




# Evaluation Matrix of Noise Pollution

Lili Grigorian

A thesis submitted for the Joint programme of  
Master in Urban Climate & Sustainability

July 2024



<b>Author</b> Lili Grigorian	<b>Publication type</b> Thesis	<b>Completion year</b> 2024
<b>Number of pages:</b> 111		
<b>Supervisor I</b> Colin Hughes	<b>Supervisor II</b> Prof. José Enrique García Ramos	
<b>Title</b> Evaluation Matrix of Noise Pollution		
<b>Degree:</b> Master in Urban Climate & Sustainability		
<b>Abstract</b> <p>Noise pollution, stemming from various human activities such as transportation, industrial processes, and urbanization, poses significant threats to human health and ecological stability. The adverse effects of noise pollution include sleep disturbances, cardiovascular diseases, cognitive impairments, and reduced quality of life. Moreover, it contributes to habitat disruption and biodiversity loss in both urban and rural environments. Despite the well-documented impacts, existing research lacks a comprehensive framework for systematically evaluating the effectiveness of noise mitigation strategies in urban areas.</p> <p>This study addresses this gap by developing an evaluation matrix for noise pollution, specifically tailored to the urban context of Glasgow. The research leverages Multi-Criteria Decision Analysis (MCDA), including methodologies such as the Analytical Hierarchy Process (AHP), to systematically evaluate and rank noise pollution sources based on multiple factors. These factors include noise intensity, duration, distance from the source to the receptor, road surface materials, tire materials, speed limitations, number of sources, topography, weather conditions, and time of day. Additionally, the social impact of noise on sensitive receptors like educational institutions, healthcare facilities, and residential areas is considered. The thesis is structured into several sections. The first section reviews existing literature on urban acoustics, providing a comprehensive overview of current definitions, approaches, and methodologies. The second section details the methodology used to develop the evaluation matrix, while the third section presents the results of applying this matrix to real-world data. The final section discusses the findings, limitations, and potential for future research.</p> <p>A significant finding from this study is the importance of considering land use types when evaluating noise pollution. The research highlights that noise levels can vary significantly depending on traffic patterns, with off-peak hours potentially being noisier than rush hours due to higher speeds and traffic volumes. This insight underscores the need for targeted noise reduction measures, particularly at night.</p> <p>The study successfully developed a Glasgow-oriented noise evaluation matrix that offers practical guidance for policymakers. This matrix not only provides a robust tool for assessing noise pollution in Glasgow but can also be adapted and further developed for broader applications in urban planning and environmental management. By bridging the gap between research and practice, this study enhances the potential for creating healthier and more sustainable urban environments, paving the way for future advancements in noise pollution management.</p>		
<b>Keywords</b> Noise, Matrix, Evaluation		
<b>Originality statement.</b> I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	<b>Signature</b> 	





## Table of Content

ACKNOWLEDGMENT.....	3
LIST OF TABLES .....	4
LIST OF FIGURES .....	5
LIST OF ACRONYMS .....	6
Notation.....	7
<b>CHAPTER 1: INTRODUCTION .....</b>	<b>9</b>
1.1. Rationale.....	9
1.2. Aim & Objectives.....	10
1.3. Outline.....	10
<b>CHAPTER 2: LITERATURE REVIEW .....</b>	<b>13</b>
2.1. Overview .....	13
2.2. Main noise sources in cities .....	13
2.3. Previous studies on Noise Pollution Evaluation .....	14
2.3.1. 24-hour Noise Mapping .....	14
2.3.2. Mobile Monitoring Technique.....	16
2.3.3. Using prediction models .....	17
2.4. Health aspects .....	17
2.4.1. Annoyance .....	21
2.4.2. Soundscape perception.....	22
2.5. Local policies and strategies (for Scotland).....	23
2.5.1. Transportation Noise Action Plan.....	23
2.6. Conclusion .....	25
<b>Chapter 3: Methodology .....</b>	<b>27</b>
3.1. Introduction.....	27
3.2. Objectives .....	27
3.3. Objective 1: Establishing main criteria.....	27
3.3.1. Noise Level (dB).....	27
3.3.2. Source of Noise.....	28
3.3.3. Distance from Noise Source .....	29
3.3.4. Surface Conditions.....	29
3.3.5. Cost Analysis .....	30
3.3.6. Receptor impacted in urban scale .....	30
3.4. Objective 2: Designing an Evaluation Matrix .....	32

3.5. Objective 3: Developing Guidelines for Implementation .....	32
3.6. Summary .....	33
<b>Chapter 4: Results .....</b>	<b>35</b>
4.1. Criteria and Sub-Criteria identified .....	35
4.1.1. Noise Level (dB) .....	35
4.1.2. Source of Noise .....	36
4.1.3. Distance from Noise Source .....	37
4.1.4. Surface Conditions .....	38
4.1.5. Cost Analysis .....	41
4.1.6. Receptors impacted .....	41
4.2. Criteria and Sub-Criteria Scoring .....	43
1 <sup>st</sup> Criteria – Noise Level (dB) .....	43
2 <sup>nd</sup> Criteria – Source of Noise .....	44
3 <sup>rd</sup> Criteria – Distance from Noise Source .....	45
4 <sup>th</sup> Criteria – Surface conditions .....	49
4.3. Objective 3 – Implementation of Guidelines .....	69
4.3.1. Integration with GIS Systems .....	71
4.4. GIS implementation .....	72
4.5. Conclusion .....	74
<b>Chapter 5: Discussion, Conclusions, Recommendations for Future Work .....</b>	<b>75</b>
5.1. Statement of Results .....	75
5.2. Comparison with other studies .....	76
5.3. Discussion .....	78
5.3.1. Positive Soundscape .....	79
5.3.2. Specific programs connected to noise .....	81
5.2. Conclusion .....	82
5.3. Limitations .....	83
5.4. Recommendations for future work .....	84
<b>Appendix A: Matrix .....</b>	<b>1</b>
<b>Appendix B: Matrix for Daytime parameters .....</b>	<b>2</b>
<b>Appendix C: Matrix for Daytime parameters .....</b>	<b>3</b>
<b>Appendix D: Proximity of Roads to Residential and Social buildings .....</b>	<b>4</b>
<b>Appendix E: Proximity of Roads to Residential and Social buildings (Great Western Road) .....</b>	<b>5</b>
<b>Appendix F: Proximity of Roads to Residential and Social buildings (Possil Park) .....</b>	<b>6</b>
<b>Appendix G: Proximity of Roads to Residential and Social buildings (Dowanhill) .....</b>	<b>7</b>
<b>Appendix H: Survey Results .....</b>	<b>8</b>

## ACKNOWLEDGMENT

I would like to present my heartfelt gratitude to all those who have supported and contributed to the completion of this project.

First and foremost, I am deeply thankful to my supervisors, Colin Hughes and Professor José Enrique García, for their unwavering guidance, invaluable feedback, and constant encouragement throughout this endeavour. Their combined expertise and mentorship have been instrumental in shaping this work.

I am incredibly grateful to MURCS for these amazing 2 years. It was the best period of my life. The program not only taught me various captivating sciences, but also taught enjoying studying, taught me making new friends, taught me adapting to any climate, culture, and language. I am happy to know all the professors, the staff and of course my classmates, happy to have these people in my life and call them friends, being able to share with them so many wonderful moments and days we had together these years.

I am also thankful for the support of my family, motivation, and encouragement throughout this journey. Their unwavering belief in me has been a constant source of strength.

With love and respect,

Lili Grigorian

## LIST OF TABLES

Table 1 - Types of noise sensitive receptors .....	31
Table 2 - Scoring Average Noise levels .....	43
Table 3 - Scoring Peak Noise levels .....	44
Table 4 - Scoring Noise Exposure limits .....	44
Table 5 - Scoring Noise sources .....	45
Table 6 - Scoring Proximity to Noise Sources.....	47
Table 7 - Scoring Proximity to Airports .....	48
Table 8 - Noise reduction of drainage asphalt (EUROCITIES) .....	50
Table 9 - Noise reduction in human perception (Acoustical surfaces, 2020).....	51
Table 10 - Matrix rule for scoring of road surfaces .....	51
Table 11 – Daytime speed scoring.....	53
Table 12 - Nighttime speed scoring .....	54
Table 13 - Average, maximum, minimum and equivalent decibel values blocked at each monitoring site .....	54
Table 14 - Mean noise measurements at each site. Recordings presented here are for setbacks at source and, 5, 10, and 20 m from source .....	55
Table 15 - Sites' description.....	56
Table 16 - Scoring of Vegetation elements.....	57
Table 17 - Scoring of Durability .....	60
Table 18 - Scoring of Rail track conditions .....	62
Table 19 - Scoring cost analysis .....	66
Table 20 - Scoring Receptors.....	69
Table 21 - Criteria 1 .....	70

## LIST OF FIGURES

Figure 1 - The traffic flow density of various types of roads. ....	15
Figure 2 - The proportion of noise receiving points that meet and exceed the noise limit in the class I area in the daytime.....	16
Figure 3 - The health effects of traffic noise.....	20
Figure 4 - Statistics of noise exposure .....	21
Figure 5 - Annoyance in relation to noise exposure (Lden e Ln), Porto, Portugal, 2012.....	22
Figure 6 - Noise levels (Muralikrishna & Manickam, 2017).....	23
Figure 7 - Step-by-step stages of the Prioritisation Process. BPS = Building Prioritisation Score; SPS = Source Prioritisation Score (see below for more detail) (TNAP).....	25
Figure 8 - Tyres types (European tyre labelling Regulation (EU 2020/740).2021) .....	39
Figure 9 - Divergence of sound waves. (Source: J McIntosh, Department of Transport, Victoria, Australia) .....	46
Figure 10 - Day map of noise distribution from Glasgow Airport .....	48
Figure 11 - Night map of noise distribution from Glasgow Airport.....	48
Figure 12 - Graphic of correlation between noise levels and speed for cars .....	53
Figure 13 - Graphic of correlation between noise levels and speed for trucks and motorcycles.....	53
Figure 14 - A comparison between quiet asphalt and normal asphalt (EURO CITIES, 2014) ..	58
Figure 15 - Methods and noise reduction potential (Oertli & Hübner, 2007) .....	62
Figure 16 - Glasgow Subway (developed for this thesis using Esri GIS data).....	63
Figure 17 - Buildings and Subway stations (developed for this thesis using Esri GIS data) .....	63
Figure 18 - Costs of three noise abatement measures for three typical cases (EURO CITIES, 2015) .....	65
Figure 19 – SIMD (Scottish Index of Multiple Deprivation, 2020) .....	68
Figure 20 - Top 5% SIMD areas (Scottish Index of Multiple Deprivation, 2020).....	69
Figure 21 - Proximity influence (Caledonian Court and GCU) (developed for this thesis using Esri GIS data).....	72
Figure 22 - Proximity to Dobbie's loan.      Figure 23 - Proximity to M8 Highway.....	73
Figure 24 - Pollock Park housing frontline (developed for this thesis using Esri GIS data).....	73
Figure 25 - Dalziel Drive housing (developed for this thesis using Esri GIS data).....	74
Figure 26 - Results of Big Noise Programme.....	81

## LIST OF ACRONYMS

AHP	Analytical Hierarchy Process
BPS	Building Prioritization Score
CNMAs	Candidate Noise Management Areas
CPCB	Central Pollution Control Board
DAC	Dense Asphalt Concrete
DALYs	Disability Adjusted Life Years
DA	Drainage Asphalt
dB	Decibels
EEA	European Environment Agency
END	Environmental Noise Directive
EU	European Union
GIS	Geographical Information Systems
HRA	Hot Rolled Asphalt
HSE	Health and Safety Executive
MCDA	Multi-criteria Decision Analysis
NISP	Noise Inspection Panel
NGD	Noise Generating Developments
NMAs	Noise Management Areas
NPPF	National Planning Policy Framework
NSRs	Noise Sensitive Receptors
PA	Porous Asphalt
QUAs	Quiet Urban Areas
SIMD	Scottish Index of Multiple Deprivation
SMA	Stone Mastic Asphalt
SPS	Source Prioritization Score
SPP	Scottish Planning Policy
TLPA	Two-layer Porous Asphalt
TNAP	Transportation Noise Action Plan
TSMA	Thin Stone Mastic Asphalt
WHO	World Health Organization

## Notation

The following symbols and units are used throughout this thesis:

Symbol	Description
m	Metres (unit of length)
m <sup>2</sup>	Square metres (unit of area)
dB	Decibels, a unit for measuring sound intensity
dB(A)	A-weighted sound level, adjusted for the human ear's sensitivity
dB(C)	C-weighted sound level, used for measuring high-level noise
Hz	Hertz, a unit of frequency (cycles per second)
L Aeq, T	Equivalent continuous sound level over time period T (in dB(A))
L Ceq, T	Equivalent continuous sound level over time period T (in dB(C))
L den	'Lden' (day-evening-night noise indicator) is the noise indicator for overall annoyance, and the annual average noise level for the day, evening, and night periods
L day	'Lday' (day-noise indicator) shall mean the noise indicator for annoyance during the day period,
L night	'Lnight' (night-time noise indicator) is the noise indicator for sleep disturbance, and the annual average noise level for night-time periods

Explanation and Usage:

**Sound Levels (dB):** Sound intensity levels are measured in decibels (dB), with specific weightings to account for human hearing sensitivity.

**Frequency (Hz):** Sound frequency is measured in Hertz, indicating the number of cycles per second.

**Weighted Sound Levels: A Weighting -** The most common weighting that is used in noise measurement is A-Weighting. Like the human ear, this effectively cuts off the lower and higher frequencies that the average person cannot hear. A-weighted measurements are expressed as dBA or dB(A).

**C Weighting -** The response of the human ear varies with the sound level. At higher levels, 100 dB and above, the ear's response is flatter. Although the A-Weighted response is used for most applications, C-Weighting is also available on many sound level meters. C Weighting is usually used for Peak measurements and in some entertainment noise measurement, where the transmission of bass noise can be a problem. C-weighted measurements are expressed as dBC or dB(C).



## CHAPTER 1: INTRODUCTION

### 1.1. Rationale

Noise pollution, arising from various human activities such as transportation, industrial processes, and urbanization, has become a significant environmental concern. It poses numerous detrimental effects on human health and reduces overall quality of life. Furthermore, noise pollution can have severe ecological consequences for urban and rural biodiversity, leading to habitat disruption and even population declines. Understanding the complex dynamics of noise pollution and its repercussions is crucial for developing effective mitigation strategies (*World Health Organisation 2018*).

The creation of an evaluation matrix for noise pollution is crucial in addressing the complexities of urban soundscapes. Existing research lacks a comprehensive framework for systematically evaluating the effectiveness of noise mitigation strategies. By focusing on this gap, this study aims to provide a structured approach to assess and compare various interventions. This will not only contribute to advancing knowledge in the field of noise pollution management but also provide practical guidance for urban planners, policymakers, designers, maintenance teams in implementing evidence-based strategies.

The implications of this study extend beyond academic discourse to practical applications in urban planning and environmental management. By developing an evaluation matrix, policymakers can make informed decisions regarding noise pollution mitigation strategies. Additionally, the findings of this study could influence the development of future research agendas, guiding researchers towards innovative solutions for addressing noise pollution. This study may help policymakers in evaluations of the current urban soundscape situation in a city. At the same time, it may help to find and quantify possible correlations with health issues of the urban population. However, it can be possible only in case of existing databases in formats suiting geographical information systems on the health issues topic.

In summary, this study on the creation of an evaluation matrix for noise pollution addresses a critical need in urban environmental management. By analysing current literature, existing experiments, and studies in the field, and providing practical insights, this study could make significant contributions to the field. With the matrix, evaluation and even prediction of situation change will become much easier, making work of many various department faster and easier. Therefore, the importance and relevance of this study lie in its capacity to bridge the gap between research and practice, ultimately enhancing the quality of urban environments for present and future generations.

## **1.2. Aim & Objectives**

This research aims to create an evaluation system capable of identifying the weakest areas in cities that require noise pollution reduction measures.

This research has 3 different objectives:

- Developing and prioritizing key criteria for assessing noise pollution.
- Designing an evaluation matrix that integrates key criteria and develops a scoring mechanism to quantify noise pollution levels.
- Develop guidelines for implementing the evaluation system within urban planning and management frameworks.

## **1.3. Outline**

This thesis focuses on creating an evaluation system, identifying, and prioritizing key criteria essential for assessing noise pollution within urban environments. For being able to identify the criteria and to manage to evaluate each of them, the study requires research and benchmarking of the various noise sources and elements that affect them, such as noise intensity, duration, distance from the source to the receptor, road surface materials, tyres materials, speed limitations, number of sources, topography, weather conditions, time of the day. At the same time, the study is taking into consideration the social aspect which means it focuses also on those who are affected by the noise – educational organisations (schools, colleges and universities, libraries), healthcare facilities (hospitals, clinics, nursing homes), homes, apartments, condominiums, and other residential properties, commercial spaces, office buildings and corporate workplaces, relational institutions, and others.

To assess the areas that have the largest quantity of factors mentioned above strengthening the noise multi-criteria decision analysis (MCDA) is used in this research. MCDA, including methodologies such as the Analytical Hierarchy Process (AHP), offers a structured approach to decision-making that is particularly beneficial when faced with complex decision problems. AHP enhances the MCDA process by providing a systematic method for capturing and quantifying decision-makers preferences and priorities, thereby improving the accuracy and consistency of decision outcomes. Aggregating these scores allows decision-makers to rank alternatives and identify the most preferred options based on their overall performance across all criteria. To justify these criteria, research is described in the literature review. Different tools were used in the process, such as Excel, ArcGIS Pro and Photoshop, among others.

The first section of this thesis focuses on the research in the field of urban acoustics, providing an overview of existing definitions, approaches and methodologies adopted at the

international level. The second part elaborates on the mentioned above methodology. Following that, the third part delves into the obtained results, while the fourth section describes these findings. Lastly, the concluding section includes the conclusions drawn from the study, its limitations, and offers recommendations for future research.



## CHAPTER 2: LITERATURE REVIEW

### 2.1. Overview

Noise pollution is a pervasive environmental issue with far-reaching implications for human health, ecological balance, and overall quality of life. As urbanization and industrialization continue to accelerate globally, the prevalence of noise pollution has become a pressing concern that demands effective assessment and management strategies (European Environment Agency, 2014). Excessive noise exposure has been linked to various adverse health outcomes, including sleep disturbances, cardiovascular diseases, and cognitive impairments, highlighting the urgent need for comprehensive approaches to evaluate and mitigate noise pollution (*World Health Organisation* 2018).

In response to this imperative, researchers and policymakers have developed various methodologies and frameworks for assessing noise pollution levels, identifying sources, and implementing mitigation measures. Traditional approaches such as noise mapping, environmental impact assessments, and regulatory standards have provided valuable insights into the extent and severity of noise pollution in different settings (Jia-Hong Tang a, Bo-Cheng Lin b, Jing-Shiang Hwang, 2022). However, these methods often lack the granularity and flexibility required to address the dynamic and multifaceted nature of noise pollution.

This literature review aims to contextualize the development of a Noise Pollution Evaluation Matrix as a novel approach to comprehensively assess and manage noise pollution. By synthesizing previous research and methodologies, this review seeks to identify gaps in existing approaches and demonstrate the need for innovative strategies to address emerging challenges in noise pollution evaluation.

### 2.2. Main noise sources in cities

To understand what we want to evaluate, first, we need to understand what we are working with, what are the sources of the noise and why it is so harmful.

Since 1972, the World Health Organization (WHO) has declared noise as a pollutant. (Noise Control Act of 1972, 1972). Nowadays, environmental acoustic quality in urban areas is threatened. The urban environment is composed of several audible sources:

- Traffic (road, rail, and air);
- Civil construction, industrial facilities;
- Social activities (parties, fairs and open-air markets, and residential noise).

These all contribute to the conversion of the soundscape in noise pollution. Road traffic noise is considered the main source of noise transportation in large urban cities and the most worrisome when it comes to annoyance (Méline et al., 2013).

### **2.3. Previous studies on Noise Pollution Evaluation**

Previous studies on noise pollution evaluation have employed diverse methodologies. Some researchers focus on creating noise dispersion maps to visualize the spread of noise across regions, which is crucial for identifying high-noise areas and potential sources of pollution (Murphy & King, 2014). Others analyse noise frequency spectra to understand the distribution and effects of different noise frequencies.

Health-related research explores the adverse effects of prolonged exposure to high noise levels, such as hearing loss and cardiovascular issues, often involving long-term noise monitoring (Stansfeld, Stephen A. & Matheson, 2003). Additionally, some studies aim to identify peak noise levels through intensive, short-term measurement campaigns (Basner et al., 2014).

Interdisciplinary studies investigate correlations between noise pollution and other environmental contaminants, offering insights into broader public health implications. Furthermore, research on quiet areas emphasizes the importance of preserving low-noise regions for public well-being and environmental quality (Pijanowski et al., 2011).

These varied methodologies highlight the complexity of noise pollution as an environmental issue and the need for a standardized evaluation framework. This thesis aims to develop a universal assessment tool to identify noise-sensitive areas, synthesizing existing knowledge on noise pollution.

#### **2.3.1. 24-hour Noise Mapping**

The noise maps show the distribution of traffic noise intuitively, which is convenient in the evaluation of traffic noise pollution. In some research, the noise map of the study area is obtained based on the interpolation of monitoring data from noise monitoring stations or collected manually, and the traffic noise pollution is evaluated based on the equivalent sound pressure of the day or night (Lagonigro et al., 2018), which is suitable for accurate assessment of small areas.

The purpose of this study was to evaluate traffic noise pollution based on noise maps. Twenty-four-hour noise maps of the Chancheng District in Foshan, China were developed for this study, and the results analysed. The study area is divided into four types, based on the land use requirements for the acoustic environment, and the calculated noise value is compared to the

noise limits of each class of the area. This shows the importance of the land use types in working with noise pollution topic.

It was also found that the noise level of the city is higher during off-peak hours than during rush hours, probably due to the faster speed and larger traffic volume during the off-peak hours. It is urgent to develop effective noise reduction measures to mitigate traffic noise pollution at night, based on the evaluation results (Weijun Yang a b, Jinying He c, Canming He c, Ming Cai a b, 2020). The traffic detection devices record the traffic volumes and speed every 3 min, allowing the traffic flow density to be calculated. The time-varying curves of the traffic flow density  $K(t)$  are shown in Figure 1. With the speed of each road segments  $V(t)$  obtained from the navigation map and the traffic flow density of each type of road  $K(t)$  from the traffic flow detectors, the traffic volumes of the road segments are estimated.

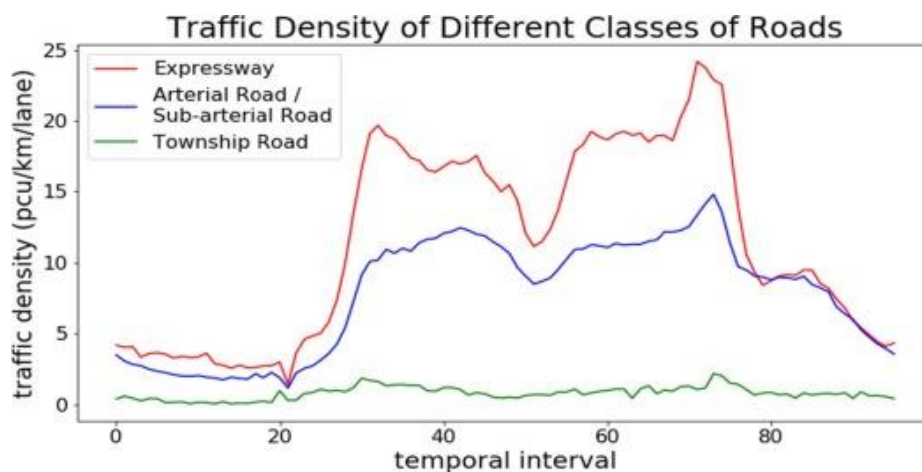


Figure 1 - The traffic flow density of various types of roads.

Research, due to unique 24-hour mapping technology, conducted an interesting discovery of the importance of hours, speed and traffic volume.

In Figure 2 - The proportion of noise receiving points that meet and exceed the noise limit in the class I area in the daytime is shown the proportion of noise receiving points in the area that meets or exceeds the noise limits in the daytime, it's unexpected to find that the number of noise receiving points meeting the limit increases during rush hour. In the intuitive impression, road traffic is extremely busy during rush hours, which may cause the traffic noise to come to a maximum. However, Figure 2 - The proportion of noise receiving points that meet and exceed the noise limit in the class I area in the daytime shows the opposite phenomenon.

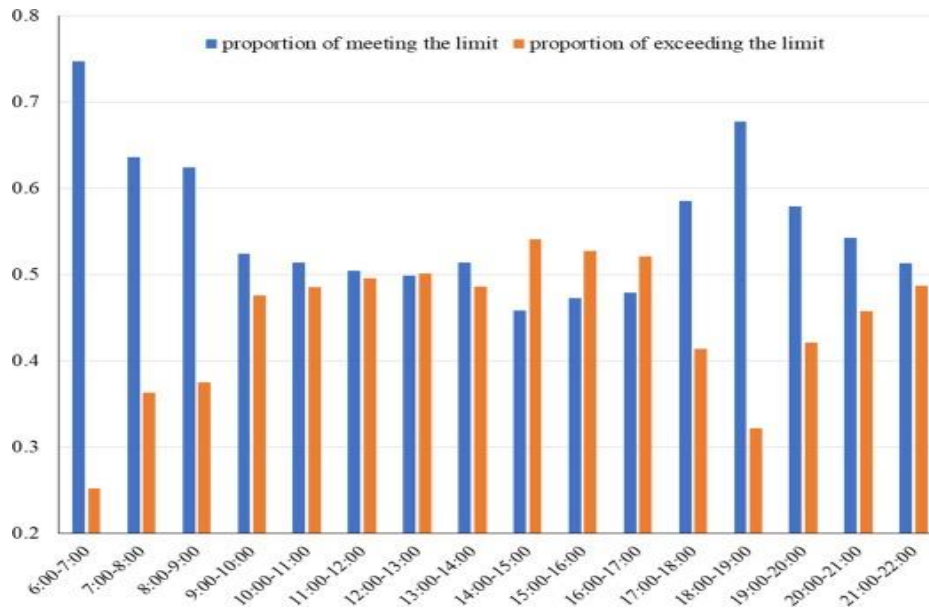


Figure 2 - The proportion of noise receiving points that meet and exceed the noise limit in the class I area in the daytime

Both the speed and traffic volume affect the road traffic noise - larger speeds and traffic volumes cause greater traffic noise emissions. This correlation can also be used in studies in opposite way. If a study finds larger traffic noise during off-peak hours, it may indicate that the speed or the traffic volume is larger during off-peak hours than during rush hours.

### 2.3.2. Mobile Monitoring Technique

Noise propagation in an urban environment is highly dynamic and influenced by several factors. Therefore, characterizing noise sources and their spatio-temporal variations demands an accurate and extensive monitoring network. An efficient and good-quality network is also helpful for policymakers to introduce necessary interventions to curb environmental noise pollution (Pradeep Lakshmi & Nagendra Shiva, 2024).

In Chennai city, a study used mobile monitoring techniques to investigate the variations of noise levels in different zones for peak and non-peak hours. Mobile measurements may provide a more accurate representation of the noise levels an urban commuter is exposed to and help capture people's actual exposure during their regular travel process. Noise measurements were carried out along predefined routes covering Chennai's major roads and traffic intersections in a moving autorickshaw.

The corrected noise levels are compared zone-wise during peak and non-peak hours. Given that there are no prescribed standards by the Central Pollution Control Board (CPCB) for traffic areas, the WHO guideline value for traffic areas (70 dB(A)) is used as a standard to compare the noise levels (World Health Organisation, 1999)

The results showed that the equivalent noise levels exceeded the guideline value of 70 dB(A), and an urban commuter experiences high noise levels (74–85 dB(A)) while travelling through the city. A paired-t test showed that urban dwellers and commuters are exposed to statistically similar noise levels during peak and non-peak traffic flow hours.

