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IMAGINE
Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

The Noise Emission Model For European Road Traffic

***Deliverable 11* of the IMAGINE project**

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EXECUTIVE SUMMARY

This report presents the final results from Work Package 5 activities within the IMAGINE project. The WP5 work was dedicated to the development of a noise emission model for road vehicles that accounted for the characteristics of different vehicle types and that accounted for the variation within the European vehicle population observed in different regions. Many different parameters that affect the road vehicle noise are included, yet the model is practical and can easily be used for noise mapping purposes.

The study presented here, is a further development of the HARMONOISE source model in which emphasis is laid towards the development of the complete definition of the emission of the average European road vehicle in 1/3rd octave bands.
The model developed exhibits the following characteristics:

1. Each road vehicle has two noise source types, one for rolling noise and one for noise from the propulsion system.
2. The differences between the sound emission characteristics of road vehicles are distinguished through vehicle categories.
3. The effect of the road surface is implemented in the rolling noise and in the propulsion noise level through a procedure developed in the related 6th framework project SILVIA
4. The effect of driving behaviour (speed and acceleration) is taken into account in the formulation of the source strength for both propulsion and rolling noise.
5. Effects of environmental conditions are taken into account through meteorological corrections.
6. Within categories shifts in vehicle fleet characteristics are taken into account by regional corrections.

The overall emission values are based on extensive measurements of pass-by events of different types of vehicles performed in UK, Italy, Netherlands, Sweden, Denmark, Poland and Greece, covering the different areas in the EU. Detailed data on the speed effect of propulsion noise was obtained from specialised on-board systems of vehicles performing urban representative drive cycles, both in real life and on test stands and from studies on test tracks. Rolling noise data was obtained from tyre/road investigations on test tracks.

This Deliverable described the starting points for the work of Work Package 5, followed by a description of the data acquisition and analysis campaigns performed over the last three years. In Chapter 4 of this Deliverable the entire road noise source model, being the result of this work, is described. In the following chapters the model is validated versus roadside measurements, and the use of the model in practice, especially the combination of our model with traffic modelling data, is explained. Finally, some essential points for the future of our model are addressed.

An Excel database has been developed with the coefficients to fill the model equations and is complementary to this report. It can be obtained through the Work Package 5 partners listed in this report.

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1 Introduction

1.1 Scope and background

This report presents the final results from Work Package 5 activities within the IMAGINE project. WP5 work was dedicated to the development of a noise emission model for road vehicles that accounted for the characteristics of different vehicle types and that accounted for the variation within the European vehicle population observed in different regions.

The emission of the noise model is such that it can be used as source part in a sound propagation calculation. Its source strength is defined as the total sound power level.

1.2 The IMAGINE project

In June 2002, the European Directive on the Assessment and Management of Environmental Noise (2002/49/EC, (further indicated by its abbreviation END) was accepted and came into force. Under this Directive, member states are obliged to produce strategic noise maps of major roads, railways, airports and large agglomerations by 30th June 2007. These noise maps shall express the environmental noise levels caused by the above sources, in terms of the harmonised noise indicators L_{den} and L_{night}. From these, other statistics such as the total number of residents exposed to certain noise levels shall be derived. This information shall then be submitted to the European Commission and made public. The next step will be to draft Noise Action Plans, the first of which will have to be produced by July 2008.

It has always been the intention of the Commission to establish common assessment methods for the production of these noise maps but until such methods are made available, the END has defined interim methods. These interim methods or a Member State’s national method, if it can be shown to be equivalent to the interim method, will be used in the first round of mapping in 2007.
As a first step to developing a common method the project HARMONOISE was initiated in August 2001. This project was partly funded by the European Commission (DG Information Society and Technology) under the 5th framework programme. Its main objective was to develop harmonised, accurate and reliable methods for the assessment of environmental noise from roads and railways. This was completed in August 2004.

This was taken further in the present project, IMAGINE, which commenced in November 2003, and is a Strategic Targeted Research Project which addresses Task 3 of the Scientific Support to Policies (SSP) Call under the 6th Framework Programme. The IMAGINE project aims to extend the Harmonoise source databases for road and rail and to use the Harmonoise methodology to develop prediction methods for aircraft and industrial noise sources.

The overall objective of both projects is therefore to provide a model which will meet the requirements of the common assessment method.

The main objective of WP5 in IMAGINE is:

> *To provide default databases for the source description of road noise, i.e. vehicle category and road surface type, for a typical fleet of European road traffic, and provide guidelines on how to deal with situations deviating from the default value.*

1.3 Work Package 5 participants

The partners involved in Work Package 5 were:

- M+P consulting engineers (The Netherlands)
- Technical University of Gdansk (Poland)
- TRL – Transport Research Laboratory (United Kindom)
- Autostrade per l'Italia (Italy)
- SP – Swedish National Testing and Research Institute (Sweden)
- JRC – EC Joint Research Centre, Institute for Health and Consumer Protection (Italy)
- Volvo Trucks – Noise & Vibration Laboratory (Sweden)
- Leicester City Council (United Kingdom)
- University of Leeds (United Kingdom)

1.4 The Harmonoise project

The IMAGINE model is a further development of the emission model that was developed by WP 1.1 within the framework of the HARMONOISE project during the years 2001 to 2004.
The foundation for IMAGINE WP5 developed in the Harmonoise project consisted of:

- a measurement procedure to determine the standardized source strength based on the SEL measurement of an individual vehicle
- distinction between rolling noise and propulsion noise and the development of a set of formulae to express the source strength in terms of external determinable parameters such as speed and acceleration
- definition of the geometry of the sources and distribution of sound power over these sources
- a definition of the categories of vehicles and its subclasses
- a collection of then available data sets on rolling noise and propulsion noise for passenger cars and heavy duty trucks from studies in Sweden, Denmark, Germany and Netherlands
- a first lay out of the source strength data and estimation of the relevant coefficients
- definition of the reference surface

In the section on starting points (chapter 2) these aspects are presented in more detail.

1.5 Development of the IMAGINE model

1.5.1 General

The study presented here, is a further development of the HARMONOISE source model in which emphasis is laid towards the development of the complete definition of the emission of the average European road vehicle in 1/3rd octave bands.

To take the variations of the noise emission of the road vehicle into account the following system was developed:

1. Each road vehicle exhibits two noise source types, one for rolling noise and one for noise from the propulsion system.
2. The differences between the sound emission characteristics of road vehicles are distinguished through categories.
3. The effect of the road surface is implemented in the rolling noise and in the propulsion noise level through a procedure developed in the related 6^{th} framework project SILVIA
4. Within categories shifts in vehicle fleet characteristics are taken into account by regional corrections.
5. The effect of driving behaviour (speed and acceleration) is taken into account in the formulation of the source strength for both propulsion and rolling noise
6. Effects of environmental conditions are taken into account through meteorological corrections.

1.5.2 Data acquisition and model development

The vehicle emission model is based on several types of data-sets, each having its specific purpose. Data sets are acquired within the framework of this project or are based on related projects and earlier studies made available through the partners.

The overall emission values are based on extensive measurements of pass-by events of different types of vehicles performed in UK, Italy, Netherlands, Sweden, Denmark, Poland and Greece, covering the different areas in the EU and consisting of over 6.000 vehicle passages. Detailed data on the speed effect of propulsion noise was obtained from specialised on-board systems of vehicles performing urban representative drive cycles, both in real life and on test stands and from studies on test tracks. Rolling noise data was obtained from tyre/road investigations on test tracks.
Vehicle and tyre manufacturers have supported with statistical and technical data to fill in the gaps.

By statistical analysis of the large data sets and through combination of the large data sets with the detailed information from test tracks, lab stands and on-board data a complete picture of the total vehicle emission is modelled.

1.5.3 Implementation of the final model

The vehicle emission model basically is the instantaneous noise production of the vehicle defined by the parameters: category, speed, acceleration and corrected for several effects.

The noise emission of a traffic stream is defined as the sound power per unit length and is the sum of the sound emission of the individual vehicles in the traffic stream taking into account the time spent by the car in the considered road section.

The implementation of the individual vehicle in the stream is through application of a traffic flow model. This subject is addressed by WP 2 in the IMAGINE project and is also addressed in section 6.

1.6 How does this work fit into the IMAGINE project

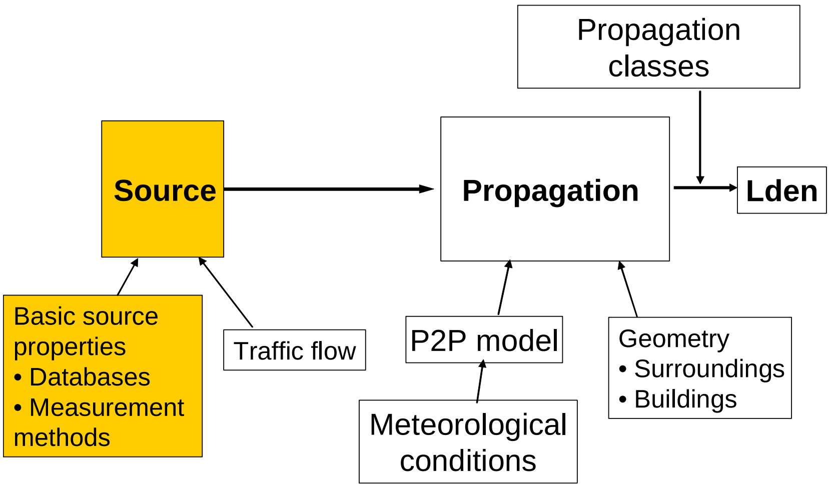


figure 1 – Global structure of the IMAGINE project

The global structure of the Harmonoise and IMAGINE methods is given in the schematic overview of figure 1. A clear separation is made in the model between the source properties and propagation.
The result of the source models is a sound power level per sub source type per source height, with certain directivity.
The P2P model, describing the noise propagation via a predefined path from one source point to one receiver point, is the basis of the propagation model. The selection of the P2P paths is made in the propagation method itself. The model also describes how meteorological conditions influence the shape of one propagation path.
The result of the propagation model is an L_{eq} at a certain receiver point for a certain meteorological class. as a summation of the contribution of the different sources via their respective propagation paths.
The long term L_{den} value is calculated from the available L_{eq} values by determining the occurrence of the different propagation classes, and summing up over the occurrence.

2 The starting points

2.1 Lay-out of the model

2.1.1 General layout of the road noise emission model

The road noise emission model shall describe the noise emission of an "average" European road vehicle in terms of a sound power level. This description of the emission model will fit tightly to a propagation calculation method developed in the Harmonoise project.
The emission model consists of a set of mathematical equations representing the two main noise sources:

a. rolling noise due to the tyre/road interaction;
b. propulsion noise produced by the driveline (engine, exhaust, etc.) of the vehicle;

Aerodynamic noise is incorporated in the rolling noise sources, since the chosen method of determination of the sound power level determined from coast-by events makes it impossible to distinguish between the two. The effect of aerodynamic noise on the source height can be neglected since detailed measurements have demonstrated that the sources for flow noise are also located in the wheel arches and under the car. Aerodynamic noise is considered to be of influence only at high vehicle speeds.

The mathematical formulae exhibit the following general form:

$$L_{i,m}(v,a) = A_{i,m} + B_{i,m} \cdot f(v)\ , \qquad (1)$$

with $f(v)$ being either a logarithmic function of the vehicle speed v in the case for rolling and aerodynamic noise, and a linear function with v in the case of propulsion noise. The sound power level $L_{i,m}$ is calculated in 1/3-octaves from 25 Hz to 10 kHz, where the subscript i indicates the spectral frequency band. The index m represents the vehicle type.

