
Figure 22: Cross-Section Noise Map – Fence Scenario: ISO 9613-2:1996 Line Source.	70
Figure 23: Cross-Section Noise Map – Fence Scenario: ISO 9613-2:2024 Line Source.	70

Abbreviations & Acronyms

A_{bar}	Barrier Attenuation
A_{curv}	Curved Surface Attenuation
ACS	Asphalt Concrete Surface
A_{fol}	Foliage Attenuation
A_{gr}	Ground Effect Attenuation
CCS	Cement Concrete Surface
AGL	Above Ground Level
CNOSSOS-EU	Common NOise aSSessment methOdS
CoRTN	Calculation of Road Traffic Noise
CPX	Close-Proximity Method
DAC	Dense Asphalt Concrete
dB	Decibel
dB(A)	A-weighted Decibel
D_c	Chimney Stack Directivity Correction Factor
D_z	Diffraction Attenuation of a Barrier
END	Environmental Noise Directive
EU	European Union
EV	Electric Vehicle
G	Ground Factor
h	Hour
HDV	Heavy-Duty Vehicles
ISO	International Organization for Standardization
K_{geo}	Ground Effect Correction Factor
K_{lin}	Foliage Attenuation Correction Factor
K_{met}	Meteorological Effect Correction Factor
km	Kilometer
$L_{\text{Aeq},15\text{min}}$	15 Minutes Equivalent Continuous Sound Pressure Level
$L_{\text{Aeq},1\text{h}}$	1 Hour Equivalent Continuous Sound Pressure Level
L_{den}	Day-Evening-Night Sound Equivalent Level
LDV	Light-Duty Vehicles
L_{night}	Night Sound Equivalent Level
LNP	Low-Noise Pavement
L_p	Sound Pressure Level
L_w	Sound Power Level

m	Meter
MAE	Mean Absolute Error
mbar	Millibar
MDV	Medium-Duty Vehicles
MP	Measurement Point
NMPB2008	New Method for Noise Prediction, 2008
Nord2000	Nordic Calculation Method, 2000
PBS	Paving Block Surface
RLS-19	Guidelines for Noise Protection on Roads, 2019
RMG2012	Calculation and Measurement Regulations for Noise, 2012
SEL	Sound Event/Exposure Level
SMA	Stone Mastic Asphalt
SPB	Statistical Pass-By Method
TRANEX	Traffic Noise Exposure
U-SPB	Urban Statistical Pass-By Method
UK	United Kingdom
veh	Vehicle
veh/h	Vehicle per Hour

1 Introduction

1.1 Overview

Noise pollution poses a critical issue in today's world. In Europe, road traffic noise is considered a major environmental pollutant in urban areas [1], being a continuous nuisance source impacting several aspects of life [2]. Road traffic noise is ranked as the second most significant environmental noise source [1,3,4] affecting the mental health and daily activities of individuals in noisy environments, thereby influencing their wellbeing [5,6,7]. Following fine particle pollution, road traffic noise is the most common environmental risk factor to human health in Europe [8]. Its mental and physical adverse health effects are mainly caused by the loud engine sounds, the continuous interaction between the tyre and the road surface, which is noisier at higher speeds, and vehicle horns, leading to a fatigued body and spirit and triggering unpleasant feelings [9]. In addition, this contributes to potential long-term risks of cardiovascular problems [10,11,12], such as heart attacks and hypertension [13,14]. In general, prolonged exposure to high noise levels can affect work and educational environments, as it can weaken our overall cognition, communication, and attention [15,16,17]. Conversely, the total burden of road traffic noise in the European Union - including direct costs and impacts, such as medical treatments and lost productivity - is estimated at 40 billion euros annually [18]. Therefore, implementing effective measures to counter these adverse effects is essential to reducing road traffic noise pollution.

The European Union introduced the Environmental Noise Directive 2002/49/EC in 2002 as an environmental noise assessment measure to address the problem and its scale thoroughly [19]. Member States are required to conduct a systematic dose-effect evaluation [20] of noise levels in densely inhabited areas, adjacent to transportation nodes, and along major thoroughfares by generating strategic noise maps from actual traffic noise data (road, railway and aircraft) [19,21]. The aim of strategic noise maps is to visually present sound levels, offering key insights that assist the authorities in ranking the intervention locations and evaluating the severity of the problem. Ultimately, this is expected to foster quieter and more comfortable living environments for individuals across the Member States. Furthermore, the European Commission introduced “The European Green Deal” in 2019, aiming to protect the health and well-being of residents from various environmental risks [22]. At its core, a Zero Pollution Action Plan was launched in 2021 with the objective of reducing environmental pollution by 2030. One of its key goals is reducing the number of people chronically affected by transport noise, including road traffic noise, by 30% compared to 2017, while ultimately striving to achieve zero pollution by 2050 [23,24]. The European Commission aims to mitigate noise at its source, by ensuring effective road construction practices and refining the regulations on tyres and road vehicles, where necessary [23]. As such, Member States are recommended to coordinate strategies aimed at mitigating noise pollution while safeguarding public health and safety. The recommended mitigation measures include the promotion

of quieter modes of transport, such as Electric Vehicles, the adoption of quieter tyres [25], the reduction of road speed limits, the application of low-noise pavements on road surfaces [26], the construction of durable noise barriers [27], and the preparation of strategic noise maps as principal tools [19].

To evaluate the effectiveness of the recommended measures and reduce their implementation costs, the methodology of noise modelling or mapping is usually applied by engineers utilizing specialized computer software, such as SoundPLAN, IMMI and CadnaA.

Environmental noise modelling or mapping is the process of predicting and visualizing how noise propagates in different environments and displaying the results as noise contour maps. However, modelling outdoor noise propagation presents considerable challenges due to the diversity of noise sources, the variability of environmental conditions, and the complexity of urban geometries characterized by multiple reflective and absorptive surfaces [28]. Since road traffic noise is considered a significant environmental pollutant [1], several standards and methods were developed by different European countries and made available in commercial noise modelling software to predict noise levels from road traffic noise, such as the RLS 19, the NMPB2008, the RMG2012, the Nord2000 and the CoRTN. However, many of these standards were developed based on specific local conditions. Therefore, their use is limited in broader applications. For example, the RLS 19 standard is mainly applied to the German road network [29], while the NMPB2008 standard is tailored to French conditions [30].

The RMG2012 standard is used in the Netherlands [31] and the Nord2000 framework is predominantly implemented across Northern Europe [32]. In addition, the CoRTN standard is widely adopted in the United Kingdom and Ireland [33].

Therefore, the END's implementation framework places strategic noise mapping at its core, employing advanced methodologies and tools to calculate and visualize sound pressure levels, which are widely recognized indicators of sound quality and potential annoyance [34]. Since 2007, EU Member States have been required to produce strategic noise maps every five years for agglomerations with more than 250,000 inhabitants, and since 2012 for those exceeding 100,000 inhabitants, as well as for major roads carrying over 3 million vehicles passing per year outside agglomerations [19,35,36]. These maps use the harmonised indicators L_{den} (day–evening–night noise level), and L_{night} (night noise level) to represent exposure [19,37].

Strategic noise mapping involves identifying and classifying noise hotspots and spatial patterns to generate a geographical representation of noise exposure, supporting national authorities in developing or adjusting policies and regulations aimed at noise mitigation [19]. It also facilitates monitoring progress or deterioration over time, enabling Member States to assess the effectiveness of their noise management strategies and to enhance public risk communication by converting noise maps into risk maps [38]. A key development under the END is the establishment of the Common NOise aSSessment methOdS (CNOSSOS-EU), which provides a harmonised

approach for environmental noise assessment across the EU.

Published in 2015 under Commission Directive (EU) 2015/996, the CNOSSOS-EU adopts a multi-disciplinary and harmonised approach to assessing road traffic noise, considering environmental, social and economic dimensions. This framework seeks to balance environmental protection with sustainable development. As such, supporting the preservation of natural habitats and cultural areas from the adverse impacts of road traffic noise [39]. For example, the CNOSSOS-EU incorporates nature-based solutions into urban planning, including acoustic landscapes and green barriers. It also divides the noise emissions models of internal combustion vehicles into four main categories, in addition to a fifth “open category” reserved for future needs, such as EVs [40,41,42]. However, such measures can only be implemented effectively when environmental experts, policymakers, and local communities across the EU work together.

The CNOSSOS-EU evaluates road traffic noise based on two primary sources: rolling noise, generated from tyre-road interaction, and propulsion noise generated by the vehicle’s driveline (engine, exhaust, etc.) [40,41], which is considered negligible for EVs [42]. It also accounts for deviations in the noise emission from non-standard road surface types relative to a Reference Road, expressed through correction coefficients provided in Annex II of the CNOSSOS-EU documentation based on the Dutch road surface network [31,40,43,44].

Road surface type and composition plays a significant role in determining the noise emissions [45], a topic that

has received increasing attention in recent automotive and acoustic engineering research [46]. In general, variations in tyre design, pavement aging, surface texture, and material mixtures all influence the magnitude of road traffic noise [45,46]. Therefore, the CNOSSOS-EU is recommended for use only in EU Member States that have already transposed the method into national legislation, as advised by the END, given the substantial variation in road surface characteristics across Europe [36,40]. Consequently, policies that encourage the use of low-noise pavements can help create more pleasant urban environments and mitigate the harmful effects of road traffic noise pollution.

One other standard that is commonly implemented in noise modelling software is the ISO 9613-2, entitled “Acoustics — Attenuation of sound during propagation outdoors — Part 2: Engineering method for the prediction of sound pressure levels outdoors”. The standard was first published in 1996 and later revised in 2024. It applies to noise generated by a broad range of sources, including industrial facilities, road traffic, railways and construction activities, and is widely used in environmental noise impact assessments. The method incorporates key physical factors influencing outdoor sound propagation, such as geometrical divergence, atmospheric absorption, ground effect, reflections from surfaces and screening by obstacles [47,48,49].

However, research on outdoor sound propagation has identified several limitations in the ISO 9613-2:1996 version, particularly in the modelling of ground effect, multi-edge diffractions, and reflections from curved surfaces [49,50,51]. To address these deficiencies, the ISO

9613-2:2024 revision was developed, offering improved methodologies for more accurate prediction of outdoor sound propagation.

The ISO 9613-2:2024 technical revision introduced several significant enhancements. These improvements include the subdivision of extended sources to eliminate uncertainty in noise modelling software implementations, an improved procedure for determining the ground factor, G , and the incorporation of a dedicated correction factor, K_{geo} , for the ground effect, A_{gr} . The update also adopts a new approach for calculating screening effects, aligned with the recommendations of the ISO 17534-3, entitled “Acoustics — Software for the calculation of sound outdoors — Part 3: Recommendations for quality assured implementation of ISO 9613-2 in software according to ISO 17534-1” [52], and revises the specifications for barrier attenuation, A_{bar} . Further refinements include the addition of a meteorological correction, K_{met} , the resolution of known deficiencies related to low barriers and large source–receiver distances, improved modelling of reflections from cylindrical surfaces, and the introduction of chimney stack directivity correction, D_c [48,49].

1.2 Literature Review

The END amended Annex II of the CNOSSOS-EU document in 2020 and re-published it in 2021 with refined correction coefficients for 14 different Dutch road surface types relative to a Reference Road [53,54]. However, no officially published method is yet available for deriving local correction coefficients for road surface types in EU Member States [44], which in turn has encouraged further

research in this area.

For example, a researcher from Sweden has explored how national road surface correction coefficients might be derived by using a prediction model as a reference. In this work, the Nord2000 was employed to generate sound exposure levels for typical Swedish road surfaces, reflecting local construction practices, road surface temperature, pavement textures, and the influence of studded tyres. These results were then compared with the corresponding CNOSSOS-EU predictions at selected receiver positions, and the differences were iteratively reduced to obtain provisional correction coefficients [54].

Similarly, research in Italy has applied an empirical approach based on Statistical Pass-By (SPB) measurements to derive correction coefficients for a motorway in line with the requirements of the CNOSSOS-EU. In this study, sound pressure levels and vehicle speeds were recorded on three adjacent sections of the A14 motorway, each surfaced with a different type of draining asphalt, using the Statistical Pass-By (SPB) method in accordance with the ISO 11819-1 [55]. The measured pass-by levels for light, medium, and heavy vehicles were then compared with the CNOSSOS-EU simulations at two receiver distances. By eliminating the discrepancies between measured and modelled levels, the researchers obtained preliminary correction coefficients for each road surface type [56].

In addition, the Transport Infrastructure in Ireland has focused on developing interim correction coefficients for the CNOSSOS-EU method using Close Proximity (CPX) measurements rather than the SPB method. This approach

was undertaken to support the national implementation of the CNOSSOS-EU for the fourth round of strategic noise mapping, particularly for the three most common road types on the Irish national road network. CPX measurements were carried out at multiple locations and speeds, in accordance with the ISO 11819-2 [57], and the resulting noise levels were compared against reference CPX spectral data representing the CNOSSOS-EU virtual reference surface. From these comparisons, interim correction coefficients were derived for each road surface type [44].

Another study that was recently published also examined how user-defined pavements can be calibrated within the CNOSSOS-EU method to obtain more reliable estimates of road traffic noise exposure, particularly for low-noise pavements (LNPs). In this study, the authors employed an adapted Urban Statistical Pass-By (U-SPB) method, which allows the extraction of pass-by acoustic indicators from standard roadside monitoring equipment without the need for dedicated SPB or CPX campaigns. Using U-SPB measurements collected on two LNP test sites, the researchers compared measured sound exposure levels with CNOSSOS-EU simulations and iteratively adjusted the LNP correction coefficients until the model reproduced the measured sound levels across frequency bands and vehicle categories. The calibrated surfaces were then tested in larger noise mapping scenarios to quantify differences in population exposure and associated health indicators, demonstrating how dedicated surface parameters can significantly influence estimates of annoyance, sleep disturbance, and adverse health effects. Although not an

official procedure, this work illustrates how locally measured data can be used to tune CNOSSOS-EU surface coefficients for specific pavement mixtures [58].

Although these approaches are not formally recognized as official methods, they illustrate how EU Member States can adapt the harmonised CNOSSOS-EU framework to the specific characteristics of their national road networks and traffic conditions, ensuring more accurate noise mapping results and supporting more effective noise-mitigation planning while maintaining compatibility with the END requirements.

On the other hand, several studies have compared the CNOSSOS-EU with existing national road traffic noise models, rather than deriving new correction coefficients, to assess how the harmonised method performs relative to established local standards and calculation practices.

In Ireland, for instance, further work has examined the implications of adopting the CNOSSOS-EU for national noise mapping by comparing its performance with the previously used CoRTN method. Using roadside measurements collected under controlled traffic conditions in Dublin, the study found that the CNOSSOS-EU reproduced measured noise levels more accurately than CoRTN, with an average deviation of less than 2 dB(A), particularly at both roadside and propagation distances. When applied to a full agglomeration-scale model, the CNOSSOS-EU also predicted higher population exposure to road traffic noise, especially above the key thresholds of 55 dB(A) L_{den} and 50 dB(A) L_{night} , suggesting that earlier assessments based on the CoRTN model may have underestimated the number of residents affected [59].

