Universidade de Aveiro Departamento de Engenharia Mecânica
2015

André Pereira de Sousa Faria

Modelação de Ruído do Tráfego Automóvel

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestrado em Engenharia Mecânica, realizada sob orientação científica de Margarida Isabel Cabrita Marques Coelho, Professora Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

O Júri

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Palavras-chave Ruído; Tráfego; Modelação; TNM; FHWA

Resumo

O ruído tem um impacto bastante elevado na saúde humana, sendo um dos grandes responsáveis por doenças cardiovasculares, perda de audição, problemas de sono, hipertensão e ainda desconforto/irritação. Este tipo de problemas leva a que sejam gastos anualmente biliões de euros, tanto na mitigação do ruído de tráfego, como na resolução dos problemas causados pelo mesmo. A elevada dependência de transportes rodoviários por parte da nossa sociedade tem levado a que a mesma esteja constantemente exposta a altos níveis de ruído. O principal objetivo desta Dissertação consiste em quantificar os níveis de ruído na principal Avenida de uma cidade de média dimensão e avaliar cenários de mitigação de ruído. Para desenvolver a modelação dos níveis de ruído recorreu-se ao software TNM (Traffic Noise Model) V25 da FHWA (Federal Highway Administration), uma referência no setor, sendo possível selecionar quais as medidas de mitigação de ruído que melhores resultados produzem. Dentro dos vários cenários de mitigação de ruído possíveis foram escolhidos 9. Nos cenários 1 e 2 alterou-se a velocidade máxima permitida de 50km/h para 30km/h e 20km/h respetivamente. No cenário 3 foi testado a alteração de pavimento, simulando 3 pavimentos diferentes: DGAC, OGAC e PCC. Durante o 4o cenário foi testada a influência de barreiras acústicas na mitigação de ruído, usando barreiras de 0.5 a 5 metros, com intervalos de altura de 0.5 metros. No quinto cenário foi introduzida uma área central composta por árvores. No sexto cenário reduziu-se o volume de tráfego automóvel mantendo o número de autocarros. No sétimo cenário testou-se a influência da remoção das interseções semaforizadas. O oitavo cenário contempla a restrição de circulação de autocarros. Já o nono cenário junta a restrição de circulação de autocarros e a remoção das interseções semaforizadas. Dentro dos cenários alternativos, apenas os cenários 4, 7, 8 e 9 apresentaram reduções de ruído significativas. No quarto cenário, aplicação de barreiras acústicas, a partir dos dois metros de altura obtiveram-se reduções de 4.8 dB(A) (-7.6%) progredindo até aos 8.26 dB(A) (-13%), para barreiras de 5 metros. No sétimo cenário, em que se retiravam as interseções semaforizadas, foi obtido um valor de redução de 5.29 dB(A) (-8.4%). No oitavo cenário, (restrição de circulação de autocarros), foi obtido um valor de 4.25 dB(A) (-6.7%) de ruído de tráfego a menos. No último cenário, em que é conjugada a restrição de circulação de autocarros e a ausência de interseções semaforizadas foi obtido o maior valor de redução, 13.26 dB(A) (-23.1%) comparativamente ao cenário base. Este cenário teria um potencial interessante de aplicação contudo carece de um estudo mais aprofundado de todas as implicações que advém do mesmo: estudo da alteração da temporização dos semáforos, implementação de rotundas e consequente distribuição de autocarros por trajetos alternativos.

Keywords Traffic Noise; TNM; FHWA

Abstract

Traffic noise has a very high impact on human health, being largely responsible for cardiovascular diseases, hearing loss, sleep problems, hypertension and even discomfort/irritation. Such problems lead to billions of euros being annually spent , either in mitigation of traffic noise or in solving the problems caused by it. The high dependency on road transport as part of our society also means that it is constantly exposed to higher noise levels. The main purpose of this Dissertation is the quantification of traffic noise levels on a main avenue of a medium-sized city and evaluate noise mitigation scenarios. To carry out this modeling, TNM software (Traffic Noise Model) V25 from FHWA (Federal Highway Administration) was used. With this work it is possible to select which noise mitigation measures that produce better results. Within the various possible noise mitigation scenarios, nine were chosen. In scenarios one and two, the speed limit changed from 50km/h to 30km/h and 20km/h respectively. In scenario three, it was tested the pavement change, simulating three different pavements: DGAC (dense-graded asphaltic concrete), PCC (Portland cement concrete) and OGAC (open-graded asphaltic concrete). During the fourth scenario the influence of acoustic barriers in noise mitigation was tested. Barriers from 0.5 to 5 meters, with height ranges from 0.5 meters were chosen. In the fifth scenario, a central area composed of trees was introduced. In the sixth scenario, the car traffic volume was reduced while maintaining the number of buses. In the seventh scenario the influence of removal of signalized intersections was tested. The eighth scenario envisages the bus restriction. In the ninth scenario the bus restriction joins the removal of signalized intersections. Within the alternative scenarios, only the forth, seventh, eighth and ninth presented significant noise reductions. On the fourth scenario, application of noise barriers, 4.8 dB(A) (-7.6%) of noise reduction was achieved (2 meter high barrier) progressing up to 8.26 dB(A) (-13%). In the seventh scenario,with the removal of traffic lights 5.29 dB(A) (-8.4%) reduction was obtained. In the eighth scenario, restriction of buses, a reduction of 4.25 dB(A) (-6.7%) was obtained. The latest scenario, bus traffic restriction and removal of signalized intersections obtained the highest reduction: 13.26 dB(A) (-23.1%). This scenario has a higher potential of application in reality but lacks further study of all the implications that come from it: study the frequency of red lights, implementation of roundabouts and subsequent distribution for alternative bus routes.

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List of Acronyms

CSV	Comma-separated values
DALY	Disability-adjusted life years
dB	Decibel
dB(A)	decibel A-weighting
DGAC	Dense-graded asphaltic concrete
DKK	Danish Krone
DRA	Assessment and Management of Environmental Noise
DXF	Drawing Exchange Format
EU	European Union
EUR	Euros
FHWA	Federal Highway Administration
GDP	Gross domestic product
LAeq	Hourly A-weighted equivalent sound level
LAeq,1h Hourly	Hourly A-weighted equivalent sound level with hourly traffic input
Ldn	Day Night Average Sound Level, where "dn" stands for day/night
Lden	Community Noise Equivalent Level (CNEL), where "den" stands for day/evening/night
Ln	Night time equivalent Sound Level
OGAC	Open-graded asphaltic concrete
PCC	Portland cement concrete
REMEL	Reference Energy Mean Emission Level
RGR	General Noise Regulation
SEK	Swedish Krona
SPL	Sound Pressure Level
TNM	Traffic Noise Model
WHO	World Health Organisation

Chapter 1

Introduction

1.1 Motivation

According to Cambridge dictionary, noise polution is defined as noise, such as that from traffic, that upsets people where they live or work and is considered to be unhealthy for them [1].

Noise is a prominent feature of the environment including noise from transport, industry and neighbours. Aircraft and road traffic noise exposure are associated with psychological symptoms but not with clinically defined psychiatric disorder. Further research is needed examining coping strategies and the possible health consequences of adaptation to noise [2].

From the engineering point-of-view, noise pollution can be divided into two types: outdoor noise and indoor noise. Whereas outdoor noise is defined as that made by transport, industrial and recreational activities [3], indoor noise can be defined as that caused by the most diverse activities in workplaces, *e.g.* from labouring machines, building activities or music performances.

The noise made by transports, can be categorized in three types: roadway noise, railway noise and aircraft noise [4]. As the name purposes roadway noise (called by some authors as simply traffic noise, and also in this Master dissertation) refers to noise made by cars, motorcycles and buses, railway noise refers to noise made by trains and aircraft noise refers to noise made by airplanes. This Master Dissertation will focus on traffic noise.

Traffic noise can be defined as the sound that is emanated from the interaction of road surface, tire, engine/transmission, aerodynamic flow, and braking elements of a road vehicle. With the evolution of the human being and technologies the use of road transportation grew deliberately as shown in figure 1.1 which presents data from European Environment Agency's (EEA) Report No 10/2012 [5]. For example, private transport is not only a need but also a facility, a pleasure and sometimes a symbol of status .

As shown in Table 1.1, Portugal is no exception in terms of the growing number of cars in the streets, so traffic noise is a problem in the urban environment.

In fact, a recent study [6] shows that Portugal is among the noisiest countries in a group of 11 countries, being traffic noise the main source of noise.

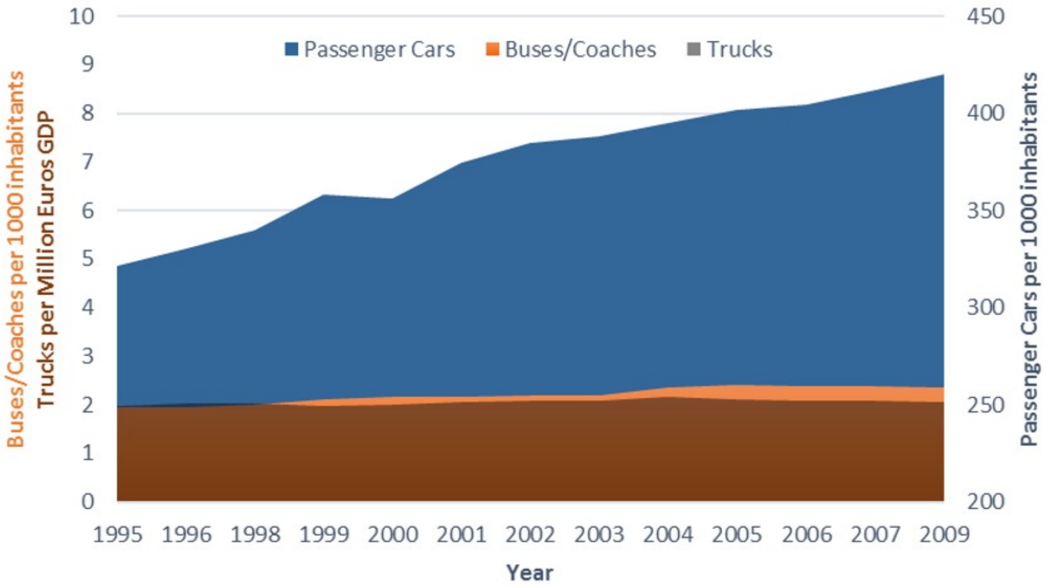


Figure 1.1: Passenger cars/buses per inhabitants and Trucks in Europe per million EUR GDP [5]

Table 1.1: Number of passenger cars per thousand inhabitants [5]

1990	1995	2000	2005	2009	2010	2012
Portugal	185	255	333	400	424	429

Until the 50's traffic noise was not widely measured, it was considered more likely a nuisance than a real problem.

Traffic noise in particular is responsible for cardiovascular diseases, cognitive impairment, tinnitus, annoyance, hearing loss and sleep disturbance [7]. Moreover it has an impact in wildlife species [8; 9].

There is also a depreciation of house and land prices in areas affected by traffic noise [10]. If these facts are relevant enough to study traffic noise and make people less exposed to it, the 40 billion EUR per year bill in Europe with traffic noise [11] makes this type of studies even more important.

Several major federal agencies in the USA, such as the Occupational Safety and Healthy Administration (OSHA) [12], the Environment Protection Agency (EPA) [13], the Federal Highway Administration (FHWA) [14] have adopted noise policies and standards to regulate noise levels. The policy guidelines are used as a basis to ensure that the broad public health and environmental objectives are met [15].

From the 1970s, successive directives have laid down specific noise emission limits for most road vehicles and for many types of outdoor equipment, but the true start of an extended knowledge based approach to the problem of noise was made by the European Commission's 1996 Green Paper on future noise policy [3].

With it a new framework for noise policy was created, which included a comprehensive set of measures to improve the accuracy and standardization of data to help improve the coherency of different actions [7]:

- Creation of a Noise Expert Network [16], whose mission is to assist the Commission in the development of its noise policy;
- EU Directive 2002/49/EC on the management of environmental noise [17];
- Follow-up and further development of existing EU legislation relating to sources of noise such as motor vehicles, aircraft and railway rolling stock, and the provision of financial support to noise-related studies and research projects.

Traffic noise is measured with suitable equipment such as noise receivers and a recording equipment. There are various ways/units of measuring traffic noise [18]

- Leq: Sound Pressure Level, equivalent to the total Sound Energy over a given period of time. Measured in decibel (dB).
- LAeq: A-weighted equivalent sound pressure level. Measured in A-weighted decibel dB(A).
- LAeq,t: A-weighted equivalent sound pressure level. Measured in dB(A).
- Ldn: A-weighted, Leq. Sound Level, measured over the 24 hour period, with a 10 dB penalty added to the levels between 23.00 and 07.00 hours. Also known as the Day-night Noise Indicator. Measured in dB(A).
- Lden: A-weighted, Leq. noise level, measured over the 24 hour period, with a 10 dB penalty added to the levels between 23.00 and 07.00 hours and a 5 dB penalty added to the levels between 19.00 and 23.00 hours to reflect people's extra sensitivity to noise during the night and the evening. Measured in dB(A).
- Ln: Night equivalent level : Leq. A-weighted, Sound Level, measured overnight 23.00 - 0700 hours.

The A-weighting filter covers the full audio range - 20 Hz to 20 kHz and the shape is similar to the response of the human ear at the lower levels [19].

Traffic noise effects on human health are so relevant that it was even created a unit to quantify the healthy years of life lost due to traffic noise. This unit, called Disability-Adjusted Life Year (DALY) can be thought of as one lost year of "healthy" life. DALYs for a disease or health condition are calculated as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) for people living with the health condition or its consequences [20].

The EU has adopted harmonized noise metrics across all of its Member States, suggesting Lden as an appropriate metric to assess annoyance and as a metric to assess sleep disturbance [17]. Noise limits are set by each EU Member State, but these metrics, available in Directive 2002/49/EC [17], are used for strategic mapping of exposure in all countries.

In Portugal the legal framework for environmental noise is the Decree-Law 9/2007 of 17th January [21], approving the General Noise Regulation (RGR) and Decree-Law No 146/2006 of 31st July [22], transposing Directive 2002/49/EC [17] on the assessment and management of environmental noise (DRA). One of the requirements of the Legislative Decree No. 9/2007 of 17th January [21] was the creation of noise maps for Portuguese cities.

Since 2007 several Portuguese cities such as Coimbra, Lisboa, Aveiro developed their noise maps to be aware of their traffic noise levels and to measure how high they are.

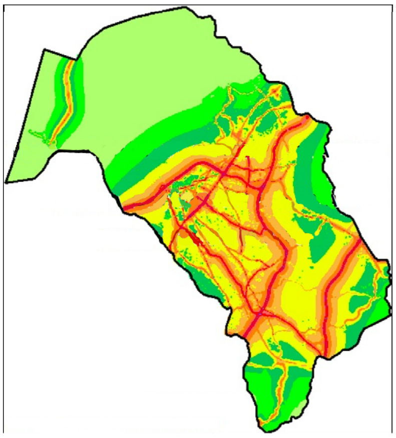


Figure 1.2: Aveiro Noise Map [25; 26]

To better understand the dimension of the traffic noise nothing better than statistics: according to a more recent study taken by the WHO (World Health Organization) [7], "20% of the population of EU countries is exposed to traffic noise levels above 65 dB(A) during the day and 30% is exposed to levels of over 55 dB(A) at night, which translates as a loss of 61,000 disability-adjusted life years(DALYs)". Seeing these numbers the WHO recognised community noise, including traffic noise, as a serious public health problem, and published guidelines on community noise in 1999 ([23]). These guidelines present noise levels above which a significant impact on human health and/or well-being is to be expected.

Years later after the WHO Guidelines [23] publishment it is still stated that traffic noise frequently exceeds the guideline values and that those exposed to them will consequently suffer an array of adverse health effects [24]. The same report [24] gives an overall summary of both statistics and health hazards caused by traffic noise 8 years later after the WHO Guidelines [23] publishment that will be quoted below:

- There is also substantial evidence for traffic noise disturbing sleep patterns,affecting cognitive functioning (especially in children) and contributing to certain cardiovascular diseases. For raised blood pressure, the evidence is increasing. For mental illness, however, the evidence is still only limited.

- The health effects of noise are not distributed uniformly across society, with vulnerable groups like children, the elderly, the sick and the poor suffering most.

- In 2000, more than 44% of the EU25 population (about 210 million people) were regularly exposed to over 55 dB of road traffic noise, a level potentially dangerous to health. In addition, 35 million people in the EU25 (about 7%) are exposed to rail traffic noise above 55 dB. EEA believes that in 2014 this number grew to 50%.

- Millions of people indeed experience health effects due to traffic noise. For example, about 57 million people are annoyed by road traffic noise, 42% of them seriously.

- A preliminary analysis shows that each year over 245,000 people in the EU25 are affected by cardiovascular diseases that can be traced to traffic noise. About 20% of these people (almost 50,000) suffered a lethal heart attack, thereby dying prematurely.

To sum up, the population increase has rised the noise level. Surveys of complaints and physical measurements, all show that traffic noise is one of the major hazards of modern life, especially in areas which are the most industrialized and urbanized.

Transportation and mobility are an important part or urban economics and the quality of life. To analyze urban transportation and its environmental impacts, a comprehensive, interdisciplinary approach is needed.

The aim of this Master Dissertation is to model the traffic noise in Dr. Lourenço Peixinho's Avenue, in Aveiro, but also to introduce alternative scenarios for traffic noise reduction. Analysing the noise maps of the city of Aveiro [25; 26] it is possible to observe that one of the streets where the measured noise exceeds by about 15dB allowed by law: Lden = 55 dB(A) and Ln = 45 dB(A) is the Dr. Lourenço Peixinho's Avenue. Being an important trade center, but also a residential area, it becomes very important to decrease the traffic noise for more healthy values.

