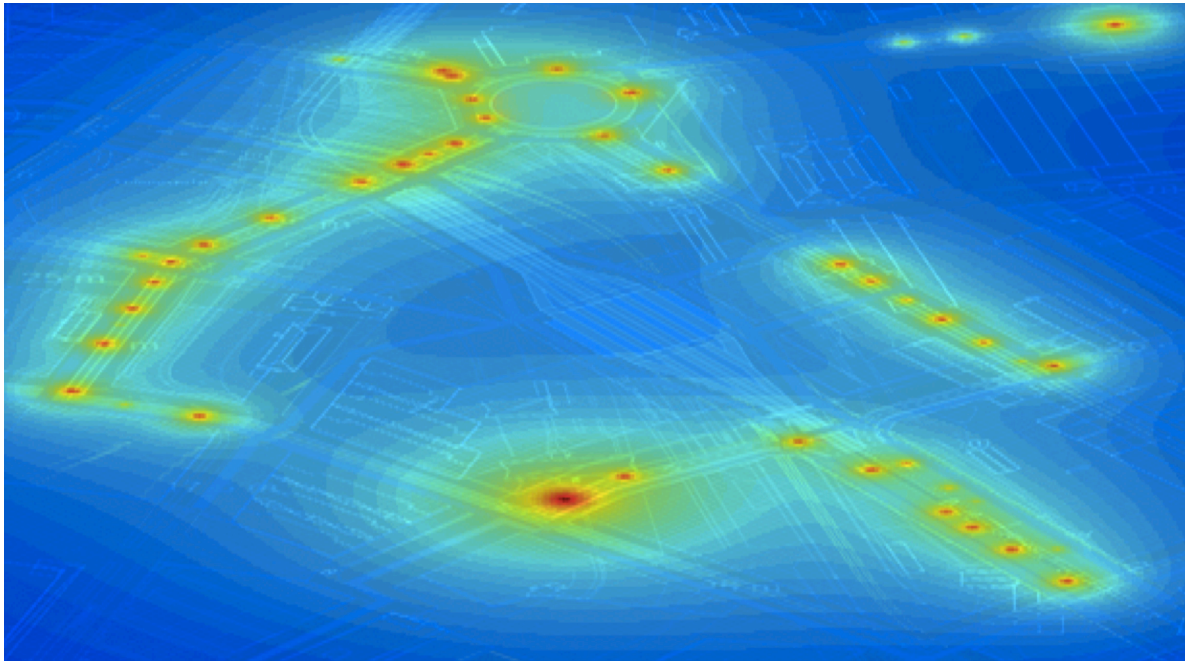


CHALMERS



Calculation of Traffic Noise Emissions Based on a Digital Traffic Model

A toolkit for evaluation of road traffic design with regard to
traffic noise emissions

*Master of Science Thesis in the Master's Programme Infrastructure and
Environmental Engineering*

**MANI FAKHAR
TARA HENGAMEH FATTAHI**

Department of Civil and Environmental Engineering
Division of GeoEngineering
Road and Traffic Research Group
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

This study presents a method for calculating traffic noise while the traffic properties are based on simulation of a digital traffic model. The traffic model is created in the simulation software PTV VISSIM while the noise emissions are estimated by the noise calculation method CNOSSOS-EU.

The study tries to show that a digital traffic model is reliable and accurate for assessing traffic properties for noise calculation. It also presents a toolkit that makes it possible to estimate instantaneous noise emission values at the source i.e. the vehicle motor and tyres moving on the road surface. Moreover the analyses for traffic noise reduction indicate that how variation in traffic design affect the sound power level at a specific point. They also show that how the variation of noise emissions can be related to different factors such as vehicle speed, acceleration and also driver's behaviour in relation to road and traffic design.

Since the method is based on a digital model, it can be helpful for analysing road and traffic designs in case of less noise production already at the design phase.

Furthermore, as the method is new there is the possibility for further investigations in this area of study.

Key words: PTV VISSIM, Noise emissions, Traffic simulation, Frihamnen, CNOSSOS-EU,

Contents

| | |
|--|-----|
| ABSTRACT | I |
| CONTENTS | III |
| PREFACE | V |
| GLOSSARY | VI |
| | |
| 1 INTRODUCTION | 2 |
| 1.1 Background | 2 |
| 1.2 Aim | 5 |
| 1.3 Limitations | 6 |
| 1.4 Method | 7 |
| 1.5 Literature study | 8 |
| 1.5.1 Definition of sound and sound scales | 8 |
| 1.5.2 Sound source | 9 |
| 1.5.3 Sound propagation | 11 |
| 1.5.4 Emissions and immissions | 12 |
| 1.5.5 Noise | 12 |
| 1.5.6 Health issues related to noise pollution | 13 |
| 1.5.7 Traffic noise measurements in Sweden | 14 |
| 1.5.8 Noise control in traffic and city planning | 14 |
| 1.5.9 Origin-Destination Matrix | 14 |
| 1.5.10 Traffic noise emission and propagation | 16 |
| 1.5.11 Car as a noise source | 18 |
| 1.5.12 Tire type | 18 |
| 1.5.13 Road surface effect | 19 |
| 1.5.14 Driving patterns effect | 19 |
| 1.5.15 Noise calculation by CNOSSOS-EU | 20 |
| | |
| 2 TRAFFIC AND NOISE SIMULATION APPROACH | 24 |
| 2.1 VISSIM- Traffic modelling | 25 |
| 2.1.1 Background image | 25 |
| 2.1.2 Links, segments and connectors | 25 |
| 2.1.3 Segment points | 26 |
| 2.1.4 Routes and OD-matrix | 27 |
| 2.1.5 Conflict areas | 29 |
| 2.1.6 Vehicle speed | 30 |
| 2.1.7 Further traffic details in VISSIM | 30 |
| 2.1.8 Measurement points | 31 |
| 2.1.9 Output data | 31 |
| 2.2 Noise emission modelling | 35 |
| 2.3 Traffic design and scenarios | 36 |
| 2.3.1 Method 1 | 36 |
| 2.3.2 Method 2 | 37 |

| | | |
|-------|---|----|
| 3 | RESULTS AND ANALYSIS | 40 |
| 3.1 | Method 1, Instantaneous noise emissions | 41 |
| 3.1.1 | Speed 50 km/h | 41 |
| 3.1.2 | Speed 70 km/h | 41 |
| 3.2 | Method 2, Average noise emissions | 43 |
| 3.3 | Four scenarios | 43 |
| 3.3.1 | Scenario 1, 50 km/h and normal tyres | 43 |
| 3.3.2 | Scenario 2, 70 km/h and normal tyres | 46 |
| 3.3.3 | Scenario 3, 50 km/h with studded tyres | 46 |
| 3.3.4 | Scenario 4, 70 km/h with studded tyres | 47 |
| 3.3.5 | Scenario comparison | 48 |
| 3.4 | Analysis on scenario 1 for noise level reduction | 51 |
| 3.4.1 | Segment 1 | 52 |
| 3.4.2 | Segment 2 | 56 |
| 3.4.3 | Segment 3 | 62 |
| 3.4.4 | Combination | 64 |
| 4 | DISCUSSION | 67 |
| 4.1 | General issues | 67 |
| 4.1.1 | Traffic model in VISSIM | 68 |
| 4.1.2 | CNOSSOS-EU | 68 |
| 4.2 | Method 1 and 2, instantaneous and average noise emissions | 68 |
| 4.2.1 | Four scenarios | 69 |
| 4.2.2 | Analysis for noise emission reduction | 70 |
| 5 | CONCLUSION | 72 |
| 6 | RECOMMENDATION FOR FURTHER STUDIES | 73 |
| 7 | REFERENCES | 74 |
| 8 | APPENDIX 1 | 1 |
| 9 | APPENDIX 2 | 12 |
| 10 | APPENDIX 3 | 14 |

Preface

In this study, traffic noise emissions are calculated by simulating a traffic model in the software PTV VISSIM. For noise emission calculations, the method CNOSSOS-EU is used.

This study is a master thesis at the department of Civil and Environmental Engineering at Chalmers University of Technology in collaboration with the engineering consulting company WSP.

The thesis has been carried out by the authors *Mani Fakhar* and *Tara Hengameh Fattahi* mainly from March to September 2014 and is published at May 2016 after some minor editorial changes during this time. The study is accomplished with supervision of *Gunnar Lanner* at the Road and Traffic Research Group at Chalmers University of Technology.

We would like to thank *Gunnar Lannér* for a valuable supervision during this study. We also thank the great support and guidance from *Jens Forssèn* and *Laura Estevez* at the division of Applied Acoustics at Chalmers University of Technology. We appreciate also *Sebastian Hasselblom* and all people working at the division of Strategy and Analysis at WSP for providing us both study supervision and facilities at WSP office in Gothenburg. We would also like to thank *Jonas Andersson* at Gothenburg Traffic & Public Transport Authority, Trafikontoret Göteborg, for his support about latest data and maps of Frihamnen area.

Göteborg, September 2014

Mani Fakhar

Tara Hengameh Fattahi

Glossary

| | |
|----------------|--|
| Trafikverket | Swedish Transport Administration |
| Trafikkontoret | Gothenburg Traffic & Public Transport Authority |
| Göteborgs stad | Gothenburg city |
| Boverket | Swedish National Board of Housing |
| CNOSSOS-EU | Common Noise Assessment Methods in Europe |
| MATLAB | Programming language |
| Göteborg | Gothenburg |
| Götaälvbron | Name of the bridge that connects Gothenburg city centre to the northern city part Hisingen |
| OD-matrix | Origin-destination matrix |
| L(eq) | Equivalent sound level, Average value for the sound level varying during a time period |
| L(max) | Maximum sound level, Maximum value of the sound level varying during a time period |
| L(den) | Average value of a 24 hour-period, Day Evening Night |
| L(night) | Average value for sound pressure level during night between 10pm - 6am |
| dB | Decibel |
| L _w | Sound power level [dB] |
| L _p | Sound pressure level [dB] |

1 Introduction

This chapter is allotted to a brief description of the study's background, purpose, method and related literature studies.

1.1 Background

Road traffic is one of the most essential components of modern societies. New roads, railroads and tunnels are constructed and more vehicles are produced for better and easier communications. Although Beside all positive aspects, traffic brings about negative consequences that influence our life quality directly and indirectly. One of these consequences is noise pollution. Accordingly, different methods and solutions are presented during the past years for calculation and control of noise. One of these methods is ‘‘Road Traffic Noise - Nordic Prediction Method’’ (Nordic Noise Group, 1996). This method predicts the sound pressure level, L_p (dB) at a particular distance from a road segment with regard to vehicle categories and average speed. According to this method equivalent sound level, L_{eq} , and maximum sound level, L_{max} , can be calculated. These sound levels show average values for a specific time period. Since the method Nordic Prediction Method is used to calculate the noise level for an entire road segment, the results show equal values for all point on the road segment.

As appose to Nordic Prediction Method, this study presents a method for estimation of sound level at the sound source, L_w (dB). This source is, for instance, a vehicle that is located on the road. Furthermore this calculation is with respect to vehicle categories and vehicle speed and acceleration.

In previous methods, traffic properties, such as vehicle speed, had to be collected manually, but in this study this data is received through simulating a traffic model in the program PTV VISSIM. This makes the method applicable for any road.

Frihamnen

For presenting a more realistic and worthwhile result in this study, the traffic simulations are applied for the area Frihamnen in Gothenburg city.

Current Frihamnen is Gothenburg's most inner harbour. It is located at the northern bank of the river Götaälv and is counted as a part of the city region Hisingen. This area will go under

reconstruction in the future as part of the modern urban area ‘Älvstaden’. Since the traffic situation is influenced by new urban plans, prediction of traffic noise can be helpful for the city planners.

The map shown in *Figure 1* is the latest version of road and traffic planning for the area although the planning is at the preliminary phase and there are still uncertainties in details. Today, public transport in the form of tram passes Frihamnen; but the current tram station is going to be developed to become a major station. This station is shown inside a red line in *Figure 1*.

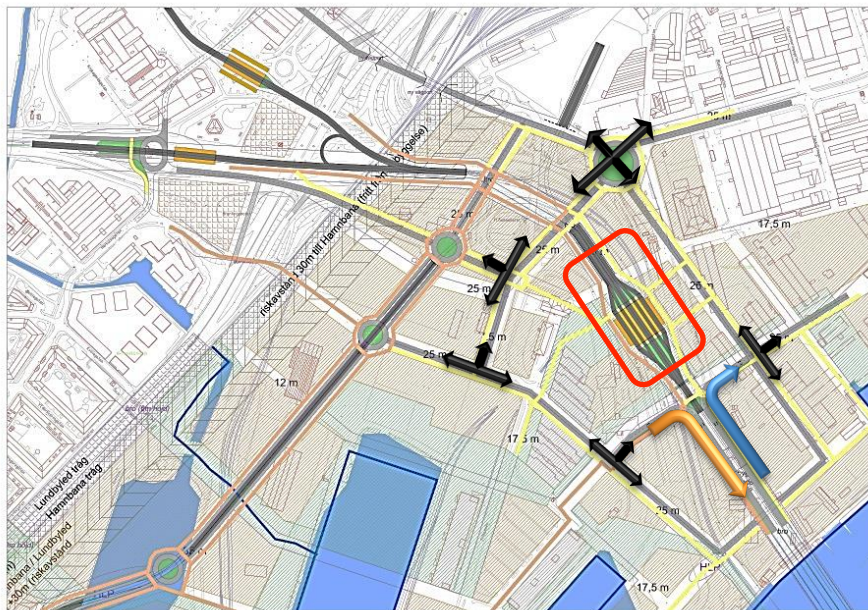


Figure 1 Traffic planning for Frihamnen

This study will focus on the road traffic and the links that connect the city centre to Hisingen. Blue and orange arrows in *Figure 1* show the two main links at the north side of the bridge. The other arrows shown by black colour indicate the links that are considered in the traffic model.

According to Gothenburg Traffic & Public Transport Authority, Trafikkontoret, modern Frihamnen will contain 15000 residents and 15000 working places, although this is still an approximate data. The large number of residents at new Frihamnen area is a good reason for noise investigation caused by traffic flow.

High vehicle acceleration and deceleration values, driving brake, different obstacles that cause traffic queues and a high traffic flow at the area are some of the issues that increase the risk of

traffic noise. Therefor an investigation of various traffic scenarios will lead to a more accurate traffic design and consequently less noise-producing traffic.

Although this study investigates noise emissions at the noise source and does not consider noise propagation in the environment, but the method will help the improvement of related studies in the future.

1.2 Aim

The main purpose of this study is to present a method for estimating traffic noise at the emission source while the traffic data, such as vehicle speed and acceleration, is collected is based on a digital traffic simulation in the program VISSIM.

The created scenarios in this study aim to show method's function, i.e. the coordination between the traffic simulation data and traffic noise calculation method CNOSSOS-EU.

Additionally, the analyses on the scenarios aim to verify its adaptation with the reality and also identify the basic causes for noise variations in a dynamic traffic.

Moreover, the study should open a way for comparing the presented method with the previous methods of noise calculation. Therefore, the result of this work is a basis of further investigations in the same area of study.

Furthermore, the presented method for calculating traffic noise at the emission source is a toolkit for urban and traffic planners to evaluate the urban plans already at the design phase.

1.3 Limitations

The traffic models are limited to road traffic and do not consider other types of traffic facilities such as railway. The vehicle categories in traffic simulations include mainly light and heavy vehicles, which are respectively passenger cars and trucks or busses.

The presented method in this study focuses on sound production at the emission source, but not noise propagation effects. Therefore, presenting solutions for moderation of noise emissions at a distance from the source is not included in this study.

1.4 Method

The first part of the study focuses on literature reviewing regarding sound concept, traffic and vehicle noise. For this purpose, technical reports, books and lecture notes have been reviewed.

Building up a traffic prognosis requires collecting data about population, working places, traffic system characters and etcetera. These data for future traffic at Frihamnen are provided among others through a meeting with Jonas Andersson at Gothenburg Traffic & Public Transport Authority.

The second part is to perform traffic simulations and noise calculations. Traffic simulations are provided in the program PTV VISSIM (version 6) and noise calculations are performed in MATLAB by using the noise calculation method CNOSSOS-EU. The simulations are done for several traffic scenarios on a background map of Frihamnen and by considering the same traffic flow as the year 2014. Jens Forssèn and Laura Estèvez Mauriz at the department of applied acoustics at Chalmers University have provided the MATLAB code based on CNOSSOS-EU.

A series of traffic properties related to each simulation is received through PTV VISSIM. These data contain traffic properties such as speed, acceleration and coordinates, which are required to calculate noise emissions by CNOSSOS method.

The final results that are presented through noise maps and graphs make it possible to compare different traffic scenarios in order to approach the goal of this study and lead to a helpful conclusion.

1.5 Literature study

In this chapter, a summary of the literature study is written. The topics give a summarized review about sound, traffic and road traffic noise.

1.5.1 Definition of sound and sound scales

Sound waves show different behaviours in gas, liquid or solid environments. With respect to each environment, sound waves are respectively called airborne, underwater and structure-borne. The device that produces sound waves has to be a type of vibrating system that transforms its energy to the molecules in the environment. These variations inside the earth atmosphere make ripples of air with higher and lower pressure than the atmospheric pressure. Fluctuation of these variations back and forth during time produces sound (Hass, 2003). The unit for expressing sound level is dB.

As the hearing sense in human is dependent on the frequency level of sound waves, four weighting filters are considered for expressing the sound level. These filters are characterised by A-, B-, C- and D-weighting. The most common filter that is conformed to frequencies that stimulate human's hearing sense is A-weighting and is expressed by the unit dB(A). For sound levels with lower frequencies, C-weighting is used and the sound level unit is expressed as dB(C). (Patrik Andersson, 2008)

Two terms that characterize sound are sound power W and sound pressure P . W refers to the emitted sound power per second at the sound source. The corresponding value for this term is sound power level L_W [dB]. P refers to the average sound pressure in time and corresponds to the sound level at a distance from the sound source where the environment's characteristics influence the sound level. The value is indicated by sound pressure level L_p [dB]. (Patrik Andersson, 2008)

Figure 2 shows an approximation of some common sound pressure levels, L_p , in our society. L_p is a logarithmical value; therefore an increasing level of 8-10 dB will be felt by a double power. For example an increasing of sound level from 45 dB to 55 dB means a two times louder sound. (Larsson, 2000)

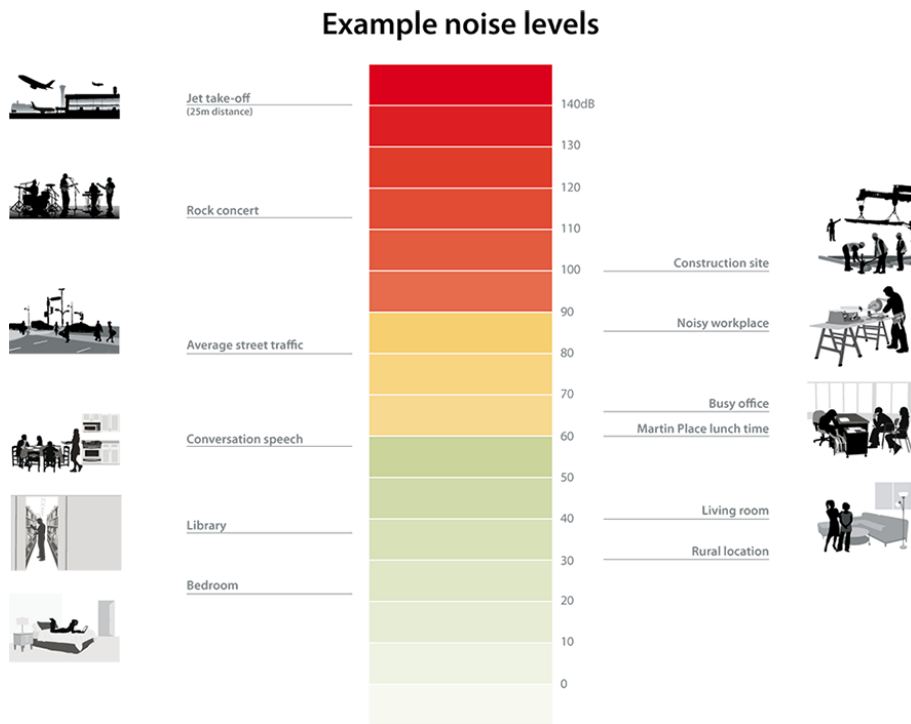


Figure 2 The approximate indoor/outdoor sound level (Aircraftnoise, n.d.)

1.5.2 Sound source

A source that sound waves are produced by is divided into two types; point source and line source. Distribution of sound waves coming from a point source is different from sound waves coming from a line source. (Institutionen för teknisk akustik, Chalmers, 2001)

1.5.2.1 Point source

The point source is a source, which is located at a particular point and radiates sound isotropically. The sound waves produced by this type of source propagate in a spherical pattern around the source, illustrated in *Figure 3*.

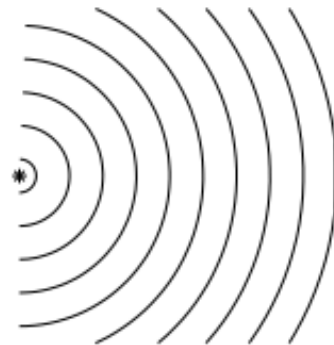


Figure 3 Spherical waves radiated from a point source

The relation shown in Equation 1 calculates sound pressure level, L_p , for a point source. (Wolfgang Kropp, n.d.)

$$L_p = L_w - 10 \log_{10} \frac{4\pi r^2}{S_{ref}} \quad [1]$$

Where

L_w = sound power level [dB]

r = radius of a wave which is a line perpendicular to the receiver's location [m]

$S_{ref} = S(R) = S_0$ = surface area of the sphere with radius r [m²]

Radius of the sphere is the distance that sound waves pass in all directions. The sound pressure level decreases in further distances of sound waves to the source. For example doubling the distance will decrease the sound pressure level by 6dB (Wolfgang Kropp, n.d.). This is shown in *Figure 4*.

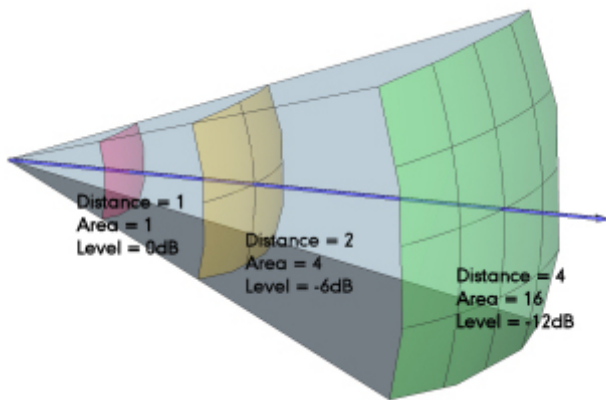


Figure 4 Decrease of sound pressure level by doubling the distance from the source (AV-Info, n.d.)

1.5.2.2 Line source

A line source is point sources extended in length. The summation of sound waves from these point sources results in a cylindrically shaped model with the source in the centre. The distance between each two adjacent source is denoted by d and the radius r is simply the shortest distance from the line source to the receiver (Wolfgang Kropp, n.d.).

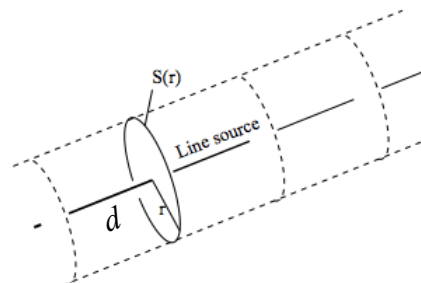


Figure 5 Cylindrical waves radiated from a line source (Institutionen för teknisk akustik, Chalmers, 2001)

This is shown in *Figure 5*.

The sound pressure level, L_p , varies depending on where the receiver is located with respect to the line source. Equation 2 calculates sound pressure level L_p for a line source.

$$L_p = L'_w - 10 \log_{10} \frac{2\pi r}{l_0} \quad [2]$$

Where

L'_w = sound power level calculated by the result of sound power per unit distance, W'

r = radius of sound waves which is a line perpendicular to the receiver's location [m]

$l_0 = d$ = distance between each point source along the line source

Figure 6 indicates a receiver located at the distance of r from the line source.

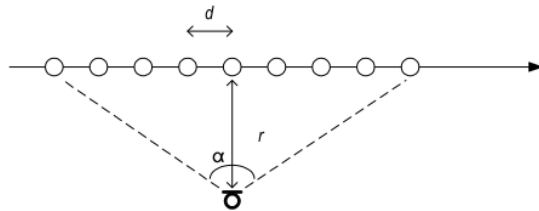


Figure 6 Two dimensional image of a receiver with a distance r from a line source (Institutionen för teknisk akustik, Chalmers, 2001)

Figure 6 simulates a two dimensional image of a receiver's location that experience sound pressure level produced by a line source. Experiencing noise from highways is the same as this situation. Because highways are commonly modelled as line sources where each individual car represents a point source. However, it is important to note that the type of line source used when modelling a road is basically incoherent. This means that each individual vehicle produces sound independently from other vehicles (Patrik Andersson, 2008).

1.5.3 Sound propagation

Sound waves travel with the constant speed of 343 m/s in a homogeneous atmosphere. Sound waves continue propagating in their original direction unless they collide with a surface that can change their velocity and direction.