Additionally, researchers from Denmark and the UK compared the CNOSSOS-EU with the Nord2000 and the TRANEX models to evaluate differences in source characterization, propagation algorithms, and predicted noise level. Using more than one hundred test cases covering a range of source–receiver configurations, the study found that both the CNOSSOS-EU and the TRANEX reproduced the Nord2000 results within approximately 3–5 dB(A) for most scenarios, although TRANEX showed slightly closer results overall. The analysis also identified several systematic discrepancies in the CNOSSOS-EU, particularly related to ground attenuation, handling of multiple diffraction, and the simplified mean-ground-plane approach, which contributed to deviations from Nord2000 in certain scenarios. The authors concluded that while the CNOSSOS-EU performs reasonably well, further refinement of its propagation algorithms would improve its suitability for widespread implementation across the EU [60].

Further comparisons between the CNOSSOS-EU and the Nord2000 models are also well documented in the literature. In Sweden, researchers evaluated how the CNOSSOS-EU compares with the national Nord2000 using newly collected pass-by measurements on SMA 0/16 road surfaces. The study found that the CNOSSOS-EU systematically underestimated sound exposure levels, SEL, at short distances relative to both measurements and the Nord2000 prediction by approximately 0.1–4 dB(A), a discrepancy largely attributed to differences in the underlying propagation algorithms, the CNOSSOS-EU’s

simplified treatment of ground reflections and its assumption of uncorrelated addition of direct and reflected sound. In contrast, the Nord2000 method, which incorporates a more detailed physical propagation model and frequency-dependent ground effects, aligned more closely with the measured spectral SEL. Based on these findings, the authors proposed updated rolling noise and propulsion noise corrections for the Nord2000 model and highlighted the need for further adaptation of the CNOSSOS-EU to better reflect Swedish vehicle fleets, road surfaces, and propagation conditions [61].

Another example comes from Finland, where researchers assessed the implementation of the CNOSSOS-EU model by comparing its outputs with those of the Nord2000 calculation method during the third round of END noise mapping for LDVs, MDVs, and HDVs across speeds ranging from 40 to 120 km/h. Since the default CNOSSOS-EU rolling and propulsion noise coefficients were found to be unsuitable for Nordic conditions, national A and B coefficients were derived from the Nord2000 emission database and applied in place of the default CNOSSOS-EU values. Even with these adjustments, the study reported notable differences between CNOSSOS-EU and the Nord2000 models of roughly 0.7–4.6 dB(A), particularly in urban areas with complex propagation paths and at locations influenced by acceleration and deceleration near intersections. The CNOSSOS-EU tended to predict higher exposure at elevated noise bands, while also showing substantial sensitivity to meteorological inputs and software-specific implementation choices. The authors concluded that although the CNOSSOS-EU can be

applied successfully in Finland once national source data are incorporated, further refinement of the model and clearer guidance are required to ensure consistency with established Nordic practices and to support reliable long-term trend assessments [62,63]. On the other hand, the CNOSSOS-EU was found to predict lower noise levels in comparison with the NMPB-96 [64,65,66,67,68,69], due to differences in vehicle categories and absorption and diffraction algorithms [70].

1.3 Research Questions

This work aims to answer the following research questions in regards with modelling environmental noise propagation.

1. How do national road surface correction coefficients in Austria, Germany, and Finland compare with the CNOSSOS-EU defaults for light, medium-heavy, and heavy vehicles, and how do these differences influence total sound power levels?
2. How might these emission differences affect comparability of strategic noise maps and predicted population exposure across borders?
3. Under which geometric and structural conditions do the ISO 9613-2:2024 outdoor propagation predictions differ from the ISO 9613-2:1996, particularly regarding ground effect, screening, and curved surface reflections?
4. For distributed road traffic sources, what is the impact of Point Source versus Line Source representations on alignment with measured near-field and far-field noise levels?

5. Given typical data availability (traffic counts versus known source power levels) and site features (barriers, embankments), what practical guidance emerges for selecting between the CNOSSOS-EU and the ISO 9613-2?

1.4 Research Objectives

Building on the body of European research that has examined the performance, limitations, and national adaptations of the CNOSSOS-EU framework, the present work extends this line of inquiry by focusing on two complementary dimensions of environmental noise modelling. The first concerns the relationship between the CNOSSOS-EU and the national road traffic noise emission models currently in use across EU Member States.

Although the CNOSSOS-EU was introduced to harmonize noise assessment practices across Europe, Member States are obliged to obtain correction coefficients for their national road networks, which are usually developed under different measurement conditions, vehicle fleet compositions, and road surface characteristics. This divergence has created a fragmented landscape in which strategic noise maps produced using the CNOSSOS-EU reference values are not always comparable across borders.

To address this gap, this work systematically compares the CNOSSOS-EU default values with the official national values published in Austria, Germany, and Finland, three countries whose road surface correction coefficients are already implemented in commercial noise mapping software, such as SoundPLAN, IMMI, and CadnaA. By

focusing on the rolling and propulsion noise components for light, medium-heavy, and heavy vehicles, the analysis provides a clear and controlled comparison of how national road surface types influence predicted noise levels relative to the harmonised CNOSSOS-EU framework. This work contributes to the ongoing discussion on the need for full CNOSSOS-EU adoption across the EU, demonstrating that inconsistencies in national coefficients can lead to significant differences in predicted exposure and affected population by road traffic noise, which in turn undermines the comparability and policy relevance of strategic noise mapping.

The second dimension of the dissertation begins with reviewing the 2024 updates of the ISO 9613-2, highlighting key parameters that are expected to improve the standard's accuracy in modelling outdoor sound propagation. It then focuses on the modelling of road traffic noise at the local scale, using a case study from Hungary to evaluate the performance of the CNOSSOS-EU method alongside the ISO 9613-2 standard, which remains one of the most widely applied international standards for environmental noise propagation predictions. This part of the research integrates measured noise levels from a local road with known parameters with predictions obtained from the CNOSSOS-EU and from both the 1996 and 2024 editions of the ISO 9613-2. Thus, it offers a holistic assessment of how these methods behave under real-world conditions and how their methodological differences, particularly in ground effect treatment, meteorological assumptions, sound propagation and screening calculations, affect the

accuracy of predicted noise levels. The comparison between the two ISO versions is especially relevant, as the 2024 revision introduces updates to ground attenuation handling and improved diffraction algorithms, which have the potential to reduce the limitations observed in the 1996 version. The findings highlight the extent to which these updates influence model performance and accuracy. This analysis not only supports the selection of appropriate modelling standards for similar traffic and environmental conditions but also positions the CNOSSOS-EU and the ISO 9613-2 within a broader international context, acknowledging their effective roles in environmental noise assessment.

Taken together, the two sides of this dissertation demonstrate the importance of harmonised, transparent, and empirically validated noise modelling practices. By placing the Hungarian case study within the wider European comparison, the work highlights the need for consistent implementation of the CNOSSOS-EU across all EU Member States, both to ensure comparability in strategic noise mapping and to support evidence-based policy decisions aimed at reducing population noise exposure. At the same time, the integration of the ISO 9613-2 into the analysis reflects the reality that environmental noise modelling operates within a global methodological ecosystem, where national and international standards coexist and evolve. Therefore, the dissertation contributes to the technical refinement of noise prediction methods as well as to the broader discussion on how environmental noise should be assessed, compared, and managed within a harmonised European framework.

1.5 Research Roadmap

This work is structured to progressively investigate environmental noise modelling through a combination of simulation, methodological analysis, and experimental validation. It begins by examining the influence of different road surface types on noise levels within the CNOSSOS-EU framework, in Germany, Austria and Finland, where appropriate traffic scenarios, surface classifications, and model inputs are defined, and the resulting variations in predicted noise levels are analysed.

The study then focuses on the impact of the ISO 9613-2:2024 updates on outdoor sound propagation by comparing previous and revised formulations under various environmental and geometrical conditions to evaluate how these updates affect sound attenuation.

Following this, a comparative assessment is carried out between the CNOSSOS-EU and the ISO 9613-2 predictions using field measurements collected under real-world conditions, allowing for a statistical evaluation of model accuracy and identification of discrepancies. The findings from these investigations are subsequently integrated and discussed to highlight the strengths, limitations, and applicability of each approach. The work then outlines the key thesis contributions, emphasizing the main scientific insights derived from the research, and concludes by summarizing the overall outcomes while proposing directions for future studies and potential improvements in environmental noise propagation modelling methodologies.

2 Influence of Road Surface Types on Noise Levels in the CNOSSOS-EU Method

2.1 Introduction

This section focuses on evaluating how different road surface types influence predicted noise levels within the CNOSSOS-EU framework. Road surface characteristics play a significant role in traffic noise levels, particularly in the interaction between tires and pavement, which directly affects rolling noise emissions. Understanding these effects is essential for improving the accuracy of strategic noise maps and for supporting effective noise mitigation strategies in urban planning. Therefore, this section investigates the extent to which variations in road surface properties impact modelled noise levels and highlights their importance within the CNOSSOS-EU methodology.

2.2 Materials and Methods

In the CNOSSOS-EU documentation, the Reference Road is defined as a road surface with an average of stone mastic asphalt (SMA 0/11) and dense asphalt concrete (DAC 0/11) surfaces between two and seven years old and in representative maintenance condition. This Reference Road serves as the basis for calculating the rolling noise coefficients (A_R , B_R) and propulsion noise coefficients (A_P , B_P). The coefficients A_R and A_P represent the sound power levels at the reference speed of 70 km/h (derived from SEL to L_W) [40,71], while B_R and B_P describe the slope, expressed as $\log(\text{speed})$. Both required input parameters (the vehicle pass-by speed and the corresponding SEL in dB) are obtained from field tests.

As mentioned earlier, the CNOSSOS-EU framework classifies vehicles into five different categories according to their noise emission characteristics, with distinct rolling and propulsion noise coefficients calculated for each category. Category 1 comprises light motor vehicles, including passenger cars, delivery vans up to 3.5 tons, sport utility vehicles, and multi-purpose vehicles, as well as trailers and caravans. Category 2 includes medium-heavy vehicles such as delivery vans over 3.5 tons, touring cars, and two-axle buses with twin rear tyres. Category 3 covers heavy-duty vehicles, including buses and touring coaches with three or more axles. Category 4 represents powered two-wheelers, subdivided into 4a (mopeds, tricycles, and quads with engine capacity ≤ 50 cc) and 4b (motorcycles, tricycles, and quads with engine capacity > 50 cc). Category 5 is an open class reserved primarily for future vehicle types, particularly electric vehicles [40,41,42].

2.2.1 Methodology

To assess the impact of different road surface types on noise levels in Austria, Germany, and Finland, the rolling noise $L_{WR,i,m}$ and propulsion noise $L_{WP,i,m}$ for each vehicle category were first calculated for the Reference Road at a constant speed of 70 km/h. These calculations employed the mathematical expressions (1) and (2) and A and B coefficients available in Annex II of the CNOSSOS-EU documentation [40,53]:

$$L_{WR,i,m}(v_m) = A_{R,i,m} + B_{R,i,m} \times \log\left(\frac{v_m}{v_{ref}}\right) \text{ dB} \quad (1)$$

$$L_{WP,i,m}(v_m) = A_{P,i,m} + B_{P,i,m} \times \frac{(v_m - v_{ref})}{v_{ref}} \text{ dB} \quad (2)$$

where,

i: represents the 1/1 octave band centre frequencies from 63 Hz to 8000 Hz.

m: represents the vehicle category based on the CNOSSOS-EU vehicle classification.

v_m : represents the vehicle speed in km/h, while $v_{ref} = 70$ km/h [40].

Then, the total sound power level $L_{W,m}$ for each vehicle category for the Reference Road was obtained utilizing expression (3) [40].

$$L_{W,i,m}(v_m) = 10 \log \left(10^{\frac{L_{WR,i,m}(v_m)}{10}} + 10^{\frac{L_{WP,i,m}(v_m)}{10}} \right) \text{ dB} \quad (3)$$

Different road surface types have a notable influence on vehicle noise emissions [40]. For this reason, the CNOSSOS-EU methodology introduces two correction coefficients for each road surface type: the coefficient $\alpha_{i,m}$, which represents a frequency-dependent pavement absorption adjustment for each vehicle category [56], and the coefficient β_m , which varies only by vehicle category and accounts for additional surface-related effects [40]. These coefficients were derived from an extensive set of SPB measurements [72], although the CPX method may also be used for this purpose [43]. Consequently, the road surface correction factors for rolling noise $\Delta L_{WR,road,i,m}$ and propulsion noise $\Delta L_{WP,road,i,m}$ were calculated using expressions (4) and (5) [40].

$$\Delta L_{WR,road,i,m}(v_m) = \alpha_{i,m} + \beta_m \times \log\left(\frac{v_m}{v_{ref}}\right) dB \quad (4)$$

$$\Delta L_{WP,road,i,m}(v_m) = \min\{\alpha_{i,m}; 0\} dB \quad (5)$$

where,

$\alpha_{i,m}$: represents the spectral correction in dB at reference speed v_{ref} for category m (1, 2, or 3) and spectral band i (octave band from 125 Hz to 4000 Hz).

β_m : represents the speed effect on rolling noise reduction for category m (1, 2, or 3).

The β coefficient is in theory frequency-dependent. However, the CNOSSOS-EU adopts a constant value because no spectral data were available in the literature to support frequency-resolved values [40].

It is also important to note that the propulsion noise correction factor is identical to the rolling noise correction factor at the reference speed, with an upper limit of zero. This implies that porous road surfaces may reduce propulsion noise, whereas dense surfaces do not lead to any increase [40]. Furthermore, all road surfaces were evaluated at a vehicle speed of $v_m = 70 \text{ km/h}$, except for those with a maximum permissible speed of 60 km/h, such as paving block surfaces, which were assessed at 60 km/h.

After determining the rolling and propulsion noise correction factors, the total sound power level for each road surface $L_{W,road,m}$ was obtained by adding these corrections to the corresponding rolling and propulsion sound power levels calculated for the Reference Road. This was carried out employing expressions (6), (7) and (8) [40].

$$L_{WR,road,i,m}(v_m) = L_{WR,i,m}(v_m) + \Delta L_{WR,road,i,m}(v_m) \text{ dB} \quad (6)$$

$$L_{WP,road,i,m}(v_m) = L_{WP,i,m}(v_m) + \Delta L_{WP,road,i,m}(v_m) \text{ dB} \quad (7)$$

$$L_{W,road,i,m}(v_m) = 10 \log \left(10^{\frac{L_{WR,road,i,m}(v_m)}{10}} + 10^{\frac{L_{WP,road,i,m}(v_m)}{10}} \right) \text{ dB} \quad (8)$$

The same steps were applied to calculate the sound power levels $L_{W,road,m}$ for all road surface types. Subsequently, the arithmetic difference between each road surface's L_W value and that of the CNOSSOS-EU Reference Road was calculated to obtain the noise emission deviation for each vehicle category, denoted as $\Delta L_{W,road,m}$. Negative calculated values indicate lower noise emissions relative to the Reference Road as shown in expression (9).

$$\Delta L_{W,road,m} = L_{W,road,m} - L_{W,Reference\ Road,m} \text{ dB} \quad (9)$$

Exceptions apply to Categories 4a and 4b, for which rolling noise is not influenced by pavement characteristics; therefore, road surface type is not expected to affect their sound emissions [40,73]. The assumptions made for the calculation of each road surface's L_W value are summarized in Table 1.