The study concludes that noise pollution is predominantly attributed to road traffic, pushing levels in the city to serious thresholds (exceeding 70 dB(A)) and recommends strategies to alleviate traffic noise and its consequences on the urban population. Personal exposure parameters exhibit elevated values, emphasizing the urgent need for comprehensive strategies and urban planning measures to address and mitigate the often-overlooked issue of noise pollution in Indian cities like Chennai.

### **2.3.3. Using prediction models**

In 2018 in Kenya, was conducted, to study and analyse the noise pollution levels in major areas in the Ota metropolis. A probability model which is capable of predicting the noise pollution level was also determined.

Datasets on the noise pollution level in 41 locations across the Ota metropolis were made. The datasets were collected thrice per day; morning, afternoon, and evening. Descriptive statistics were performed, and an analysis of variance was also conducted using Minitab version 17.0 software. Easy fit software was however used to select the appropriate probability model that would best describe the dataset.

The noise levels were much greater than the WHO recommended levels. Also, there is no significant difference in the effects of the noise pollution level for all the times of the day considered. The log-logistic distribution provided the best fit to the dataset based on the Kolmogorov-Smirnov goodness of fit test.

The fitted probability model can help in the prediction of noise pollution and act as a yardstick in the reduction of noise pollution, thereby improving the public health of the populace (Oguntunde et al., 2019).

### **2.4. Health aspects**

The paper by Aletta, Oberman, and Kang (Aletta et al., 2018) explores the associations between positive health-related effects and perceptual constructs of soundscapes. It highlights the potential of sound perception as an enhancer of the human experience in the urban environment, emphasizing the importance of considering sounds as resources that promote healthy and supportive environments.

In particular, the paper identifies several health issues and diseases that can be positively influenced by soundscapes. These include:

**Stress Recovery:** Positive soundscapes are associated with faster recovery from stress, as demonstrated in laboratory experiments.

**Self-Reported Health:** Surveys indicated that individuals exposed to pleasant soundscapes report better overall health.

**Mental Well-being:** Reduced stress-related mental health risks and improved cognitive functioning were noted in environments with positive soundscapes.

It is worth noting that, positive soundscapes are auditory environments filled with pleasing and calming sounds, such as birdsong, rustling leaves, and flowing water. These natural sounds enhance well-being, reduce stress, and improve mood. By fostering a sense of tranquillity and connection to nature, positive soundscapes contribute significantly to mental and emotional health.

The paper supports the notion that sound perception can enhance urban life quality, moving beyond the traditional view of noise as merely a negative factor. Instead, it advocates for incorporating soundscapes into urban design to foster healthier and more supportive environments.

Chitra, Jain, and Chundelli delve into how landscape elements in urban parks shape their soundscapes and influence public perception (Chitra et al., 2020). It emphasizes the significant role of natural features, such as trees, water bodies, and vegetation, in enhancing the acoustic environment of these spaces. Water features, such as fountains and streams, are particularly highlighted for their ability to mask undesirable noise, thereby improving the overall soundscape quality. This masking effect helps create a more pleasant auditory experience for park visitors.

The research underscores the importance of incorporating natural elements into the design and management of urban green spaces to foster healthier acoustic environments. By enhancing positive sounds and mitigating unwanted noise, these natural features contribute to a more supportive and enjoyable urban experience. This approach aligns with broader urban planning and public health objectives, aiming to create environments that promote well-being and reduce the adverse effects of noise pollution.

**Key Points:**

**Natural Features:**

- Trees, water bodies, and vegetation significantly influence soundscapes.
- Water features are effective at masking unwanted noise.

Health and Well-being:

- Improved soundscapes contribute to stress reduction and better mental health.
- Pleasant sounds enhance the overall experience of urban parks.

Urban Planning Implications:

- Integrating natural elements is crucial for effective park design.
- Soundscape considerations should be integral to urban green space management.

By focusing on the physical characteristics of urban parks, this study provides valuable insights for urban planners and landscape architects. It highlights the need to design spaces that not only meet aesthetic and recreational needs but also create healthy acoustic environments that enhance public well-being.

The potential role of nearby green areas in mitigating noise and promoting well-being in urban residential environments is examined in research of 2007 (Gidlof-Gunnarsson & Ohrstrom, 2007). The study highlights the importance of the perceived availability of green spaces in reducing the negative impacts of noise on individuals' well-being.

Hong, Wang, Liu, and Lan (Hong et al., 2019) investigate the cognitive persistence of soundscape in urban parks. They explore how individuals' cognitive perception of soundscape evolves over time and identify the factors influencing its persistence. This research contributes to a deeper understanding of the long-term effects of soundscape in urban park environments.

This study by the UK Health Security Agency (UK Health Security Agency, 2023) highlights several important correlations between noise pollution and health. The primary health issues linked to noise exposure include:

1. **Chronic Annoyance and Sleep Disturbance:** These are the most common impacts, affecting well-being and quality of life.
2. **Cardiovascular Diseases:** Long-term exposure to noise, particularly from road traffic, can lead to increased risks of stroke and ischemic heart disease.
3. **Diabetes:** There is a notable association between noise exposure and an increased risk of diabetes.
4. **Mental Health:** Noise annoyance and sleep disturbance are linked to higher risks of depression and anxiety.

The 2023 report (UK Health Security Agency, 2023), provides an in-depth examination of the adverse health effects associated with noise pollution. The health effects of traffic noise (from report) are presented in Figure 3. The report highlights chronic annoyance and sleep disturbance as the most immediate and prevalent impacts of environmental noise, particularly from road

traffic. It further correlates long-term exposure to noise with significant health issues, including cardiovascular diseases such as stroke and ischemic heart disease, as well as an increased risk of diabetes. Mental health repercussions, such as elevated risks of depression and anxiety, are also noted.

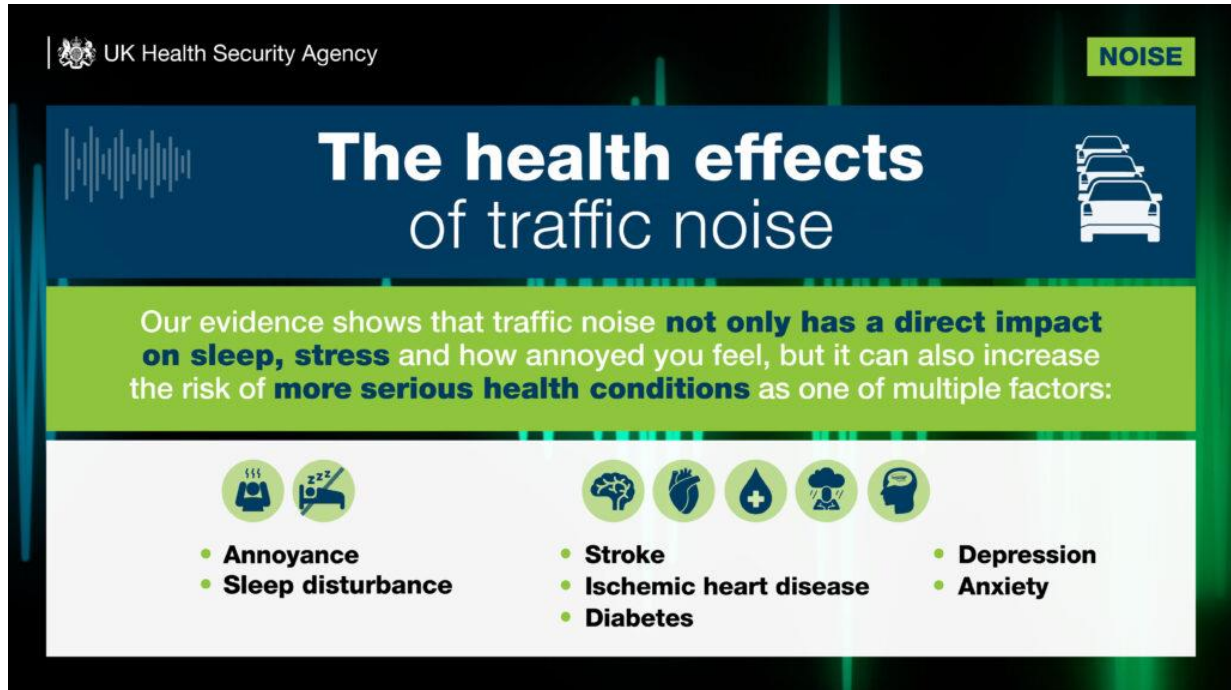


Figure 3 - The health effects of traffic noise

To quantify the health burden, the study employs Disability Adjusted Life Years (DALYs), revealing substantial losses attributed to noise from road traffic, railways, and aircraft. The findings underscore the importance of integrating noise considerations into urban planning and transport infrastructure decisions. By addressing noise pollution through improved design and regulatory measures, the report suggests potential mitigation of its detrimental health impacts, thus promoting public health and well-being.

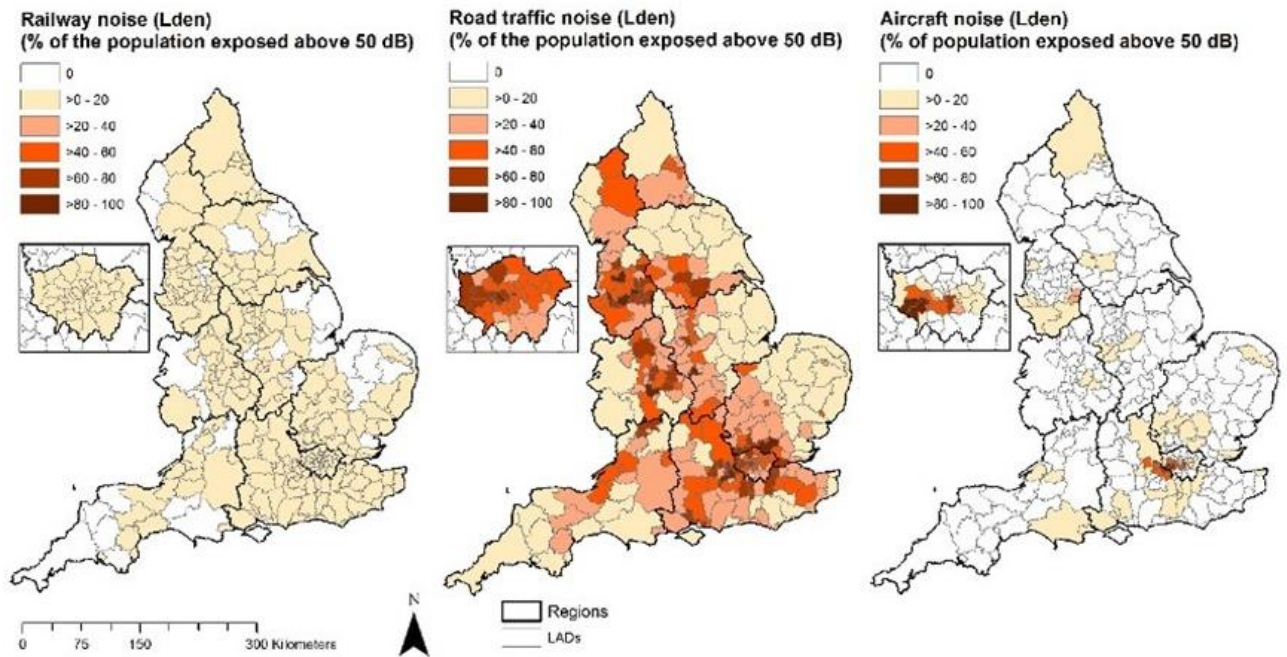


Figure 4 - Statistics of noise exposure

Figure 4 - Statistics of noise exposure represents that most of the percentage of people exposed to road traffic, railway, and aircraft noise. From the figure, one can see that it clearly illustrates that a significantly higher number of people are exposed to road traffic noise compared to aircraft and railway noise. This suggests that road traffic noise poses a greater impact on a larger population, highlighting the need for measures to mitigate its effects. L den is Daytime noise levels, typically ranging from 7 AM to 10 PM in the UK standards.

### 2.4.1. Annoyance

Another big statistical study shows that with the growth of the level of noise grows also the level of human annoyance (de Paiva Vianna et al., 2015) what is represented in Figure 5. The same study proved that the home-based scenarios configured the urban soundscape where there was the greatest perception of noise sources; reports of annoyance regarding the perceived noise and bad quality of sleep were identified.

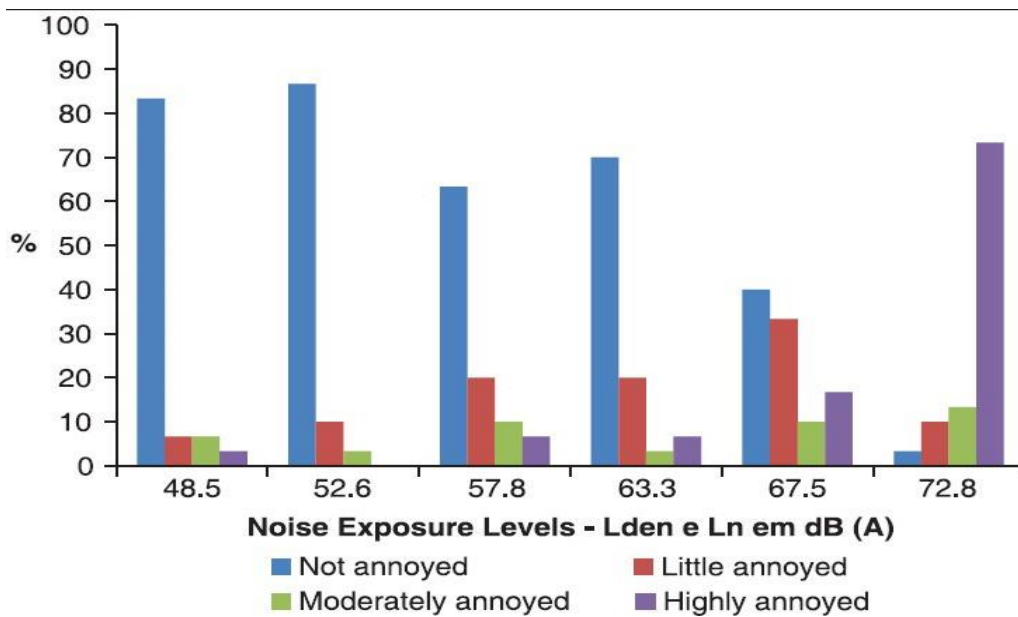


Figure 5 - Annoyance in relation to noise exposure (*Lden e Ln*), Porto, Portugal, 2012

This soundscape requires attention since it represents a scenario of rest, family interactions, and relaxation. The ever-expanding urban growth and industrialization of developing countries compromised the necessary urban planning for guaranteed sustainability in large cities, compromising health and the population's quality of life.

### 2.4.2. Soundscape perception

One important variable in soundscape perception is simply how people think about different sounds. Noise pollution can be considered one of the main agents of loss of environmental and life quality in a metropolis and its dissemination pushed the boundaries of industrial facilities, spreading through the streets and also for leisure activities, moments of rest and work. However, its perception is based on the interrelationship between person, place, and activity in space and time (Davies et al., 2013).

At the same time, it has been reported that high intensities, high frequencies, and intermittent nature of noise are the factors of annoyance for workers. Such situations not only bring about physical and psychological damages but also impair workers' efficiency, giving rise to their low production and causing dissatisfaction (Muralikrishna & Manickam, 2017).

The A-weighted decibel (dB) scale begins at zero. This represents the faintest sound that can be heard by humans with very good hearing. The loudness of sounds (that is, how loud they seem to humans) varies from person to person, so there is no precise definition of loudness. However, based on many tests of large numbers of people, a sound level of 70 dBA is twice as loud to the listener as a level of 60 dB as represented in Figure 6 - Noise levels (Muralikrishna & Manickam, 2017).

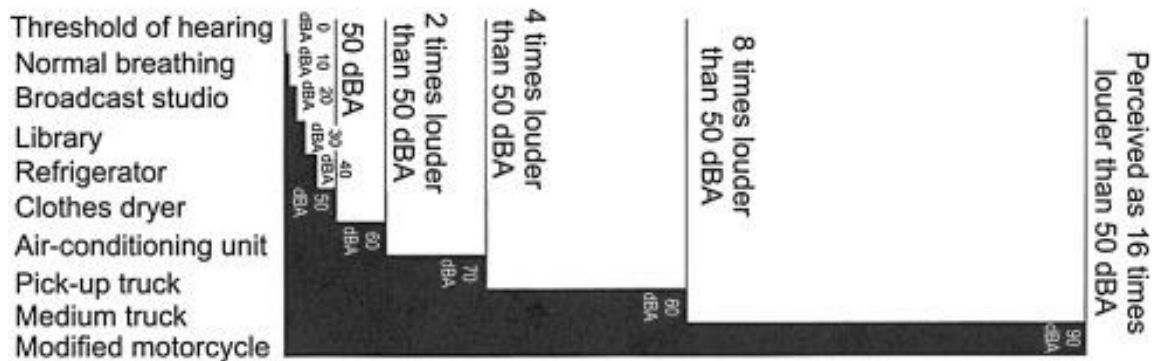


Figure 6 - Noise levels (Muralikrishna & Manickam, 2017)

## 2.5. Local policies and strategies (for Scotland)

The Scottish Government is committed to understanding and managing the environmental impact of our transport network. The government acknowledge that noise can be distressing, affects our quality of life, and can impact people's health and environment.

### 2.5.1. Transportation Noise Action Plan

Attitudes to noise are changing and it has been suggested that people are becoming less tolerant of their noise environment (TNAP&nbsp;, 2019)

The Transportation Noise Action Plan (TNAP) prepared by Transport Scotland - The national transport agency for Scotland, outlines specific measures to reduce noise pollution from roads and railways.

These measures include:

Incorporating noise management into all transport-related activities, including design, construction, maintenance, policy, and point-to-point transportation activities.

1. Seeking to manage noise levels where necessary and practicable at Noise Management Areas (NMAs) and aiming to preserve environmental noise quality where it is good.

2. Prioritizing process, including the Building Prioritization Score (BPS), Source Prioritization Score (SPS), and Candidate Noise Management Areas (CNMAs) to identify areas where noise reduction measures are most needed.

3. Establishing and operating a Noise Inspection Panel (NISP) to assess issues on transport noise from a source, transmission, and receptor perspective to support the delivery of the TNAP. These measures are part of the overall approach to address noise pollution from roads and railways as outlined in the TNAP. The specific measures outlined in the TNAP address the harmful effects of environmental noise on communities in Scotland by prioritizing the management of noise in areas outside of agglomerations. The TNAP aims to ensure that noise management is incorporated into all transport-related activities, including design, construction, maintenance, policy, and point-to-point transportation activities. It also seeks to

manage noise levels at Noise Management Areas (NMAs) and preserve environmental noise quality where it is good. Additionally, the TNAP includes a prioritization process, key objectives, and actions to address environmental noise. Furthermore, the plan establishes a NISP to assess issues on transport noise from a source, transmission, and reception perspective.

Another important thing to mention is that Noise from lawful use of existing roads and railways cannot be construed as noise nuisance, under the terms of the Environmental Protection Act. Noise from new roads can be managed via the planning process, as detailed in Planning Advice Note 1/2011, PAN 51 and Noise Insulation (Scotland) Regulations (The Noise Insulation (Scotland) Regulations, 1975).

Harmful noise, as defined in the Environmental Noise Directive (END), refers to the unwanted or damaging sound created by human activities. This includes noise from transportation such as road traffic, rail traffic, and air traffic, as well as noise from industrial activity sites. It does not include noise caused by the person exposed to the noise, domestic activities, noise from neighbours, or noise at workplaces, as these are addressed through separate legislation (*Environmental Noise Directive - 2002/49* ).

From analysis of the END noise maps, the prioritisation process is a method of determining the provisional assignment of CNMAs and thereafter NMAs. *Figure 7 - Step-by-step stages of the Prioritisation Process*. BPS = Building Prioritisation Score; SPS = Source Prioritisation Score (see below for more detail) outlines the step-by-step journey of the prioritisation process of the TNAP. As noted in TNAP, the noise contour maps alone are not sufficient to determine where noise management is required.

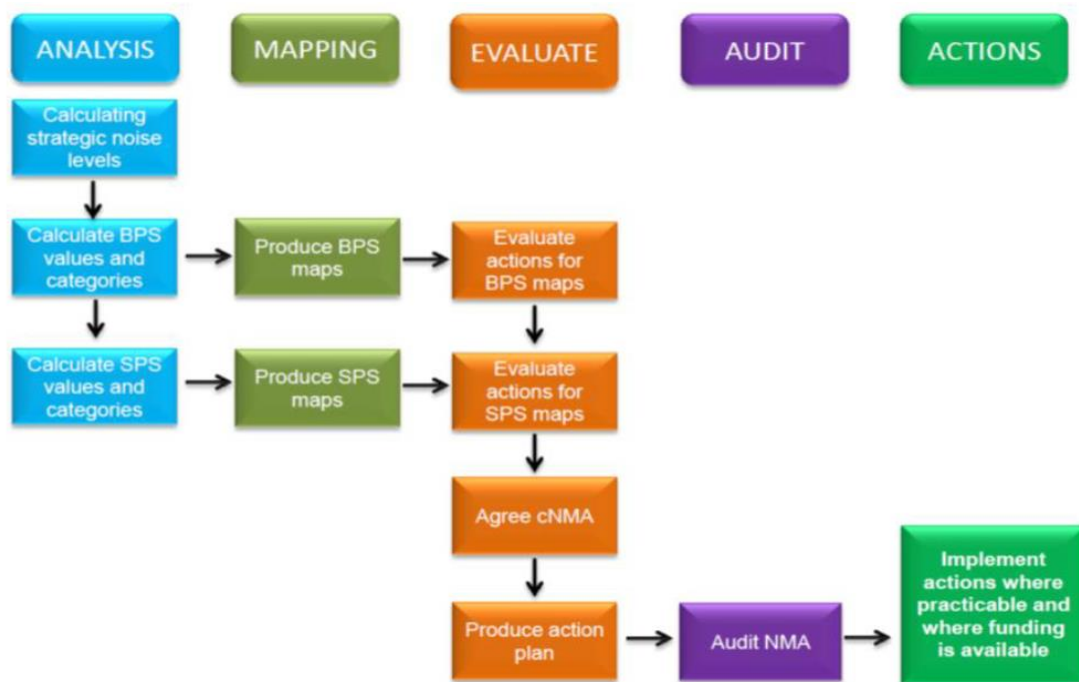


Figure 7 - Step-by-step stages of the Prioritisation Process. BPS = Building Prioritisation Score; SPS = Source Prioritisation Score (see below for more detail) (TNAP)

Another important fact to mention from TNAP is that local government is aware of changes in the type of vehicles being used in the city, with plug-in hybrid and fully electric vehicles expected to become much more commonplace. This means that these changes will be taken into consideration during policymaking.

Regular updates, guidance, information, and progress are provided on the TNAP actions to the Scottish Noise Mapping Website via links to the Transport Scotland/SCOTS website and social media platforms.

EU Directive on Environmental Noise defines Quiet Urban Areas (QUAs) definition not clear enough to allow an appropriate assessment and management of QUAs in urban environments and it leaves the Member States free to delimitate, assess, and plan the areas. The consequence of this “freedom of choice” resulted in non-homogeneous collections of data as well as in a divergent approach across the EU (EU Report, 2015). The main result of this project is a guideline about a harmonized methodology for selection, assessment, and management (action planning) of QUAs.

## 2.6. Conclusion

In conclusion, the literature review has provided a comprehensive overview of the diverse methodologies and approaches utilized in evaluating noise pollution. From noise mapping techniques to frequency analysis and health impact assessments, researchers have employed

various tools to measure and understand the complexities of noise pollution in different environments. While these studies have contributed valuable insights into the spatial distribution and health implications of noise pollution, a notable gap remains in the availability of a universal evaluation tool for decision-making purposes.

Despite the wealth of research in this field, the absence of a standardized matrix for noise pollution evaluation hinders the ability of policymakers and urban planners to effectively prioritize mitigation efforts and allocate resources.

Building upon the foundation laid by previous research, this thesis aims to address this gap by developing a novel evaluation matrix for noise pollution. By synthesizing existing knowledge and drawing upon diverse methodologies, the proposed matrix seeks to provide a systematic and user-friendly approach to identifying sensitive areas and prioritizing interventions. By integrating key indicators and criteria relevant to noise pollution assessment, this matrix will enable stakeholders to make informed decisions that promote environmental health and quality of life in urban settings.

In doing so, this research represents a significant step forward in the field of noise pollution evaluation. By bridging the gap between existing methodologies and the need for standardized decision-making tools, this thesis builds upon previous work while offering a novel contribution to the field. Through the development of a universal evaluation matrix, this research seeks to empower decision-makers with the tools necessary to address the complex challenges posed by noise pollution in the modern urban landscape.

## Chapter 3: Methodology

### 3.1. Introduction

As we embark on the methodology phase of this research, our focus shifts towards realizing the objectives outlined to develop an evaluation system for mitigating urban noise pollution. This section elucidates the strategic approach taken to achieve each objective, ensuring a systematic and comprehensive methodology tailored to the unique challenges posed by noise pollution in urban environments.

Noise pollution is a pervasive environmental issue that poses significant challenges to public health, environmental quality, and quality of life in urban and industrialized areas. In this study, we aim to develop an evaluation matrix for assessing noise pollution using the AHP as a multicriteria decision-making tool. This methodology will provide a systematic framework for evaluating the severity and impact of noise pollution across various contexts and inform evidence-based policy and management strategies.

### 3.2. Objectives

It is important to recall the aims of this research:

- 1: Developing and prioritizing key criteria for assessing noise pollution.
- 2: Designing an evaluation matrix that integrates key criteria and develops a scoring mechanism to quantify noise pollution levels.
- 3: Develop guidelines for implementing the evaluation system within urban planning and management frameworks.

### 3.3. Objective 1: Establishing main criteria

To develop the evaluation matrix, we will identify the following criteria and sub-criteria for assessing noise pollution. This will be achieved through a comprehensive review of existing literature and reports from reputable sources such as the European Environment Agency (EEA), the World Health Organization (WHO), and national guidelines such as those from the Scottish Government. To reach this we will use a Research method or so-called Expert Delphi Method.

The Delphi method is a structured approach for obtaining input from a panel of experts through a series of iterative surveys or rounds of discussion. It is particularly useful for consensus-building and prioritizing criteria based on expert judgment.

#### 3.3.1. Noise Level (dB)

Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion is essential as it quantifies the intensity of noise, which is directly related

to its impact on human health and well-being. High noise levels are associated with a range of adverse effects, including hearing loss, stress, and sleep disturbances (*World Health Organisation* 2018). Daytime noise levels, typically ranging from 7 AM to 10 PM, are important for assessing noise pollution's impact on productivity and daily activities, with studies indicating that noise levels above 55 dB during the day can cause annoyance and reduce quality of life (Babisch et al., 2005). Nighttime noise levels, from 10 PM to 7 AM, are critical for sleep quality and overall health, with the World Health Organization recommending that these levels should not exceed 40 dB to prevent sleep disturbances and long-term health issues (*WHO* 1980). Peak noise levels, referring to the highest noise levels recorded during specific periods, often caused by transient events like traffic, sirens, or construction activities, can be particularly disruptive and harmful (Murphy & King, 2014).

### **3.3.2. Source of Noise**

Identifying sources of noise is essential for developing targeted mitigation strategies, as different sources contribute varying levels and types of noise pollution affecting areas differently. Traffic noise, one of the most significant contributors to urban noise pollution, includes noise from cars, buses, trucks, and motorcycles, with studies showing that proximity to busy roads is associated with higher noise levels and increased health risks (de Kluizenaar et al., 2009). Railway noise, generated by trains including operational noise, whistles, and track noise, significantly affects nearby residential areas and has been linked to sleep disturbances and increased stress levels (Öhrström & Skånberg, 2006).