1.2 Objectives

The main goal of this Master Dissertation is to model the traffic noise levels on a main avenue of a medium-sized city and evaluate noise mitigation scenarios.

The chosen avenue was Dr. Lourenço Peixinho's avenue due to its importance to the city of Aveiro. The software chosen was FHWA's TNM V25 [27] due to being a reference in the noise mitigation area but also because of being free to use and with good support.

According to Öhrström *et al.* [28] to protect most people (80%) from annoyance and other adverse effects, sound levels from road traffic should not exceed (LAeq,24h) 60 dB(A) at the most-exposed side. Taking as reference the 69.4 db(A) Lden measured on Dr. Lourenço Peixinho's avenue for the Noise Maps in 2008 [25], around 10 dB(A) is reduction goal to consider for this dissertation.

In order to achieve these levels, nine different scenarios were modelled, a baseline scenario which represents the avenue as it is in reality and then 9 alternative scenarios.

Scenarios one and two consist in changing the speed limit, from 50km/h to 30km/h and 20km/h respectively. In the third scenario it was tested a change of pavement, simulating three different pavements: DGAC (Dense Graded Asphalt Concrete), OGAC (Open Graded Asphalt Concrete) and PCC (Portland Cement Concrete). During the fourth scenario the influence of acoustic barriers in noise mitigation was tested. Barriers from 0.5 to 5 meters, with height ranges from 0.5 meters were chosen. In the fifth scenario it was introduced a central area composed of trees. In the sixth scenario, the car traffic volume was reduced while maintaining the number of buses. In the seventh, scenario the influence of removal of signalized intersections was tested. The eighth scenario envisages the bus restriction. In the ninth scenario the bus restriction joins the removal of signalized intersections.

Having the scenarios defined it is now possible to simulate them using FHWA's TNM V25 and suggest noise mitigation solutions for Dr. Lourenço Peixinho's avenue.

1.3 Master Dissertation Organization

The presented Dissertation is divided into five parts. In order to offer the reader a practical reading guide, in the following lines a short description of all parts and their contents is indicated.

Chapter 1 has 4 sections: Motivation, Master Dissertation Organization and Objectives. The first section begins by addressing the issue of Roadway noise, the importance of its study and the consequences of noise exposure. There is also a review of legislation in Portugal and the measures provided by the European Commission for Mobility and Transport.

The second section gives a brief guideline for the overall organization of the Dissertation and the third one talks about the main goals of this dissertation.

Chapter 2 sets out the literature review undertaken as part of this dissertation, which serves mainly to cover the research studies within the modelling of traffic noise, specially using the TNM V25. [27].

The third chapter presents the Methodology and Methods used, the steps taken and the problems that occurred in order to achieve the objectives.

The first section, Case Study, presents all the relevant data regarding Dr. Lourenço Peixinho's Avenue. The second section, Simulation, presents the used software and all data input in TNM. In the fourth chapter the results achieved are presented and discussed. In the fifth and latest chapter, conclusions are expressed and the ideas for future work are given.

Chapter 2

Literature Review

Hellbruck *et al.* said that "Noise is defined as a sound which is perceived as a nuisance and detrimental to well-being, performance and health as well as the social coexistence of humans and beyond that it may also have socio-economic adverse effects" [29; 30].

These effects created the necessity of developing noise mitigation means. Although hard studied before implemented, noise mitigation means were tested in two ways: on laboratory or by trial and error, this made noise mitigation even more expensive as it can be seen on figure 2.1.

In order to optimize and reduce the cost of this noise mitigation, noise modelling tools were developed.

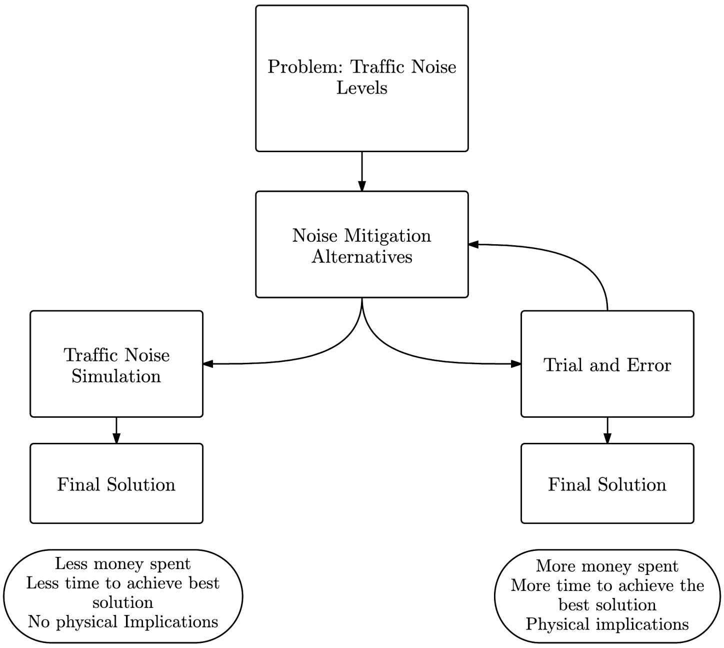


Figure 2.1: Traffic Noise Model vs Trial and Error Method

2.1 Noise Impacts

Öhrström *et al.* demonstrated that the access to quiet indoor and outdoor sections of one's dwelling supports health producing a lower degree and extent of annoyance and disturbed daytime relaxation, improving sleep and contributing to physiological and psychological well being [28].

In terms of numbers, the same paper [28] states that reducing 5 dB(A) (LAeq,24h) at the most-exposed side of a dwelling reduces disturbances by an average of 30-50%. In order to protect most people (80%) from annoyance and other adverse effects, traffic noise levels should not exceed (LAeq,24h) 60 dB(A) at the most-exposed side of a dwelling, even if there is access to a quiet side of a dwelling (LAeq,24h 45 dB(A)).

Exploring in depth this subject, we can still find evidence in the most recent articles of the health impact of the noise such as:

- purely negative emotional annoyance [30]
- consciously perceived impairment of work efficiency and communication [30]
- sleep disturbance [30]
- endocrine effects (release of stress hormones)[30]
- cardiovascular diseases such as hypertension and ischemic heart disease [30]
- morning tiredness,headaches and milder psychological conditions [31]
- prevalence of common mental disorder [31]
- Tinnitus: Tinnitus is defined by WHO [7] as the sensation of sound in the absence of an external sound source. It is caused by excessive noise exposure. In some people, tinnitus can cause sleep disturbance, cognitive effects, anxiety, psychological distress, depression, communication problems, frustration, irritability, tension, inability to work, reduced efficiency and restricted participation in social life.

Frei *et al.* [32] found that the effects of nocturnal traffic noise on objective sleep quality are independent of perceived noise annoyance, but the association between self-reported sleep quality and noise is through noise annoyance.

In the report "Noise in Europe 2014" EEA [33] ends concluding:

- noise pollution is a major environmental health problem in Europe;
- road traffic is the most dominant source of environmental noise with an estimated 125 million people affected by noise levels greater than 55 dB Lden (Day-Evening-Night Sound Level);
- environmental noise causes at least 10 000 cases of premature death in Europe each year;
- almost 20 million adults are annoyed and further 8 million suffer sleep disturbance due to environmental noise;
- over 900 000 cases of hypertension are caused by environmental noise each year;

- noise pollution causes 43 000 hospital admissions in Europe per year;

As WHO states [7], there is sufficient evidence from large-scale epidemiological studies linking the population's exposure to environmental noise (where traffic noise takes great part) with adverse health effects, so environmental noise should be considered not only as a cause of nuisance but also as a concern for public health and environmental health. Even with large evidence of traffic noise on human health, very recently Halonen *et al.* [34] decided to examine the effects of long-term exposure to road traffic noise on hospital admissions and mortality in London's population, concluding that long-term exposure to road traffic noise was associated with small increased risks of all-cause mortality and cardiovascular mortality and morbidity in London's population, particularly for stroke in the elderly.

Roadways and their noise do not only affect the humans surrounding them but also the biodiversity surrounding it [9; 35]. The noise maps of Europe reveal levels of noise such as 55 dB Lden are consuming more and more territorial area outside of urban areas threatening valuable habitats and species that are particularly susceptible to noise [33].

Whether in land or sea, many species rely on acoustic communication for important aspects of life, such as finding food or locating a mate [7]. This year Marcin Polak et al [8] stated that roads carrying heavy traffic can modify the distribution and species diversity to a significant extent. Their study [8] also indicates that noise levels above 49 dB significantly influence the number of birds and species diversity and that the number of individuals per point and species richness was lower near the road.It was also found that road noise can change key survival behaviours of prey species[9] breaking food chains.

As it is widely known wild life is of an extreme importance not only to maintain ecological balance and the food chain but also nature cycles. Thus the impact of traffic noise in wild life is another reason to reduce it to safer levels.

The scenario of noise mitigation is so critical that Milford *et al.* [36] stated that within 20 years, the cost of reducing noise annoyance by one will vary from 15 to 1800 EUR per year, depending on the measure.

Back in 1996 the European Commission presented within its Green Paper [3] an estimation of an annual economic damage to the EU due to environmental noise from 13 million to 30 billion Euro. This estimation considered elements such as: reduction of house prices, reduced possibilities of land use, increased medical costs and the cost of lost productivity in workplaces due to illness caused by the effects of noise pollution.

In their 2011 report [37], the value grew to EUR 40 billion per year, of which 90 % was related to passenger cars and goods vehicles. With the influence of the traffic noise on people's life it was detected that people are willing to pay for noise reduction [38] near their homes.

As an example, traffic noise cost in Sweden is estimated as being over 16 billion SEK [39] and in Switzerland 1.21 billion EUR [40]. In Denmark it is estimated that there are several hundred premature deaths each year due to road traffic noise. Solving this problem, mitigating the noise in places with noise levels above 68 dB can deliver an overall socio-economic gain of DKK 12.7 billion over a 20-year period, equivalent to 958 million DKK per year [33].

With the higher traffic noise near lands it was also noted that the price of those units exposed to noise were decreasing their prices at a rate of 1.3% per 1% increase in traffic noise [10]. The same behaviour was observed for house market values and rents which tend to lower when located at noisier locations [41].

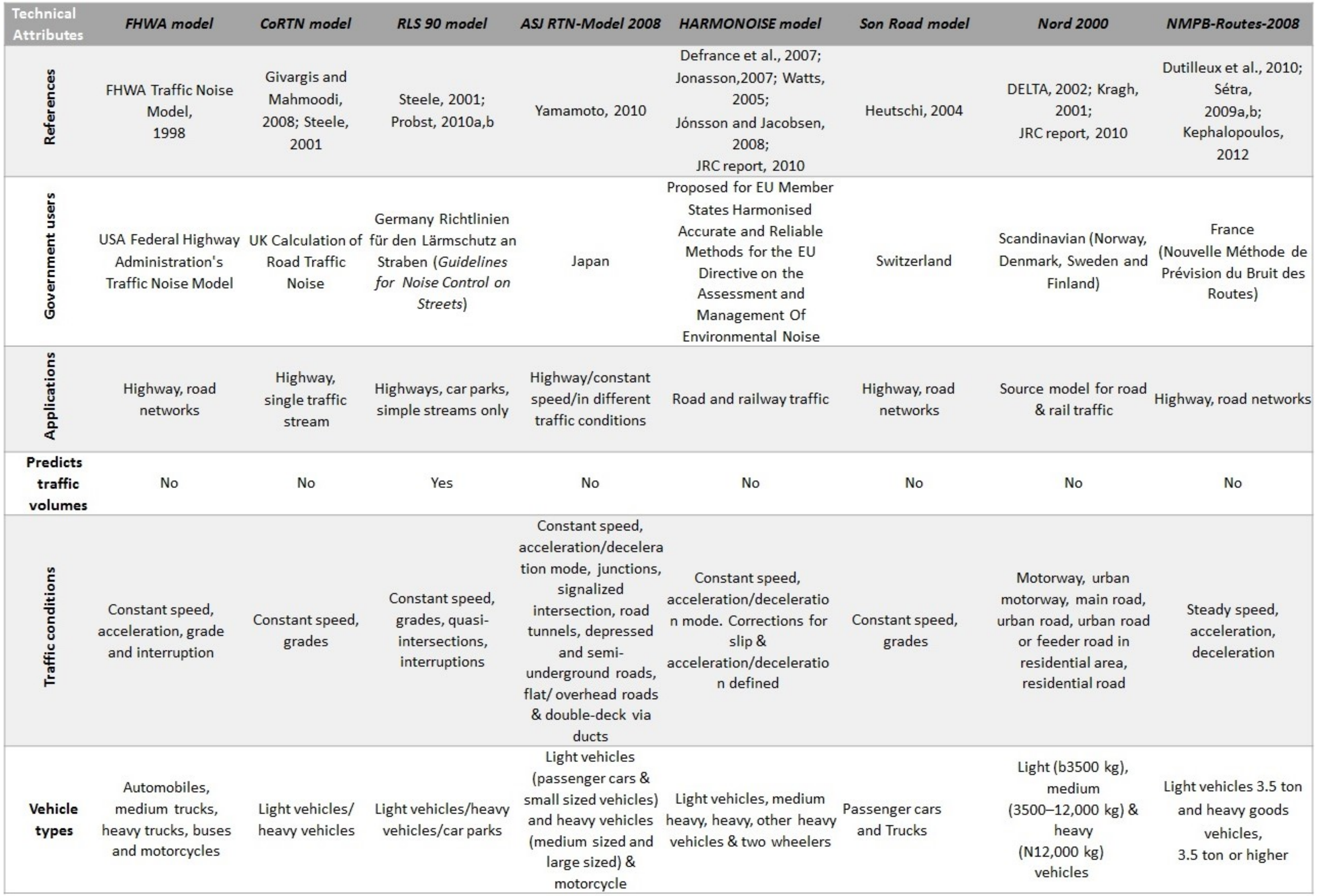
2.2 Traffic Noise Models

Noise prediction is one of the vital tools for town planners for noise abatement and control [42]. European Directive about Environmental Noise 2002/49/EC gives the impetus to many of scientific models developed in recent years. All the models have been developed and validated in respective countries and brought in regular usage for generating noise maps. In order to be aware of the limitations and other possibilities, in this section a comparison of models are adressed, formelly developed by Steele *et al.*[43] and recently updated by the work of Garg *et al.* [42] was taken into account.

Garg *et al.* made an exaustive list of the models used by high speed processing computers and skilled operators for noise modeling, putting emphasis in their comparison in order to ascertain their suitability in general and also to find out the best approach amongst them for traffic noise modelling. The various models discussed in Garg's paper [42] are: FHWA TNM of USA, ASJ RTN 2008 of Japan, CoRTN of UK, RLS 90 of Germany, Son Road of Switzerland, Harmonoise of Europe, Nord 2000 of Scandinavian countries and NMPB-Routes-2008 of France.

The exhaustive review of the principal traffic noise models shows that early used empirical models have been replaced by most real models based on scientific principles as seen in figure 2.2 and in Appendix.

The concept of an *ideal model* proposed by Steele in 2001 [43] is beeing replaced quickly by a set of recent models covering each of the technical attributes exclusively. However, the application of these models widely is still uncertain as source model is best suited for that particular country only. The described models evidentiate the need of harmonized approach to be followed in for sound propagation modelling. According to Garg *et al.* [42], CNOSSOS-EU model utilizing NMPB-Routes-2008 algorithms can be one solution for such problem. Several commercial software packages are available for traffic noise predictions like CadnaA (Datakustik, Germany); Sound Plan (U.K.); IMMI (Wolfel);Mithra-SIG (CSTB); NovaPoint (Vianova Systems); and Predictor-LIMA (BK, Denmark).



Technical Attributes	FHWA model	CoRTN model	RLS 90 model	ASJ RTN-Model 2008	HARMONOISE model	Son Road model	Nord 2000	NMPB-Routes-2008
References	FHWA Traffic Noise Model, 1998	Givargis and Mahmoodi, 2008; Steele, 2001	Steele, 2001; Probst, 2010a,b	Yamamoto, 2010	Defrance et al., 2007; Jonasson,2007; Watts, 2005; Jónsson and Jacobsen, 2008; JRC report, 2010	Heutschi, 2004	DELTA, 2002; Kragh, 2001; JRC report, 2010	Dutilleux et al., 2010; Sétra, 2009a,b; Kephalopoulos, 2012
Government users	USA Federal Highway Administration's Traffic Noise Model	UK Calculation of Road Traffic Noise	Germany Richtlinien für den Lärmschutz an Straben (*Guidelines for Noise Control on Streets*)	Japan	Proposed for EU Member States Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management Of Environmental Noise	Switzerland	Scandinavian (Norway, Denmark, Sweden and Finland)	France (Nouvelle Méthode de Prévision du Bruit des Routes)
Applications	Highway, road networks	Highway, single traffic stream	Highways, car parks, simple streams only	Highway/constant speed/in different traffic conditions	Road and railway traffic	Highway, road networks	Source model for road & rail traffic	Highway, road networks
Predicts traffic volumes	No	No	Yes	No	No	No	No	No
Traffic conditions	Constant speed, acceleration, grade and interruption	Constant speed, grades	Constant speed, grades, quasi-intersections, interruptions	Constant speed, acceleration/deceleration mode, junctions, signalized intersection, road tunnels, depressed and semi-underground roads, flat/ overhead roads & double-deck via ducts	Constant speed, acceleration/deceleration mode. Corrections for slip & acceleration/deceleration defined	Constant speed, grades	Motorway, urban motorway, main road, urban road, urban road or feeder road in residential area, residential road	Steady speed, acceleration, deceleration
Vehicle types	Automobiles, medium trucks, heavy trucks, buses and motorcycles	Light vehicles/ heavy vehicles	Light vehicles/heavy vehicles/car parks	Light vehicles (passenger cars & small sized vehicles) and heavy vehicles (medium sized and large sized) & motorcycle	Light vehicles, medium heavy, heavy, other heavy vehicles & two wheelers	Passenger cars and Trucks	Light (b3500 kg), medium (3500–12,000 kg) & heavy (N12,000 kg) vehicles	Light vehicles 3.5 ton and heavy goods vehicles, 3.5 ton or higher

Figure 2.2: Summary of the comparison of the Trafic Noise Models made by Garg *et al.*[42]

It is important to note that the comparisons made here do not intend to choose the perfect traffic noise model, but to enlight the users of the pros and cons of each model and decide which one suits best the situation analysis. The models presented highlight some of the TNM sofware constraints, however, for academic purpose it was chosen TNM V25 due to being one of older and still maintained traffic noise models, and also being used by the USA Federal Highway Administration. As this USA governmental institute uses this sofware as a standard tool for noise modelling, we think that it can be used for academic research in general and particularly in the scope of the work developed here.