Propagation of sound in the environment depends on different factors such as

- Distance of sound source from the receiver
- Absorption of sound waves by air molecules
- Inhomogeneity of atmosphere according to factors such as wind or precipitation
- Reflection by the ground surface
- Reflection by other barriers

(Patrik Andersson, 2008)

1.5.4 Emissions and immissions

Sound pressure level varies depending on the placement of receiver. Sound waves with the pressure level at their source are called sound emission. This level decreases according to different factors. For a receiver locating at a distance from the source, the pressure level is not as high as the source location. In this case the sound waves are called immissions that is according to receiver's experience of sound in a distance. Factors that affect sound propagation and cause sound level difference between emissions and immissions are listed as below (Larsson, 2000).

- Distance
- Field type, the field can be of hard or soft material in an acoustical point of view
- Noise shields
- Reflexing materials and surfaces
- Wind
- Temperature in different elevations
- Humidity
- Building isolation at the facade
- Sound frequency

One or several factors can simultaneously affect emissions.

1.5.5 Noise

The term ‘noise’ is unwanted sound waves that lead to irritation and even health problems in a broad aspect. The result of an investigation regarding traffic noise disturbance is presented in the *Table 1*. These results contain an approximate proportion of inhabitants in an urban area in relation to the outdoor equivalent sound level cause by traffic.

Table 1 Waves that lead to irritation (Svenska kommunförbundet, 1998)

| Equivalent Sound level [dBA] | Proportion of disturbed inhabitants |
|------------------------------|-------------------------------------|
| <55 | 10% |
| 56-60 | 25% |
| 61-65 | 45% |
| 66-70 | 70% |
| >70 | 100% |

As seen in the *Table 1*, all inhabitants are disturbed when the sound level is 70 dBA or higher.

1.5.6 Health issues related to noise pollution

Health concerns has become increasingly more important in designing traffic solutions (Boverket, 2008). A noisy environment has a negative effect on our health and it leads to a decrease in the quality of life. According to a study published by the Swedish National Board of Housing, there are significant evidences that show humans are negatively affected by both temporary and permanent noise. These negative effects include sleep disorders in terms of difficulty in falling asleep, awakening and changes in sleep depth, elevated blood pressure, increased heart and pulse rate, respiration problems and increased number of body movements during sleep. There are also secondary effects such as the perception of a decreased sleep quality, extreme fatigue, depression and reduced performance. Furthermore, research has shown that traffic noise can lead to an increase risk for developing cardiovascular diseases.

The problems due to noise pollution by infrastructure facilities are so expanding that they have caused threatening issues for environment. According to an article called “ Boat noise disrupts orientation behaviour in a coral reef fish’”, published June 27th 2013, the environmental impacts of traffic noise is not limited to human lives, but even the whole ecosystem in a noisy area, such as a sea bed, can be affected.

Traffic noise caused by cars at the roads or caused by trains passing railroads are the two major types of noise pollution that have direct and indirect effects on our urban society.

1.5.7 Traffic noise measurements in Sweden

For measuring traffic noise in Sweden, Nordic Prediction Method for Road Traffic Noise is used which is based on the following items: (Nordic Noise Group, 1996)

- Equivalent noise level that is average noise level over a given time period (L_{eq})
- Maximum level that is maximum noise level during a given time period (L_{max})

1.5.8 Noise control in traffic and city planning

Controlling traffic noise depends on the location of roads and their distance to the residential areas. For preventing noise problems in urban areas, several solutions can be performed such as guarding, moderating the noise at the source and traffic regulation. Noise moderation is a considerable subject already at the preliminary phases of urban area designing. This subject is considered deeply for those areas that are supposed to be near the infrastructure facilities such as roads and railroads. Noise regulation is particularly necessary in central parts of big cities and in populated areas that are located in a short distance from roads. In these areas, noise moderation facilities such as sound isolation layers are used inside the building frame such as walls. These facilities are mostly important at the building facades, which face the trafficked roads where the equivalent sound level is more than 65 dBA. By having an average daily traffic of 1000 vehicle per day, the equivalent noise level can be around 55 dBA by the building facade that are 10 meters away from the road. The average daily traffic in central parts of big cities is more than 1000 vehicles where obtaining as low sound level as 55 dBA by the facade is difficult. Although there are some solutions for controlling traffic noise in crowded urban areas such as noise shields that cover the residential areas, and also changes in road design. Examples for these solutions respectively are tightening window gaps, glass or lumber shields in a distance between roads and buildings, and covering the road surface by particular asphalt material. (Larsson, 2000)

1.5.9 Origin-Destination Matrix

For describing number of trips from a given set of origins to a set of destination, it is common that the method Origin-Destination (OD) matrix is used for identification of vehicle route choice. The rows and columns of the matrix, shown in .

Table 2, are specified by origin nodes and destinations nodes. Adding all the entries in a row will give total traffic from the respective origin in that row and adding all the entries in a column will give the total traffic flow toward the destination in that column. These origin and destination nodes are shown in *Figure 7*.

Table 2 Origin-Destination (OD) matrix

| Origin/Destination | Node ₁ | Node ₂ | Node ₃ | Node ₄ | |
|-------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Node₁ | m_{11} | m_{12} | m_{13} | m_{14} | $\sum_{i=0}^4 m_{1,i}$ |
| Node₂ | m_{21} | m_{22} | m_{23} | m_{24} | $\sum_{i=0}^4 m_{2,i}$ |
| Node₃ | m_{31} | m_{32} | m_{33} | m_{34} | $\sum_{i=0}^4 m_{3,i}$ |
| Node₄ | m_{41} | m_{42} | m_{43} | m_{44} | $\sum_{i=0}^4 m_{4,i}$ |
| | $\sum_{i=0}^4 m_{i,1}$ | $\sum_{i=0}^4 m_{i,2}$ | $\sum_{i=0}^4 m_{i,3}$ | $\sum_{i=0}^4 m_{i,4}$ | |

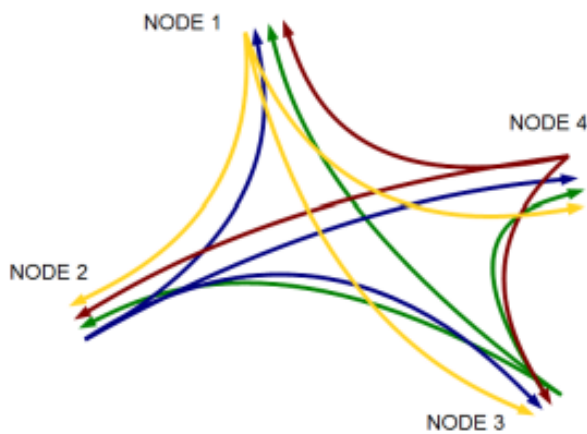


Figure 7 The total traffic flow to a specific destination (Sergio Varela Ramirez, 2013)

1.5.9.1 Traffic elements

The use of the signalized light at intersections plays a major role in increasing the mobility. Creating a signal program with fixed cycle time for each traffic light device helps to obtain a reduction of crash frequency and to increase the mobility for the road users.

Traffic light

Traffic signals are a common form of traffic device to control traffic flow at intersections. At an intersection the traffic is controlled by coloured traffic signals, i.e. red yellow and green light (**Unsupported source type (ElectronicSource) for source Tra04.**)

Roundabout

Roundabouts are intersections with a round structure where the vehicles move in an anticlockwise direction as seen in *Figure 8*. According to the Swedish traffic regulations, the vehicles that are about to enter the roundabout must give yield to the vehicle in the roundabout (Swedish Traffic Administration, 2014).

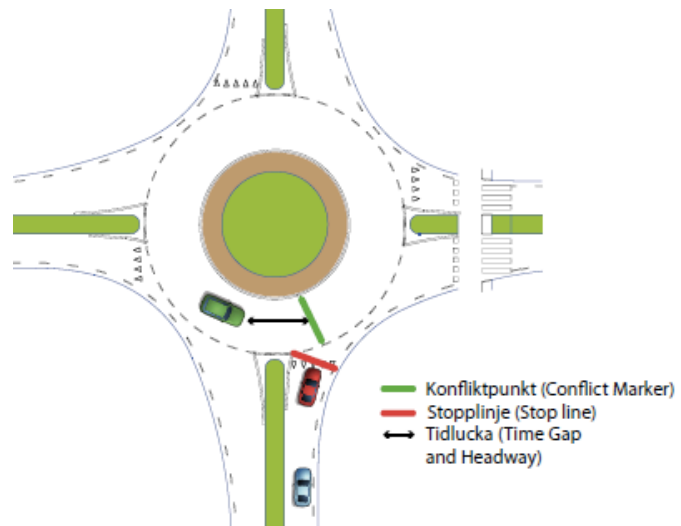


Figure 8 A typical roundabout, vehicles in the round about have priority to the ones that want to enter the roundabout

Bump

Speed bumps are specifically made to reduce traffic speed in a place where there is risk for high speeds. Controlled speed is essential for achieving a safer traffic and decrease the noise at the place. *Figure 9* shows a bump with 1.50 m width. (Swedish Traffic Administration, 2004-05)

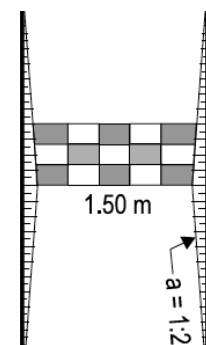


Figure 9
Traffic bump

1.5.10 Traffic noise emission and propagation

Emissions regarding road traffic noise are affected by different factors. Some of these factors are presented in *Table 3*, including the approximate effect on the sound power.

Table 3 Traffic's noise by different factors

| Type of factor | Sound level variation related to the factor [dBA] |
|--|--|
| Vehicle and tire type | Up to 20 dBA |
| Driving pattern | Up to 10 dBA |
| Traffic quantity | 3 dBA for double vehicle numbers |
| Proportion of heavy vehicles | Increase of 0-10% in number of heavy vehicles results in increasing of equivalent level by 3 dBA and maximum level by 8-10 dBA |
| Vehicle's speed | Increased speed from 50 to 70 km/h results in 4 dBA of noise level |
| Road's slope | 2-3 dBA by 50% slope and depending on heavy vehicles' proportion |
| Road surface material | About 4 dBA |
| Road surface conditions (For instance depending on precipitation) | 3 dBA increase by a wet road surface / 3dBA decrease by snow-covered road surface |

Spread of traffic noise emissions depends also on a few factors such as the road design, type and number of vehicles using the road and also the speed and acceleration of the cars that have effect on the sound of car motor. (Swedish Traffic Administration, 2014)

The general factors that help to any kind of sound to spread easier are the surrounding environment, the ground type, the weather and even type of climate in a region. In an urban area with many buildings and hard surfaces, the sound vibrations can spread more easily. This spreading depends also on the type of material used in the constructions in the area. For example concrete and common asphalt are materials that reflect the sound vibrations and

therefore help the noise propagation in a city area. On the other hand grass surfaces, soil ground, trees and other vegetation absorb and moderate sound vibrations. Sound propagation depends also on the weather conditions. These emissions are different on snowy and rainy days. This is because snow absorbs sound vibrations while water and rain reflects them. The effect of climate can be seen by the spread of sound waves by wind direction. This will be a reason for hearing traffic noise differently for instance in two sides of a highway. (Swedish Traffic Administration, 2014)

1.5.11 Car as a noise source

Car as the main cause of noise production on the roads is a point source, which contains different sub-sources. The sound from a car comes from two main sub-sources (Stylianios Kephelopoulos, 2012):

- Noise produced by rolling tires and their contact with the road surface
- Noise produced by propulsion processes inside the car engine

In general, heavy vehicles produce more noise than light vehicles. Light vehicles, which are referred to the vehicles lighter than 3.5 tonnes, stand for about 93% of road traffic and produce 60% of traffic noise. Heavy vehicles, on the other hand, stand for 7% of road traffic amount on the road and produce 40% of the noise emissions.

Depending on car speed, the effect of two sources, which are listed above, varies. In speeds lower than 30-50 km/h, the noise source in a light car is due to the driveline processes. The effect of the rolling noise is dominant at higher speeds. The speed limit is different for heavy vehicles and their rolling noise increase for speeds higher than 50-70 km/h (Stylianios Kephelopoulos, 2012).

1.5.12 Tire type

Tire noise can induce sounds in two ways; mechanically and aerodynamically. Mechanical noise is caused by unevenness in the road surface and the tire's structure. All these irregularities lead to vibrations in the tire carcass. These vibrations radiate noise into the environment that we perceive as unwanted sound. Aerodynamic noise occurs when the tire pushes down air between the pattern and the road surface. Noise through this way is produced by the friction and vibration in the tires. Although today more quiet engines are developed and cars are more aerodynamic, but the tires still generate as much noise as 40 years ago.

1.5.13 Road surface effect

Noise level from the tires increases profoundly with higher car speed. This makes the role of the road surface condition of vital importance (P G Abbott, 2010). In order to keep the noise levels as low as possible, it is necessary to have good road surfaces and maintain high quality roads. The noise level from a road that is in a bad condition can vary up to 10 dB differences. Studies have indicated that the sound equivalent level is affected up to ten times more on a road surface that is in need of maintenance compared to a newly paved road. This would as a result be equivalent to a 10 times more traffic volume. In Sweden, the most common coating ABS16 or ABS11 is rock rich asphalt concrete with a maximum fraction of 16 mm. To resist the abrasion of studded tires and high speeds, a higher stone size is used. The noise on roads with high rock fraction can be expected to be higher than with low rock fraction.

1.5.14 Driving patterns effect

Noise levels are affected by traffic volume. If the traffic volume is decreased by 50%, it will result in a 3dB decrease in noise (Ellebjerg, 2008). A decrease in the volume of traffic will impact the driving pattern by allowing an increase in the number of unhindered drivers. The driving pattern also has a considerable impact on the overall noise level. An aggressive driving pattern with high acceleration leads to an increase in noise level. This increase is further amplified if the vehicle is heavy which is demonstrated in *Table 4*. This can be important to consider when designing a road junction; since certain intersections lead to a driving pattern with a heavy acceleration. For instance, by reducing the acceleration of a car that is travelling 50 km/h from 2m/s^2 to 1m/s^2 , the noise level can be reduced by 3 dBA.

Table 4 The increase/decrease in noise level caused by varying levels of acceleration/deceleration and different vehicle types with speed of 50 km/h, (Ellebjerg, 2008)

| Acceleration/deceleration [m/s^2] | Vehicle type | Noise influence [dB] | Note |
|---|--------------|-------------------------|--------------------------|
| 1 | Light | 1.7 | Moderate acceleration |
| 2 | Light | 4.5 | High acceleration |
| 0.5 | Heavy | 2.1 | Moderate acceleration |
| 1 | Heavy | 4.5 | High acceleration |

| | | | |
|------|------------------|------|--------------------------|
| -1 | Light | -0.8 | Slow deceleration |
| -2 | Light | -1.2 | High deceleration |
| -1.5 | Heavy 2 axles | -4.5 | Moderate deceleration |
| -1.5 | Heavy 3 axles | +4.5 | Moderate deceleration |

1.5.15 Noise calculation by CNOSSOS-EU

According to the standard method for calculating road traffic noise, CNOSSOS-EU, the traffic noise source is produced from four different vehicle categories (Stylianos Kephelopoulos, 2012).

1. Light motor vehicles
2. Medium heavy vehicle
3. Heavy vehicles
4. Powered two-wheelers

Category 1 includes passenger cars; category 2 is vans and smaller trucks, category 3, trucks and busses and category 4, different types of motorcycles. This categorization is based on the fact that traffic noise source is a combination of sub-sources in a vehicle; i.e. rolling noise and propulsion noise and these sub-sources vary in each vehicle category.

For estimation of traffic noise emissions in this method, it is important to specify the location of the point source in the road. This point source which is presented by a vehicle in any of the categories 1, 2, 3 and 4, is assumed in the centre of the road lane and 0.05 m above the road surface as shown in *Figure 10*. (Stylianos Kephelopoulos, 2012)

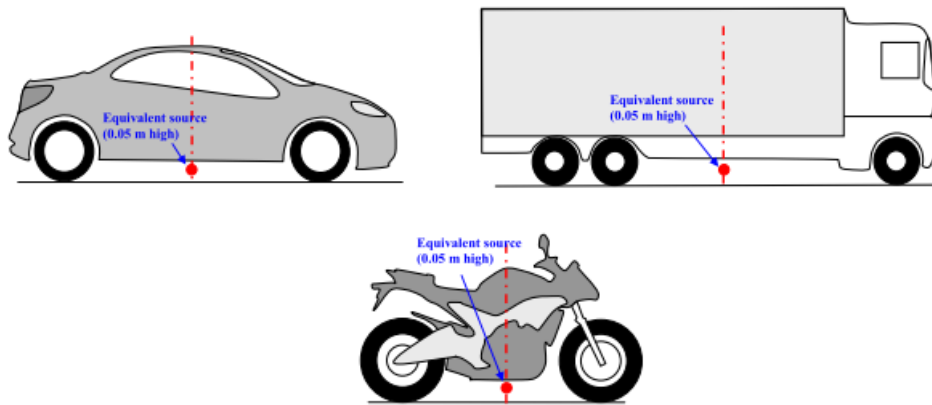


Figure 10 Location of equivalent point source on light vehicles (category 1), heavy vehicles (categories 2 and 3) and two-wheelers (category 4)

In this method, vehicle's category and speed play the most important roles in noise production. The equations that are used in the emission model for an individual vehicle are related to the two main sound sources; "rolling noise" and "propulsion noise" as describes in chapter 1.5.11.

For calculations based on this method, a number of traffic and meteorological conditions are required to be valid. These reference conditions are listed in Table 5.

Table 5 The reference conditions

| | |
|--|---|
| Vehicle speed (v_{ref}) | Constant |
| Road slope | 0, flat road |
| Air temperature, τ | 20 °C |
| Road surface material | Consisting of an average amount of asphalts of the type <i>asphalt concrete</i> and <i>stone mastic asphalt</i> with the aggregate size of 0/11 mm and the age of 2 to 7 years. |
| Road surface conditions | Dry |
| Tires | No studded tires |

A general form of the relation is shown as equation 5. This relation shows the sound power level due to rolling or propulsion process.

$$L_{W,i,mL}(v_m) = A_{i,m} + B_{i,m} \cdot f(v_m) \quad (5)$$

Where,

L_W = sound power

i = the frequency band index which according to CNOSSOS method has a value between the range of 125 Hz - 4kHz for road traffic noise

m = vehicle category 1, 2 or 3

v_m = average rolling speed of each vehicle category m , v_m can be between 20 to 130 km/h

A and B = coefficients dependent on vehicle category¹.

Rolling noise

While the sound source refers to rolling noise, the equation 6 is written in a logarithmic form and the sound power level is shown as $L_{WR,i,m}$.

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m} \cdot \log\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m}(v_m) \quad (6)$$

Propulsion noise

For calculation of sound power level due to propulsion noise, equation 6 is written in a linear form and is shown as equation 7. The sound power level in this case is shown as $L_{WP,i,m}$.

$$L_{WP,i,m} = A_{P,i,m} + B_{P,i,m} \cdot \left(\frac{v_m - v_{ref}}{v_{ref}}\right) + \Delta L_{WP,i,m}(v_m) \quad (7)$$

In both the equations 6 and 7, A and B are coefficients. Corresponding values to A and B depend on different octave bands with regard to different vehicle categories.

Correction coefficients

The equations 6 and 7 are corrected by a series of coefficients in case of dissimilar conditions compared to reference conditions in *Table 5*; for instance if the temperature is higher or lower than 20 °C, or in case of having studded tires or road slope. These corrections help to calculate the precise value of sound power level in every case. The sum of sound power variations due to these corrections is indicated as ΔL_W . Depending on the rolling or propulsion noise, this is respectively shown as $\Delta L_{WR,i,m}(v_m)$ and $\Delta L_{WP,i,m}(v_m)$.

¹ The value is chosen from the appendix tables in the reference descriptions of CNOSSOS-EU method.

$$\Delta L_{WR,i,m}(v_m) = \Delta L_{WR,road,i,m}(v_m) + \Delta L_{studded\ tyres,i,m=1}(v_m) + \Delta L_{WR,acc,i,m} + \Delta L_{W,temp}(\tau) \quad (8)$$

In the equation 8, which refers to rolling noise as the dominant sound source, $\Delta L_{WR,road,i,m}(v_m)$ provides the correction value while having the road surface with different material than the reference material in *Table 5*. $\Delta L_{studded\ tyres,i,m=1}(v_m)$ accounts the difference in sound power while having studded tyres for light vehicles. $\Delta L_{WR,acc,i,m}$ refers to the differences in rolling noise due to acceleration in roundabouts or due to traffic lights and $\Delta L_{W,temp}(\tau)$ counts the correction value while the temperature is below or over the reference temperature shown in *Table 5*.

Correction coefficients that effect on the propulsion noise are calculated by equation 9.

$$\Delta L_{WP,i,m}(v_m) = \Delta L_{WP,road,i,m}(v_m) + \Delta L_{WP,acc,i,m} + \Delta L_{WP,grad,i,m}(v_m) \quad (9)$$

$\Delta L_{WP,road,i,m}(v_m)$ and $\Delta L_{WP,acc,i,m}$ are the correction coefficients related to road surface properties and driving conditions respectively, while the acoustic effect is on propulsion noise. $\Delta L_{WP,grad,i,m}(v_m)$ refers to the differences in sound power due to road gradient.

2 Traffic and noise simulation approach

In order to simulate traffic flow, the computer software VISSIM 6.0 was used. This program was designed by PTV GROUP for traffic simulation purposes in a microscopic scale. The software gives the possibility to study each vehicle's behaviour individually and also to simulate traffic in both 2D and 3D. By means of traffic simulation output, sound power level due to each vehicle as an individual point source is calculated by using the noise calculation method CNOSSOS-EU.

Traffic Simulation

The simulation process by VISSIM is done in different steps:

- i. Locating the background image with the suitable scale
- ii. Choosing the traffic routes and dividing them into shorter segments
- iii. Connecting the different links
- iv. Choosing the precise traffic routes
- v. Providing OD-matrix
- vi. Specifying the traffic flow for each route
- vii. Considering vehicle priorities at intersections (conflict areas)
- viii. Specifying a desired speed for the system
- ix. Adding further details to the model such as measurement points, speed reduction areas and traffic light at essential cases
- x. Running the simulation and printing the desirable output

CNOSSOS-EU and MATLAB

MATLAB, which is a mathematic programming tool, is chosen to calculate noise emission values. The calculation method is briefly called CNOSSOS-EU. The term CNOSSOS stands for **C**ommon **NO**ise **a**SSessment meth**OD**S. This method is developed to be applicable for all main roads in the EU.

The traffic properties such as speed and acceleration are known for each individual vehicle through VISSIM output data. This data is then used as input data in MATLAB for calculation of noise emission.

2.1 VISSIM- Traffic modelling

In this chapter, the traffic simulation functions that are used in this study are described in detail. The topics are ordered according to the processes that are performed to approach the study's aim and are mentioned in the beginning of chapter 6.

2.1.1 Background image

The background map for simulations is based on the latest road design proposal by the Gothenburg Traffic & Public Transport Authority. This map is shown in *Figure 11*.

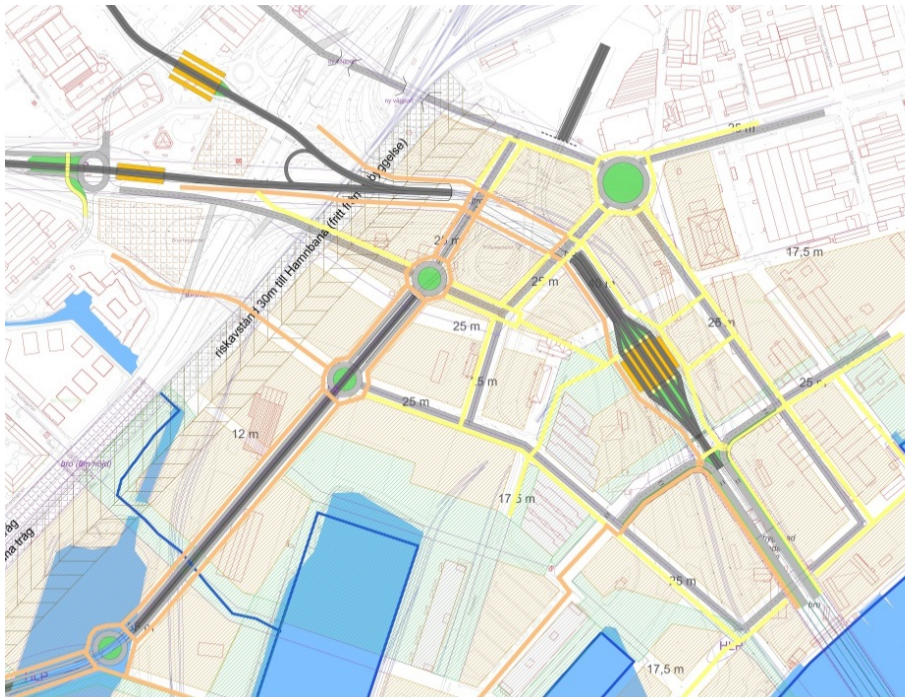


Figure 11 A road design proposal for Frihamnen area in Gothenburg

2.1.2 Links, segments and connectors

Among the total road network in the background image, the highlighted links indicated in *Figure 12* are chosen as the traffic simulation area in this study. Some of the reasons for selecting these links are as follows:

- They are estimated to carry a high traffic flow in the area and therefore constitute a substantial noise source for the environment.
- They are the most trafficked links that connects Gothenburg city centre to the areas Frihamnen and Hisings backa.
- These links are the main links for distribution of traffic into the close neighbourhoods.
- Heavy vehicle traffic and high vehicle speed are more likely in these links

- Offices and buildings will be built close to these links; therefore noise pollution leads to annoyance for residents of these buildings.