Aircraft noise, a major concern for communities near airports, from take-offs, landings, and overflights, can cause significant annoyance and health issues, including sleep disruption and hypertension (Stansfeld, S. A. et al., 2005)

. Industrial noise from manufacturing and construction varies based on the type of industry and proximity to residential areas (Basner et al., 2014). Construction noise, typically intermittent but highly disruptive, includes sounds from machinery and equipment, with prolonged exposure leading to hearing impairment and increased stress (Golmohammadi et al., 2013). Public and recreational noise from human activities such as public events, recreational activities, and nightlife significantly contribute to urban noise levels, causing considerable disturbance (Guski, 1999). Finally, commercial noise from activities like retail stores, restaurants, and bars, including noise from customers, music, and operational activities, adds to the urban noise environment, necessitating effective management to maintain a healthy living environment (Williams & Short, 2022).

### **3.3.3. Distance from Noise Source**

Various studies show that the impact of noise diminishes with increasing distance from the source. This criterion evaluates the proximity of noise-sensitive areas such as residential zones, schools, and hospitals to major noise sources (Maekawa, 2003).

Proximity to traffic is a critical factor in evaluating noise pollution, as vehicles in urban areas are significant noise sources linked to various health issues, including stress, sleep disturbances, cardiovascular diseases, and reduced cognitive performance in children (World Health Organization, 2011). Factors such as traffic volume, speed, and vehicle type influence traffic noise intensity, with heavy trucks generating more noise than smaller cars, prompting urban planning and noise mitigation strategies to prioritize reducing traffic noise exposure in residential areas for better public health (Murphy & King, 2014).

As mentioned above, industrial sites contribute significantly to noise levels (Passchier-Vermeer & Passchier, 2000) construction sites, although temporary, also produce substantial intermittent noise (Goines & Hagler, 2007) (Construction Noise: Exposure, Effects, and the Potential for Remediation; A Review and Analysis.2010) so the distance from them should be considered. Airports, generating high decibel levels during aircraft operations (Basner et al., 2014) (Eulalia Peris, 2020), railway lines, especially ones used by high-speed and freight trains, affecting residents' quality of life, and causing long-term health issues (Öhrström & Skånberg, 2006) (Andersson et al., 2013) will also be important for these criteria of the Matrix.

### **3.3.4. Surface Conditions**

Surface conditions, including ground cover and surrounding structures, significantly affect noise propagation and attenuation, influencing overall noise levels in an area. The type of ground cover, such as grass or asphalt, plays a crucial role, with grass and soil absorbing sound waves more effectively than hard surfaces like asphalt and concrete, reducing noise levels and making green spaces vital for urban noise management (Renterghem, 2014).

Vegetation and trees act as natural sound barriers, with vegetative buffers potentially reducing noise levels by up to 5-10 dB (in case of high density), and also providing psychological benefits that enhance perceived noise reduction, contributing to improved mental health (Dzhambov & Dimitrova, 2014). Open spaces, like parks and plazas, help mitigate noise pollution by allowing noise to dissipate and serving as buffers between noise sources and residential areas, enhancing the urban soundscape and improving residents' quality of life (Kang, 2016) (Frederic Steiner, 1996).

### **3.3.5. Cost Analysis**

Cost-benefit analysis is a critical component in the evaluation and management of noise pollution, as it helps policymakers and stakeholders balance the financial investment in noise reduction measures against the potential health and economic benefits. By quantifying both the costs of implementing noise mitigation strategies, such as sound barriers, improved road surfaces, or building insulation, and the benefits, such as reduced healthcare costs, improved quality of life, and increased productivity, decision-makers can ensure that resources are allocated efficiently. This approach not only helps in justifying the expenses associated with noise control but also promotes sustainable and economically viable solutions that maximize public health outcomes and community well-being. According to the World Health Organization's Environmental Noise Guidelines for the European Region (2018), incorporating cost-benefit analyses into noise management strategies is essential for creating effective public health policies that are both practical and impactful (World Health Organization, 2018)

### **3.3.6. Receptor impacted in urban scale**

To find out most vulnerable areas with receptor will help functional zoning. Functional zoning of cities is crucial for effective noise management, tailoring mitigation strategies to specific urban areas based on their function and population density. Residential zones, characterized by high population density and prolonged exposure to noise from transportation and recreational activities, require sound insulation measures and urban planning that prioritizes quieter transport routes to mitigate annoyance, sleep disturbance, and cardiovascular effects (World Health Organization, 2018). Commercial zones, hosting diverse businesses like retail outlets and restaurants, necessitate noise assessment and management to protect workers' health and maintain a conducive business environment.

Industrial zones, governed by EU directives like the (*Environmental Noise Directive - 2002/49.* ), aim to manage noise from industrial activities to safeguard human health and the environment (European Environmental Agency, 2010). Recreational zones, including parks and sports fields, require noise considerations to preserve their intended functions of relaxation and physical activity without disruption (*World Health Organisation 2018*). Mixed zones, combining residential, commercial, and industrial uses, demand integrated urban planning strategies such as green spaces and noise barriers to harmonize diverse activities while minimizing noise conflicts (European Environmental Agency, 2010). By aligning noise abatement measures with functional zoning, policymakers can create sustainable urban environments that protect public health and enhance residents' quality of life.

Also, Scottish standards say that for noise generating developments (NGD), it may be sufficient to identify the nearest noise sensitive receptors (NSRs). They have a chapter dedicated to process of finding the NSRs and have developed types noise sensitive receptors ( Scottish Government, 2011). Examples and Types of noise sensitive receptors are presented in Table 1.

Sensitivity	Description	Examples of NSR
High	Receptors where people or operations are particularly susceptible to noise	Residential, including private gardens where appropriate. Quiet outdoor areas used for recreation Conference facilities Theatres/Auditoria/Studios Schools during the daytime Hospitals/residential care homes Places of worship
Medium	Receptors moderately sensitive to noise, where it may cause some distraction or disturbance	Offices Bars/Cafes/Restaurants where external noise may be intrusive Sports grounds when spectator noise is not a normal part of the event and where quiet conditions are necessary (e.g. tennis, golf, bowls)
Low	Receptors where distraction or disturbance from noise is minimal	Buildings not occupied during working hours Factories and working environments with existing high noise levels Sports grounds when spectator noise is a normal part of the event Night Clubs

*Table 1 - Types of noise sensitive receptors*

These criteria are selected based on their documented impact on public health, as indicated in WHO and EEA reports and Scottish Noise Regulations, which highlight the links between noise levels and adverse health outcomes such as cardiovascular diseases, sleep disturbances, and annoyance.

### **3.4. Objective 2: Designing an Evaluation Matrix**

Objective 2 aims to develop an evaluation matrix utilizing the AHP, a structured methodology for managing complex decisions rooted in mathematical and psychological principles. The process involves several key steps:

1. **Hierarchy Development:** Establishing a hierarchical structure of criteria and sub-criteria identified through a comprehensive literature review. This structure ensures clarity in depicting the relative importance and interrelationships among criteria.

2. **Pairwise Comparisons:** Conducting pairwise comparisons of criteria within each level of the hierarchy. Expert judgments are employed to assign relative weights to each criterion, drawing upon documented impacts from authoritative sources such as WHO and EEA reports.

3. **Consistency Check:** Computing the consistency ratio to verify the coherence of judgments made during pairwise comparisons. Adjustments are made if the consistency ratio exceeds predefined thresholds, ensuring the reliability of the weighting process.

4. **Scoring Mechanism:** Developing a standardized scoring mechanism to quantitatively assess noise pollution levels based on the weighted criteria. This involves defining specific scales and benchmarks for factors like noise level, duration, frequency of noise events, and temporal distribution.

The selection of AHP is grounded in its efficacy for managing intricate decision-making scenarios involving multiple criteria. By facilitating systematic prioritization and rigorous evaluation through pairwise comparisons and consistency checks, AHP ensures robust and reliable criteria weighting.

Ultimately, the objective is to create an evaluation matrix that seamlessly integrates critical criteria and a scoring mechanism, thereby enabling the quantitative assessment of noise pollution levels.

### **3.5. Objective 3: Developing Guidelines for Implementation**

Objective 3 focuses on developing guidelines for the practical implementation of the evaluation system within urban planning and management frameworks.

As mentioned earlier, the Matrix will help to prioritise problematic areas within a city, it will be extremely helpful for many specialists, decision makers, designers, maintenance programmers as a decision-making toolkit for scheduling and prioritising future projects.

The steps involved are as follows:

1. **Integration with Urban Planning:**

Reviewing existing urban planning and noise management policies specific to Glasgow. Identifying opportunities and challenges for integrating the evaluation matrix into these established frameworks.

#### 2. Guideline Development:

Implementation of GIS maps for highlighting visual part of Matrix to see all potentially vulnerable areas. Creating comprehensive guidelines detailing the application of the evaluation matrix within urban planning processes. Developing application forms for user of the Matrix. Inclusion of protocols for systematic data collection, rigorous analysis, and standardized reporting procedures. Creating a web page dedicated to matrix visual and evaluating parts.

As an extra step, can be an expansion of the web page, together with other governmental institutions, in case if the Matrix will have more data from their organisations (for example health-noise correlation maps together with NHS or other health related organisations).

#### 3. Stakeholder Engagement:

Engaging with key stakeholders, such as city planners, local government officials, public health experts, and community organizations. Ensuring that the developed guidelines address the diverse needs and concerns of all relevant stakeholders.

#### 4. Training and Capacity Building:

Developing tailored training programs and educational materials aimed at practitioners involved in urban planning and noise management. Conducting workshops and seminars to enhance the capacity of stakeholders in effectively utilizing the evaluation matrix.

Expected outcomes include the establishment of practical guidelines that facilitate the seamless integration and application of the evaluation system within Glasgow's urban planning and management frameworks. These guidelines are designed to promote informed decision-making, enhance coordination among stakeholders, and ultimately contribute to the improvement of urban living conditions and public health outcomes.

### **3.6. Summary**

Chapter 3 initiates the development of an evaluation framework to address urban noise pollution systematically. This methodology is structured to achieve three primary objectives: identification of essential criteria, formulation of an evaluation matrix using the AHP, and creation of implementation guidelines tailored for urban planning frameworks.

Urban noise pollution presents significant challenges to public health and urban liveability. Employing AHP, a rigorous decision-making tool, involves constructing a hierarchical structure of criteria derived from comprehensive literature reviews and expert insights. Through pairwise

comparisons, criteria are assigned relative weights, while consistency checks ensure the reliability of judgments. The resulting evaluation matrix integrates factors such as noise levels, sources, proximity to noise-emitting sources, surface conditions, and cost considerations, facilitating quantitative assessments of noise pollution impacts.

Furthermore, this methodology entails the development of practical guidelines for embedding the evaluation matrix within Glasgow's urban planning policies. This includes aligning the matrix with existing frameworks, engaging diverse stakeholders, and enhancing operational capacities through targeted training initiatives. Ultimately, this approach aims to inform evidence-based urban policies and strategies that promote enhanced urban living conditions and improved public health outcomes.

## Chapter 4: Results

### 4.1. Criteria and Sub-Criteria identified

To identify criteria and sub-criteria this thesis carefully selected most important noise influencing factors, based on documented impact on public health and annoyance, indicated in WHO and EEA reports, and independent researches, guidelines, and rules.

#### 4.1.1. Noise Level (dB)

Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion is essential as it quantifies the intensity of noise, which is directly related to its impact on human health and well-being. High noise levels are associated with a range of adverse effects, including hearing loss, stress, and sleep disturbances (*World Health Organisation* 2018).

Sub-criteria:

##### 1. Daytime Noise Level (dB)

Daytime noise levels typically range from 7 AM to 10 PM. This period is crucial for assessing noise pollution as it affects productivity and daily activities. Studies have shown that noise levels above 55 dB during the day can cause annoyance and reduce the quality of life (Babisch et al., 2005).

##### 2. Nighttime Noise Level (dB)

Nighttime noise levels, from 10 PM to 7 AM, are critical due to their impact on sleep quality and overall health. The World Health Organization recommends that nighttime noise (*WHO* 1980) levels should not exceed 40 dB to prevent sleep disturbances and long-term health issues. However local policies of different country claim other numeric parameters for this criterion.

##### 3. Peak Noise Level (dB)

Peak noise levels refer to the highest noise levels recorded during a specific period. These peaks, often caused by transient events like traffic, sirens, or construction activities, can be particularly disruptive and harmful (Murphy & King, 2014).

##### 4. Noise exposure

According to World Health Organisation, it is important to not be exposed to high levels of noise during long periods of time. In the United Kingdom, European Union (EU) countries members work regulations, that restrict the noise levels for 8 hours period (World Health Organization, 2018).

### **4.1.2. Source of Noise**

Identifying the sources of noise is crucial for developing targeted noise mitigation strategies. Different sources contribute varying levels and types of noise pollution, affecting areas differently.

Sub-criteria:

#### **1. Traffic Noise**

Traffic noise is one of the most significant contributors to urban noise pollution. It includes noise from cars, buses, trucks, and motorcycles. Studies have shown that proximity to busy roads is associated with higher noise levels and increased health risks (de Kluizenaar et al., 2009).

#### **2. Railway Noise**

Noise generated by trains, including operational noise, whistles, and track noise, significantly affects nearby residential areas. Continuous exposure to railway noise has been linked to sleep disturbances and increased stress levels (Öhrström & Skånberg, 2006).

#### **3. Aircraft Noise**

Aircraft noise is a major concern for communities near airports. The noise from take-offs, landings, and overflights can cause significant annoyance and health issues, including sleep disruption and hypertension (Stansfeld, S. A. et al., 2005)

#### **4. Industrial Noise**

Industrial activities, including manufacturing and construction, generate significant noise pollution. The impact of industrial noise varies based on the type of industry and proximity to residential areas (Basner et al., 2014).

#### **5. Construction Noise**

Noise from construction sites is typically intermittent but can be highly disruptive. It includes sounds from machinery, equipment, and construction activities. Prolonged exposure to high levels of construction noise can lead to hearing impairment and increased stress (Golmohammadi et al., 2013).

#### **6. Neighbourhood Noise**

Typical neighbourhood noise comes from premises and installations related to the catering trade (restaurant, cafeterias, discotheques, etc.); from public work, from live or recorded music; sport events including motor sports; playgrounds; car parks; and domestic animals such as barking dogs. It is important to take it into consideration, that neighbourhood noise can cause same harm to residence, especially at night times (World Health Organisation, 1999). It is

important to mention, that neighbourhood noise is hard for quantifying, and this can be considered as a limitation for this thesis.

### **4.1.3. Distance from Noise Source**

Various studies show that the impact of noise diminishes with increasing distance from the source. This criterion evaluates the proximity of noise-sensitive areas such as residential zones, schools, and hospitals to major noise sources (Maekawa, 2003).

Sub-criteria:

#### **1. Proximity to Traffic**

Proximity to traffic is a critical criterion for evaluating noise pollution because vehicles, particularly in urban areas, are a significant source of environmental noise. Traffic noise has been linked to various health issues, including stress, sleep disturbances, cardiovascular diseases, and reduced cognitive performance in children (World Health Organization, 2011). The intensity of traffic noise is influenced by factors such as traffic volume, speed, and the type of vehicles, with heavy trucks generating more noise than smaller cars. Urban planning and noise mitigation strategies often prioritize reducing traffic noise exposure in residential areas to improve public health and quality of life (Murphy & King, 2014).

#### **2. Proximity to Industrial Sites**

Industrial sites are major sources of noise pollution due to the operation of heavy machinery, production processes, and transportation of goods. Proximity to industrial sites can significantly impact the noise environment of surrounding areas, contributing to higher noise levels and potentially adverse health effects on nearby populations. Studies have shown that chronic exposure to industrial noise can lead to hearing loss, increased stress levels, and hypertension (Passchier-Vermeer & Passchier, 2000).

#### **3. Proximity to Construction Sites**

Construction sites are temporary but substantial sources of noise pollution, characterized by high levels of intermittent noise from activities such as drilling, hammering, and the operation of heavy machinery. Proximity to construction sites can disrupt the daily lives of residents, leading to sleep disturbances, stress, and reduced overall well-being (Goines & Hagler, 2007). The impact of construction noise is often mitigated through regulations that limit construction hours and require the use of quieter equipment and noise barriers. Monitoring and managing construction noise is crucial in urban planning to minimize its adverse effects on nearby populations (Construction Noise: Exposure, Effects, and the Potential for Remediation; A Review and Analysis.2010).

#### 4. Proximity to Airports

Airports are significant contributors to environmental noise pollution due to the high decibel levels generated by aircraft during take-off, landing, and ground operations. Proximity to airports is associated with increased exposure to high noise levels, which can lead to various health issues, including sleep disturbances, cardiovascular diseases, and annoyance (Basner et al., 2014). Noise contours around airports are often used to assess the impact on surrounding communities and inform land-use planning and noise abatement strategies. Implementing measures such as curfews on night flights and the development of quieter aircraft technologies can help mitigate the adverse effects of airport noise (Eulalia Peris, 2020)

#### 5. Proximity to Railway Lines

Railway lines contribute to environmental noise pollution through the operation of trains, particularly high-speed and freight trains, which generate significant noise levels. Proximity to railway lines can affect residents' quality of life, causing annoyance, sleep disturbances, and potentially leading to long-term health issues such as hypertension and cardiovascular diseases (Öhrström & Skånberg, 2006). Noise mitigation measures, including sound barriers, track modifications, and the use of quieter train technologies, are essential to reduce the impact of railway noise on nearby communities. Understanding the extent of noise pollution from railway lines is crucial for effective urban and transportation planning (Andersson et al., 2013).

#### **4.1.4. Surface Conditions**

Surface conditions, such as the type of ground cover and surrounding structures, affect noise propagation and attenuation. This criterion considers how different surfaces and environments influence noise levels.

Sub-criteria:

##### 1. Road surface materials

The type of ground cover significantly influences noise pollution levels due to its sound absorption properties. Surfaces like grass and soil are known to absorb sound waves more effectively compared to hard surfaces like asphalt and concrete, which tend to reflect sound. This absorption can reduce the overall noise levels in an area, making green spaces crucial in urban noise management (Renterghem, 2014).

It is important to mention that nowadays, there are two new technological inventions that help to reduce noise - electric vehicles with almost zero transmission noise and ultra quiet tyres.

The EU introduced a new tyre labelling scheme to enhance road safety, environmental, and economic efficiency by promoting fuel-efficient, safe, and low-noise tyres. This regulation helps

buyers make informed choices, but actual fuel savings and safety also depend on proper tyre maintenance and driver behaviour. Figure 8 presents new tyres classification from (EU Tyre Labelling Association, 2021). As this section discusses the results of research done, it is important to mention that these two new technologies are related to the aim of the thesis and can be extremely helpful for noise reduction nowadays.

However, these parameters will not be considered as separate criteria in the matrix. Mentioning them may cause doubling of the criteria. At the same time, not every vehicle is advance with these new technologies, and the average parameters of road noise levels for certain time periods as for Criteria 1, and Road Surface Conditions (EU Tyre Labelling Association, 2021).

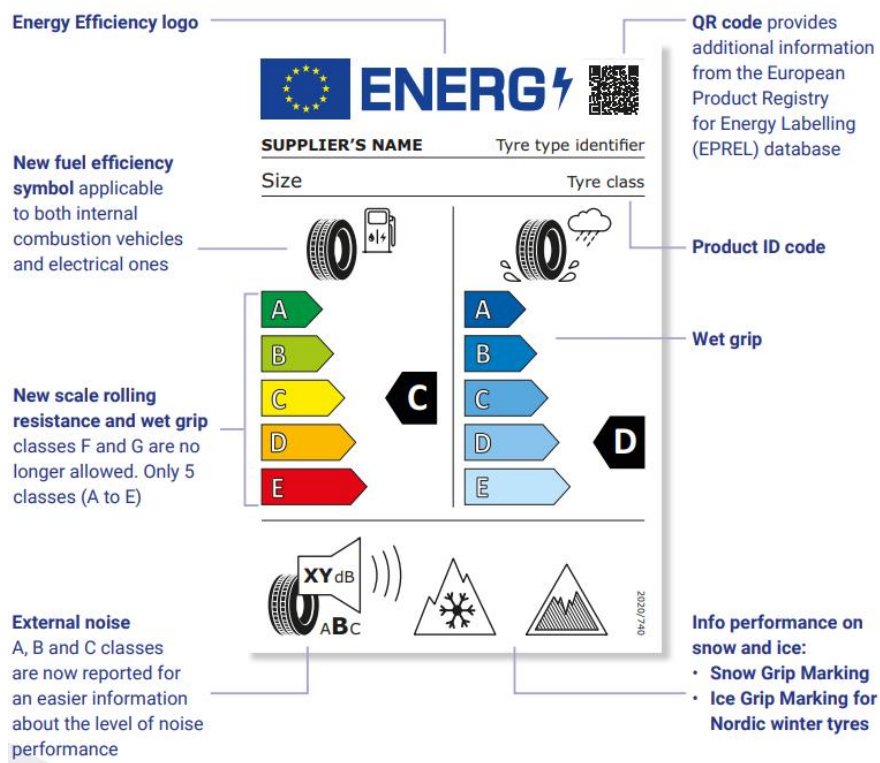


Figure 8 - Tyres types (EU Tyre Labelling Association, 2021)

## 2. Speed limit

Speed of vehicles is one of the most important parameters for consideration while working with noise pollution. Most of the noise maps are built only due to this parameter. Many experiments are conducted by independent research groups, measuring the correlation of noise levels and speed of vehicles (US Department of Transportation, 2005). This parameter will have a big influence for the Matrix and any other study related to the topic.

## 3. Presence of Vegetation and Trees between sources and receptors

Vegetation and trees play a critical role in reducing noise pollution by acting as natural sound barriers. The presence of trees and dense vegetation can significantly attenuate noise through the absorption and diffusion of sound waves. Studies have shown that vegetative buffers can reduce noise levels by up to 5-10 dB, making them an effective and aesthetically pleasing noise mitigation strategy (Dzhambov & Dimitrova, 2014). The incorporation of vegetation and trees in urban design is essential for creating healthier and more liveable cities.

#### 4. Durability of surfaces

Maintenance processes are considered as constructional noise, and seriously increase average sound pressure of a certain area. It is important for evaluation process to know life time of surfaces. The durability of road surfaces significantly affects their ability to maintain noise-reducing properties over time. More durable materials require fewer repairs and replacements, minimizing periods of increased noise during maintenance. Evaluating the durability of road materials is crucial for selecting options that provide long-term noise reduction benefits, thus enhancing community well-being (Danish Road Institute, 2010)

#### 5. Rail track condition

Modifying track properties, particularly by increasing the stiffness of rail pads, significantly reduces vibration and noise levels, addressing the higher impact of short-wavelength irregularities and ensuring compliance with Indian Railway standards. This adjustment is crucial for enhancing ride quality and maintaining acceptable noise levels (Kedia & Kumar, 2021).

##### 5.1. Subways

As was mentioned previously this thesis focused on the UK official documents and regulations, especially Scottish ones, and where possible Glasgow ones. As the Matrix is being developed for Glasgow it is important to mention all types of transportation that exist in the city.

It is important to mention that rail tracks are used not only for intercity trains but also for underground subways. Glasgow has third oldest in the world subway systems designed and developed in 19<sup>th</sup> century. Those times technologies were not as advanced as modern ones and did not allow do build subway deep under the ground, that is why the average burial depth is about 10 meters (*Glasgow Subway* 2024) Such a small distance from surface bring to a city a potential risk of noise pollution coming from subway. However, there were no fixed complains, articles or studies dedicated to the noise coming from the underground from the people on streets, walking above subway routs and infrastructure.

At the same time, visitors of ground levels of buildings located above the subway infrastructure may hear subway work. The proximity to this type of noise source is at its

minimum in the ground levels and especially basements of such buildings and can be causing annoyance to people. The noise levels in these buildings have never been measured.

This research aims to prepare the closest to real life conditions evaluation system. It is important to take into consideration all existing noise sources of Glasgow, but it is hard to be able to count parameters that were not studied and do not have any quantifying justification. This is a big limitation for developing a separate criterion. That is why, the Matrix is taking into consideration subway noise, but will not separate subway noise as separate noise source.

For other cities, in case of adaption of the Matrix, it will be also important to take into consideration existing tram system, tram lines, and other possible public transportation.

#### **4.1.5. Cost Analysis**

Noise pollution mitigation efforts often involve significant financial considerations alongside their environmental and social benefits. Evaluating the financial costs associated with noise reduction measures is crucial for decision-makers and stakeholders. Understanding these costs helps in prioritizing interventions and optimizing resource allocation for maximum impact (World Health Organization, 2018).

#### **4.1.6. Receptors impacted**

Ensuring noise mitigation solutions are suitable for different urban areas based on their function and population density. Functional zoning is crucial in urban noise management, as it helps tailor noise mitigation strategies to the specific needs and characteristics of different urban areas. Scottish Government standards, planning advice notes (PANs) and Technical Advice Note (TAN) together with the WHO in its Environmental Noise Guidelines (World Health Organization, 2018) emphasize that different urban zones, such as residential, commercial, and industrial areas, have varying noise tolerance levels and exposure patterns that are important for consideration for policy makes.

Sub-criteria:

##### **1. Residential Zones**

Residential zones are critical in noise evaluation due to their high population density and the potential for prolonged exposure to noise sources, which can impact residents' health and well-being. According to the WHO, noise from transportation, industry, and recreational activities in residential areas can lead to annoyance, sleep disturbance, and cardiovascular effects. Effective noise management strategies, including sound insulation measures and urban planning that prioritizes quieter transport routes, are essential to mitigate these impacts (*World Health Organisation 2018*).

## 2. Social zones

WHO, European noise agencies, researchers admit that high levels of noise close to social instances cause focusing problems among students, cause various heart diseases, and are extremely harmful for human health. It is important to take into consideration these vulnerable areas while prioritizing areas for future interventions (*World Health Organisation 2018*).

## 3. Commercial Zones

Commercial zones typically host a variety of businesses, including retail outlets, restaurants, and offices, where noise levels can vary significantly throughout the day. The EEA emphasizes the importance of noise assessment and management in commercial areas to protect workers' health and ensure a conducive environment for business operations. Noise from commercial activities can affect nearby residential areas and should be carefully considered in urban planning to balance economic development with noise control measures (European Environmental Agency, 2010)

## 4. Industrial Zones

EU has regulations and directives aimed at managing and mitigating noise pollution in industrial zones to protect human health and the environment. END is one of the key legislative instruments in this regard. It requires EU member states to assess and manage environmental noise from various sources, including industrial activities, with the goal of preventing or reducing its harmful effects on human health (*Environmental Noise Directive - 2002/49.* )

## 5. Recreational Zones

The WHO emphasizes the importance of considering noise pollution in recreational zones due to its potential impact on human health and well-being. Recreational areas such as parks, playgrounds, and sports fields are meant to provide spaces for relaxation, physical activity, and social interaction. Excessive noise levels can disrupt these activities, leading to annoyance, stress, and reduced enjoyment for users (*World Health Organisation 2018*) It is important to remember that recreational zone that are usually considered as quiet areas by most of policies, sometimes can play role of noise source, producing exceeded levels of noise, which can be a difficult aspect for quantifying in certain situations.

## 6. Mixed Zones

Mixed-use zones combine residential, commercial, and sometimes industrial activities within a single area, presenting unique challenges for noise management. According to urban planning guidelines, integrating compatible land uses and implementing noise mitigation measures are essential to minimize conflicts between different activities. The integration of green spaces, noise barriers, and building design features that enhance sound insulation can contribute

to creating harmonious mixed-use environments that prioritize both noise reduction and urban functionality (European Environmental Agency, 2010).

## 4.2. Criteria and Sub-Criteria Scoring

### 1<sup>st</sup> Criteria – Noise Level (dB)

1.1. END requires two main indicators to be applied in the assessment and management of environmental noise. The first indicator (Lden) is the annual average noise level for the day, evening and night periods and is designed to measure ‘annoyance.’ The END defines an Lden threshold of 55 dB. The second indicator (Lnight) is the annual average noise level for night-time periods and is designed to assess sleep disturbance. The END defines an Lnight threshold of 50 dB.