2.3 Mitigation Alternatives

This section is written both as complement for the measures that will be taken in the methodology but also as an addition of possible solutions for noise mitigation that although cannot be computed using TNM, can be implemented in reality and help solving an existent problem. Solutions will be exposed and then criticized about whether it would be viable for our scenario or not.

Milford *et al.* stated that handling noise at source is the most cost effective approach to reduce noise annoyance, and specially to address the vehicle noise [36], meaning that the key source of traffic noise comes from the tyre interaction with the road surface [33].

The author goes beyond and compares various noise reduction alternatives: on the vehicle, on the road surfaces, in facades and with noise barriers stating that the most effective is reducing the noise on the vehicle, followed by the improvement of road surfaces (8 times more than the first option) followed by facade insulation (in form of windows upgrade it cost 2 times more than the previous option) being the most costly the noise barriers (which can be distinct from facade insulation due to noise reduction in the outdoor areas).

Giving this statement it is secure to say that the most productive action on road traffic noise reduction is to lower vehicle noise emission limits, but only if it is based upon an appropriate test methodology, and even then, it may take many years before it is represented in the european vehicle fleet [33]. In terms of tyre legislation there are already requirements for labelling tyres [33], but most drivers are not sensitized for choosing low noise tyres, and even if they would like to choose, it may be difficult to find the right low-noise tyre for his/her car.

To change this scenario a new project [44] of a multimedia awareness campaign together with an user-friendly tyre database was created in Switzerland.

Ho *et al.* [45] also shown that the effect of mechanical tyre wear on noise is small while the ageing effect can increase noise by 67dB.

Going from tyres to pavements, there are some alternative solutions more focused on noise reduction:

- High Viscosity Asphalt Rubber Binder: classified as a laid porous pavement capable of 35 dB(A) noise reduction compared to non-porous pavement [46]. In addition there other improvements such as: water drainage, reduction in light reflection and headlight glare, skid resistance and vehicle-rolling resistance is reduced. These improvements increase road safety. A negative point is that porous pavements tend to clog easily and thus sound attenuation reduces overtime [47]. Luoung *et al.* [48]

tested this type of pavement and concluded that the use of a high viscosity asphalt rubber binder does not influence on acoustic absorption as foreseen.

- Arizona Asphaltic Rubberized Friction Course pavement: Kim *et al.* [49] tested this type of pavement and got an average of 2dB(A) noise reduction on unmitigated noise levels .
- Asphalt mixtures with crumb rubber: Paje *et al.* [50] characterized the acoustical behavior of bituminous mixtures fabricated with recycled rubber crumb and managed to reduce the noise from the tire/pavement interaction up to 2 dB(A).

Still on the pavement side, during years it was thought that the speed bumps related with speed decrease would diminish the traffic noise due to consequent speed decrease. Behzad *et al.* [51] tested numerically and experimentally different dimensions of bumps and different speeds of vehicle and proved the opposite, being the speed bumps responsible for noise increases from 1 to 19dB.

Going from the pavement to green mitigation methods there are three types of methods: trees (trees, folliage, bushes, etc), green roofs [52] and green walls [53]. From the beginning trees were thought to be noise mitigation "devices", but how many or how much would be sufficient for notorious noise reduction? Reynolds *et al.* [54] concluded that in order to attenuate unwanted noise, it is needed a zone of at least 20 meters wide and consisting of trees, ground foliage and bushes. It was also found that limiting the spacing in between trees and increasing the trunk diameter favours noise reduction [55]. In Nature there is randomness in the trees position and their trunk diameter, this randomness was also found to be positive for noise reduction [55].

From trees to green walls, Azkorra *et al.* [53] concluded that this coating provides not only energy savings, biodiversity support, storm-water control, but also noise attenuation for buildings. During the laboratory tests a weighted sound reduction index (Rw) of 15 dB was achieved.

Upping from walls to roofs, Renterghem *et al.* [56] found that their shape is important, being responsible for differences in road traffic noise shielding exceeding 10 dB(A). The flat roof proved to be the best shielding type, but since there are saddle back roof types there is also a way to improve their noise shielding, using green roofs with good results [52].

To end this section it is important to say that although all these measures are very cost efficient, in some cases, the cost is not the priority, but the final noise attenuation. In order to have a global idea of noise reduction provided by some methods, it is relevant to quote some conclusions of Louen *et al.* in "Analysis of the Effectiveness of Different Noise Reducing Measures Based on Individual Perception in Germany" [30]:

- Noise reductions of Less than 3 dB(A) are not perceived by humans.
- Double wall windows can be a noise mitigation device for inside building scenarios. It was found that their reduction is always more than 2 dB(A).
- Noise Barriers dependent a lot on size, type, material, etc. but they are capable of big noise reductions.
- High grass can be a noise mitigation device. In some scenarios of this cited article 2 dB(A) of noise reduction was achieved.

Being this Master Dissertation a work with the objective to model the traffic noise on an Avenue of Aveiro, but also to find alternative noise mitigation scenarios for it, this literature review provided a solid base for it. It was covered motivational information such as: traffic noise impact on human health, impact on people's work, impact on land (both nature and prices) and also all the money spent on solving all traffic noise caused problems but also traffic noise mitigation alternatives, from the more known, such as noise barriers, pavement change, but also implementation of green zones, change of tyres to more noise efficient ones, windows upgrade etc. All covered topics had their place in the choice of alternative traffic noise mitigation scenarios simulated in this Master Dissertation.

2.4 Noise Barriers

Noise Barriers are external sources designed to reduce noise pollution. They can have different height, different widths, materials and even shapes.

As told in the section above Noise Barriers are the most efficient Noise Mitigation devices [30].

According to FHWA [14] noise barriers can achieve 5 dB noise level reduction when they are tall enough to break the line-of-sight from the highway to the receiver and after they break the line-of-sight, 1.5 dB of additional noise level reduction for each meter of barrier height can be achieved.

Another critical noise barrier characteristic is its material/coating which is of two types:

- Reflective
- Absorptive

Most common building materials such as wood, metal and masonry have hard surfaces and so they reflect noise. These are considered reflective barriers.

Although cheaper, easy to get and easier to build, when sound strikes the surface of this type of barrier, some energy is transmitted through the wall but the bulk is reflected back as exemplified in figure 2.3.

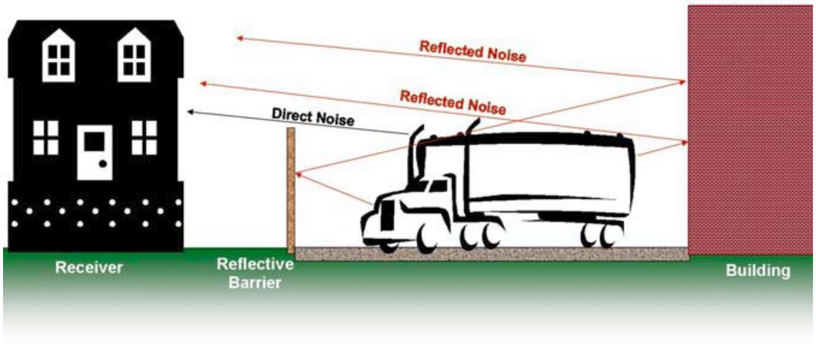


Figure 2.3: Reflective Noise Barrier Example[57]

To avoid this phenomenon Absorptive Noise Barriers were created. These barriers are either coated with absorptive materials or entirely made as "sandwich" of various materials as exemplified in Figure 2.5.

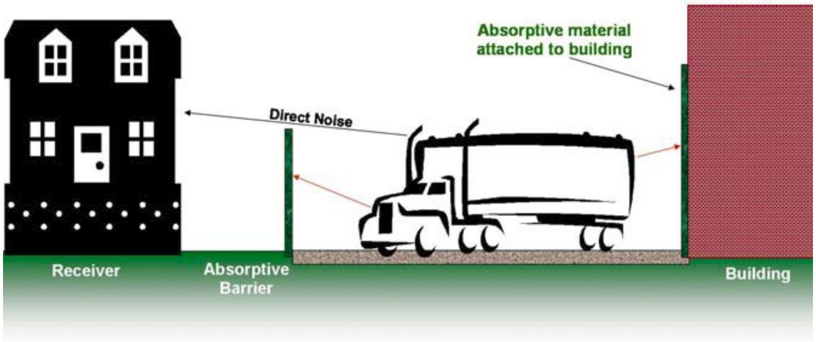


Figure 2.4: Absorptive Noise Barrier Example [57]

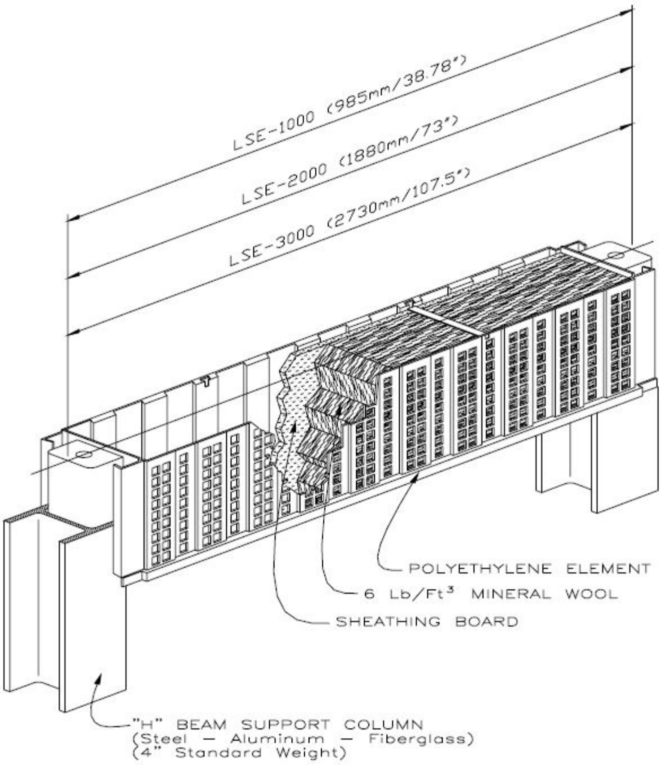


Figure 2.5: Absorptive Noise Barrier Construction [57]

With all this information, applying Noise Barriers may seem like an impossible task, with many variables, but it is safe to say that up to 10 dB of noise reduction is fairly straightforward to obtain with simple barriers. Within a range of 15-17 dB is practical to obtain, but more than 20 dB of reduction is difficult to obtain, and more than 25 dB is impossible to obtain [57].

Chapter 3

Methodology and Methods

The methodology followed in this Master Dissertation is shown in figure 3.1 and described below.

Task 1 Literature Review

- Literature review on traffic noise, traffic noise modelling and noise mitigation methods. We made a comparative analisys of the different traffic noise modelling software and comparison with the FHWA TNM software. Installation and preliminary modelation of some examples of the literature using the FHWA TNM software.

Task 2 Traffic Noise Modelling

- Modelling of baseline scenario using FHWA's TNM V25, replicating Dr. Lourenço Peixinho's Avenue. First we drew a real model of the Avenue regarding the shape, traffic flow values and signalized intersections found in the documentation available.

Task 3 Establish and simulate alternative scenarios

- With the information gathered in literature review, nine alternative scenarios were defined. It was implemented each particular condition using the FHWA's TNM V25 in software and gather all the data produced with the software for the next task.

Task 4 Analysis of Results

- In the end of the simulation of the alternative scenarios, all results were gathered from previous simulations, evaluating the noise mitigation efficiency of each measure simulated. Additional tests to be made in future works were deliniated and the limitations of the simulated results discussed.

Task 5 Writing of Dissertation

- The dissertation writing is finished using the simulation results. The comparative analysis of the different tested scenarios was compared and the conclusions outlined.

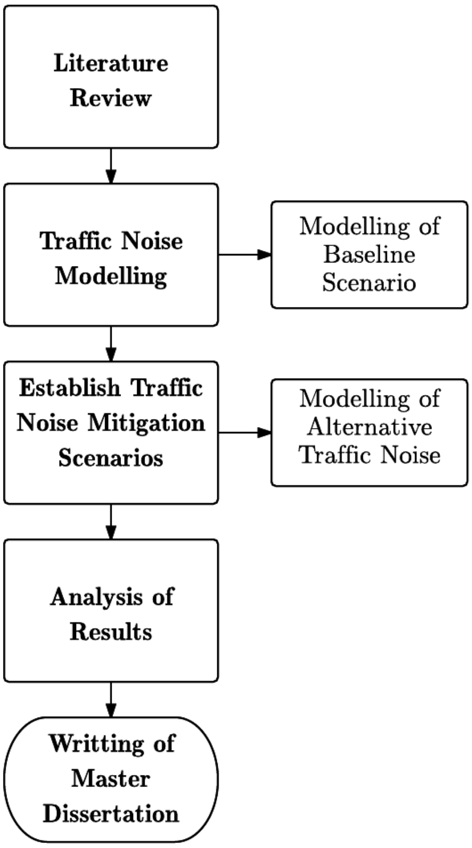


Figure 3.1: Master Dissertation Workflow

3.1 Case of Study

Dr. Lourenço Peixinho's Avenue was selected as case study because it is an important trade center, a residential area but also a citizen space. Also typical cross section of the avenue are shown in the figure 3.2.

The city hall has an intervention plan for the Avenue called "The Future of Dr. Lourenço Peixinho's Avenue". This intervention plan gathers different types of solutions, from restricting the traffic completely from the avenue, to an overall reconstruction that permits both traffic and pedestrians and new parking places.

Since this intervention is in a long way to take place, it was decided to make the life of pedestrians, and those who live or have business there, a little better and arrange solutions to lower the traffic noise.

In order to meet this goal, the software TNM V2.5 from FHWA will be used, testing a range solutions which vary from noise barriers, to pavement change and lower speed limits.

After having the scenarios defined, the modelling process can be initiated, starting with drawing in the software the street model, defining pavement, placing noise receivers, traffic flow devices and inserting data values such as traffic flow (vehicles per hour and their speed). After all parameters verified the simulation can begin, resulting in a table with traffic noise values measured for each receiver. Although the simulation is saved in two files, one .dat and other .idx, the results shown in the tables can be exported to Microsoft Excel spreadsheets being easy to work with.

For each alternative scenario, a new file is generated, starting from the base scenario, changing the needed parameters.

In the end of the simulations all results were exported to a spreadsheet in order to be compared and so that conclusions can be made.

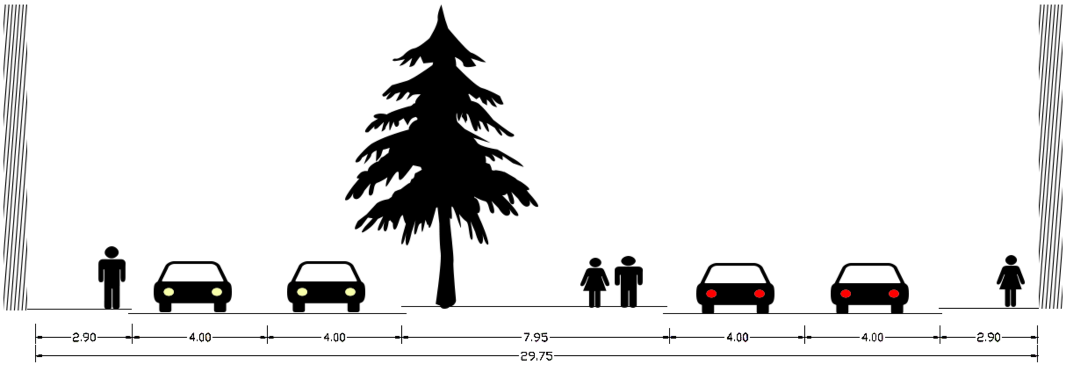


Figure 3.2: Dr. Lourenço's Peixinho's Avenue

3.2 Methods

The purpose of this study was to model the roadway noise in the Dr. Lourenço Peixinho's Avenue using the Traffic Noise Model V25 developed by the Federal Highway Administration [27; 58; 59; 60] which is considered a reference. Among the several qualities that can be given to FHWA's TNM V25, there are some features/functions that are very important to enlight:

- Having available several standard vehicles types such as automobiles, medium trucks, heavy truck, buses and motorcyces but also the possibility of having user-defined vehicles [60];
- Enable to model both constant (non-interrupted) and interruped flow using a 1994/1995 field measured database, including the effects of the pavement type, graded roadways and the attenuation over/through rows of buildings and dense vegetation[60];
- Compute sound level based on a one-third octave-band data base and algorithms[60];
- Allows to have design and optimization of noise barriers [60];
- Allows multiple diffraction and parallel barrier analysis [60].