The rolling and propulsion noise production of the road vehicle at the reference speed of 70 km/h is represented by the values $A_{i,m}$. $B_{i,m}.f(v)$ represent the change in noise production due to a difference in vehicle speed relative to a reference speed.
In the paragraphs below we will go into the aspects of the noise production formulations.

2.1.2 Vehicle classes

Within the IMAGINE project the following vehicle classes are distinguished:

table I - Vehicle classes identified in the IMAGINE project

category	name	description		vehicle category in EU/ECE type approval
1	Light motor vehicles	Passenger cars, delivery vans 3.5 tons, SUV's, MPV's including trailers and caravans		M1 and N1
2	Medium heavy vehicles	Medium heavy vehicles, delivery vans > 3.5 tons, buses, touring cars, etc. with two axles and twin tyre mounting on rear axle		M2, M3 and N2, N3
3	Heavy vehicles	Heavy duty vehicles, touring cars, buses, with three or more axles		M2- and N2 with trailer, M3 and N3
4	Powered two-wheelers	4a	mopeds, tricycles or quads with 50 cc	L1, L2, L6
		4b	motorcycles, tricycles or quads with > 50 cc	L3, L4, L5, L7

This table lacks the detailed nature of the table originally developed in Harmonoise project [2]. (see table II) but has higher practical value since such detailed distribution of traffic into the several sub categories is often not available. The system of "regional corrections" allows you to take care of shifts in axle configurations of trucks, or higher then average amount of vans.
In the case of Powered two-wheelers, motorcycles and mopeds are defined as separate sub-classes, since they operate in totally different driving modes, and also their occurrence differs strongly.

table II - Vehicle classes identified in the HARMONOISE project

Main category (type)	No.	Sub-categories: Example of vehicle types	Notes
Light vehicles	1a	Cars (incl. MPV's up to 7 seats)	2 axles, max 4 wheels
	1b	Vans, SUV, pickup trucks, RV, car+trailer or car+caravan[1], MPV's with 8-9 seats	2-4 axles[1], max 2 wheels per axle
	1c	Electric vehicles, hybrid vehicles driven in electric mode[2]	Driven in combustion engine mode[2]
Medium heavy vehicles	2a	Buses	2 axles (6 wheels)
	2b	Light trucks and heavy vans	2 axles (6 wheels)[3]
	2c	Medium heavy trucks	2 axles (6 wheels)[3]

[1] 3-4 axles on car + trailer or car + caravan
[2] Hybrid vehicles driven in combustion engine mode: Classify as either 1a or 1b
[3] Also 4-wheel trucks, if it is evident that they are >3,5 tons

	2d	Trolley buses	2 axles
	2e	Vehicles designed for extra low noise driving[4]	2 axles
Heavy vehicles	3a	Buses	3-4 axles
	3b	Heavy trucks[5]	3 axles
	3c	Heavy trucks[5]	4-5 axles
	3d	Heavy trucks[5]	≥ 6 axles
	3e	Trolley buses	3-4 axles
	3f	Vehicles designed for extra low noise driving[4]	3-4 axles
Two-wheelers	4a	Mopeds, scooters	Include also 3-wheel motorcycles
	4b	Motorcycles	

2.1.3 The geometrical properties of the source model

For the calculation of the noise propagation, the emission L_W, each vehicle is represented by two point sources, which are depicted in figure 2 below. The lowest source is located at 0,01 m above the road, the highest source is located at 0,3 m for light motor vehicles and at 0,75 m for heavy motor vehicles. The lowest carries 80% of the rolling sound power and 20% of the propulsion sound power, the highest represents 20% of the rolling noise and 80% of the propulsion noise. For two-wheelers only one point source at the height of 30 cm is defined, since the contribution of rolling noise for these vehicles can be assumed to be negligible.

About 1% of the heavy vehicles have a high exhaust. For normal purposes this can be neglected. Only when a significantly higher fraction has this configurations (for instance, close to building sites, where many construction trucks are present) and when combined with shielding effects, an additional high source at 3,50 m should be used. The propulsion noise should then be distributed 80% to this 3,50 m source, and 20% to the source at 0,75 m. The rolling noise distribution is unchanged.

The vertical resolution of the sources is relevant for the fit to the propulsion model. Ground effects, originating from the interference between direct and reflected components are strongly affected by variation in source height. In reality these sources, of course, do not exhibit such sharp distributions. This has been accounted for by using a smeared out source position when transferring road side measurements into sound power level. In the propagation modelling, these strong interference effects should also be avoided, perhaps by assigning a certain finite dimension to these point sources.

[4] For example, there are some delivery trucks designed for extra low noise (meeting more stringent standards than the current EU limiting levels) combined with a driving mode called “whisper mode”

[5] If a high exhaust is noted, identify this in the test report. Categorize this as 3b′, 3c′, 3d′ or 4a′

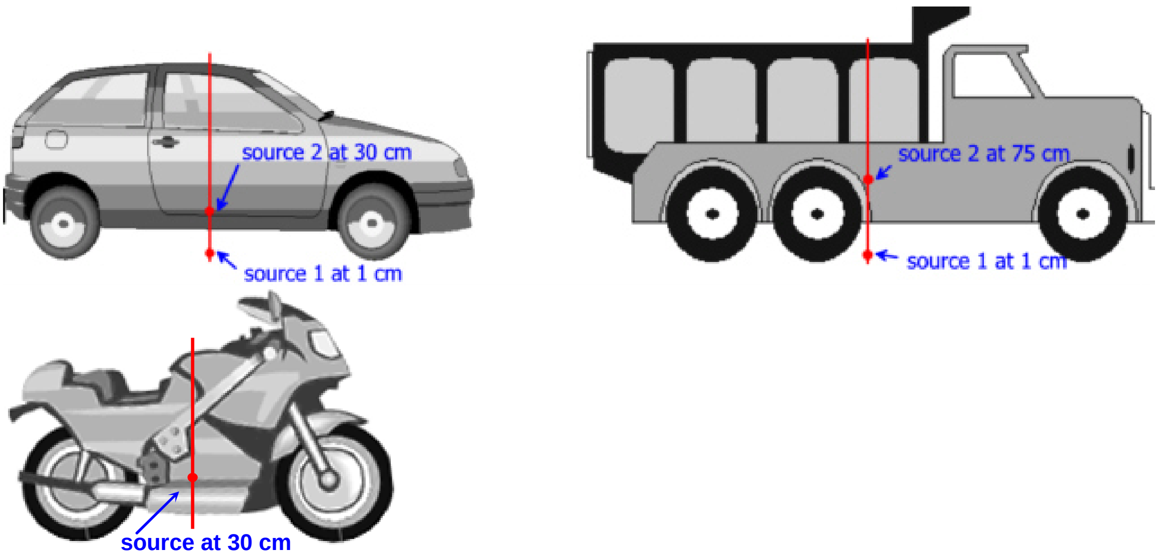


figure 2 – Drawing of noise source positions

Horizontal resolution in the driving direction is not relevant since a traffic stream will be represented by a line source. This line source is located vertical plane of the nearest wheel.
The sound power is defined as the total sound power of the source without any disturbing objects in its surrounding (including reflection at the road surface). The radiation in different directions is given by a directivity function in both the horizontal and vertical plane.

2.2 Source equations

2.2.1 Rolling noise and aerodynamic noise

For rolling noise, the general accepted and widely validated logarithmic relation between sound power and rolling speed is used. The emission L_{WR} is formulated as follows:

$$L_{WR} = A_R + B_R \cdot \lg\left(\frac{v}{v_{ref}}\right), \qquad (2)$$

where, as stated above, the coefficients A_R and B_R are given in 1/3-octave bands for each vehicle class, and v_{ref} = 70 km/h.
As stated above, the aerodynamic noise of the vehicle is incorporated in this rolling noise equation.

2.2.2 Propulsion noise

The propulsion noise emission L_{WP} includes all contributions from engine, exhaust, gears, air intake, etc. For propulsion noise, the emission L_{WP} is formulated as follows:

$$L_{WP} = A_P + B_P \cdot \frac{v - v_{ref}}{v_{ref}}, \qquad (3)$$

where the coefficients A_P and B_P are given in 1/3-octave bands for each vehicle class, and v_{ref} = 70 km/h. In this formulation, the speed dependence is a linear one. This is based on the combined effect of the effect of vehicle speed on engine speed and the effect of engine speed on noise. The first effect is mainly steered by the gear shifting behaviour of the vehicle or driver.

Several field tests has shown that although the driver operates the vehicle in a limited engine speed range, there is a clear tendency for higher engine speeds at higher vehicle speeds.
The relation between noise production and engine speed is a logarithmic one.
The two combined is approached by the formula above. The larger deviations from this approached linear relation occur at very low speed (but they are less relevant for the $L_{A,eq}$ level) and at high speeds (but here the rolling noise is dominating the overall noise production).

2.3 Correction factors

2.3.1 Vehicle categories

The basis of the noise emission modelling is the average European road vehicle subdivided in the following categories (see also table I):

1. passenger cars
2. light duty vehicles
3. heavy duty vehicles
4. powered two wheelers

Only within category 4 are two types distinguished; mopeds/scooters and motorcycles, each belonging to powered two wheelers but with distinct noise properties.

2.3.2 Regional corrections

Between countries and regions of Europe one notices differences in the fleet composition, even within a category. These differences cannot be neglected in a high quality noise source model as the IMAGINE model. Clearly noticeable is the fraction of diesel engines in passenger cars that differs between over 60% in certain areas and below 15% in others. The effect of tyre mounting, especially winter tyres is also taken into account. In Scandinavia the fraction of studded tyres is above 75%, while in southern countries winter tyres are rarely applied. These effects are incorporated in the IMAGINE model through the regional corrections.
The following effects on the noise emission are taken into account in the regional corrections:

1. engine type (only cat 1) (Otto, Diesel)
2. tyre width (only cat 1) through its relation with weight
3. tyre mounting (summer, winter, studded)
4. age (only cat 1)
5. fraction of IRESS (illegal replacement exhaust silencing systems) (all categories)
6. fraction of VANs in cat 1.
7. distinction between three and multi-axle HDV's.

Effects of variation in fraction of automatic gearboxes are neglected in this model, since it is found that there exists no acoustical significant difference between the shifting behaviour of these systems and that of manual gear boxes under normal driving conditions.

Since several of these entities are part of the vehicle classification in the official EU type regulation for motor vehicles, statistical data about the composition of the vehicle fleet with these aspects are more or less easy to find. Other statistics such as on IRESS and on tyre mounting can be obtained from vehicle and car manufacturers and also national statistics.
(see section 2.3 and table II).

Some data are acquired within the frame work of this project and are presented in [8].

2.3.3 Meteorological corrections

Two meteo-effects are taken into account:

1. the effect of temperature. Tyre/road noise tends to increase with decreasing temperature, most probably due to the increased stiffness of the tread compound. This effect is highest for cat 1 and the coefficients are based on the work of working group ISO/TC43/SC1/WG27.
2. rolling noise on wet road surfaces are higher then on dry surfaces, mainly because the water film affects aero-dynamic process in the tyre/road contact patch. In this effect we distinguish between dense and porous surfaces.

2.3.4 Correction for driving conditions

A correction is made to the propulsion noise for the driving conditions:

$$\Delta L_{WP,acc} = C_P \cdot a$$

This correction refers to the effect on propulsion noise emission from accelerating or decelerating driving. Closely connected to this is the effect of up- and down-hill driving. This effect only applies to propulsion noise and combines the effect of higher engine load and lower gear ratio.
This effect is presented as a linear relationship with the acceleration or deceleration *a* in m/s^2. The coefficient C_p is defined in 3rd octave bands, and represents the effect of changing engine load at the firing frequency and higher mechanical noise levels in the mid-frequency range.