END and EEA recommend to prepare noise maps that show the levels of environmental noise from various sources such as road traffic, railways, and industrial sites. These maps must use 55 dB Lden and 50 dB Lnight as reference points to identify areas with harmful noise exposure (*Environmental Noise Directive - 2002/49.* )

However, according to (Guidance on Noise nuisance .2004) The time periods and corresponding permitted noise levels for Scotland have been defined as follows:

- Daytime 07.00 – 19.00 hours  $L_{Aeq}$  41 dB;
- Evening 19.00 – 23.00 hours  $L_{Aeq}$  37 dB;
- Night-time 23.00 – 07.00 hours  $L_{Aeq}$  31 dB.

From all of the above references including World health organisation noise guidelines and report (1999, 2009, 2018), EEA and TNAP of Scotland, taking into consideration that for work END and EEA recommend to use 5 dB steps, but TNAP uses 10 dB step, this Matrix will consider next scoring for noise Average Levels (Lden for day measures 07:00-23:00 and Lnight for night measure 23:00-07:00) presented in Table 2:

	Weight	Calculation (dB)	Weight	Calculation (dB)	Weight	Calculation (dB)
Day	0,5	$\geq 55$	0,5	$\geq 65$	1	$\geq 75$
Night	0,5	$\geq 50$	0,5	$\geq 60$	1	$\geq 70$

*Table 2 - Scoring Average Noise levels*

Where 0 is the lowest score representing that the area is not vulnerable for the criteria, 1 is the highest score showing that the criteria are strongly affecting the area, and all the scores in between (0,4; 0,5; 0,7; 0,8; etc) as more or less acceptable.

1.2. For peak noise levels from the references above scoring is presented in Table 3:

	Calculation	Weight (dB)	Calculation	Weight (dB)
Day	1	$\geq 75$	0	$< 75$
Night	1	$\geq 70$	0	$< 70$

*Table 3 - Scoring Peak Noise levels*

### 1.3. Noise Exposure limits

According to WHO for adults exposed to impulse noise at the workplace, the noise limit is set at peak sound pressure levels of 140 dB, and the same limit is assumed to be appropriate for environmental and leisure-time noise. In the case of children, however, considering their habits while playing with noisy toys, the peak sound pressure should never exceed 120 dB.

In the UK policies (the Health and Safety Executive (HSE) in the United Kingdom, 2005) the lower exposure action values are - a daily or weekly personal noise exposure of 80 dB (A-weighted); and a peak sound pressure of 135 dB (C-weighted).

The upper exposure action values are - a daily or weekly personal noise exposure of 85 dB (A-weighted); and a peak sound pressure of 137 dB (C-weighted). The exposure limit values are - a daily or weekly personal noise exposure of 87 dB (A-weighted); and a peak sound pressure of 140 dB (C-weighted).

Based on this information, the Matrix offers scoring for Noise Exposure Criteria presented in Table 4:

Weight	Calculation	Weight	Calculation	Weight	Calculation
1	above 85 dB during 8 h	0,5	from 80 dB to 85 dB during 8 h	0	below 80 dB during 8 h

*Table 4 - Scoring Noise Exposure limits*

## 2<sup>nd</sup> Criteria – Source of Noise

Community noise (also called environmental noise, residential noise, or domestic noise) is defined as noise emitted from all sources except noise at the industrial workplace. Main sources of community noise include road, rail and air traffic, industries, construction and public work, and the neighbourhood. The main indoor sources of noise are ventilation systems, office machines, home appliances and neighbours. Typical neighbourhood noise comes from premises and installations related to the catering trade (restaurant, cafeterias, discotheques, etc.); from live or recorded music; sport events including motor sports; playgrounds; car parks; and domestic animals such as barking dogs (World Health Organisation, 1999).

In the Chapter 4.1 of this thesis, we identified Noise Source as a criteria and Traffic noise, Railway noise, Aircraft noise, Neighbourhood noise, Industrial and Construction noise as sub-criteria. Considering that each of these noise sources can exceed permitted noise limits and pose risks to human health, the Matrix assigns equal scoring to all noise sources presented in Table 5.

Sub criteria	Weight	Calculation
2.1 Traffic Noise	1	Presence in the area
2.2 Railway Noise	1	Presence in the area
2.3 Aircraft Noise	1	Presence in the area
2.4 Industrial Noise	1	Presence in the area
2.5 Construction Noise	1	Presence in the area
2.6 Neighbourhood Noise	1	Presence in the area

*Table 5 - Scoring Noise sources*

### **3<sup>rd</sup> Criteria – Distance from Noise Source**

To make a correct assessment of noise it is important to have some appreciation of the characteristics of environmental noise sources and of how sound propagates from them. One should consider the directionality of noise sources, the variability with time and the frequency content. Most of the types of environmental noise are produced by multiple sources, which in many cases are moving. Thus, the characteristics of individual sources, as well as the characteristics of the combined sources, must be considered (World Health Organisation, 1999).

For example, we can consider the radiation of sound from individual vehicles, as well as from a line of vehicles on a particular road. Sound from an ideal point source (i.e. non-directional source) will spread out spherically and sound pressure levels would decrease 6 dB for each doubling of distance from the source. However, for a line of such sources, or for an integration over the complete pass-by of an individual moving source, the combined effect leads to sound that spreads cylindrically and to sound pressure levels that decrease at 3 dB per doubling of distance. Thus, there are distinct differences between the propagation of sound from an ideal point source and from moving sources. In practice one cannot adequately assess the noise from a fixed source with measurements at a single location; it is essential to measure in several directions from the source (World Health Organisation, 1999)

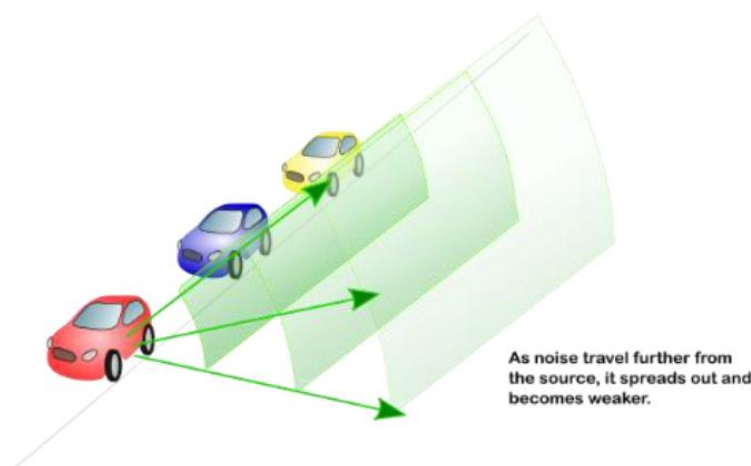
Temperature and wind gradients can cause propagating sound to curve either upwards or downwards, creating either areas of increased or decreased sound pressure levels at points quite distant from the source. Atmospheric turbulence can randomize sound so that the interference effects resulting from combinations of sound paths are reduced. Higher frequency sound is

absorbed by air depending on the exact temperature and relative humidity of the air. Because there are many complex effects, it is not usually possible to accurately predict sound pressure levels at large distances from a source (World Health Organisation, 1999)

It is well known, due to several studies, that air with higher amount of water in its texture, helps sound waves to spread faster and to longer distance. Scotland is a country with good amount of rain, and Glasgow has rainy weather in all 4 seasons of the year. It is important to mention this, however, the Matrix will not focus on weather role in noise pollution because this topic do not have enough studies, providing numeric parameters (the most valuable for Matrix) and researches openly claim wind, precipitations and other connected to them aspects as errors in their studies, or as a limitation.

However, it is already a common knowledge that the level of sound decreases with increasing distance from the source of the sound as shown in Figure 9 - Divergence of sound waves. (Source: J McIntosh, Department of Transport, Victoria, Australia). The most significant reason is divergence of the sound waves. For traffic noise, as sound waves travel away from a road with dense, flowing traffic, they spread out over an increasing cylindrical area. This spreading out results in the sound energy reducing by about half each time the distance from the road doubles, which equates to a reduction in the sound level of approximately 3 dB.

However, propagation of sound in the atmosphere is not so simple. A phenomenon called refraction can significantly change how much sound decreases over distances of more than around 100 m.



*Figure 9 - Divergence of sound waves. (Source: J McIntosh, Department of Transport, Victoria, Australia)*

The area of a surface around a point sound source increases with the square of the distance from the source. This means that the same sound energy from the source is distributed over a

larger area and the energy intensity reduces with the square of the distance from the source (Inverse Square Law).

For every doubling of distance, the sound level reduces by 6 decibels (dB), (e.g. moving from 10 to 20 metres away from a sound source). But the next 6 dB reduction means moving from 20 to 40 metres, then from 40 to 80 metres for a further 6 dB reduction (Collman, 2015).

It is important to mention that for the criteria we discuss the noise spread in open areas, without barriers, and the criteria is based on the studies exploring the noise distribution in such certain conditions. The role of the barriers and their effect on noise is mention in another criteria.

According to several Scottish and UK Planning Policies the distance between frontages in residential streets typically ranges from 12 m to 18 m (The Scottish Government, )(Department of Transport, ). For high street it ranges from 18 m to 30 m, for Boulevards 27 m - 36 m, for squares 18 – 100 m. (The Scottish Government, ) also says that to rigid standards on street widths should be avoided and new streets should be laid out with consideration given to the relationship between scale and the nature of the space created.

Based on the researches and city standards the Matrix developed next table and offers scoring for Proximity to Noise Sources presented in Table 6 below:

Sub criteria	Calculation	Weight	Calculation (m)	Weight	Calculation (m)	Weight	Calculation (m)	Weight	Calculation (m)
3.1 Proximity to Traffic	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30
3.2 Proximity to Industrial Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30
3.3 Proximity to Construction Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30
3.5 Proximity to Railway Lines	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30

*Table 6 - Scoring Proximity to Noise Sources*

Speaking about proximity to Airports we will take into consideration national recommendations on distance from Airports. If the area of interest in inside of 1000 m radius proximity and or the area is inside of an air pathway of the planes defined by Noise Maps of Glasgow city (at least 50% of its square), then the scoring will be equal to maximum – 1; if they are in in none of the mentioned, the scoring will be minimum – 0, scoring is presented in Table 7 below developed for Matrix scoring:

3.4 Proximity to Airports	Distance in metres	1	less than 1000 m	0	more than 1000 m
	Presence in air pathways areas more t	1	>=50% of square	0	<50% of its square

Table 7 - Scoring Proximity to Airports

In Figure 10 - Day map of noise distribution from Glasgow Airport is presented the area of Aircraft noise distribution in Glasgow city during day. There is also a night version of this area, presented in Figure 11 - Night map of noise distribution from Glasgow Airport that should be used for night version of the Matrix calculations.

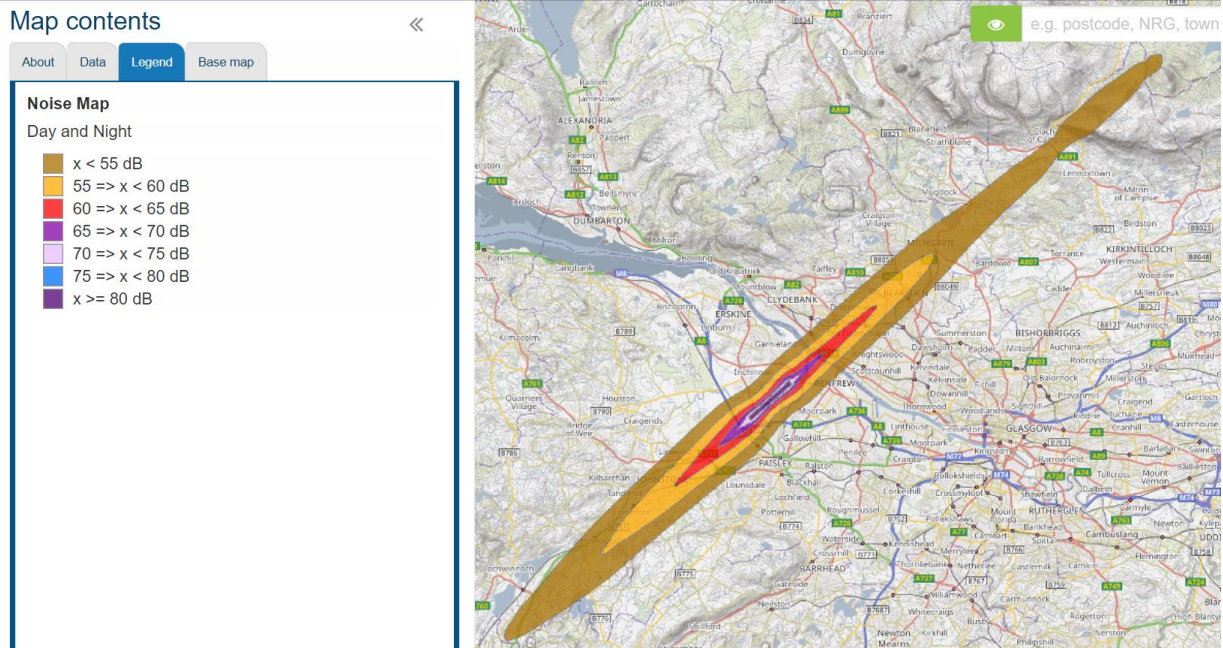


Figure 10 - Day map of noise distribution from Glasgow Airport

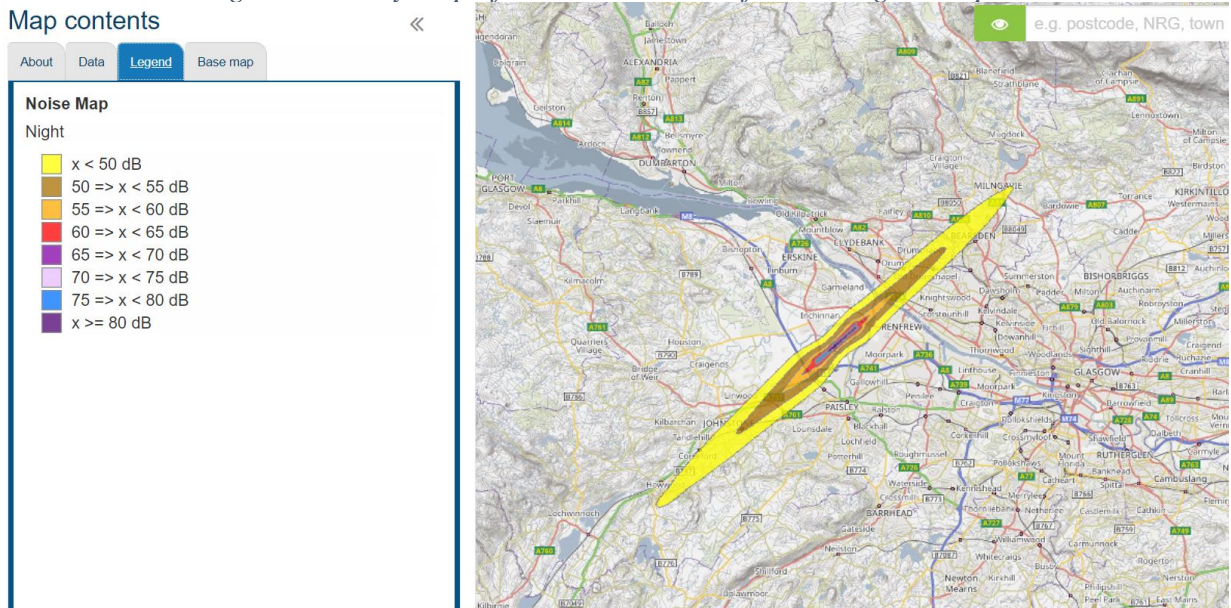


Figure 11 - Night map of noise distribution from Glasgow Airport

## **4<sup>th</sup> Criteria – Surface conditions**

### **1. Surface materials – Sub criteria.**

There are several types of silent road surfaces and their application are mainly determined by the featured noise reduction, the allowable traffic speed, the composition of the traffic flow and the possible wrenching of tyres on the surface due to parking movements. For urban situations three surface types are commonly applied:

- A. Thin Surface Layers
- B. Stone Mastic Asphalt (SMA)
- C. (Double-layered) Porous Asphalt

#### **A. Thin asphalt layers:**

These thin layered bitumen surfaces exhibit moderate porosity and acoustic absorption, but, due to the fine grading, optimal surface texture. This result in a surface with an acceptable durability, moderate costs and quite positive noise reducing properties. This asphalt reduces noise relative to dense asphalt concrete (DAC) DAC 0/16 by 2 to 5 dB in urban situations.

#### **B. Stone Mastic Asphalt:**

Stone mastic asphalt is popular because of its durability and its resistance against rutting. Stone Mastic Asphalt with an aggregate size of 5 to 6 mm has an optimal texture of the surface. The noise reduction for this type of SMA is a maximum of 2 dB in urban situations relative to DAC 0/16. Although considered noise reducing road surfaces, the versions with larger stone sizes can be quite noisy. The effect of a 40 % increase in aggregate size is 1,5 dB for passenger cars.

#### **C. (Double-layered) porous asphalt:**

Drainage or porous asphalt shares its stone skeleton with SMA, but due to the lower amount of mortar, holes are not closed, but form open channels through the material. The porosity gives the road surface good absorptive properties. The noise suppressing effect is maximal when the surface is smooth (by use of a fine fraction in the top layer) and the thickness is optimized so the acoustical absorption is maximal for reducing traffic noise. With this road surface, noise reductions of more than 4 dB can be achieved. But, this type of asphalt needs regular maintenance. Without maintenance the noise reduction performance drops rapidly. The durability of this asphalt is low, especially in urban circumstances. In suburban areas (ring roads for example) porous asphalt appears to be more suitable (EURO CITIES, 2014)

In Demark experts have measured noise stability on several experimental pavements for several years and will continue this measurement as long as the pavements perform safely. The

results are shown in Table 8 - Noise reduction of drainage asphalt **Error! Reference source not found.**

Year/Surface	0	1	2	3	4	5	6	7
DA8 18–22%	-3.6	-4.4	-4.0	-3.7	-3.3	-3.4	-2.8	-0.7
DA8 >22%	-3.2	-4.4	-4.3	-4.1	-4.2	-3.0	-3.3	-0.9
DA12	-1.5	-3.8	-4.0	-2.5	-2.4	-1.4	-1.0	+0.9
AB12a	+0.8	+0.6	+0.3	+0.6	+0.9	+1.2	+1.4	+2

Table 8 - Noise reduction of drainage asphalt (EUROCITIES)

The drainage asphalt (DA) with the smallest chip size (8 mm) and the highest percentage of built-in voids (over 22 percent) had the best noise reduction (3 to 4 dB) and retained its porosity. Thin open layers are being placed experimentally in urban areas to determine noise-reduction capacities while extending service life and reducing maintenance costs.

Single- and double-layer porous mixes and thin surfacing have all been used as noise-reducing pavement mixes. The porous mixes have the greatest potential to reduce noise by more than 3 to 5 dB, but have experienced performance problems (clogging, durability, etc.).

The thin mixes are more cost effective and appear to be more durable, but provide only limited noise reduction (1 to 3 dB).

The Danes have completed three case studies in which they compared the cost of PA, noise barriers, and sound insulation for three road categories: city street, ring road, and freeway. They concluded, “Compared to noise barriers and façade insulation, porous asphalt gives a much higher noise reduction per invested Euro.”(US Department of Transportation, 2005)

In a recent comparison test of dense asphalt concrete, PA (single-layer), TLPA (two-layer porous asphalt, and thin top layer (Microflex 0/6), TLPA was quieter at all speeds tested (30 to 130 kilometres per hour (km/h)), as much as 4 dB quieter than the next best mixes (thin layer and porous single layer) at high speed (130 km/h), and as much as 9 dB quieter than conventional dense-graded asphalt.

Another consideration noted by the Dutch was that these porous mixes do not perform as well as conventional dense mixes when there is more braking, acceleration, and turning, or “wringing” actions, as might be expected in urban areas. These considerations make a case for the following application classifications:

- ✓ National highways—PA or TLPA;
- ✓ Inner-city roads—thin, semi-dense top layers.

The following decibel chart in Table 9 - Noise reduction in human perception shows various dB levels and the corresponding reduction in actual sound pressure level (SPL) as well as the human perceived volume reduction for reducing noise levels (Acoustical surfaces, 2020)

dB	Actual SPL Reduction	Perceived Volume Reduction
3 dB	50.00%	18.77%
6 dB	75.00%	34.02%
9 dB	87.50%	46.41%
12 dB	93.75%	56.47%
15 dB	96.88%	64.64%
18 dB	98.44%	71.28%
21 dB	99.22%	76.67%
24 dB	99.61%	81.05%
27 dB	99.80%	84.61%
30 dB	99.90%	87.50%

*Table 9 - Noise reduction in human perception (Acoustical surfaces, 2020)*

Based on the perception of human ears to noise volumes represented in Table 9 - Noise reduction in human perception and numerous researches on quiet surfaces the Matrix developed a scoring based on the average number of dB of noise reduction skills of a material.

N	Surface types	Noise reduction (dB)	Score
1.	If a material has no noise reduction qualities	0	1
2.	If a material has noise reduction from 0 dB to 3 dB	< 3	0,8
3.	If a material has noise reduction from 3 dB up to 6 dB	$\geq 3$ and $< 6$	0,65
4.	If a material has noise reduction from 6 dB up to 9 dB	$\geq 6$ and $< 9$	0,55
5.	If a material has noise reduction above 9 dB	$\geq 9$	0
	<i>Examples:</i>		
6.	Thin noise-reducing asphalt road surfaces (2-4 dB)	2 - 4	0,65
7.	Single-layer porous asphalt (1-3 dB)	1 - 3	0,8
8.	Two-layer porous asphalt (5-7 dB)	5 - 7	0,55
9.	Stone Mastic Asphalt 0/6 (1,5 dB)	1,5	1

*Table 10 - Matrix rule for scoring of road surfaces*

Even though in research (US Department of Transportation, 2005) is stated that in the UK for a surface to obtain approval as a quiet pavement mixture, it must provide at least a 2.5 dB noise reduction (compared to Hot Rolled Asphalt (HRA)) the Matrix takes into consideration a human's perception for providing results closer to real life conditions.

## 2. Speed limits – Sub criteria.

Motor vehicles, like cars, buses, vans, and trucks, produce several types of noise when operating, which all contribute to the total noise emission of the vehicle. There is the noise generated by the engine, by the tyres interacting with the road surface, by the exhaust, by the air inlet and by the cooling fan as well as aerodynamic noise.

Even in streets with low speeds, such as in built-up areas, it is desirable to reduce tyre/road noise, especially for cars. This applies even more – and to heavy vehicles – on medium to high-speed roads (EURO CITIES, 2015).

The acoustic emission of modern passenger cars is dominated by the noise of the rolling tyres. Only under conditions of strong acceleration or speeds below 30 km/h propulsion noise can dominate. Also, for heavy duty vehicles at speeds above 60 km/h, rolling noise starts to become the major source. Rolling noise is influenced by the properties of the road surface like surface texture, acoustical absorption, and aero-dynamical processes (air-pumping). Improving the surface properties in such a way that the efficiency of the noise generating and amplifying processes are reduced will result in a lower rolling noise level (EURO CITIES, 2014).

Experts from Eurocities – the biggest network in the European continent after several years of tests dedicated to traffic noise, presented graphic of correlation between noise levels and speed of vehicles. The experiments produced data that is starting at speed point equal 30 km/h. However, using prediction functions of tradeline due to Excel is possible to predict noise level starting from 0 km/h. Below in Figure 12 and Figure 13 is presented analysis done by this thesis for this purpose.

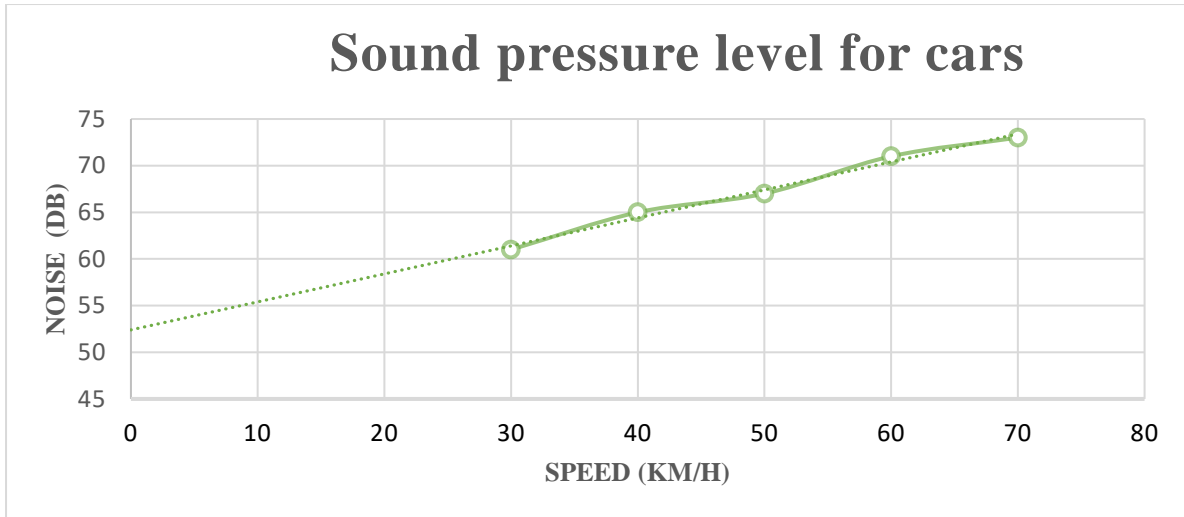


Figure 12 - Graphic of correlation between noise levels and speed for cars

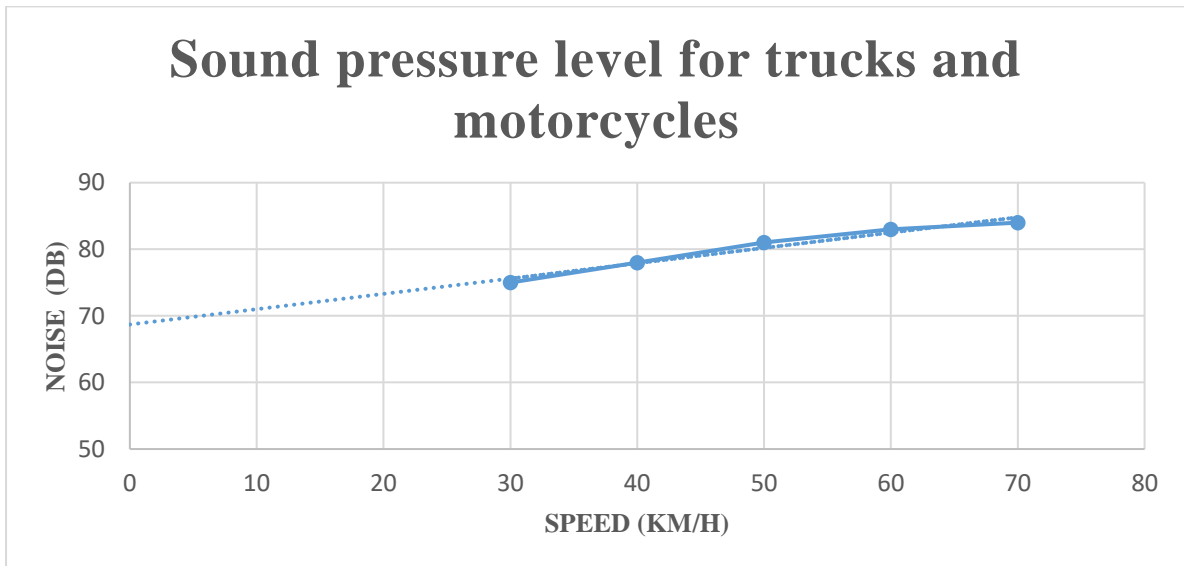


Figure 13 - Graphic of correlation between noise levels and speed for trucks and motorcycles

Based on these studies and acceptable noise levels chosen as levels of discomfort in discussion of Criteria 1 in Table 11 – Daytime speed scoring and Table 12 - Nighttime speed scoring the Matrix propose next scoring for developed for Sub criteria Speed Limits for the day:

Weight	Calculation	Weight	Calculation	Weight	Calculation
0	FOR CARS: ABOVE 30 km/h	0,5	FOR CARS: ABOVE 40 km/h	1	FOR CARS: ABOVE 80 km/h
0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 20 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 30 km/h

Table 11 – Daytime speed scoring

for the night time:

Weight	Calculation	Weight	Calculation	Weight	Calculation
0	FOR CARS: ABOVE 25 km/h	0,5	FOR CARS: ABOVE 30 km/h	1	FOR CARS: ABOVE 30 km/h
0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 10 km/h

*Table 12 - Nighttime speed scoring*

### 3. Presence of vegetation

There are many various studying exploring the influence of vegetation on traffic noise. All of them admit that presence of vegetation always has a positive impact. For this sub-criterion of the Matrix is important to understand numeric power of green spaces on noise reduction.