Since TNM V25 was released in 2004, the setup where it ran is also an important input, allowing future users to run it without problems.

Unfortunately TNM V25 did not run in Windows 8.1 64bit. The solution found was running it virtualized using Oracle's VM Virtualbox. More details about the hardware and software configuration are given in Appendix.

According to the TNM V1.0 User Manual [58] there is a general workflow to be followed which adapted to the needs of this Master Dissertation and reproduced in the figure 3.2. This workflow was followed and to have a more precise idea of the work done steps and choices are documented in the subsection Setup Inputs.

To have a more global idea of FHWA's TNM Inputs and Outputs, the most relevant ones are presented in the table 3.1 and fully explained in the next section.

TMN Input Name	**Data**	**Output**
Roadways	Coordinates (X,Y,Z)	Traffic Noise Level dB(A)
	Width	
	Pavement Type	
	LAeq1h: Veh/hr and their speed (km/h)	
	Flow Control Devices	
Receivers	Coordinates (X,Y,Z)	
	Height above the ground	
	Dwelling Units	
	Levels Criteria	
Barriers	Coordinates (X,Y,Z)	
	Height, Min. Height, Max. Height, Perturbations	
	Costs	
	Noise Reflection Coefficient	
Building Rows	Coordinates (X,Y,Z)	
	Average Height	
	Building Percentage	
Terrain Lines	Coordinates (X,Y,Z)	
Ground Zones	Coordinates (X,Y,Z)	
	Type of Pavement	
Tree Zones	Coordinates (X,Y,Z)	
	Average Height	

Table 3.1: TMN Inputs and Outputs

3.2.1 Setup Inputs

The first step is defining the general inputs available in "General Input" menu: Units: Metric

Type: LAeq,1h (The data available was in this format)

Relative Humidity (%): 85

Temp (deg C): 15

Default Ground Type: Pavement. There are 8 possible choices: Pavement, Water, Hard Soil, Loose Soil, Field Grass, Granular Snow, Powder Snow, this was the one that corresponded to reality. It is worth mentioning that according to [61] "In general, a ground zone must cover about 20% of the source-receiver distance to have more than 1 dB effect".

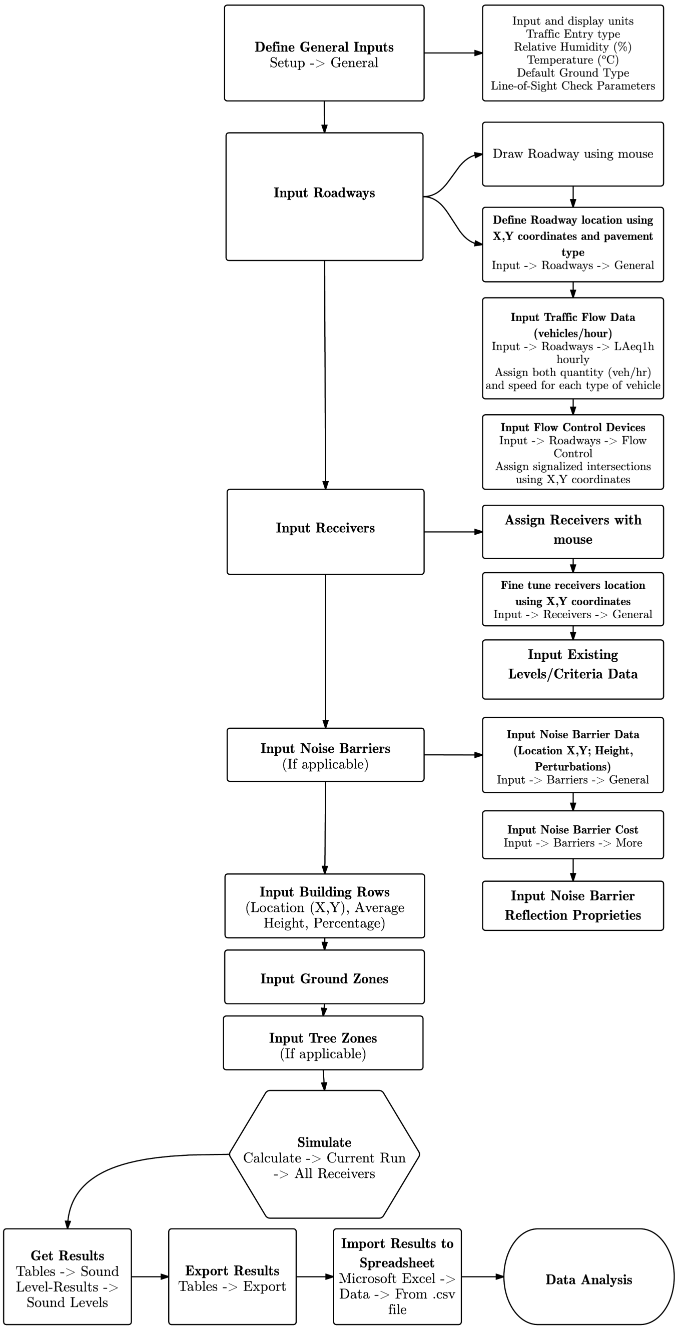


Figure 3.3: TNM Workflow

Line-of-Sight Check:

According to TNM Manual [58] this function allows to determine if selected barrier(s) break the lines-of-sight from vehicles on nearby roadways to the selected receivers.

Subsource Height (m): 3.50 (default), it is the height of the source you will be checking line-of-sight to, e.g., exhaust stacks for heavy trucks.

Distance Limit: 150.00 (default), it is the maximum distance between receiver, and sub source height for the path to be included in the line-of-sight check.

3.2.2 Map Leading Procedures

In order to have the street input on TNM V25 there were three options:

- Have access to a Street Plan and a Digitizer
- Have access to a digital Street Plan and import it as a DXF File
- Draw the street plan with the graphical tools of TNM V25

Since there was no access to a Digitizer, the DXF importation feature was chosen, but due to all compability problems and the final DXF not being with correct proportions it was agreed to simplify the model to basic lines that would match the dimensions of the Avenue, and its spacings. With the model finished it was possible to proceed to the next step.

3.2.3 Roadways Input

In this subsection all inputs related to roadways are going to be described. Each step represents the sections available in each menu of the program.

As almost every object in TNM, roadways are defined by points with X, Y and Z coordinates. These coordinates can be either input manually in order to draw lines or assigned visually. As it was said above the Avenue Model was drawn manually, so every point has already its coordinates. Only the missing inputs were assigned for each coordinate.

Step 2: Input - Roadways - General

Pavement type: TNM V25 has the following options: Average (DGAC+PCC combined), DGAC (dense-graded asphaltic concrete), PCC (Portland cement concrete) and OGAC (open-graded asphaltic concrete). In Dr. Lourenço Peixinho's avenue there are two types of pavement: granite cubic pavement and DGAC (dense-graded asphaltic concrete). Since granite cubic pavement is not available and DGAC is only in small quantities in the avenue, the pavement assumed as Average. The average pavement type consists of Reference Energy Mean Emission Level (REMEL) data measured on Dense-graded asphalt pavement (DGAC) and Portland Cement Concrete (PCC) pavements combined [62; 63].

Width: 8.00m

Step 2.1: Input - Roadways - LAeq,1h Hourly

This subsection relates to the traffic flow. For this Master Dissertation it was considered both light vehicles (Auto in TNM) and Buses. Light vehicle volumes and average speeds were extracted from a previous study in the University of Aveiro [64]. Bus data was taken from the timetables of two companies that run in Aveiro and average speed of buses was taken from activity indicator of one of the major bus operator in Portugal [65]. The complete data is shown in table 3.2.

In this table, for certain roadways, there are more buses than automobiles, this is due to the data sources. For automobiles the data was taken from a previous work and adapted to TNM roadways, as for the buses it was gathered from the companies that operate in Aveiro, and this value was considered the same for every roadway. As said

Table 3.2: Roadway Input data

Roadway	Veh/hr	Speed of Automobiles (km/h)	Buses	Speed of Bus (km/h)
1	350	35.78	25	14.6
2	35	35.54	25	14.6
3	297	17.41	25	14.6
4	297	17.41	25	14.6
5	130	34.99	25	14.6
6	217	47.32	25	14.6
7	150	48.00	25	14.6
8	86	39.42	25	14.6
9	2	17.76	25	14.6
10	2	17.38	25	14.6
11	2	42.67	25	14.6
12	2	9.00	25	14.6
13	2	17.38	25	14.6
14	265	26.45	25	14.6
15	270	26.44	25	14.6
16	265	26.44	25	14.6
17	275	26.44	25	14.6
18	206	20.4	25	14.6
19	215	20.4	25	14.6
20	20	18.00	0	0
24	40	35.07	0	0
25	10	15.35	0	0
26	33	34.03	0	0
27	2	17.03	0	0
28	10	18.00	0	0
29	15	20.45	0	0
30	50	30.04	0	0
31	40	25.00	0	0

before, two of the nine alternative scnearios are done without buses in order to better understand their influence on traffic noise and traffic noise mitigation.

Step 2.2: Input - Roadways - Flow Control

In this subsection flow control devices such as stops, signals, onramps and tolls are inserted.

For Dr. Lourenço Peixinho's avenue there is only one type of flow control device, the traffic signals. Each traffic signal was assigned to its matching point in the roadway.

3.2.4 Receivers Input

Step 3: Input - Receivers - General

In this step the receivers and their characteristics were included, according to their coordinates (X, Y, Z). The receivers have Y coordinates of 15.8, 0 and -15.8 and variable X coordinates till the end of the avenue. Still, there are two different inputs that are needed to assign:

Dwelling Units: 1 (default) Number of dwelling units represented by each receiver.

Height Above the Ground (m): 1.5 (default) - receiver's ear height.

Step 3.1: Input - Receivers - Levels/Criteria

In this menu important data related to the noise is input:

Existing Level (db(A)): 69.4. This is a base level or a measured noise level that can be input so it is possible to compare the computed results with the real ones. The value input was taken from noise maps of Aveiro City for the Avenue. It is necessary to keep in mind that when analysing the results that the scenario of the noise maps considers every type of vehicle and is done for Lden not LAeq,1h so there will be variations.

Noise Reduction Goal (dB(A)): 10 dB(A). As the name suggests, this is the reduction goal express in dB(A). According to Öhrström et al. [28], to protect most people (80%) from annoyance and other adverse effects, sound levels from road traffic should not exceed (LAeq,24h) 60 dB(A) at the most-exposed side. Taking as reference the 69.4 db(A) Lden measured for the Noise Maps in 2008, 10 dB(A) is the expected reduction (on the safe side).

Impact Criteria Level (dB(A)): 66 (default)
This can be explained as the value which causes interferences in speech interference and other matters non dependent upon existing noise levels. No change was made to the default value.

Substantial Increase (dB(A)): 10.00 (default) This is a criteria for judgement of relative noise impact. In its results table, TNM tallies a receiver as "impacted, substantial increase," if its calculated sound level minus its existing level is greater than this criteria [58].

Step 3.2: Input - Receivers - Adj. Factors

No adjusting factors were considered.

Step 4: Input - Barriers - General

Barrier Type: Wall. TNM V25 has two options: Wall or Berms, due to the physical aspects of this street, the berm is not applicable.

Height (m): regarding the scenario that was tested, the height of the barrier was written here, or else it was left at zero.

Perturbation Increment (m): 0 The segment's perturbation increment, up and down from the input heights of its two end points.

Perturbation Up: 0 (Default) Number of perturbation up. Perturbation Up is the height increment that a noise barrier's input height is increased during the barrier design process [66].

Perturbation Down: 0 (Default) Number of perturbations down. Perturbation Down is the height increment that a noise barrier's input height is decreased during the barrier design process.

Min. Height (m): regarding the scenario that was tested the height of the barrier was written here, if not it was left at zero.

Max. height (m): regarding the scenario that was tested the height of the barrier was written here, if not it was left at zero.

Since the barrier design used was simple, mainly due to the geography of the street (flat terrain) the height, minimum height and maximum height are the same.

Step 4.1: Input - Barriers - More

In this section, TNM gives the user the option to compute the cost of the barrier solution by inputting two values:

1)Cost per square meter of the barrier

2)Additional cost - for example, costs of the barrier's engineering design, clearing and grubbing, and landscaping [58].

For the first one the values supplied in the article "The true cost of road traffic noise in Portugal" [67] was considered. In this article three options are given, shown in Table 3.2.4. Due to the type of street, the acrylic is the best option because it gives the possibility for people to look through it, not penalizing the stores in terms of view and solar light. Also acrylic noise barriers can be decorated to make them more attractive. An example of clear acrylic noise barriers is given of figure 3.2.4.

Table 3.3: Materials for Noise Barriers and their price

Type	Price/m$\hat{2}$
Leca Block wall with absorption (Leca Mursom)	70-80
Metallic with absorption	120-140
Acrylic	140-150

Figure 3.4: Plastral Clear Noise Barrier [68]

Step 4.2: Input - Barriers - Structure

This part is for barriers built on an elevated structure, which does not apply to the case study.

Step 4.3: Input - Barriers - Reflections

In this section it is possible to introduce the Noise Reduction Coefficients for both right and left side of the barrier. According to TNM V1.0 Manual [58]: Each barrier has a left and right side, depending upon the direction you input it. As you walk along the barrier in the direction of input, the left side of the barrier is to your left, the right side to your right. In every simulation the NRC value used was 0.23.

Step 4.4: Input - Barriers - Notes

This section is used to take notes of particular characteristics of barriers or their points/segments. It was not used in the simulations done.

Step 5: Input - Building Rows

According to TNM V1.0 Manual [58] these rows are long rows of buildings, with gaps, that intervene between roadways and receivers, like barriers, to reduce sound levels.

However, unlike barriers a portion of the sound energy penetrates through building-row gaps, so they are less effective than comparable-height barriers. Note that height and percentage of building rows cannot be varied from segment to segment. If these two parameters change substantially, you must end one TNM building row and begin another. You do not have to be overly precise in these two parameters. Plus or minus 2m is precise enough for average height, as long as most buildings are within a storey of one another. For building percentage, it is not necessary that building spacing is highly regular.

In order to simplify the simulation, an average height was calculated for the street using the following method: for each floor of building a 3m height was assumed, the floors of the buildings for each side were counted. A median height was calculated for each side and the average of both was calculated. An average height of 11.25m was achieved.

About building percentage, due to the nature of this avenue it was easy to say that it would be close to 100% but as said in TMN V10 Manual [58], the maximum that can be applied is 80% (TNM developers say that 100% is equal to a barrier).

Similar to section 5.3 the building row input menu has a section for taking notes, in this case it was not used.

Step 6: Input - Terrain Lines

According to the TNM V1.0 Manual [58]: TNM terrain lines define where the terrain is located, both horizontally and vertically. Due to the nature of the avenue analysed, this feature will not be used.

Step 7: Input - Ground Zones

According to the TNM V10 Manual [58] TNM ground zones define the type of intervening ground wherever the ground differs the chosen default ground type. Considering the nature of this avenue where "after" the road the only ground type we have are the sidewalks (made with granite cubic pavement, 2.90m wide) followed by the building rows. The ground zone type that better suits this scenario is "Pavement". In the zones that are not defined, TNM automatically sets the ground type to the default. As in other input categories also in Ground Zones input menu there is a place for notes, which again was not used.

Step 8: Input - Tree Zones

According to TNM V10 Manual [58]: TNM tree zones consist of long, wide regions of heavy woods and undergrowth that intervene between roadways and receivers. The trees and undergrowth should obstruct vision of the traffic.

As told before in the avenue analysed there is only a row of trees which do not fit in this description. To not leave this subject limited by the TNM Manual, further investigation was made about the influence of trees in the noise mitigation. Reynolds et al. [54] concluded that if trees and bushes are used to attenuate unwanted noise, the buffer zone that is composed of them should be at least 20 meters wide and should consist of trees, ground foliage and bushes. That is definitely not the case of the Dr. Lourenço Peixinho's avenue, so the existing trees were not input in the baseline simulation.

3.3 Scenarios

In order to give an overall idea of which parameters were changed (compared to the baseline scenario) a small summary will be shown below:

- Scenario 1: which consists on changing the speed limit from 50 to 30km/h, basically all data entered in step2.1 was changed. Speed Values were multiplied by a factor of 0.6.

- Scenario 2: which consists on changing the speed limit from 50 to 20km/h, basically all data entered in step2.1 was changed. Speed Values were multiplied by a factor of 0.4.

- Scenario 3: consists in testing three different pavements: DGAC, OGAC and PCC. The baseline scenario has "Average" as pavement, this type of pavement consists of data for DGAC and PCC combined, and according to TNM Manual [58] should be used in nearly all situations. In order to simulate a diferent pavement, the type of pavement, as shown in step 2 should be changed to the one that is wanted to test.

- Scenario 4: consists on simulating the influence of acoustic barriers in noise mitigation. In order to do so, in step 4, on the field Height it is needed to input the desire barrier height. For this scenario values from 0.5m to 5m, with 0.5m intervals were chosen.

- Scenario 5: a central area composed of trees is inserted. In order to do it, the central ground zones were deleted and replaced by tree zones of the same size. The tree height considered was 3m.

- Scenario 6: reduction of traffic volume, leaving bus volume intact. To do this, in step 2.1 all "auto" values (veh/hr) were reduced in 10%, 20%, 30%, 40% and 50%. Speed values remained untouched.