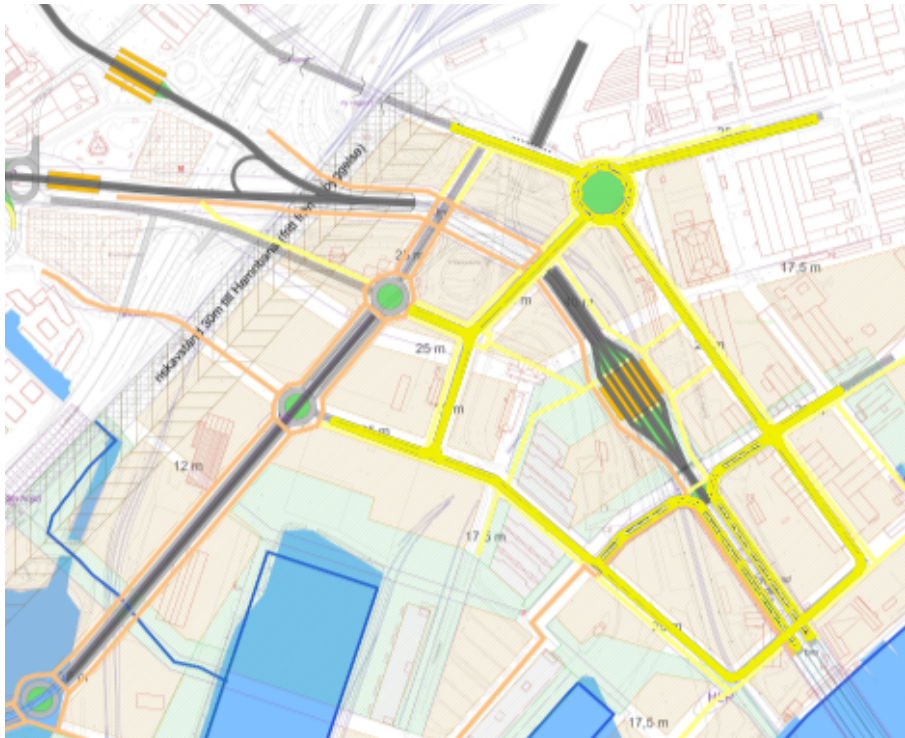


Figure 12 The chosen links for traffic simulations

2.1.3 Segment points

The routes are divided into shorter links and numbered for an easier traffic design. This division is based on the following list and is shown in *Figure 13* with corresponding numbers.

1. The bridge Götaälvsbron to Hisingen (northward)
2. The street toward Ringön area
3. The street Ringövägen
4. The street toward Kvillebäcken area
5. The street Hjalmar Brantingsgatan
6. The southern street that intersects Lundby Hamngata
7. The bridge Götaälvsbron to city centre (southward)

All links contain traffic in both directions except for number 1 and 7. Segment 1 contains one-direction traffic northward while segment 7 southward.

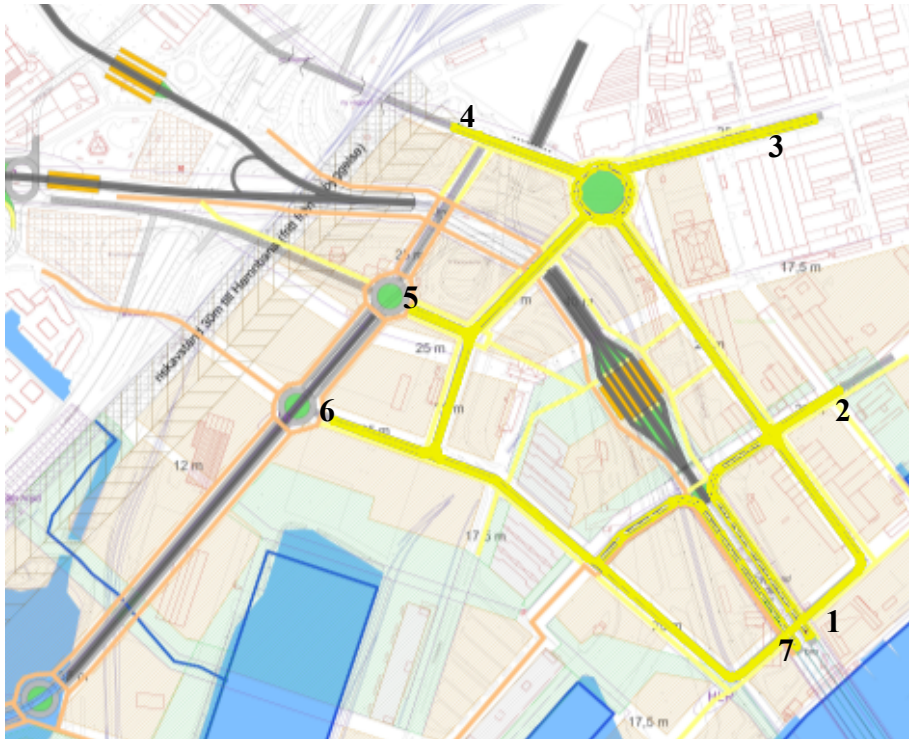


Figure 13 Numbering the segments

2.1.4 Routes and OD-matrix

In order to run a simulation in VISSIM, it is necessary to define routes with start and end points in the traffic flow. In some cases, there is more than one possible route toward an ending point. In such cases, it is important to specify these different possible routes and the proportion of traffic flow passing through each route. One of the two possible routes from point 1 to 5 is highlighted in *Figure 14*.

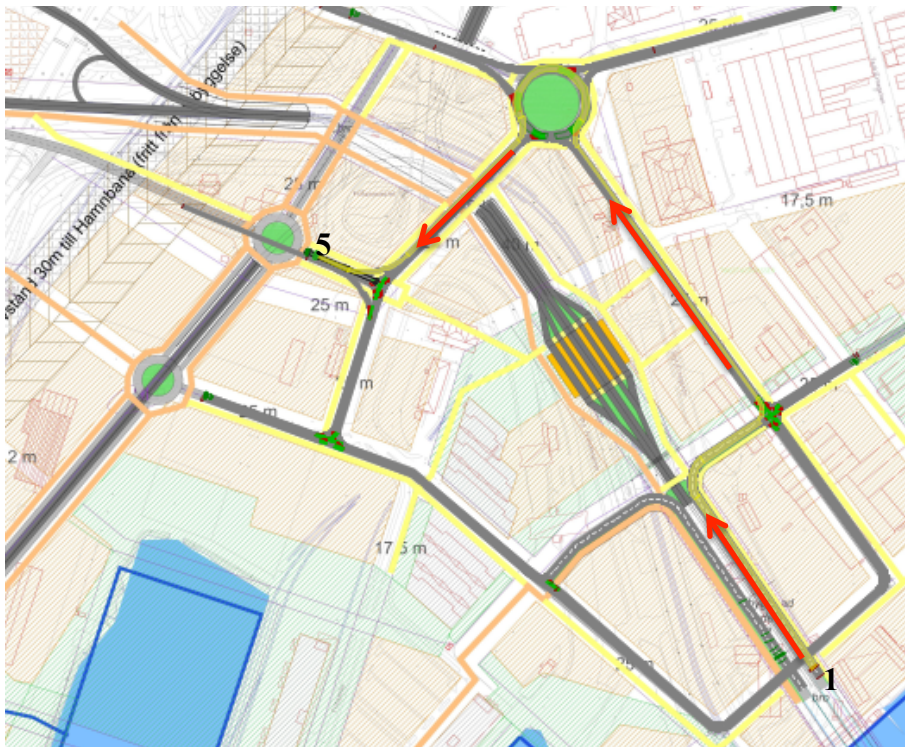


Figure 14 Route 1 to 5, one of the designed traffic routes in the simulation system

The OD-matrix is provided with regard to traffic flow estimation in several routes. The estimation of traffic flow is according to the traffic flow of the current year, 2014, at the area. This is based on the flow that is exchanged between the city centre and Hisingen, which pass through the bridge Götaälvbro.

The OD-matrix for the traffic system in this study is designed so that it matches the registered traffic flow data corresponding to maximum afternoon traffic over the bridge Götaälvbro. The total flow over the bridge in the maximum afternoon hour is estimated to an average value of 2650 vehicles per hour during the years 2004 and 2013 (Göteborgs stad, n.d.). According to the same database, average traffic flow from the city centre toward the bridge is calculated to 1130 vehicles per hour, from the bridge toward the city centre, the average flow is 1520 vehicles per hour. The total flow on the bridge is estimated to be 2700 vehicles per hour, of which 1200 vehicles per hour pass link 1 which is from the centre to the bridge and 1500 vehicle per hour in the opposite direction, link 7.

There are other proportion of vehicles that enter the system through the links 2, 3, 4, 5 and 6. This leads to a total traffic flow of 3280 vehicles per hour in the whole simulation system. Table 6 shows the designed OD-matrix according to this traffic flow.

Table 6 The designed OD-matrix for traffic flow at Frihamnen with regard to maximum afternoon traffic

| Origin/ Destination | 1 | 2 | 3 | 4 | 5 | 6 | 7 | From |
|------------------------|---|-----|-----|-----|-----|-----|------|------|
| 1 | 0 | 50 | 190 | 450 | 450 | 50 | 10 | 1200 |
| 2 | 0 | 0 | 25 | 30 | 15 | 5 | 75 | 150 |
| 3 | 0 | 5 | 0 | 30 | 25 | 5 | 165 | 230 |
| 4 | 0 | 50 | 50 | 0 | 50 | 50 | 600 | 800 |
| 5 | 0 | 40 | 40 | 80 | 0 | 40 | 600 | 800 |
| 6 | 0 | 0 | 10 | 20 | 20 | 0 | 50 | 100 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| To | 0 | 145 | 315 | 610 | 560 | 150 | 1500 | 3280 |

Traffic flow distribution from link 1 to other destinations has the highest traffic volume among the routes with other start point. The flow is 1200 vehicles per hour which signifies the number of vehicles that pass the bridge toward Hisingen. It is also evident that the last link, number 7, that connects Frihamnen to Gothenburg city centre through the bridge, is the most trafficked link with its total flow of 1500 vehicles per hour. The main percentage of traffic volume in the system flows between the links 1, 4, 5 and 7. Link 4 and 5 are counted as the next main links after number 1 and 7 for distribution of traffic. This is seen in the OD-matrix, traffic flow from and to the points 4 and 5 have the highest volume after point 1 and 7.

2.1.5 Conflict areas

There are four intersections and one roundabout in the model that can cause obstacles in the traffic flow. Therefore, priority rules are defined manually at junctions. The related tool in VISSIM for these manual regulations is called *conflict areas* and gives the possibility to define the priorities by green and red colour when two streets collide with each other. These definitions are done in the program before running the simulations. An example of these settings is seen in *Figure 15*.



Figure 15 The first intersection in the system after link 1 with priority settings

These colours indicate that the car passing through the green path has the priority to the car in the red path. These priorities have a significant role in increasing or decreasing traffic queues. Therefore choosing the most appropriate design according to the traffic rules is essential. In this study, the priority design at the conflict areas are according to the Swedish traffic regulations.

2.1.6 Vehicle speed

Before running a simulation in VISSIM, a desired vehicle speed should be defined for each vehicle category. This is the maximum speed that the vehicles in the whole system are supposed to have when not hindered by obstacles such as traffic lights or traffic queues. The desired speed 50 km/h and 70 km/h are considered for light and heavy vehicles in different cases.

2.1.7 Further traffic details in VISSIM

There are additional features in the program for changing the desired speed manually in a specific area. Examples of these kinds of tools are *bumps* and *speed reduction areas*. Speed reduction area is the name of a low speed stretch for reducing the speed along a longer distance than a bump; for example before or in front of a school or a hospital.

These tools are applied in this study in order to reduce noise emissions at particular areas, such as the use of the speed reduction feature for roundabouts.

Another feature that can be altered in VISSIM is that of traffic lights which is essential for the junctions with high traffic flows.

2.1.8 Measurement points

Measurement points or *data collection points* in VISSIM is a feature that is used for any desirable section of a link for collecting traffic properties of the vehicles that pass each measurement point; such as speed, acceleration, quantity, etcetera.

Data collection points are used in this study to collect traffic data regarding speed and acceleration of the vehicles that move in the system during the simulation. 290 data collection points are applied and the collected data is used in MATLAB for analysis of noise emission at the location of these points.

2.1.9 Output data

During the simulation time, it is always possible to make a copy of instantaneous properties of the traffic such as vehicle coordinates, vehicle categories or speed. The type of desired property is chosen among a list of ‘‘attributes’’. This means that the chosen attributes will be shown in the simulation window. *Figure 16* shows an example of the filtering window in VISSIM. The desirable properties are chosen from the list in the left window and are moved to the right list.

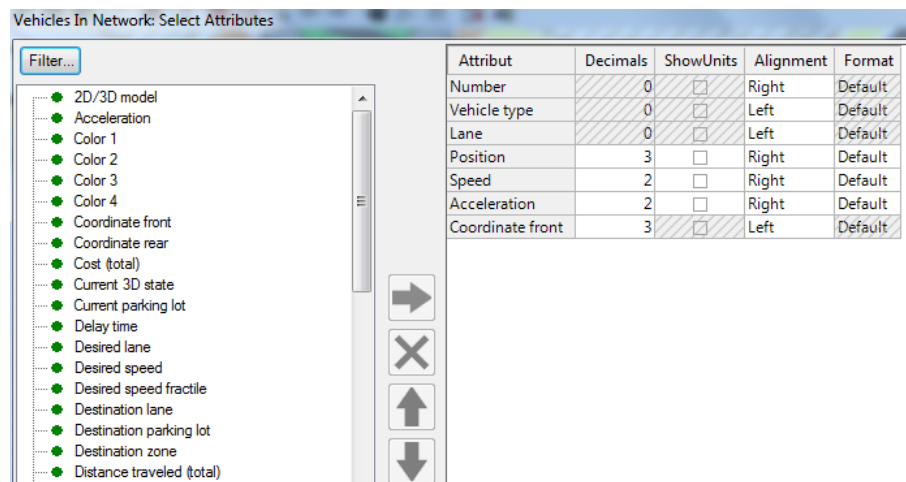


Figure 16 Traffic attribute selection window in VISSIM

After choosing the required properties, the corresponding data are printed continuously during the simulation time. An example of the printed data while running VISSIM simulation is shown in *Figure 17*.

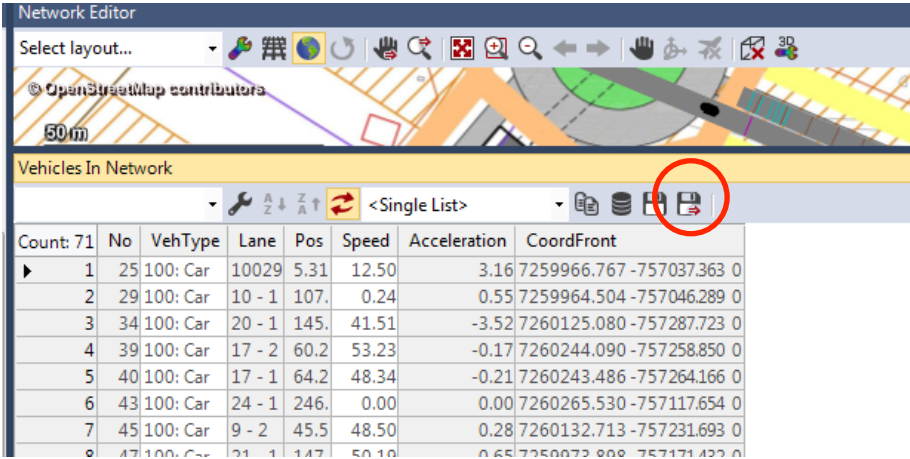


Figure 17 Printed output data in VISSIM

By clicking on the copy button, indicated by the red circle in *Figure 18*, the printed data corresponding to the moment will be saved. The attributes that are chosen for the simulation in this study are listed in *Table 7*.

Table 7 The filtered output data that has been selected from the attribute list in VISSIM.

| Output data for each vehicle in the system | Indicator/value |
|--|--|
| Counter | The number of objects* in the system |
| Number | The individual number that is dedicated to each object* by VISSIM |
| Category | 100 as the indicator of light vehicles (Category 1) 200 as the indicator of heavy vehicles (Category 3) |
| Position | The distance that the vehicles have passed from the segment’s start point [m] |
| Coordinate | The coordinates of the vehicle in the system [m] |

| | |
|---------------------|---|
| Speed | Vehicle speed [km/h] |
| Acceleration | Vehicle acceleration [m/s ²] |
| Lane | Output data in the lane column indicates which start and end point the vehicle is going to pass according to the OD-matrix. The corresponding value is shown in the form a-b where <i>a</i> is the start link and <i>b</i> is the end link. |

*An object in this study refers to a vehicle or a measurement point for which the related properties are received

Counter is the attribute that counts the number of desired object in the simulation. For example, the vehicles are counted according to their entrance order into the system.

Number is the specific number that the program defines for each object according to the object creation order and is individual for each of them.

Two vehicle *Categories* are considered in this study; category 1, which are light vehicles, and category 3, which are heavy vehicles. VISSIM defines light vehicles in the system by the code 100 and heavy vehicles by the code 200.

When the study objects are vehicles and the output data related to this object is desired, the *Position* of each vehicle will indicate the vehicle's current distance from the entering point to the system.

The *Coordinate* of each individual object, regardless its type, is defined automatically by the program as the simulation is running and the data is registered in the related column.

Speed and *Acceleration* of each vehicle in the system is registered at every moment of the simulation. These data are the most essential output data in this study. This is because these factors carry the main role in creation and variation of noise emissions.

The data that VISSIM registers in the column *Lane* shows the route at which a vehicle travels during the simulation time. The information in this column is not necessarily used in MATLAB but it is helpful in controlling the system while the simulation is running.

2.2 Noise emission modelling

CNOSSOS method is applied through MATLAB that uses the traffic simulation output to calculate the sound power level in dBA. This means that output data from VISSIM is the input data for noise calculation through CNOSSOS.

There is the possibility to plot the final results on the map at each vehicles position. This is because vehicles' coordinates are accessible in VISSIM. By having coordinates from VISSIM and emission values in MATLAB, the plot can be provided. This plot shows emissions as circles that have various diameters. The circle size is according to the emission value. The higher the sound power level is, the larger the circle is plotted. To adapt the received plot with the background map, the program Photoshop is also used.

CNOSSOS in MATLAB

MATLAB codes are applicable for three vehicle categories 1, 2 and 3, which correspond to light, medium heavy and heavy vehicles respectively. However, only category 1 and 3 are considered in the traffic model. In calculation processes, the reference conditions that are mentioned in chapter 1.5.15 are assumed according to *Table 8*.

Table 8 Defined reference conditions as the requirements in CNOSSOS method

| | |
|---|--|
| Vehicle speed (v_{ref}) | Constant = 70 km/h |
| Road slope | 0, flat road |
| Air temperature, τ | 8 °C (Average temperature in Gothenburg) |
| Road surface material | According to CNOSSOS method default. See chapter 1.5.15 |
| Road surface conditions | Dry |
| Tires | Normal / Studded |

In this study, air temperature has been corrected since the annual average temperature in Gothenburg is 8 C while the default value in CNOSSOS is 20. Also noise emissions in scenarios that consider studded tyres are calculated by the correction related to studded tyres. The reference vehicle speed, v_{ref} , is set at a constant value of 70 km/h. Other factors such as road slope, surface material and condition, air temperature and type of tyres are assumed as default values in CNOSSOS.

2.3 Traffic design and scenarios

In order to approve the presented tool in this study for calculation of sound emissions, two methods are considered. Each method results in a series of related scenarios.

After running the traffic simulation by the defined routes and OD-matrix, traffic queues appeared at some points. To make the traffic model practical, a series of traffic adjustments are carried out to avoid long queues. To moderate the traffic queue at junction 2, two ramps divide the right-turn traffic from the straight-going traffic. Moreover, traffic light is also applied at this area for improving the traffic solution. These ramps are highlighted in *Figure 18*. These solutions are constant during both methods.

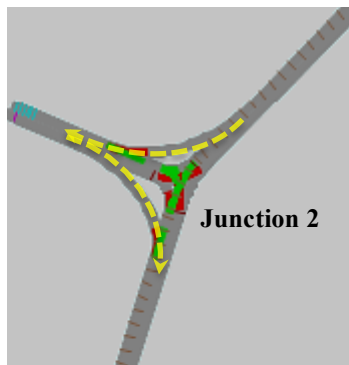


Figure 18 Ramps at junction 2

2.3.1 Method 1

In the first method, the whole area is assumed in the traffic simulations. The traffic routes and traffic flows in the system are according to the designed OD-matrix that is described in chapter 2.1.4. Traffic simulations output in this step corresponds to an instantaneous traffic flow, which means that the output traffic data in a random moment is derived. This data is used for calculating noise emission at the taken moment.

MATLAB prints the emissions regarding each vehicle at its position and plot the noise map according the vehicles' coordinates. The instantaneous data is derived twice intended for two desired speeds 50 km/h and 70 km/h.

2.3.2 Method 2

Method 2 is developed to present more practical results in comparison to method 1.

In this method, a traffic pattern is presented along a chosen route and in one direction with start and end points on the bridge according to *Figure 19*.



Figure 19 The chosen route in method 2

The reason for choosing this specific route is that it carries the main traffic flow in the area and contains all the four junctions and the one roundabout in the system that cause more challenges in the simulation.

This route is divided into 289 five-meter sections with 290 measurement points as observed in *Figure 20*. Points 1, 100, 200 and 290 are also shown in this figure.

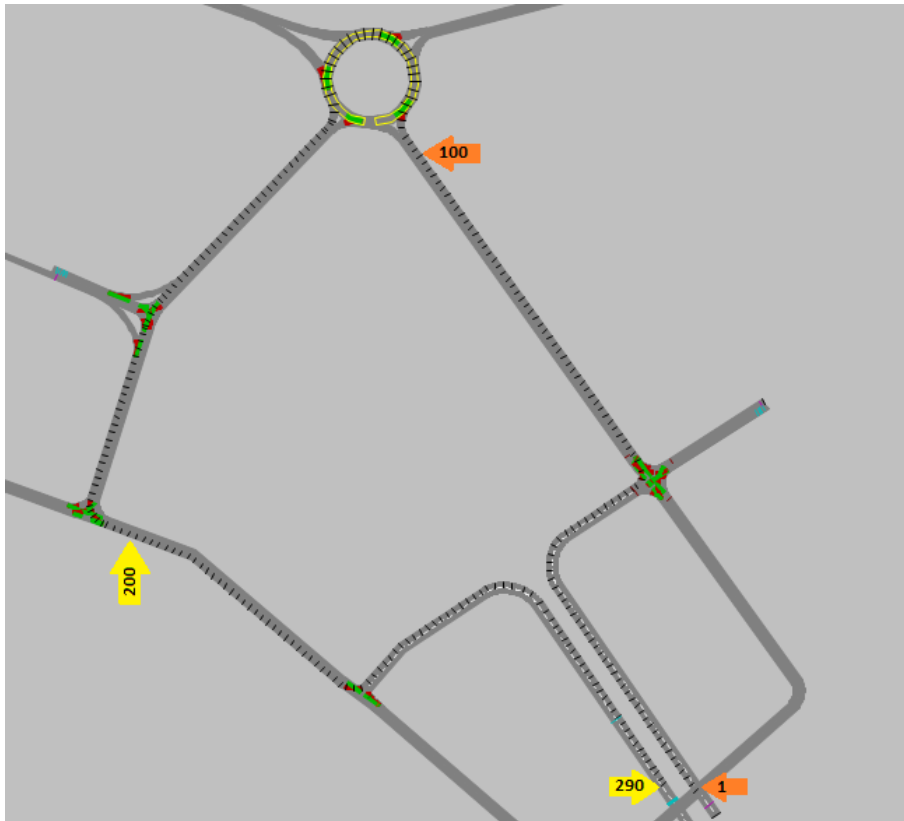


Figure 20 Division of the chosen route by 290 measurement points

Based on using measurement points in method 2, the VISSIM output has some differences compared to the method 1.

In method 1, the studied objects are light and heavy vehicles in a dynamic system and the results refer to instantaneous speed and acceleration. In method 2, the studied objects are measurement points and the results refer to average speed and acceleration of all light vehicles that pass each measurement point. The average speed and acceleration considers the simulation period and the calculation is automatically done by VISSIM. The results consider only light vehicles because the average sound power level containing both light and heavy vehicles will give a less precise result.

In method 2, input data for calculating noise emissions should include average speed, average acceleration, number of each measurement points and vehicle type. The final results will be the average sound power level for each measurement point due to light vehicle traffic.

These results are presented in two-dimensional graphs with the horizontal axis corresponding to the number of measurement points and the vertical axis corresponding to the calculated sound power level.

Method 2 is approached in two parts. In the first part four scenarios are created based on the vehicle speed and tyre type. Details of these scenarios are shown in *Table 9*. The results of these scenarios are compared with each other.