A group of landscape architects, urbanists and acoustic scientists made large research on the ability of low vegetation intensity, medium vegetation intensity and high vegetation intensity to reduce noise levels. From their research was outlined that every type of vegetation can reduce different number of decibels solely and aligned with other types of greenery. The measurements were done every 5 metres from the noise source up till 60 metres distance from source in all 3 different locations chosen by the green elements' intensity.

In the Table 13 is represented how the noise was changing in each location. Location A had low vegetation intensity, B - medium vegetation intensity, C - high vegetation intensity. The intensity differs from the number of green elements and their types amount in each area, the more are the types and amounts, the higher is intensity.

Dist.	Site A				Site B				Site C			
	Aver. dB <sub>eq</sub>	Max. dB (A)	Min. dB (A)	dB <sub>eq</sub> blocked	Aver. dB <sub>eq</sub>	Max. dB (A)	Min. dB (A)	dB <sub>eq</sub> blocked	Aver. dB <sub>eq</sub>	Max. dB (A)	Min. dB (A)	dB <sub>eq</sub> blocked
0	66.8	91.1	55.7	0	73.3	101.4	60.8	0	69.9	91.9	49.9	0
5	68.6	80.7	57.1	1.7	70.1	82.5	60.0	3.2	67.0	84.8	52.6	5.7
10	64.8	73.7	55.7	2.8	69.0	84.9	60.9	5.4	63.6	80.8	48.0	6.3
15	64.1	82.6	56.7	6.1	68.3	77.9	59.0	6.9	63.6	81.2	49.5	8.6
20	61.8	72.2	55.6	8.7	66.7	85.4	58.3	8.4	61.0	78.3	51.9	12.2
25	62.0	74.0	55.4	9.8	66.0	79.3	55.7	9.0	59.9	72.0	47.5	12.9
30	59.0	64.6	54.4	9.7	64.6	86.5	58.2	9.9	59.9	67.3	49.7	13.2
35	59.3	69.5	54.9	11.2	65.1	72.6	58.1	9.5	61.3	75.7	54.3	13.4
40	60.4	70.3	54.9	10.3	63.4	77.5	57.3	11.2	59.5	68.9	48.2	14.8
45	59.7	71.0	55.1	11.8	64.6	84.3	58.5	14.2	58.9	78.9	49.3	14.2
50	59.7	63.8	56.6	10.3	64.1	75.0	50.8	10.8	58.0	66.0	50.2	12.9
55	59.1	65.1	53.7	11.3	63.7	72.4	57.3	11.7	57.8	68.0	50.3	14.4
60	59.4	65.0	57.3	8.5	63.3	76.9	58.1	9.9	57.2	63.8	50.9	15.6

*Table 13 - Average, maximum, minimum and equivalent decibel values blocked at each monitoring site*

Trees and other vegetation types in conjunction with landforms reduce road noise by 6-15 decibels (with dense vegetation), while trees in combination with solid barriers reduce noise by

5-8 decibels; in comparison, a masonry wall, a typical sound barrier, reduces noise levels by 15 decibels, but imposes high costs (Oliveira et al., 2021)

The results of another study showed that the traffic noise was reduced by 50% when vegetation was enhanced from a minimal to moderate planting intensity, and no enhancement in noise reduction was observed as vegetation was further increased to a dense intensity. A 5 m depth of vegetation barrier was found to be an ideal depth for traffic noise reduction. Without the vegetative barrier, the observed mean noise levels were 78 dB. On average, vegetative barriers (moderate to dense) were able to reduce traffic noise by 9–11 dB. In following developed by this thesis Table 14 **Error! Reference source not found.** are presented results of noise reduction with various density in 5, 10, and 20 m distance points from traffic (Urban cities and road traffic noise: Reduction through vegetation.2017).

Site	At source dB(A)	Difference between source & at 5 m	5 m from source dB(A)	Difference between 5 and 10 m	10 m from source dB(A)	Difference between 10 and 20 m	20 m from source dB(A)	Total reduction dB(A)	Average vehicle rate per min
Minimal planting scheme	78	1	77	2	75	1	74	4	4.2
Sparse to medium planting scheme	73	3	70	3	67	2	65	8	4.3
Dense planting scheme	67	2	65	2	63	2	61	6	4.0

*Table 14 - Mean noise measurements at each site. Recordings presented here are for setbacks at source and, 5, 10, and 20 m from source*

For the study is important the vegetation description. In this study from 2017, Table 15 contains description of test sites (Urban cities and road traffic noise: Reduction through vegetation.2017).

Site	Description of site locations and vegetative cover
<i>Highway (with vegetation)</i>	

Site	Description of site locations and vegetative cover
a. Sparse to medium planting	Open field. Thin screen of ornamental shrubs as high as car roofs, with some ornamental trees rising above this
b. Dense planting	Open field. Deep belt of mature trees. Cover at vehicle height provided mainly by thick tree trunks and small bushes
<i>Highway (without vegetation)</i>	
a. Minimal planting	Open, recreational ground with housing estate, minimal screening by small shrubs. Highway slightly elevated

*Table 15 - Sites' description*

Another study in China using LiDAR data created 3D model of the study area and compared how types of vegetation, its density, distance from noise source and from each other effect the noise reduction (Xu et al., 2022). This study investigated the relationship between urban roadside green space vegetation characteristics and their effectiveness in reducing traffic noise using LiDAR point cloud and noise data. Significant positive correlations were found between noise attenuation and vegetation width, coverage degree at 5 m height, leaf area index at 5 m height, horizontal occlusion degree at 5 m height, and percentage of point cloud grid at 5 m height.

However, no correlation was found between coverage degree, leaf area index, and actual noise attenuation at absolute height. Horizontal occlusion degree and percentage of point cloud grid are important for studying noise reduction in complex green spaces. Green spaces with a 50 m length quadrat are more effective at noise reduction than those with 30 m and 40 m lengths.

Vegetation near the road has a greater effect on noise reduction than vegetation farther from the road. Effective regression models can be constructed using vegetation characteristics, excluding coverage degree, to explain noise reduction effects. There is no linear relationship between noise attenuation and vegetation characteristics; interactions between factors contribute to the noise reduction effect. The noise reduction effect of green spaces is more prominent in areas with serious noise pollution.

To improve noise reduction, it is recommended to increase the width of green spaces and focus on planting below 5 m. Additionally, increasing near-side vegetation, selecting trees and shrubs with low branching points, increasing planting quantity and density, and improving frontal horizontal occlusion are effective methods.

These studies are chosen for the scoring of sub-criteria because they have good descriptions of scoring mechanisms for green elements and various numerous parameters of noise levels reduction by them. Due to the studies analysed, and based on mentioned on the previously mentioned studies and characteristics from Table 9 and Table 10 the Matrix offers next scoring:

Weight	Calculation	Weight	Calculation	Weight	Calculation
1	No vegetation and or solid surfaces	0,5	Medium and moderate dense vegetation between source and receptor	0	High dense vegetation between source and receptor, preferably with under 5 m high elements and close to source

*Table 16 - Scoring of Vegetation elements*

#### 4. Durability of use

Previously, when we discussed various quiet noise surfaces, we also slightly discussed their durability and quality. There is a trade-off between the noise reduction and the lifetime of the upper layer of the asphalt, the wearing course. Low noise-road surfaces tend to lose their noise reducing capacity during their lifetime.

PA is more difficult to maintain in winter. Porous asphalt types are about 1 decibel quieter on average than dense ones, but they have a shorter life span than dense asphalt. The typical lifetime of a thin surface layer is 7 to 9 years. The most common problems are ravelling (loss of aggregates from the surface) and de-bonding from the underlying layer (EURO CITIES, 2015).

In 2011 the city of Rotterdam started a test with two types of asphalt (a durable type and low-noise type) that are more suitable for roads carrying heavy goods traffic. The first results indicate that these asphalts (thin layer and stone mastic asphalt) are promising in terms of durability and noise reductions. Thin layered asphalt roads as a quiet surface have an acceptable durability, moderate costs and quite positive noise reducing properties. (Double-layered) porous asphalt roads can achieve more than 4 dB in noise reductions. But, this type of asphalt needs regular maintenance. Without maintenance the noise reduction performance drops rapidly. The durability of this asphalt is low, especially in urban circumstances. In suburban areas (ring roads for example) PA appears to be more suitable (EURO CITIES, 2014)

It is known that the surface properties which cause the acoustic reduction change in time. In almost all situations this led to a decline of the noise suppressing capabilities. By lack of monitoring programmes, there is insufficient general knowledge of the material's long-term behaviour regarding civil engineering and acoustic properties. Most relevant processes are the

roughening of surface texture due to stone loss in the surface and increasing of flow resistance due to clogging of the pores.

When conducting a study into acoustic properties over time, it is important to evaluate the road surface depending on the expected life. A conventional road surface such as dense asphalt concrete (DAC) or SMA, will show less acoustic degradation, but these surfaces have a significantly longer life. A quick decline in noise reduction for conventional road surfaces thus has a greater effect over the long term than for low noise road surfaces. In the Figure 14 Figure 14 the blue line is silent road surface and the red one conventional road surface. The presented dashed lines are the averaged life times (EURO CITIES, 2014)

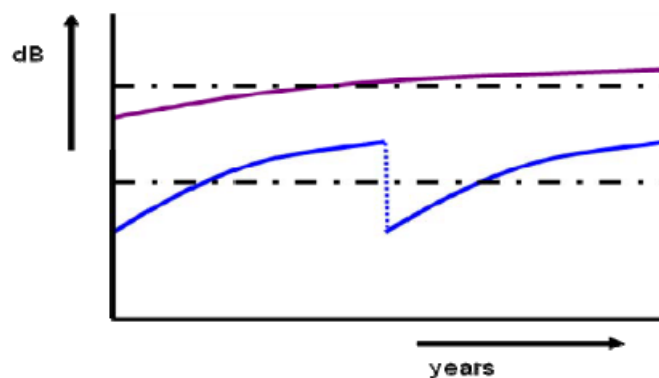


Figure 14 - A comparison between quiet asphalt and normal asphalt (EURO CITIES, 2014)

Durability of low-noise pavement systems varies from 7 to 15 years, depending on the pavement system and the experience level of the owner agency.

Previously mentioned practical studies and big work done by U.S. Transportation Department in 6 European countries leading in Noise reduction technologies and policies (US Department of Transportation, 2005) shows that lost in noise reducing abilities of certain quiet surfaces is 1 dB per 5-6 year. For others this number is equal to 1 dB per each year.

The initial reduction is about 5 to 6 dB for the two-layer system of PA on high-speed facilities, and about 3 to 5 dB on low-speed (30-to-55 km/h) roadways. The pavement life or durability for PA mixes is about 8 to 10 years, compared to 10 to 12 years for DAC. The pavement warranty covers durability, but not noise. Over the pavement life, the acoustical durability is about 4 dB. The loss in acoustics is because of clogging and ravelling. France showed data results for pavement aged 1 to 5 years, with limited data out to 6 and 7 years. There was not much difference with most pavements tested, about 1 dB over 5 years.

Some pavements gain 1 dB per year, but some in 5-6 years. To have the best offer for the Matrix we will take as a reference a study conducted in the UK describes in the same document. For 15 years of maintenance a prediction for PA is equal to 2-3 dB.

For a quiet pavement there is a reduction in block snap and air pumping mechanisms, plus absorption across porous surfaces. This last characteristic tends to deteriorate with age (about 50 percent loss of benefit overall after 5 to 6 years).

The same, should be considered and for rail tracks. As a source of noise, just like surface, they must be maintained. There are several ways how noise levels from this source type can be reduced. Most of them show high values in dB of noise reduction. The elements of rail track that can be considered as noise reducing are extra layers as pads (removing short-waved type of noise which is a leading one), acoustic rail grinding, that requires monitoring of the railway lines and frequent grinding with special grinding machines, removal of corrugation by grinding etc. However, just like surface, most of these methods require extra maintenance works, which bring another additional noise.

#### Examples from Scotland

In the webpage on Transport Scotland are published several reports on roads in Scotland or Europe, that were tested and constructed together with other organisations. One of the pages discusses outcomes of the report TRL PPR443 - A review of road surface noise reduction techniques, 2010 (Transport Scotland, 2023b) is a detailed review of the available research on road surface noise reduction. The report discusses a trial using Thin Stone Mastic Asphalt (TSMA) on the M8 in Scotland which was showing positive results for early life skid resistance, and that monitoring of the actual noise characteristics is also planned.

Based on responses from 27 Local Authorities “Most Departments report that HRA is the most cost-effective surface material. It was believed that, although the initial costs are higher there is a longer life expectancy for HRA than TSMA which means less maintenance and therefore reduced costs in the longer term.” Further that, “noise reduction benefits are not, as yet, considered a major factor when determining road surface material.”

Surface noise reduction performances are predicted for TSMA using the Harmonise/Imagine calculation method, relative to HRA 20 mm. Initial reductions of 1 to 4 dB(A) are predicted at speeds up to 60 kmph, independent of aggregate size. At higher speeds, aggregate size does affect noise emissions and at speeds of 110 kmph reductions of 4, 5 and 6 dB(A) were estimated as aggregate size decreased from 20 mm to 14, 10 and 6 mm, respectively. – It is not clear if these reductions are in relation to a new or worn/aged reference HRA surface.

Over time the noise performance of TSMA deteriorates at a rate of about 0.5 dB(A)/year compared with about 0.2 dB(A)/year for dense surfacing such as HRA.

A simplified assessment of whole life costs (60 years) has been undertaken which concluded that the benefit of SMA, due to lower noise levels, outweighed the costs over the 60-

year period. However, a -4.8 dB(A) surface correction (benefit compared to HRA) appears to have been used for all roads (regardless of speed), with no apparent adjustment for a deterioration in noise performance over time. The report acknowledges there are limitations in the assumptions made and the need for further research in this area.

A discussion on cost benefit analysis is provided which includes how the benefits are monetised by considering the impact of changes in noise affecting households and the resulting house price or ‘willingness to pay.’ – This approach has since been replaced by the current method of monetising impacts on human health and quality of life.

Transport Scotland representatives also explored EURO CITIES reports and field experiments on low noise surfaces and published the most important for them outlines in the same webpage:

“Various issues with porous asphalt surfaces are discussed, however, regarding SMA the leaflet states it is popular because of its durability and its resistance against rutting. It states SMA “with an aggregate size of 5 to 6 mm has an optimal texture of the surface. The noise reduction for this type of SMA is a maximum of 2 dB in urban situations relative to DAC 0/16. Although considered noise reducing road surfaces, the versions with larger stone sizes can be quite noisy. The effect of a 40 % increase in aggregate size is 1.5 dB for passenger cars”.

The durability of the acoustical effects is also discussed, stating that “when conducting a study into acoustic properties over time, it is important to evaluate the road surface depending on the expected life. A conventional road surface such as DAC or SMA, will show less acoustic degradation, but these surfaces have a significantly longer life.”(Transport Scotland, 2023b).

Taking into consideration that maintenance (renovation, pavement replacement and etc) is also itself a noise source (Constructional noise) for both railways and traffic, that increases the average noise parameters in the nearest areas, the Matrix offers scoring in Table 17 based on the years required for maintenance:

Weight	Calculation	Weight	Calculation	Weight	Calculation
1	<= 5 years	0,5	>5 and <=10 years	0	road need maintenance every 10+ years

*Table 17 - Scoring of Durability*

## 5. Rail track conditions

The study made in 2021 investigates the impact of short and long wavelength track irregularities on train-induced vibration and noise using a train-track interaction model, where

an Indian rail vehicle is modelled as a spring-mass-damper system and the track as an infinite rail on a viscoelastic foundation. Short-wavelength irregularities, generated using the Sato track spectrum, and long-wavelength irregularities, obtained from field data, reveal that vibration and noise levels are significantly higher for short-wavelength irregularities, exceeding Indian Railway standards (Kedia & Kumar, 2021).

By modifying the track properties, specifically increasing the stiffness of the rail pads, vibration levels were reduced by 7 dB to 24 dB and noise levels by 8 dB to 14 dB. This adjustment not only mitigates the effects of short-wavelength irregularities but also maintains acceptable levels for long-wavelength irregularities, underscoring the necessity of focusing on short-wavelength modifications to ensure compliance and enhance ride quality.

There are also other ways to reduce noise for railways. Noise reduction at the source can be achieved by either reducing this roughness or by preventing its growth. This is usually attained by either improving the running gear of the rolling stock and/or the track. Lower speeds also reduce noise at the source, but large changes in train speed are required to give noticeable changes in noise and are therefore contrary to efforts to attain a modal shift from road to rail (Oertli & Hübner, 2007).

EU transport policies call for more sustainable and more effective transport systems. With this aim, was prepared a report by representative of 2 big rail organisations to see the benefits of modifications, in noise reduction aspect. The report summarised European studies and field measures of different types of renovations of rail tracks, acoustical protection elements and other elements. Briefly, one can see the noise reduction potential of all methods tested in Figure 15 - Methods and noise reduction potential below.

Noise abatement method	Overall noise reduction potential	Noise abatement effect	Comment
<i>At the source</i>			
Retrofitting with composite brake blocks	8 – 10 dB(A)	Network wide	Considered method of choice for freight vehicles by the railway sector.
Wheel absorbers	1 – 4 dB(A)	Network wide	Wheel maintenance difficulties may occur. Solutions for disk-braked wheel-sets exist, for tread tread-braked wheels development is still in progress.
Track absorbers	1 – 4 dB(A)	Local	Track maintenance difficulties may occur, homologated in several countries
Removal of corrugation by grinding	up to 20 dB(A) in comparison to poorly maintained track to achieve well maintained noise level.	Local	Is usually a measure of standard track maintenance
Track renewal	up to 10 dB(A) in comparison to old and poorly maintained track	Local	Is usually a measure of standard track maintenance
Acoustic rail grinding	1 – 3 dB(A)	Local	Requires monitoring of the railway lines and usually frequent grinding with special grinding machines. Smooth wheels are a precondition for a good effect. Reduction potential depends on average rail surface quality of standard track.
Operational changes	Variable	Local	Negative effect on operations and rail-way capacity. Method hinders railway traffic and is therefore not in line with the EU White Paper.
<i>Between source and inhabitant</i>			
Noise barriers	Depends on height, usually 5 – 15 dB(A)	Local	Negative effect on landscape, influence on railway maintenance procedures, unattractive for railway passengers and residents.
<i>Near inhabitant</i>			
Noise insulated windows	10 – 30 dB(A)	Local	Effect is only achieved when windows are closed

Figure 15 - Methods and noise reduction potential (Oerli & Hübner, 2007)

Based on the studied influence of noise reducing methods, in Table 18 the Matrix offers to give the maximum value to the areas, where noise reduction instruments/layers/pads are not installed in the rail track's structure, and minimum scoring (0) to the area with installed ones:

Weight	Calculation	Weight	Calculation
1	no noise reducing elements	0	installed noise reducing elements

Table 18 - Scoring of Rail track conditions

To mention subways, it was stated earlier that the Matrix will not consider subways noise as separate criteria due to lack of studies and research. However, this research analysed the subway in GIS and in Figure 16 - Glasgow Subway and Figure 17 this thesis highlights the location of Glasgow Subway infrastructure and buildings located above them.

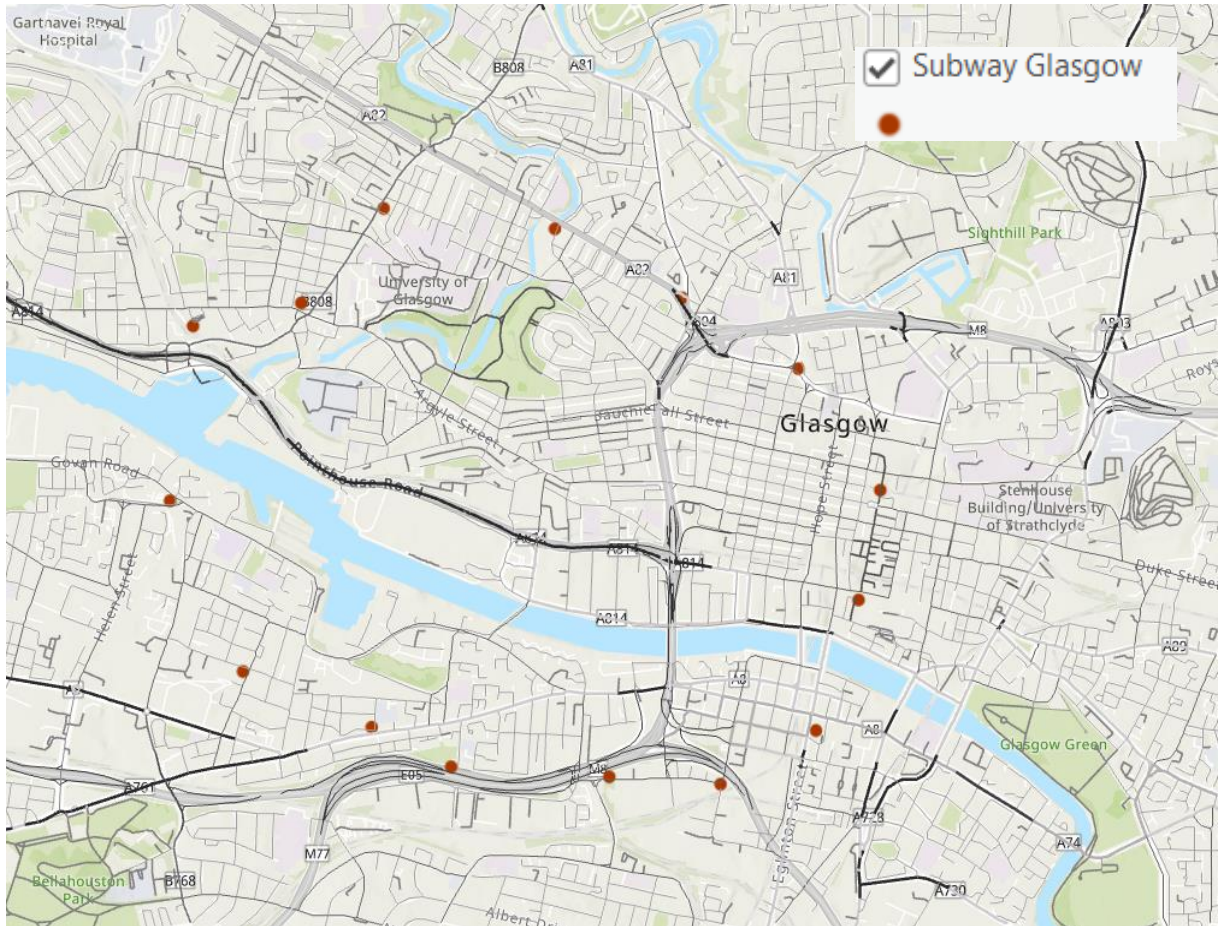


Figure 16 - Glasgow Subway (developed for this thesis using Esri GIS data)



Figure 17 - Buildings and Subway stations (developed for this thesis using Esri GIS data)

As one can see from Figure 17 - Buildings and Subway stations not all stations are located under buildings. Just a few of the subway stations are located under buildings. Thankfully, most of the building in Glasgow, have commercial spaces and just a few areas allow to have residential flats from ground floors.

#### 5<sup>th</sup> Criteria – Cost analysis

A silent road surface is more expensive to lay most of the time and more expensive to maintain than a conventional surface. At the same time the expected life time of a silent road surface is shorter. Its cost efficiency can only be proved by comparing these costs to those of conventional noise measures (noise screens or façade insulation). Although silent road surfaces are expensive, they are most of the time the cheapest noise reduction measure. The following aspects had been taken also in amount regarding silent road surfaces:

- For porous layers the durability of the sideway drainage is an extra aspect for attention. Periodically cleaning or extra precautions can be expensive;
- The contribution of porous layers to the bearing capacity of the pavement construction is relatively small, so strengthening can be necessary;
- Almost all silent road surfaces are not adequately resistant to wrenching tyres and therefore not a suitable application for crossings, roundabouts etc. The general rule is: more reduction means more voids, and thus a shorter service life (EURO CITIES, 2014)

Low-noise Road surfaces are more expensive than conventional dense asphalt concrete. They cost roughly 10% more for thin asphalt layers and up to 200 % more for two-layer porous asphalt. However, costs for other noise abatement measures are reduced.

What is cheaper? Quiet road surfaces or other measures? This depends on the individual case. When there is only a single house in the wide vicinity of a road, facade insulation can be an efficient solution. In many cases, however, low-noise road surfaces are better, including from a financial point of view. For instance, Danish researchers compared the costs of treating 1 km of road in a city, 1 km of a ring road and 1 km of a motorway with three different noise abatement measures: two-layer porous asphalt, a noise screen, and facade insulation. Both the total investment costs over a period of thirty years and the costs per decibel noise reduction were by far the lowest with the two-layer porous asphalt, results are in Figure 18 (EURO CITIES, 2015)

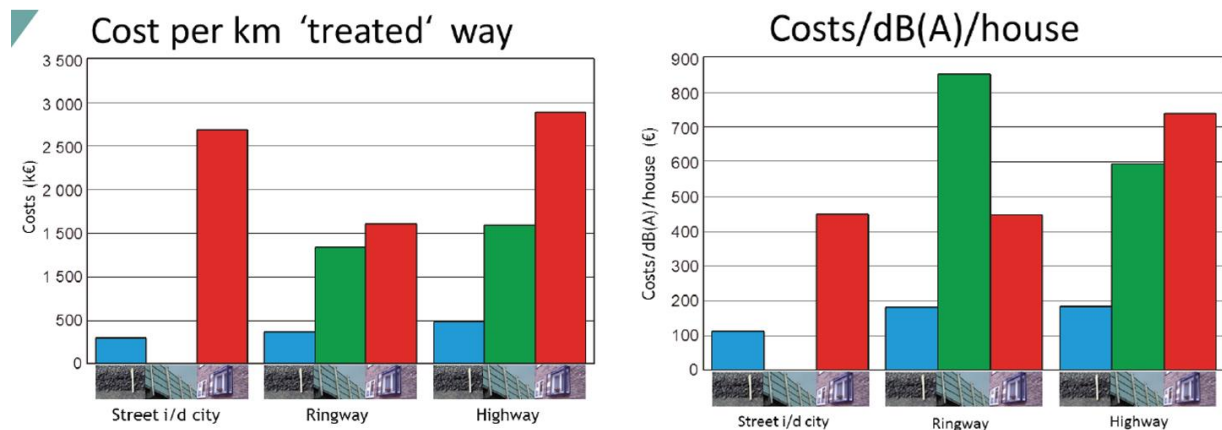


Figure 18 - Costs of three noise abatement measures for three typical cases (EURO CITIES, 2015)

Same study was described in various reports. But the results stayed same over years. They concluded, “Compared to noise barriers and facade insulation, PA gives a much higher noise reduction per invested Euro.”

Speaking about Scotland, Transport Scotland reports analysis was mentioned earlier for previous sub-criteria. (Transport Scotland, 2023a) The section dedicated to cost-benefit analysis presents a cost-benefit analysis of the TS2010 road surface, focusing on its potential for noise reduction over a 60-year period. The benefits of noise reduction are primarily linked to health improvements, with the WebTAG guidance from the Department for Transport monetizing these benefits based on household impacts. The cost of TS2010 is approximately £19/m<sup>2</sup>, similar to other surfaces like HRA, suggesting that for roads due for resurfacing, the cost could be neutral.