- Scenario 7: signalized intersections removed. As told in section step 2.2 signalized intersections were input. For this scenario they were removed.

- Scenario 8: restriction of bus circulation. For this scenario, auto values remained intact (compared to the baseline scenario), but buses were removed in the section described in step 2.1.

- Scenario 9: restriction of bus circulation and semofarized intersections removed. Basically reproducing the steps taken in scenarios 7 and 8.

Finishing the insertion of all inputs for each scenario the simulation can start. All inputs are checked by TNM and then the simulation begins. After finished, the results are obtained through the Tables menu (Sound-Level Results, Sound Levels).

A complete report with noise values for each receiver is given. In order to analyse this data it is exported to Comma-separated values (CSV) Microsoft Excel files.

Unfortunately it is impossible to calibrate this simulations because the values of traffic noise supplied by the traffic noise maps, are not made with the traffic volumes that was used in this work. The main aim of this simulations is to discover what scenarios influence more the traffic noise.

Chapter 4

Results and Discussion

In this chapter the simulation results from baseline scenario and alternative scenarios will be exposed, discussed and compared with the former one. In a total 10 simulations of trafic noise, they all were made using TNM software. The simulated mitigation alternatives are described as follows:

- Alternative Scenario 1: Maximum Speed Change: 30 km/h
- Alternative Scenario 2: Maximum Speed Change: 20 km/h
- Alternative Scenario 3: Pavement Change
- Alternative Scenario 4: Noise Barriers Implementation
- Alternative Scenario 5: Tree Zone Implementation
- Alternative Scenario 6: Traffic Reduction while maintaining Buses circulation
- Alternative Scenario 7: Absence of signalized intersections
- Alternative Scenario 8: Restriction of buses circulation
- Alternative Scenario 9: Absence of signalized intersections + Restriction of bus circulation

4.1 Baseline Scenario

Here is represented the baseline simulation, as mentioned before, this simulation represents the avenue as it is in reality, with "average" pavement, signalized intersections and traffic flow data without any changes.

There are three "lines" of noise receivers,as stated in the fourth step of the previous chapter, one at Y=15.8m (corresponding to left sidewalk of the avenue), other at Y=0 (corresponding to the center of the avenue) and other at Y=-15.8 (corresponding to the right sidewalk of the avenue). The overall plan of the avenue can be seen in the figure 4.1.

After modelling and simulating, an average traffic noise value of 63.24 dB(A). Comparing with the value reported in the 2008 report [25], 69.4 dB(A) it is 8,87% lower. This can be justified by the different data, in the noise maps [25; 26] it was measured both in Lden and Ln, where in the simulations made the data contains only vehicles per hour LAeq,1h (measured in one hour).

An interesting analysis is the one seen in figure 4.2 where it is possible to see the traffic noise distribution along the avenue. It is clear that the traffic noise achieves higher values in the center of the avenue, affecting pedrestians that walk on the center sidewalk. During the simulations of alternative scenarios it was observed that this patern is common to all scenarios.

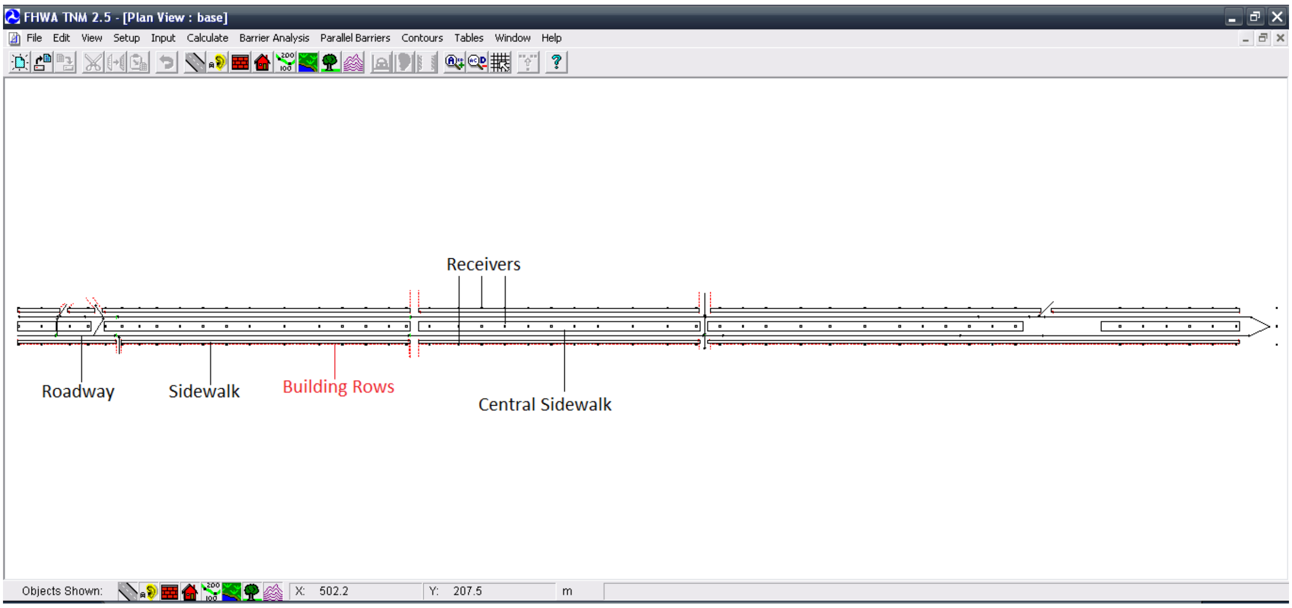


Figure 4.1: Baseline Scenario TMN Plan View

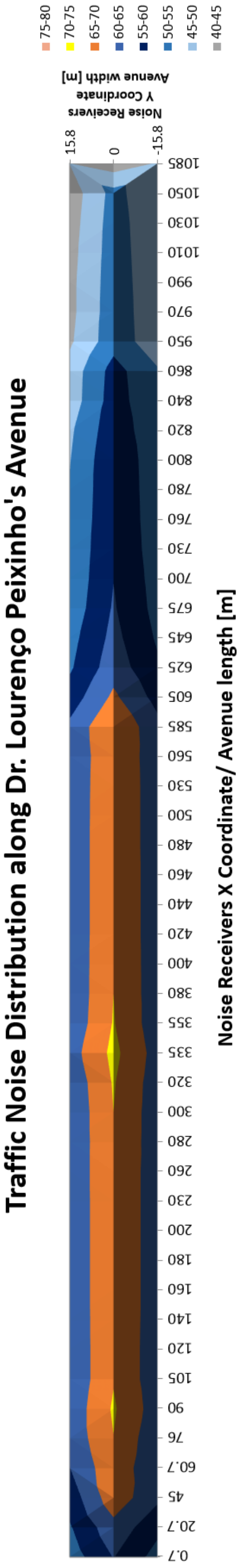


Figure 4.2: Baseline Scenario Traffic Noise Distribution

4.2 Alternative Scenario 1: Maximum Speed Change to 30 km/h

In Dr. Lourenço Peixinho's Avenue, the maximum speed is 50km/h. In this scenario it was tested the effect of reducing it to 30km/h. In the simulation, reducing the maximum speed to 30km/h made the traffic noise increase almost 1.76 dB(A) (+2.78%) as it can be seen in figure 4.3. This result was not expected. The empirical formulation used in TNM to compute A-weighted emissions in 1/3rd octave band in terms of speed Si in km/h is [42]

$$E_A(S_i) = (0,6214 * S_i)^{A/10} * 10^{B/10} + 10^{C/10} \tag{4.1}$$

As can be seen, reducing speed should reduce the traffic noise. This simulation was sent to FHWA TNM team to investigate and nothing wrong was found, although it was said that the overall traffic noise should increase. This simulation was repeated several times in different computers with different operative systems to ensure nothing was causing problems, but the overall result was always the same.

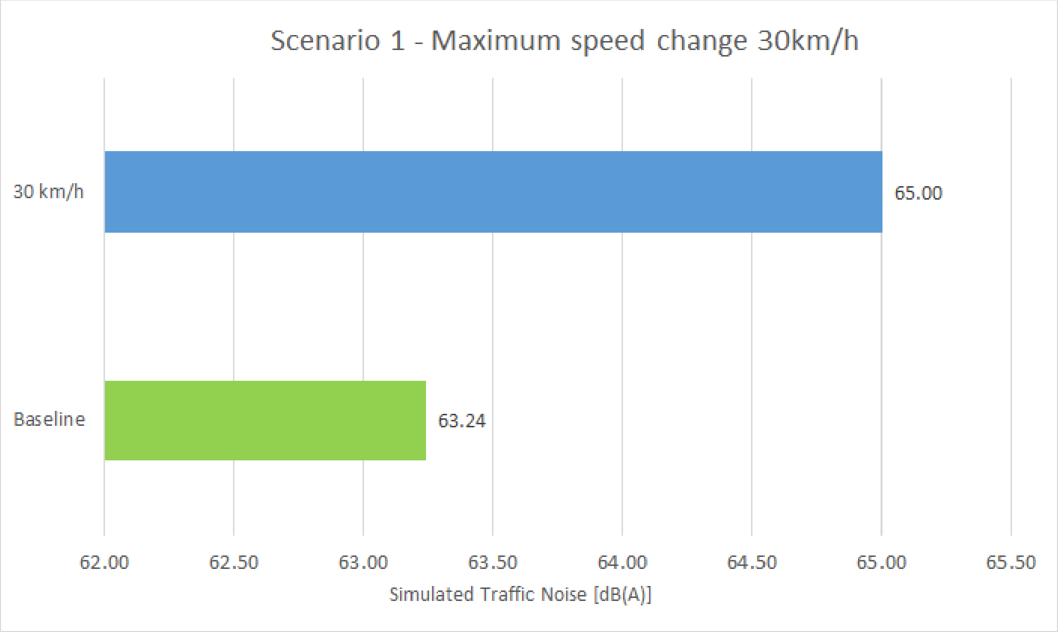


Figure 4.3: Alternative Scenario 1 Simulated Traffic Noise compared to Baseline Scenario

4.3 Alternative Scenario 2: Maximum Speed Change to 20 km/h

Since the result with maximum speed of 30 km/h was not satisfactory it was decided to create an alternative scenario with even lower maximum speed: 20 km/h. Unfortunately the result was even worse, with this scenario producing more 3.46 dB(A) (+5,47%) compared to the baseline scenario as can be seen in 4.4. Again the simulation was made from scratch, all values input again, but the result remained the same.

Again, this alternative scenario was sent to TNM support team. Their answer was that there are some very specific cases where increasing speed could reduce levels (e.g. cases where frequency shifts make barriers more effective), but these are very rare and definitely not the case of the ones sent. The team suggested to remake the database files and simulations in another computer, but unfortunately that did not solve the problem, achieving always the same results.

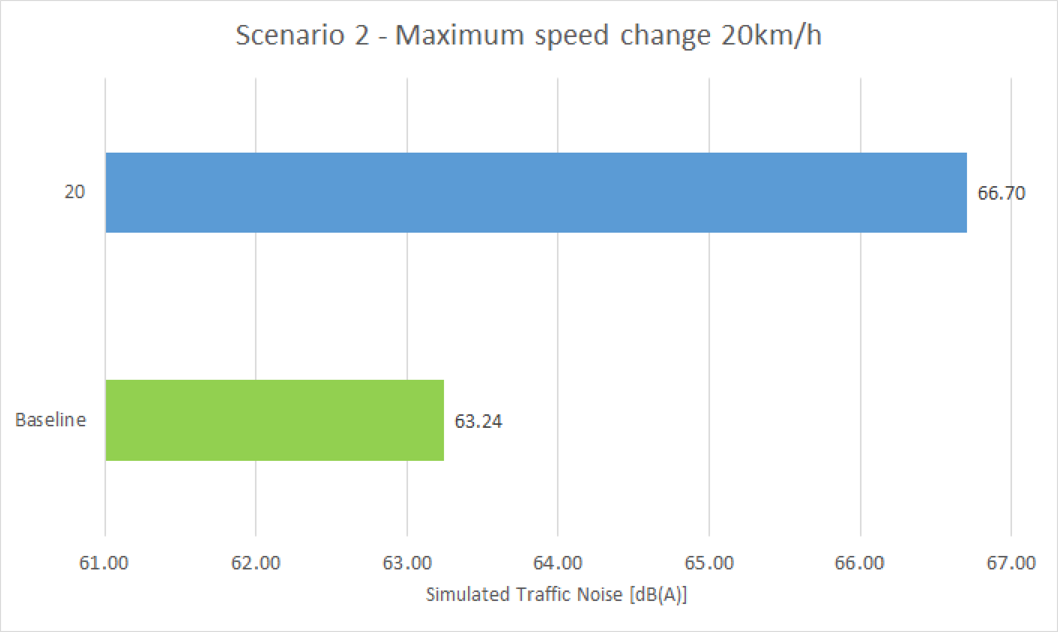


Figure 4.4: Alternative Scenario 2 Simulated Traffic Noise compared to Baseline Scenario

4.4 Alternative Scenario 3: Pavement Change

In the third scenario different pavements were tested and compared against the "average" pavement used in the baseline scenario. Unfortunatelly none of the three pavements revealed to be a good noise mitigation alternative for Dr. Lourenço Peixinho's Avenue. Both OGAC and PCC showed no improvement at all compared to the "Average" pavement, and DGAC even increased average traffic noise values by 0.01 dB(A).

According to FHWA, pavement changes do not give linear results: in some situations both DGAC and OGAC give traffic noise reductions compared to the "Average" pavement and PCC give higher traffic noise values compared to the "Average" pavement, but in others do not.

This results may be also justified by the lower traffic noise volumes of this simulations.

4.5 Alternative Scenario 4: Noise Barriers Implementation

Noise barriers are considered one of the most efficient traffic noise mitigation options. In this Master Dissertation a range of noise barriers from 0.5m to 5m, with 0.5m interval were tested. Barriers with more than 2.5-3m, in this avenue are not feasible, it would destroy the harmony of the avenue, although it was considered important to test these values as an academic exercise.

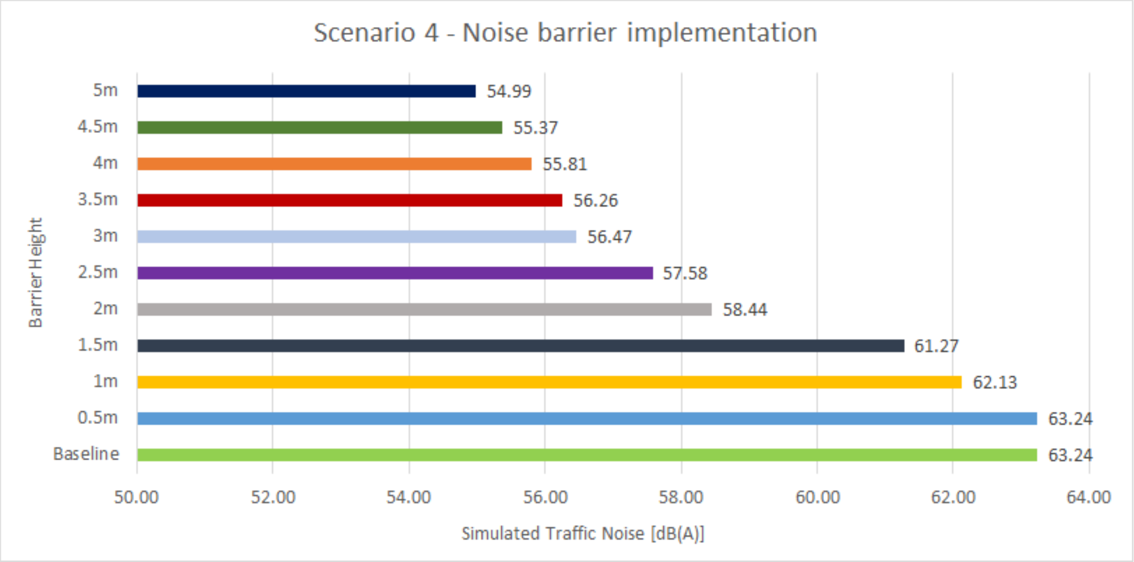


Figure 4.5: Alternative Scenario 4 Simulated Traffic Noise compared to Baseline Scenario

To better understand the traffic noise reduction relationship with the noise barrier height all heights and respective traffic noise reductions are expressed in the table 4.1.

Barrier Height (m)	Traffic Noise Reduction (dB(A))	Reduction (%)
0.5	0	0
1	-1.12	-1,8
1.5	-1.97	-3,2
2	-4.8	-7,6
2.5	-5.66	-8.9
3	-6.78	-10.7
3.5	-6.98	-11.0
4	-7.44	-11.8
4.5	-7.87	-12.4
5	-8.26	-13.1

Table 4.1: Noise barrier height and respective noise reduction compared to the baseline scenario

4.6 Alternative Scenario 5: Tree Zone Implementation

Although the literature says that less than 20m wide tree zone would not have impact on noise reduction [54], it was decided to test what would be the impact of a tree zone in the center sidewalk of avenue. The overall plan of this scenario can be seen in the figure 4.6.

As can be seen in the figure 4.7, the reduction was 0.69 dB(A) which is insignificant.