2.3.5 Correction for road surface

The type of road surface significantly influences the noise production of a vehicle. In pass-by events differences up to 15 dB(A) are recorded for the same vehicle and speed. The road surface affects mainly rolling noise level, but porous, sound absorbing surfaces, will also affect propulsion noise.
The variety of road surface types and conditions of road surfaces over Europe is large and the IMAGINE study has not addressed that in detail, but refers to the results of the 6th framework project SILVIA, where procedures for labelling, conformity checking and monitoring of the surface correction, indicated there as $_{road}$ are developed. This report will present the correction factors for a representative selection of EU road surfaces.

3 Data acquisition and analysis

The IMAGINE road vehicle emission model is based on several data sources and data acquisition programmes, executed inside and outside the IMAGINE frame work. In the following paragraphs specific information on the rolling noise source and the propulsion sound source are described. After that the overall road side measurement programmes are presented, incorporating several vehicle categories.

3.1 Category 1 vehicles

For this category, the emphasis is laid on rolling noise, since for the largest part of the operating conditions, this is the most dominant source. The modelling of slow driving vehicles or accelerating vehicles at junctions and the effects of noisy exhausts, propulsion noise are also studied.

3.1.1 Analysis of Venom model data (TU Gdansk)

Description of work

The TU Gdansk and VTI from Sweden have developed a multi source model for the prediction of the pass-by noise levels of light motor vehicles, as a function of vehicle speed, acceleration and gear, based on detailed study of a limited number of passenger cars and motorcycles that were tested under different driving conditions at a test track [20]. The underlying measurement data are re-analysed in order to develop the A_P, B_P and C_P coefficients, as a function of frequency, required for our model.

To do so, the L_W source power levels have been calculated from the $L_{A,max}$ values used in the Venom model using simple propagation model. A regression analysis using the propulsion noise equation $L_{W,i} = A_{P,i} + B_{P,i} \cdot (v - v_{ref} / v_{ref}) + C_{P,i} \cdot a$ has been performed on the L_W levels per spectral band *i* to give the required coefficients as a function of frequency.

Results

In figure 3 below, the A_P and B_P coefficients found by TUG and those found in the Harmonoise model are plotted vs. the frequency. The values correspond quite well, given a certain uncertainty margin for both sets. The TUG graph has been smoothened so it will probably under-estimate the levels at the firing frequency (around 80 Hz).

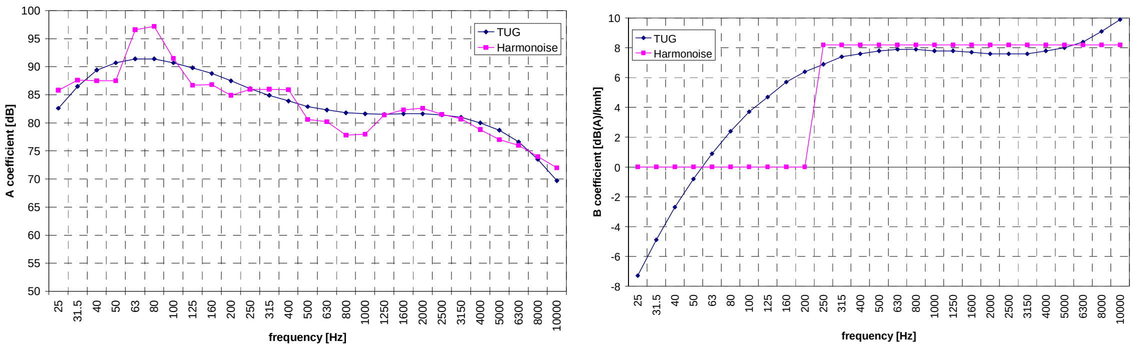


figure 3 – Results of re-analysing of the TUG-Venom model; left: the coefficient A_P, being the sound power level at the reference speed of 70 km/h,; right: The speed coefficient B_P as a function of frequency. For comparison the Harmonoise date are given.

3.1.2 Analysis of rolling noise measurements for car tyres (M+P)

During the period 1997-2001, an extensive research project was conducted by M+P and Müller-BBM for the German Bundesanstalt für Straßenwesen (BASt), to establish a tyre/road rolling noise emission model. A test track with 42 different asphalt and concrete road surfaces was laid down in Sperenberg (DE) and an extensive amount of rolling noise measurements with two different vehicles and 8 different tyres for each vehicles, as well as 4 truck tyres, was conducted, along with measurements of the surface texture and sound absorption, and other road parameters.

Some of these data have been re-analysed for the Harmonoise and IMAGINE projects to develop the rolling noise emission model for category 1 vehicles. The images and graphs below have been taken from the project report [14].

figure 4 – Rolling noise measurements at Sperenberg, Germany; <u>top</u>: tyres used for the rolling noise measurements with Mercedes C280 , <u>bottom</u>: the Sperenberg concrete test fields with measurement set-up

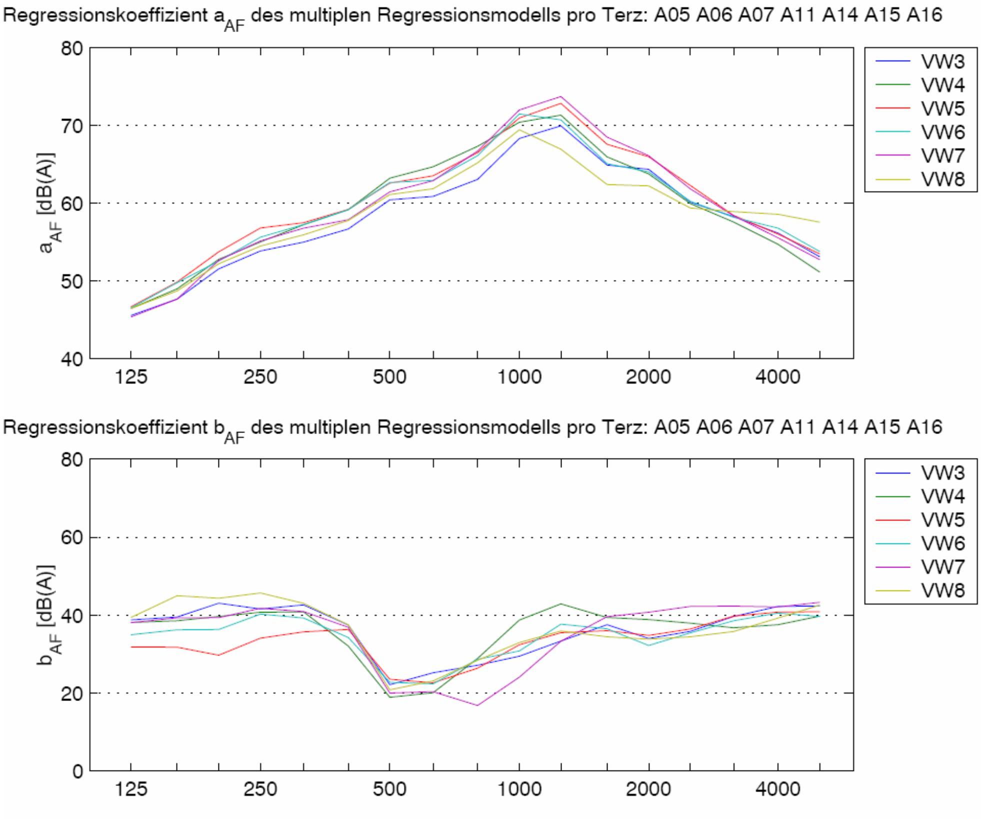


figure 5 – Example of results from the tyre/road noise measurements with VW Polo, at 1.2m height and 7.5m distance: noise spectrum at 70 km/h (top) and speed coefficients (bottom), for six different tyres averaged over several asphalt surfaces

3.2 Category 2 and 3

3.2.1 Analysis of rolling noise measurements for truck tyres (M+P)

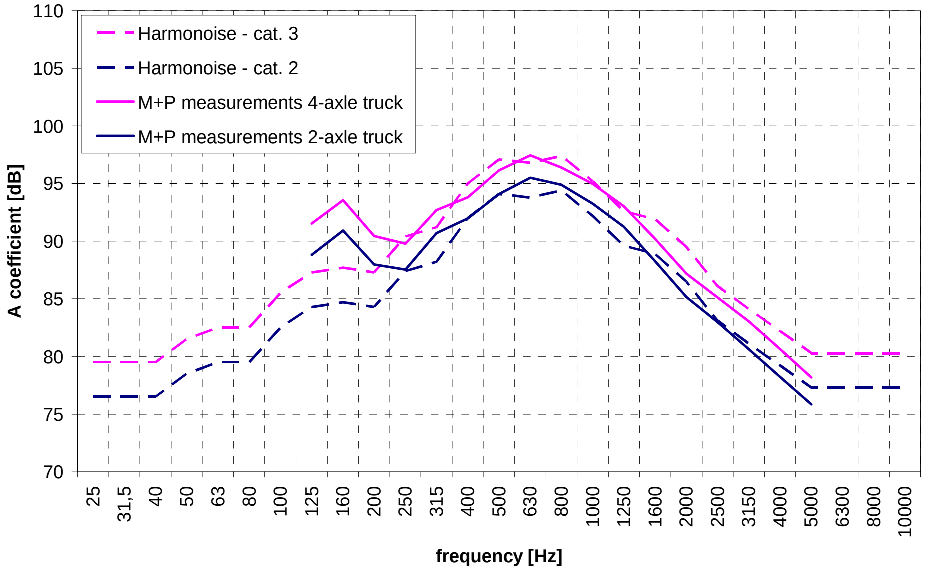
Description of work

In September/October 2003, M+P has performed a large series of measurements on 15 types of truck tyres for “Innovatieprogramma Geluid” of the Dutch Ministry of Transport. Tyre types included tyres for the steering (315mm rib profile), traction (315 block profile) and trailer (385 rib profile). Tyres were tested in new and in (artificially) worn condition. Pass-by measurements were conducted on 12 types of asphalt surfaces at vehicle speeds ranging 45 to 95 km/h, at 1.2m height and 7.5m distance. Both SEL and L_{max} levels were recorded. Data are presented in [24].

For our project, the measurement data were re-analysed to give the A_R and B_R rolling noise coefficients for the IMAGINE model. From all tyre types and asphalt surfaces, the coefficients were developed for a “composite” 2-axle and 4-axle truck, containing an average of normal steering, driving and trailer axle tyres. The SEL level of a two axle vehicle is the addition of the SEL levels of four traction tyres and two steering tyres. The SEL level of a 4 axle truck is made up of 2 steering tyres, 4 traction tyres and 4 trailer tyres. SEL levels are used that are found on a set of asphalt surfaces that are within the IMAGINE reference surface definition.

Results

In figure 6 below, the results of the M+P analysis are plotted together with the rolling noise values found in Harmonoise. The overall levels (A coefficients) from the measurements correspond quite well from 250 Hz upwards, but show somewhat higher values at 125 – 200 Hz, as can be seen from figure 6. The speed coefficients of Harmonoise are much higher than the current measurements in the range 125 – 500 Hz, but correspond well above 500 Hz.