Three case studies are presented to illustrate the potential benefits and costs of using TS2010 in different CNMAs. In the first example, along the M74 in Kirkmuirhill, noise reduction benefits vary depending on speed adjustments, potentially providing net present value benefits between £22,109 and £99,626. The second example, on the M90 in Glenfarg, shows potential benefits up to £99,626 if speeds are assumed to be around 75 kmph. The third example, on the A92 in Glenrothes, estimates benefit up to £106,154 with assumed speeds of 75 kmph. These examples highlight that more properties near the treated areas could increase the benefits.

The analysis underscores that TS2010 might have a cost advantage over HRA due to its longer lifespan, requiring fewer resurfacing applications over the 60-year period. However, more detailed cost assessments are recommended. Additionally, noise reduction benefits are particularly significant on high-speed roads, with less impact at lower speeds where engine noise is more prominent. Further noise measurements using the Statistical Pass-By method are suggested to provide more accurate data on TS2010's performance.

As a result, in Table 19 we can conduct for Matrix that surface moderation is the most beneficial interventions for noise reduction. However, our Matrix focuses on identification and

evaluation of most vulnerable environments, so the developed scoring for this criterion can be only if the planned intervention fit with the budget project or not, getting the highest and lowest scores respectively.

Sub criteria	Weight	Calculation	Weight	Calculation
5.1. Financial Costs	1	the renovation is in budget limits	0	the renovation is not in budget limits

*Table 19 - Scoring cost analysis*

## 5. Receptors impacted

This criterion will take into consideration society groups trying to divide them by vulnerability. According to WHO Regional Office for Europe has therefore developed environmental noise guidelines for the European Region, proposing an updated set of public health recommendations on exposure to environmental noise. The main purpose of these guidelines is to provide recommendations for protecting human health from exposure to environmental noise originating from various sources: transportation (road traffic, railway, and aircraft) noise, wind turbine noise and leisure noise.

Exposure to noise can lead to auditory and nonauditory effects on health. Through direct injury to the auditory system, noise leads to auditory effects such as hearing loss and tinnitus. Noise is also a nonspecific stressor that has been shown to have an adverse effect on human health, especially following long-term exposure. These effects are the result of psychological and physiological distress, as well as a disturbance of the organism's homeostasis and increasing allostatic load (Basner et al., 2011).

There is plenty of evidence that sleep is a biological necessity, and disturbed sleep is associated with several health problems. Studies of sleep disturbance in children and in shift workers clearly show the adverse effects. Noise disturbs sleep by several direct and indirect pathways. Even at very low levels physiological reactions (increase in heart rate, body movements and arousals) can be reliably measured. Also, it was shown that awakening reactions are relatively rare, occurring at a much higher level than the physiological reactions.

Children have a higher awakening threshold than adults and therefore are often seen to be less sensitive to night noise. For other effects, however, children seem to be equally or more reactive than adults. As children also spend more time in bed they are exposed more to night noise levels. For these reasons children are considered a risk group. Since with age the sleep structure becomes more fragmented, elderly people are more vulnerable to disturbance. This also happens in pregnant women and people with ill health, so they too are a group at risk. Finally,

shift workers are at risk because their sleep structure is under stress due to the adaptations of their circadian rhythm (World Health Organisation, 2009).

The Community noise guidance recommends limits for preventing hearing loss from industrial, commercial shopping and traffic areas, indoors and outdoors (World Health Organisation, 1999). Health and safety regulations are usually based on an exposure profile of a typical worker (eight hours per day, five days per week).

A common dose-effect curve for the relationship between road traffic noise (outdoors) and the risk of myocardial infarction was developed. This curve can be used for a quantitative risk assessment and the calculation of attributable cases in a community. However, decisions regarding limit values must be made within the spectrum between discomfort (annoyance) and ill health (disease). Whereas quality targets at the lower end of the effects scale may be more flexible, quality targets at the upper end may be more obligatory. For example, for ethical reasons (equality principle) it does not seem to be justified if (ill) health-based limit values are varied according to the type of living area as expressed in land development plans (for example residential, mixed, or commercial), (World Health Organisation, 2009).

As we talk about Glasgow, it is important to mention that local authorities developed and implemented the Scottish Index of Multiple Deprivation (SIMD). SIMD looks at the extent to which an area is deprived across seven domains: income, employment, education, health, access to services, crime, and housing.

SIMD is the Scottish Government's standard approach to identify areas of multiple deprivation in Scotland. It helps to improve understanding about the outcomes and circumstances of people living in the most deprived areas in Scotland. It also allows effective targeting of policies and funding where the aim is to wholly or partly tackle or take account of area concentrations of multiple deprivation.

SIMD ranks data zones from most deprived (ranked 1) to least deprived (ranked 6,976). People using SIMD will often focus on the data zones below a certain rank, for example, the 5%, 10%, 15% or 20% most deprived data zones in Scotland. A map of zones is presented below in Figure 19.

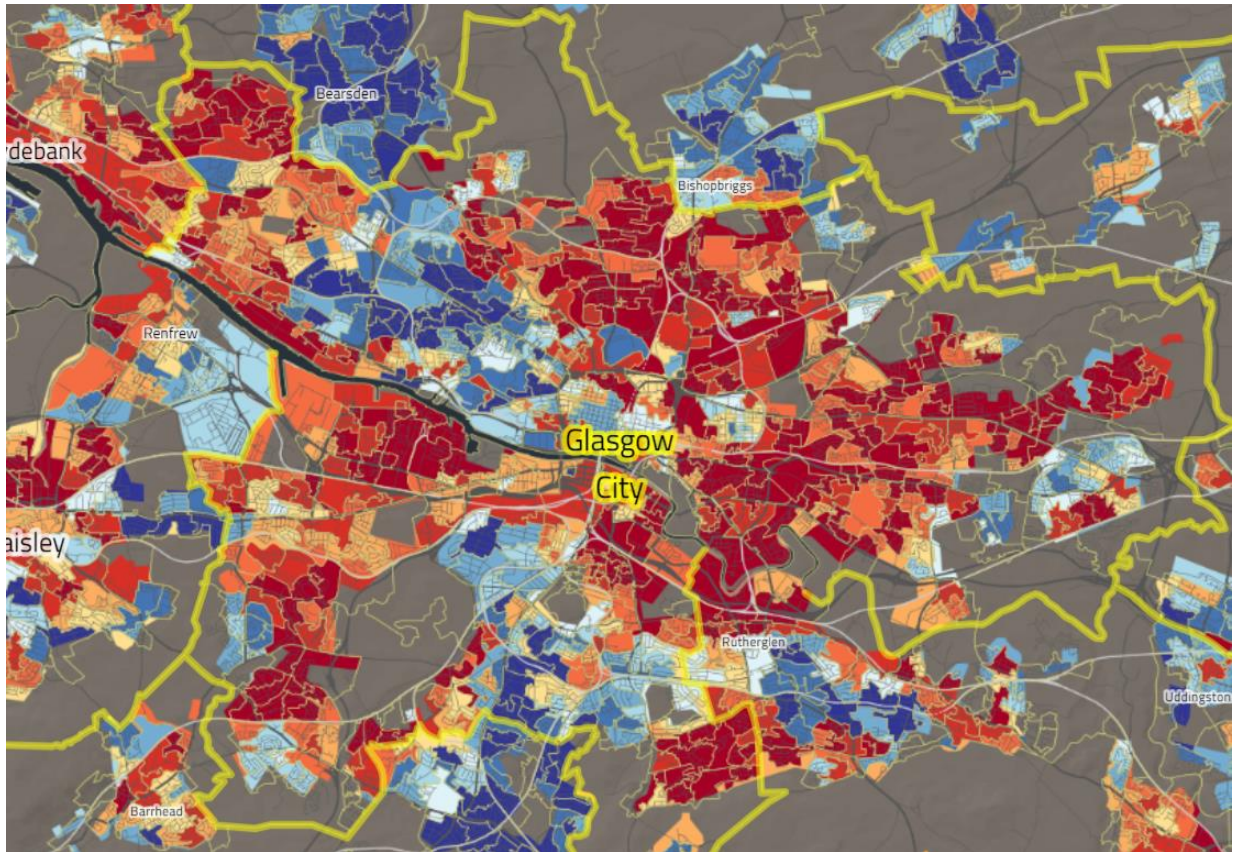


Figure 19 – SIMD (Scottish Index of Multiple Deprivation 2020. 2020)

Closer look at top 5% is presented in Figure 20 below. From the maps one can see that not necessarily all these areas are located next to main roads or railways, or even subway. As mentioned below, there are 7 parameters that make these areas deprived. Even though this thesis takes into consideration the importance of city development and urban structure, and offers noise evaluation valuable for all societies of Glasgow, it will not be efficient to include the information provided by SIMD as a separate criteria or sub-criteria. All residential zones in Glasgow are equally valuable, and other criteria and sub-criteria of the Matrix, that are highlighting the actual (most realistic) situation with noise pollution will help to highlight most vulnerable areas in the city. SIMD should be a valuable parameter for policymakers working with the problem of noise or any other urban problem, to help people from those zones (*Scottish Index of Multiple Deprivation 2020. 2020*).

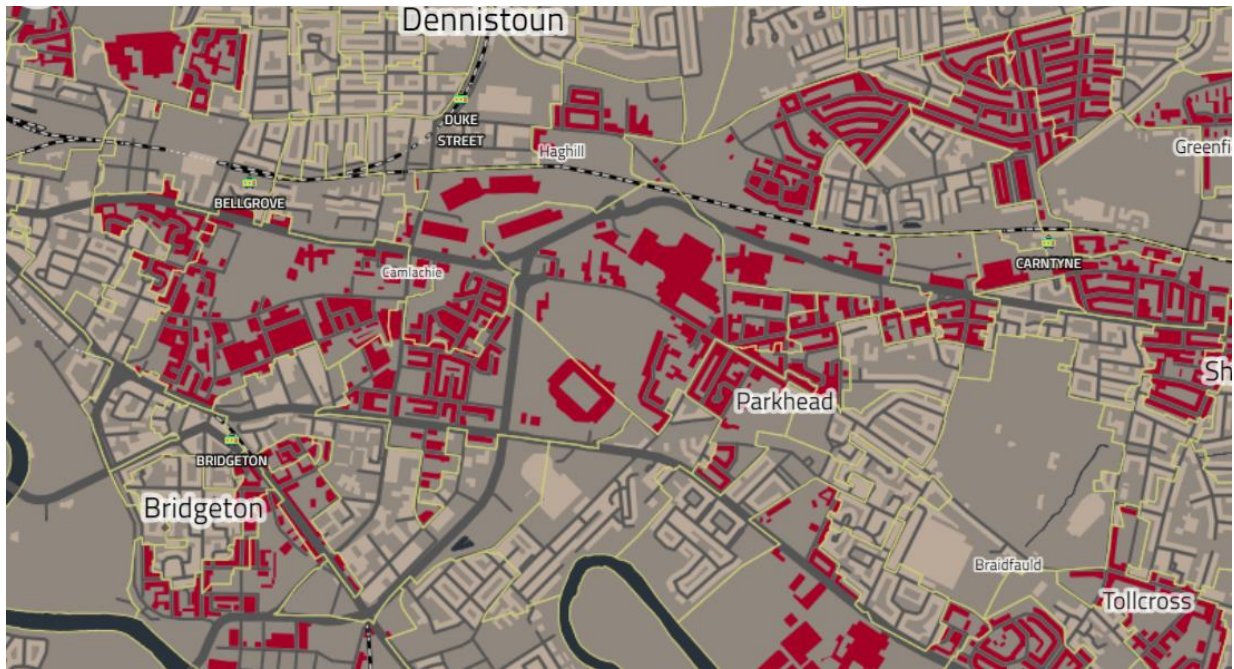


Figure 20 - Top 5% SIMD areas (Scottish Index of Multiple Deprivation 2020. 2020)

WHO strictly divided day and noise sound levels for each noise source and even by society groups, highlighting the health issues appearing or developing (in case if they already existed) for various social groups and city zones. It also highlights that noise level are distracting, annoying, affecting not only physical condition but also mental. Based on this knowledge the Matrix developed scoring in Table 20, divided by day and night time based on land use.

Sub criteria	Calculation	Weight		Weight	
6.1 Residential Zones residents	Yes or No	0,5	for L day	1	for L night
6.2. Social Zones (education and health related institutions)	Yes or No	0	for L day	1	for L night
6.3 Commercial Zones	Yes or No	1	for L day	0	for L night
6.4 Industrial Zones	Yes or No	1	for L day	0	for L night
6.5 Recreational Zones	Yes or No	1	for L day	1	for L night
6.6 Mixed Zones	Yes or No	1	for L day	1	for L night

Table 20 - Scoring Receptors

### 4.3. Objective 3 – Implementation of Guidelines

To successfully implement the evaluation matrix for noise pollution, several key steps must be undertaken to ensure its effective integration into urban planning and management

frameworks. These guidelines are designed to make the matrix a robust tool for policymakers, urban planners, and other stakeholders.

Currently, the evaluation matrix is available in both Excel and Word formats, encompassing both a scoring system and a text section that justifies each score. The Excel format allows users to input data, calculate scores, and understand the rationale behind each assessment with ease. Similarly, the Word document provides a textual explanation of the scores. The simplicity of these formats ensures that the matrix is accessible and user-friendly for a wide range of users, including policymakers, urban planners, and citizens. The matrix’s design facilitates straightforward adoption and integration into various workflows. The full matrix is presented in Appendixes A, B, C, while the Table 21 below illustrates the first criterion developed by Matrix along with its sub-criteria and their respective weights.

Criteria	Description	Sub-criteria	Parameter	Weight	Calculation	Weight	Calculation	Weight	Calculation
1. Noise Level (dB)	Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion quantifies the intensity of noise and its impact on health.	1.1 Daytime Noise Level (dB)	Average L day	0	>=55	0,5	>=65	1	>=75
		1.1 Nighttime Noise Level (dB)	Average L night (11pm-7am)	0	>=50	0,5	>=60	1	>=70
		1.2 Peak Noise Level (dB) day	Max L day	1	above 75 dB	0	below 75 dB		
		1.2 Peak Noise Level (dB) night	Max L night	1	above 70 dB	0	below 70 dB		
		1.3 Noise Exposure limits	Time	1	above 85 dB during 8h	0,5	from 80 dB to 85 dB during 8h	0	below 80 dB during 8h

Table 21 - Criteria 1

Policymakers should be encouraged to use the matrix as a foundation for evidence-based decision-making in urban planning and environmental management. By providing a clear, quantitative assessment of noise pollution, the matrix can help prioritize interventions in the most affected areas.

To ensure effective noise pollution management, the evaluation matrix should be a preliminary step for any policymaker considering the construction of noise barriers, noise-related renovations, or area development projects. By identifying noise-vulnerable areas, the matrix can guide policymakers and urban planners in making informed decisions that mitigate noise impacts. Distributing the matrix among Glasgow policymakers during the analytical stage of project planning will ensure that noise considerations are integrated into urban development strategies, enhancing the overall quality of life for residents.

Users should be able to utilize a simple blank form to input their data and calculate scores. The system will then summarize these scores to identify areas with the highest noise pollution levels. The highest score will indicate the most affected area. This approach ensures that users can quickly and easily determine the areas requiring the most urgent attention. The ease of use is a key feature, as it enables users to effectively engage with the matrix without requiring specialized training or extensive technical knowledge.

Standardized data collection forms should be developed to ensure consistency and accuracy in data entry. These forms should facilitate manual input or allow for automated data feeds from noise monitoring systems. Additionally, automated scoring mechanisms within the platform can provide real-time calculations of noise pollution scores for different areas, enabling prompt analysis and identification of the most affected locations.

To further enhance accessibility and usability, it is recommended that the evaluation matrix be made available on an open-access platform. A suitable platform for this integration is the Scottish Government's noise mapping website, Scotland's Noise (<https://noise.environment.gov.scot/noisemap/>), which provides extensive data on noise pollution across Scotland. An intuitive user interface should be developed to allow users to easily input data, calculate scores, and interpret results. This could be achieved through the creation of an interactive webpage or application that integrates with the existing Scottish Noise Mapping website.

By implementing these guidelines, the evaluation matrix can become an invaluable tool in managing noise pollution, making the process more efficient and accessible for all stakeholders involved.

#### **4.3.1. Integration with GIS Systems**

The integration of Geographical Information Systems (GIS) enhances the effectiveness of the evaluation matrix by providing a visual representation of noise pollution data. Key visual parts of the matrix, such as the distance to residential and social buildings, are highlighted using GIS components. Additionally, GIS can display distances from roads, railways, and airports, as developed on the Scottish Noise Mapping website. This integration facilitates a comprehensive visualization of noise pollution sources and their proximity to sensitive areas.

To ensure effective use of the evaluation matrix, workshops and training sessions should be organized for policymakers, urban planners, and other stakeholders. These sessions will familiarize them with the matrix, providing detailed instructions on how to use the tool, interpret the results, and apply the findings in decision-making processes. Comprehensive user manuals and online help resources should also be developed to assist users in navigating the platform and utilizing the matrix effectively.

The matrix should be updated regularly to incorporate new data, refine the scoring mechanism, and enhance functionality based on technological advancements.

#### 4.4. GIS implementation

Due to useful spatial analysis tools like ArcGIS, it is possible to implement visual parameters of the matrix to the map and find most vulnerable to noise area in Glasgow. To have a visible part of the Matrix, Proximity criteria was implemented through GIS tool. A map of Glasgow was developed and highlighted the proximity of roads (10 m, 20 m, 30 m, 40 m, 50 m) to residential and social housing. The result of this is varying from green (for less vulnerable) to dark-red colour (for most vulnerable buildings or building parts). In figure 21-25 one can see the result of mentioned above GIS analysis in different city locations. In Appendix D is presented a map presenting this correlation for entire city.

In the Figure 21 below (developed as part of the Matrix) one can see a city part containing Caledonian Court – student housing area next to Caledonian University. In Appendixes E, F, G one can find a map of entire Glasgow, and closer looks on several streets.



Figure 21 - Proximity influence (Caledonian Court and GCU) (developed for this thesis using Esri GIS data)

As we can see from Figure 22 and 23 the distance from Dobbie's loan road to the Facade of nearest building is less than 7,5 metres, which is why the area has bright orange, almost red colour. At the same time, in the North-East part of Caledonian Court, one can see green areas (less vulnerable) first of all because of high contrast in distance length (more than 43 metres to a Motor Highway) and of course due to Green Barrier in the area.



Figure 22 - Proximity to Dobbie's loan.



Figure 23 - Proximity to M8 Highway

(both developed for this thesis using Esri GIS data)

Interesting situation is in the area close to Pollok Park presented in Figure 24. Even though a big piece of recreation land is so close to a recreational city part, the proximity to B769 and B768 highways strongly influences on noise in the area, especially to the frontline housing.

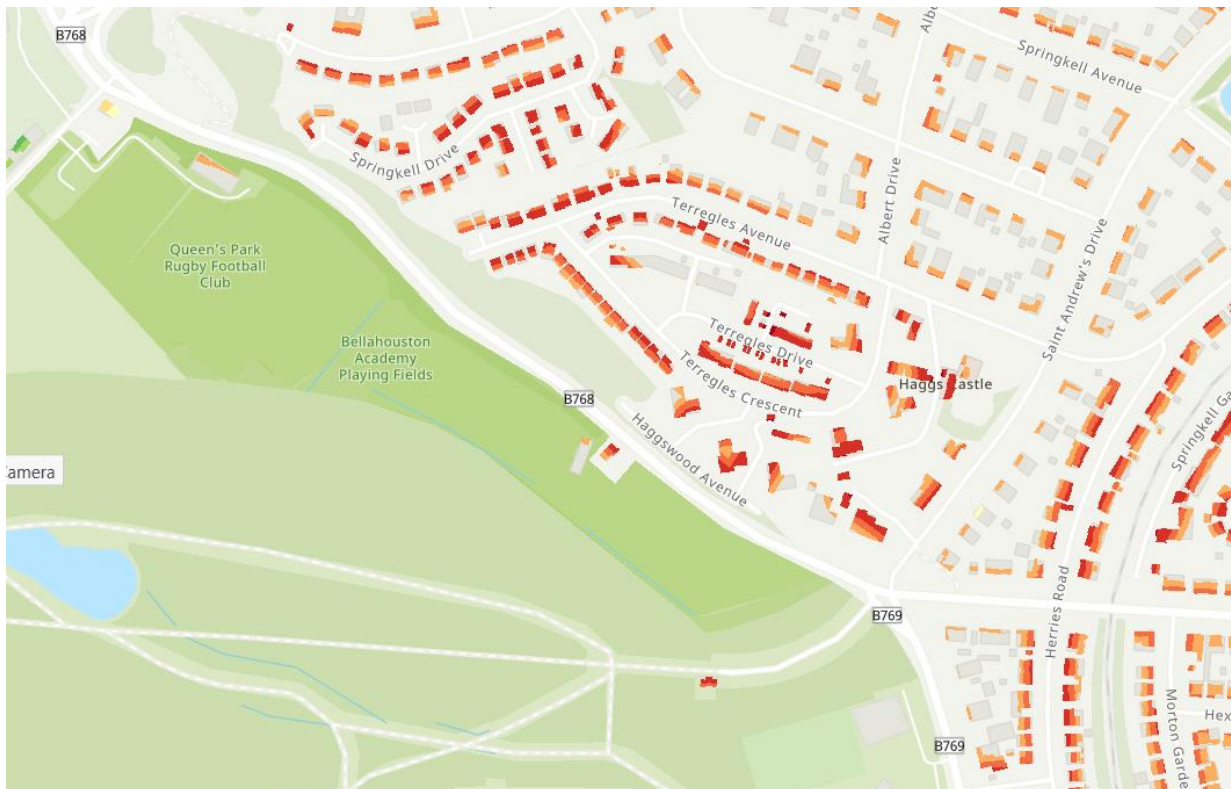


Figure 24 - Pollock Park housing frontline (developed for this thesis using Esri GIS data)

Housing quartal at the Dalziel Drive presented in Figure 25 also represents influence of distance from traffic to noise vulnerability. A road is surrounding entire residential block, but the distance from it to facades of the houses is far enough to not influence to the living their people.

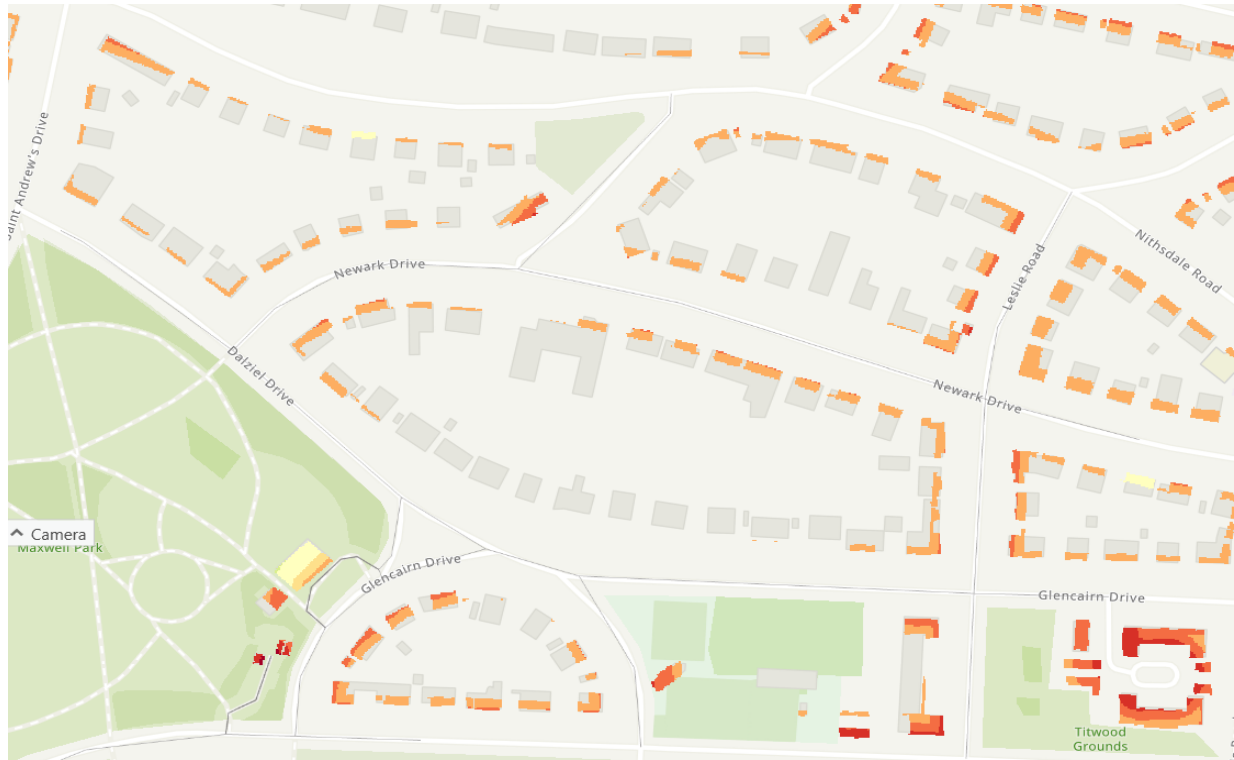


Figure 25 - Dalziel Drive housing (developed for this thesis using Esri GIS data)

## 4.5. Conclusion

Based on the scoring of the Noise Evaluation Matrix criteria and sub-criteria using WHO and EEA, EU reports, guidelines, directive, Scottish planning regulations, standards and Transport Scotland numerous reports, and other numerous studies explored, it is evident that noise pollution poses significant challenges across health, environmental, and social dimensions.

The findings underscore the critical need for robust policy measures focusing on noise reduction in urban planning and infrastructure development.

All these findings helped to identify and justify choice of criteria, their value, their role in the Matrix and their weight. This chapter provides a clear view on the Results of work on objective 1 - Developing and prioritizing key criteria for assessing noise pollution and Objective 2 - Designing an evaluation matrix that integrates key criteria and develops a scoring mechanism to quantify noise pollution levels. The Chapter also provided actions for opening usefulness of the Matrix, developing guidelines of its implementation, achieving Objective 3.

## **Chapter 5: Discussion, Conclusions, Recommendations for Future Work**

### **5.1. Statement of Results**

Our study focused on developing an evaluation system for identifying the weakest areas in cities that require noise pollution reduction measures. The key findings are summarized as follows:

Objective 1 - Development and Prioritization of Key Criteria for Assessing Noise Pollution:

We identified five primary criteria: Noise Level (sub criteria - Daytime Noise Level (dB), Nighttime Noise Level (dB), Peak Noise Level (dB) day, Peak Noise Level (dB) night, Noise Exposure limits), Source of Noise (sub criteria - Traffic Noise, Railway Noise, Aircraft Noise, Industrial Noise, Construction Noise, Neighbourhood Noise), Distance from Noise Source (sub criteria - Proximity to Traffic, Proximity to Industrial Sites, Proximity to Construction Sites, Proximity to Airports, Proximity to Railway Lines), Surface Conditions (sub criteria - Road Surface Materials, Speed Limit, Presence of Vegetation and Trees Between Sources and Receptors, Durability of Use, Rail Track Condition), Cost Analysis (sub criteria - Financial Costs), Receptors impacted (sub criteria - Residential Zones Residents, Social Zones (Education and Health Related Institutions), Commercial Zones, Industrial Zones, Recreational Zones, Mixed Zones).

Using a Delphi method (Research method), from the variety of factors we prioritized these criteria based on their impact on urban noise pollution, with traffic factors and urban activity emerging as the most significant factors. We considered all important parameters that should be considered while working with noise pollution and gave justification why certain of them were not considered with a clear justification.

Objective 2 - Design of an Evaluation Matrix and Scoring Mechanism:

For having a result that is most close reality the Matrix was developed based on AHP method – Analytic Hierarchy Process. This method usually helps to policy makers and decision makers. AHP is a structured technique for organizing and analysing complex decisions. It represents an accurate approach to quantifying the weights of decision criteria.