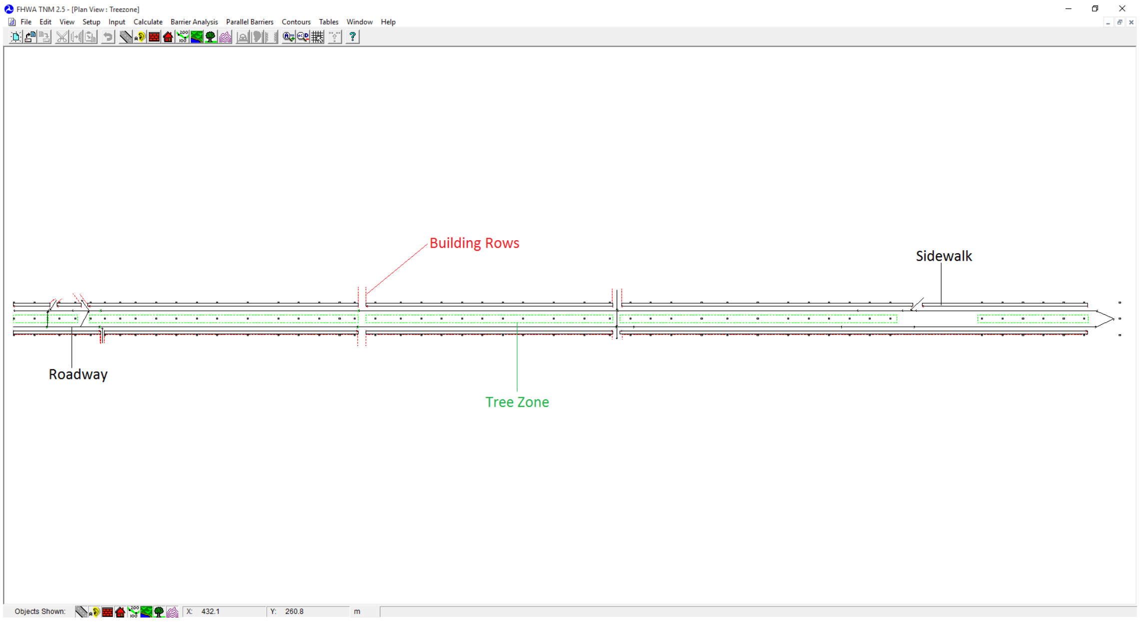


Figure 4.6: Alternative Scenario 5 TMN Plan View

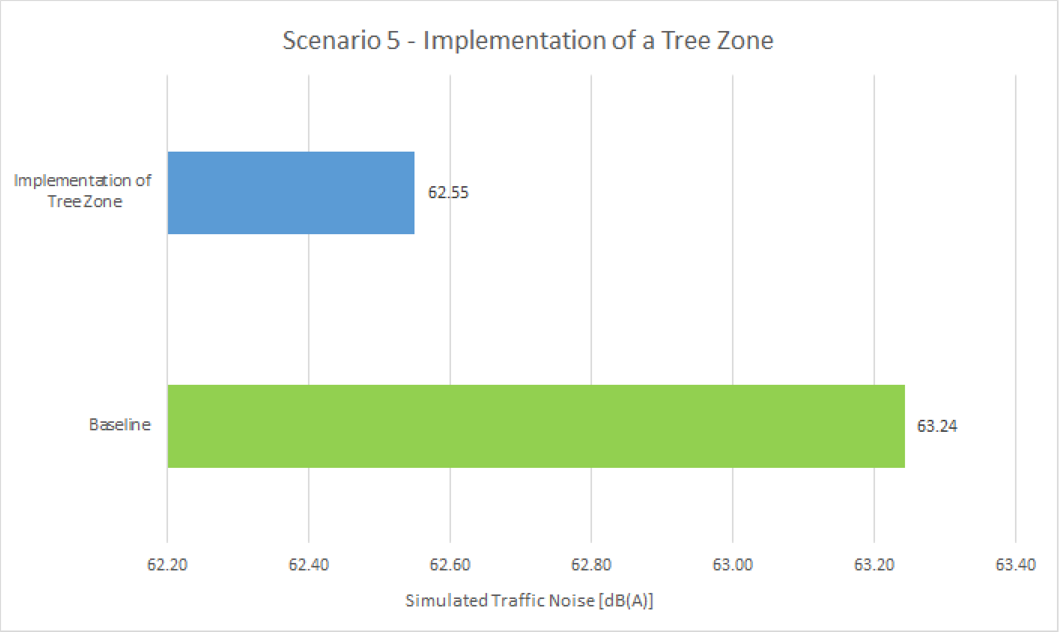


Figure 4.7: Alternative Scenario 5 Simulated Traffic Noise compared to Baseline Scenario

4.7 Alternative Scenario 6: Road Traffic Reduction

For the sixth alternative scenario, traffic reduction was tested, while maitaining buses circulation. Different reduction percentages were tested: 10%, 20%, 30%, 40% and 50%.

Results can be seen both on figure 4.8 and overall reductions on table 4.2.

Table 4.2: Traffic reduction relationship with traffic noise

Traffic Reduction (%)	Traffic Noise Reduction (dB(A))	Traffic Noise Reduction (%)
10%	-0.20	-0.3%
20%	-0.40	-0.6%
30%	-0.63	-1.0%
40%	-0.86	-1.3%
50%	-1.12	-1.8%

The global traffic noise reduction are very low (from 0.3% to 1.8%) and only a result of 50% would have some noticeable reduction, and still that would be very low (1.8% reduction, equivalent to 1.1 dB(A)).

Although all results in this Master Dissertation are in form of average value from all traffic noise receivers, in this scenario, all receivers were analysed individually and compared to the baseline values (of the same receiver) to ensure that, for example, there was reduction in some areas of the avenue but they were being masked by areas were the reduction was not achieved. All receivers showed similar reduction to the average values.

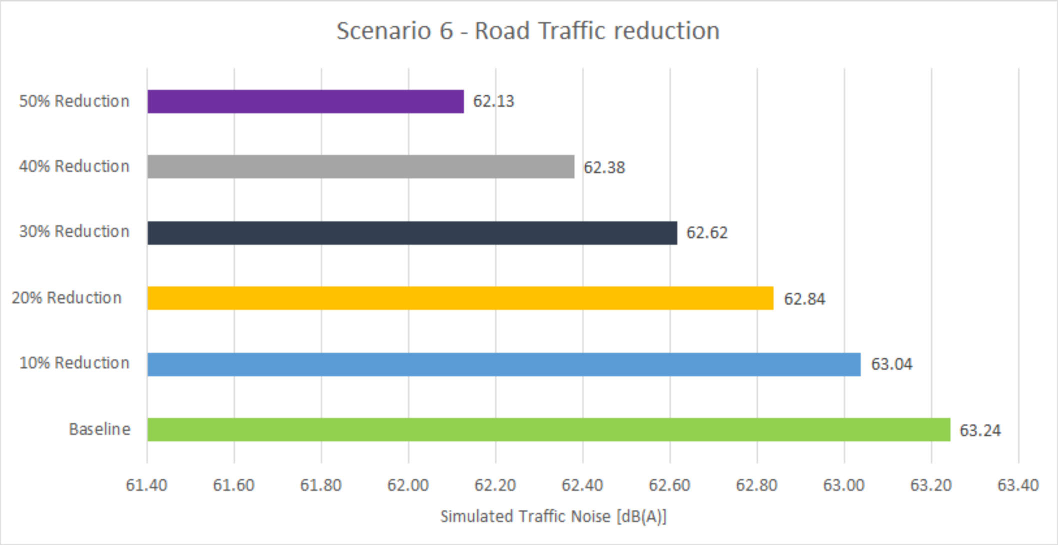


Figure 4.8: Alternative Scenario 6 Simulated Traffic Noise compared to Baseline Scenario

4.8 Alternative Scenario 7: Absence of signalized intersections

For the seventh scenario it was proposed to test the absence of signalized intersections. This scenario revealed a reduction in traffic noise of 5.29 dB(A) (-8.37%) as it can be seen in figure 4.9, which can be due to a better traffic flow. This results shows that not only signalized intersections are very important, and so their frequency should be optimized for a better traffic flow, but also that every device or situation that will harm traffic flow will increase the traffic noise levels.

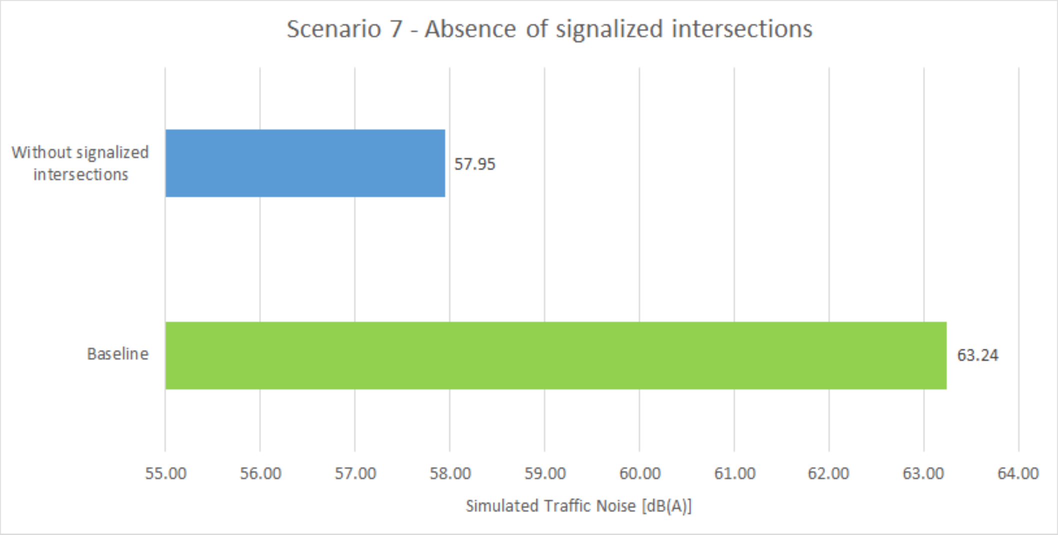


Figure 4.9: Alternative Scenario 7 Simulated Traffic Noise compared to Baseline Scenario

4.9 Alternative Scenario 8: Restriction of bus circulation

In the eighth scenario it was decided to test the influence of buses circulation in the traffic noise values. An overall good reduction of 4.25 dB(A) (-6.71%) of traffic noise reduction was achieved as can be seen in figure 4.10.

This simulation was made in order to show what is the influence of buses in traffic noise. In reality it is impossible to end the circulation of buses in the avenue, but their routes could be optimized so traffic noise would not be concentrated in the avenue.

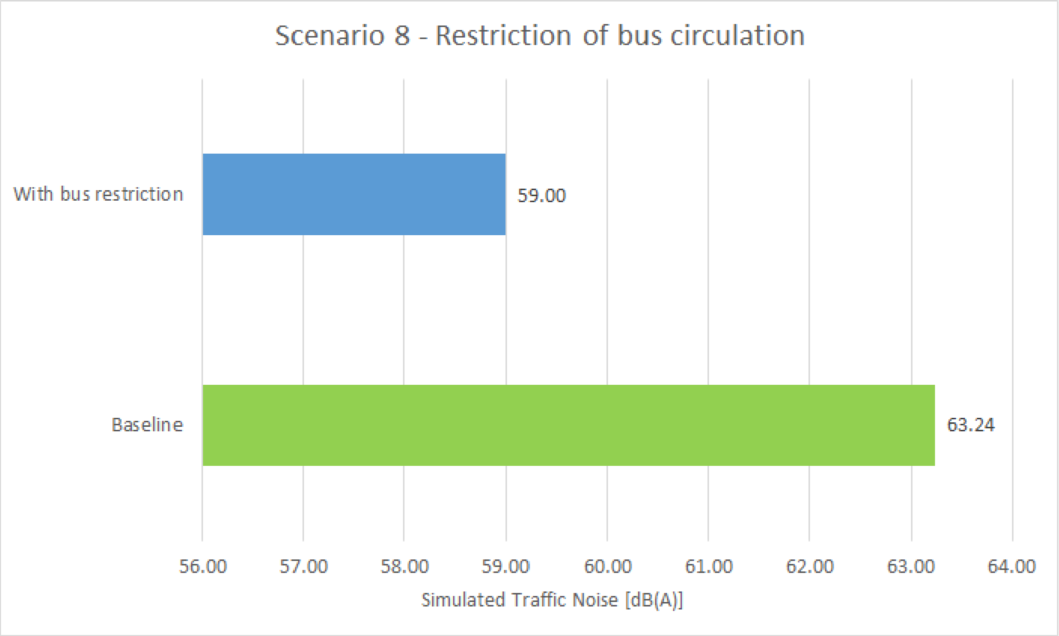


Figure 4.10: Alternative Scenario 8 Simulated Traffic Noise compared to Baseline Scenario

4.10 Alternative Scenario 9: Absence of signalized intersections + Restriction of bus circulation

The ninth scenario was created by joining two of the best scenarios: absence of signalized intersections and restriction of bus circulation. This scenario revealed to be the best of the 9 scenarios, with a very high traffic noise reduction of 13.26 dB(A) (-23,10%) as can be seen in figure 4.11, surpassing the objective of 10 dB.

Figure 4.11: Alternative Scenario 9 Simulated Traffic Noise compared to Baseline Scenario

Chapter 5

Conclusions and future work

Traffic noise is the sound that results from the interaction of road surface, tire, engine/transmission, aerodynamic flow, and braking elements of a road vehicle. With the evolution of the human being and technologies the use of road transportation is continuouslly increasing. It is becoming a major issue to study different strategies to mitigate the trafic noise on nowadays cities.

An intensive literature review was made, pointing to problems caused by road traffic noise such as cardiovascular diseases, hearing loss, sleep disturbance and their cost, but also the solutions available. In this dissertation the FWHA TNM 2.5 software was used to model the noise reduction potential of different aproaches in a real scenario. This Dissertation was the starting point of Traffic Noise in Mechanical Engineering Department of University of Aveiro, and also the first one using TNM V25. The study of the different approaches was organized using different scenarios that allowed to draw some conclusions and give suggestions for future works.

Regarding the simulated results, noise reductions up to 23% were observed. Out of the tested scenarios, the one that produces higher noise reduction (from 63.24 dB to 49.99 dB, 23%) is the scenario that combines the absence of signalized intersections with the restriction of bus circulation in the Avenue. However, some interesting conclusions can be taken from the other simulated scenarios.

First, in accordance to the literature results, it was demonstrated that noise barriers are one of the methods that allow noise reduction values by worthy values, ranging from 1-13% when the barrier heights goes from 0.5 to 5 meters. Another interesting conclusion was the influence of buses in traffic noise, being responsible for 7% of the traffic noise in the avenue: 4.25 dB(A) of noise reduction in the scenario without buses, compared to the baseline scenario. This means that it is important to keep the bus fleet as silent as possible: using newer low-noise tyres, newer buses with newer and more silent engines and more efficient noise isolation.

By the simulations, it was also possible to conclude that the absence of signalized intersections achieved respectful noise reduction values. However this scenario can raise other problems of traffic management, such as weaker traffic performance and a higher probability of road craches, that lie outside of the scope of this work.

A further analysis of the simulated noise maps allowed us to identify the most sensitive points in terms of noise, being the center of the avenue, where pedestrians usually walk. Unfortunately there is no simple solution to overcome this limitation. A deep traffic management would be needed, in order to decrease the overall traffic noise in this Avenue.

This redirection would also help decrease the overall traffic noise in the Avenue.

In terms of feasibility of the tested scenarios, it is safe to say that although the 4th scenario (noise barriers implementation) achieved good results, implementing 2.5m-3m noise barriers in Dr. Lourenço Peixinho's avenue would not be feasible. To implement a measure like the one tested in scenario 7 (absence of signalized intersections) which would be possible, but it would add the need of a roundabout. In this scenario would be interesting to to test other cycles for the traffic lights, in order to optimize the phases distribution to attain a better traffic performance. The developed work also outlines some questions to be adressed in future works. The main point that deserves further improvement is the aquisition of real noise values. If it could be measured in LAeq1h so that the TNM simulated model could, eventually, be validated or reformulated to mimic the actual contitions, measured in the real-context. In the present Dissertation it was used the traffic volumes values were extracted from a report of 2011 [64] whereas the simulated results were compared with trafic noise values from Aveiro noise maps, collected 7 years before, in 2008 [25].

Also the viability and noise results of switching from traffic signals to roundabouts could be tested. TNM V25 does not allow to simulate roundabouts, but maybe the upcoming 3.0 version will bring this feature, otherwise the simulation would need to be re-done in a different software.

Newer and "noise reducing" pavements such as ARFC (asphalt rubber friction courses) pavement as tested by Kim et al. [49] should be tested. This new pavement is said to provide a smoother ride for motorists lower the traffic noise level.

Another point of interest is that being TNM an American software, its vehicles' database may be based on the American fleet, so it would be interesting to simulate again with a newer database based on the European fleet.

Also, it should be emphasized that in this work the attention was focused on the relative results (percentage of variation between scenarios) and not in the absolute noise levels.

The noise barrier study can also be widely evolved, because there are different types and designs. An interesting prototype design that would match the avenue perfectly is the new low-height noise barrier design tested by Jolibois *et. al.* [69].

In a more advanced stage, measuring traffic noise levels with a sound level meter but also analysing the effectiveness of different noise reducing measures based on individual perception: instead of only numerical analysis, inquiries to the people about how they feel before and after the noise mitigation measures are implemented.

References

[1] Noise pollution - Cambridge English Dictionary. (2015, October 31). Retrieved from: http://dictionary.cambridge.org/dictionary/english/noise-pollution.

[2] Stephen A. Stansfeld. Noise pollution: non-auditory effects on health. *British Medical Bulletin*, 68(1):243–257, 2003.

[3] EC. Future Noise Policy European Commission Green Paper. (96):35, 1996.