Table 1: Road Surface Parameters.

Parameter	Calculation Standard	Air Temperature	Tyres	Vehicle Speed	Road Surface Conditions
Assumption	CNOSSOS-EU (2021)	20 °C	Non-studded tyres	Constant, reference speed, 70 km/h*	Dry flat road surface

*Except for road surfaces allowing a maximum speed of 60 km/h.

This work assumes identical parameters and conditions

for all assessed road surface types. Consequently, any differences observed in the calculated noise emissions can be attributed solely to the influence of the road surface itself.

Figure 1 summarizes the sequence of steps followed to calculate the noise emission differences of the various road surface types relative to the Reference Road.

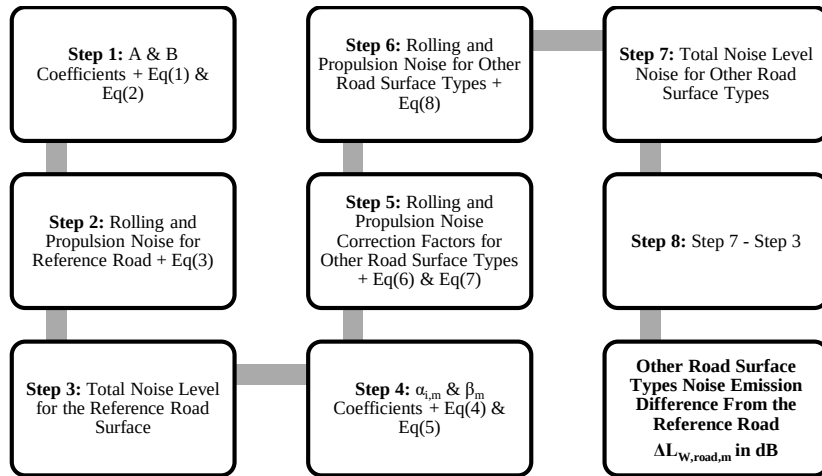


Figure 1: Noise Emission Difference Calculation Steps.

2.2.2 Road Surface Types in the Examined Countries

In Europe, road surface types and compositions vary considerably, resulting in notable differences in their acoustic behaviour. Within the CNOSSOS-EU framework, no unified procedure for assessing the acoustic properties of all pavement types has been identified in the literature [40]. Nevertheless, a guidance document providing recommendations for monitoring and verifying the acoustic classification of road surfaces has been published [74]. The current CNOSSOS-EU specification includes, in Annex II, tables of $\alpha_{i,m}$ and β_m coefficients for fourteen road surface types, ranging from low-noise pavements to

asphalt, concrete, and cobblestone surfaces, derived from the Dutch road traffic noise calculation method [31,44].

EU Member States are obliged to transpose the CNOSSOS-EU methodology into national legislation to meet the requirements of the upcoming round of strategic noise mapping [75]. However, this research focuses specifically on the road surface types available in widely used noise mapping software databases, including SoundPLAN, CadnaA, and IMMI. Table 2 provides an overview of the road surface types identified in Germany [76,77], Austria [77,78], and Finland [79,80], alongside those listed in the CNOSSOS-EU documentation [53]. The selection is based on broad pavement categories, such as asphalt concrete, cement concrete, and paving blocks [81,82]. Importantly, no direct correspondence between the rows is implied; the entries are presented sequentially within each surface type category. Each surface type is therefore listed independently according to its classification, without suggesting any hierarchical, functional, or relational alignment among the countries.

Table 2: Road Surface Types in the Examined Countries.

Surface Type\Country	CNOSSOS-EU	Germany	Austria	Finland
Reference	Reference surface - 0	National reference (non-fluted mastic asphalt) – G0	Reference surface – A0	Reference surface – F0

Surface Type\Country	CNOSSOS-EU	Germany	Austria	Finland
Bituminous Mixes/ Asphalt Concrete Surface - ACS	Single layer porous asphalt ZOAB – NL01	Open-pored asphalt PA 0/11 – G-ACS-1	Open porous asphalt – A-ACS-1	SMA/DAC 16 – F-ACS-1
	Two-layer porous asphalt ZOAB – NL02	Open-pored asphalt PA 0/8 – G-ACS-2	Noise-reducing stone mastic asphalt – A-ACS-2	SMA 8 – F-ACS-2
	Two-layer porous asphalt (fine) ZOAB – NL03	Stone mastic asphalt SMA 0/5 and SMA 0/8 – G-ACS-3	Stone mastic asphalt – A-ACS-3	
	Stone mastic asphalt SMA-NL5 – NL04	Stone mastic asphalt SMA 0/8 and SMA 0/11 – G-ACS-4	Asphalt concrete – A-ACS-4	
	Stone mastic asphalt SMA-NL8 – NL05	Low-noise mastic asphalt – G-ACS-5		
	Thin layer A – NL13	Noise-optimised asphalt SMA LA 0/8 – G-ACS-6		
	Thin layer B – NL14	Thin asphalt wearing courses in hot application (≥ 70 km/h) – G-ACS-7		
		Asphalt concrete AC 11 (≥ 70 km/h) – G-ACS-8		
		Noise-optimised asphalt AC D LOA – G-ACS-9		
Cement Concrete Surface – CCS	Brushed down concrete – NL06	Concretes according to ZTV Beton-StB 07 with washed concrete – G-CCS-10	washed concrete – A-CCS-5	

Surface Type\Country	CNOSSOS-EU	Germany	Austria	Finland
Cement Concrete Surface – CCS	Optimized brushed down concrete – NL07		Noise-reducing washed concrete GK8 – A-CCS-6	
	Fine broomed concrete – NL08		Noise-reducing washed concrete GK11 (2019) – A-CCS-7	
	Worked surface – NL09			
Paving Block Surface or Setts – PBS	Hard elements in herring bone – NL10	Hard elements with flat surface with $b \leq 5$ mm and $b+2f \leq 9$ mm – G-PBS-11		Even paving stones – F-PBS-3
	Hard elements not in herring bone – NL11	Hard elements with $b > 5$ mm or $f > 2$ mm or other hard elements – G-PBS-12		Uneven paving stones – F-PBS-4
	Quiet hard elements – NL12			

2.3 Results

Table 3 summarizes the outcomes of the $\Delta L_{W,road,m}$ calculations for light, medium-heavy, and heavy vehicles across the CNOSSOS-EU road surface types officially used in Germany, Austria, and Finland. Negative $\Delta L_{W,road,m}$ values represent reduced noise emissions relative to the Reference Road surface when assessed at a constant speed of 70 km/h, except for surfaces with a maximum permitted speed of 60 km/h, which were evaluated at that speed.

Since CNOSSOS-EU accounts only for propulsion noise in vehicle Categories 4a and 4b, variations in road surface type at the assessed speeds are not expected to affect the resulting emissions [40,41,73]. As such, they were not included in the evaluation.

Table 3: Sound Power Level Difference from the Reference Surface in dB.

Country	Pavement Type	Road Surface	$\Delta L_{W,road,m}$ in dB		
			m=1	m=2	m=3
CNOSSOS-EU	Reference	0	0	0	0
	ACS	NL01	-1.1	-3.1	-2.8
		NL02	-4.5	-5.3	-5.3
		NL03	-6.6	-5.8	-5.7
		NL04	-1.8	0	0
		NL05	-0.8	0	0
		NL13	-3.3	-1.3	-1.2
		NL14	-4.9	-1.3	-1.2
CNOSSOS-EU	CCS	NL06	1.8	-0.2	-0.2
		NL07	0.2	-1.9	-1.7
		NL08	1.7	2	2
		NL09	2.8	-0.4	-0.2
	PBS	NL10*	2.3	4.4	4.8
		NL11*	6.1	8.2	8.4
		NL12*	-1.4	2.2	2.2
Germany	National Reference	G0	0.9	3.5	3
	ACS	G-ACS-1	-4	-1.9	-3.1
		G-ACS-2	-5.3	-4.4	-5.2
		G-ACS-3*	-1.5	1.0	0.1
		G-ACS-4	-1	1.6	0.7
		G-ACS-5	-1.2	2	1.3
		G-ACS-6	-2.1	-2	-3.2
		G-ACS-7	-2	1.1	0.2
		G-ACS-8	-1.1	1.5	0.5
		G-ACS-9*	-2.4	1.5	0.2
	CCS	G-CCS-10	-0.4	1.1	0.5
	PBS	G-PBS-11*	3	4.1	3.1
		G-PBS-12*	7	7.8	6.9
Austria	Reference	A0	0	0	0
	ACS	A-ACS-1	-3.7	-3.1	-3.3

Country	Pavement Type	Road Surface	$\Delta L_{W,road,m}$ in dB		
			m=1	m=2	m=3
Austria	ACS	A-ACS-2	-3	-1.1	-1.1
		A-ACS-3	0	0.8	0.9
		A-ACS-4	-0.5	1.3	1.5
	CCS	A-CCS-5	0.9	0.9	0.9
		A-CCS-6	-0.1	0.1	0.1
		A-CCS-7	2.3	3.8	4.1
	Reference	F0	0	0	0
Finland	ACS	F-ACS-1	1.5	0.9	1
		F-ACS-2	-0.5	-0.5	-0.5
	PBS	F-PBS-3*	2.7	1.0	1.1
		F-PBS-4*	5.6	2.2	2.4

*Surfaces with a maximum permitted speed of 60 km/h.

2.3.1 Comparison of Sound Power Level Differences for the CNOSSOS-EU Road Surfaces

Figure 2 illustrates the noise reduction performance of the road surfaces included in Annex II of the CNOSSOS-EU document for light, medium and heavy motor vehicles. The results show that Asphalt Concrete Surfaces provide the greatest reduction in noise relative to the Reference Road. They also produce lower emissions for Category 1 vehicles, except for surface type NL01.

Moreover, road surfaces, such as NL13 and NL14 are more suitable for road sections with a higher share of light vehicle traffic, whereas NL07 performs better on roads where a larger number of medium and heavy vehicle pass-bys are expected. The road surface with the highest noise reduction capabilities is NL03, which reduces noise by 6.6 dB for light motor vehicles and by an average of 5.75 dB for Category 2 and 3 vehicles.

In contrast, NL11 surface can increase emissions by 6.1 dB for Category 1 vehicles and by an average of 8.3 dB for Categories 2 and 3. Given that the maximum permitted

speed on Paving Block Surfaces is 60 km/h [40], the use of such surfaces is generally discouraged in densely populated urban areas, particularly in new developments.

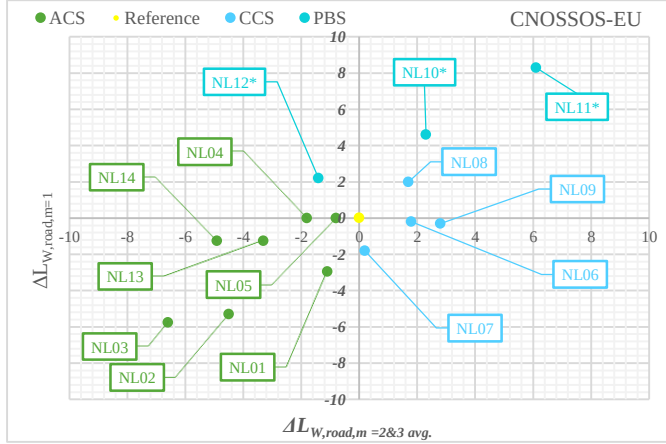


Figure 2: Noise Reduction Capabilities of the CNOSSOS-EU Road Surfaces.

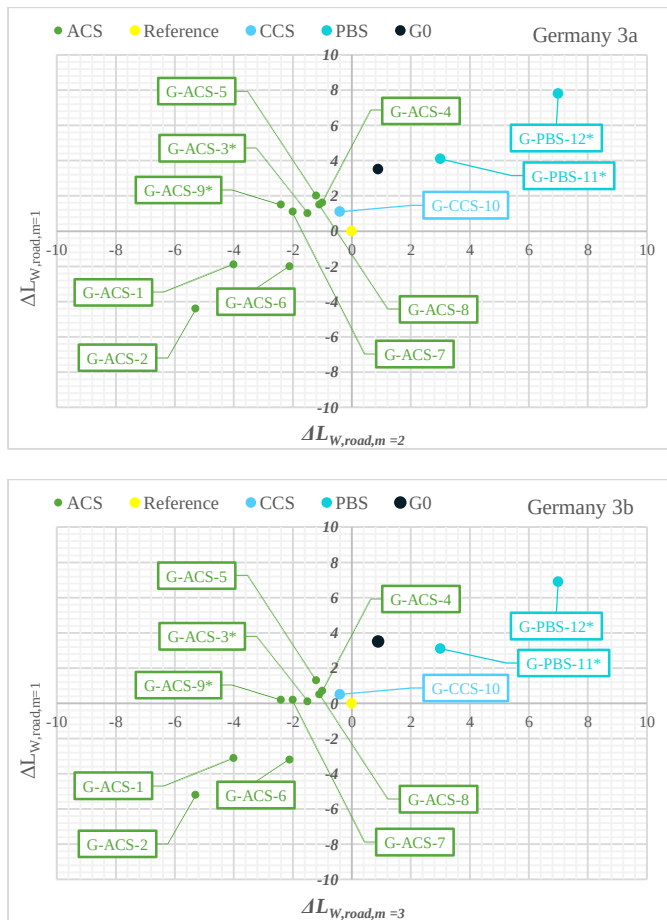
2.3.2 Comparison of Sound Power Level Differences for the German Road Surfaces

In Germany, G-ACS-2 surface exhibited the greatest noise reduction performance across all vehicle categories, whereas the G-PBS-12 surface led to a substantial increase in sound emissions. Unlike the CNOSSOS-EU road surfaces, the G-CCS-10 surface was also found to increase emissions for Category 2 and Category 3 vehicles.

German road surfaces showed pronounced variability in the noise emissions between Category 2 and Category 3 vehicles compared with other countries, with Category 2 vehicles producing higher emissions. As a result, averaging the noise reduction values of these two categories does not accurately represent the behaviour of each category. This discrepancy is linked to the $\alpha_{i,m}$ and β_m coefficients derived from German measurement data, which differ

considerably between the two categories. Since the β_m coefficient is assumed to be frequency independent and constant [40,76], these fluctuations warrant further investigation.

Figures 3a/b illustrate the noise reduction performance of German road surfaces by comparing light motor vehicles with medium-heavy vehicles, and light motor vehicles with heavy vehicles, respectively.



Figures 3a/b: Noise Reduction Capabilities of the German Road Surfaces.

2.3.3 Comparison of Sound Power Level Differences for the Austrian and the Finnish Road Surfaces

In Austria and Finland, a smaller selection of road surfaces was assessed during the transposition of CNOSSOS-EU into national legislation, with Austria evaluating no PBS and Finland evaluating no CCS [77,78,79]. In Austria, A-ACS-1 surface showed the greatest noise reduction performance across all vehicle categories, whereas A-CCS-7 surface showed the weakest noise reduction.