Table 9 Scenarios in method 2

| Scenarios/driving conditions | 50 km/h | 70 km/h | Normal tyres | Studded tyres |
|------------------------------|---------|---------|--------------|---------------|
| Scenario 1 | X | - | X | - |
| Scenario 2 | - | X | X | - |
| Scenario 3 | X | - | - | X |
| Scenario 4 | - | X | - | X |

In the second part, scenario 1 is chosen and called as ‘‘basic model’’ for traffic analysis with purpose of noise emission reduction. The analyses are provided with regard to highest sound emission levels on the corresponding graph and are performed through applying traffic adjustments such as speed reduction tools or traffic lights.

For a more organized analysis, the chosen route is divided into three minor segments; the first segment from point 1 to 100, the second segment from point 100 to 200 and the third segment from point 200 to 290 as presented in *Figure 20*. This division leads to a closer look at each segment of the route and attempts to control the possible effect of traffic changes in one area on other areas.

According to the results of emissions due to basic model, scenario 1, three traffic solutions are chosen for segment 1 and 2 respectively and 1 solution for segment 3. The most proper solution corresponding to each segment is chosen for a last simulation containing a solution mixture to lower the graph for the entire route.

3 Results and analysis

In this chapter, simulation results and analyses are described.

At the first step, the noise maps related to method 1 and at the second step, results of method 2 are shown. At the final step, images and graphs corresponding to the sound power reduction due to traffic regulations are presented.

3.1 Method 1, Instantaneous noise emissions

The noise emissions due to the traffic with the two desired speeds 50 km/h and 70 km/h are plotted separately in two maps. The tyre type is considered as normal in both simulations.

3.1.1 Speed 50 km/h

The noise map of the whole area with regard to a random moment, while the desired vehicle speed is 50 km/h, is shown in *Figure 21*.

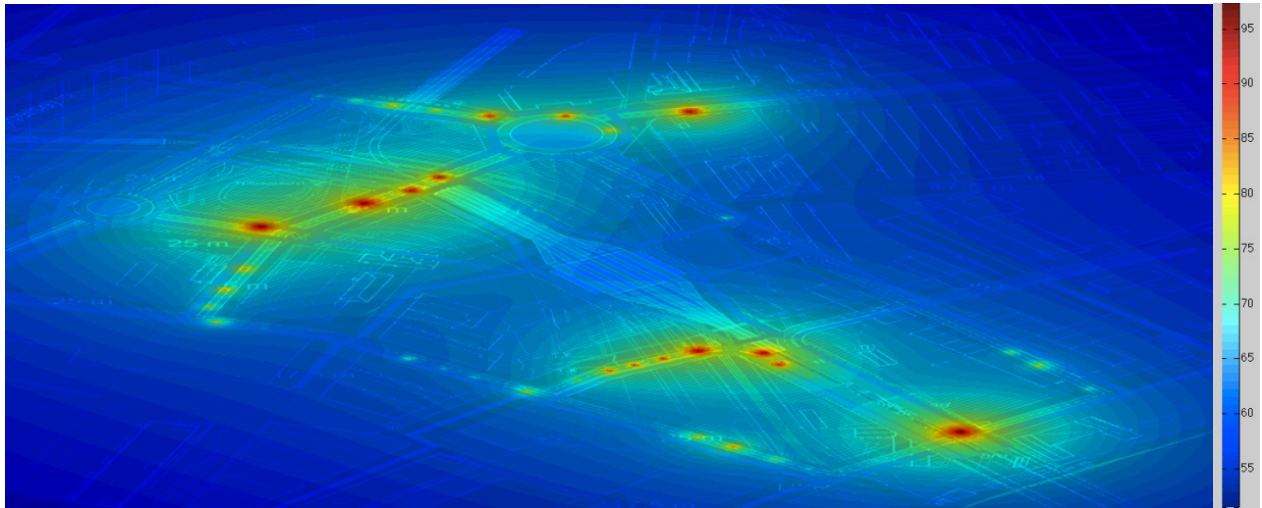


Figure 21 Noise map of a random moment according to traffic simulation with desired speed of 50 km/h

In this figure some areas along the routes are facing higher emissions. As seen in the map guide, yellow colour indicates sound power level 80 dBA while the orange and red points indicate higher sound power level reaching almost 100 dBA.

The circles with the largest diameters are located on the bridge and near junction 2. These points indicate the highest noise emission in the area at the taken moment..

3.1.2 Speed 70 km/h

The noise map of the whole area regarding a random moment, while the desired speed is 70 km/h, is shown in *Figure 22*.

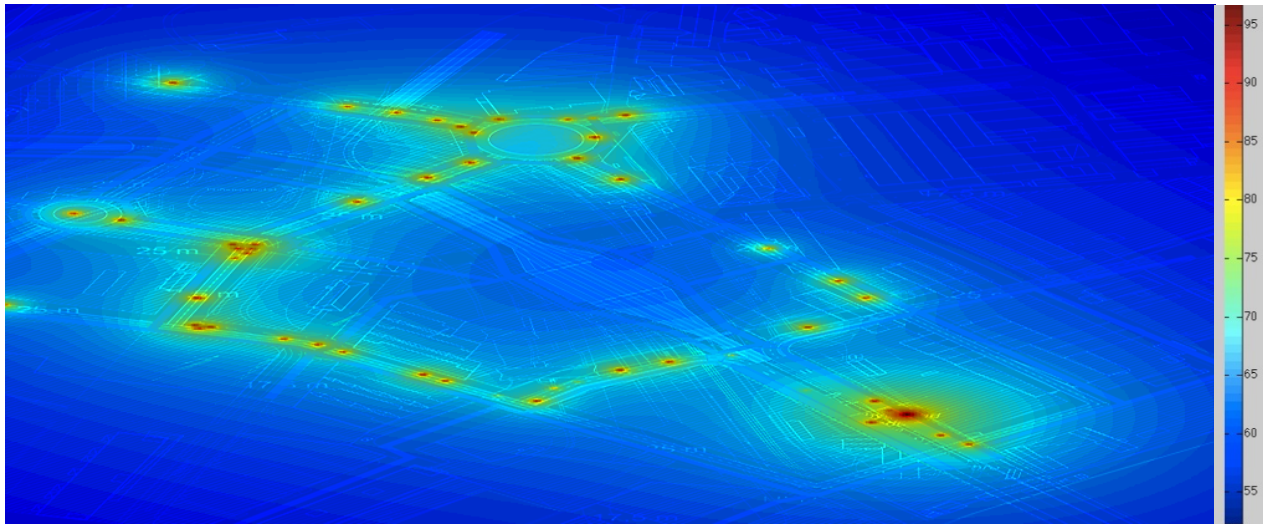


Figure 22 Noise map of a random moment according to the simulation with desired speed of 70 km/h

The map according to the vehicle speed 70 km/h also indicates high emissions at some points.

3.2 Method 2, Average noise emissions

In this section, average sound power level that is calculated at each measurement point is presented by respective images and graphs through four scenarios and comparisons between relevant results are carried out.

3.3 Four scenarios

The plotted graphs related to four scenarios are individually shown and described. The route chosen for the scenarios is shown in *Figure 23*. Every 10 measurement points is highlighted by its associated number and each of the four junctions are shown by numbers 1, 2, 3 and 4.

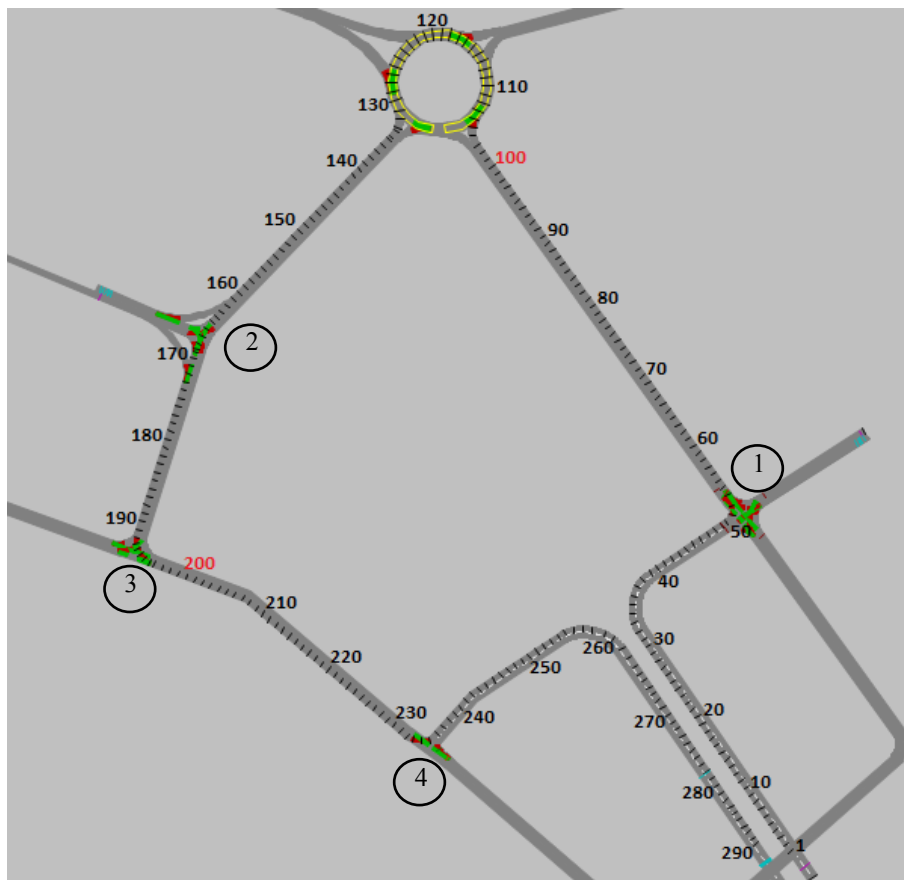


Figure 23 Numbering of measurement points and location of junctions

3.3.1 Scenario 1, 50 km/h and normal tyres

The initial conditions in scenario 1 are speed 50 km/h and normal tyre type. The results are shown in *Figure 24*.

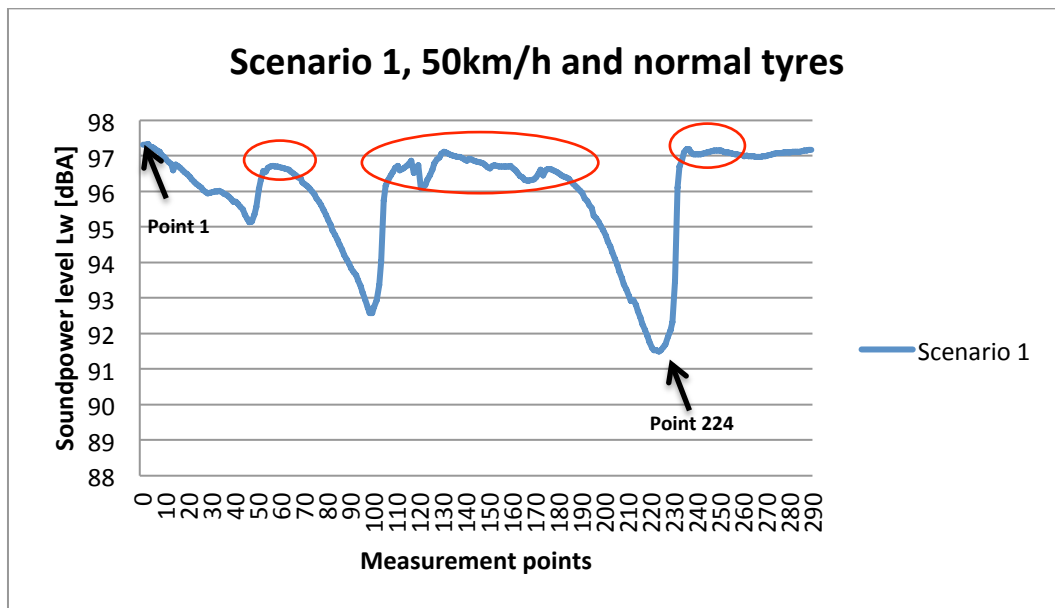


Figure 24 Sound power level with regard to measurement points in scenario 1

According to this graph, the highest average sound power level is 97.28 dBA and is located at measurement point 1. This point is located exactly after the bridge at the entrance area to the system. The lowest sound power level is at the point 224 with 91.49 dBA. This point is located almost 30 meters before junction 4.

Moreover, the points at the entrance and exit parts of the system as well as several other peaks that cause an emission higher than 96 dBA are marked by red circles. The first peak is in the measurement point interval 50 to 70 with a maximum emission of 96.71 dBA at point 57. These points are located at junction 1 and 100 meters ahead. The second area that contains high emissions includes a larger interval that is located between the points 105 and 185. The first point of this interval is located at the entrance of the roundabout and the last point is located before the third junction in the area. The position of these points are observable in Figure 23. The highest peak in this interval reaches 97.1 dBA and is located at point 131.

The third peak that shows high emission values is in an interval between the point 235 and the last point of the route. The area inside the second red circle shows a maximum noise emission of 97 dBA at its peak which is point 237. This area is located at junction 4 where vehicles turn toward the bridge.

Figure 25 indicated the same graph related to sound power level in scenario 1 in relation to speed changes along the route.

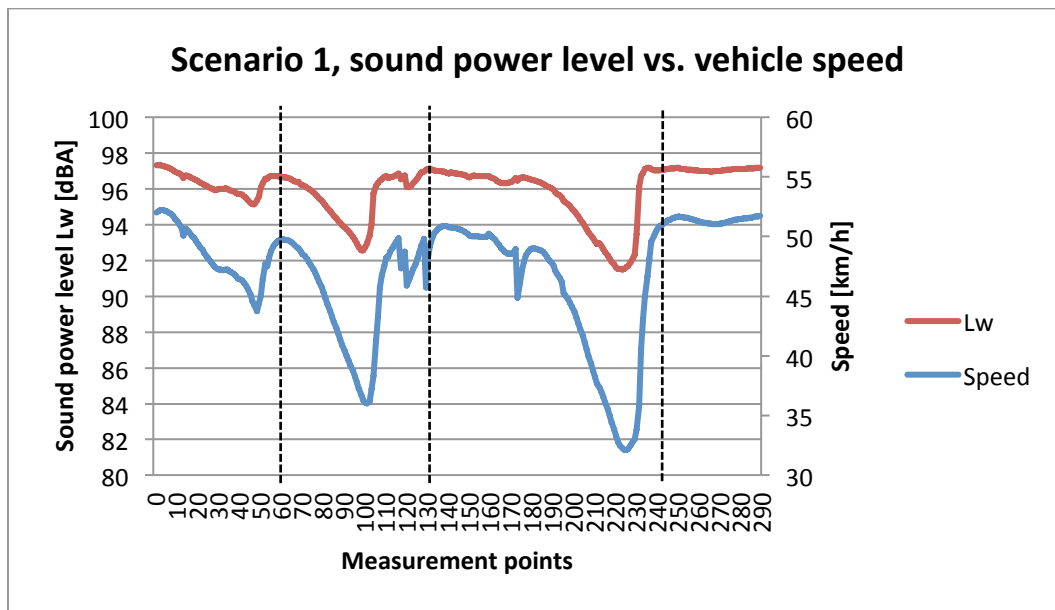


Figure 25 Sound power level and vehicle speed in scenario 1

According to this figure, the peaks in both graphs are located on common measurement points. The black dashed lines in Figure 25 show these peaks on both diagrams.

The reason for the emission peaks is likely to be high speed and acceleration at each respective area. For a closer look Figure 26 shows the acceleration variations along the route.

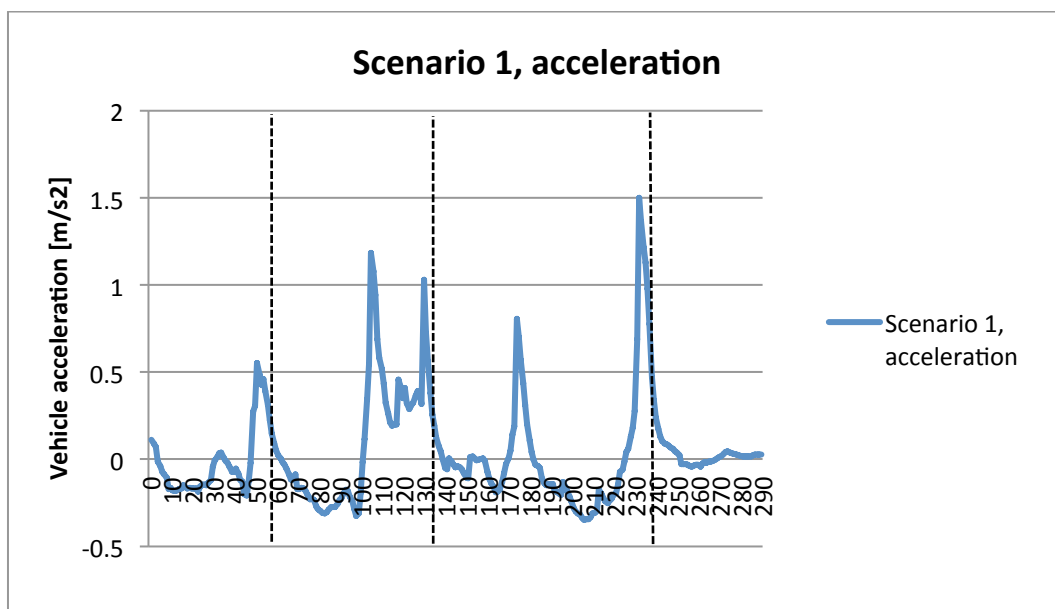


Figure 26 Vehicle acceleration in every measurement point in scenario 1

The black dashed lines are located at the points with noise emission peaks. The complete output data for this scenario is available in Appendix 1.

3.3.2 Scenario 2, 70 km/h and normal tyres

Noise emissions at measurement points with vehicle speed 70 km/h and normal tyre type is presented in the graph in *Figure 27*.

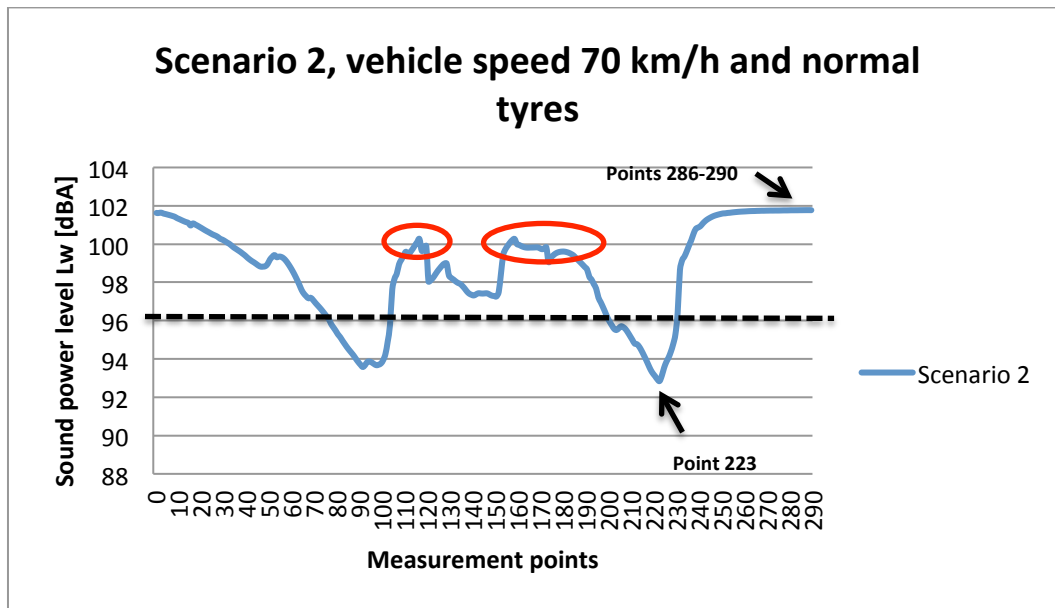


Figure 27 Sound power level with regard to measurement points in scenario 2

In this diagram, points 286-290 has the highest sound power level at 101.77 dBA. The lowest value is at point 223 with a value of 92.84 dBA..

As seen in *Figure 27* the major part of the area has noise emissions higher than 96 dBA, reaching almost 101.77 dBA at the highest peak. This area includes the points located above the black dashed line in the figure.

The two peaks that are shown by red circles in the figure are located between the point intervals 110-125 and 155-185 that are respectively located along the roundabout and at junction 2.

3.3.3 Scenario 3, 50 km/h with studded tyres

Noise emission levels due to light vehicle traffic with speed 50 km/h, which of them 48.1% have studded tyres, are indicated in *Figure 28*.

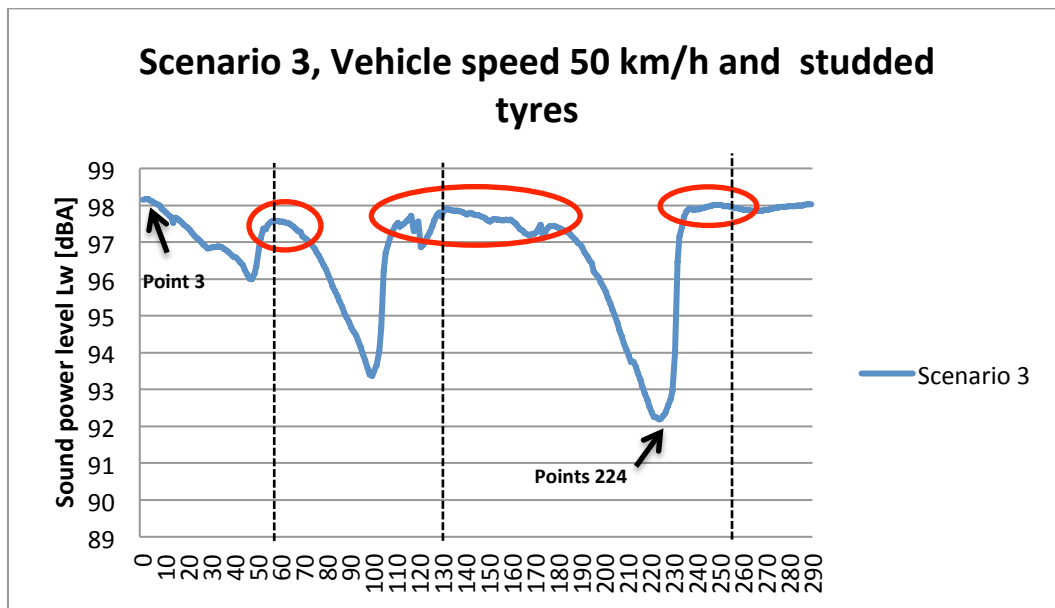


Figure 28 Traffic noise emissions according to scenario 3

The highest sound power level in this scenario is at point 3 with the value of 98.17 dBA. As seen in *Figure 23*, this point is located at the beginning of the route. The lowest emission is 92.18 dBA at point 224.

Some other peaks that are above 96 dBA are indicated by red circles. These areas are located inside the same intervals as scenario 1 but with an entirely higher sound emission along the whole route. The highest sound power level inside the first red circle is 97.57 dBA and is located at point 58 which is located after junction 1.

The highest sound power level at the area inside the second red circle is 97.88 dBA at point 132. The highest sound power level inside the third peak is about 98 dBA between the points 240 and 253. Black dashed lines indicate these peaks at respective points.

The reason for variation of the graph in this scenario is likely to be similar to scenario 1 but with entirely higher emissions due to the proportion of studded tyres in the system.

3.3.4 Scenario 4, 70 km/h with studded tyres

Noise emission due to light vehicle traffic with the speed 70 km/h, of which 48.1% have studded tyres, is indicated in *Figure 29*.

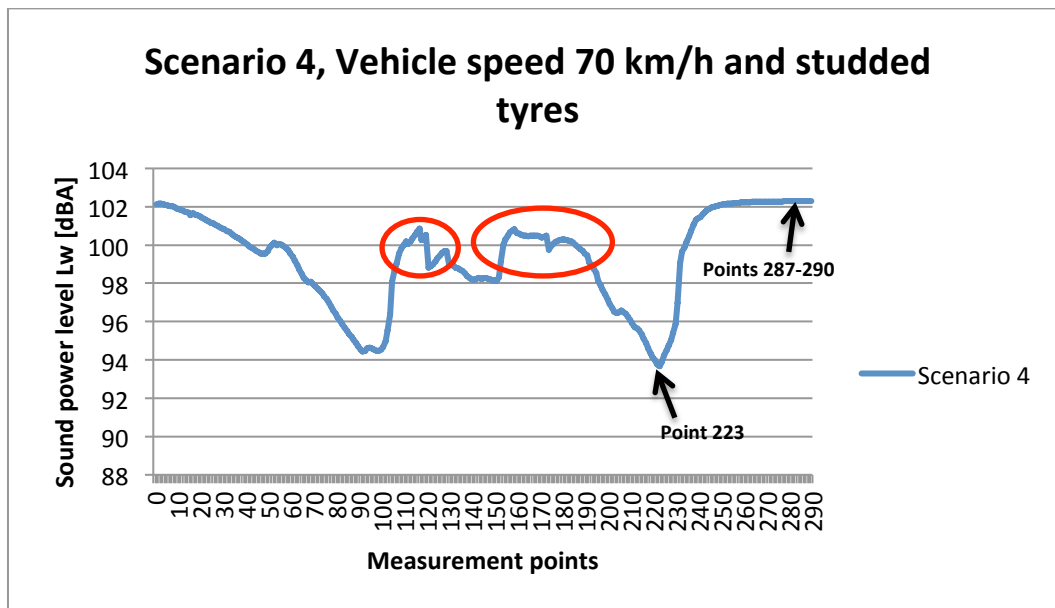


Figure 29 Traffic noise emissions according to scenario 4

The highest emission level in this graph is related to the last four points, i.e. points 287-290 with a value of 102.3 dBA. The lowest emission is 93.66 dBA at point 223.