[4] EEA. Good practice guide on noise exposure and potential health effects. Technical Report 1, European Environment Agency, 2010.

[5] EEA. The contribution of transport to air quality TERM 2012: transport indicators tracking progress towards environmental targets in Europe. Technical Report 10, European Environment Agency, 2012.

[6] Coping with Noise. (2015, November 2). Retrieved from: http://wwwtestsp.amplifon.com/Italiano/societa/Pubblicazioni/Pages/default.aspx.

[7] WHO. Burden of disease from environmental noise. *World Health Organization*, pages 1–105, 2011.

[8] Marcin Polak, Marek Kucharczyk, and Janusz Bohatkiewicz. Landscape and Urban Planning The influence of road traffic on birds during autumn period : Implications for planning and management of road network. 134:76–82, 2015.

[9] Graeme Shannon, Lisa M. Angeloni, George Wittemyer, Kurt M. Fristrup, and Kevin R. Crooks. Road traffic noise modifies behaviour of a keystone species. *Animal Behaviour*, 94:135–141, 2014.

[10] Kwang Sik Kim, Sung Joong Park, and Young-Jun Kweon. Highway traffic noise effects on land price in an urban area. *Transportation Research Part D: Transport and Environment*, 12(4):275–280, 2007.

[11] EC. Report From The Commission to the European Parliament and the Council On the implementation of the Environmental Noise Directive in accordance with Article 11 of Directive 2002/49/EC. Technical report, European Commission, 2011.

[12] Occupational Safety and Health Administration. (2015, May 5). Retrieved from: https://www.osha.gov/.

[13] US EPA. US Environmental Protection Agency. (2015, October 31). Retrieved from: http://www.epa.gov/.

[14] Federal Highway Administration. (2015, march 5). retrieved from: http://www.fhwa.dot.gov/.

[15] Hang See Pheng. *Noise Modeling in Universiti Sains Malaysia and offshore oil and gas platform.* PhD thesis, Universiti Sains Malaysia, 2007.

[16] European Commission. The EU Noise Expert Network. (2011, January 1). Retrieved from: http://ec.europa.eu/environment/noise/expert.htm using web-archieve, 2010.

[17] Parlamento Europeu. Directiva 2002/49/CE do Parlamento Europeu e do Conselho de 25 de Junho de 2002 relativa à avaliação e gestão do ruído ambiente. *Jornal Oficial das Comunidades Europeias*, 2002.

[18] Acoustic Glossary - Sound and Vibration : Definitions, Terms, Units, Measurements. (2015, November 2). Retrieved from: http://www.acoustic-glossary.co.uk/definitions-l.htm.

[19] Acoustic Glossary - Frequency Weighted Sound Levels - Definitions, Terms, Units and Measurements. (2015, July 30). Retrieved from: http://www.acoustic-glossary.co.uk/frequency-weighting.htm.

[20] WHO. Metrics: Disability-Adjusted Life Year (DALY). (2015, May 15). Retrieved from: http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/.

[21] Assembleia da República. Decreto-lei 9/2007 de 17 de Janeiro. pages 389–398, 2007.

[22] Assembleia da República. Decreto Lei 146/2006. 2006.

[23] Birgitta Berglund, Thomas Lindvall, and Dietrich Schwela. New WHO guidelines for community noise. 31:24–29, 2000.

[24] Eelco den Boer and Arno Schroten. Traffic noise reduction in Europe Health effects, social costs and technical and policy options to reduce road and rail traffic noise. *CE Delft*, (August):70, 2007.

[25] Nuno Pereira and Augusto Lopes. Mapas de Ruído de Aveiro. Technical report, 2009.

[26] Nuno Pereira and Augusto Lopes. Actualização dos Mapas de Ruído do Concelho de Aveiro. Technical report, 2012.

[27] FHWA. FHWA Traffic Noise Model Version 2.5. (2015, March 5). Retrieved from: http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25/.

[28] Evy Ohrstrom, Annbritt Skanberg, Helena Svensson, and Anita Gidlof-Gunnarsson. Effects of road traffic noise and the benefit of access to quietness. *Journal of Sound and Vibration*, 295(1-2):40–59, 2006.

[29] Dieter Frey and Carl Graf Hoyos. *Psychologie in Gesellschaft, Kultur und Umwelt: Handbuch.* 2005.

[30] Conny Louen, Alexander Wehrens, and Dirk Vallée. Analysis of the Effectiveness of Different Noise Reducing Measures Based on Individual Perception in Germany. *Transportation Research Procedia*, 4:472–481, 2014.

[31] Karin Sygna, Gunn Marit Aasvang, Geir Aamodt, Bente Oftedal, and Norun Hjertager Krog. Road traffic noise, sleep and mental health. *Environmental Research*, 131:17–24, 2014.

[32] Patrizia Frei, Evelyn Mohler, and Martin Roosli. Effect of nocturnal road traffic noise exposure and annoyance on objective and subjective sleep quality. *International journal of hygiene and environmental health*, 217(2-3):188–95, 2014.

[33] EEA. Noise in Europe 2014. Technical Report 10, European Environment Agency, 2014.

[34] Jaana Halonen, Anna Hansell, John Gulliver, David Morley, Marta Blangiardo, Daniela Fecht, Mireille Toledano, Sean Beevers, Hugo Anderson, Frank Kelly, and Cathryn Tonne. Road traffic noise is associated with increased cardiovascular morbidity and mortality and all-cause mortality in London. *European Heart Journal*, 2015.

[35] Guillaume Dutilleux. Anthropogenic outdoor sound and wildlife: it's not just bioacoustics! *Société Française d'Acoustique.*, Acoustics(April):2301–2306, 2012.

[36] Ingunn Milford, Sigve J. Aasebo, and Kjell Strommer. Value for money in road traffic noise abatement. *Procedia - Social and Behavioral Sciences*, 48:1366 – 1374, 2012. Transport Research Arena 2012.

[37] EC. White Paper: Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system. 2011.

[38] Fernando Lera-López, Javier Faulin, and Mercedes Sánchez. Determinants of the willingness-to-pay for reducing the environmental impacts of road transportation. *Transportation Research Part D: Transport and Environment*, 17(3):215–220, 2012.

[39] Crispin Dickson and Johanna Thorén. Kartläggning av antalet överexponerade för buller. Technical Report 3581062000, Sweco, Stockholm, 2014.

[40] External Costs and Benefits of Transport in Switzerland Road, rail, air and waterborne transport 2010, and trends since 2005. Technical report, Federal Office for the Environment Switzerland, 2010.

[41] Patrick Hofstetter and Ruedi Müller-Wenk. Monetization of health damages from road noise with implications for monetizing health impacts in life cycle assessment. *Journal of Cleaner Production*, 13(13-14):1235–1245, 2005.

[42] Naveen Garg and Sagar Maji. A critical review of principal traffic noise models : Strategies and implications. 46:68–81, 2014.

[43] Campbell Steele. A critical review of some traffic noise prediction models. *Applied Acoustics*, 62(3):271–287, 2001.

[44] Reifenetikette - sichere, energiesparende und leise Reifen. (2015, July 28). Retrieved from: http://www.reifenetikette.ch/.

[45] Ka-Yee Ho, Wing-Tat Hung, Chung-Fai Ng, Yat-Ken Lam, Randolph Leung, and Eddy Kam. The effects of road surface and tyre deterioration on tyre/road noise emission. *Applied Acoustics*, 74(7):921–925, 2013.

[46] Jean-Francois Hamet and Michel Berengier. Acoustical Characteristics of porous pavements: a new phenomenological model. 1993.

[47] Filippo G. Praticò and Fabienne Anfosso-Lédée. Trends and Issues in Mitigating Traffic Noise through Quiet Pavements. *Procedia - Social and Behavioral Sciences*, 53:203–212, 2012.

[48] Jeanne Luong, Moisés Bueno, Victoriano F. Vázquez, and Santiago E. Paje. Ultrathin porous pavement made with high viscosity asphalt rubber binder: A better acoustic absorption? *Applied Acoustics*, 79:117–123, 2014.

[49] Jonghoon Kim, Ning Shu, and Dan D Koo. Noise Impact Analysis Using the Traffic Noise Model (TNM) Comparing Different Pavement Types Average vs . ARFC. *ARPN Journal of Science and Technology*, 5(1):32–36, 2015.

[50] Santiago E. Paje, Moisés Bueno, Francisco Terán, Rodrigo Miró, Félix Pérez-Jiménez, and Adriana H. Martínez. Acoustic field evaluation of asphalt mixtures with crumb rubber. *Applied Acoustics*, 71(6):578–582, 2010.

[51] Mandi Behzad, Mohammad Hodaei, and Iraj Alimohammadi. Experimental and numerical investigation of the effect of a speed bump on car noise emission level. *Applied Acoustics*, 68(11-12):1346–1356, 2007.

[52] Timothy Van Renterghem and Dick Botteldooren. Reducing the acoustical façade load from road traffic with green roofs. *Building and Environment*, 44(5):1081–1087, 2009.

[53] Zaloa Azkorra, Gabriel Pérez, Julià Coma, Luisa F. Cabeza, Silvia Bures, Juan E. Álvaro, Aitor Erkoreka, and Miguel Urrestarazu. Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics*, 89:46–56, 2015.

[54] Douglas Reynolds. *Engineering principles of acoustics: noise and vibration control*. Allyn and Bacon Boston, 1981.

[55] Timothy Van Renterghem. Guidelines for optimizing road traffic noise shielding by non-deep tree belts. *Ecological Engineering*, 69:276–286, 2014.

[56] Timothy Van Renterghem and Dick Botteldooren. The importance of roof shape for road traffic noise shielding in the urban environment. *Journal of Sound and Vibration*, 329(9):1422–1434, 2010.

[57] Patrick Harrison. Sound Walls Absorptive versus reflective design and effectiveness. Technical Report 318.

[58] Federal Highway. FHWA Traffic Noise Model User Guide. 1998.

[59] U.S. Department of Transportation. FHWA Traffic Noise Model Users Guide (Version 2.5 Addendum). Technical report, U.S. Department of Transportation, 2004.

[60] FHWA Traffic Noise Model.(2015, May 7). Retrieved from: http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/.

[61] Transportation Research Board of the National Academies. Supplemental Guidance on the Application of FHWA Traffic Noise Model (TNM). Technical report, 2014.

[62] Federal Highway Administration. Highway Traffic Noise: Analysis and Abatement Guidance. (June 2010):75, 2011.

[63] U.S. Department of Transportation. Title 23, Part 772- Procedures for Abatement of Highway Traffic Noise and Construction Noise. 2012.

[64] Amorim Jorge H., Pereira Sérgio R., Coelho Margarida C., Dias Daniela, Sá Emy, Borrego Carlos, Fontes Tânia, Fernandes Paulo, Bandeira Jorge, and Tchepel Oxana. Impact of road transport on urban air quality: GIS and GPS as a support for a modeling framework. In *GIS Ostrava 2014*, 2014.

[65] Indicadores de Atividade - Carris. (2015, May 11). Retrieved from: http://carris.transporteslisboa.pt/pt/indicadores-de-atividade/.

[66] FHWA - Noise Barrier Design Handbook - Terminology. (2015, July 30). Retrieved from: `http://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/design02.cfm`.

[67] Cecília Rocha and António Carvalho. The true cost of road traffic noise in Portugal. 2009.

[68] Plastral | Aluminium composite panel, hdpe, acrylic sheets, polycarbonate sheets, chemicals, polymers, plastic welding. (2015, May 7). Retrieved from: http://www.plastral.com.au.

[69] Alexandre Jolibois, Jérôme Defrance, H. Koreneff, Philippe Jean, Denis Duhamel, and Victor W. Sparrow. In situ measurement of the acoustic performance of a full scale tramway low height noise barrier prototype. *Applied Acoustics*, 94:57–68, 2015.

[70] TNM Faqs - Traffic Noise Model - FHWA. (2015, May 3). Retrieved from: http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_faqs/faq00.cfm.

Annexes

Below is a comparison of some of the most relevant Traffic Noise models done by Garg *et al.* [42].

Table 1. Comparison of various traffic noise models based on different technical attributes

Technical attributes	FHWA model	CoRTN model	RLS 90 model	ASJ RTN-Model 2008	HARMONOISE model	Son Road model	Nord 2000	NMPB-Routes-2008
References	FHWA Traffic Noise Model, 1998	Givargis and Mahmoodi, 2008; Steele, 2001	Steele, 2001; Probst, 2010a,b	Yamamoto, 2010	Defrance et al., 2007; Jonasson, 2007; Watts, 2005; Jónsson and Jacobsen, 2008; JRC report, 2010	Heutschi, 2004	DELTA, 2002; Kragh, 2001; JRC report, 2010	Dutilleux et al., 2010; Sétra, 2009a,b; Kephalopoulos, 2012
Government users	USA Federal Highway Administration's Traffic Noise Model	UK Calculation of Road Traffic Noise	Germany *Richtlinien für den Lärmschutz an Straben* (Guidelines for Noise Control on Streets)	Japan	Proposed for EU Member States Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management Of Environmental *Noise*	Switzerland	Scandinavian (Norway, Denmark, Sweden and Finland)	France (Nouvelle Méthode de Prévision du Bruit des Routes)
Applications	Highway, road networks	Highway, single traffic stream	Highways, car parks, simple streams only	Highway/constant speed/in different traffic conditions	Road and railway traffic	Highway, road networks	Source model for road & rail traffic	Highway, road networks
Predicts traffic volumes	No	No	Yes	No	No	No	No	No
Traffic conditions	Constant speed, acceleration, grade and interruption	Constant speed, grades	Constant speed, grades, quasi-intersections, interruptions	Constant speed, acceleration/deceleration mode, junctions, signalized intersection, road tunnels, depressed and semi-underground roads, flat/overhead roads & double-deck via ducts	Constant speed, acceleration/deceleration mode. Corrections for slip & acceleration/deceleration defined	Constant speed, grades	Motorway, urban motorway, main road, urban road, urban road or feeder road in residential area, residential road	Steady speed, acceleration, deceleration
Vehicle types	Automobiles, medium trucks, heavy trucks, buses and motorcycles	Light vehicles/heavy vehicles	Light vehicles/heavy vehicles/car parks	Light vehicles (passenger cars & small sized vehicles) and heavy vehicles (medium sized and large sized) & motorcycle	Light vehicles, medium heavy, heavy, other heavy vehicles & two wheelers	Passenger cars and Trucks	Light (<3500 kg), medium (3500–12,000 kg) & heavy (>12,000 kg) vehicles	Light vehicles <3.5 tonnes and heavy goods vehicles, 3.5 tonnes or higher
Technical Attributes	FHWA model	CoRTN model	RLS 90 model	ASJ RTN-model 2008	HARMONOISEmodel	Son Roadmodel	Nord 2000	NMPB-Routes-2008
Propagation	Energy type Propagation in 1/3rd octave band is modelled considering atmospheric absorption, divergence, acoustical characterization and topography of intervening ground, walls, berms and their combinations, intervening rows of buildings and intervening areas of heavy vegetation.	Energy type	Energy type The calculation is made starting from an average level $L_{m,E}$ measurable at a distance of 25 m from the centre of the road lane. It includes corrections due to presence of obstacles, vegetation, air absorption, reflection and diffraction, ground absorption, etc.	Energy type The model is developed based on Geometrical Acoustics and it contains effects of shielding by barriers or buildings, ground surface, air absorption and meteorological condition. The procedures of application to roads with special cases such as interchange, signalized intersection, double deck viaducts, road tunnel, semi-underground road and roads with built-up areas are also included.	Energy type Reference model employs three propagation models viz., Parabolic Equation (PE) Model, straight-ray (RAY) & Boundary Element Method (BEM). Atmospheric refraction is taken into account by PE. In the region outside the source region, a PE model is used. For a flat ground surface, the Crank-Nicholson PE (CNPE) model or the Green's Function (GFPE) model is used. For a ground surface with smooth hills, the generalized-terrain PE model (GTPE) is used. BEM and RAY are used for obstacles with complex shapes, while CNPE & GFPE for rectangular obstacles. Point-to-Point propagation is dependent on speed-sound gradient calculated from the wind speed, wind direction and temperature profile.	Energy type Propagation model calculates geometrical spreading, air absorption, reflections at vertical surfaces, possible shielding effects and the constructive and destructive interference between direct and ground reflected sound waves.	Energy type The propagation model which is based on analytical solution (geometrical ray theory & theory of diffraction) calculates the 1/3rd octave band attenuation from 25 Hz to 10 kHz for a homogeneous atmosphere. Refraction by geometrical modification of rays based on heuristic approach is incorporated. Model is applicable for any terrain profile assuming that terrain is approx by a number of straight segments characterized by surface impedance and roughness. Fresnel zone interpolation is preferred for all terrains	Energy type Propagation model includes calculation of probability of occurrence of downward refraction conditions for each direction, search for propagation trajectories between each source and receiver, calculation of attenuation in downward refraction conditions & homogenous conditions. Sound levels are weighted by average occurrence p_i of downward refraction conditions and homogenous conditions