In Finland, ACS types exhibited little to no effect on noise emissions relative to the Reference Road surface for all categories. On the other hand, both PBS types were found to increase noise emissions rather than reduce them across all vehicle categories.

Figure 4 presents a comparison of the noise reduction performance of the representative Austrian and Finnish road surfaces, used in strategic noise mapping applications, for light, medium and heavy motor vehicles.

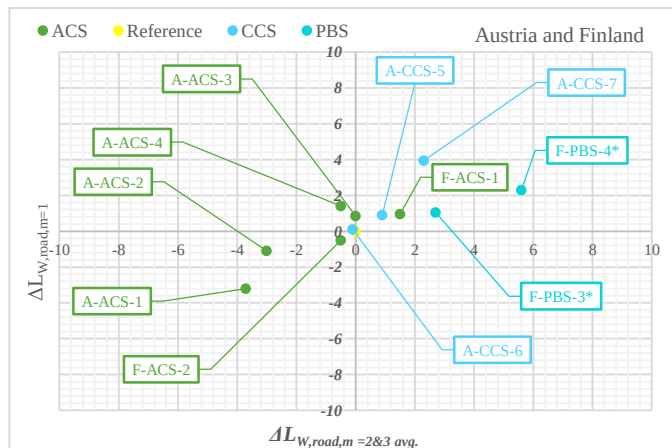


Figure 4: Noise Reduction Capabilities of Austrian and Finnish Road Surfaces.

3 Impact of the ISO 9613-2:2024 Updates on Outdoor Sound Propagation

3.1 Introduction

This section examines the impact of the ISO 9613-2:2024 updates on outdoor sound propagation. Sound propagation models are essential for predicting how noise travels from a source to a receiver under varying environmental conditions, including ground and obstacles effects. With the recent updates to the ISO 9613-2, it is important to assess how these modifications influence prediction accuracy and overall model behaviour. Therefore, this section analyses the differences between previous and updated formulations, focusing on the resulting changes in sound attenuation and their implications for environmental noise assessment. The analysis follows a structured approach. It begins with a review of the revised ISO 9613-2 methodology, which relies on octave band calculations to predict outdoor sound levels while accounting for ground effects, atmospheric absorption, geometrical divergence, reflections, and screening by obstacles [47,48]. It then examines the influence of the refinements by applying them within a commercial noise mapping software, SoundPLAN 9.1, and presenting the resulting noise maps.

3.2 Materials and Methods

The present section introduces the key ISO 9613-2 parameters considered in the noise modelling process and outlines the principal updates included in the 2024 revision, particularly those related to advances in outdoor

sound propagation modelling.

The ISO 9613-2:2024 edition incorporates several clarifications adopted from the ISO 17534-3, including improvements to screening effects calculations [52]. The mathematical refinements examined in this research are as follows:

- K_{geo} : a geometric correction factor that eliminates ground effect attenuation (A_{gr}) under certain height conditions,
- A_{bar} : barrier attenuation,
- A_{curv} : which considers additional attenuation from curved surfaces,
- A_{fol} : foliage attenuation, and
- D_c : chimney stack directivity factor.

3.2.1 Ground Effect Correction Factor

The K_{geo} factor introduced in the 2024 revision sheds light on the need to account for ground interactions with propagating sound waves. It depends both on the ground surface characteristics and source-receiver geometry, and is defined as highlighted in expression (10) [48]:

$$K_{geo} = \frac{d_p^2 + (h_s - h_R)^2}{d_p^2 + (h_s + h_R)^2} \quad (10)$$

where,

d_p : represents the source to receiver distance projected on the horizontal plane, expressed in meters.

h_s : represents the height of the source above ground, expressed in meters.

h_R : represents the height of the receiver above ground,

expressed in meters.

The introduction of this factor required a revision of the existing expression for calculating the ground-effect attenuation A_{gr} in dB for a specific frequency band as illustrated in expressions (11) and (12) [48]:

$$A_{gr} = 10 \log[1 + (10^{\frac{-A'_{gr}}{10}} + 1) \times K_{geo}] \quad (11)$$

$$A'_{gr} = A_S + A_R + A_m \quad (12)$$

where,

A_S : represents the source region, stretching over a distance from the source towards the receiver of $30 h_S$, with a maximum distance of d_p , and calculated based on the ground factor (G_S).

A_R : represents the receiver region, stretching over a distance from the receiver back towards the source of $30 h_R$, with a maximum distance of d_p , and calculated based on the ground factor (G_R).

A_m : represents a middle region, stretching over the distance between the source and receiver regions, and calculated based on the ground factor (G_m). If $d_p < (30 h_S + 30 h_R)$, the source and receiver regions will overlap, and there is no middle region.

In summary, the K_{geo} factor effectively suppresses the ground effect contribution when the source and receiver heights are large relative to their separation distance. This behaviour aligns with findings in the literature, which emphasized the need for such a correction to improve modelling accuracy and address inconsistencies in ground-reflection treatment in earlier methods [83].

3.2.2 Cylindrical Surface Reflections

ISO 9613-2:2024 introduces significant refinements in two main areas; planar reflections and curved structure reflections, such as chimney stacks, storage tanks and silos. A new reflection model for cylindrical surfaces has been incorporated, enabling the calculation of additional attenuation as a function of the cylinder radius and the angle of incidence.

The behaviour of sound waves interacting with curved surfaces highlights limitations in earlier modelling approaches, particularly in urban environments. Curved architectural elements can create unintended focal points and localized sound amplification [84], underscoring the need for improved modelling tools to support acoustic robust design.

Further updates address diffraction and screening. Complex barrier configurations or multi-screen arrangements [85] often lead to an underestimation of noise reduction when the single edge diffraction model of the ISO 9613-2:1996 is applied. The revised standard enhances this by introducing side screening factors that account for diffraction across multiple edges, resulting in more accurate predictions of screening attenuation.

Figure 5 explains the expected behaviour of sound rays reflecting from a cylindrical surface.

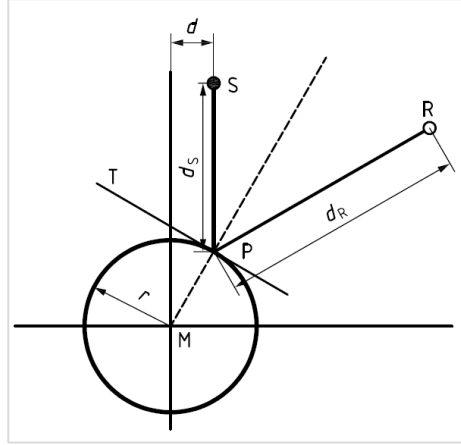


Figure 5: Sound Ray Reflection at a Cylinder [48].

The additional attenuation term introduced in the 2024 version, A_{curv} , extends the model to include reflections from cylindrical surfaces, expressed in dB. The term is defined as illustrated in expressions (13) and (14) [48]:

$$A_{\text{curv}} = 10 \log \left[1 + \frac{2d_s d_R}{r(d_s + d_R)} (1 - k^2)^{-\frac{1}{2}} \right] \quad (13)$$

$$k = \frac{d}{r} \quad (14)$$

where,

M: represents the centre-point.

S: represents the point source.

R: represents the receiver.

r: represents the radius, expressed in meters.

P: represents the point of reflection.

T: represents the tangent in the point of reflection.

d_s : represents the source-receiver distance, expressed in meters.

d_R represents the point of reflection-receiver distance, expressed in meters.

d: represents the distance of the straight line defined by the incident ray from the centre-point, expressed in meters.

3.2.3 Enhanced Screening Calculations

As noted earlier, the updated version of the standard provides a substantially expanded treatment of screening effect. This effect varies with the height at which noise is measured and with the distances between the sound source, the barrier, and the receiver [86]. The improvement is achieved by refining the calculation of the barrier attenuation, A_{bar} , which is determined using the minimum difference between the direct sound path (as if no barrier were present) and the diffracted path over the barrier, Z_{min} . This refinement is particularly valuable in multi-edge diffraction scenarios commonly present in urban environments.

In addition, the ISO 9613-2:2024 incorporates the reflection condition recommended in the ISO 17534-3. The barrier attenuation, A_{bar} , expressed in dB, represents the sound reduction due to the presence of a barrier and is calculated as summarized in expressions (15) and (16) [48]:

If $A_{gr} > 0$, then

$$A_{bar} = D_z - A_{gr} > 0 \quad (15)$$

And, if $A_{gr} < 0$, then

$$A_{bar} = D_z > 0 \quad (16)$$

where,

D_z : represents the diffraction attenuation of the barrier for each octave band.

A_{gr} : represents the ground attenuation in the absence of the barrier.

3.2.4 Chimney Stack Directivity

The 2024 revision also introduces a directivity correction factor for chimney stacks, D_c . In the ISO 9613-2:1996, stacks were treated as point sources with an assumed omnidirectional radiation pattern. However, the updated standard recognizes that industrial stacks have pronounced directional behaviours, making a correction factor necessary for accurate receiver level calculations. The new term, D_c , embedded in the 2024 update, accounts for this behaviour as a function of the stack opening geometry and its frequency-dependent radiation characteristics. As a result, the chimney stack directivity correction is incorporated into the calculation of the equivalent continuous downwind octave band source sound pressure level at the location of the receiver.

3.2.5 Foliage Attenuation

Finally, the ISO 9613-2:2024 introduces a substantially more detailed method for estimating foliage attenuation, A_{fol} , whereas the 1996 edition relied on a simple empirical correction applicable only to tree belts or general vegetation. The updated method incorporates five forestry-related parameters: horizontal structuring (S), low height foliage (Z), stem diameter (D) and basal area (G).

Previous research has shown that vegetation density, thickness, and structural characteristics have a significant influence on sound attenuation in both urban and suburban environments [87], making this enhancement consistent with established findings.

In addition, the 2024 revision introduces a frequency-dependent attenuation factor, K_{lin} , to improve prediction

accuracy under varying environmental conditions. Figure 6 illustrates the typical ranges of K_{lin} as specified in the ISO 9613-2:2024 [48].

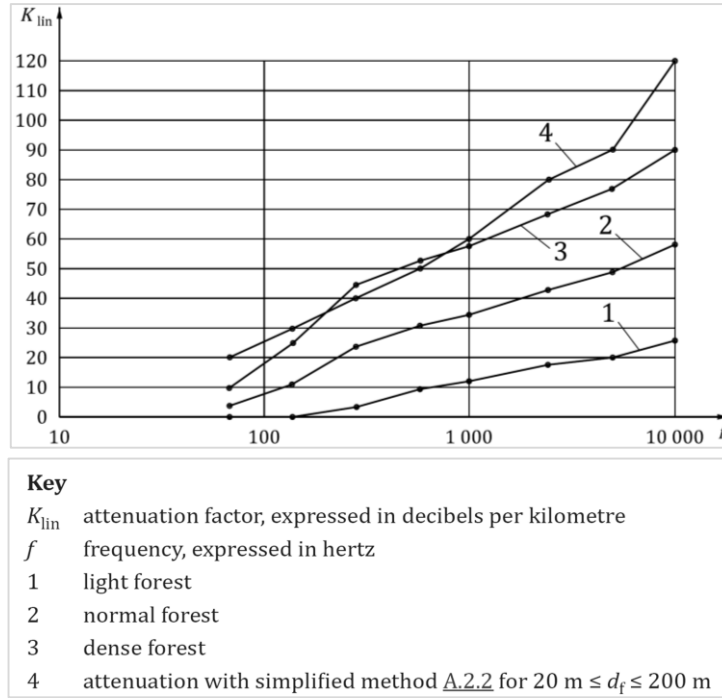


Figure 6: Typical K_{lin} Factors for Different Forestry Parameters [48].

3.3 Results

This section presents the results of three key updates introduced in the ISO 9613-2:2024, namely: the revised ground effect correction factor, the new treatment of cylindrical surface reflections, and the updated chimney stack directivity, and compares their influence on outdoor sound propagation against the corresponding approaches in the 1996 edition. The influence of these three updates was evaluated using SoundPLAN 9.1, and the resulting differences relative to ISO 9613-2:1996 are presented in the form of noise maps in the following sub-sections.

3.3.1 Ground Effect Correction Factor

To assess the influence of K_{geo} on outdoor sound propagation, two scenarios were modelled assuming a fully reflective ground surface ($G=0$), and noise maps were produced to illustrate the differences between the 1996 and 2024 versions of the standard. In Figure 7, a point source was positioned 50 m above ground level, and a vertical cross-sectional noise map was generated to visualize the resulting level differences. At short horizontal distances and at the same height as the source, a difference of approximately 3 dB was observed. This behaviour is consistent with the fact that K_{geo} eliminates the ground effect contributions when both source and receiver heights are large relative to their separation distance. In contrast, Figure 8 shows the case where the source was placed 2 m above ground level, in which the difference between the two ISO 9613-2 versions becomes negligible.

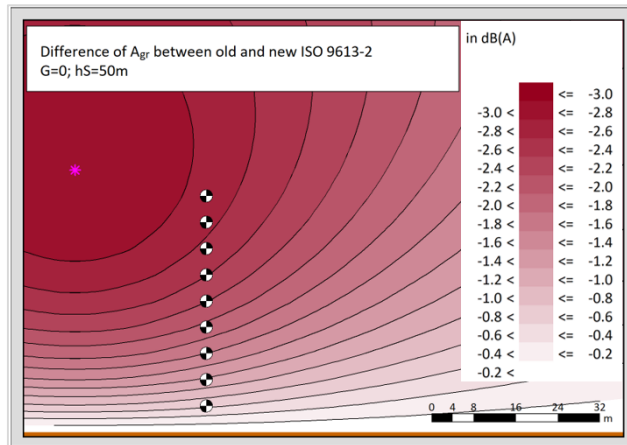


Figure 7: A_{gr} Difference between the 1996 and 2024 ISO 9613-2. Source Height: 50 m AGL.

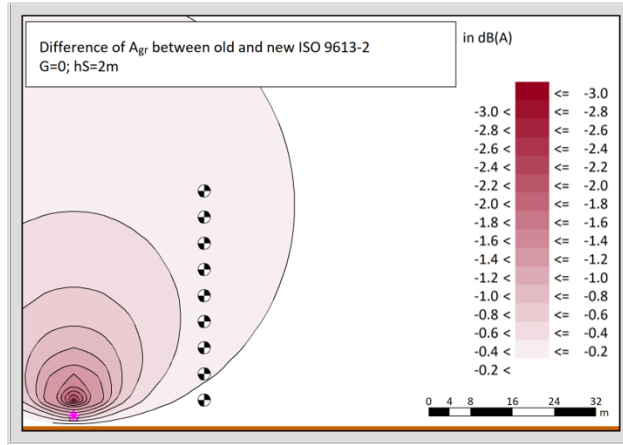


Figure 8: A_{gr} Difference between the 1996 and 2024 ISO 9613-2. Source Height: 2 m AGL.