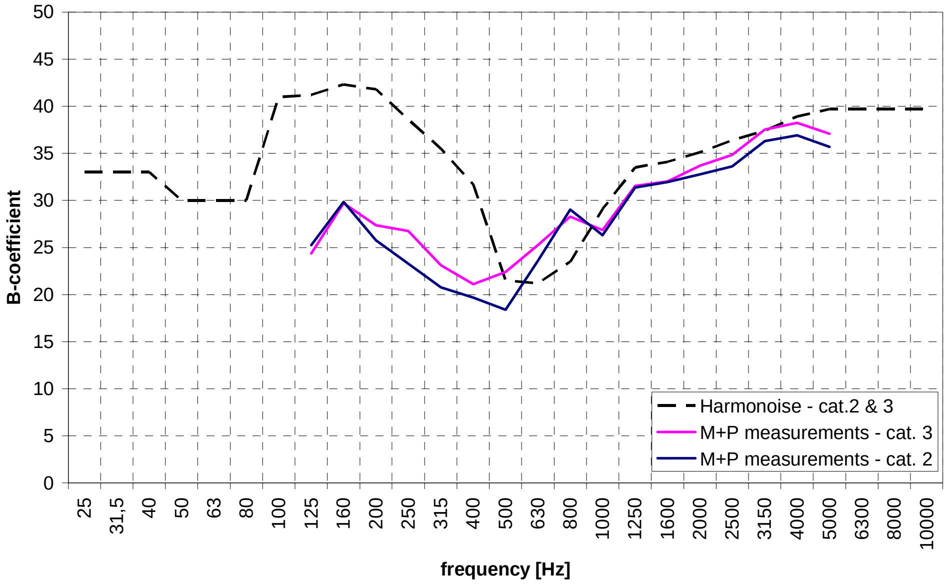


figure 6 – Results of analysis of M+P truck tyre noise levels for category 2 and 3 trucks. Presented is the Sound Power levels at the reference speed (coefficients A_P) and the speed coefficients B_P. Results are compared with the Harmonoise coefficients.

In figure 7 the M+P measurements are compared to two tyres (315 mm steer axle tyres) measured by TRL in coast-by on and SMA 0/14 surface; the graph shows overall A-weighted SEL spectra at 7.5 m from the road. The spectra found by TRL correspond well to the M+P measurements of the average steering axle (S) tyre on an SMA 0/11 surface. The average of the spectra found for the tyres on the "composite" 2-axle (category 2) truck found by M+P are somewhat higher, explainable since the average includes traction tyres on the driving axle.

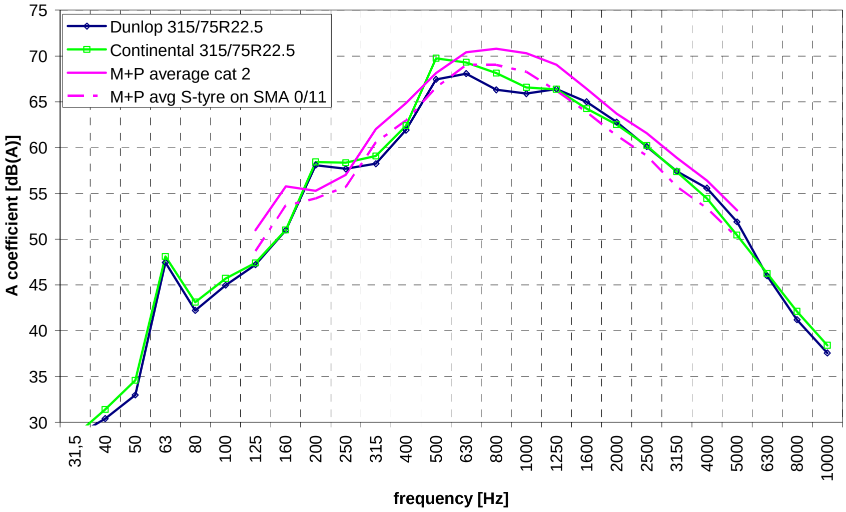


figure 7 – Comparison of M+P analysis with TRL measurements, overall A-weighted levels at 70 km/h

3.2.2 Volvo laboratory measurements of HDV propulsion noise

Description of work

In the first half of 2005, Volvo has performed several propulsion noise tests in their indoor truck laboratory. The results have been reported separately in [10]. An overview of this study is presented here.

Three types of test programmes were accomplished, using the ISO 3744 method for measuring sound power levels:

1. propulsion noise measurements using only the driveline configuration with a partial car body to simulate shielding (see figure 8);
2. propulsion noise measurements using a full truck in the truck chamber with shielded rear wheels on a dynamometer (see figure 8);
3. city cycle simulations in the truck chamber.

figure 8 – Volvo noise laboratory: the driveline rig (left) and the truck chamber (right)

During the first two tests the propulsion noise source levels were determined driving at constant speed at different gears, while varying parameters such as the vehicle load, road gradient and gear shifting behaviour. The city cycle tests were performed in the truck chamber, where the driver was instructed to do a standard programme representative for driving in an urban area.

This programme included acceleration from 0 – 70 km/h, constant speed, engine braking, etc. (see [10] for details).

Results

The figure 9 and figure 10 below present the A_P and B_P coefficients found from the Volvo measurements in the truck chamber, compared with the Harmonoise coefficients for categories 2 and 3. From figure 9 it is clear that the propulsion noise in the Harmonoise model was overrated, especially from 80 – 400 Hz and above 1600 Hz.

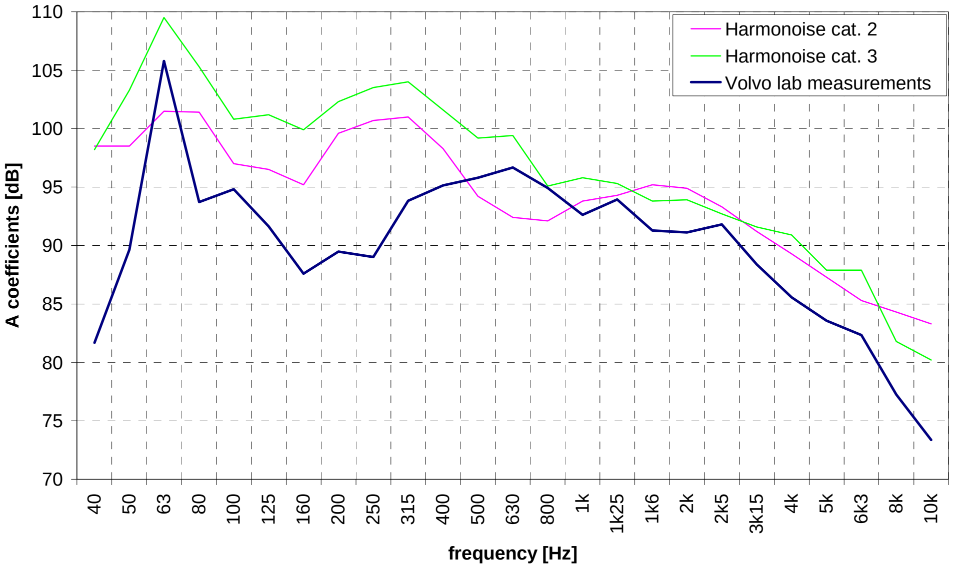


figure 9 – Comparison of A_p coefficients from Volvo lab measurements in truck chamber compared with Harmonoise values

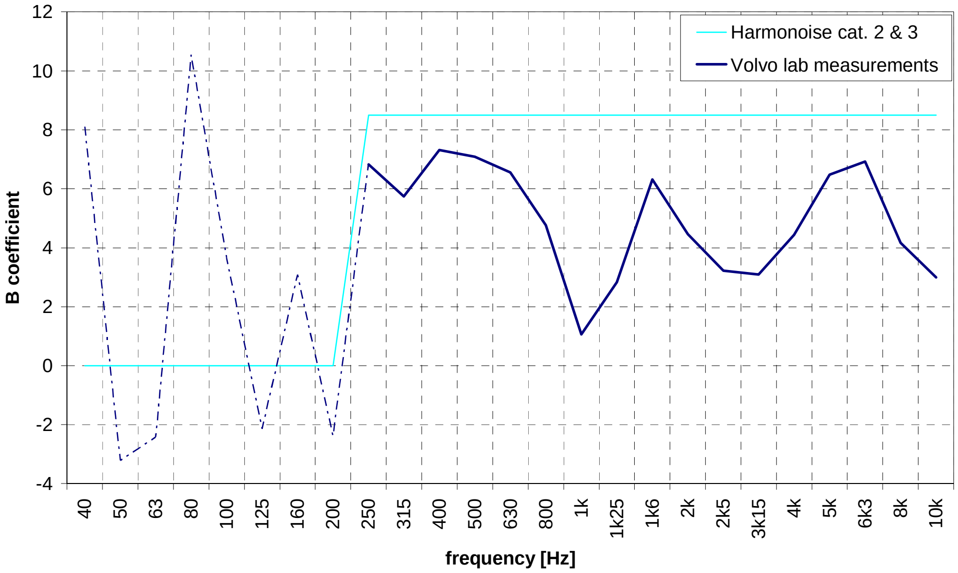


figure 10 – Comparison of *B* coefficients from Volvo lab measurements in truck chamber with Harmonoise values

3.2.3 Pull-away tests (TRL)

Additional information on the relation between acceleration and propulsion noise level is found in results of tests performed by TRL on HDV vehicles (both lorries and busses) when pulling away from stand still. In this situation rolling noise can be neglected. These tests were performed in another TRL research programme conducted for the UK Department for Transport, and the data were reanalysed for IMAGINE.

Figure 11 shows a picture of the test site, as well as some results showing the measured SEL levels in dB(A) at 20 km/h vs. the vehicle acceleration, for four category 3 vehicles. For this graph, the speed effect of the measurements was taken out by assuming a certain speed dependence; the error thus made will not be large since the speeds did not deviate much from 20 km/h.

A clear trend can be seen for three of the vehicles, with an increase of 8 dB(A) per m/s^2. Results for other vehicles did not correlate very well. Another analysis approach using multi-regression analysis has been tried, but did not deliver better results. Finally, it should be noted that these vehicles accelerated in one gear, without any gear shifting. This method therefore overrates the acceleration effect somewhat, since in real traffic situations gear shifting will result in lower engine speed, and lower noise levels. Within the Harmonoise project, an increase of 5.6 dB(A) per m/s^2 was found.