Two other peaks in the area are also highlighted by red circles. These areas are the same peak areas as in scenario 2 but with higher values in the diagram. The highest sound power level in the first area is 100.85 dBA at point 117 and in the second area is 100.84 dBA at point 159.

3.3.5 Scenario comparison

Figure 30 contains the graphs corresponding to scenarios 1 and 2, it shows the simulation results for speed 50 km/h and 70 km/h and normal tyres.

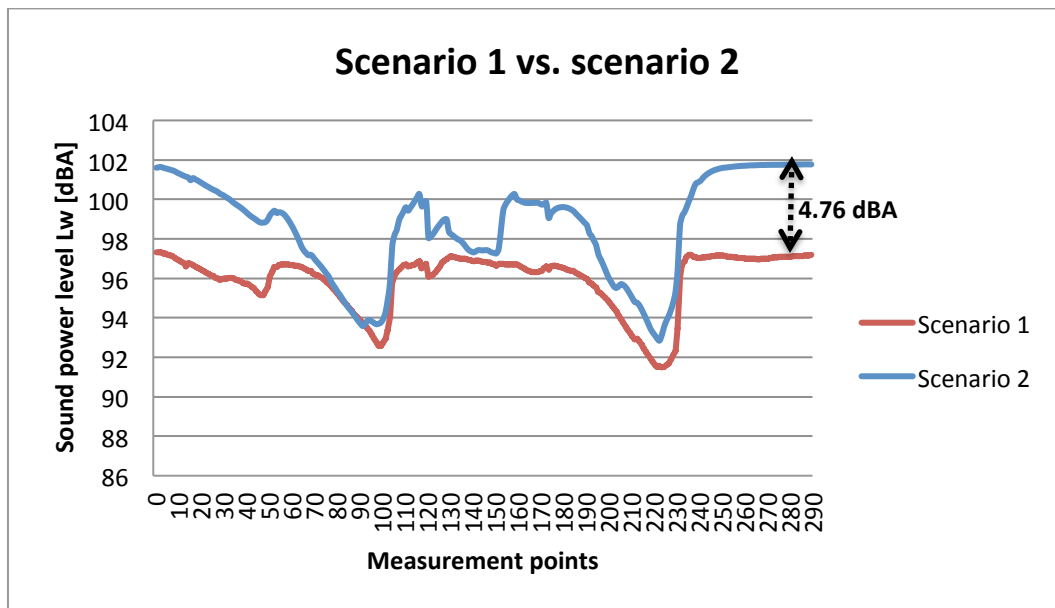


Figure 30 Comparison between noise emissions with regard to desired speed change

As shown in this figure, the upper graph that refers to vehicle speed 70 km/h shows higher emissions along the entire route compared to the lower speed 50 km/h.

Analysing the output data in both scenarios shows that the emission at point 268 has the highest difference by 4.76 dBA. For analysing the relation between vehicle speed differences and noise emission differences, Figure 31 is provided.

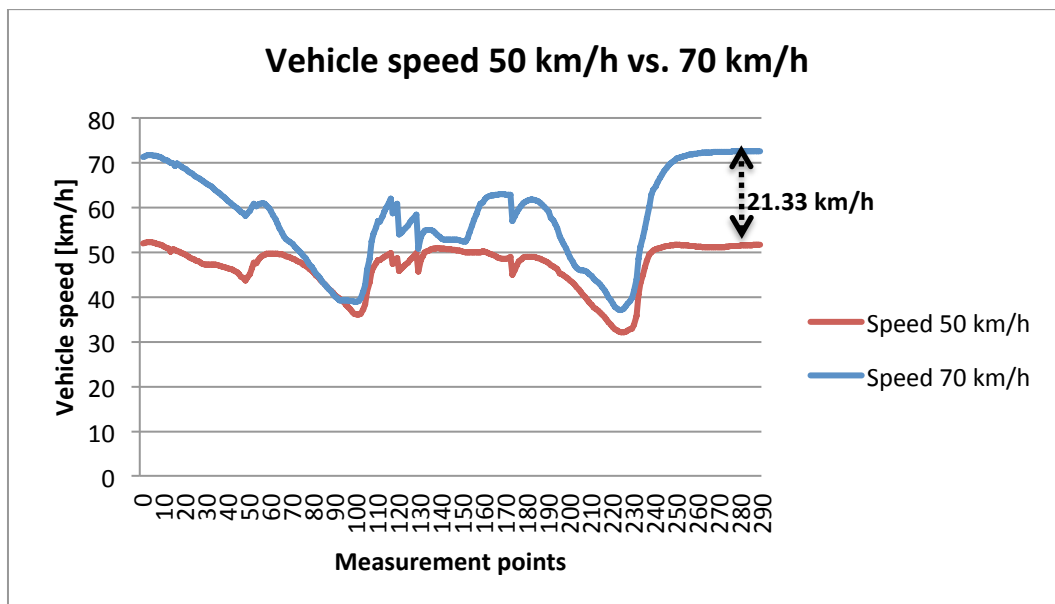


Figure 31 Speed variations in scenario 1 and scenario 3

Accordingly, the area with the highest emission difference also shows the highest speed difference. At point 268, the speed difference is 21.33 km/h as shown in the figure.

Another comparison is between scenario 1 and scenario 3. In both scenarios the vehicle speed is equal (50 km/h) but the tyre type is different which causes differences in noise emissions. These differences are illustrated in *Figure 32*.

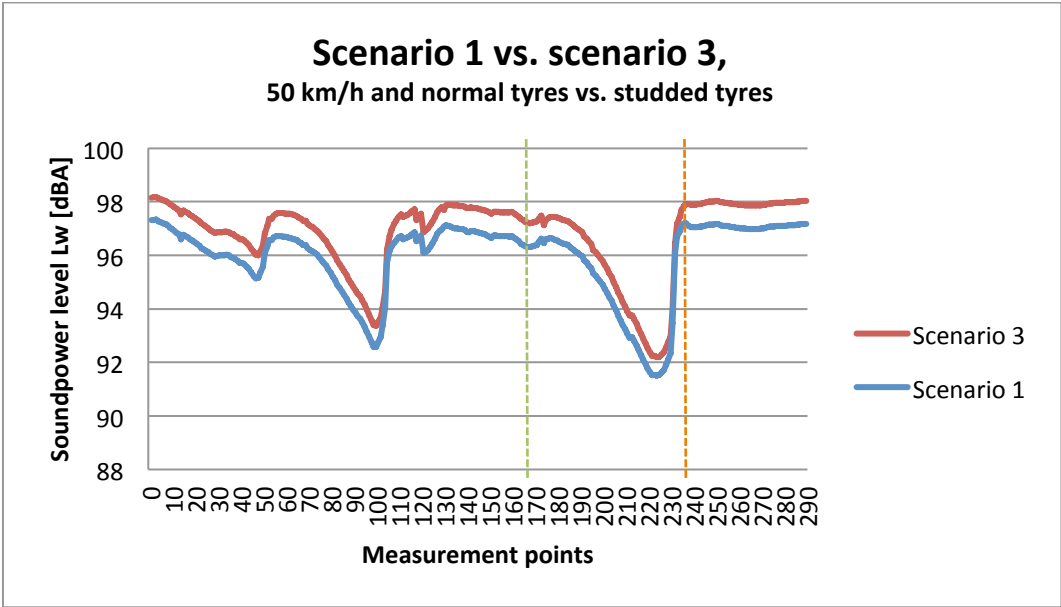


Figure 32 Comparison between noise emission due to similar vehicle speed 50km/h and different tyre types

The graph related to the simulation that contains vehicles with studded tyres show higher noise emissions with an average difference of 0.84 dBA.

The maximum difference is 0.91 dBA at point 164. This point, which is highlighted by a green dashed line in the graph, is located exactly before junction 2 where acceleration variations are expected. The minimum difference is 0.35 dBA at point 232 which is located exactly before junction number 4 and is marked by an orange line in the graph.

3.4 Analysis on scenario 1 for noise level reduction

The graph of scenario 1 is shown again in *Figure 33*, dividing the traffic route into three main segments: 1, 2 and 3. The result of the noise emission reduction is presented with regard to each segment's properties. The complete output data for basic graph is available in Appendix 1.

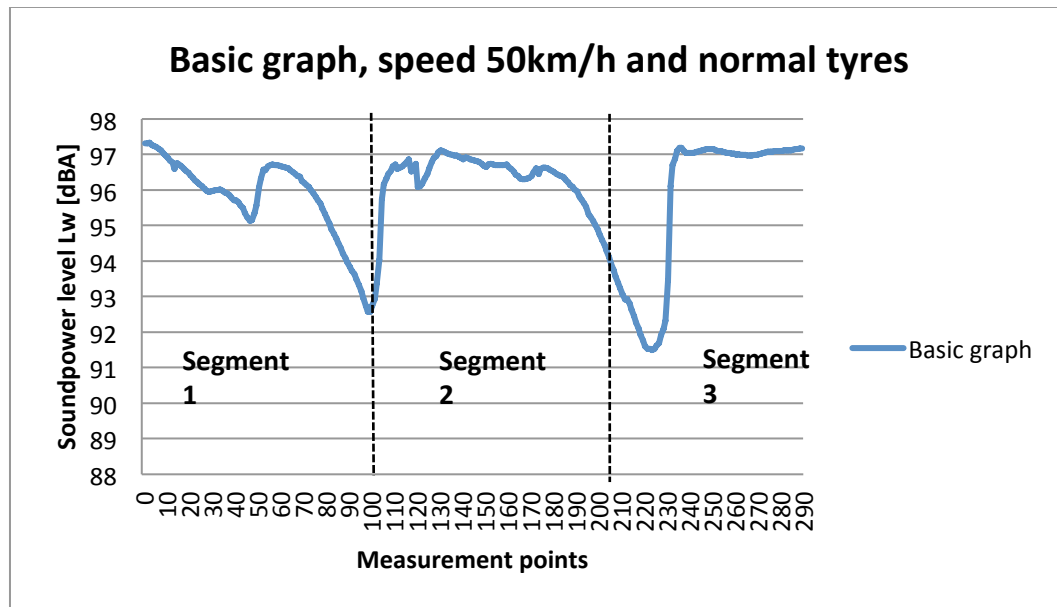


Figure 33 Division of the basic graph into three main segments

The three segments are divided at measurement points 100 and 200 which are respectively located before the roundabout and after junction 3.

In order to lower the peaks in each segment, a series of traffic configurations are applied in new simulations. The noise emission moderation for the beginning and ending point of the route, i.e. point intervals 1 to 40 and 250 to 290, are not considered in the noise reduction simulation.

There are quite high emissions along the entire segment 2. Therefore, several traffic solutions are applied in different parts of these segments.

Segment 3 has one high peak which begins at the fourth junction. Therefore, the traffic emission analysis is focused on this area.

3.4.1 Segment 1

In segment 1, the highest emissions are found in the link between the first junction and the roundabout. For this reason, the traffic arrangements, such as bumps or a speed reduction, are applied between the points 50 and 100.

At the first step, the two bumps 1 and 2 are considered at measurement points 68 and 92 that are shown in *Figure 34*. Maximum vehicle speed on these bumps is set to 20 km/h in VISSIM.

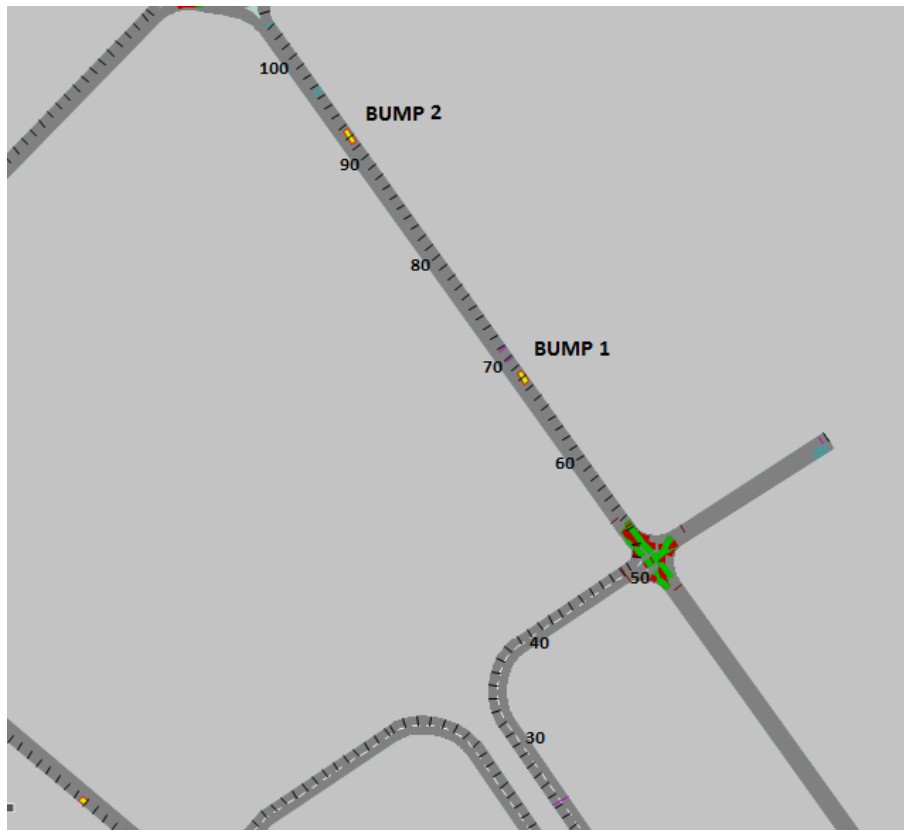


Figure 34 Two bumps for lowering of emissions at segment 1

The new results after a new traffic simulation in VISSIM shows that the basic graph is lowered in two points where the bumps are located. The related graphs are observed in *Figure 35*.

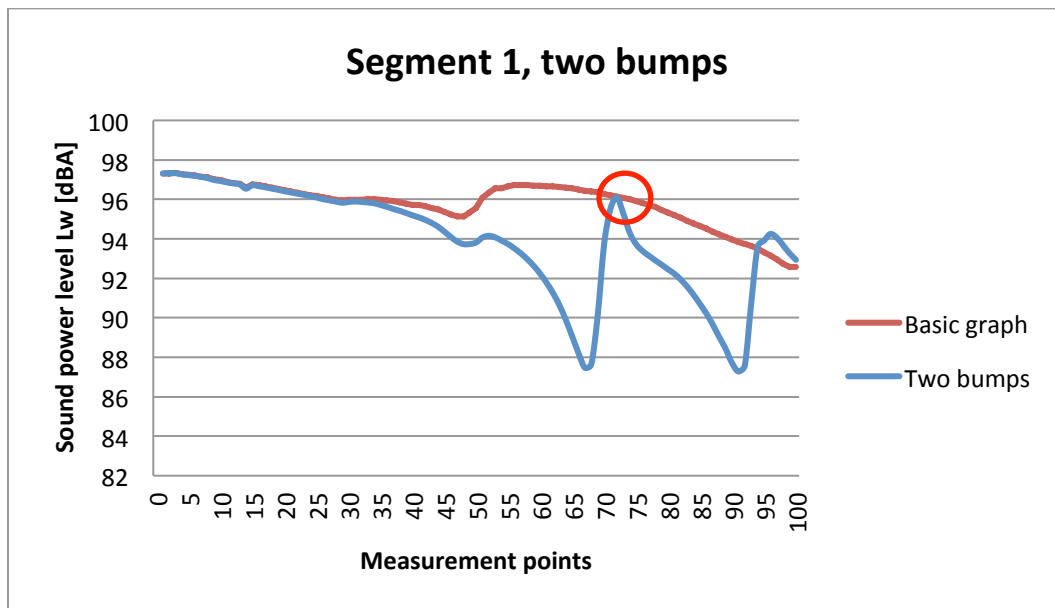


Figure 35 Noise emission reduction by two bumps at segment 1

The maximum sound power level reduction occurs at points 67 and 91. These points are located 5 meters before each bump's centre.

Comparing the output results before and after considering bumps, which are respectively available in Appendix 1 and Appendix 2, show that the emissions at point 67 are reduced by almost 9 dBA, that is from 96.44 dBA to 87.46 dBA. At point 91, the reduction is 6 dBA that is a decrease from 93.73 dBA to 87.27 dBA.

It is observed in *Figure 35* that the graph is only lowered at two points where the bumps are placed. In order to lower the peak between these points, which is indicated by a red circle, another bump is placed at measurement point 80. This new bump is shown in *Figure 36* as bump number 3.

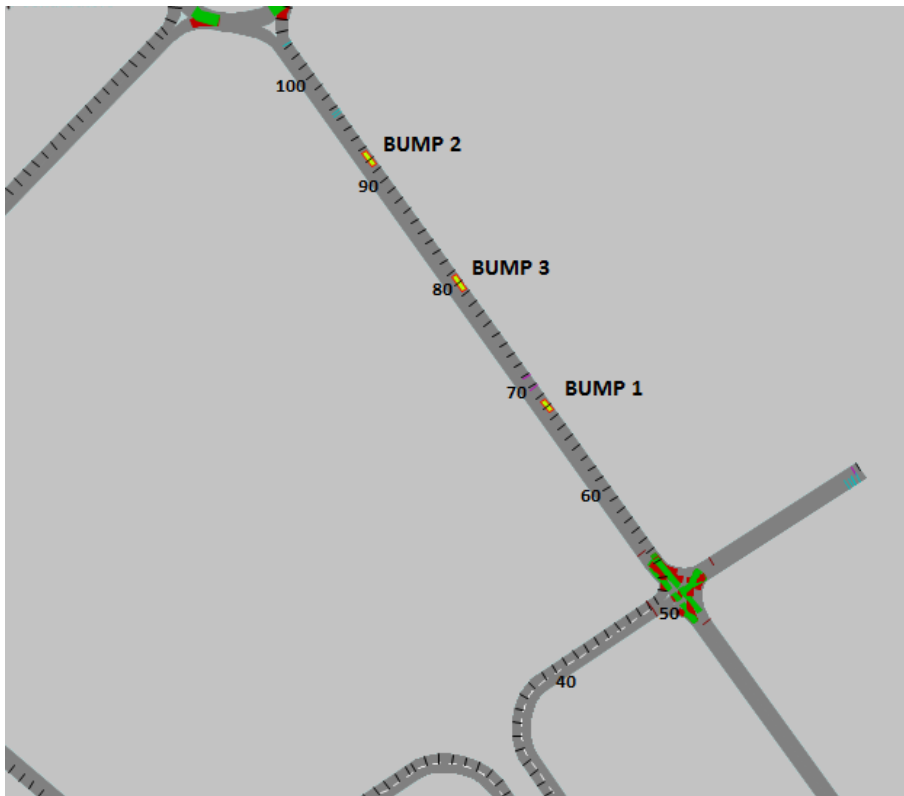


Figure 36 Three bumps for lowering of emissions at segment 1

The new traffic simulation including the third bump leads to new results. The respective graph is shown in Figure 37 with a new lowered point that is shown inside a green circle in the figure.

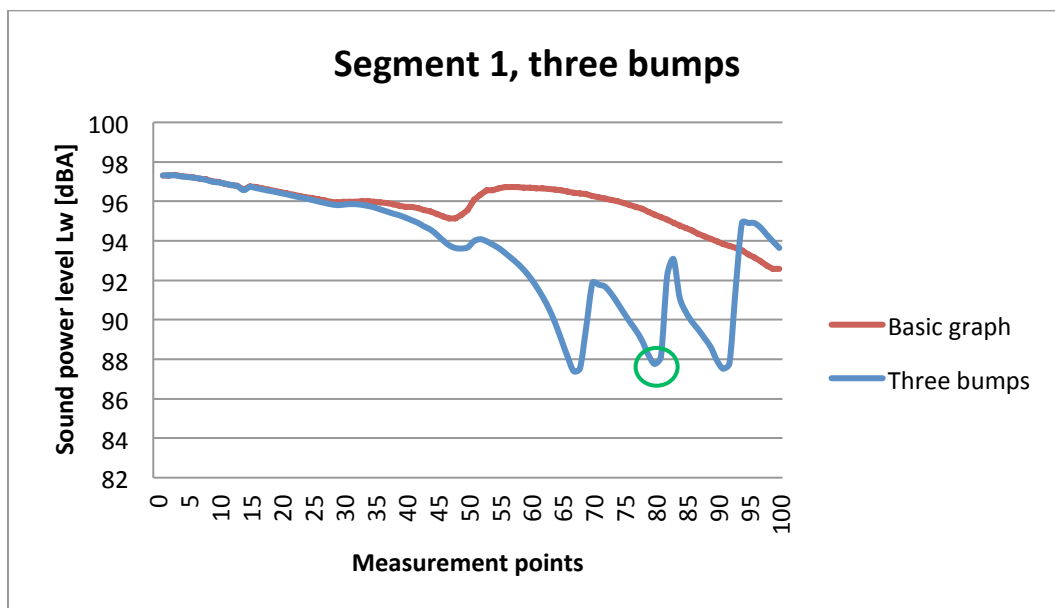


Figure 37 Noise emission reduction by three bumps at segment 1

The maximum sound power reduction regarding bump 3 is observed at point 80 by 7.58 dBA, that is from 95.34 dBA to 87.75 dBA. According to the output data, the sound power level reduction by using three bumps is extended from point 30 to 93.

The next solution for reducing the peak points in the basic model is to replace bumps with a speed reduction area along the segment. *Figure 38* shows the location of this speed reduction area.

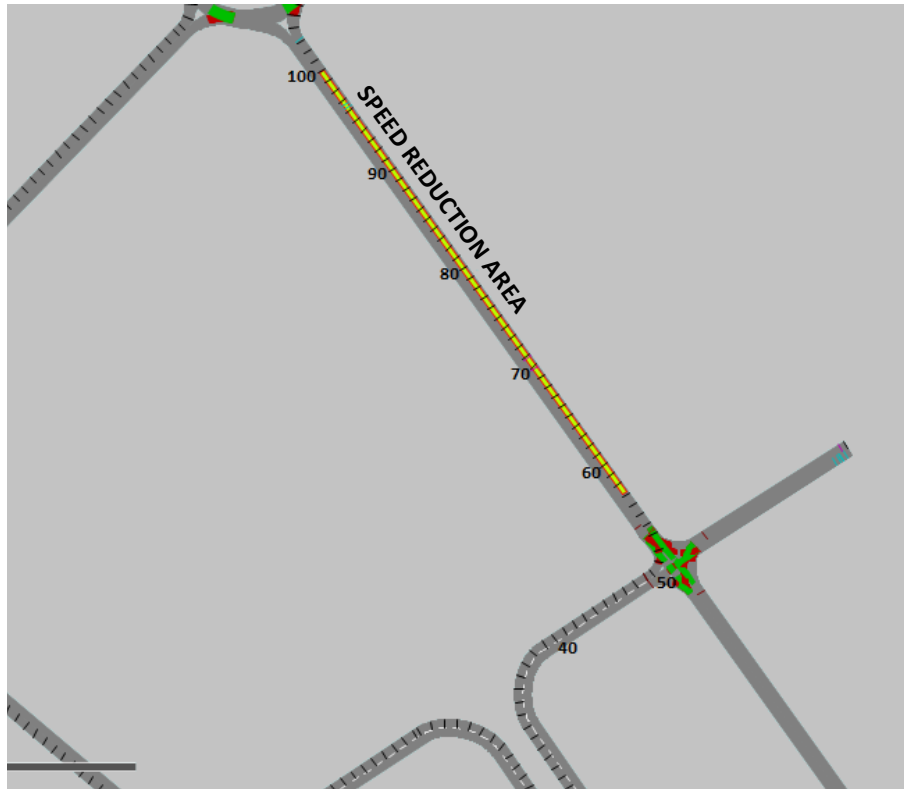


Figure 38 Speed reduction area for lowering the emission at segment 1

This area is between points 57 and 100 with a length of 215 meters. The desired speed on this area is chosen to 30 km/h and the new graph after applying the speed reduction tool is observed in *Figure 39*.