3.3.2 Cylindrical Surface Reflections

Figure 9 and Figure 10 illustrate the differences in sound-ray reflections between polygonal and cylindrical objects across the 1/1 octave bands from 63 Hz to 8000 Hz. The parameter A_{curv} was not defined in the 1996 version, meaning that cylindrical surfaces had to be modelled as polygons. With the introduction of A_{curv} in the ISO 9613-2:2024, full cylindrical objects can now be implemented, allowing additional reflection points to be considered.

The results show that cylinders produce continuous reflections across all frequencies, whereas polygons show very limited reflections up to 500 Hz and then generate straight line reflection patterns from 1 kHz to 8 kHz due to their multi-edge geometry.

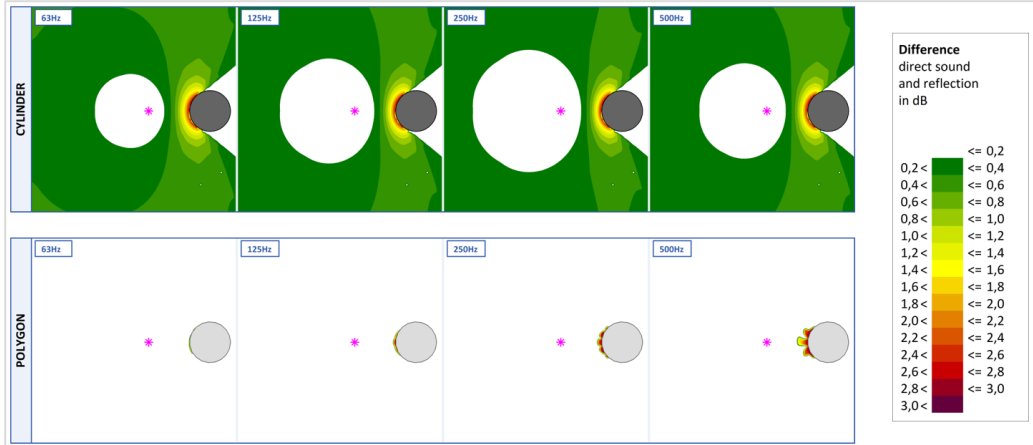


Figure 9: Direct Sound and Reflection Difference for 1/1 Octave Bands from 63 Hz to 500 Hz at Polygon and Cylinder Objects.

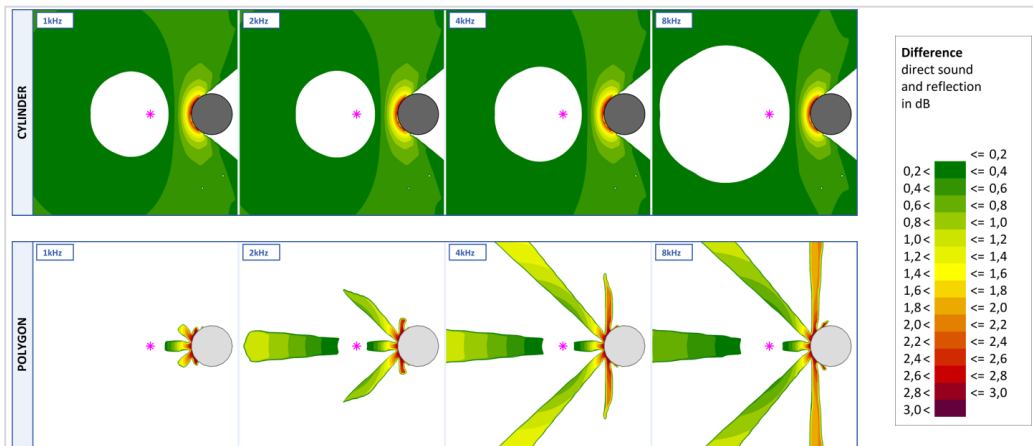


Figure 10. Direct Sound and Reflection Difference for 1/1 Octave Bands from 1 kHz to 8 kHz at Polygon and Cylinder Objects.

3.3.3 Chimney Stack Directivity

Chimney stacks and other vertical, upward-facing openings are modelled as point sources located at the centre of the opening in the ISO 9613-2:1996, with the assumption of omnidirectional radiation. However, a frequency-dependent directivity correction factor, D_c , is introduced in the ISO 9613-2:2024 and is considered in

noise mapping software based on tables derived from measurement data obtained from large industrial chimneys [48].

Figure 11 shows the resulting sound propagation patterns at 125 Hz and 4000 Hz after applying D_c in SoundPLAN 9.1. Incorporating this directivity adjustment is expected to improve the precision and accuracy of noise modelling results when compared with in-situ sound propagation behaviour of chimney stacks.

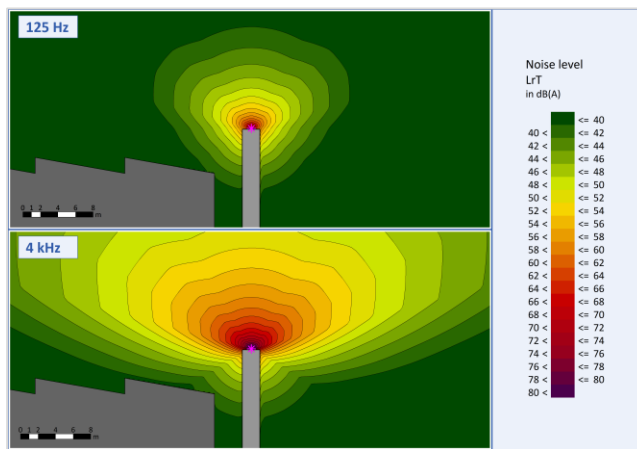


Figure 11: Sound Propagation of a Chimney Stack with 1 m Radius Implementing Directivity Correction at 125 Hz and 4 kHz.

4 Comparison of the CNOSSOS-EU and the ISO 9613-2 Predictions with Field Measurements

4.1 Introduction

This section presents a comparative evaluation of the CNOSSOS-EU and ISO 9613-2 noise prediction models against real-world field measurements. Accurate validation is essential to determine how well these models represent actual environmental noise conditions under varying traffic and propagation scenarios. Therefore, this section outlines the measurement setup, data collection procedures, and modelling approaches applied to both methods, followed by an analysis of the differences between predicted and observed noise levels. The comparison provides insight into the accuracy, reliability, and practical applicability of each model, as well as identifying potential sources of deviation and areas for improvement in environmental noise prediction.

4.2 Materials and Methods

To assess the accuracy of the CNOSSOS-EU and the ISO 9613-2 road traffic models, this case study applies a combined approach integrating noise measurements with noise modelling. The present section summarizes the methods, materials, assumptions and parameters implemented in the SoundPLAN 9.1 noise modelling software for each model.

4.2.1 Methodology

A consecutive eight-day noise measurement campaign was carried out during daytime hours (9:00–17:00) along a road segment with relatively low daily traffic volumes. Equivalent continuous sound pressure levels were collected simultaneously at two measurement points, MP1 and MP2, with recordings taken every 15 minutes, $L_{Aeq,15min}$. The two points were positioned perpendicular to the road section, as presented in Figure 13.

MP1 was placed 6 m from the road centreline at a height of 1.75 m above ground level, to represent near-field propagations. MP2 was positioned 65 m from the centreline at a height of 4.65 m, representing far-field propagation. It is important to highlight that the ground level at MP1 was roughly 2 m higher than at MP2 due to the presence of the road embankment. Figure 12 shows the distances between MP1, MP2 and the centreline of the road.

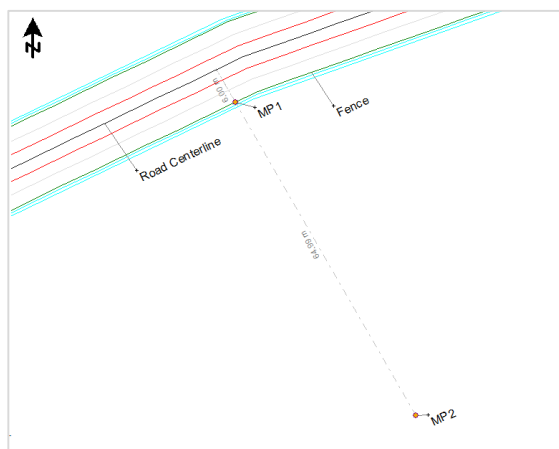


Figure 12: MP1 and MP2 Distances from the Centreline.

The measured data were subsequently processed to calculate the hourly average noise levels, $L_{Aeq,1h}$, for the

daytime period. Table 4 shows an example of how the 15-minute values, $L_{Aeq,15min}$, were combined to obtain the hourly averages using expression (17) [88].

$$L_{Aeq,1h} = 10 \log \left(\frac{10^{\frac{L_{Aeq,15m}}{10}} + 10^{\frac{L_{Aeq,15m}}{10}} + 10^{\frac{L_{Aeq,15m}}{10}} + 10^{\frac{L_{Aeq,15m}}{10}}}{4} \right) \quad (17)$$

The same procedure was applied to all measurement data to derive the corresponding $L_{Aeq,1h}$ values.

For the noise modelling step, ten hours representing peak weekday traffic (Monday–Friday) during daytime were selected. These hours were considered representative of the full measurement campaign, as the recorded noise levels showed very little variation between days due to the low and steady traffic volumes indicating consistent weekday traffic behaviour.

Table 4: Measurement Data Processing.

Measurement Point	Measurement Time	L _{Aeq,15min}	L _{Aeq,1h}
MP1	9:00-9:15	74.80	73.73
	09:15-09:30	73.20	
	09:30-09:45	73.10	
	09:45-10:00	73.60	
MP2	9:00-9:15	59.20	58.20
	09:15-09:30	57.60	
	09:30-09:45	58.20	
	09:45-10:00	57.70	
MP1	10:15-10:30	74.40	73.60
	10:30-10:45	73.30	
	10:45-11:00	73.30	
	11:00-11:15	73.30	
MP2	10:15-10:30	58.40	58.11
	10:30-10:45	58.40	
	10:45-11:00	58.50	
	11:00-11:15	57.80	
MP1	11:30-11:45	73.70	73.22
	11:45-12:00	73.40	
	12:00-12:15	73.10	
	12:15-12:30	72.60	
MP2	11:30-11:45	58.30	57.82
	11:45-12:00	58.00	
	12:00-12:15	57.60	
	12:15-12:30	57.20	
MP1	12:45-13:00	73.40	73.18
	13:00-13:15	73.40	
	13:15-13:30	72.90	
	13:30-13:45	73.00	
MP2	12:45-13:00	57.60	57.50
	13:00-13:15	57.90	
	13:15-13:30	57.00	
	13:30-13:45	57.10	
MP1	14:00-14:15	74.10	73.20
	14:15-14:30	73.00	
	14:30-14:45	71.90	
	14:45-15:00	73.50	
MP2	14:00-14:15	58.80	57.90
	14:15-14:30	57.50	
	14:30-14:45	56.80	
	14:45-15:00	58.30	

Measurement Point	Measurement Time	L _{Aeq,15min}	L _{Aeq,1h}
MP1	15:15–15:30	74.50	74.11
	15:30–15:45	74.00	
	15:45–16:00	73.80	
	16:00–16:15	74.10	
MP2	15:15–15:30	59.00	59.10
	15:30–15:45	59.00	
	15:45–16:00	58.60	
	16:00–16:15	59.30	
MP1	12:00–12:15	73.00	72.54
	12:15–12:30	72.10	
	12:30–12:45	72.60	
	12:45–13:00	72.40	
MP2	12:00–12:15	56.80	57.00
	12:15–12:30	56.70	
	12:30–12:45	57.30	
	12:45–13:00	57.30	
MP1	13:00–13:15	73.20	73.43
	13:15–13:30	73.00	
	13:30–13:45	74.20	
	13:45–14:00	73.20	
MP2	13:00–13:15	57.80	58.10
	13:15–13:30	57.50	
	13:30–13:45	58.90	
	13:45–14:00	58.30	
MP1	14:45–15:00	73.20	73.79
	15:00–15:15	74.00	
	15:15–15:30	73.70	
	15:30–15:45	74.20	
MP2	14:45–15:00	58.60	58.80
	15:00–15:15	59.50	
	15:15–15:30	58.60	
	15:30–15:45	58.80	
MP1	15:45–16:00	73.60	74.15
	16:00–16:15	74.40	
	16:15–16:30	74.70	
	16:30–16:45	74.80	
MP2	15:45–16:00	58.30	58.72
	16:00–16:15	58.80	
	16:15–16:30	58.60	
	16:30–16:45	59.10	

During the measurement campaign, it was noted that the surrounding terrain was generally flat, except for the road itself, which sits on an embankment and is raised by about 2 m above the nearby ground. The road surface is characterized as hard ground, while the neighbouring agricultural fields correspond to soft ground conditions. Figures 14a/b/c illustrate the site conditions observed during the measurement campaign.

The galvanized steel safety fence shown in Figure 13 was also measured and was found to have a thickness of roughly 0.3 m and a height of 0.5 m above the road surface. Average meteorological conditions during the campaign were 15 °C air temperature, 1013.3 mbar atmospheric pressure, and 70% relative humidity.



Figure 13: Adjustment of MP1 and MP2 In-Situ.

These observations and measurements were then used to construct the base noise model in SoundPLAN 9.1. In the model setup, the road surface was assigned a ground factor of 0 to represent acoustically hard, non-absorbing ground, while the surrounding agricultural land was assigned a ground factor of 1 to represent acoustically soft, highly

absorbing ground [47,48,89]. The modelling approaches examined in this case study include the CNOSSOS-EU road traffic noise model, as well as the ISO 9613-2:1996 and ISO 9613-2:2024 Point Source and Line Source models.

In this study, the simulations were performed using SoundPLAN 9.1, a professional environmental noise modelling software widely used in engineering practice and regulatory assessments. The software provides a comprehensive set of tools for building detailed 3D environments, such as buildings and roads. It allows for managing ground type data and incorporating meteorological and traffic flow parameters. It also supports multiple standardized noise calculation methods, including the CNOSSOS-EU and both versions of the ISO 9613-2 (1996 and 2024), allowing direct comparison of modelling approaches within the same framework. SoundPLAN also enables the integration of measurement data, flexible source definitions, and advanced visualization of noise contours, making it suitable for evaluating the methodological differences examined in this research.



Figures 14a/b/c: Site Conditions Observed During the Measurement Campaign.

The following sub-sections outline the modelling configuration and the parameters applied for each approach.

4.2.2 The CNOSSOS-EU Model Setup

As discussed earlier, the CNOSSOS-EU road traffic noise model classifies vehicles into five categories based on their weight and number of axles. It also considers an equivalent noise source positioned 0.05 m above the road level to account for the effective height of the tyre-road interaction noise [40].

The number of vehicles passing a road section per hour, expressed as veh/h, is a required input to build the model. Therefore, Table 5 presents the traffic counts recorded during the measurement campaign for the ten representative hours used in the modelling exercise.

Table 5: Traffic Counts for the Representative Ten Hours in veh/h.