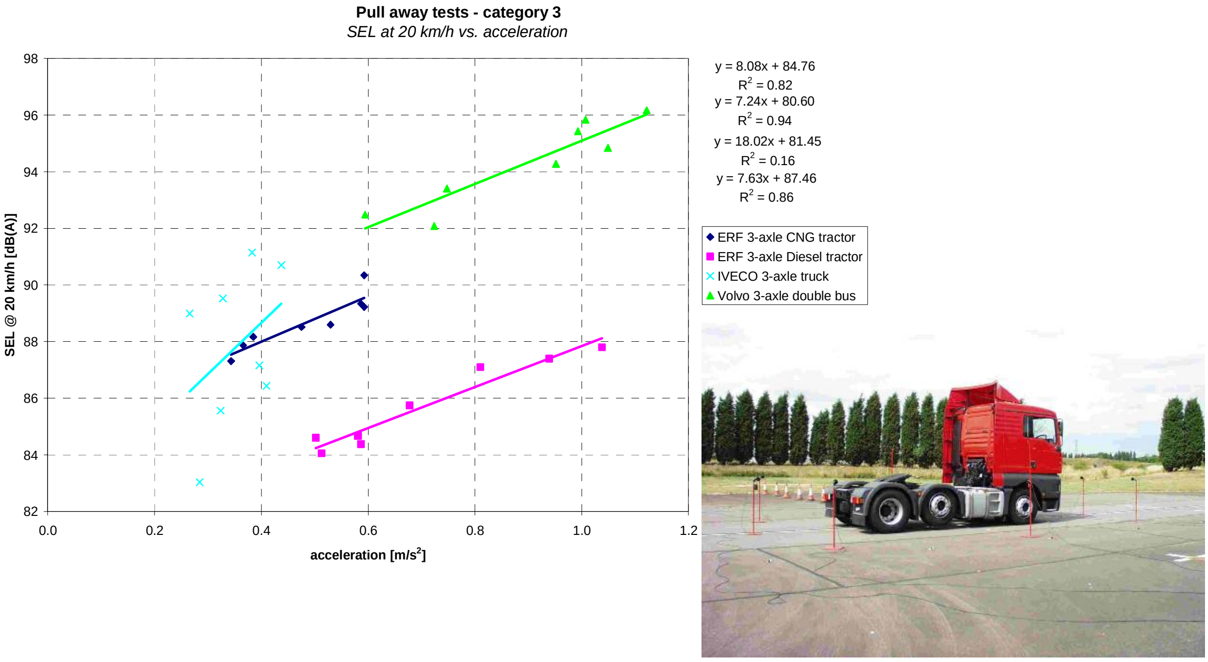


figure 11 – TRL pull-away tests; left: SEL at 20 km/h vs. vehicle acceleration, right: picture of an ERF truck on the test site

3.3 Powered Two-Wheelers

Mopeds and motorcycles do not contribute significantly to the overall L_{den} level on both highways and urban areas. Nevertheless are they of special interest because of their relative high annoyance rating. The wish to include them in our model was specifically expressed by the Commission and we have performed several detailed studies to do so.

3.3.1 On board sound measurements at city driving (M+P)

In depth investigation on the driving states and related noise emission was done by instrumentation of three test vehicles; a 50 cc scooter with automatic gearbox, a 80 cc (illegal) moped with manual gear and a 3 cylinder 885 cc motorcycle with manual gear.

Each of them was equipped with a data-logging system, capable of storing 8 channels with dc-20 kHz bandwidth recording sound signal at engine intake and exhaust, engine speed, vehicle speed and throttle position (see figure 12 for some example results).

Through analysis of the relation between speed, acceleration, and average noise level at the two positions, coefficients were calculated for the effect of speed and the effect of acceleration (see figure 13).

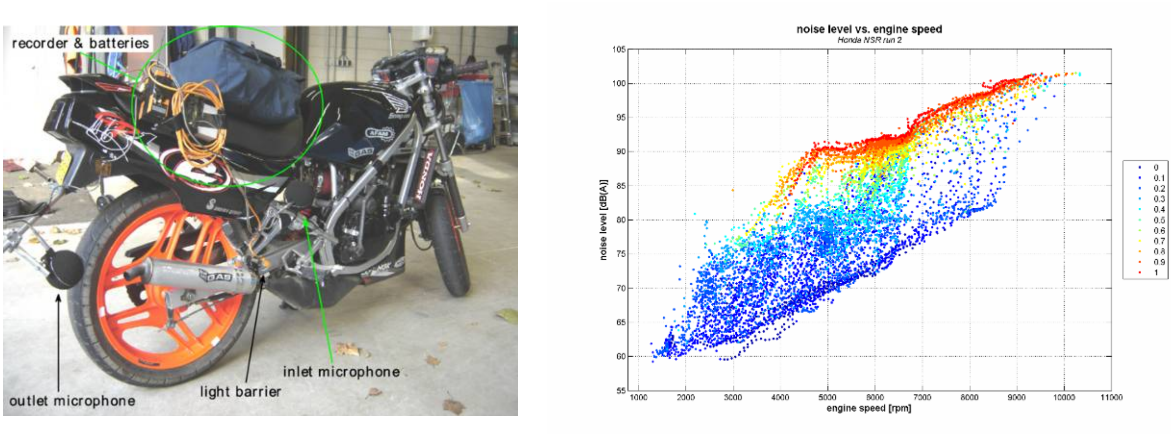


figure 12 – Picture of the measurement setup of Honda NSR moped (left) and plot of noise level versus engine speed with colours denoting the throttle position, indicating the engine load (right).

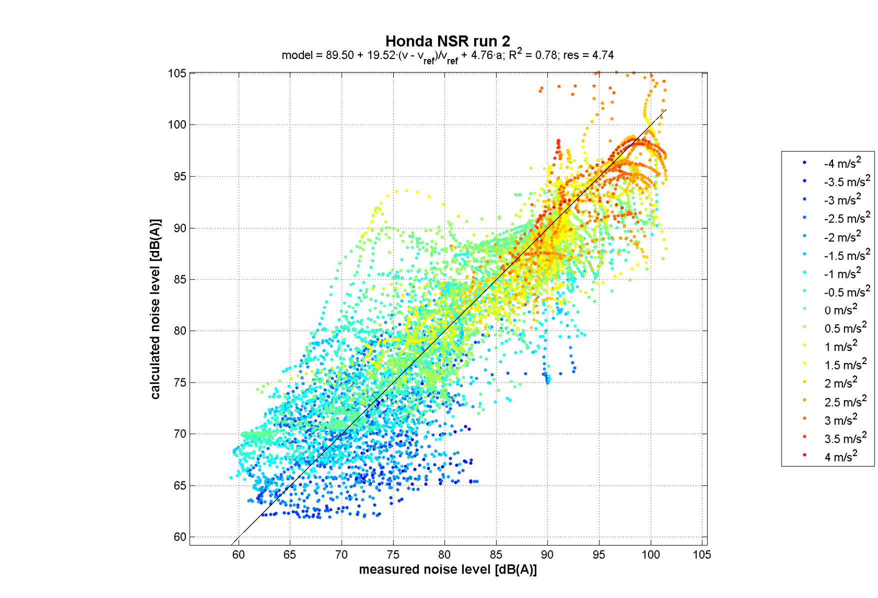


figure 13 – result of two parameter regression analysis on the Honda NSR data, the best fit is obtained with the formula given above the graph, the residual variation is 4,7 dB. This is due to the engine speed not being part of the model.

3.3.2 Driving condition monitoring during driving (IMMA, M+P)

The International Motorcycle Manufacturer Association has studied the driving states of a large number of motorcycles in urban, rural and highway driving situations. An example of one test is given in the graph below.

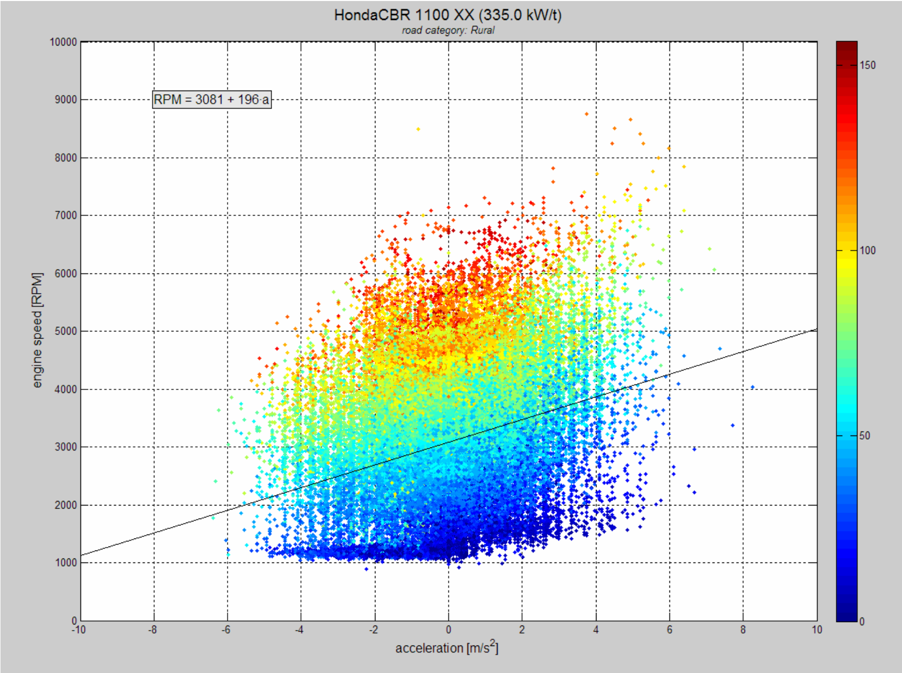


figure 14 – Example of relation between engine speed, vehicle speed and acceleration: IMMA data base, Honda CBR 1100 (335 kW/t). The regression line is given by: *engine speed=3081+196·acceleration.* Colours denote the vehicle speed in km/h from 0 to 160 km/h.

3.3.3 Dedicated road side measurements (TUG, JRC, M+P, Autostrade)

Road side measurements on a larger population of motorcycles were performed at those places and dates where higher than normal concentration is expected, such as on the road to and from the international motorcycle race in Assen (NL), the route of an organized tour through the Dutch country-side near the river Waal, The Greek island of Mykonos, and in Italy on a city road.

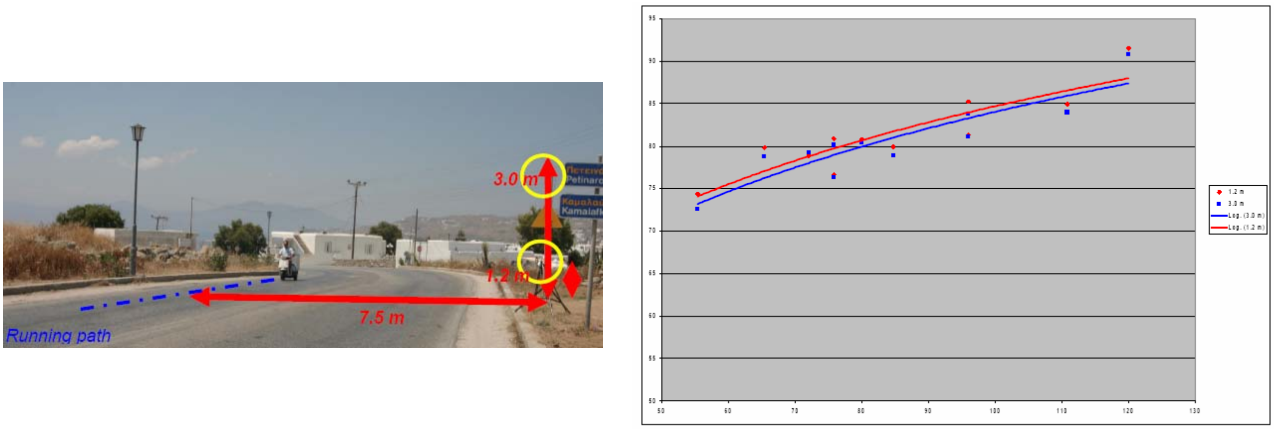


figure 15 – left: one of the measuring locations at Mykonos island, right: value as a function of speed for motorcycles, data Mykonos