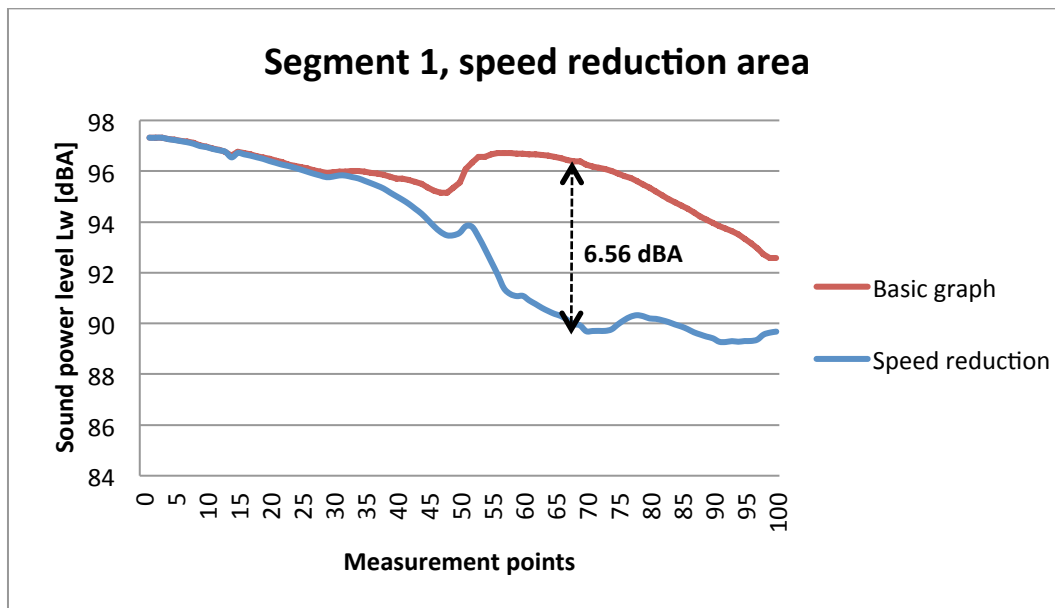


Figure 39 Noise emission reduction by speed reduction area at segment 1

The maximum sound power reduction along this area is 6.56 dBA at point 70 which is indicated in Figure 39.

It is observed that the effect of speed reduction between points 57 and 100 is not limited only to this interval, but the graph is already lowered from point 25 to point 103.

Of the three solutions to reduce the sound power level along the segment, the two bumps 1 and 2 lead to a maximum reduction of 9 dBA and 6 dBA. Using the third bump causes a maximum reduction of 4.7 dBA. As observed in the related graph, the emissions increase when the speed increases after each bump. Therefore the final graph is not particularly a smooth graph.

Using a speed reduction path along the segment results in a more stable and smoother graph if compared to the bump effect.

3.4.2 Segment 2

Segment 2 is the area with high emission levels along the whole stretch. For reducing the noise emission peaks in the area, three methods are applied. These methods are tested individually without combining with the other methods.

The first method is considered for emission reduction in the roundabout, i.e. point interval 105 to 135. The chosen solution is speed reduction to a desired speed of 30 km/h along the highlighted link in *Figure 40*.

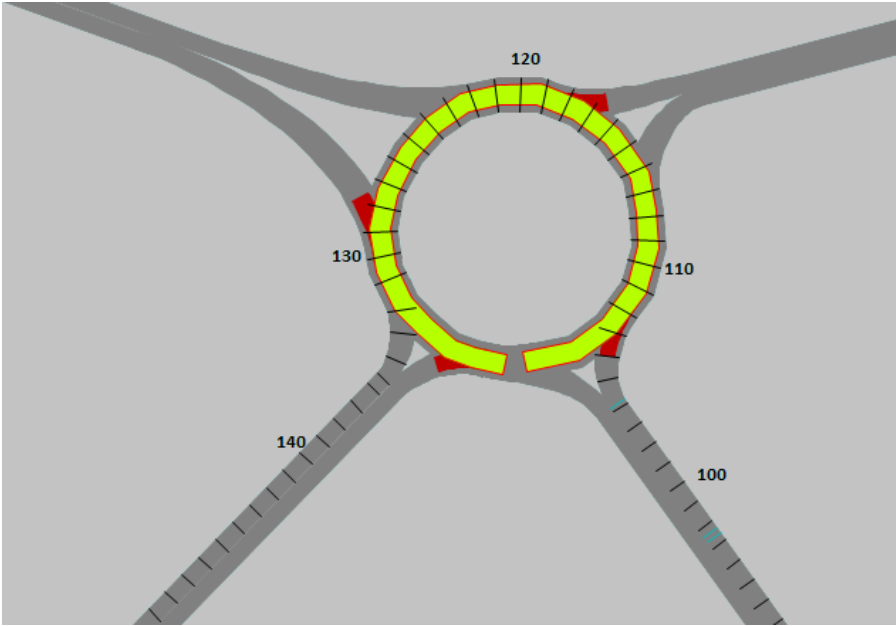


Figure 40 Speed reduction area for lowering the emissions at segment 2

The noise emission graph after a new simulation is presented in *Figure 41* compared to the basic graph.

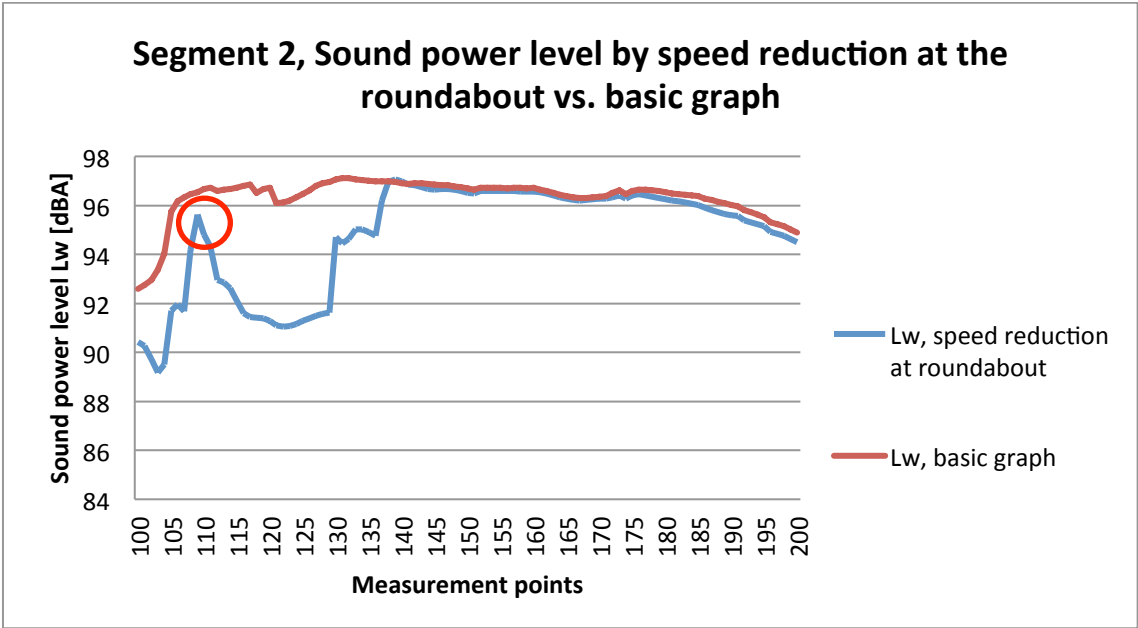


Figure 41 Noise emission changes by speed reduction area at the roundabout in segment 2

As seen in the graphs, the emissions are reduced at all points on the roundabout; point 105 to 135. The maximum sound power reduction has occurred at point 120 by 5.44 dBA.

The noise reduction domain is from the middle of segment 1, point 65 to point 140.

The emission in the new model has a peak at point 109, shown inside the red circle in *Figure 41*, that is located at the entrance of the roundabout. The output data show that the vehicle speed at point 109 is 46.85 km/h which is almost at the same speed range as the adjacent points and the acceleration reaches to its highest value. *Table 10* contains the data regarding speed, acceleration and noise emission corresponding to the points at this section.

Table 10 Simulation output related to measurement points 106 to 113

| Measurement point | Vehicle speed [km/h] | Vehicle acceleration [m/s ²] | Sound power level. Lw [dBA] |
|-------------------|----------------------|--|-----------------------------|
| 106 | 41.2233 | 1.0776 | 91.97102 |
| 107 | 43.2348 | 0.9350 | 91.68627 |
| 108 | 45.8000 | 0.7177 | 94.1773 |
| 109 | 46.8580 | 0.6188 | 95.61991 |
| 110 | 48.7079 | 0.5212 | 94.80091 |
| 111 | 48.3707 | 0.4165 | 94.314 |
| 112 | 48.3005 | 0-3098 | 92.94911 |
| 113 | 48.6844 | 0.2598 | 92.84929 |

The second solution at segment 2 is to place two bumps between the roundabout and the junction number 2 as shown in *Figure 42*.

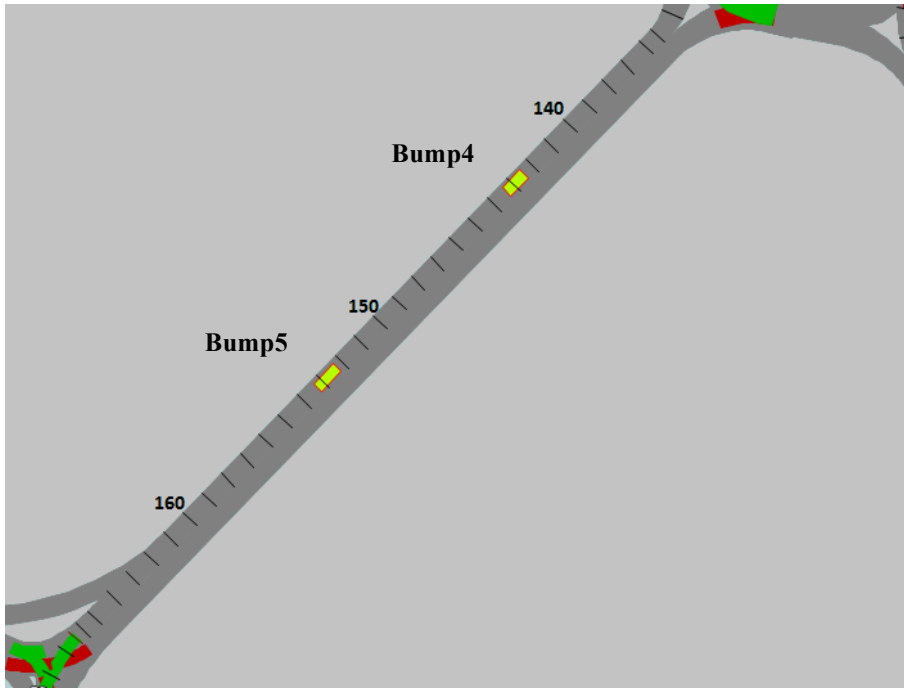


Figure 42 Two bumps for lowering the emissions at segment 2

These bumps are set on the points 143 (bump 4) and 153 (bump 5) with a desired speed of 30 km/h. The result of new simulations after setting the bumps is shown in Figure 43. Comparing this new graph with the basic graph in the figure proves the sound power reduction at the location of the bumps.

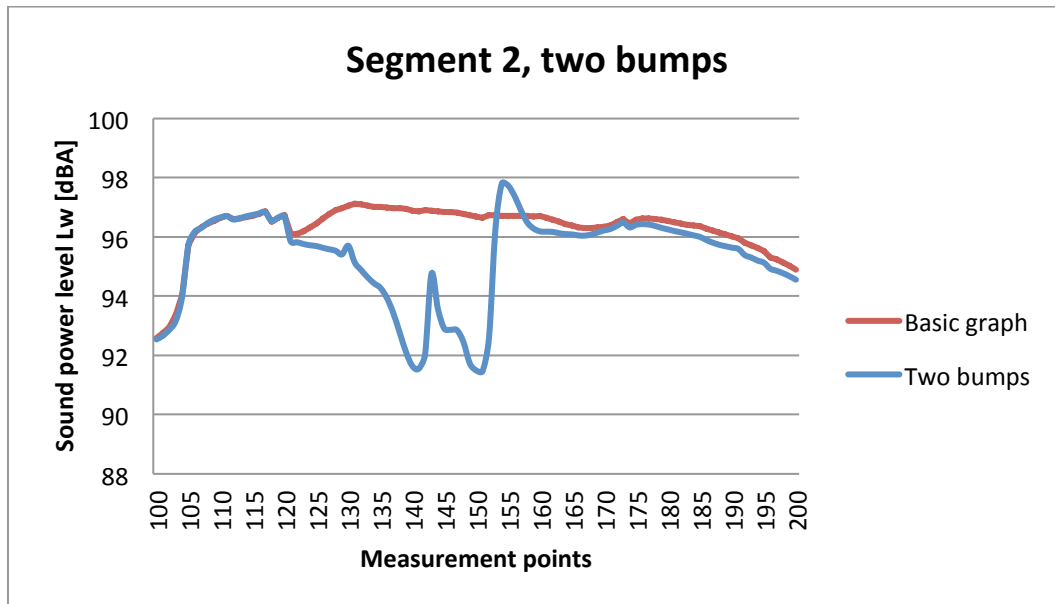


Figure 43 Noise emission changes by using bumps at segment 2

The results show that bump 4 causes a maximum emission reduction of 5.31 dBA at point 141 while Bump 5 causes a maximum emission reduction of 5.19 dBA at point 150. The maximum reduction due to each bump is 5 to 10 meters before respective bump. The data related to vehicle speed at these points, found in Appendix 3, confirms that the sound power level is at its lowest level exactly before the lowest vehicle speed.

After the second reduction point, there is a sound power level jump over the basic graph to a maximum of 1.08 dBA at point 154. This happens exactly after bump 5. According to a comparison between vehicle speed in basic model and the latest simulation, the vehicle speed at point 154 is 11 km/h less than the model without bumps. This shows that the emission level jump at this point cannot be due to speed increase. In order to estimate the reason, the accelerations in both cases are compared in *Figure 44*.

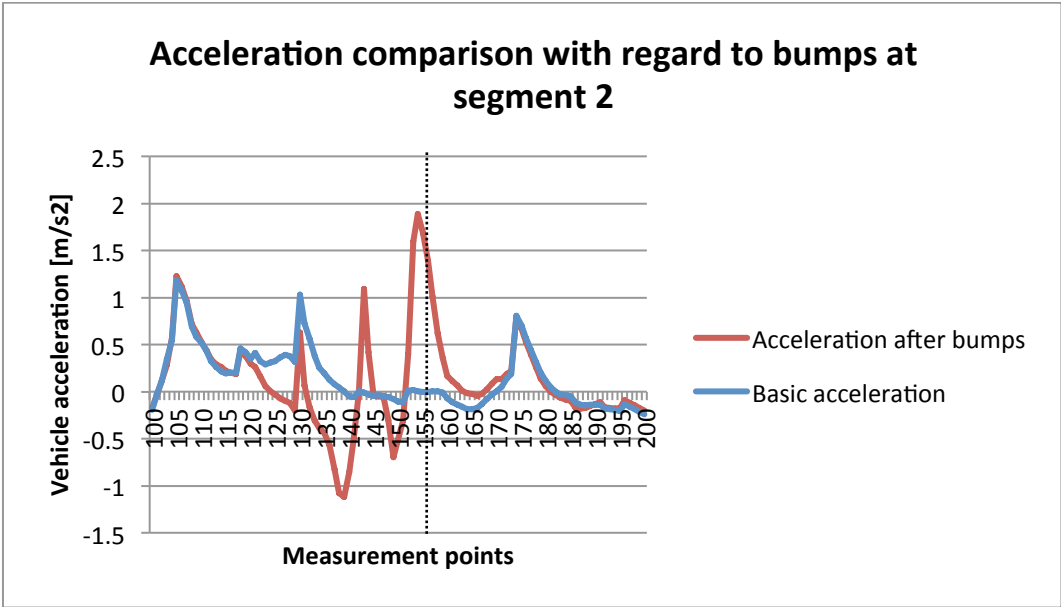


Figure 44 Acceleration difference between basic model and considering bump at segment 2

The dashed line in the figure shows the acceleration at point 154 before and after placement of bumps. The difference between the two graphs at this point is 1.88 m/s².

The third solution for lowering the sound power at segment 2 is considering the traffic light at junction 2. For regulating the traffic at this area, three traffic lights are placed in three directions as shown in *Figure 45*.

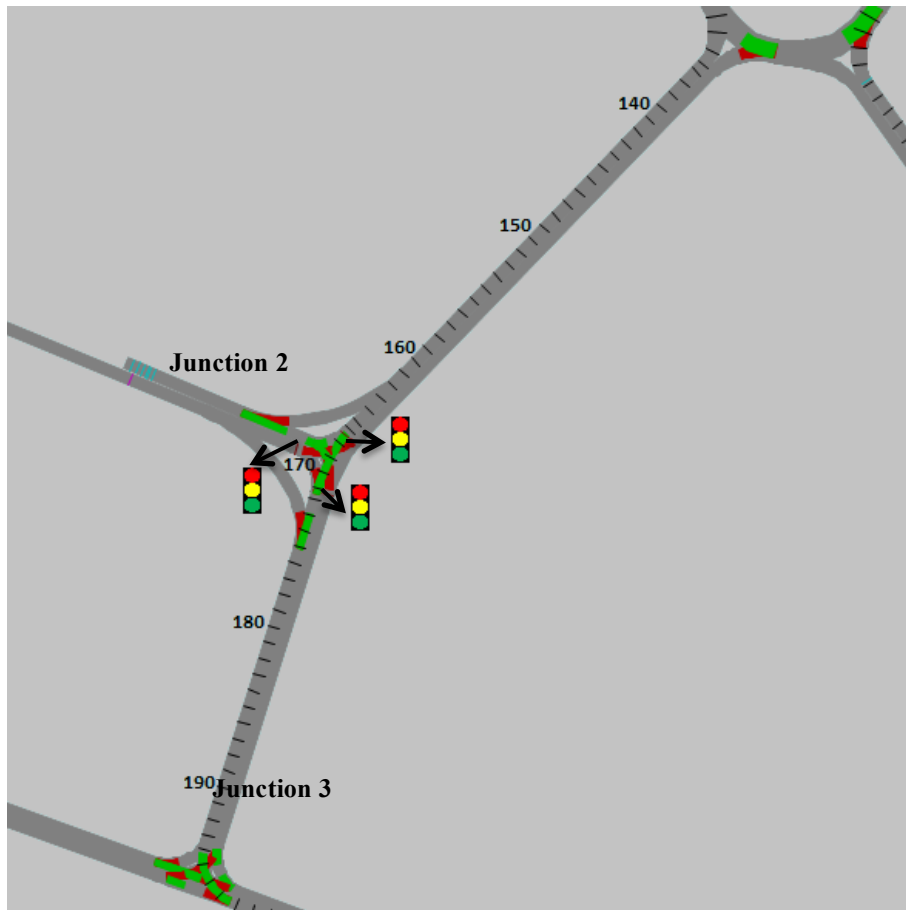


Figure 45 Traffic light adjustment for reduction of emission at segment 2

The simulation with traffic lights results in a new graph that is observed in *Figure 46* beside the basic graph. Comparing this model with the basic model shows that the noise emissions are lowered between the measurement points 121, which is located on the roundabout, and the last point of segment 2 which is the point number 200 and is located after junction 3.

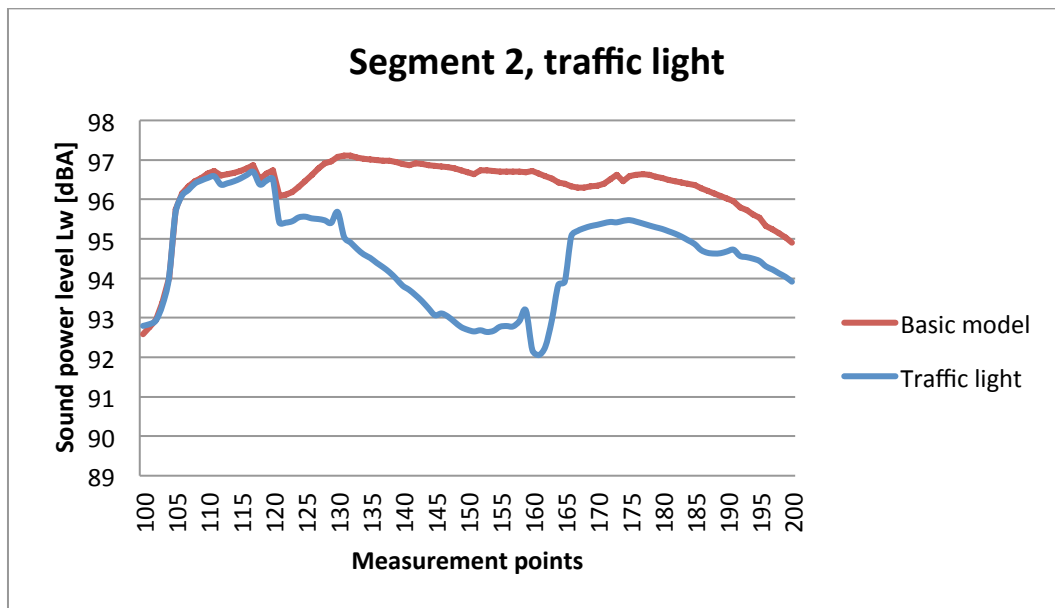


Figure 46 Noise emission reduction by traffic light at segment 2

According to the results, regulation the traffic by traffic light has a broad impact on the taraffic and thouth the reduction of sound power level; the noise reduction is continued to the point 230 which is in segment 3.

The sound power level reduction is almost 0 in the beginning of the segment and it increases to a maximum reduction of 4.59 dBA at point 161. This point is located 30 to 40 meters before the traffic light at the junction.

Of three methods applied in segment 2, the emission reduction through speed reduction at the roundabout reached a maximum of 5.44 dBA and by means of bumps 4 and 5 to maximum of 5 dBA, although this was only at the bumps' location. The final method also reduced the emissions up to 4.5 dBA with a smoother graph along the whole segment.

3.4.3 Segment 3

Traffic at segment 3 in the basic model leads to low emission levels in the beginning of the segment. As noticed in chapter 3.3.1 that shows the results for the basic graph, the sound power level is as low as 91.49 dBA at point 224 and is located before junction 4 while it is increased then to 97.18 dBA at point 237 which is located after junction 4. For lowering the emissions after the junction, two traffic lights are placed in order to moderate the traffic queues. *Figure 47* shows the location of traffic lights.

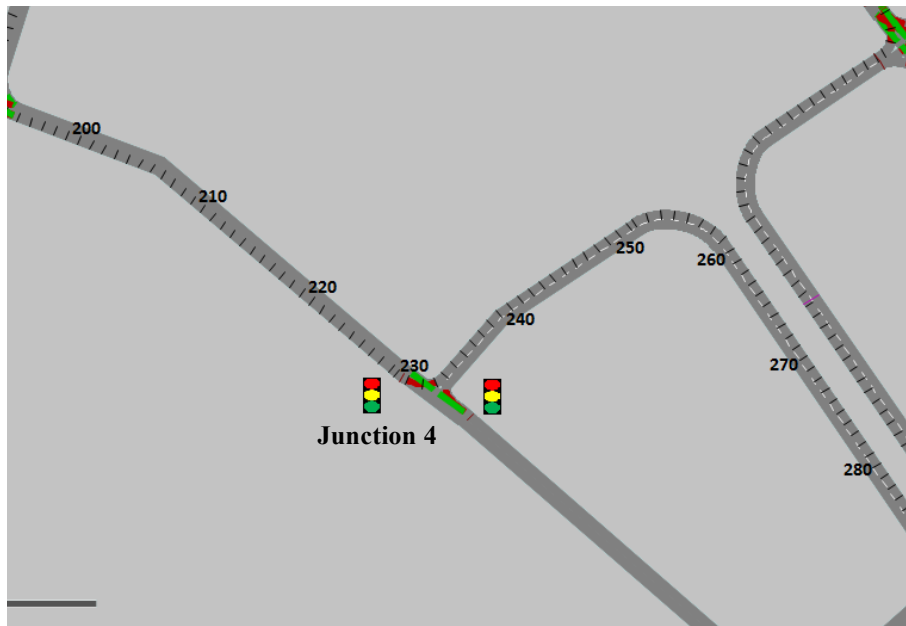


Figure 47 Traffic light at junction 4 to reduce the emissions at segment 3

Although the traffic lights regulate the traffic queues, the graph of noise emissions has higher values between points 212 and 231 compared to the basic model. The rest of points in the segment have almost the same emission level as the basic graph as seen in Figure 48.

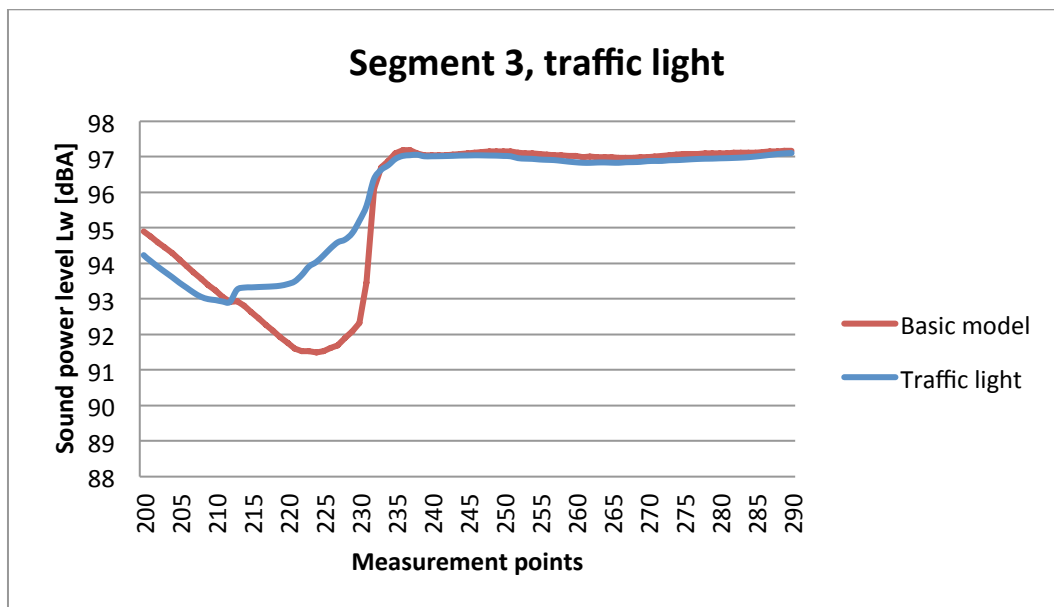


Figure 48 Noise emission differences due to traffic light at junction 4

For analysing the reason for the recent behavior of the graph, vehicle speed at the area is compared to the vehicle speed in basic model.