Vehicle Category	Measurement Hour									
	h 1	h 2	h 3	h 4	h 5	h 6	h 7	h 8	h 9	h 10
	9:00- 10:00	10:15- 11:15	11:30- 12:30	12:45- 13:45	14:00- 15:00	15:15- 16:15	12:00- 13:00	13:00- 14:00	14:45- 15:45	15:45- 16:45
Cat 1	326	293	317	378	353	550	360	380	474	636
Cat 2	28	30	22	17	26	23	17	30	30	26
Cat 3	53	49	49	37	33	38	30	40	29	13
Cat 4a	0	0	0	0	0	0	0	0	0	0
Cat 4b	0	0	0	0	0	0	0	0	0	0

Several additional factors affect the CNOSSOS-EU road traffic noise model, including vehicle speed and the type of road surface [36,40]. To achieve reliable results, all necessary modelling inputs were gathered during the measurement campaign and supplemented with information from official local sources. Table 3 provides an overview of the parameters applied in the CNOSSOS-EU model.

Table 6: Parameters of the CNOSSOS-EU Model.

Parameter	Vehicle Speed	Tyres	Road Surface Type	Lane Width
Value	Constant, 80 km/h*	Non-studded Tyres	B217 SMA-11	3.9 m
Source	Measurement	Measurement	Hungarian Local Road Authority [90]	Measurement

*Represents the average speed.

The Ministry of Justice of Hungary implemented the transposition of the CNOSSOS-EU into the national law officially in June 2025 and the most common road surface types available in the country and their $\alpha_{i,m}$ and β_m coefficients were published officially [91]. Table 7 summarizes those coefficients for the crushed stone mastic asphalt road surface type, B217 SMA-11, considered in the model.

Table 7: $\alpha_{i,m}$ and β_m Coefficients for B217 SMA-11 [90,91].

Road Surface Type	Vehicle Category	$\alpha_{i,m}$								β_m
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	
B217 SMA-11	Cat 1	1.3	1.3	1.4	0.4	0.1	-1.1	-1.3	-0.5	4.9
	Cat 2	2.2	2.6	2.7	1.5	0.7	0.4	0.7	1.5	5.7
	Cat 3	1.7	1.6	3.1	0.7	0.7	0.8	1.1	1.4	4.2

After that, the emission time slice was defined as 1 hour, and the noise levels at MP1 and MP2 were predicted for the ten representative hours using the traffic count data shown in Table 5. Figure 15 presents the CNOSSOS-EU road traffic noise model in SoundPLAN 9.1.

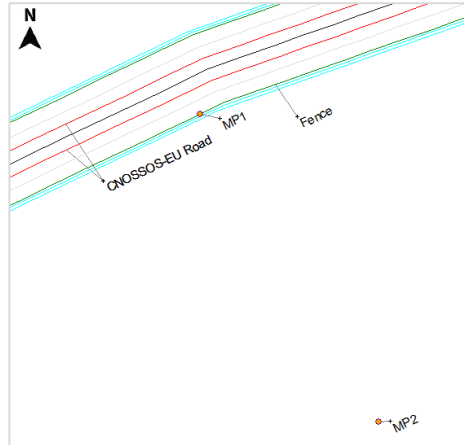


Figure 15: CNOSSOS-EU Model in SoundPLAN 9.1.

4.2.3 The ISO 9613-2 Model Setups

Within the ISO 9613-2 framework, this case study evaluates two modelling approaches, point source and line source as follows:

- ISO 9613-2:1996 Point and Line Source models
- ISO 9613-2:2024 Point and Line Source models

The point source models were configured with a single point source positioned at the centreline of the road, perpendicular to MP1, at a height of 0.05 m above ground level to maintain consistency with the CNOSSOS-EU model setup. The sound power level of the point source was back calculated from the measured $L_{Aeq,1h}$ at MP1 for the ten representative hours and then used to simulate the hourly equivalent noise levels, $L_{Aeq,1h}$, at MP2. This method was applied to evaluate the far field propagation in both versions of ISO 9613-2 due to the lack of sound power level data of the vehicles. For the line source models, the same configuration was adopted, with the only difference being that the point source was replaced by a continuous line source extending along the entire road section, also

positioned at 0.05 m above ground level.

Since this case study evaluates road traffic noise, it is limited to highlighting the impact of K_{geo} and A_{bar} on the modelled results which were introduced in the ISO 9613-2:2024. Accordingly, the study does not seek to assess the full scope of the standard. Instead, it concentrates on how these specific updates affect the accuracy of the sound propagation predictions under the selected measurement conditions, with the goal of determining which approach most closely reflects the noise levels observed at MP1 and MP2.

Figure 16 presents the ISO 9613-2 Point Source model built in SoundPLAN 9.1.

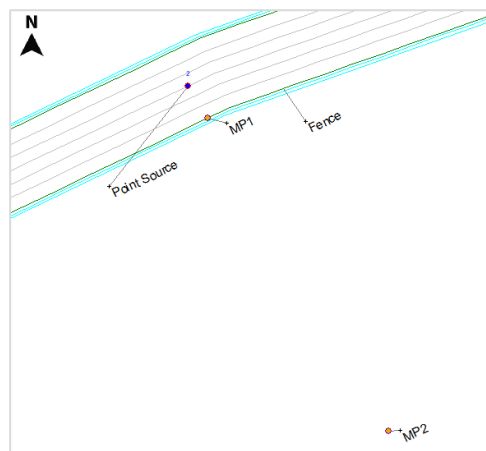


Figure 16: ISO 9613-2 Point Source Model in SoundPLAN 9.1.

Figure 17 presents the ISO 9613-2 Line Source model built in SoundPLAN 9.1.

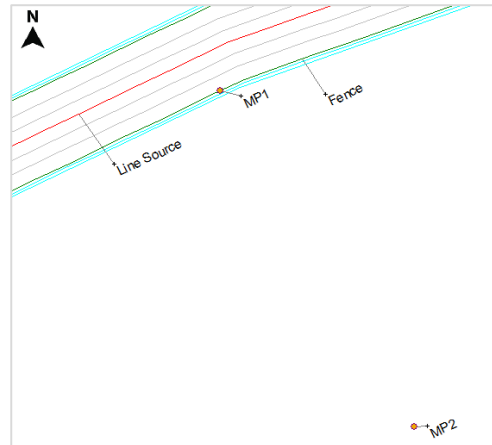


Figure 17: ISO 9613-2 Line Source Model in SoundPLAN 9.1.

The noise modelling exercise was carried out for two modelling scenarios to assess the influence of roadside infrastructure on outdoor sound propagation. In the first scenario, the galvanized metal safety fence was excluded from the model to represent free-field sound transmission. In the second scenario, the fence was included to evaluate how its presence alters the propagation path and affects predicted noise levels. Comparing these two configurations provided a clear assessment of the fence's impact on the acoustic environment.

4.3 Results

This section presents the findings of the case study comparing the CNOSSOS-EU road traffic noise model with both the 1996 and 2024 versions of ISO 9613-2, evaluated using Point Source and Line Source model approaches, against noise measurements collected along a road segment in Debrecen, Hungary. Table 8 summarizes the measured hourly sound levels, $L_{Aeq,1h}$, for the ten representative hours at MP1 and MP2. It was observed that across all measurement hours, the recorded noise levels at MP1 are approximately 15 dB(A) higher than at MP2, which is attributed to the locations of the two measurement points. This consistent gap indicates that road traffic noise is the dominant source at the site, and that background (ambient) noise plays only a minor role.

Based on these observations, it is reasonable to assume that the measured noise levels predominantly represent road traffic noise without significant interference from other environmental sources, thereby validating the direct comparison between the models and the measurement results presented in this research.

Table 8: Measured Noise Levels, $L_{eq,1h}$, in dB(A).

MP	Measurement Time									
	h 1	h 2	h 3	h 4	h 5	h 6	h 7	h 8	h 9	h 10
	9:00-10:00	10:15-11:15	11:30-12:30	12:45-13:45	14:00-15:00	15:15-16:15	12:00-13:00	13:00-14:00	14:45-15:45	15:45-16:45
MP1	73.73	73.60	73.22	73.18	73.20	74.11	72.54	73.43	73.79	74.15
MP2	58.20	58.11	57.82	57.50	57.90	59.10	57.00	58.10	58.80	58.72

The following sub-sections present the results of noise modelling obtained from the CNOSSOS-EU, the ISO 9613-2:1996 and the ISO 9613-2:2024 for two scenarios,

to evaluate the impact of the metal fence depicted in Figure 13.

4.3.1 Modelled Noise Levels without Considering the Fence

The galvanized steel safety fence located on both sides of the road, positioned 0.5 m above road level and approximately 0.3 m thick, was initially excluded from the model in this scenario to compare the predicted free-field sound propagation results with the measured noise levels. Table 9 presents the modelled noise levels from each approach without the fence.

Table 9: Modelled Noise Levels, $L_{eq,1h}$, without the Fence in dB(A).

Model	MP	Measurement Time									
		h 1	h 2	h 3	h 4	h 5	h 6	h 7	h 8	h 9	h 10
CNOSSOS-EU	MP1	73.81	73.49	73.51	73.40	73.25	74.58	73	73.76	73.99	74.38
	MP2	60.99	60.67	60.68	60.57	60.42	61.75	60.17	60.93	61.16	61.55
ISO 9613-2:1996 Point Source	MP1	73.73	73.60	73.22	73.18	73.20	74.11	72.54	73.43	73.79	74.15
	MP2	51.81	51.67	51.29	51.25	51.27	52.18	50.62	51.49	51.86	52.22
ISO 9613-2:1996 Line Source	MP1	73.73	73.60	73.22	73.18	73.20	74.11	72.54	73.43	73.79	74.15
	MP2	61.32	61.19	60.81	60.77	60.79	61.7	60.13	61.01	61.38	61.74
ISO 9613-2:2024 Point Source	MP1	73.73	73.60	73.22	73.18	73.20	74.11	72.54	73.43	73.79	74.15
	MP2	51.81	51.67	51.29	51.25	51.27	52.18	50.62	51.49	51.86	52.22
ISO 9613-2:2024 Line Source	MP1	73.73	73.60	73.22	73.18	73.20	74.11	72.54	73.43	73.79	74.15
	MP2	61.32	61.19	60.81	60.77	60.79	61.7	60.13	61.01	61.38	61.74

The results presented above indicate that the CNOSSOS-EU road traffic noise model slightly over predict MP1 by an average of +0.22 dB(A) and over predict MP2 by an average of +2.76 dB(A).

For all the ISO 9613-2 model variants (both 1996 and 2024, Point Source and Line Source), the sound power level of the source was derived inversely from the measured values at MP1. As a result, the difference at MP1 is 0 dB(A). This approach was applied to ensure perfect alignment at MP1, which allowed an accurate evaluation of free-field sound propagation at MP2.

At MP2, the ISO 9613-2 Point Source models (both 1996 and 2024) under predict the measured level by an average of -6.56 dB(A), while the ISO 9613-2 Line Source models (both 1996 and 2024) over predict the measured level by an average of +2.96 dB(A). It was also observed that the sound propagation results of the ISO 9613-2:2024 match those of the ISO 9613-2:1996, as the source and receiver heights in this case are small relative to their distance between them, limiting the influence of the updated A_{gr} formula [48,49]. Figure 18 presents the Mean Average Error and Standard Deviation between the measured and modelled noise levels.

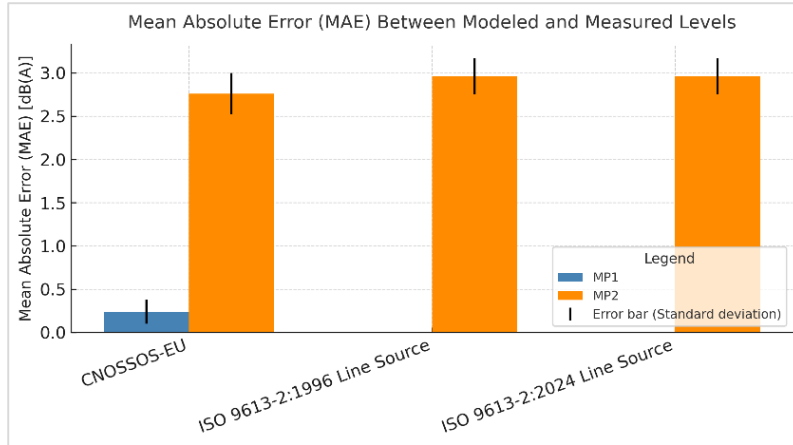


Figure 18: Mean Average Error without the Fence in dB(A).

In summary, the results without considering the fence indicate that the CNOSSOS-EU and the ISO 9613-2 Line Source models tend to over predict, whereas the ISO 9613-2 Point Source models tend to substantially under prediction [92].

4.3.2 Modelled Noise Levels Considering the Fence

In this scenario, the galvanized steel safety fence was included and assigned a high reflection coefficient (0.9) [93,94,95] to evaluate its impact on sound propagation, despite its relatively small surface area. Since MP1 is located directly at the barrier, no effect on its modelled noise levels was observed. Therefore, Table 10 presents the modelled noise levels at MP2 only.

The galvanized steel safety fence was found to have a negligible impact in the CNOSSOS-EU model, resulting in only a 0.21 dB(A) reduction, which can be attributed to the way sound propagation is defined in this method [40].

In contrast, the effect is much more pronounced in all ISO 9613-2 variants: the ISO 9613-2:1996 Point Source

model shows a 4.43 dB(A) reduction, while the ISO 9613-2:2024 Point Source model shows a 3.49 dB(A) reduction. Similarly, the ISO 9613-2:1996 and 2024 Line Source models reduce predicted noise levels at MP2 by 4.49 dB(A) and 2.73 dB(A), respectively. Overall, the largest reductions occur in the ISO 9613-2:1996 Point Source and Line Source models, whereas the smallest reduction is observed in the CNOSSOS-EU model. The differences in the noise reduction between the two ISO 9613-2 versions can be linked to the improved screening calculations introduced in the ISO 9613-2:2024 [48,49].

Table 10: Modelled Noise Levels, $L_{eq,1h}$, with the Fence in dB(A).

Model	MP	Measurement Time									
		h 1	h 2	h 3	h 4	h 5	h 6	h 7	h 8	h 9	h 10
CNOSSOS-EU	MP2	60.78	60.46	60.47	60.36	60.21	61.54	59.96	60.72	60.94	61.33
ISO 9613-2:1996 Point Source		47.38	47.24	46.86	46.82	46.84	47.75	46.19	47.06	47.43	47.79
ISO 9613-2:1996 Line Source		56.83	56.7	56.32	56.28	56.3	57.21	55.64	56.52	56.89	57.25
ISO 9613-2:2024 Point Source		48.32	48.18	47.8	47.76	47.78	48.69	47.13	48.00	48.37	48.73
ISO 9613-2:2024 Line Source		58.59	58.46	58.08	58.04	58.06	58.97	57.40	58.28	58.65	59.01

Table 11 presents the differences between the predicted noise levels considering the fence and the measured noise levels at MP2, where a negative value indicates that the modelled noise level is lower than the corresponding measurement. On average, the CNOSSOS-EU dropped slightly from +2.76 dB(A) to +2.55 dB(A), while the ISO 9613-2 Point Source models differences increased by

about -4 dB(A). The ISO 9613-2:1996 Line Source model reduced the predicted level at MP2 to -1.5 dB(A) below the measurement, whereas the ISO 9613-2:2024 Line Source model aligned most closely with the measurements, remaining only +0.23 dB(A) above the observed value.