3.4 Accelerating and decelerating vehicles

3.4.1 Stop and go traffic at toll station (Autostrade)

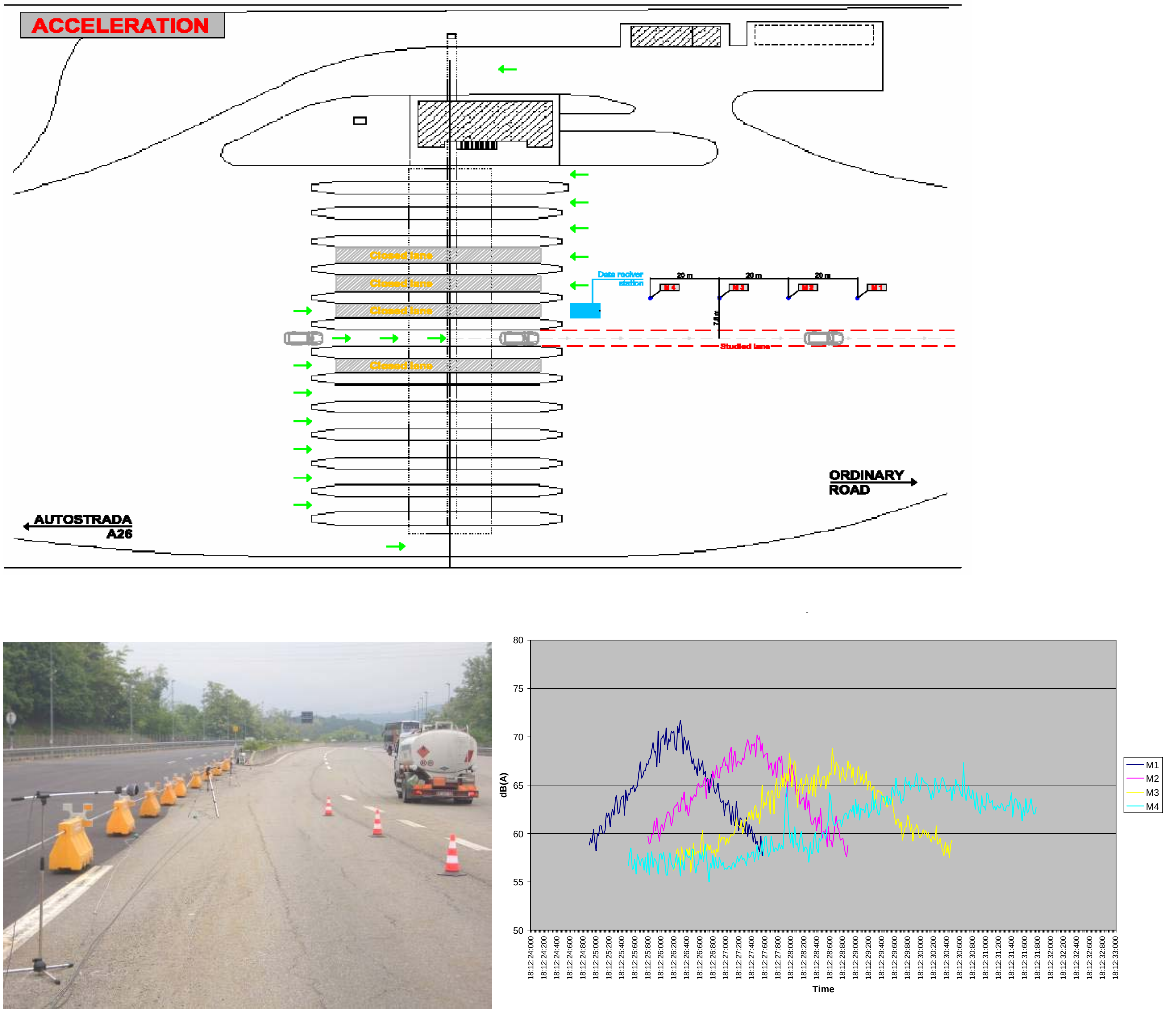


figure 16 – Measurements of stop & go traffic at the toll station on an Italian motorway; top: lay-out of the measurement site for accelerating traffic; bottom left: a truck accelerating past the microphones; bottom right: overall levels of fhe four microphones recorded during a single pass-by

A series of pass-by measurements have been made by Autostrade near the toll barrier *Lago Maggiore* along the A26 motorway (Genova – Gravellona Toce). Here, vehicles entering and leaving the toll station were measured while accelerating or decelerating, in order to acquire more measurement data for the effect of vehicle acceleration on the noise emission. As can be seen from the sketch and picture in figure 16 above, the noise levels were measured at four different locations along the vehicle path, so four measurements at different speeds could be obtained from each pass-by. For each pass-by, the SEL levels and 1/3-octave band spectra are recorded as a function of time.

Two different measurement campaigns were conducted: in the first, vehicles were forced to decelerate to a full stop before accelerating. In the second measurement campaign, only vehicles passing through the automatic TelePass gate were measured; these vehicles are registered at the toll station automatically and therefore do not have to stop. This will result in lower de- and acceleration values, so a certain spread in measurement variables is obtained. For more information on the Stop & Go measurements, see the separate measurement report [30].

3.4.2 Measurements near an intersection (M+P)

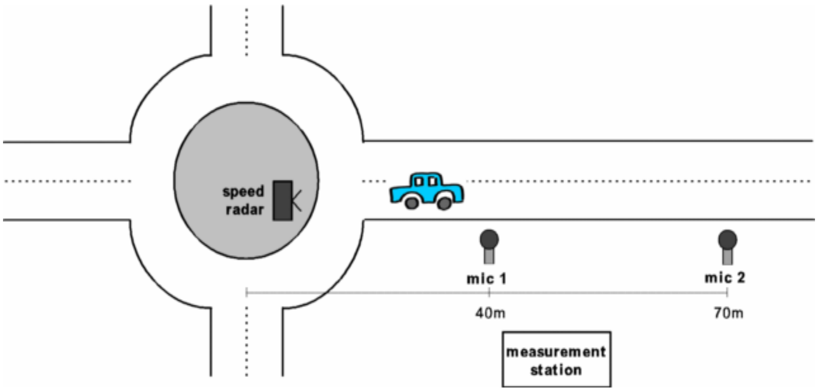


figure 17 – Measurement set-up for pass-by measurements of accelerating traffic

To investigate the influence of vehicle acceleration on propulsion noise, a series of measurements was conducted by M+P near a roundabout, on a 100 km/h suburban road section. Two microphones were placed at 40 and 70 m from the centre of the roundabout, and the roadside noise of all vehicles accelerating from the roundabout were measured, while the vehicle speed was continuously monitored over the entire road section by placing a speed radar in line with the vehicle path (see figure 17). Though all vehicles passing were included in the measurement, the number of measurements was too small for category 2 and 3 vehicles to give reliable results. For each vehicle, detailed information was gathered by license plate registration, so the results could be separated for Diesel and Otto engines, for instance.

One of the problems with this measurement method is that it is difficult to distinguish the vehicle speed from the acceleration effect: vehicles that have high acceleration will pass the microphones with a higher speed as well. The rather high correlation between speed and acceleration makes a reliable regression analysis of the noise levels difficult. Another problem is that the rolling noise cannot be separated from the propulsion noise. Although propulsion noise is assumed to be dominating over rolling noise, a certain amount of rolling noise may be present in the measured levels.

In figure 18 below the increase in propulsion noise is given, estimated by assuming a certain speed dependence and a fixed fraction of rolling noise, based on Harmonoise results as well as data from the Dutch interim method. The effect of acceleration thus found is comparable to the effect found in the Harmonoise project.

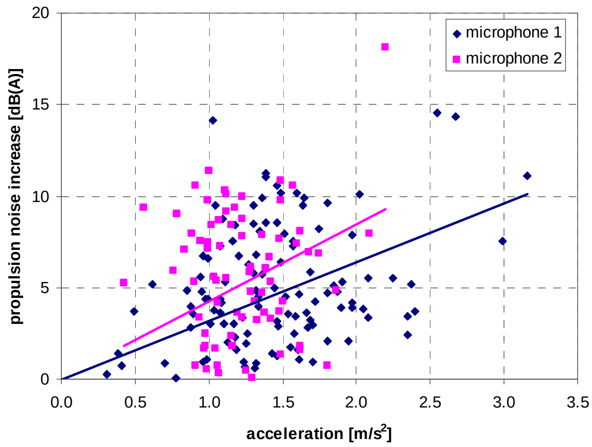


figure 18 – Estimated increase of propulsion noise vs. vehicle acceleration, for category 1 vehicles

3.5 Regional corrections

3.5.1 General remarks

The road noise emission model that was developed in our Work Package 5 is representative of the average European vehicle fleet, being based on measurements from various European countries, for each vehicle category.

However, the local vehicle fleet may be different from this European average in several aspects. These differences may occur:

- on a multi-national level: due to differences between weather conditions in Northern and Southern Europe, for instance;
- on a national level: due to tax regulations, for instance, or the maintenance regime for illegal exhausts;
- on a regional level: due to mountainous areas, for instance;
- on a local level: differences may occur between highways and local roads or between urban and industrial areas, for instance.

To identify and correct for these regional differences, one could perform noise measurements on every location where significant deviations occur, but i) identifying all of these regions is a difficult task, ii) performing noise measurements at each location would take too much time and budget, and iii) one would have to repeat these measurements every couple of years to keep up-to-date with the actual situation.

A better way is to base the noise level corrections on the actual vehicle parameters (i.e. changes in noise level with respect to vehicle weight, Diesel engines, etc.), and then combine these corrections with regional vehicle statistics. This has the advantage that if the local vehicle statistics are available, corrections can be made for any location, without having to perform measurements. Furthermore, these corrections can be used to model future trends in vehicle fleets (i.e. increasing vehicle weight or tyre width).

Within this project, it was considered unfeasible to collect a large database of vehicle fleet statistics for each national or local area. It was concluded from a first statistical exercise, however, that significant differences in vehicle fleet parameters, such as vehicle weight and engine fuel type, do occur. Examples are given in the next paragraphs.

Finally, it should be noted that these regional corrections are considered a second-order effect, and the effects on the noise levels are not very large. Most of the attention within our Work Package has therefore been spent on the issue of establishing accurate coefficients for the source model, and on developing correction factors for other, more important effects. Some of these regional effects, however, have been investigated, and the conclusions have been implemented in our model.

Some of this work has been presented in deliverable D3 [1]. In the paragraphs below, a few other effects are addressed.

3.5.2 Vehicle weight & tyre width

The width of the tyres has an effect on the rolling noise of a vehicle: a wider tyre will produce more noise. For passenger cars this is about 0.3 dB per 10 mm increase of tyre width. Tyre widths vary over different regions and over time, due to:

- the variations of vehicle weight over Europe: in Nordic and Western countries, vehicles tend to be larger and heavier than in Southern and Eastern Europe (see figure 19);
- an overall trend of increasing vehicle weight, coming from the popularity of SUV's and MPV's;
- a trend in more "sporty" vehicles, where vehicles are mounted with wider tyres than normal to increase the road performance.

figure 19 – Distributions of vehicle weight in several European countries

Since no large amounts of statistical data on tyre width could be found, a linear relation was established between the vehicle weight and tyre width, based on vehicle catalogue data for 650 passenger car types. For each type of car, its weight and standard mounted tyre dimensions were noted, resulting in the graph of figure 20, and an approximate linear relation between the two was found. Using this approach, it was possible to estimate the variations in tyre widths.

Based on the statistics of figure 19 the effect on rolling noise with respect to the European average was found to range from -0.5 to +0.5 dB.