The relative importance of the criteria can be determined with the help of the AHP by comparing the criteria and, if applicable, the sub-criteria in pairs by experts or decision-makers. On this basis, the best alternative can be found. AHP is designed for group decision-making and is applied in various fields, including government, business, industry, healthcare, and education.

Instead of dictating a "correct" decision, AHP aids decision-makers in identifying the choice that aligns best with their objectives and their comprehension of the issue at hand. It offers a thorough and logical framework for structuring a decision problem, representing, and quantifying its components, linking these elements to overarching goals, and assessing alternative solutions.

The evaluation Matrix was developed integrating the six key criteria (plus sub criteria for each). Each criterion was assigned a weight based on researches conducted while achieving Objective 1 and 2 of this thesis and extra researched needed for providing a strong justification of scoring mechanism. A scoring mechanism was created, allowing for the quantification of noise pollution levels. Scores were assigned on a scale from 0 to 1, with higher scores indicating higher levels of noise pollution.

### **Summary**

To summarize, our study aimed to develop an evaluation system to identify urban areas most in need of noise pollution reduction measures. We established key criteria and used the Delphi method to prioritize them, highlighting traffic factors and urban activity as significant contributors to noise pollution.

By designing an evaluation matrix and scoring mechanism using the Analytic Hierarchy Process (AHP), we effectively quantified the weights of decision criteria. This method provided a robust framework for policymakers, enabling informed decisions about noise reduction efforts. These results demonstrate the system's effectiveness in pinpointing critical areas for noise pollution reduction, offering a valuable tool for urban planners to prioritize interventions.

## **5.2. Comparison with other studies**

Previously in literature review we spoke about studies that were aiming on identifying or evaluating noise pollution levels in cities. It is essential to compare and contrast the methodologies and findings with similar studies in the field. This comparison helps to validate the results, identify potential improvements, and position the current study within the broader research landscape.

Several studies have addressed noise pollution using various evaluation systems. For instance, Murphy and King in 2014 developed a comprehensive noise pollution assessment framework that integrated physical measurements with socio-environmental impacts. Their approach emphasized the importance of including public perception and health impacts alongside decibel measurements, which aligns with our study's inclusion of both quantitative and qualitative data. They detailed methodologies for noise mapping, public health implications, and

strategic noise management, providing a robust model for evaluating urban noise pollution (Enda Murphy, 2014).

Another noteworthy study by Zannin (Ferreira et al., 2001) employed a multifaceted noise assessment framework that combined environmental noise measurements with GIS mapping and public health data. This approach highlighted the spatial distribution of noise pollution and its correlation with health outcomes, reinforcing the importance of a holistic assessment strategy in understanding and mitigating noise pollution.

Comparatively, our study leverages similar multi-dimensional evaluation matrices, incorporating not only sound level measurements but also public health data and community feedback. This holistic approach is crucial for developing comprehensive noise mitigation policies and strategies that address the specific needs of affected populations.

Murphy and King's framework particularly emphasizes the necessity of strategic noise mapping and public dissemination of noise pollution data, which are critical components for effective noise management policies (Enda Murphy, 2014). These elements ensure that both policymakers and the public are well-informed about noise levels and their potential impacts, facilitating more effective interventions and community engagement.

A key distinction of our study is that the development of an evaluation matrix specifically tailored to the urban context of Glasgow and has the most realistic – focused on human perception analytical approach. We incorporated the AHP to prevent the doubling of scoring and ensure a balanced and unbiased assessment of various noise pollution sources. This method allowed us to prioritize factors like traffic noise and urban activity, which emerged as the most significant contributors to noise pollution for the city. Moreover, our study uniquely considers social factors through zoning (residential, social, commercial, industrial, recreational, and mixed zones), providing a nuanced understanding of how different areas within a city are impacted by noise pollution.

Additionally, our approach stands out by integrating surface conditions and cost analysis into the evaluation matrix. These criteria are essential for understanding the real-life implications of noise pollution and the feasibility of implementing mitigation measures. By considering factors such as road surface materials, speed limits, and the presence of vegetation, our study offers practical insights into effective noise reduction strategies.

In summary, by comparing our methodology with those employed by Murphy and King, as well as Zannin, we can see that the integration of environmental measurements with socio-economic and health data provides a more comprehensive understanding of noise pollution. This multi-faceted approach is essential for developing effective noise mitigation strategies that are

both scientifically sound and socially relevant. Our study's application to the city of Glasgow underscores its practical value, providing urban planners and policymakers with a robust tool for identifying and prioritizing areas in need of noise pollution reduction measures. Looking at these studies may be inspirations for future developers and users of the Matix.

### **5.3. Discussion**

The work conducted for the noise evaluation matrix had several notable strengths and areas for improvement. Firstly, the comprehensive criteria development was a significant achievement. Drawing from reputable sources such as the WHO, EEA, EU reports, Scottish planning regulations, and Transport Scotland reports, reliable experiments and researches, the criteria were meticulously developed. This solid foundation ensured that the evaluation matrix encompassed all relevant aspects of noise pollution, providing a robust framework for analysis.

Another positive aspect was the integration of various noise sources, including traffic, railways, and subways, along with their respective noise reduction methods. This holistic approach allowed for the matrix's application across different urban settings and noise pollution scenarios, making it versatile and widely applicable. The use of Geographic Information Systems (GIS) for spatial analysis further enhanced the matrix's practicality. By visualizing noise impact zones and identifying vulnerable areas in Glasgow, the spatial component provided valuable insights for urban planning and policy-making.

Additionally, incorporating considerations of long-term durability and maintenance of noise-reducing surfaces added a realistic perspective on the interventions' effectiveness and associated costs. This focus on sustainability is crucial for informed urban planning decisions. Furthermore, accounting for the vulnerability of different societal groups, such as children, the elderly, and shift workers, aligned the matrix with WHO guidelines. This ensured that the evaluation addressed not only noise levels but also their impact on public health.

Despite these strengths, the project encountered several challenges. One notable issue was that not all relevant factors could be quantitatively assessed and included in the matrix. Certain qualitative aspects were difficult to measure and incorporate systematically. This limitation suggests that while the matrix provides a robust framework for evaluating noise pollution, it may not capture the full scope of its effects on urban populations.

Additionally, the initial development phase of the matrix highlighted some difficulties in balancing comprehensive coverage with practical applicability. Striving for an all-encompassing matrix occasionally resulted in overly complex criteria, which could hinder its usability for urban planners and policymakers. Streamlining these criteria without losing essential details proved to

be a challenging task. The chosen format of Matrix in Excel is great for this stage, however, in case of practical use, the format of matrix may change depending on the users' needs. This complexity underscores the need for further refinement to ensure the matrix remains both thorough and user-friendly.

To enhance the work, several improvements could be implemented. Comprehensive and long-term monitoring programs for various noise-reducing materials and interventions should be established to provide more robust data. This would improve the accuracy of predictions regarding durability and maintenance, leading to better decision-making. Developing a more standardized and transparent process for assigning weights to criteria would also reduce subjectivity.

In Appendix H a result of a short survey among professionals of Acoustics sphere in Glasgow is presented. As we can see, there are many various options for future development of such a useful tool. The Matrix may play essential role in noise pollution reduction role for such a fast-growing city.

Future research should aim to gather data on subway noise and its impact to create a more inclusive assessment tool, particularly for cities with extensive subway networks. Conducting more detailed and dynamic cost-benefit analyses, including sensitivity analyses for different economic scenarios, would offer a clearer picture of the long-term economic feasibility of various noise abatement measures. Engaging with local communities and stakeholders in the assessment process could provide valuable insights into the real-world impacts of noise pollution (especially Neighbourhood noise) and the effectiveness of different interventions. This participatory approach would enhance the matrix's relevance and acceptance.

In conclusion, while the survey work for developing the noise evaluation matrix had several successes, including comprehensive criteria development and the use of GIS for spatial analysis, challenges related to data quality, weight assignment, and the exclusion of certain noise sources were encountered. Future improvements should focus on enhanced data collection, refined weight assignment processes, and increased community engagement to create a more robust and applicable noise evaluation matrix.

### **5.3.1. Positive Soundscape**

It is important to underline also another important topic. The concept of a positive urban soundscape offers a valuable dimension to the evaluation of noise pollution, one that our current matrix does not fully encompass. Urban soundscapes are characterized not only by the absence of negative noise but also by the presence of sounds that contribute positively to the urban

experience, such as birdsong, flowing water, wind, or even distant church bells. Integrating this criterion into our matrix could provide a more holistic approach to urban noise management.

Incorporating positive urban soundscapes as a criterion could significantly affect our study by broadening the scope of what is considered in noise pollution assessments. Currently, the matrix focuses predominantly on the evaluating of unwanted noise. By adding positive soundscapes as a criterion, the matrix could also evaluate the enhancement of auditory environments. This dual focus could help create urban spaces that are not only quieter but also more acoustically pleasant.

To integrate this into our scoring system, we could introduce a negative scoring mechanism for the presence of positive soundscape elements. Areas lacking in positive soundscape features would score higher, thereby emphasizing the importance of these sounds in urban planning and design. This adjustment would encourage urban planners to consider the enhancement of soundscapes as part of their noise mitigation strategies.

The inclusion of positive soundscapes could also have implications for the assignment of weights to different criteria. It may require a recalibration of the matrix to ensure that the benefits of positive soundscapes are adequately reflected in the overall score. Additionally, expert opinions and community feedback would be essential in determining what constitutes a positive soundscape and how it should be weighted relative to other criteria.

By expanding the matrix to include positive urban soundscapes, our study would provide a more comprehensive tool for urban noise management. This inclusion would not only address the reduction of negative noise but also promote the creation of auditory environments that enhance the quality of life in urban areas.

To support the inclusion of positive urban soundscapes in our Matrix, we can reference the work of the World Health Organization (WHO). The WHO's guidelines on environmental noise emphasize that a well-designed urban environment should not only mitigate harmful noise but also consider the quality of the soundscape, which includes pleasant and restorative acoustic elements.

According to the WHO's "Environmental Noise Guidelines for the European Region" (2018) (World Health Organization, 2018), the health impacts of noise are not solely related to the loudness of unwanted sounds but also to the overall acoustic environment. The guidelines suggest that a positive soundscape, which includes natural and pleasant sounds, contributes to overall well-being and should be integrated into noise management strategies. The report notes that incorporating soundscape considerations can enhance the health benefits of urban environments by promoting auditory experiences that support relaxation and stress reduction.

### 5.3.2. Specific programs connected to noise

According to a study in Scotland, correct levels and organisation of noise can positively influence people health and behaviour (*Evaluation of Sistema Scotland*. 2020). In recent years, programs like Sistema Scotland have emerged, reflecting a growing recognition of the multifaceted nature of noise in urban environments. Rather than striving to eliminate noise pollution entirely—a goal that is neither feasible nor necessarily beneficial—these initiatives embrace the positive aspects of noise and leverage them to enhance community well-being.

According to a 2020 study evaluating Sistema Scotland, the effective management and organization of noise can positively influence health and behaviour. Modelled after Venezuela's El Sistema, Sistema Scotland aims to use music as a tool to promote well-being, confidence, self-esteem, pride, and aspiration among children and young people.

The Big Noise programme, a central component of this initiative, emphasizes early intervention and long-term impact. It begins with engaging children in nursery and Primary 1 and 2, progressively fostering core skills such as listening, concentration, rhythm, rhyme, and teamwork through group music activities. This approach not only helps in skill development but also integrates noise in a constructive manner.

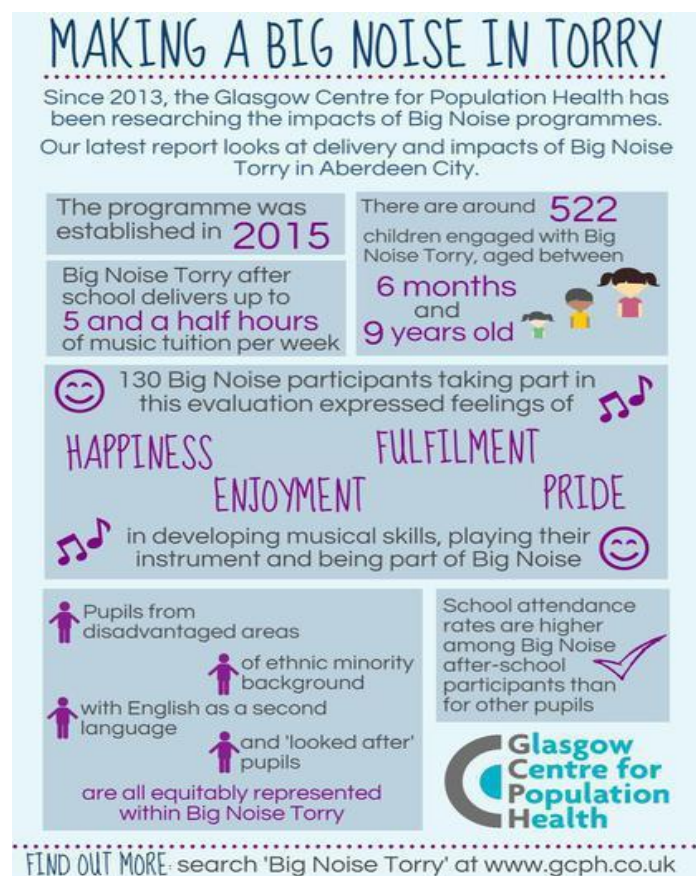


Figure 26 - Results of Big Noise Programme

The outcomes of nearly a decade of the Big Noise programme, as shown in Figure 26, illustrate its broad benefits:

- Increased confidence, discipline, pride, and aspiration
- Enhanced teamwork, communication, and leadership abilities
- Improved academic skills, including listening, concentration, and creativity
- Greater resilience, happiness, and a sense of belonging and fulfilment
- Development of strong musical skills
- Increased physical activity, healthier eating habits, and avoidance of detrimental behaviours
- Formation of positive social groups, peer relationships, and cultural engagement
- Provision of respite and protection for vulnerable participants

These findings suggest that rather than aiming for a reduction in noise to the point of complete elimination, incorporating the positive aspects of noise through well-designed programs can yield substantial benefits. Such programs not only manage noise pollution but also utilize its constructive potential to foster social, educational, and personal growth, highlighting a more nuanced approach to urban soundscape management.

## **5.2. Conclusion**

Our study aimed to develop a robust evaluation system for identifying urban areas most in need of noise pollution reduction measures, utilizing a detailed matrix and scoring mechanism to prioritize interventions.

### **Key Findings:**

We successfully identified and prioritized key criteria for assessing noise pollution, including noise levels, sources, distances, surface conditions, and cost analysis. The Delphi method helped emphasize the importance of traffic and urban activity as primary contributors to noise pollution.

The matrix was developed using the Analytic Hierarchy Process (AHP), which enabled a structured approach to weighting and quantifying various criteria. This framework provided a comprehensive tool for policymakers, allowing for a nuanced assessment of noise pollution and its impacts.

Our study's approach aligns with established methodologies, but also offers unique contributions. By focusing on Glasgow-specific factors and integrating surface conditions and cost analyses, our matrix provides practical insights tailored to urban planning needs. While the matrix effectively addresses many quantitative factors, it struggles with incorporating qualitative

aspects like social and psychological impacts of noise. Future work should aim to include these dimensions more comprehensively.

Balancing comprehensive coverage with usability posed challenges. Simplifying criteria while retaining essential details will be crucial for practical application in urban planning. Engaging local communities and stakeholders, and incorporating their feedback, could provide valuable insights into the real-world impacts of noise and the effectiveness of different interventions.

Overall, the study demonstrates the effectiveness of the developed evaluation matrix in identifying critical areas for noise reduction. The Matrix, developed within this thesis project is a very helpful tool ready to use. It is unique, close to real life perception, focused and tailored for Glasgow. Future improvements should focus on refining data collection, simplifying criteria, and increasing community engagement to strengthen the matrix's applicability and impact.

### **5.3. Limitations**

Reading articles, guidelines, reports, and policies provided valuable information that helped justify each step of this thesis. However, a few aspects remained unclear and difficult to ascertain.

While researching urban planning standards for Glasgow and, more broadly, the United Kingdom, the topic of distance between residential housing and various types of roads remained ambiguous. Some online pages provided suggested distances between residential houses and highways or major roads, but references to these numeric parameters were never properly cited. Even after examining documents such as the National Planning Policy Framework (NPPF), Manual for Streets, Action Plan for Glasgow Agglomeration, Scottish Planning Policy (SPP), Glasgow City Council Local Development Plan, Designing Streets: A Policy Statement for Scotland, and Scottish Building Standards: Technical Handbooks, these parameters were not found. This limitation is noted in Chapter 4.

Another challenging topic was the regulation of distances between residential housing and airports in the UK. There is not a specific, universally mandated minimum distance. Instead, planning and development near airports are governed by a combination of local planning policies, environmental assessments, and specific regulations related to noise and air quality.

Working with the sub-criteria for Neighbourhood Noise (sub-criteria 2.6) also posed a challenge. This source of noise is particularly difficult to quantify accurately. Various studies highlight it as a significant source of error when assessing noise pollution. High levels of

neighbourhood noise usually come from multiple, often mobile, sources that have lower speeds but cover larger areas, making calculations complex.

The role of weather conditions in noise pollution remains a topic of ongoing debate among scientists. There is uncertainty about how factors such as humidity, precipitation, air pressure, wind speed, and wet surfaces post-rainfall influence noise levels. Research has shown that weather conditions significantly affect noise pollution, either amplifying or diminishing noise levels. However, the impact of these parameters varies widely, with even minor wind variations sometimes causing substantial increases or decreases in noise levels. This variability underscores the importance of obtaining consistent and repeatable experimental data, which are crucial for advancing research and developing reliable noise pollution models.

Scottish noise regulations are currently under review for a crucial update to better address contemporary challenges. This revision aims to foster a more harmonious environment, ensuring communities can enjoy greater peace and tranquillity. This anticipated update represents a significant consideration that could impact the limitations and future directions of this research.

#### **5.4. Recommendations for future work**

Future research and development in the field of noise pollution management can build upon the foundation established by this thesis. Several key recommendations for future work include enhancing the integration of GIS technology, improving data accuracy, and increasing accessibility through dedicated online platforms.

A significant advancement in noise pollution research would involve the integration of GIS with health data. By linking noise pollution levels to health outcomes, researchers can identify correlations between high noise levels and adverse health impacts. This capability would enable policymakers and urban planners to implement proactive measures to mitigate potential health risks associated with noise pollution. The near real-time monitoring and analysis of health data alongside noise data could provide valuable insights for preventing negative health effects in advance.

Another crucial step is the incorporation of traffic flow data into GIS systems. Accurate and up-to-date traffic information can significantly enhance the precision of noise pollution assessments. By integrating traffic data, which is regularly updated in Scotland, GIS can provide more accurate and dynamic representations of noise pollution levels. This enhancement would allow for better monitoring and management of noise pollution, particularly in urban areas with fluctuating traffic patterns.

To reach high-developed accessibility and usability, the entire body of work, including the evaluation matrix and GIS maps, should be consolidated into a single dedicated web page focused on noise pollution. As another option, this platform could be integrated with the existing Scottish Government's noise mapping website, Scotland's Noise (<https://noise.environment.gov.scot/noisemap/>). A unified platform would provide an intuitive interface for users to input data, calculate scores, visualize noise pollution, and access justifications for scores. It would also facilitate the sharing of information and collaboration among policymakers, urban planners, researchers, and the public.

Ensuring the tool remains relevant and effective necessitates the establishment of a feedback mechanism for users. Regular updates to the evaluation matrix and GIS maps based on user feedback and the latest research findings will help maintain the tool's accuracy and utility. Training sessions and comprehensive user manuals should also be provided to ensure stakeholders are well-equipped to use the tool effectively.

By implementing these recommendations, future research can further advance the understanding and management of noise pollution, ultimately leading to healthier and more liveable urban environments.





## Appendix A: Matrix

Criteria	Description	Sub-criteria	Parameter	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Sub criteria weight	
<b>1. Noise Level (dB)</b>	Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion quantifies the intensity of noise and its impact on health.	1.1 Daytime Noise Level (dB)	Average L day	0	>=55	0,5	>=65	1	>=75							0.5	
		1.1 Nighttime Noise Level (dB)	Average L night (11pm-7am)	0	>=50	0,5	>=60	1	>=70								1
		1.2 Peak Noise Level (dB) day	Max L day	1	above 75 dB	0	below 75 dB										0.5
		1.2 Peak Noise Level (dB) night	Max L night	1	above 70 dB	0	below 70 dB										1
		1.3 Noise Exposure limits	Time	1	above 85 dB during 8h	0,5	from 80 dB to 85 dB during 8h	0	below 80 dB during 8h								0.5
<b>2. Source of Noise</b>	Identifying noise sources is crucial for developing targeted noise mitigation strategies. Different sources contribute varying levels and types of noise pollution.	2.1 Traffic Noise	Yes or No	1	Yes	0	No										
		2.2 Railway Noise	Yes or No	1	Yes	0	No										
		2.3 Aircraft Noise	Yes or No	1	Yes	0	No										
		2.4 Industrial Noise	Yes or No	1	Yes	0	No										
		2.5 Construction Noise	Yes or No	1	Yes	0	No										
		2.6 Neighbourhood Noise	Yes or No	1	Yes	0	No										
<b>3. Distance from Noise Source</b>	The impact of noise diminishes with increasing distance from the source. This criterion evaluates proximity to noise-sensitive areas like residential zones, schools, and hospitals.	3.1 Proximity to Traffic	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30						
		3.2 Proximity to Industrial Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30						
		3.3 Proximity to Construction Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30						
		3.4 Proximity to Airports	Distance in metres	1	less than 1000 m or belong to the Noise pollution area at Glasgow Airport	0	more than 1000 m and do not belong to the Noise pollution area at Glasgow Airport										
		3.5 Proximity to Railway Lines	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30						
<b>4. Surface Conditions</b>	Surface conditions, such as ground cover and surrounding structures, affect noise propagation and attenuation. This criterion considers how different surfaces influence noise levels.	4.1 Road surface materials	Material	1	equal 0	0,8	> 0 and < 3	0,65	<= 3 and <6	0,55	<= 6 and <9	0	>9				
		4.2 Speed limit	Speed of vehicles	0	FOR CARS: ABOVE 30 km/h	0,5	FOR CARS: ABOVE 40 km/h	1	FOR CARS: ABOVE 80 km/h	0	FOR CARS: ABOVE 25 km/h	0,5	FOR CARS: ABOVE 30 km/h	1	FOR CARS: ABOVE 30 km/h		
				0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 20 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 30 km/h	0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 10 km/h		
		4.3 Presence of Vegetation and Trees between sources and receptors	Presence of vegetation between source and receptor	1	No vegetation and or solid surfaces	0	Trees in combination with solid barriers reduce noise by 5-8 decibels (ref 149)	0	Trees and other vegetation types in conjunction with landforms (soft surfaces aka grass) reduce road noise by 6-15 decibels road need maintenance every 10+ years								
		4.4 Durability of use	years	1	<= 5 years	0,5	>5 and <=10 years	0									
<b>5. Cost Analysis</b>	Evaluating the financial costs.	4.5. Rail track condition	presence of noise pads	1	no noise reducing pads/layers	0	installed noise reducing pads /layers										
		5.1. Financial Costs	The budget	1	if the renovation is in budget limits	0	if the renovation is not in budget limits										
<b>6. Receptors impacted</b>	Ensuring noise mitigation solutions are suitable for different urban areas based on their function and population density.	6.1 Residential Zones residents	Yes or No	0,5	for L day	1	during L evening and L night										
		6.2. Social Zones (education and health related institutions)	Yes or No	0	for L day	1	during L evening and L night										
		6.3 Commercial Zones	Yes or No	1	for L day	0	during L night										
		6.4 Industrial Zones	Yes or No	1	for L day	0	during L night										
		6.5 Recreational Zones	Yes or No	1	for L day	1	during L night										
		6.6 Mixed Zones	Yes or No	1	for L day	1	during L night										

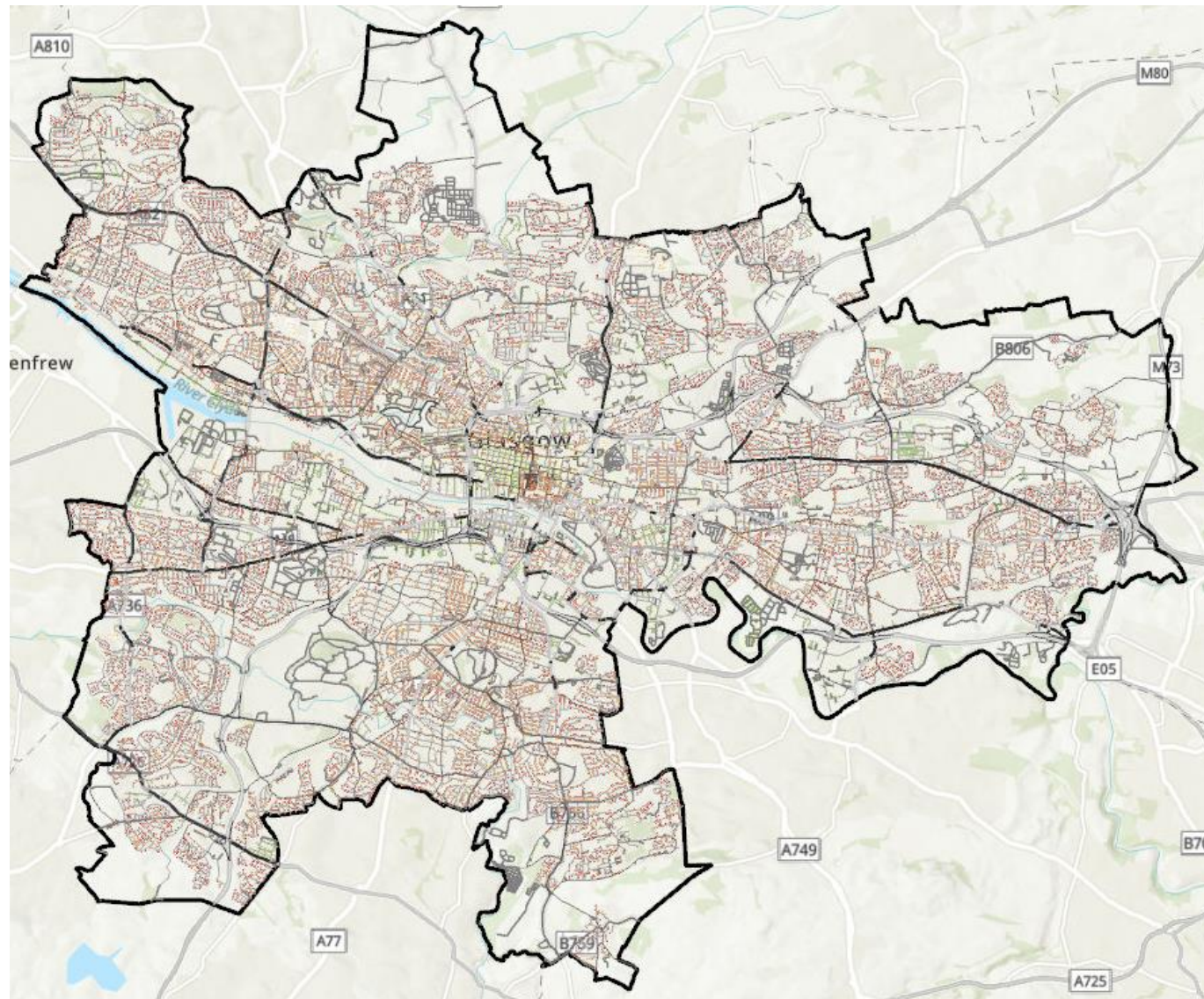
## Appendix B: Matrix for Daytime parameters