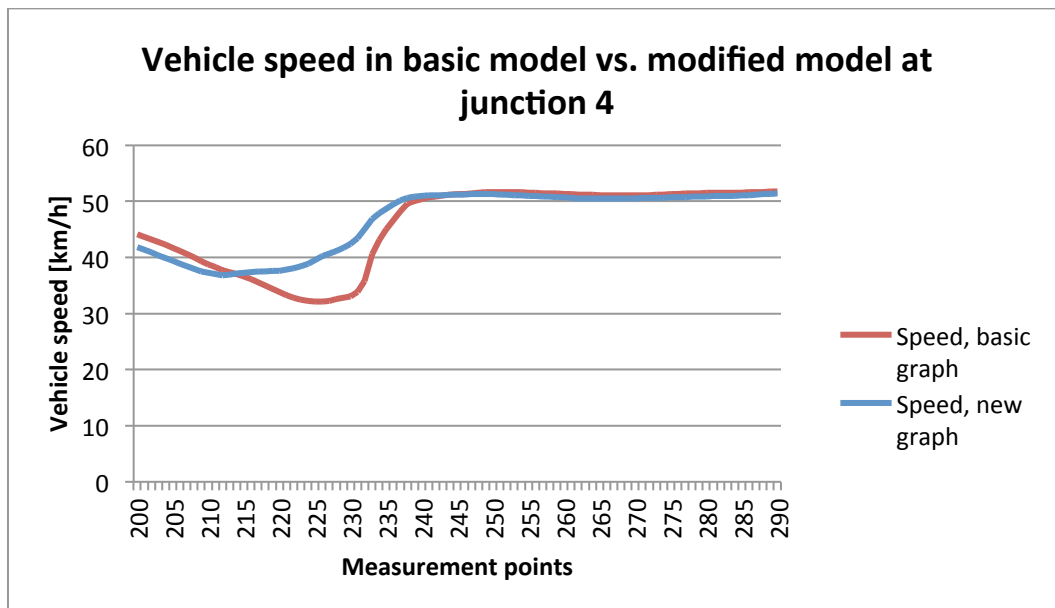


Figure 49 Vehicle speed comparison due to traffic regulation at segment 3

As observed in *Figure 49*, vehicle speed between points 214 till 244 is higher after traffic regulation by traffic light. The reason is likely to be the decrease of traffic queue that makes the traffic more dynamic. This argument is likely to be the reason for increasing the noise levels compared to the based model.

3.4.4 Combination

The last simulation is performed by combining the most effective methods in reducing the noise emissions along the entire route without. This simulation is with regard to not causing extra traffic issues such as long queues.

At segment 1, speed reduction area between points 57 and 100 is chosen. At segment 2, both the solution of having a speed reduction in the roundabout as well as traffic lights at junction 3 are considered. The traffic lights at segment 3 does not have a positive effect on sound emission reduction, therefore the basic model is kept in the combination model. *Figure 50* shows the used tools in the combination model.

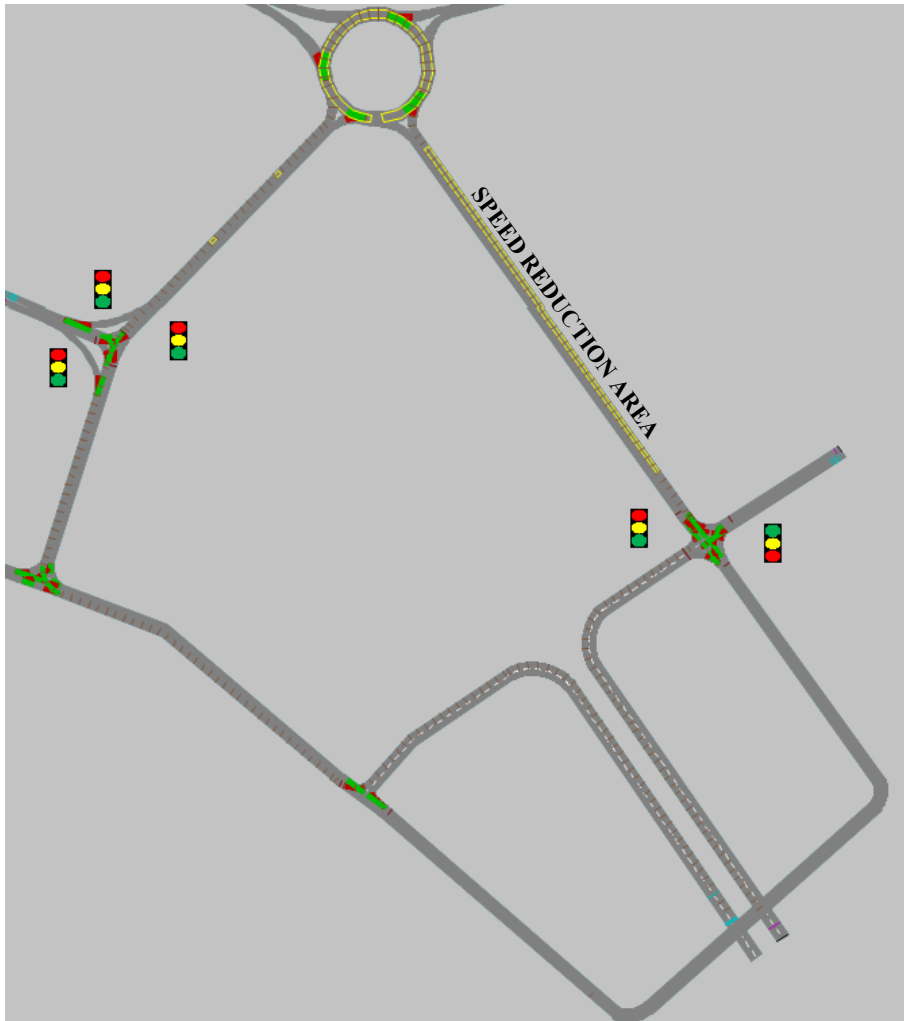


Figure 50 Chosen tools for noise emission reduction at the entire route

The final results after traffic simulation is compared to the basic graph as seen in Figure 51.

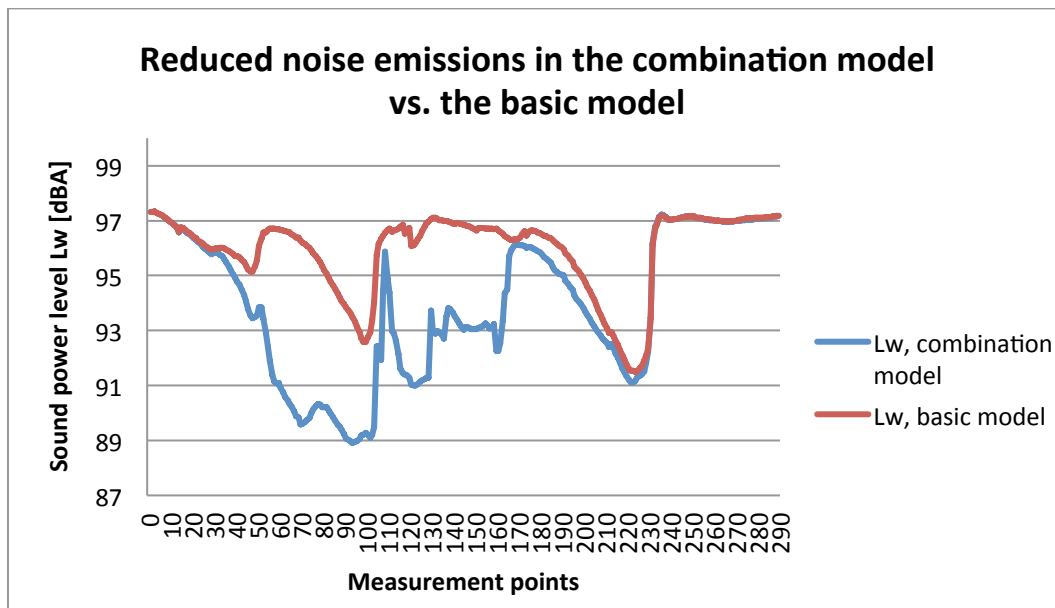


Figure 51 Noise emission reduction at the entire route due to combination of methods

The final graph indicates an obvious noise emission reduction along the major part of the route. The lowest emissions are related to points 60 to 105 on the link between junction 1 and the roundabout with emission levels lower than 91 dBA. The configurations have led to a total variation in the graph.

4 Discussion

The first part of the discussion takes general issues of the study's method into consideration. At the second part, more details about traffic scenarios and noise reduction analysis are discussed.

The discussion focuses on two significant aspects; first is accuracy of the presented toolkit and second is feasible reasons for unexpected behaviours of the graphs in the noise emission analyses.

4.1 General issues

Since the traffic simulation by VISSIM is based on a stochastic model, the results lead to a few uncertainties. These uncertainties are related to vehicle's properties, such as speed and acceleration. The difference in different vehicles' structures such as motor function technics and tyre types, make the emitted noise level different from one vehicle to another. This is more essential when it comes to the drivers' behaviour with regard to their age, gender, reaction aggressiveness in a particular situation. The driver's behaviour has a key role in acceleration changes, for instance at speed reduction areas and junctions. Therefore the choice of reaction at each traffic situation affects on the level of noise emissions. In the current method the car model and driver's behaviour are chosen stochastically by VISSIM.

Another related issue is the gear choice, which is not included among VISSIM tools or in CNOSSOS noise calculation method. A vehicle with specific speed and acceleration in one gear choice can produce a different noise level than the same vehicle with the same speed and acceleration in another gear choice. Lack of this tool causes uncertainties in calculating the precise noise level although this issue plays a less important role while using vehicles with automatic gearbox. Nevertheless all these uncertainties, VISSIM provides quite detailed traffic model. The possibility to chose various vehicle categories, making traffic obstacles such as bumps, or traffic regulation tools such as traffic lights and also making a detailed output data are some of the benefits of the program that make the created models reliable.

The coordination of the output data from VISSIM simulation with the required data in CNOSSOS method is a beneficial factor that makes the toolkit practical. This adaption creates the possibility of calculation the noise at a particular moment and at each vehicle's location. The classic methods of noise calculation method did not make this type of noise calculation possible with the same accuracy.

4.1.1 Traffic model in VISSIM

Although there is the possibility to create a traffic model by different vehicle categories in VISSIM, such as light or heavy vehicles, busses, motorcycles and even bikes, only two categories light and heavy vehicles are chosen in the traffic simulations. Moreover, since the noise emission levels are different due to each vehicle category, the most reasonable method is calculating the emission individually for each vehicle category.

In populated urban areas, there are further elements involved in road traffic such as crosswalks, which can be counted as speed reduction areas, or buss stations that cause frequent changes in speed and acceleration along the streets. In this study none of these elements are considered in the traffic models. Considering frequent obstacles along the roads are likely to lead to more variations in noise emissions.

The simulation time interval is limited to one hour. Longer or shorter time intervals would influence the final results when it comes to average noise emissions. For instance, at an intersection, the noise emissions during the green light time period, is higher than the red light time period because of the traffic flow variations.

4.1.2 CNOSSOS-EU

In reality, factors such as road slope and road surface material, meteorological factors such as temperature and wind vary depending on time and location. In the traffic noise calculation method, CNOSSOS-EU, these factors are assumed as constant values. These assumptions reduce the accuracy of the final results.

4.2 Method 1 and 2, instantaneous and average noise emissions

In this method, each noise map is unique because the results are based on one specific moment in the dynamic traffic model. Comparing the results from two different moments is not practical for judging the traffic model. Moreover, the noise maps give only an approximate and general picture of the emission at one particular moment.

On the other hand, a conclusion about road traffic noise emissions based on instantaneous results is not comprehensive. Although the instantaneous simulation for each and every moment of a simulation can give accurate results but this is a time consuming method. This is a motive for considering the second method.

4.2.1 Four scenarios

Choosing only one specific route out of all possible routes is in order to illustrate the feasibility of the model. Moreover, the noise emission corresponding to the measurement points at one specific traffic direction is not representative for the opposite direction. Therefore calculating the noise emissions in other routes and opposite directions of the system is possible with the same method.

Because the traffic data for each measurement point is an average value, the sound power level at each point can vary widely from the instantaneous emissions at respective point.

The entering and exit links, that connect Frihamnen to Gothenburg's city centre, are one-direction traffic links. The graphs of all scenarios indicate that the sound emissions on these two links have almost the highest emissions. The reason is that the vehicles drive with the desired speed without any obstacle for breaking. Analysing the noise emission variation in highways and several-lane roads such as these links will require a separate study as the desired speed in these links can vary from smaller roads e.g. from 70 to 50 km/h.

In this method, noise emission peaks were observed in the result graph of all scenarios at all junctions' areas. The high emission after each junction is on account of acceleration and speed increase.

Comparison between scenario 1 and 3 in Figure 31, 50 km/h and 70 km/h and normal tyres, showed an emission difference of 4.76 dBA at point 268. According to Table 3, the sound level variation, if the vehicle speed increases from 50 km/h to 70 km/h, is 4 dBA which is supposed as a confirmation of our result.

As observed in Figure 31 the precise speed difference between two scenarios at point 268 is 21.33 km/h that is 1.33 km/h more than the difference between desired speeds 70 and 50 km/h. On the other hand, the acceleration at point 268 in scenario 1 is almost 0 while it is 0.02 m/s^2 in scenario 3. These differences are likely to be two of the reasons for the sound power level difference between 4.76 dBA and 4 dBA i.e. 0.76 dBA.

Noise emissions according to vehicles with studded tyres are calculated according to proportion of studded tyres during January and February 2013 as pointed out in chapter 3.3.4. This means that at summer period, the emission graph for the chosen route is similar to the graph corresponding normal tyres.

4.2.2 Analysis for noise emission reduction

In general, by applying any tool for reducing the emission at one direction, the noise emissions could rise at the other direction, for example at an intersection. In this study though, the traffic models are designed in a way to keep a practical traffic flow. This means that the models that would create long queues or make a chaos in any location of the system is not considered for analyses.

The links connected to the bridge, i.e. points intervals 1 to 50 and 240 to 290 are not included in sound power reduction investigation. It is supposed that since there are no residential or working offices near these links, as they are on the bridge, there is less necessity for sound reduction. The other reason, as expressed before, is that the initial speed is higher in these several-lane links that results to different range of noise emissions. Although by considering speed reduction tools along these links, the emission could be lowered.

4.2.2.1 Segment 1

The stretch between point 50 and 100, where sound reduction investigations are carried out, has a length equal to 250 m. according to the results, it is possible to reduce noise levels by means of several bumps. But frequent bumps in a short distance have negative effects on driver's comfort level, vehicle's lifetime and also environmental aspects. Because the vehicle speed is only reduced at the area close to each bump, the noise is not reduced along the entire stretch and the residents at the area have different experiences of noise levels depending on their location. On the other hand, speed reduction along a longer distance does not have as much as the abovementioned negative consequences, i.e. reduction of driver's comfort and vehicle's lifetime.

4.2.2.2 Segment 2

According to the results after reducing speed at the roundabout, the noise emissions are lowered. But there is still an emission peak at the entrance of the roundabout. This is according to higher acceleration at this point compared to adjacent points. The almost perpendicular connection angle between the entering link and the roundabout is estimated to be the reason which is a subject related to the road's design. Changing the design of the roundabout including its radius and the angle at the entrance to the roundabout could affect the vehicles' acceleration.

Using two bumps at a distance of 150 meters between the roundabout and junction 2 has the same issues as the bumps in segment 1. By observing the resulted graphs according to these bumps, it is remarkable that traffic solutions such as bumps are location-based solutions and there is the risk for high accelerations after passing them.

At junction 2, the traffic lights' cycle time is chosen manually at VISSIM. The variation in cycle time can vary the average vehicle speed during different time intervals and emission production.

The average level of emissions at junction 2 is the average result of high and low emissions; high while traffic light is green and low while it is red. Therefore even traffic light is a suitable traffic solution for regulating the traffic flow, but cannot be the best solution for reducing the noise emissions at all moments. On the other hand, when the red light turns into green, increasing acceleration for reaching the desired speed will cause the rise of average noise emission. Although, for creating the best solution both in case of controlling the traffic and noise emissions, considering both traffic directions at the area is essential.

4.2.2.3 Segment 3

The traffic light at junction 4 caused higher emissions. The reason is likely to be the decrease of traffic queue that makes the traffic more dynamic.

4.2.2.4 Combination model

The combination of traffic configurations lowered the entire emissions along the chosen route but does not represent the emissions at the other routes and opposite directions. By every traffic variation at the chosen direction, the traffic at the other direction can be affected.

5 Conclusion

The function of the presented method in this study shows that although traffic models in VISSIM are based on stochastic data, the simulations still provides realistic results. Therefore creating a digital traffic model with the purpose of traffic noise calculating can replace properly the manual traffic data collection.

Estimating the noise emissions at the emission source that is presented by CNOSSOS-EU is a unique way of having access to this data. Besides, the possibility of calculating the instantaneous sound level at all noise sources along a road is the result of taking advantage of the digital traffic model. Getting this kind of result with the same accuracy is not practically possible through the other noise calculation methods, since the traffic data collection method is manually or the sound levels are calculated for a particular distance from the source.

Analysing the traffic model with the purpose of reducing the noise emission factors show that how road and traffic design regulations can influence the noise emissions. These analyses are also useful in identifying the leading parameter in producing noise, i.g. acceleration, speed, traffic light's time intervals. These analyses on a real urban map indicate that this method is a beneficial toolkit for the traffic and city planers. The toolkit can be used at the designing phase of projects to evaluate for example the effect of traffic light time period on producing noise.

6 Recommendation for further studies

Providing the basics for a noise calculation method that is based on a digital model opens up ideas for developing further investigation.

One study that can evaluate the presented toolkit by this study is to compare it with other methods in detail. Estimated traffic noise by CNOSSOS does not include the noise level in a distance from the road. However emission results can be an input data for calculation of immissions. It is interesting to evaluate the accuracy of immission values by this method in comparison to the immissions values estimated by Nordic Prediction Method.

There is also possibility for comparing noise immission levels based on the results of this method with the immission values estimated by noise simulation program SoundPlan. The comparison results can be interesting when the same traffic properties from VISSIM are used in both cases as input data.

Controlling the variations in noise production at both direction of a road by this tool is also another possible further investigation.

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8 Appendix 1

Scenario 1, 50 km/h and normal tyres, basic model

| Point nr. | Vehicle type | Average speed [km/h] | Average acceleration [m/s ²] | Distance [m] | Sound power level L _w [dBA] |
|-----------|--------------|----------------------|--|--------------|--|
| 1 | 100 | 51.993505 | 0.111390 | 0 | 97.31235198 |
| 2 | 100 | 52.096482 | 0.091183 | 5 | 97.32066771 |
| 3 | 100 | 52.204503 | 0.069831 | 10 | 97.329648 |
| 4 | 100 | 52.229671 | -0.012973 | 15 | 97.26956073 |
| 5 | 100 | 52.191719 | -0.039985 | 20 | 97.23933307 |
| 6 | 100 | 52.126879 | -0.072528 | 25 | 97.19862701 |
| 7 | 100 | 52.021682 | -0.087222 | 30 | 97.16119168 |
| 8 | 100 | 51.897766 | -0.106598 | 35 | 97.1156267 |
| 9 | 100 | 51.723398 | -0.170799 | 40 | 97.02577497 |
| 10 | 100 | 51.480264 | -0.164687 | 45 | 96.96756356 |
| 11 | 100 | 51.253464 | -0.177933 | 50 | 96.89987265 |
| 12 | 100 | 51.014565 | -0.180271 | 55 | 96.83641377 |
| 13 | 100 | 50.779576 | -0.179067 | 60 | 96.77623685 |
| 14 | 100 | 50.088772 | -0.171724 | 65 | 96.6010042 |
| 15 | 100 | 50.688961 | -0.168357 | 70 | 96.76026971 |
| 16 | 100 | 50.492408 | -0.148571 | 75 | 96.72341155 |
| 17 | 100 | 50.277864 | -0.159450 | 80 | 96.65948133 |
| 18 | 100 | 50.062136 | -0.168578 | 85 | 96.59630476 |
| 19 | 100 | 49.853837 | -0.165254 | 90 | 96.54399659 |
| 20 | 100 | 49.614812 | -0.168034 | 95 | 96.47892331 |
| 21 | 100 | 49.368498 | -0.166703 | 100 | 96.41474863 |
| 22 | 100 | 49.125631 | -0.167694 | 105 | 96.34952867 |

| | | | | | |
|----|-----|-----------|-----------|-----|-------------|
| 23 | 100 | 48.874666 | -0.183903 | 110 | 96.27041215 |
| 24 | 100 | 48.597929 | -0.157433 | 115 | 96.21659049 |
| 25 | 100 | 48.370527 | -0.146316 | 120 | 96.16436198 |
| 26 | 100 | 48.147144 | -0.144805 | 125 | 96.10556264 |
| 27 | 100 | 47.896515 | -0.147136 | 130 | 96.03615827 |
| 28 | 100 | 47.684296 | -0.135978 | 135 | 95.98783603 |
| 29 | 100 | 47.450659 | -0.119542 | 140 | 95.93815676 |
| 30 | 100 | 47.315535 | -0.043529 | 145 | 95.96724525 |
| 31 | 100 | 47.259281 | -0.004159 | 150 | 95.98784403 |
| 32 | 100 | 47.213031 | 0.013795 | 155 | 95.99215254 |
| 33 | 100 | 47.196518 | 0.033698 | 160 | 96.00654365 |
| 34 | 100 | 47.212566 | 0.037239 | 165 | 96.01420121 |
| 35 | 100 | 47.214889 | 0.009991 | 170 | 95.98909087 |
| 36 | 100 | 47.073329 | -0.008396 | 175 | 95.9340409 |
| 37 | 100 | 46.998353 | -0.021042 | 180 | 95.90221381 |
| 38 | 100 | 46.867884 | -0.041548 | 185 | 95.84827311 |
| 39 | 100 | 46.701016 | -0.072721 | 190 | 95.77497053 |
| 40 | 100 | 46.486380 | -0.072257 | 195 | 95.71688668 |
| 41 | 100 | 46.413506 | -0.053986 | 200 | 95.71355727 |
| 42 | 100 | 46.301048 | -0.081975 | 205 | 95.65748835 |
| 43 | 100 | 46.105431 | -0.120369 | 210 | 95.56967071 |
| 44 | 100 | 45.871533 | -0.128426 | 215 | 95.49792538 |
| 45 | 100 | 45.556429 | -0.199326 | 220 | 95.34920151 |
| 46 | 100 | 45.120950 | -0.208758 | 225 | 95.21858404 |
| 47 | 100 | 44.575580 | -0.126205 | 230 | 95.13763383 |
| 48 | 100 | 44.258984 | -0.021052 | 235 | 95.15078794 |
| 49 | 100 | 43.735143 | 0.272856 | 240 | 95.34546565 |

| | | | | | |
|----|-----|-----------|-----------|-----|-------------|
| 50 | 100 | 44.385977 | 0.305748 | 245 | 95.5615436 |
| 51 | 100 | 45.060330 | 0.552344 | 250 | 96.07959339 |
| 52 | 100 | 46.445415 | 0.485178 | 255 | 96.33196707 |
| 53 | 100 | 47.701523 | 0.427879 | 260 | 96.57206289 |
| 54 | 100 | 47.511660 | 0.459719 | 265 | 96.56534342 |
| 55 | 100 | 48.236331 | 0.392056 | 270 | 96.66184466 |
| 56 | 100 | 48.793463 | 0.313750 | 275 | 96.71064597 |
| 57 | 100 | 49.197496 | 0.225843 | 280 | 96.7181237 |
| 58 | 100 | 49.461007 | 0.148870 | 285 | 96.70827323 |
| 59 | 100 | 49.622497 | 0.090566 | 290 | 96.69476477 |
| 60 | 100 | 49.706286 | 0.047761 | 295 | 96.6777925 |
| 61 | 100 | 49.745894 | 0.023671 | 300 | 96.66695258 |
| 62 | 100 | 49.752993 | 0.003648 | 305 | 96.65160651 |
| 63 | 100 | 49.728531 | -0.018212 | 310 | 96.62681737 |
| 64 | 100 | 49.680539 | -0.030887 | 315 | 96.60378519 |
| 65 | 100 | 49.607202 | -0.053401 | 320 | 96.56614902 |
| 66 | 100 | 49.490434 | -0.087279 | 325 | 96.50826566 |
| 67 | 100 | 49.326247 | -0.115821 | 330 | 96.44252875 |
| 68 | 100 | 49.138102 | -0.119985 | 335 | 96.38955661 |
| 69 | 100 | 49.007685 | -0.087318 | 340 | 96.3811268 |
| 70 | 100 | 48.781625 | -0.169876 | 345 | 96.25615587 |
| 71 | 100 | 48.548259 | -0.170816 | 350 | 96.19295364 |
| 72 | 100 | 48.339542 | -0.163144 | 355 | 96.14285022 |
| 73 | 100 | 48.123269 | -0.167091 | 360 | 96.08153927 |
| 74 | 100 | 47.895349 | -0.181195 | 365 | 96.00890672 |
| 75 | 100 | 47.619616 | -0.204183 | 370 | 95.9161097 |
| 76 | 100 | 47.298406 | -0.229920 | 375 | 95.80840661 |