Table 11: Differences in Measured and Modelled Noise Levels Considering the Fence at MP2 in dB(A).

Model	MP	Measurement Time									
		h 1	h 2	h 3	h 4	h 5	h 6	h 7	h 8	h 9	h 10
CNOSSOS-EU	MP2	2.58	2.35	2.65	2.86	2.31	2.44	2.96	2.62	2.14	2.61
ISO 9613-2:1996 Point Source		-10.82	-10.87	-10.96	-10.68	-11.06	-11.35	-10.81	-11.04	-11.37	-10.93
ISO 9613-2:1996 Line Source		-1.37	-1.41	-1.50	-1.22	-1.60	-1.89	-1.36	-1.58	-1.91	-1.47
ISO 9613-2:2024 Point Source		-9.88	-9.93	-10.02	-9.74	-10.12	-10.41	-9.87	-10.10	-10.43	-9.99
ISO 9613-2:2024 Line Source		0.39	0.35	0.26	0.54	0.16	-0.13	0.40	0.18	-0.15	0.29

In summary, including the fence in the model leads to an improved accuracy of the CNOSSOS-EU and ISO 9613-2 Line Source models' predictions for far outdoor sound propagation. However, the ISO 9613-2 Point Source models do not reflect the measured conditions well.

5 Discussion and Limitations

This research focuses on two complementary aspects of environmental noise modelling. The first concerns the influence of different road surface types on the CNOSSOS-EU road traffic noise model.

The results presented in sub-section 2.3 and Table 3 confirm that road surface types have a pronounced impact on the predicted noise levels relative to the Reference Road across Category 1, Category 2 and Category 3 vehicles. Additionally, fluctuations in noise levels for the same road surface types were also observed between the evaluated countries. For example, in the Asphalt Concrete Surfaces, $\Delta L_{W,SMA\ 0/8,1}$ ranges from -1.0 to -0.5 dB, $\Delta L_{W,SMA\ 0/8,2}$ from -0.5 to 1.6 dB and $\Delta L_{W,SMA\ 0/8,3}$ from -0.5 to 0.7 dB. These fluctuations can be attributed to differences in the acoustical characteristics of similar road surface types across EU countries [36,40].

Porous asphalt pavements offered the highest noise reduction performance, influenced by factors, such as the number of layers, air-void ratio, thickness, and texture. In general, higher air-void ratios lead to greater noise reduction [96], although a value of around 20% is recommended for practical use [97]. It was also observed that for double-layer systems with a total thickness of 6 cm, noise reduction performance decreases when the lower layer is thinner than the upper layer. Increasing the texture depth of very thin surfaces with small aggregates can improve sound absorption but also increase vibration transmission, which may generate additional vibration-related noise. Conversely, smoother surfaces tend to produce lower noise levels than surfaces with small

or irregular texture patterns [96].

The recommended application of porous asphalt pavements is limited to roads with low traffic flow and without junctions, tight curves, or turning lanes. This is due to durability concerns: under high traffic loads, the voids in porous pavements compress, increasing the need for maintenance and reducing cost-effectiveness [98].

Paving Block Surfaces or Setts generally generate higher noise levels than the Reference Road from Category 1, Category 2 and Category 3 vehicles, largely due to their low air-void ratio. For example, Category 1 vehicles show increases of 2.5–2.8 dB on CNOSSOS-EU, German, and Finnish herringbone road surfaces, while Category 2 and Category 3 vehicles increase noise levels by 1.3–5.3 dB on the same surfaces. These variations may pose challenges for other Member States when adopting the CNOSSOS-EU without aligning national regulations with the methodology.

A review of relevant literature further supports these observations. Noise reduction mechanisms include porous sound absorption, resonance absorption, control of the propagation path, vibration damping, and connected-pore excretion, or combinations of these [99]. Porous Asphalt Pavements can reduce noise levels by up to 6 dB [100], Rubber Asphalt Pavements by 1–3 dB compared with ordinary asphalt [101], and Porous Elastic Pavements by 7–12 dB compared with Dense Asphalt Pavements [102,103,104]. Low-noise pavements stand as the most effective mitigation measure for road traffic noise, although their health-related benefits remain difficult to quantify due to incomplete acoustical characterization

[58]. However, since different pavement evaluation techniques have been used in previous studies [99], the results may differ if assessed using the CNOSSOS-EU methodology.

Future updates to the CNOSSOS-EU road surface database will be important, particularly if new low-noise pavements become widespread. Member States should assess the acoustic performance of new surfaces and update national regulations accordingly. Low-noise pavements are typically implemented during resurfacing or when required by law, and the 2023 END evaluation recommended that Member States consider them as a key mitigation measure alongside quiet tyres and reduced speed limits [26]. The CNOSSOS-EU framework allows countries to define new surfaces by introducing their own $\alpha_{i,m}$ and β_m correction coefficients [40]. Although the procedure for determining these coefficients is not yet fully established, recent research has estimated them for two low-noise pavements and found the U-SPB method suitable for defining new surfaces within the CNOSSOS-EU road traffic noise model [58].

Although the comparison presented in this work is limited to countries whose national road surface types and coefficients are already available in noise mapping software following the CNOSSOS-EU adoption, specifically, Germany, Austria, and Finland, the results can serve as a useful reference for other EU Member States currently transitioning to the CNOSSOS-EU. It also supports further investigations into a wider range of road surfaces and helps address variations in noise levels across different road surface types. The findings are expected to

be valuable for noise mapping experts, as they provide a clear overview of how noise levels differ across road surface types in various countries

Therefore, when selecting road surface types from noise mapping software databases for projects using the CNOSSOS-EU road traffic noise model, it is essential to recognize that similar surface types may differ between countries. For accurate results, the CNOSSOS-EU method should be applied only to countries whose road surface $\alpha_{i,m}$ and β_m correction coefficients are already included in the software databases. This ensures consistency and reliability in noise mapping across different regions and road surface types within the EU [36].

The second aspect reviews the updates introduced in the 2024 edition of the ISO 9613-2, highlighting key parameters that are expected to improve the standard's accuracy in modelling outdoor sound propagation. It then focuses on the modelling of road traffic noise at the local scale, using a case study from Hungary to evaluate the performance of the CNOSSOS-EU method alongside the ISO 9613-2 standard, which remains one of the most widely applied international standards for environmental noise propagation predictions.

The results of the ISO 9613-2:2024 review presented in sub-section 3.3 indicate that the accuracy of outdoor noise modelling improved by introducing key updates that are directly relevant to outdoor sound propagation. Applying these updates in noise mapping software, such as SoundPLAN, confirm that parameters like K_{geo} , A_{bar} , D_c and A_{curv} influence sound propagation and visualise how source and receiver heights and distances impact ground

attenuation. These improvements are expected to strengthen noise mapping practices and increase the reliability of environmental noise assessments [49].

The results obtained from the noise modelling case study presented in sub-section 4.3, particularly in Table 9 and Table 10, indicate that the galvanized steel safety fence scenario provided higher accuracy relative to the measured noise levels. However, in both scenarios, it was observed that the free-field sound propagation results of the ISO 9613-2 Point Source models at MP2 do not reflect the measured conditions well. This is because, even under low traffic conditions, the point source approach does not account for the distributed nature of traffic flow along the road but instead models noise emissions as originating from a single point. In contrast, the ISO 9613-2 Line Source models provided more realistic predictions, showing smaller deviations from the measured values at MP2.

Although the CNOSSOS-EU method was designed primarily for strategic noise mapping applications [40], its predictions in both scenarios showed almost no deviation from the measurements at MP1 and remained within 3 dB(A) at MP2, an uncertainty range considered acceptable when comparing modelled and measured noise levels [47,48,105]. The identical CNOSSOS-EU predicted results at MP1 in both scenarios are expected, as the receiver height of 1.75 m places it well above the fence.

It is important to note that the CNOSSOS-EU road traffic noise model is advised for use only in EU Member States that have formally transposed it into their national legislation [40], particularly because road surface types

influence road traffic noise emissions significantly as illustrated in sub-section 2.3 [36,40].

It was also observed that the newly introduced ground effect correction factor, K_{geo} , in the ISO 9613-2:2024 has no significant influence on the results, as the source and receiver heights are small relative to their separation distance [47,48]. This finding is consistent with the discussion in sub-section 3.3.1, which showed that the correction factor becomes relevant only when height differences are large enough to contribute to the modelling uncertainty present in the ISO 9613-2:1996 [49]. On the other hand, the refinement of the barrier attenuation calculations, A_{bar} , in the 2024 update contributed to lower predicted noise levels at MP2, reducing the results by 1 dB(A) in the ISO 9613-2 Point Source model and 1.76 dB(A) in the Line Source model compared with the 1996 version.

Figure 19 and Figure 20 compare the vertical sound propagation patterns in the CNOSSOS-EU models using the measurement data of Hour 1. At the MP2 location, the influence of the modelled conditions becomes more pronounced at approximately 9 m above ground level rather than at the measurement height of 4.65 m. As a result, both scenarios yield nearly identical predicted noise levels at MP2, differing by only 0.2 dB(A).

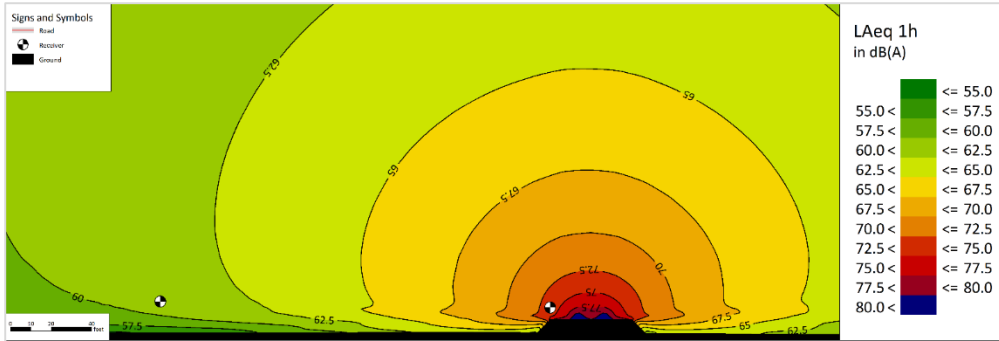


Figure 19: Cross-Section Noise Map – No Fence Scenario: CNOSSOS-EU.

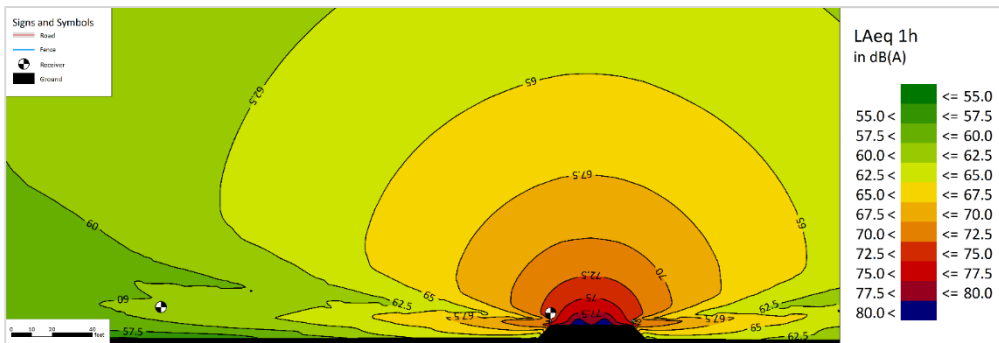


Figure 20: Cross-Section Noise Map – Fence Scenario: CNOSSOS-EU.

Figure 21, Figure 22 and Figure 23 illustrate the vertical sound propagation patterns for the ISO 9613-2:1996 and 2024 Line Source models without the fence, as well as the ISO 9613-2:1996 and 2024 Line Source models with the fence, utilizing the measurement data of Hour 1. In the no fence scenario, both versions of the ISO 9613-2 exhibit identical sound propagation behaviour, as the influence of K_{geo} is minimal [49]. In contrast, the effect of A_{bar} becomes more notable in the fence scenario: the predicted noise level of the 2024 version at MP2 is +0.23 dB(A) above the measured value, yielding higher accuracy and predictions that align more closely with the measured value.

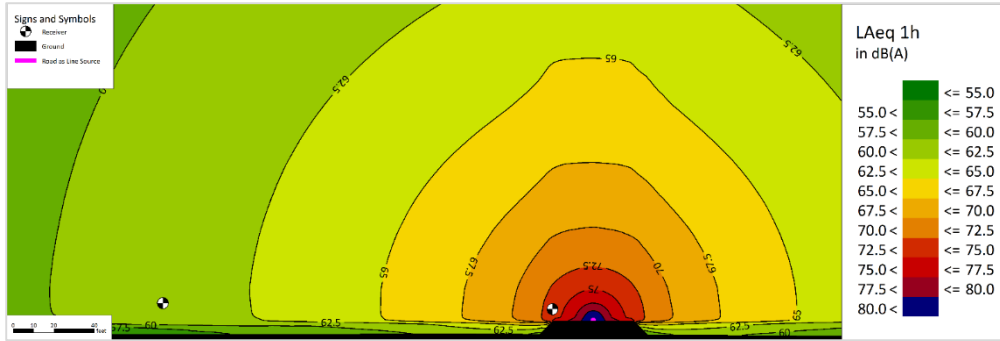


Figure 21: Cross-Section Noise Map – No Fence Scenario: ISO 9613-2:1996 and 2024 Line Source.

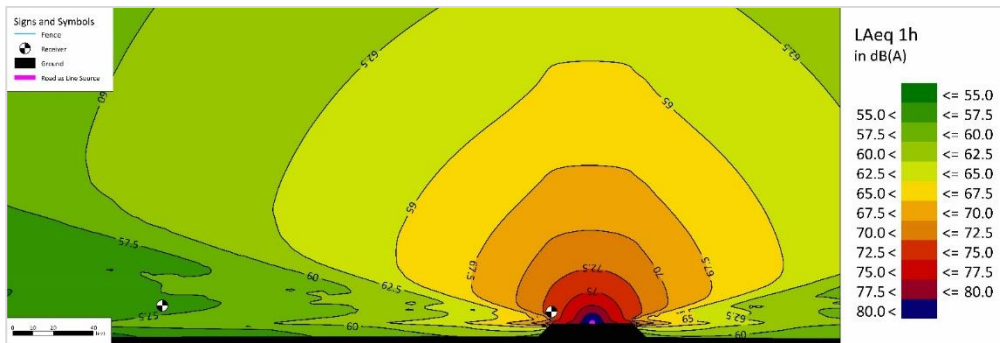


Figure 22: Cross-Section Noise Map – Fence Scenario: ISO 9613-2:1996 Line Source.