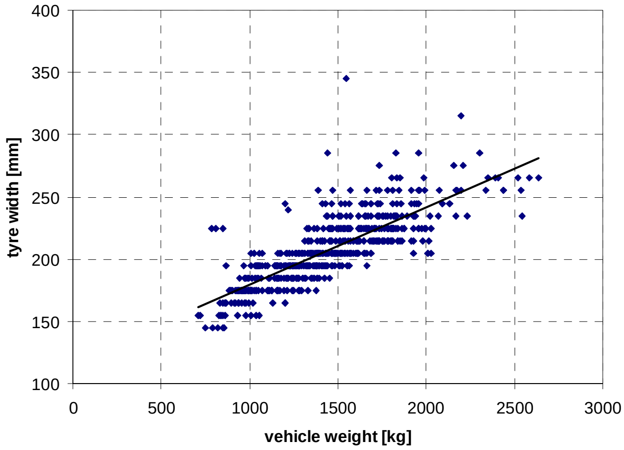


figure 20 – Tyre width vs. vehicle weight for 650 types of passenger cars

For trucks, such statistical differences could not be found; truck tyre width data for some countries were found, but no significant variations between countries were observed. Vehicle weights do vary quite much between countries, however, but this mainly affects the number of axles on a truck: in Sweden, 6 or 7 axle trucks are common, for instance, while in central Europe, the average is 4 axles. This is mainly due to the maximum allowed vehicle weight, dependent on national regulations.

3.5.3 Effect of IRESS (IMMA)

In a report from the International Motorcycle Manufacturers Association from 1996 [11], it was estimated that about 1/3rd of the motorcycles and about 2/3rd of the mopeds are equipped with illegal silencing systems (mainly exhausts but many times combined with non-standard intake silencers). These figures differ over regions, in the south these modifications are more common then in the north of Europe [11]. Not only cat 4. exhibit this type of equipment, but also they are found with cat 1, 2 and 3. It should be noted that these figures may be out-of-date; recent pass-by measurements performed in Italy indicated far less amounts of IRESS systems than mentioned in the IMMA report.

It is found that by such systems the sound power of that specific vehicle increases with about 5 to 15 dB, see references [11] and [12] and when a substantial fraction is using this equipment, it affects overall sound power levels. Even with a 1% fraction a level increase in the range of 0,5 dB can be found and increases up to 7 dB are estimated for the average motorcycle and moped population. It is clear that this effect shall be taken into account when determining the sound power level of motorcycle traffic in certain countries.

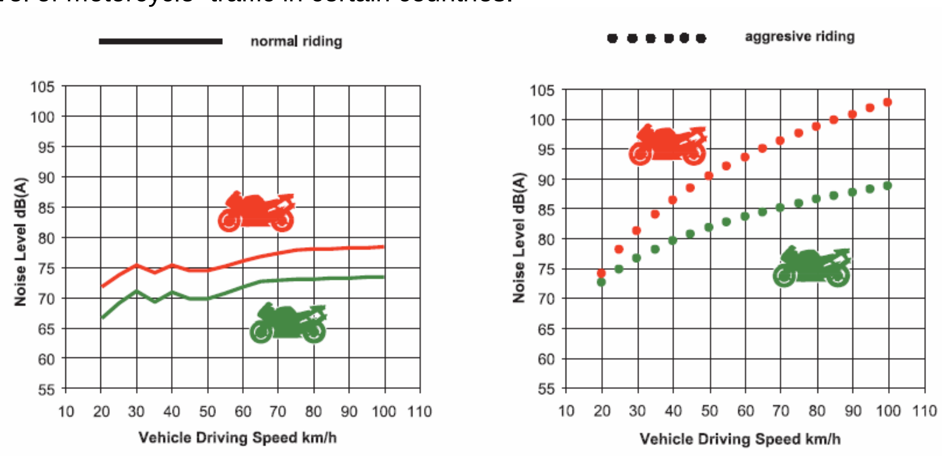


figure 21 – Effect of illegal silencers on noise level of motorcycles (source[12]), red line indicates IRESS, green line indicates no modifications

3.5.4 Different distribution of sub-categories

In the current model, four main vehicle classes are available, where the Powered two-wheeler class has been explicitly split up into two sub-classes. In the Harmonoise categorization, multiple sub-categories were originally defined (see § 2.1.2). The coefficients defined in the IMAGINE model presented here are representative of the average vehicle in each main class, therefore including an average distribution of sub-classes in each main class.

For some countries, however, the amounts of each sub-class in the main vehicle class may deviate from the average. For category 1 vehicles, a significant amount of delivery vans (3.5 tons) may be present in some countries whereas other countries may have much less of these vehicles, the difference mainly arising from tax regulation. A difference ranging from 6% in Sweden and Switzerland to 17% in Denmark was found from our recent investigation in vehicle park statistics. An older available study shows 5% for Germany, 35% for Portugal, and a EU-15 average of 11%.

Only limited noise data on these delivery vans are available. From TRL measurements, reanalysed from the SILVIA project, and from recent M+P measurements in the Netherlands, an increase of 0.9 – 1.2 dB(A) of delivery vans with respect to passenger cars was found in the speed range 80 to 110 km/h. From M+P onboard measurements performed for the Harmonoise project, the difference was estimated to be +5 dB(A) on propulsion noise and +1 dB(A) for rolling noise. In these estimations, a mixture of 2/3 light vans (< 2.8 tons, i.e. Peugeot Partner, Citroen Berlingo, Mercedes Vito) and 1/3 heavy vans (2.8 – 3.5 tons, i.e. Mercedes Sprinter, Iveco Daily) was assumed.

For category 2 vehicles, a similar effect may be present for the amount of heavy delivery vans[6]. Not enough data on these vehicle were available, however, to obtain their average noise emission.

3.6 Road surface corrections

3.6.1 Definition of road surface effect

The road surface significantly affects the level of both the rolling noise and the propulsion noise; rolling noise through the excitation of the tyre structure by its surface roughness, rolling and propulsion noise through its absorption of the reflected components. Differences in pass-by noise levels of more than 15 dB can occur between rough transversely grooved concrete and 2-layer porous asphalt concrete. The figure below presents pass-by measurements of several thousand vehicles on two different surfaces. Clearly seen is the large effect of the surface, that dominates over the spread within the vehicle category.
Within the 6th framework SILVIA project, an acoustic classification procedure for road surfaces was developed that formalizes the assessment of the road surface effect. This labelling procedure within in this classification system, is based on the effect it has on the noise level of passing vehicles and this effect is defined and formulated in such a way that it directly interfaces with the definition and formulation of the rolling noise and propulsion noise used in the IMAGINE model.

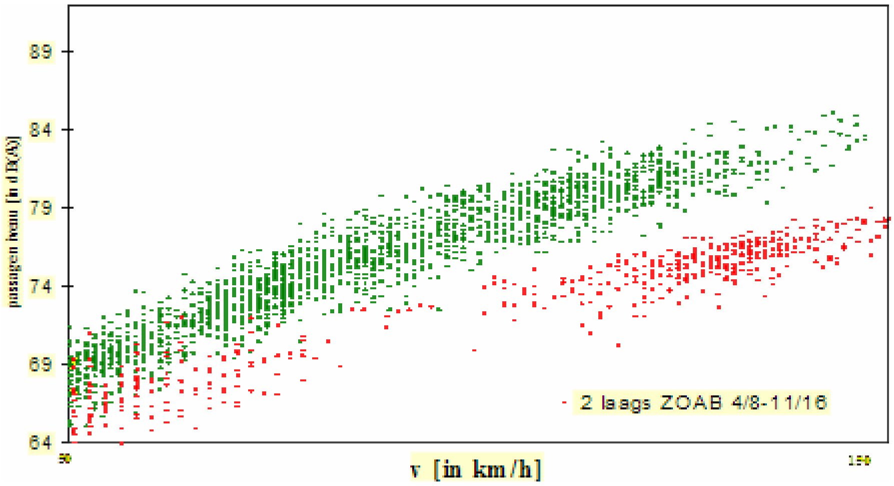


figure 22 – effect of road surface type on pass-by noise. Green dots: brushed concrete, red dots: 2 layer porous asphalt.

[6] Category 2 vans are “heavy vans”, with a total vehicle weight of > 3500 kg, which usually have double mounted tyres on the rear axle

This procedure distinguishes between the effect on passenger cars and on that of heavy duty vehicles. There is no distinction between category 2 and 3 since it is estimated that, since the type of tyres and the type of drive line are similar, the differences due to road surfaces are about the same.
The procedure also includes the spectral effect. Porous surfaces in particular exhibit strong spectral differences that, when neglected, lead to errors in propagation calculations over barriers, over long distances or through facades.

The effect of the road surface on the rolling noise levels is given by:

$$\Delta L_{road,rolling} = \alpha_{i,m} + \beta_m \lg\left(\frac{v}{v_{ref}}\right)$$

with α: spectral reduction at reference speed of 70 km/h for category m (1 or 3) and spectral band i (octave bands from 250 to 4000 Hz). For other spectral bands the value is zero.
β: Speed effect on rolling noise reduction.

For propulsion noise the surface effect is originating from absorption of sound in the process of reflection against the road surface under and close to the vehicle body. It is defined as a single spectrum reduction, only depending on vehicle category and on spectral band:

$$\Delta L_{road,propulsion} = \max(\alpha_{i,m}, 0)$$

We distinguish between porous and dense surfaces. For dense surfaces the value of *α* is zero, for porous surfaces the value is identical as that for rolling noise, but with a maximum of zero; porous surfaces will decrease the propulsion noise, but closed surfaces will not increase it.

3.6.2 Determination of coefficients

The coefficients in the formulation are determined according to a procedure developed by the SILVIA project and that is given in [16]. The reduction values are defined as a difference of the emission on a certain surface and the emission of that same category on the reference surface. Since these determination has to be done on trafficked roads, the mandatory measurement method is the SPB method [5]. Although the SPB method is slightly different from the preferred method applied in this study, it can be used since we only use it as determination of a difference and not an absolute value.

A few remarks:

1. we do not assume any effect for motorcycles, firstly because rolling noise does not contribute to the overall level, second since reflection plays a lesser role in the propagation
2. one must carefully distinguish between the source effect and the propagation effect of porous surfaces. In the presented reduction values the local reflection is already included in the surface effect and shall not be included in propagation calculations.

3.6.3 Age effect

It is known that the noise characteristics of road surfaces vary with age, with a tendency to become louder. In the proposed method this is included to a certain extent:

1. The surface effect generally determined in new condition, but will also be compared to a reference surface in new condition. In time, not only the studied surface, but also the

reference surface will become noisier, but this will not affect the difference. It is only when the studied surface degrades more with age than the reference, that the difference value changes. Estimation is that an increase of rolling noise up to 2 dB can be regarded as normal surface degradation. The acoustic lifetime of low noise surfaces is more limited then for instance concrete surfaces and shall therefore be monitored regularly.

2. The SILVIA method for monitoring of the acoustic performance of new road surfaces can be used to obtain the increase of rolling noise with time; using this method assures that the results can be implemented in our noise emission model.

3.6.4 Surface wetness

Vehicles on wet surfaces emit higher noise levels then the same on dry surfaces. The figure below presents measurement results from test done by TUG (ref [21]). Although the effect on dense surfaces has a different nature than the effect on porous surfaces, wetness effects are approximated by the following formula:

$$\Delta L_{wetness} = \max\{(15.\lg(f) - 12.\lg(v) - 27), 0\}$$

with *f:* Centre frequency of 1/3rd octave band.
v: Speed of the vehicle .

The resulting speed and frequency graphs are displayed in the figure below.