Basic model	It computes vertical subsource vehicle emissions depending upon vehicle type, pavement type and throttle conditions. Seventeen constants defined depending upon variables for converting A-weighted noise level emissions to 1/3rd octave band spectra. Emission based on vehicles pass-by at 15 m over flat absorptive ground	L_{10} in terms of total hourly flow is calculated at a reference distance of 10 m and reference hourly mean traffic speed of 75 kmph	Average level L_{mE} at a distance of 25 m from centre of road lane and is function of amount of vehicles per hour and of % of heavy trucks	Sound Power Level is defined as function of vehicle speed with change in noise generated due to pavement type, road gradient and noise directivity considered in correction terms. Sound power level defined for steady and non-steady traffic flow. For signalized intersections and junctions, the coefficient of deceleration and steady flow are same, while coefficients for acceleration and non-steady flow are the same.	Each vehicle category is represented by two point sources each having a specified sound power contribution from rolling and propulsion noise. For calculating the sound power from whole vehicle, the sound power between lowest and the highest source is distributed. The effect of speed & acceleration is taken into account in formulation of source strength for rolling and propulsion noise.	Sound Power Level derived from maximum pass-by level of single vehicle at a distance of 7.5 m and at a height of 1.2 m above ground. Effective source height is 0.45 m.	Sound Power level derived from pass-by measurements with result normalized to 10 m and angle of integration of 2.75 rad. Method provides 1/3rd octave band results from 25 Hz to 10 kHz.	Noise emission of traffic lane and characterized by its Sound Power Level per metre and per vehicle $L_{w/m/veh}$ which is sum of power unit noise component and rolling noise component. Rolling noise component defined for three road surfaces $R1$, $R2$ & $R3$.
Geometrical divergence	Adjustment for distance A_d from the elemental roadway segment to receiver defined $A_d = 10\log\left(\frac{15}{d}\right)\left(\frac{\alpha}{180}\right)$ α is angle subtended by elemental roadway segment in degrees	Δ_d is distance adjustment defined	$D_{S,\perp,}$ is attenuation to distance and air absorption defined in model $D_s = 11.2–20 \times \log(s) - (s/200)$ where s is distance between emission and emission point	$L_A = L_{WA} - 8–20\log(r) + \Delta L_{cor}$ where L_{WA} is A-weighted Sound Power level of single running vehicle and ΔL_{cor} accounts for corrections for diffraction, ground effect and atmospheric absorption	Point source: $\Delta L_d = 10\log(4\pi d^2/d_0^2)$ d = propagation distance, $d_0 = 1$ m Line source: $\Delta L = 10\log(\Delta\theta/4\pi d)$ $\Delta\theta$ = angle of view from receiver to segment	$A_{div,f} = 20\log \times (d) + 11$	$\Delta L_d = 10\log(4\pi R^2/R_0^2)$ R = propagation distance, $R_0 = 1$ m	$20\log_{10}(d) + 11$
Source characteristics & height of source	Simple stream Energy apportioned to two source heights: one at pavement level & one at 1.5 m above the pavement except for Heavy trucks, where the upper height is 3.66 m above the pavement	Single stream Noise levels are obtained at a reference distance of 10 m from the nearest carriageway edge of highway	Single stream The starting point of the calculation is L_{mE} measurable at a distance of 25 m from centre of road lane. The model is also able to evaluate the sound emission of the parking lot	Simple straight stream	Harmonoise distributes 80% of tyre/road noise on a source 0.01 m above the ground and 20% either on 0.30 m or 0.75 depending on type of vehicle. For propulsion noise, it is the other way round. For heavy construction equipments, additional point source for exhaust noise at 3.5 is used.	Single vehicle with microphone position at a distance of 7.5 m and at height of 1.2 m	Road and railway lines are represented by a number of vertically and horizontally spaced point sources. Vehicle is represented by noise source at height 0.01 m, 0.30 m and 0.75 m. Heavy vehicles have an extra source height of 3.5 m	Each source line is broken down into a set of sound point sources, placed 0.05 m above roadway. GdBN08 describes the pass-by maximum levels in dB(A) measured at 7.5 m horizontal distance and 1.2 m height above the ground surface
Input data	Traffic type, flow, speed, road & emission data, local characteristics	% Heavy vehicles, flow, speed, road and environmental data, Gradient	Traffic type, flow, park or road data	Traffic type, speed, barrier geometry, road surface and gradient, flow (steady/non-steady) distance from source to prediction point, mean wind speed & density of buildings	Traffic speed, composition, intensity (flow), flow characteristics viz., acceleration/deceleration	Vehicle type, speed, grade of road and surface type	Traffic intensity, speed and composition, no of vehicles per lane per unit time, type of road surface and temperature, local topography (terrain shapes, screens/buildings, road surface type), Relative air humidity, aerodynamic roughness length of ground	Average hourly flow rate for each category of vehicle, speed and traffic flow type of each vehicle category, road platform surface category, road gradient.
Noise descriptor	One hour L_{Aeq}, DNL & CNEL (community noise equivalent level)	$L_{10\ (1\text{-hour})}$ & $L_{10\ (18\text{-hour})}$	L_{eq}, $L_{m,E}$, L_m (mean level for each lane)	L_{WA}, L_A, $L_{Aeq,\ T}$	$L_{Aeq,\ T}$, L_{den} & L_{night}	A-weighted sound power level, emmission level L_f in 1/3rd octave band	L_{Aeq}, $L_{Aeq,\ T}$, L_{den} & L_{night}	L_{Aeq}, $L_{Aeq,LT}$
Type of mapping	Multipledual→points grid	Line → point	Line → point	Line → point	Incoherent Line source → point	Line → point	Line → point	Line → point
Gradient effect	Model computes adjusted speeds based on user input speeds, roadway grade & traffic control devices. TNM reduces input speeds depending upon steepness and length of upgrades	Gradient correction: $\Delta_G = 0.3\ G$ dBA	Gradient correction: $R_{RS} = 0.6\ \lvert g\rvert - 3$ for $g > 5\%$ $R_{RS} = 0$ for $g \leq 5\%$	Gradient correction: $\Delta L_{grad} = 0.14\ i_{grad} + 0.05\ i_{grad}^2$ where i_{grad} is gradient of road (%). It is applied only to heavy vehicles ascending inclined roads	The effect of gradient is described as $a = a_1 + g \sin(\alpha)$ where a_1 is acceleration of vehicle	Δ_s, correction for uphill grade g(%), where $\Delta_s = 0.8\ g$	Each segment of terrain profile is assumed to be perfectly flat. Ground fluctuations handled by segmented terrain & specifying ground roughness. Four roughness class N, S, M & L defined	Correction term ΔL_m defined for uphill, downhill and horizontal pavements. Three potential gradient defined: horizontal (gradient less than 2%), upwards (gradient of 2% to 6%) & downwards (gradient of 2% to 6%)

(continued on next page)

Table 1 (*continued*)

Technical attributes	FHWA model	CoRTN model	RLS 90 model	ASJ RTN-Model 2008	HARMONOISE model	Son Road model	Nord 2000	NMPB-Routes-2008
Directivity	Subsource-split ratio for vehicle emission, r_i defined in terms of five constants	Angle of view adjustment defined	Not mentioned	Directivity function defined	Directivity functions defined for rolling & propulsion noise	Not mentioned	Directivity function defined	Not mentioned
Ground effect	TNM model for reflection coefficients based on approach of Chessell incorporating the single-parameter ground impedance model	Not defined	Level difference caused by ground absorption and meteorological influences in free field, D_{BM} defined in model.	Correction for ground effect ΔL_{grad} for excess attenuation defined. Ground reflection coefficient $\mathrm{R_m}$ defined in terms of complex error function and admittance β and coefficient of finiteness of reflecting surface $\mathrm{G_m}$ defined in model.	Analytical formula established by Chien and Soroka. Additional correction factor of coherence due to presence of turbulent eddies near ground surface defined. Each impedance discontinuity is modelled through a Fresnel weighting approach	Correction A_{gr} defined. Coherence loss factor (K) defined in model for signifying summation is completely phase sensitive ($K = 1$) or purely energetic ($K = 0$). Sound pressure of ground reflected wave is calculated using Chessel's approach	Use of geometric ray theory, Chien and Soroka model.Coherence factor defined for effects from frequency band averaging& turbulence, fluctuating refraction, surface roughness & scattering zones	Attenuation due to ground in downward refraction conditions $A_{\mathrm{ground,F}}$ and in homogenous conditions $A_{\mathrm{ground,H}}$ in third octave band defined. Formula is asymptotic approx of Chein & Soroka's formulation.
Atmospheric absorption & rarefaction	Atmospheric absorption defined in terms of ambient air temperature, reference air temperature 20 ° C and oxygen relaxation frequency f_{r0}	No mention	$D_{\mathrm{S},\perp}$, attenuation due to distance & air absorption defined	Correction term $\Delta \mathrm{L_{air}}$ is calculated considering standard state of atmosphere (20 °C, 60% R.H & 101.325 kPa) as a function of distance from source to prediction point	Uses straight rays & curves the ground to simulate refraction; radius of curvature determined from maximum height of curve. Effect of air absorption is calculated with ISO 9613–1.Curved ground-analogy is adopted by inverse curving of the terrain rather than curving sound rays	Air absorption in third octave band f according to ISO 9613–1 for temperature +8 °C & RH 76%	Refraction modelled by using curved sound rays. The curvature depends upon vertical sound speed profile & is determined by semi-analytical approach. Air absorption calculated in accordance with ISO 9613-1	Atmospheric rarefaction in downward conditions taken into account by means of height correction terms. Turbulence also taken into account. Attenuation due to atmospheric absorption A_{atm} defined
Meteorological effects	TNM doesn't account for atmospheric effects such as varying wind speed or direction or temperature gradient. TNM assumes neutral atmospheric conditions	Not mentioned	D_{BM} is attenuation due to ground and atmospheric effect	Change in L_{Aeq} due to effect of wind defined $\Delta L_{\mathrm{m,line}}$	$A_{\mathrm{excess,j}}$ is excess attenuation represents the effect of ground, meteorology, barrier and air absorption. Standard P2P model for homogenous atmosphere is used Sound speed profile is approximated by means of Lin–Log function	Meteorological effects on sound propagation are ignored	Wind and temperature gradient used to approx the vertical effective sound speed profile by lin–log relationship	Two classes of meteorological conditions: Homogenous and downward propagation defined
Correction for road surfaces	TNM defines energy average emission levels depending upon road	Correction for concrete & bituminous surface; impervious bituminous & pervious road surface	Correction for road surface D_{Stro} defined	Frequency characteristics of road vehicle noise on dense asphalt and drainage asphalt pavement defined	Correction for road temperature, tyres with & without studs, road surface wetness & ageing defined	Correction for road surface Δ_{BG} defined	Correction for type of road surfaces, air temperature, ageing, max aggregate size & Country DK; FI, NO & SE have additional corrections	Road pavement influence addressed by grouping pavement into 3 categories ($R1$, $R2$ & $R3$), correction for ageing effect. Correction for air temperature included
Noise at intersections & roundabouts	Two accepted methods for modelling intersections: modelling roadways that stop short of and restart after an intersection and modelling a complex series of intersecting roadway segments	Not mentioned	Correction term for increased effect of traffic light controlled intersections	Four calculation methods defined viz., Precise, semi-precise, simplified model & summing the contributions from two intersecting roads under non-steady flow conditions	Micro-simulation based correction factor C_s applied to emission level. C_s is evaluated as average of correctionfunction $C(x)$ over length of segment estimated by simulated noise emission profiles. Curve $C(x)$ fitted to noise emission profiles using least squares method	Not mentioned	Correction on vehicle noise emission for continuous acceleration (after crossing) and continuous deceleration (before a crossing). Model recommends to use cruising vehicle emission values	Not mentioned

Impedance effect	TNM allows users to enter various ground types based on effective flow resistivity (cgs rayls) measured by Embelton. The ground type & associated effective flow resistivity (EFR) is defined. TNM averages the ground impedance in vicinity of reflection point using Boulanger's approach	Not mentioned	Not mentioned	Complex sound pressure reflection Coefficient R_m defined in terms of complex error function or Faddeeva function and admittance β calculated as $\frac{1}{\beta}=\left(1+5.50\left(\frac{\sigma_e}{f}\right)^{0.632}\right)+\left(i8.43\left(\frac{\sigma_e}{f}\right)^{0.632}\right)$ Where σ_e is effective flow resistivity in kPa s/m^2	For porous road surface: Hamet model; ISO road surface: One parameter model with flow resistivity 2 MPa s/m^2, surface with cluster: One parameter model with flow resistivity 200 MPa s/m^2	Ground impedance is described by one parameter model of Delany & Bazley, the error function is calculated by algorithm from Gautschi	Ground surfaces classified into seven classes *A* to *H* based on flow resistivity. Impedance calculated by "Delany and Bazley" model. Road surface represented by ground type *G* ($\sigma = 20{,}000$ kPa s/m^2)	Acoustic absorption of ground is represented by a frequency independent dimensionless coefficient *G* between 0 and 1. *Gtrajet* is defined as the fraction of absorbent ground present in the whole of the path covered. $G = \text{Min}\left[\left(\frac{300}{\sigma}\right)^{0.57}, 1\right]$ σ *cgs rayls*
Diffraction effect	Multiple reflections between parallel barriers computed in two dimensions; double diffraction included; in case of three or more pertubable barrier, TNM chooses most effective pair of barriers based on their input heights in accordance with "Foss selection algorithm"	Reflection adjustment defined	D_B is attenuation due to topography & building dimension defined in model. D_E is correction for absorption characteristic of building surfaces	The fundamental correction term for diffraction is calculated as a function of path length. Empirical formulation for simple barrier, finite length barrier, thick barrier, multiple barrier with overhang, edge modified, low height and transmission through barrier defined	BEM & RAY can be used for obstacles of complex shapes. CNPE & GFPE can also be used for rectangular obstacles; GTPE is used for propagation over smooth hills. Degouts approximation of Fresnel integrals gives attenuation as a function of path length difference and wavelength. Reflections from the faces of wedges/thick barriers are taken into account as ground effects	Correction $A_{gr/bar/\mathrm{refl},}(f)$ included in propagation attenuation to take care of ground effect & barrier attenuation including effect of reflecting objects in third octave band	Hadden–Pierce ray solution for a wedge with finite impedance faces is used for single screens and Salomons approach for multiple. The Jonasson image method is used with diffraction by Hadden-Pierce and ground effect by Chien and Soroka for screen on ground surface	Correction term defined in model in terms of Fresnel number (*N*) and corrective term C_h. Barrier diffractions is calculated using Maekawa's approximated formulation considering barrier as a hard surface.
Tyre type corrections	No	No	No	No	Yes	No	Yes	No
Bridges, tunnels, viaducts, defined	No Rows of buildings as optional element included	No	No RLS considers parking lot emissions	Yes	No GTPE is used for ground surface with smooth hills	No	No Nord 2000 handles only tunnel openings	No Special elements like trenches, tunnels & partial covers included
Vegetation effect	Attenuation through dense foliage and tree zones incorporated in propagation path. Berms can be selected with user selectable heights, top widths and side slopes	Not mentioned	D_B is attenuation coefficient due to topography and building dimensions	Not mentioned	Rough terrain with vegetation can be described by terrain roughness and ground impedance. Diffraction effects of earth mounds taken into account by Deygout approx. The attenuation as a result from propagation through tress $A_{\mathrm{scat,i}}$ defined	Correction $A_{\mathrm{fol},f}$ according to ISO 9613-2	Statistical scattering model influenced by reflection, scattering & absorption due to trunks, branches & foliage	Roughness parameter defined for sparse habitat (farms, villages, trees and hedges)

In order to ran the tests necessary for this dissertation TNM V25 was installed in a personal computer, all details about its configuration are given bellow:

Main Hardware:

- Lenovo Thinkpad X230 (Bios 2.64)
- Intel i5-3320M 2.6GHz Processor
- 16Gb Ram
- 256Gb Samsung 830 Solid State Drive (SSD)
- Windows 8.1 Pro 64bit (with all updates installed till the date of the simulations)

As told before, it was not possible to run TNM V25 under Windows 8.1. Contacting TNM Support Team it was said that TNM V25 was supposed to work with Windows 8.1 64bit in compatibility mode which in this case was not feasible. The solution was to run the program virtualbox There would not be given step by step tutorial on how to create a virtualized operative system run, but every necessary input is given below, to ensure the possibility of replicating the results achieved.

Version of Oracle's VM Virtualbox used: 4.3.26

Configuration - General

Type: Microsoft Windows

Version: Windows XP (32bit)

It was used Windows XP SP3 32bit PT-PT kindly provided by Microsoft's MSDNAA protocol with University of Aveiro. Prior to TNM instalation every available update was installed to ensure best stability.

During the simulations, errors such as "Assertion failed - Lemis" and TNM Shutdowns occured. Consulting the TNM FAQ [70] for the "Assertion failed - Lemis" error returned: Check your traffic input and make sure the speed and volume data in the columns were not switched when entered. Unfortunately that was not the scenario.

Contacting TNM Support Team with the model and videos showing the errors happening could not solve the problem, in fact the TNM Support Team could not replicate the error. It was found that the Regional and Language Options format must be English (United states), otherwise the program will not work correctly mainly because of the decimal mark difference, coma (Portugal) vs point (USA). The bug was reported to TNM Support in order to be corrected in Version 3.0 of TNM.

Configuration-System

- CPUs: 1
- Execution Cap: 100%
- Enable PAE/NX: checked
- Enable VT-x/AMD-V: checked
- Enable Nested Paging: checked
- Base Memory: 768MB

- Chipset: PIIX3
- Pointing Device: USB Tablet
- Enable I/O APIC: unchecked
- Enable EFI: unchecked
- Hardware Clock in UTC Time: unchecked

Configuration-Display

- Video Memory: 18MB
- Monitor Count: 1
- Enable 3D Acceleration: unchecked
- Enable 2D Acceleration: checked

Configuration-Storage

- Name: IDE
- Type: PIIX4
- Virtual Size 15,00GB
- Details: Dynamically Allocated Storage
- Solid State Drive: checked (due to the real hard drive being a solid state unit

Other options were left as they came prior to installation.