Description	Sub-criteria	Parameter	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Sub-criteria
Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion quantifies the intensity of noise and its impact on health.	1.1 Daytime Noise Level (dB)	Average L day	0	>=55	0,5	>=65	1	>=75					0.5
	1.2 Peak Noise Level (dB) day	Max L day	1	above 75 dB	0	below 75 dB							0.5
	1.3 Noise Exposure limits	Time	1	above 85 dB during 8h	0,5	from 80 dB to 85 dB during 8h	0	below 80 dB during 8h					0.5
Identifying noise sources is crucial for developing targeted noise mitigation strategies. Different sources contribute varying levels and types of noise pollution.	2.1 Traffic Noise	Yes or No	1	Yes	0	No							
	2.2 Railway Noise	Yes or No	1	Yes	0	No							
	2.3 Aircraft Noise	Yes or No	1	Yes	0	No							
	2.4 Industrial Noise	Yes or No	1	Yes	0	No							
	2.5 Construction Noise	Yes or No	1	Yes	0	No							
	2.6 Neighbourhood Noise	Yes or No	1	Yes	0	No							
The impact of noise diminishes with increasing distance from the source. This criterion evaluates proximity to noise-sensitive areas like residential zones, schools, and hospitals.	3.1 Proximity to Traffic	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30			
	3.2 Proximity to Industrial Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30			
	3.3 Proximity to Construction Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30			
	3.4 Proximity to Airports	Distance in metres	1	less than 1000 m or belong to the Noise pollution area at	0	more than 1000 m and do not belong to the Noise pollution area							
	3.5 Proximity to Railway Lines	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30			
Surface conditions, such as ground cover and surrounding structures, affect noise propagation and attenuation. This criterion considers how different surfaces influence noise levels.	4.1 Road surface materials	Material	1	equal 0	0,8	> 0 and < 3	0,65	<= 3 and <6	0,55	<= 6 and <9	0	>9	
	4.2 Speed limit	Speed of vehicles	0	FOR CARS: ABOVE 30 km/h	0,5	FOR CARS: ABOVE 40 km/h	1	FOR CARS: ABOVE 80 km/h					
			0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 20 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 30 km/h					
	4.3 Presence of Vegetation and Trees between sources and receptors	Presence of vegetation between source and receptor	1	No vegetation and or solid surfaces	0	Trees in combination with solid barriers reduce noise by 5-8	0	Trees and other vegetation types in conjunction with landforms (soft surfaces)					
	4.4 Durability of use	years	1	<= 5 years	0,5	>5 and <=10 years	0	road need maintenance every 10+ years					
4.5. Rail track condition	presence of noise pads	1	no noise reducing pads/layers	0	installed noise reducing pads /layers								
Evaluating the financial costs.	5.1. Financial Costs	The budget	1	If the renovation is in budget limits	0	If the renovation is not in budget limits							
Ensuring noise mitigation solutions are suitable for different urban areas based on their function and population density.	6.1 Residential Zones residents	Yes or No	0,5	for L day	1	during L evening and L night							
	6.2. Social Zones (education and health related institutions)	Yes or No	0	for L day	1	during L evening and L night							
	6.3 Commercial Zones	Yes or No	1	for L day	0	during L night							
	6.4 Industrial Zones	Yes or No	1	for L day	0	during L night							
	6.5 Recreational Zones	Yes or No	1	for L day	1	during L night							
	6.6 Mixed Zones	Yes or No	1	for L day	1	during L night							

## Appendix C: Matrix for Daytime parameters

Description	Sub-criteria	Parameter	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Weight	Calculation	Sub criteria
Noise levels, measured in decibels (dB), are a primary criterion for evaluating noise pollution. This criterion quantifies the intensity of noise and its impact on health.	1.1 Nighttime Noise Level (dB)	Average L night (11pm-7am)	0	>=50	0,5	>=60	1	>=70	1				
	1.2 Peak Noise Level (dB) night	Max L night	1	above 70 dB	0	below 70 dB	1						
	1.3 Noise Exposure limits	Time	1	above 85 dB during 8h	0,5	from 80 dB to 85 dB during 8h	0	below 80 dB during 8h	0,5				
Identifying noise sources is crucial for developing targeted noise mitigation strategies. Different sources contribute varying levels and types of noise pollution.	2.1 Traffic Noise	Yes or No	1	Yes	0	No	1						
	2.2 Railway Noise	Yes or No	1	Yes	0	No	1						
	2.3 Aircraft Noise	Yes or No	1	Yes	0	No	1						
	2.4 Industrial Noise	Yes or No	1	Yes	0	No	1						
	2.5 Construction Noise	Yes or No	1	Yes	0	No	1						
	2.6 Neighbourhood Noise	Yes or No	1	Yes	0	No	1						
The impact of noise diminishes with increasing distance from the source. This criterion evaluates proximity to noise-sensitive areas like residential zones, schools, and hospitals.	3.1 Proximity to Traffic	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30	1		
	3.2 Proximity to Industrial Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30	1		
	3.3 Proximity to Construction Sites	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30	1		
	3.4 Proximity to Airports	Distance in metres	1	less than 1000 m or belong to the Noise pollution area at	0	more than 1000 m and do not belong to the Noise pollution area	0						
	3.5 Proximity to Railway Lines	Distance in metres	1	<=10	0,7	<=20	0,4	<=30	0	>30	1		
Surface conditions, such as ground cover and surrounding structures, affect noise propagation and attenuation. This criterion considers how different surfaces influence noise levels.	4.1 Road surface materials	Material	1	equal 0	0,8	> 0 and < 3	0,65	<= 3 and <6	0,55	<= 6 and <9	0	>9	1
	4.2 Speed limit	Speed of vehicles	0	FOR CARS: ABOVE 25 km/h	0,5	FOR CARS: ABOVE 30 km/h	1	FOR CARS: ABOVE 30 km/h	1				
			0	FOR TRUCKS AND MOTORCYCLES: above 0 km/h	0,5	FOR TRUCKS AND MOTORCYCLES: above 10 km/h	1	FOR TRUCKS AND MOTORCYCLES: above 10 km/h	1				
	4.3 Presence of Vegetation and Trees between sources and receptors	Presence of vegetation between source and receptor	1	No vegetation and or solid surfaces	0	Trees in combination with solid barriers reduce noise by 5-8	0	Trees and other vegetation types in conjunction with landforms (soft surfaces)	0,5				
4.4 Durability of use	years	1	<= 5 years	0,5	>5 and <=10 years	0	road need maintenance every 10+ years	0					
4.5, Rail track condition	presence of noise pads	1	no noise reducing pads/layers	0	installed noise reducing pads /layers	1							
Evaluating the financial costs.	5.1. Financial Costs	The budget	1	If the renovation is in budget limits	0	If the renovation is not in budget limits	0						
Ensuring noise mitigation solutions are suitable for different urban areas based on their function and population density.	6.1 Residential Zones residents	Yes or No	0,5	for L day	1	during L evening and L night	1						
	6.2 Social Zones (education and health related institutions)	Yes or No	0	for L day	1	during L evening and L night	1						
	6.3 Commercial Zones	Yes or No	1	for L day	0	during L night	1						
	6.4 Industrial Zones	Yes or No	1	for L day	0	during L night	0,5						
	6.5 Recreational Zones	Yes or No	1	for L day	1	during L night	1						
	6.6 Mixed Zones	Yes or No	1	for L day	1	during L night	1						

## Appendix D: Proximity of Roads to Residential and Social buildings



## Appendix E: Proximity of Roads to Residential and Social buildings (Great Western Road)



## Appendix F: Proximity of Roads to Residential and Social buildings (Possil Park)



## Appendix G: Proximity of Roads to Residential and Social buildings (Dowanhill)



# Appendix H: Survey Results

What is your name ?  
1 ответ  
Cesar Bustos

Which organization do you represent?  
1 ответ  
Arup

What is your job title?  
1 ответ  
Senior Acoustics Consultant

What is your email address?  
1 ответ  
cesar.bustos@arup.com



What is, in your opinion, the definition of a noise in a city? Please describe:

1 ответ

Unwanted sound which leads to adverse health effects upon people and the environment

What is the definition of a noise-prone areas according to the assessment carried out by your organisation/department? Please describe:

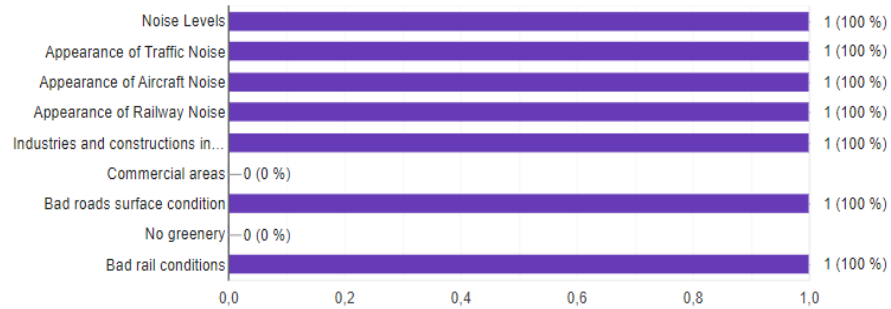
1 ответ

Areas which are exposed to relatively high levels of noise and are in close proximity to noise sources such as roads, rail, airports, construction sites, industrial facilities, etc.

According to your analysis, which are the indicators for the delimitation and identification of noise-prone areas?

[Копировать](#)

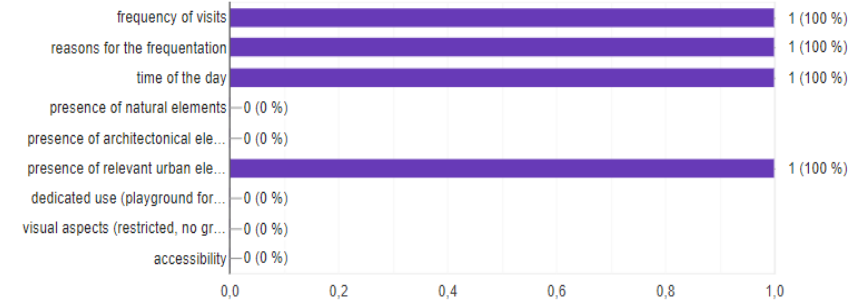
1 ответ



What are the indicators for a general characterization (without considering the acoustic indicators) of a noise-prone areas?

[Копировать](#)

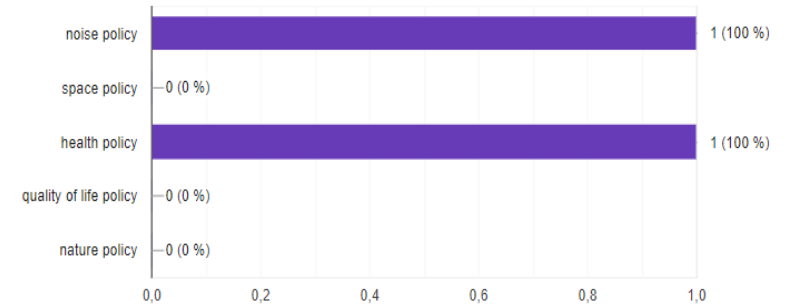
1 ответ



What is the municipal policy goal (target) with respect to the designation, improvement and/or preservation of noisy areas? On which policy is it based?

[Копировать](#)

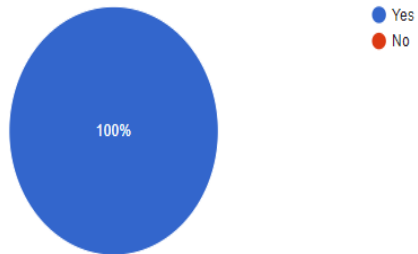
1 ответ



Did you ever tried to develop or worked with a system for evaluating noise pollution ?

Копировать

1 ответ



What are the most critical criteria that should be included in an evaluation matrix for assessing noise pollution? (give 3-6 criteria)

1 ответ

type of noise source, absolute noise levels, number of receptors impacted, soundscape, benefit cost ratio of mitigation measure that could reduce noise exposure,

Which social aspects would you consider while creating a system for evaluation of noise pollution?

1 ответ

type of receptor to be assessed e.g. residential, commercial, hospital, etc. For distributional impact assessment, I'd consider income of deprivation domain per Lower-layer Super Output Areas

How in you opinion a matrix for evaluation of noise pollution would look?

1 ответ

First: identify the level of impact to which receptor is subject to in terms of health effects e.g. major adverse, moderate adverse, minor adverse, etc - Noise Important Areas are a good example of this for road and rail noise sources. Second: The number of receptors impacted. Third: Income of Deprivation Domain (or similar), Forth: Benefit Cost Ratio

Can you provide examples of successful noise pollution evaluation or mitigation projects you have worked on?

1 ответ

A66 Northern Transpennine Project: Design of noise barriers to reduce noise levels at receptors impacted by project. WebTag workbooks demonstrate the benefit.  
Darlington Northern Link Road: Design of road scheme to de-traffic congested roads and receptors within a number of Noise Important Areas.  
HS2 noise barriers: Design of noise barriers for new railway line

What are the primary sources of noise pollution in urban areas that should be prioritized in an evaluation matrix?

1 ответ

road traffic noise, rail traffic noise, aircraft noise, industrial noise, construction noise, commercial noise (restaurants, pubs, etc.)

How do you currently count and analyze areas suffering from noise pollution in your work?

1 ответ

Noise impact assessments are undertaken in line with national guidance and best practice. In particular reference is made to IEMA, BS8223, BS5228, BS4142, DMRB LA111, among others.

What data do you consider most important when evaluating the impact of noise pollution on public health?

1 ответ

the level of noise to which receptors are exposed to and the type of receptor potentially impacted

Could you share any case studies or research papers that provide valuable insights into effective noise pollution management?

1 ответ

A66 Northern Transpennine Project DCO

What challenges have you encountered in the assessment or mitigation of noise pollution, and how have you addressed them?

What challenges have you encountered in the assessment or mitigation of noise pollution, and how have you addressed them?

1 ответ

Main challenge is cost - it's difficult to quantify the benefit of noise mitigation. WebTag is a good starting point but needs a lot more research. Stakeholder expectation is also a challenge, but can be dealt with with adequate consultation

What role do you believe technological advancements (such as noise-canceling infrastructure or real-time monitoring systems) play in future noise pollution evaluation?

1 ответ

AI will make it more efficient to identify receptors needing mitigation and design mitigation measures. Real time monitoring system and cheaper but accurate sound level meters and Internet of Things (IoT) will make it also more efficient to measure noise and make prediction models better

Based on your experience, what policy recommendations would you suggest for improving noise pollution evaluation and control at the municipal or national level?

1 ответ

More implementation of measurements when developing noise models. Strategic noise models do not have detail, so when certain communities/receptors are identified as having high priority need for mitigation, then a more detail noise model needs to be developed.



## References

Scottish Government. (2011). *Assessment of noise: technical advice note*

Acoustical surfaces. (2020). *Perceived Noise Reduction & Charting Noise with Decibels (dB)*.

[https://www.acousticalsurfaces.com/soundproofing\\_tips/noise\\_reduction.htm](https://www.acousticalsurfaces.com/soundproofing_tips/noise_reduction.htm)

Aletta, F., Oberman, T., & Kang, J. (2018). Associations between Positive Health-Related Effects and Soundscapes Perceptual Constructs: A Systematic Review. *International Journal of Environmental Research and Public Health*, 15(11), 2392.

10.3390/ijerph15112392

Andersson, H., Jonsson, L., & Ögren, M. (2013). Benefit measures for noise abatement: calculations for road and rail traffic noise. *European Transport Research Review*, 5(3), 135-148. 10.1007/s12544-013-0091-3

Babisch, W., Beule, B., Schust, M., Kersten, N., & Ising, H. (2005). Traffic Noise and Risk of Myocardial Infarction. *Epidemiology (Cambridge, Mass.)*, 16, 33-40.

10.1097/01.ede.0000147104.84424.24

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *Lancet (London, England)*, 383(9925), 1325-1332. 10.1016/S0140-6736(13)61613-X

Basner, M., Müller, U., & Elmenhorst, E. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep*, 34(1), 11-23.

10.1093/sleep/34.1.11

Chitra, B., Jain, M., & Chundelli, F. A. (2020). Understanding the soundscape environment of an urban park through landscape elements. *Environmental Technology & Innovation*, 19, 100998. 10.1016/j.eti.2020.100998

Collman, R. (2015). Distance Attenuation: How Sound Reduces with Distance. <https://www.acoustical.co.uk/distance-attenuation/how-sound-reduces-with-distance-from-a-point-source/>

Construction Noise: Exposure, Effects, and the Potential for Remediation; A Review and Analysis. (2010). <https://www.tandfonline.com/doi/abs/10.1080/15428110208984768>

Danish Road Institute. (2010). *Noise Reducing Pavements*. <https://www.scribd.com/document/611712424/Noise-Reducing-Pavements>

Davies, W. J., Adams, M. D., Bruce, N. S., Cain, R., Carlyle, A., Cusack, P., Hall, D. A., Hume, K. I., Irwin, A., Jennings, P., Marselle, M., Plack, C. J., & Poxon, J. (2013). Perception of soundscapes: An interdisciplinary approach. *Applied Acoustics*, 74(2), 224-231. 10.1016/j.apacoust.2012.05.010

de Kluizenaar, Y., Janssen, S., Lenthe, F., Miedema, H., & Mackenbach, J. (2009). Long-term road traffic noise exposure is associated with an increase in morning tiredness. *The Journal of the Acoustical Society of America*, 126, 626-33. 10.1121/1.3158834

de Paiva Vianna, K. M., Alves Cardoso, M. R., & Rodrigues, R. M. C. (2015). Noise pollution and annoyance: An urban soundscapes study. *Noise & Health*, 17(76), 125-133. 10.4103/1463-1741.155833

Department of Transport. Manual for the Streets.

[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/341513/pdfmanforstreets.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/341513/pdfmanforstreets.pdf)

Dzhambov, A. M., & Dimitrova, D. D. (2014). Urban green spaces' effectiveness as a psychological buffer for the negative health impact of noise pollution: a systematic review. *Noise & Health*, 16(70), 157-165. 10.4103/1463-1741.134916

EEA. (2020). *Environmental noise in Europe*. © European Environment Agency, 2020.

Enda Murphy, E. K. (2014). *Environmental Noise Pollution* (1st ed.). Elsevier Science. 10.1016/C2012-0-13587-0

*Environmental Noise Directive - 2002/49*.

<https://eur-lex.europa.eu/eli/dir/2002/49/oj>

EU Report. (2015). *Quiet Areas Definition and Management in Action Plans*. ()

[http://www.quadmap.eu/wp-content/uploads/2016/01/Final-Report QUADMAP technical.pdf](http://www.quadmap.eu/wp-content/uploads/2016/01/Final-Report_QUADMAP_technical.pdf)

EU Tyre Labelling Association. (2021). *European tyre labelling Regulation*

EURO CITIES. (2014). *Quiet Road Surfaces*

EURO CITIES. (2015). *Low-noise road surfaces*

European Environment Agency. (2014). Noise in Europe 2020. <file:///C:/Users/lily-/OneDrive/%D0%A0%D0%B0%D0%B1%D0%BE%D1%87%D0%B8%D0%B9%20>

[%D1%81%D1%82%D0%BE%D0%BB/Thesis/EEA%2010-2014%20Noise%20in%20Europe%202014.pdf](#)

European Environmental Agency. (2010). Good practice guide on noise exposure and potential health effects. <https://www.eea.europa.eu/publications/good-practice-guide-on-noise>

*Evaluation of Sistema Scotland*. (2020). <https://www.gcph.co.uk/our-work/40-evaluation-of-sistema-scotland>

Ferreira, A., Diniz, F., Paz, E., & Zannin, P. (2001). Evaluation of the noise pollution in urban parks of Curitiba, Brazil. *Journal of the Acoustical Society of America - J ACOUST SOC AMER*, 115, 2622-2622. 10.1121/1.4779184

Frederic Steiner. (1996). *The Ecological City: Preserving and Restoring Urban Biodiversity; Urban Environmental Management: Environmental Change and Urban Design* - ProQuest. <https://www.proquest.com/openview/f244fa9ff65c37623c07fdccfafa0b7/1?pq-origsite=gscholar&cbl=41477>

Gidlof-Gunnarsson, A., & Ohrstrom, E. (2007). Noise and well-being in urban residential environments: The potential role of perceived availability to nearby green areas. *Landscape and Urban Planning*, 83(2), 115-126. 10.1016/j.landurbplan.2007.03.003

*Glasgow Subway*. (2024). [https://en.wikipedia.org/w/index.php?title=Glasgow\\_Subway&oldid=1235439779](https://en.wikipedia.org/w/index.php?title=Glasgow_Subway&oldid=1235439779)

Goines, L., & Hagler, L. (2007). Noise Pollution: A Modern Plague. *Southern Medical Journal*, 100, 287-94. 10.1097/SMJ.0b013e3180318be5

Golmohammadi, R., Mohammadi, H., Bayat, H., Habibi Mohraz, M., & Soltanian, A. (2013). Noise Annoyance Due to Construction Worksites. *Journal of Research in Health Sciences*, 13, 201-207.

Guidance on Noise nuisance . (2004).

<https://www.gov.scot/binaries/content/documents/govscot/publications/advice-and-guidance/2004/10/antisocial-behaviour-etc-scotland-act-2004-guidance-noise- nuisance/documents/0025278-pdf/0025278-pdf/govscot%3Adocument/0025278.pdf>

Guski, R. (1999). Personal and social variables as co-determinants of noise annoyance. *Noise & Health*, 1(3), 45-56.

Hong, X., Wang, G., Liu, J., & Lan, S. (2019). Cognitive persistence of soundscape in urban parks. *Sustainable Cities and Society*, 51, 101706. 10.1016/j.scs.2019.101706

Jia-Hong Tang a, Bo-Cheng Lin b, Jing-Shiang Hwang. (2022). Dynamic modeling for noise mapping in urban areas - ScienceDirect.

<https://www.sciencedirect.com/science/article/pii/S0195925522001305>

Kang, J. (2016). *Soundscape and the Built Environment*

Kedia, & Kumar. (2021). Effect of Rail Irregularities and Rail Pad on Track Vibration and Noise. <https://link.springer.com/article/10.1007/s12205-021-1345-6>

Lagonigro, R., Martori Joan Carles, & Apparicio Philippe. (2018). Environmental noise inequity in the city of Barcelona - ScienceDirect.

<https://www.sciencedirect.com/science/article/pii/S1361920918301597>

Maekawa, Z. (2003). Noise reduction by distance from sources of various shapes. *ScienceDirect*,

<https://www.sciencedirect.com/science/article/abs/pii/0003682X70900277>

Méline, J., Van Hulst, A., Thomas, F., Karusisi, N., & Chaix, B. (2013). Transportation noise and annoyance related to road traffic in the French RECORD study. *International Journal of Health Geographics*, 12, 44. 10.1186/1476-072X-12-44

Muralikrishna, I. V., & Manickam, V. (2017). Chapter Fifteen - Noise Pollution and Its Control. In I. V. Muralikrishna, & V. Manickam (Eds.), *Environmental Management* (pp. 399-429). Butterworth-Heinemann.

Murphy, E., & King, E. (2014). *Environmental Noise Pollution: Noise Mapping, Public Health, and Policy*

Noise Control Act of 1972, (1972). [https://ballotpedia.org/Noise\\_Control\\_Act\\_of\\_1972](https://ballotpedia.org/Noise_Control_Act_of_1972)

The Noise Insulation (Scotland) Regulations, (1975).

<https://www.legislation.gov.uk/ukSI/1975/460/contents/made>

Oertli, S., & Hübner, U. (2007). *Noise Reduction in Rail Freight*. ()

<https://uic.org/IMG/pdf/uic-fret-en.pdf>

Oguntunde, P. E., Okagbue, H. I., Oguntunde, O. A., & Odetunmibi, O. O. (2019). A Study of Noise Pollution Measurements and Possible Effects on Public Health in Ota

Metropolis, Nigeria. *Open Access Macedonian Journal of Medical Sciences*, 7(8), 1391-1395. 10.3889/oamjms.2019.234

Öhrström, & Skånberg. (2006). Effects of road traffic noise and the benefit of access to quietness - ScienceDirect.

<https://www.sciencedirect.com/science/article/abs/pii/S0022460X06000927>

Oliveira, Biondi, Reis, & Viezzer. (2021). Landscape visual and sound quality influence on noise pollution .

Passchier-Vermeer, W., & Passchier, W. (2000). Noise Exposure and Public Health.

*Environmental Health Perspectives*, 108 Suppl 1, 123-31. 10.2307/3454637

Pijanowski, B., Villanueva-Rivera, L., Dumyahn, S., Farina, A., Krause, B., Napoletano, B.,

Gage, S., & Pieretti, N. (2011). Soundscape Ecology: The Science of Sound in the Landscape. *BioScience*, 6110.1525/bio.2011.61.3.6

Pradeep Lakshmi, & Nagendra Shiva. (2024). Evaluating variations in environmental noise pollution of Chennai city using a mobile monitoring technique . *Science Direct*,

<https://www.sciencedirect.com/science/article/pii/S2214140524000021>

Renterghem, T. (2014). Guidelines for optimizing road traffic noise shielding by non-deep tree belts. *Ecological Engineering*, 69, 276-286. 10.1016/j.ecoleng.2014.04.029

*Scottish Index of Multiple Deprivation 2020*. (2020).

<https://www.gov.scot/collections/scottish-index-of-multiple-deprivation-2020/>

Stansfeld, S. A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., Haines, M.

M., Head, J., Hygge, S., van Kamp, I., & Berry, B. F. (2005). Aircraft and road traffic

noise and children's cognition and health: a cross-national study. *The Lancet*, 365(9475), 1942-1949. 10.1016/S0140-6736(05)66660-3

Stansfeld, S. A., & Matheson, M. P. (2003). Noise pollution: non-auditory effects on health. *British Medical Bulletin*, 68, 243-257. 10.1093/bmb/ldg033

the Health and Safety Executive (HSE) in the United Kingdom. (2005). The Control of Noise at Work Regulations 2005.

<https://www.legislation.gov.uk/uksi/2005/1643/introduction/made>

The Scottish Government. Designing Streets: A Policy Statement for Scotland.

<https://www.gov.scot/binaries/content/documents/govscot/publications/corporate-report/2010/03/designing-streets-policy-statement-scotland/documents/0096540-pdf/0096540-pdf/govscot%3Adocument/0096540.pdf>

TNAP. (2019). *Transportation Noise Action Plan*

Transport Scotland. (2023a). Cost Benefit of TS2010 - Examples.

<https://www.transport.gov.scot/publication/ts2010-noise-reduction-performance-review-initial-assessment/5-cost-benefit-of-ts2010-examples/>

Transport Scotland. (2023b). Transport Scotland.

<https://www.transport.gov.scot/publication/ts2010-noise-reduction-performance-review-initial-assessment/2-literature-review/>

UK Health Security Agency. (2023). *Noise pollution: mapping the health impacts of transportation noise in England*. <https://ukhsa.blog.gov.uk/2023/06/29/noise-pollution-mapping-the-health-impacts-of-transportation-noise-in-england/>

Urban cities and road traffic noise: Reduction through vegetation. (2017). *Applied Acoustics*, 120, 15-20. 10.1016/j.apacoust.2017.01.007

US Department of Transportation. (2005). *Quiet pavement systems in Europe*. ().

Weijun Yang a b, Jinying He c, Canming He c, Ming Cai a b. (2020). Evaluation of urban traffic noise pollution based on noise maps - ScienceDirect. <https://www.sciencedirect.com/science/article/pii/S1361920920307033>

WHO (1980).

Williams, G., & Short, A. (2022). Effects of noise on anxiety related to dining in restaurants. *Music and Medicine*, 1410.47513/mmd.v14i1.806

World Health Organisation. (1999). *GUIDELINES FOR COMMUNITY NOISE*

World Health Organisation. (2009). *Night noise guidelines for Europe*

*World Health Organisation* (2018).

World Health Organization. (2011). *Burden of disease from environmental noise*. ().WHO. <https://iris.who.int/handle/10665/326424>

World Health Organization. (2018). *Environmental noise guidelines for the European Region*

Xu, Han, & Wu. (2022). Assessing the Traffic Noise Reduction Effect of Roadside Green Space Using LiDAR Point Cloud Data in Shenzhen, China.

<https://www.mdpi.com/1999-4907/13/5/765>