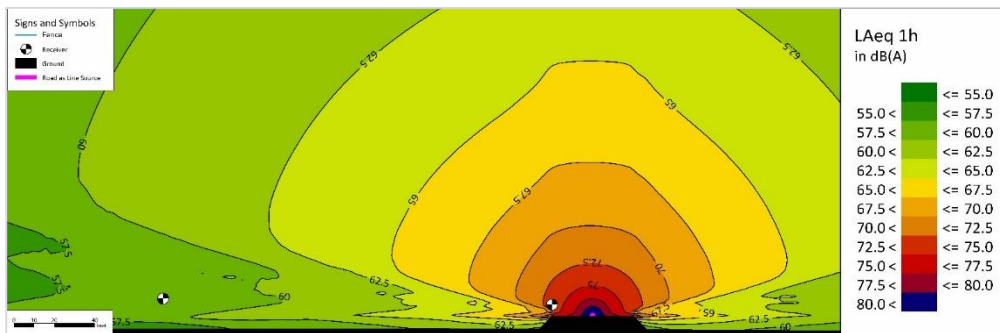


Figure 23: Cross-Section Noise Map – Fence Scenario: ISO 9613-2:2024 Line Source.

The results from both modelled scenarios indicate that, under relatively light traffic volumes, the ISO 9613-2:2024

Line Source model is the most accurate approach within noise modelling software to represent the measured conditions. However, this method requires the sound power level or sound pressure level of the source to be known. In contrast, the CNOSSOS-EU method offers lower accuracy with increasing distance from the source but remains straight-forward to apply when the parameters of the road surface type are available [36,40], as it relies primarily on traffic counts to derive the road's sound power level.

Despite the careful planning of both the modelling and measurement campaign, several limitations were identified. The investigation was carried out on a single road segment characterized by low and relatively stable traffic flows, which may not represent conditions found on busier or more complex road networks. The analysis also focused solely on weekday peak periods under favourable meteorological conditions, meaning that potential effects related to night-time traffic or seasonal changes were not evaluated. These aspects may introduce some uncertainty and restrict the wider applicability of the findings. However, the outcomes establish a baseline for future work seeking to evaluate the performance of the CNOSSOS-EU and the ISO 9613-2 methods across heavier traffic volumes and different environmental conditions.

6 Thesis Points and Novelty

6.1 Thesis 1: Influence of Asphalt Concrete Surfaces (ACS) on Noise Emissions in the CNOSSOS-EU Method

6.1.1 Thesis Point

It is shown that ACS surfaces provide the highest noise reduction potential, reaching up to -6.6 dB for light vehicles and -5.7 dB for heavy vehicles compared to the Reference Road. Porous and multilayer asphalt structures significantly enhance noise reduction due to increased air void content and absorption properties. It is further proven that similar asphalt mixtures exhibit different acoustic behaviour across countries, demonstrating that the CNOSSOS-EU default coefficients are insufficient without national calibration.

Contributing Paper:

Odeh, O., Khayyat, A., & Kocsis, D. (2025). CNOSSOS-EU road surface types: Evaluation of the influence of different national values on noise emissions. Noise Mapping, 12(1), 20250017 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.1.2 Problem Statement

Road surface corrections in the CNOSSOS-EU are assumed to be harmonized across the EU, yet the real acoustic performance of asphalt pavements varies significantly.

6.1.3 Approach

A systematic analysis of Asphalt Concrete Surfaces (ACS) was conducted using the CNOSSOS-EU formulations by comparing multiple European surface

types and national coefficients to a Reference Road surface under controlled conditions.

6.1.4 Novelty

First controlled, cross-national comparison of the CNOSSOS-EU defaults versus national Asphalt Concrete road surface correction coefficients (Austria, Germany, Finland) under identical assumptions, by vehicle category and pavement type, quantifying $\Delta L_{W,road,m}$ differences relevant to a Reference Road.

6.2 Thesis 2: Acoustic Behaviour of Cement Concrete Surfaces (CCS) in the CNOSSOS-EU Method

6.2.1 Thesis Point

It is shown that CCS surfaces exhibit high variability in noise emissions, ranging from slight reductions to increases of up to +2 to +3 dB, depending on surface finishing techniques. It is proven that surface texture and treatment, such as brushed, washed, or worked concrete, strongly influence noise generation, making CCS less predictable and less efficient than ACS for noise mitigation.

Contributing Paper:

Odeh, O., Khayyat, A., & Kocsis, D. (2025). CNOSSOS-EU road surface types: Evaluation of the influence of different national values on noise emissions. Noise Mapping, 12(1), 20250017 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.2.2 Problem Statement

Concrete pavements are widely used in road construction, yet their acoustic behaviour is not consistently represented in the CNOSSOS-EU.

6.2.3 Approach

Different Cement Concrete Surface (CCS) types were evaluated using the CNOSSOS-EU correction coefficients and compared to the Reference Road across vehicle categories and national implementations.

6.2.4 Novelty

First controlled, cross-national comparison of the CNOSSOS-EU defaults versus national Cement Concrete road surface correction coefficients (Austria, Germany, Finland) under identical assumptions, by vehicle category and pavement type, quantifying $\Delta L_{W,road,m}$ differences relevant to a Reference Road.

6.3 Thesis 3: Noise Impact of Paving Block Surfaces (PBS) in the CNOSSOS-EU Method

6.3.1 Thesis Point

It is shown that PBS surfaces generate the highest noise emissions among all surface categories, with increases of up to +8.4 dB for heavy vehicles. It is proven that low air void ratios and surface discontinuities increase tyre–road interaction noise, making PBS unsuitable for noise-sensitive environments. The results demonstrate that PBS should be avoided in urban noise mitigation strategies, especially in areas with significant heavy traffic.

Contributing Paper:

Odeh, O., Khayyat, A., & Kocsis, D. (2025). *CNOSSOS-EU road surface types: Evaluation of the influence of different national values on noise emissions*. *Noise Mapping*, 12(1), 20250017 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.3.2 Problem Statement

Paving Block Surfaces are commonly used in urban areas, yet their impact on road traffic noise is often underestimated.

6.3.3 Approach

PBS types from multiple European datasets were analysed within the CNOSSOS-EU framework and compared to the Reference Road.

6.3.4 Novelty

First controlled, cross-national comparison of the CNOSSOS-EU defaults versus national Paving Block road surface correction coefficients (Austria, Germany, Finland) under identical assumptions, by vehicle category and pavement type, quantifying $\Delta L_{W,road,m}$ differences relevant to a Reference Road.

6.4 Thesis 4: Impact of the ISO 9613-2:2024 Updates on Outdoor Sound Propagation

6.4.1 Thesis Point

It is shown that the ISO 9613-2:2024 introduces significant improvements in modelling representation of real-world conditions, particularly in complex environments involving barriers and reflections. It is proven that enhanced screening (A_{bar}) improves prediction accuracy, while the ground correction factor (K_{geo}) has limited impact in low-height road traffic scenarios. The updated standard provides a more physically consistent representation of sound propagation.

Contributing Papers:

Primary: Odeh, O., Khayyat, A., & Kocsis, D. (2026). *Key Updates in ISO 9613-2:2024 — What's New in Outdoor Noise Prediction Standards? Proceedings of Forum Acusticum / EuroNoise 2025*, 1259–1264 (Scopus).

Secondary: Odeh, O., & Kocsis, D. (2026). *From models to reality: how CNOSSOS-EU and ISO 9613-2 perform against measured road traffic noise*. *Noise Mapping*, 12(1), 20250023 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.4.2 Problem Statement

The ISO 9613-2:1996 standard has known limitations in modelling ground effects, reflections, and screening.

6.4.3 Approach

The updated ISO 9613-2:2024 model was implemented and compared with the 1996 version to evaluate the effect of new parameters such as K_{geo} , A_{bar} , A_{curv} , and D_c .

6.4.4 Novelty

Early practice-oriented evaluation of the ISO 9613-2:2024 vs 1996 within a commercial software implementation, focusing on K_{geo} , A_{bar} , A_{curv} , D_c , and foliage attenuation, clarifying when the updates affect predictions.

6.5 Thesis 5: Comparative Validation of the CNOSSOS-EU and the ISO 9613-2 Models

6.5.1 Thesis Point

It is shown that the CNOSSOS-EU model provides stable and reliable results, with deviations within +3 dB(A). It is proven that the ISO 9613-2 Line Source model, particularly the 2024 version, achieved the highest

accuracy, with deviations as low as +0.23 dB(A) under realistic conditions.

Contributing Paper:

Odeh, O., & Kocsis, D. (2026). *From models to reality: how CNOSSOS-EU and ISO 9613-2 perform against measured road traffic noise*. *Noise Mapping*, 12(1), 20250023 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.5.2 Problem Statement

The accuracy of environmental noise models depends on their ability to represent real-world conditions.

6.5.3 Approach

A field measurement campaign was conducted, and predictions from the CNOSSOS-EU and the ISO 9613-2:1996 and the ISO 9613-2:2024 Point and Line Source models were compared against measured data.

6.5.4 Novelty

Integrated measurement and modelling validation using an eight-day campaign on a Hungarian road segment to test the CNOSSOS-EU road traffic noise model and the ISO 9613-2 Line Source models performance, revealing the improved screening performance in the 2024 update.

6.6 Thesis 6: Practical Applicability of the CNOSSOS-EU and the ISO 9613-2 for Road Traffic Noise Modelling

6.6.1 Thesis Point

It is shown that the CNOSSOS-EU is most suitable for large-scale strategic noise mapping, as it relies on traffic data and standardized inputs. It is proven that the ISO

9613-2:2024 is more suitable for detailed local-scale modelling, particularly in the presence of barriers and complex propagation paths. The findings demonstrate that model selection should be based on data availability, modelling scale, and environmental complexity.

Contributing Paper:

Odeh, O., & Kocsis, D. (2026). *From models to reality: how CNOSSOS-EU and ISO 9613-2 perform against measured road traffic noise*. *Noise Mapping*, 12(1), 20250023 (Walter de Gruyter, Scopus, Q2, IF: 2.4).

6.6.2 Problem Statement

Selecting an appropriate noise modelling method is critical for reliable environmental assessments.

6.6.3 Approach

The performance, input requirements, and prediction accuracy of the CNOSSOS-EU and the ISO 9613-2 were evaluated under identical conditions.

6.6.4 Novelty

1. Practical guidance for model selection in noise mapping software: the CNOSSOS-EU when traffic counts and national surface parameters are available; the ISO 9613-2:2024 Line Source for structure-sensitive propagation.
2. Policy-relevant insight that without validated, up-to-date national road surface coefficients, cross-border exposure comparisons risk systematic bias; software databases should make provenance/versioning transparent.

7 Conclusion and Future Work

This research discusses the advancements in outdoor sound propagation in noise mapping software using two calculation methods: the CNOSSOS-EU road traffic noise model and the ISO 9613-2 standard.

By evaluating the influence of different road surface types on noise levels, reviewing the updates introduced in the ISO 9613-2:2024 and comparing the performance of the CNOSSOS-EU road traffic noise model and the ISO 9613-2 Point Source and Line Source models against measured noise levels on a road segment in Hungary for two scenarios, this work contributes to a deeper understanding of model behaviour, identifies the strengths and limitations of each calculation method, and supports more informed decision-making in environmental noise assessments.

The impact of various European road surface types on the total sound power levels of light, medium-heavy, and heavy vehicles was assessed by isolating this parameter and harmonizing all other CNOSSOS-EU inputs, such as temperature, studded tyres, and related factors. A virtual road surface, representing an average of stone mastic asphalt (SMA 0/11) and dense asphalt concrete (DAC 0/11) surfaces, aged between two and seven years old, and maintained in typical conditions, was selected as the baseline for the road traffic noise calculations and is defined as the “Reference Road.”

The available literature provides 1/1 octave band data for rolling and propulsion noise separately. Therefore, both components were combined using the CNOSSOS-EU equations to calculate the total sound power level for each

road surface type. The resulting values were then subtracted from the total sound power level of the Reference Road, expressed in this work as $\Delta L_{W,road,m}$. A negative $\Delta L_{W,road,m}$ indicates that the evaluated surface is expected to produce lower noise levels than the Reference Road. The results show that $\Delta L_{W,road,m}$ for road surfaces with similar pavement mixes can differ significantly between countries, confirming that similar pavement categories across Europe may exhibit different acoustic characteristics.

Although this study focuses on highlighting differences in the coefficients currently available in noise mapping software for Germany, Austria, and Finland, it also establishes a foundation for broader future comparisons. Such analyses will become feasible once all EU Member States officially publish their national road surface coefficients following the transposition of the CNOSSOS-EU into national legislation.

The findings demonstrate that the road surface correction factors provided in the CNOSSOS-EU documentation do not universally represent the acoustic behaviour of road surfaces across all EU countries, even when road surfaces fall within the same pavement category. Nevertheless, the CNOSSOS-EU methodology offers a consistent and robust framework that should be adopted by all Member States to derive their national correction factors. This highlights the importance of fully implementing the CNOSSOS-EU across Europe, particularly for the application of strategic noise mapping [36].

The review of the ISO 9613-2:2024 version updates shows significant enhancements in comparison with the

1996 edition. The introduction of K_{geo} for ground effects, A_{curv} for cylindrical wave reflections, refined screening calculations and an expanded foliage attenuation formula, were found to improve the accuracy of outdoor sound propagation predictions. These updates have proven beneficial for integration in noise mapping software, such as SoundPLAN 9.1, as they provide increased accuracy in noise assessments and support more effective mitigation measures. Overall, the updates ensure that the ISO 9613-2 remains a dependable standard for outdoor sound predictions, serving the needs of environmental engineers, urban planners, and regulatory authorities [49].

The comparison of the CNOSSOS-EU road traffic noise model and the ISO 9613-2 Point Source and Line Source models was carried out for two scenarios to assess the influence of a galvanized thin safety metal fence installed along both sides of the road and compare the prediction results with measured noise levels to identify the most realistic modelling approach.

To enhance the reliability of the analysis, a consecutive eight-day measurement campaign was conducted, during which all relevant input parameters, weather conditions, traffic counts, vehicle speeds, and other site-specific data, were collected. The measurement data were then processed, and ten one-hour samples, $L_{\text{Aeq},1\text{h}}$, were selected as representative for comparison with the modelled noise levels. The results show that incorporating the fence into the models improved alignment with the measured data, indicating that the fence has a positive impact on prediction accuracy.

While the primary focus of this study is the comparison between the CNOSSOS-EU and the ISO 9613-2

predictions and the corresponding measurements, the findings also open the door to broader investigations. Future work could extend the analysis to roads with higher traffic volumes and include additional national road traffic noise models such as RLS-19, NMPB2008, RMG2012, and Nord2000. Such comparisons would support the identification of the most appropriate road traffic noise modelling technique for different contexts.

In summary, the ISO 9613-2:2024 Line Source model provides the most realistic sound propagation predictions for roads with light traffic volumes, while the ISO 9613-2:1996 and ISO 9613-2:2024 Point Source models proved unsuitable for road traffic noise simulations. The CNOSSOS-EU road traffic noise model remains a viable alternative, but only when national road surface correction factors, $\alpha_{i,m}$ and β_m , are available and the method has been formally integrated into the legislation of the respective EU Member State [36,92].

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9 List of Publications

1. Odeh, O., & Kocsis, D. (2026). From models to reality: how CNOSSOS-EU and ISO 9613-2 perform against measured road traffic noise. *Noise Mapping*, 12(1), 20250023 (Walter de Gruyter, Scopus, Q2, IF: 2.4).
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