| | | | | | |
|------------|-----|-----------|-----------|-----|-------------|
| 77 | 100 | 46.954903 | -0.224994 | 380 | 95.71764342 |
| 78 | 100 | 46.608988 | -0.234904 | 385 | 95.61418317 |
| 79 | 100 | 46.212788 | -0.274618 | 390 | 95.47287403 |
| 80 | 100 | 45.776077 | -0.287753 | 395 | 95.33984142 |
| 81 | 100 | 45.323593 | -0.297361 | 400 | 95.20403957 |
| 82 | 100 | 44.845433 | -0.308474 | 405 | 95.05861619 |
| 83 | 100 | 44.332159 | -0.312233 | 410 | 94.90768315 |
| 84 | 100 | 43.828455 | -0.303131 | 415 | 94.76885601 |
| 85 | 100 | 43.334568 | -0.288452 | 420 | 94.6369323 |
| 86 | 100 | 42.855927 | -0.273174 | 425 | 94.50964871 |
| 87 | 100 | 42.375437 | -0.275099 | 430 | 94.36601624 |
| 88 | 100 | 41.868735 | -0.274461 | 435 | 94.21585538 |
| 89 | 100 | 41.370326 | -0.255028 | 440 | 94.08487025 |
| 90 | 100 | 40.901531 | -0.231604 | 445 | 93.96677762 |
| 91 | 100 | 40.450620 | -0.220880 | 450 | 93.84155577 |
| 92 | 100 | 40.007967 | -0.198149 | 455 | 93.73114212 |
| 93 | 100 | 39.604729 | -0.176317 | 460 | 93.63227649 |
| 94 | 100 | 39.196099 | -0.181896 | 465 | 93.50168984 |
| 95 | 100 | 38.749896 | -0.214182 | 470 | 93.32893959 |
| 96 | 100 | 38.282229 | -0.242055 | 475 | 93.15297679 |
| 97 | 100 | 37.779071 | -0.283829 | 480 | 92.94895734 |
| 98 | 100 | 37.248437 | -0.325710 | 485 | 92.73423441 |
| 99 | 100 | 36.708939 | -0.309532 | 490 | 92.57867018 |
| 100 | 100 | 36.274996 | -0.192848 | 495 | 92.5789363 |
| 101 | 100 | 36.087533 | -0.017745 | 500 | 92.75568898 |
| 102 | 100 | 36.052540 | 0.114950 | 505 | 92.94420625 |
| 103 | 100 | 36.208144 | 0.341871 | 510 | 93.37100825 |

| | | | | | |
|------------|-----|-----------|----------|-----|-------------|
| 104 | 100 | 37.216982 | 0.546518 | 515 | 94.03115088 |
| 105 | 100 | 38.315796 | 1.183796 | 520 | 95.74266072 |
| 106 | 100 | 41.280355 | 1.079031 | 525 | 96.1574217 |
| 107 | 100 | 43.288357 | 0.941033 | 530 | 96.32706989 |
| 108 | 100 | 45.722881 | 0.688041 | 535 | 96.45427258 |
| 109 | 100 | 46.729408 | 0.583636 | 540 | 96.54157393 |
| 110 | 100 | 47.565748 | 0.519315 | 545 | 96.6578655 |
| 111 | 100 | 48.257150 | 0.433689 | 550 | 96.71817306 |
| 112 | 100 | 48.311074 | 0.323362 | 555 | 96.59973227 |
| 113 | 100 | 48.713795 | 0.260804 | 560 | 96.63222508 |
| 114 | 100 | 49.036457 | 0.212515 | 565 | 96.66341309 |
| 115 | 100 | 49.307209 | 0.192906 | 570 | 96.71242937 |
| 116 | 100 | 49.575806 | 0.199059 | 575 | 96.78684659 |
| 117 | 100 | 49.854046 | 0.200864 | 580 | 96.85907039 |
| 118 | 100 | 47.326409 | 0.457515 | 585 | 96.51612351 |
| 119 | 100 | 48.088527 | 0.418713 | 590 | 96.65748656 |
| 120 | 100 | 48.712739 | 0.350271 | 595 | 96.7319156 |
| 121 | 100 | 45.877463 | 0.410627 | 600 | 96.08739152 |
| 122 | 100 | 46.425010 | 0.320849 | 605 | 96.11429604 |
| 123 | 100 | 46.852539 | 0.289930 | 610 | 96.18786613 |
| 124 | 100 | 47.274742 | 0.310980 | 615 | 96.32132563 |
| 125 | 100 | 47.718945 | 0.326494 | 620 | 96.45305952 |
| 126 | 100 | 48.205174 | 0.364787 | 625 | 96.62133909 |
| 127 | 100 | 48.740330 | 0.391451 | 630 | 96.78710798 |
| 128 | 100 | 49.294399 | 0.377113 | 635 | 96.90813054 |
| 129 | 100 | 49.785652 | 0.316914 | 640 | 96.96268846 |
| 130 | 100 | 45.723956 | 1.031715 | 645 | 97.06866464 |

| | | | | | |
|-----|-----|-----------|-----------|-----|-------------|
| 131 | 100 | 48.221620 | 0.727038 | 650 | 97.11591886 |
| 132 | 100 | 49.153699 | 0.563621 | 655 | 97.10547901 |
| 133 | 100 | 49.899631 | 0.379049 | 660 | 97.06009431 |
| 134 | 100 | 50.292798 | 0.255345 | 665 | 97.02414219 |
| 135 | 100 | 50.469772 | 0.192574 | 670 | 97.005995 |
| 136 | 100 | 50.673697 | 0.124601 | 675 | 96.99350017 |
| 137 | 100 | 50.795346 | 0.075910 | 680 | 96.98086725 |
| 138 | 100 | 50.870170 | 0.044902 | 685 | 96.97317879 |
| 139 | 100 | 50.904681 | 0.001269 | 690 | 96.94562494 |
| 140 | 100 | 50.860619 | -0.051379 | 695 | 96.89220488 |
| 141 | 100 | 50.786090 | -0.058311 | 700 | 96.86763853 |
| 142 | 100 | 50.757551 | 0.006188 | 705 | 96.91210634 |
| 143 | 100 | 50.749464 | -0.011625 | 710 | 96.89545165 |
| 144 | 100 | 50.716716 | -0.030895 | 715 | 96.87150865 |
| 145 | 100 | 50.658595 | -0.045338 | 720 | 96.84506777 |
| 146 | 100 | 50.603489 | -0.039153 | 725 | 96.83581714 |
| 147 | 100 | 50.541699 | -0.047565 | 730 | 96.81321068 |
| 148 | 100 | 50.461910 | -0.058175 | 735 | 96.78422698 |
| 149 | 100 | 50.363905 | -0.079396 | 740 | 96.74223913 |
| 150 | 100 | 50.229612 | -0.106011 | 745 | 96.68682848 |
| 151 | 100 | 50.073921 | -0.109968 | 750 | 96.64322546 |
| 152 | 100 | 50.016509 | 0.013055 | 755 | 96.7276918 |
| 153 | 100 | 50.022732 | 0.015650 | 760 | 96.73150373 |
| 154 | 100 | 50.021446 | 0.006337 | 765 | 96.72327029 |
| 155 | 100 | 50.003351 | -0.004344 | 770 | 96.70960761 |
| 156 | 100 | 49.979880 | -0.003698 | 775 | 96.70408581 |
| 157 | 100 | 49.968681 | 0.002787 | 780 | 96.70665277 |

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|-----|-----|-----------|-----------|-----|-------------|
| 158 | 100 | 49.972163 | 0.004636 | 785 | 96.70911406 |
| 159 | 100 | 49.959505 | -0.009094 | 790 | 96.69429744 |
| 160 | 100 | 50.221948 | -0.070825 | 795 | 96.71215071 |
| 161 | 100 | 50.100925 | -0.111740 | 800 | 96.64891476 |
| 162 | 100 | 49.935284 | -0.136142 | 805 | 96.58708144 |
| 163 | 100 | 49.740074 | -0.159026 | 810 | 96.51865488 |
| 164 | 100 | 49.497020 | -0.189902 | 815 | 96.43165248 |
| 165 | 100 | 49.332616 | -0.187291 | 820 | 96.38993514 |
| 166 | 100 | 49.074636 | -0.174012 | 825 | 96.33119882 |
| 167 | 100 | 48.839377 | -0.130888 | 830 | 96.30173913 |
| 168 | 100 | 48.691639 | -0.079167 | 835 | 96.30415476 |
| 169 | 100 | 48.601551 | -0.028814 | 840 | 96.32278827 |
| 170 | 100 | 48.577658 | 0.003965 | 845 | 96.34514429 |
| 171 | 100 | 48.591112 | 0.050260 | 850 | 96.39046074 |
| 172 | 100 | 48.700654 | 0.142291 | 855 | 96.50654733 |
| 173 | 100 | 48.947805 | 0.187551 | 860 | 96.61528825 |
| 174 | 100 | 44.897293 | 0.806236 | 865 | 96.45415904 |
| 175 | 100 | 46.170509 | 0.704566 | 870 | 96.58950782 |
| 176 | 100 | 47.170414 | 0.569273 | 875 | 96.62958005 |
| 177 | 100 | 47.906233 | 0.436095 | 880 | 96.6336691 |
| 178 | 100 | 48.423701 | 0.310513 | 885 | 96.61360002 |
| 179 | 100 | 48.754904 | 0.199765 | 890 | 96.57837096 |
| 180 | 100 | 48.943707 | 0.109644 | 895 | 96.53770636 |
| 181 | 100 | 49.023939 | 0.042483 | 900 | 96.49631562 |
| 182 | 100 | 49.030483 | -0.001782 | 905 | 96.45888411 |
| 183 | 100 | 48.977334 | -0.031363 | 910 | 96.41954936 |
| 184 | 100 | 48.907776 | -0.039774 | 915 | 96.39413485 |

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|------------|-----|-----------|-----------|------|-------------|
| 185 | 100 | 48.834501 | -0.049287 | 920 | 96.36681069 |
| 186 | 100 | 48.719940 | -0.109715 | 925 | 96.28680235 |
| 187 | 100 | 48.526773 | -0.136676 | 930 | 96.21381378 |
| 188 | 100 | 48.306743 | -0.147283 | 935 | 96.1464839 |
| 189 | 100 | 48.067303 | -0.141542 | 940 | 96.08668451 |
| 190 | 100 | 47.834222 | -0.140227 | 945 | 96.02490227 |
| 191 | 100 | 47.608065 | -0.140691 | 950 | 95.96335924 |
| 192 | 100 | 47.118365 | -0.176665 | 955 | 95.80084226 |
| 193 | 100 | 46.868159 | -0.184480 | 960 | 95.7258734 |
| 194 | 100 | 46.530039 | -0.196163 | 965 | 95.62314317 |
| 195 | 100 | 46.209853 | -0.203507 | 970 | 95.52833599 |
| 196 | 100 | 45.232641 | -0.130834 | 975 | 95.31793614 |
| 197 | 100 | 45.036118 | -0.161400 | 980 | 95.23559142 |
| 198 | 100 | 44.769189 | -0.186355 | 985 | 95.13828943 |
| 199 | 100 | 44.457295 | -0.212106 | 990 | 95.02716543 |
| 200 | 100 | 44.104085 | -0.241529 | 995 | 94.9005166 |
| 201 | 100 | 43.688969 | -0.279250 | 1000 | 94.74820367 |
| 202 | 100 | 43.231591 | -0.299974 | 1005 | 94.59693869 |
| 203 | 100 | 42.757475 | -0.309375 | 1010 | 94.44911696 |
| 204 | 100 | 42.250987 | -0.317390 | 1015 | 94.29160424 |
| 205 | 100 | 41.717979 | -0.337028 | 1020 | 94.1144814 |
| 206 | 100 | 41.139408 | -0.348611 | 1025 | 93.92884436 |
| 207 | 100 | 40.537154 | -0.344419 | 1030 | 93.74839732 |
| 208 | 100 | 39.945113 | -0.344283 | 1035 | 93.56587929 |
| 209 | 100 | 39.347347 | -0.331215 | 1040 | 93.39262646 |
| 210 | 100 | 38.777650 | -0.309513 | 1045 | 93.23624729 |
| 211 | 100 | 38.247123 | -0.308247 | 1050 | 93.07069998 |

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|-----|-----|-----------|-----------|------|-------------|
| 212 | 100 | 37.701724 | -0.294348 | 1055 | 92.91296977 |
| 213 | 100 | 37.364673 | -0.176283 | 1060 | 92.94241012 |
| 214 | 100 | 37.007981 | -0.197714 | 1065 | 92.8046468 |
| 215 | 100 | 36.570780 | -0.222798 | 1070 | 92.63593652 |
| 216 | 100 | 36.080523 | -0.239249 | 1075 | 92.45929156 |
| 217 | 100 | 35.545724 | -0.249924 | 1080 | 92.27377763 |
| 218 | 100 | 34.984596 | -0.238442 | 1085 | 92.10641716 |
| 219 | 100 | 34.394391 | -0.226430 | 1090 | 91.93004835 |
| 220 | 100 | 33.825574 | -0.204995 | 1095 | 91.77369145 |
| 221 | 100 | 33.277979 | -0.192382 | 1100 | 91.61247174 |
| 222 | 100 | 32.807516 | -0.145286 | 1105 | 91.52912372 |
| 223 | 100 | 32.475687 | -0.071894 | 1110 | 91.53820147 |
| 224 | 100 | 32.268302 | -0.059185 | 1115 | 91.49269873 |
| 225 | 100 | 32.124146 | -0.014320 | 1120 | 91.52281893 |
| 226 | 100 | 32.129778 | 0.042402 | 1125 | 91.62412941 |
| 227 | 100 | 32.238272 | 0.061112 | 1130 | 91.69142491 |
| 228 | 100 | 32.535977 | 0.129580 | 1135 | 91.90766772 |
| 229 | 100 | 32.819773 | 0.180705 | 1140 | 92.08864152 |
| 230 | 100 | 33.000866 | 0.278135 | 1145 | 92.32970698 |
| 231 | 100 | 33.853036 | 0.690127 | 1150 | 93.4556536 |
| 232 | 100 | 35.807060 | 1.498726 | 1155 | 96.1005114 |
| 233 | 100 | 40.545142 | 1.365416 | 1160 | 96.69925854 |
| 234 | 100 | 43.052734 | 1.218862 | 1165 | 96.87533324 |
| 235 | 100 | 44.959468 | 1.128790 | 1170 | 97.09581022 |
| 236 | 100 | 46.653248 | 0.980258 | 1175 | 97.18092934 |
| 237 | 100 | 48.174686 | 0.778441 | 1180 | 97.18486706 |
| 238 | 100 | 49.590740 | 0.472275 | 1185 | 97.09465729 |

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|------------|-----|-----------|-----------|------|-------------|
| 239 | 100 | 50.019138 | 0.337860 | 1190 | 97.04357709 |
| 240 | 100 | 50.405230 | 0.240441 | 1195 | 97.03708849 |
| 241 | 100 | 50.673037 | 0.176084 | 1200 | 97.04119859 |
| 242 | 100 | 50.867631 | 0.131094 | 1205 | 97.04827922 |
| 243 | 100 | 51.014306 | 0.105792 | 1210 | 97.06246636 |
| 244 | 100 | 51.137899 | 0.090621 | 1215 | 97.08024236 |
| 245 | 100 | 51.247015 | 0.085389 | 1220 | 97.10316418 |
| 246 | 100 | 51.344705 | 0.077932 | 1225 | 97.12131361 |
| 247 | 100 | 51.436653 | 0.068255 | 1230 | 97.13618052 |
| 248 | 100 | 51.516342 | 0.059812 | 1235 | 97.14908734 |
| 249 | 100 | 51.581185 | 0.047264 | 1240 | 97.15490965 |
| 250 | 100 | 51.632506 | 0.037019 | 1245 | 97.15935689 |
| 251 | 100 | 51.669442 | 0.025519 | 1250 | 97.1592501 |
| 252 | 100 | 51.651455 | -0.027038 | 1255 | 97.11285036 |
| 253 | 100 | 51.613761 | -0.026396 | 1260 | 97.10380171 |
| 254 | 100 | 51.597935 | -0.026596 | 1265 | 97.09963481 |
| 255 | 100 | 51.558020 | -0.032043 | 1270 | 97.08526544 |
| 256 | 100 | 51.509995 | -0.039876 | 1275 | 97.06698878 |
| 257 | 100 | 51.454584 | -0.041807 | 1280 | 97.05140681 |
| 258 | 100 | 51.399908 | -0.035217 | 1285 | 97.04262476 |
| 259 | 100 | 51.354376 | -0.029976 | 1290 | 97.03514532 |
| 260 | 100 | 51.309450 | -0.032439 | 1295 | 97.02177964 |
| 261 | 100 | 51.253882 | -0.042674 | 1300 | 96.99961723 |
| 262 | 100 | 51.206923 | -0.024268 | 1305 | 97.00211321 |
| 263 | 100 | 51.164989 | -0.017117 | 1310 | 96.99712042 |
| 264 | 100 | 51.131406 | -0.020366 | 1315 | 96.98597218 |
| 265 | 100 | 51.105844 | -0.014398 | 1320 | 96.98422835 |

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|------------|-----|-----------|-----------|------|-------------|
| 266 | 100 | 51.077768 | -0.013972 | 1325 | 96.97741465 |
| 267 | 100 | 51.056936 | -0.009227 | 1330 | 96.97592276 |
| 268 | 100 | 51.050486 | -0.002399 | 1335 | 96.9798019 |
| 269 | 100 | 51.048496 | 0.004034 | 1340 | 96.98452747 |
| 270 | 100 | 51.060592 | 0.011517 | 1345 | 96.99372505 |
| 271 | 100 | 51.078406 | 0.021914 | 1350 | 97.00681422 |
| 272 | 100 | 51.118765 | 0.031507 | 1355 | 97.02501325 |
| 273 | 100 | 51.166735 | 0.043769 | 1360 | 97.04741348 |
| 274 | 100 | 51.229080 | 0.045605 | 1365 | 97.06472338 |
| 275 | 100 | 51.284585 | 0.038427 | 1370 | 97.07275651 |
| 276 | 100 | 51.332010 | 0.035265 | 1375 | 97.08211741 |
| 277 | 100 | 51.366376 | 0.030954 | 1380 | 97.08723708 |
| 278 | 100 | 51.399772 | 0.028647 | 1385 | 97.09377574 |
| 279 | 100 | 51.435634 | 0.024575 | 1390 | 97.09949459 |
| 280 | 100 | 51.463722 | 0.021031 | 1395 | 97.10369445 |
| 281 | 100 | 51.487319 | 0.018133 | 1400 | 97.10729589 |
| 282 | 100 | 51.508266 | 0.015172 | 1405 | 97.110184 |
| 283 | 100 | 51.527256 | 0.015049 | 1410 | 97.11488221 |
| 284 | 100 | 51.547440 | 0.017771 | 1415 | 97.12218723 |
| 285 | 100 | 51.563870 | 0.017343 | 1420 | 97.125988 |
| 286 | 100 | 51.592621 | 0.024644 | 1425 | 97.13917736 |
| 287 | 100 | 51.626251 | 0.028245 | 1430 | 97.15059168 |
| 288 | 100 | 51.662716 | 0.028942 | 1435 | 97.16034549 |
| 289 | 100 | 51.698165 | 0.028059 | 1440 | 97.1685503 |
| 290 | 100 | 51.729309 | 0.027111 | 1445 | 97.17561698 |

9 Appendix 2

Phase 2, Segment 1, two bumps

| Point nr. | Vehicle type | Average speed [km/h] | Average acceleration [m/s ²] | Distance [m] | Sound power level L _w [dBA] |
|-----------|--------------|----------------------|--|--------------|--|
| 60 | 100 | 36.556798 | -0.601597 | 295 | 92.23210277 |
| 61 | 100 | 35.443756 | -0.684022 | 300 | 91.77614818 |
| 62 | 100 | 34.163622 | -0.761151 | 305 | 91.25409061 |
| 63 | 100 | 32.678743 | -0.830853 | 310 | 90.6474627 |
| 64 | 100 | 30.970196 | -0.929790 | 315 | 89.90476007 |
| 65 | 100 | 28.986298 | -0.981869 | 320 | 89.06642543 |
| 66 | 100 | 26.844627 | -0.967329 | 325 | 88.20410954 |
| 67 | 100 | 24.592127 | -0.828369 | 330 | 87.46449828 |
| 68 | 100 | 23.010379 | -0.409454 | 335 | 87.64733839 |
| 69 | 100 | 22.709132 | 0.525349 | 340 | 90.12583582 |
| 70 | 100 | 25.136321 | 1.411223 | 345 | 93.71897366 |
| 71 | 100 | 28.644129 | 1.731599 | 350 | 95.53220743 |
| 72 | 100 | 32.192901 | 1.711050 | 355 | 96.09820621 |
| 73 | 100 | 35.063196 | 1.276143 | 360 | 95.28283916 |
| 74 | 100 | 36.915645 | 0.721539 | 365 | 94.31246013 |
| 75 | 100 | 37.806690 | 0.286394 | 370 | 93.72827542 |
| 76 | 100 | 38.043119 | 0.009074 | 375 | 93.38598073 |
| 77 | 100 | 37.907601 | -0.148149 | 380 | 93.14492196 |
| 78 | 100 | 37.546433 | -0.254378 | 385 | 92.90817239 |
| 79 | 100 | 37.039779 | -0.307848 | 390 | 92.68693302 |
| 80 | 100 | 36.446928 | -0.344062 | 395 | 92.45511301 |

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|-----------|-----|-----------|-----------|-----|-------------|
| 81 | 100 | 35.799218 | -0.357804 | 400 | 92.22779417 |
| 82 | 100 | 35.077710 | -0.406999 | 405 | 91.93238488 |
| 83 | 100 | 34.250003 | -0.475982 | 410 | 91.57386005 |
| 84 | 100 | 33.282870 | -0.548580 | 415 | 91.15633333 |
| 85 | 100 | 32.167562 | -0.606107 | 420 | 90.69368071 |
| 86 | 100 | 30.944697 | -0.636767 | 425 | 90.21149687 |
| 87 | 100 | 29.602290 | -0.685836 | 430 | 89.649148 |
| 88 | 100 | 28.096968 | -0.720923 | 435 | 89.02562413 |
| 89 | 100 | 26.539716 | -0.709925 | 440 | 88.43193636 |
| 90 | 100 | 24.868467 | -0.743913 | 445 | 87.71331985 |
| 91 | 100 | 23.033339 | -0.586011 | 450 | 87.27952086 |
| 92 | 100 | 21.838962 | -0.266889 | 455 | 87.57646053 |
| 93 | 100 | 21.981301 | 0.753350 | 460 | 90.71931006 |
| 94 | 100 | 24.834981 | 1.391217 | 465 | 93.58908253 |

10 Appendix 3

Phase 2, segment 2, two bumps

| Point nr. | Vehicle type | Average speed [km/h] | Average acceleration [m/s ²] | Distance [m] | Sound power level L _w [dBA] |
|-----------|--------------|----------------------|--|--------------|--|
| 136 | 100 | 41.804766 | -0.570235 | 675 | 93.95515458 |
| 137 | 100 | 40.744459 | -0.825673 | 680 | 93.45052165 |
| 138 | 100 | 39.193841 | -1.075203 | 685 | 92.79550483 |
| 139 | 100 | 37.328784 | -1.120372 | 690 | 92.12501542 |
| 140 | 100 | 35.474388 | -0.849704 | 695 | 91.64764465 |
| 141 | 100 | 34.246750 | -0.498346 | 700 | 91.54772493 |
| 142 | 100 | 33.665849 | -0.001513 | 705 | 92.02963344 |
| 143 | 100 | 34.986099 | 1.094001 | 710 | 94.75512443 |
| 144 | 100 | 36.466612 | 0.417052 | 715 | 93.58072723 |
| 145 | 100 | 36.703642 | -0.043932 | 720 | 92.90815927 |
| 146 | 100 | 36.604328 | -0.052347 | 725 | 92.86612546 |
| 147 | 100 | 36.523741 | -0.045411 | 730 | 92.85085945 |
| 148 | 100 | 36.295116 | -0.301972 | 735 | 92.45367674 |
| 149 | 100 | 35.333281 | -0.694179 | 740 | 91.7285327 |
| 150 | 100 | 34.134663 | -0.512906 | 745 | 91.4929744 |
| 151 | 100 | 33.357410 | -0.311226 | 750 | 91.47330793 |
| 152 | 100 | 33.073462 | 0.399972 | 755 | 92.59844568 |
| 153 | 100 | 35.114292 | 1.592993 | 760 | 96.25825535 |
| 154 | 100 | 38.296178 | 1.887518 | 765 | 97.80601461 |
| 155 | 100 | 41.154303 | 1.692448 | 770 | 97.73383146 |