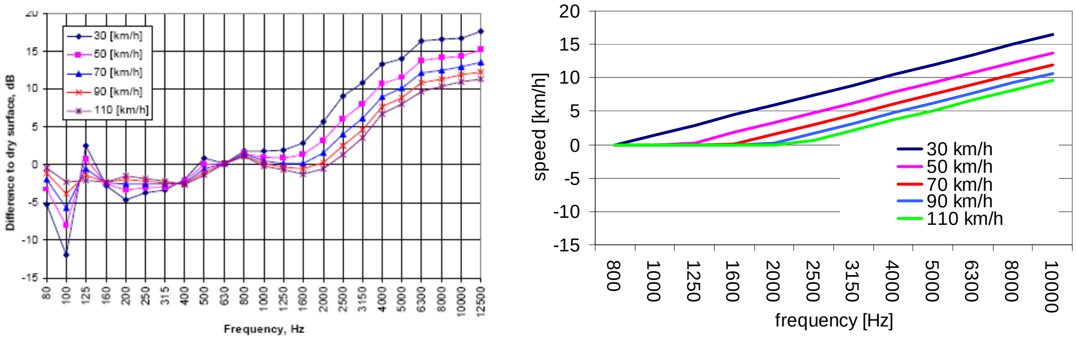


figure 23 – effect of road surfaces wetness on rolling noise of cat.1 vehicles. Left: measurement results, right: approximated correction formula.

The effect is only relevant for category 1 vehicle and the correction shall only applied during and shortly after rainfall, when a film of water is clearly visible on the road. No effect was found by dampness of the road, i.e. when the colour of the road indicates humidity but a water layer is not present. For category 2 and 3 no significant effect was found in the TUG study.

3.7 Summary of data acquisition campaigns

3.7.1 Data available and re-analysed by WP5 partners

For the development of our model, the partners within Work Package 5 have provided many data sets that were available through past or ongoing research projects. These data have all been analysed by various partners once more to fit the needs of the IMAGINE model. Table III provides a list of the data used in our Work Package, and the partners that have kindly provided them.

table III – List of available data to be used by WP5

description	***source(s)***	***period***
Rolling noise levels of 15 truck tyres on 12 surfaces	M+P, contract of Dutch Transport Ministry	2003
Data base on driving conditions of PTW's	IMMA, International Motorcycle Manufacturers Association	2000
“pull away” tests of (medium) Heavy Duty Vehicles	TRL, contract of Departmet for Transport	
coast-by measurements of some trucks	TRL	
SEL measurements on general traffic	M+P & TRL, for the SILVIA project	2004
CPB measurements at SIRUUS test fields	Autostrade	
rolling noise measurements on LMV and trucks	M+P, for ACEA	
propulsion noise data on light motor vehicles	TUG, in their Vehicle Noise Model (VENOM)	
Nord2000 measurement data, transfer functions and model calculations	SP	

3.7.2 Overview of data acquisition campaigns

To fill the remaining data needs, several new data acquisition campaigns have been performed by partners in Work Package 5 throughout the project. Separate reports have been written for some of these campaigns, for which only the most important results are presented in this deliverable. A list of new data campaigns is given in table IV below.

table IV – List of WP5 data acquisition campaigns

description	***partner(s)***	***period***
on-board measurements of Powered Two-Wheelers	M+P	October – December 2004
propulsion noise laboratory measurements of Heavy Duty Vehicles	Volvo	January – June 2005
outdoor noise measurements of Heavy Duty Vehicles at test track / roundabout	Volvo / SP	June – September 2005
pass-by measurements at UK highway	TRL	September 2005
pass-by measurements in Nordic countries	SP	2nd half 2005
pass-by measurements in Poland	TUG	2005
pass-by measurements in Poland	TUG / M+P	July 2006
pass-by measurements in Italy	M+P	May 2006
pass-by measurements on several locations in NL	M+P	July – August 2006
pass-by measurements on scooters, motorcycles & other traffic in Italy	JRC / Autostrade	September 2005
pass-by measurements on Powered Two-Wheelers on Mykonos island, Greece	JRC / TUG	June 2006
pass-by measurements of trucks at low velocities	M+P	April 2006
pass-by measurements of Powered Two-Wheelers	M+P	May – September 2005
pass-by measurements of accelerating traffic	M+P	October 2005
stop and go measurements at Italian motorway toll station	Autostrade	May / October 2006
statistical data gathering	M+P, TRL, JRC	November 2004 – end 2006

4 The final model

This chapter completely describes the WP5 road noise emission model which, together with the database of coefficients, allows for the calculation of all source noise levels and correction factors.

4.1 Source equations and coefficients

4.1.1 Source equations

For rolling noise, the emission L_{WR} is formulated as follows:

$$L_{WR} = A_R + B_R \cdot \lg\left(\frac{v}{v_{ref}}\right),$$

where the coefficients A_R and B_R are given in 1/3-octave bands for each vehicle class, and v_{ref} = 70 km/h. The aerodynamic noise of the vehicle is incorporated in this rolling noise equation.

The propulsion noise emission L_{WP} is formulated as follows:

$$L_{WP} = A_P + B_P \cdot \frac{v - v_{ref}}{v_{ref}},$$

where the coefficients A_P and B_P are given in 1/3-octave bands for each vehicle class, and v_{ref} = 70 km/h.

These formulas, together with the coefficients described in the next paragraph, predict the sound power level emitted by a road vehicle as a function of speed, under the reference condition as defined in § 4.1.2.

4.1.2 Reference conditions

The source equations and coefficients are derived to be valid under reference conditions for meteorology and traffic situation. For situations deviating from these reference conditions, correction factors have been developed, which are described in § 0. These reference conditions are:

- constant vehicle speed,
- a flat (non-sloped) road,
- an air temperature of 20 °C,
- a virtual reference road surface, consisting of a mixture of DAC 0/11 and SMA 0/11 with an age of 2 years or more but not at the end of its life time,
- a dry road surface, and
- a vehicle fleet representing the average of vehicles over the whole of Europe:
    - 187mm tyre width for Category 1,
    - 19% diesel for Category 1,
    - 10.5% delivery vans in Category 1,
    - no studded tyres,
    - 4 axles for Category 3,
    - 35% IRESS for Category 4, 1% for other categories.

- a sound reflecting surface under the vehicle and in the area close to the vehicle, where the first reflection takes place; the modified reflection by absorbing road surfaces is included in the correction effect for the road surface (see § 4.3.4).

4.1.3 Coefficients for the source equations

In the graphs of figure 24 (page 37) the A_R and B_R coefficients for rolling noise and the A_P and B_P coefficients for propulsion noise are plotted for all vehicle categories. For category 4 the rolling noise coefficients are zero; this graph shows only the A_P and B_P coefficients for both subcategories 4a and 4b.

The axes of each graph are equal for each vehicle category; the height of the curves can therefore be compared between the various categories. The exact values of these coefficients are available in the Work Package 5 Excel database, which can be obtained through the WP5 partners.

4.2 Sound emission as a function of speed

In figure 25 (page 38), the overall L_W levels in dB(A) of rolling, propulsion and total noise are plotted vs. the vehicle speed, for the first three vehicle categories only, since category 4 is only propulsion noise. As is clear from the figure, the propulsion noise increases approximately linearly with speed[7], while the rolling noise increases in a logarithmic manner. Therefore the propulsion noise dominates at low vehicle speeds, while the rolling noise is dominant at higher speeds.

The “break-even” point between the two is higher for trucks (70 / 100 km/h) than for passenger cars (30 km/h), which is in agreement with experience. What may be counterintuitive is the fact that this value is higher for medium heavy vehicles (cat. 2: 100 km/h) than for heavy vehicles (cat. 3: 70 km/h). This is explained, by the fact that propulsion noise for light trucks is only slightly lower than for heavy trucks, while the rolling noise is much lower because of the smaller number of axles (2 for medium, 4 for heavy).

[7] Note that the increase is not exactly linear; the increase is linear per 1/3-octave band but the speed coefficients are different, therefore the energetic spectral sum is non-linear

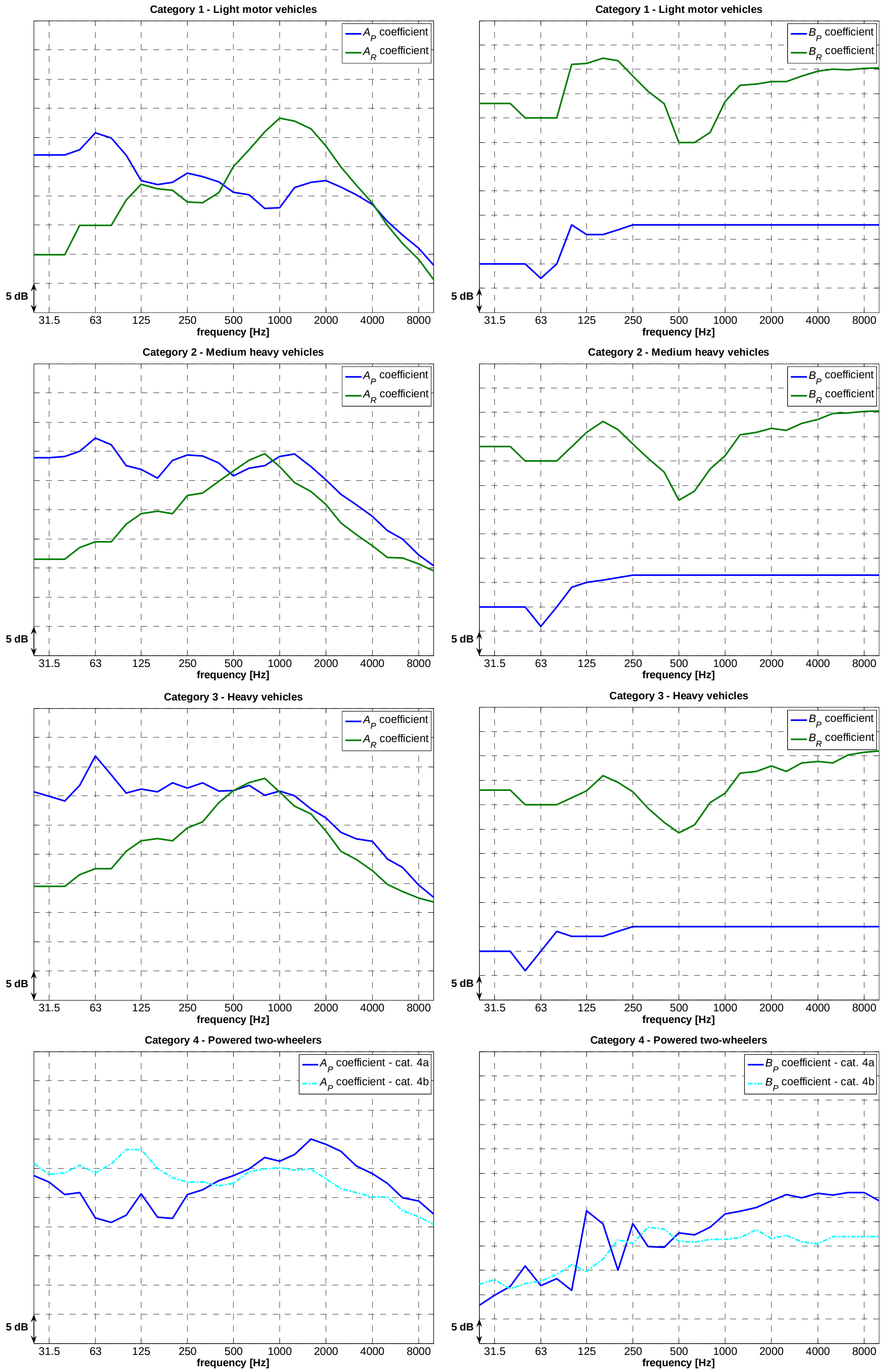


figure 24 – *A* and *B* coefficient for rolling and propulsion noise, for all categories

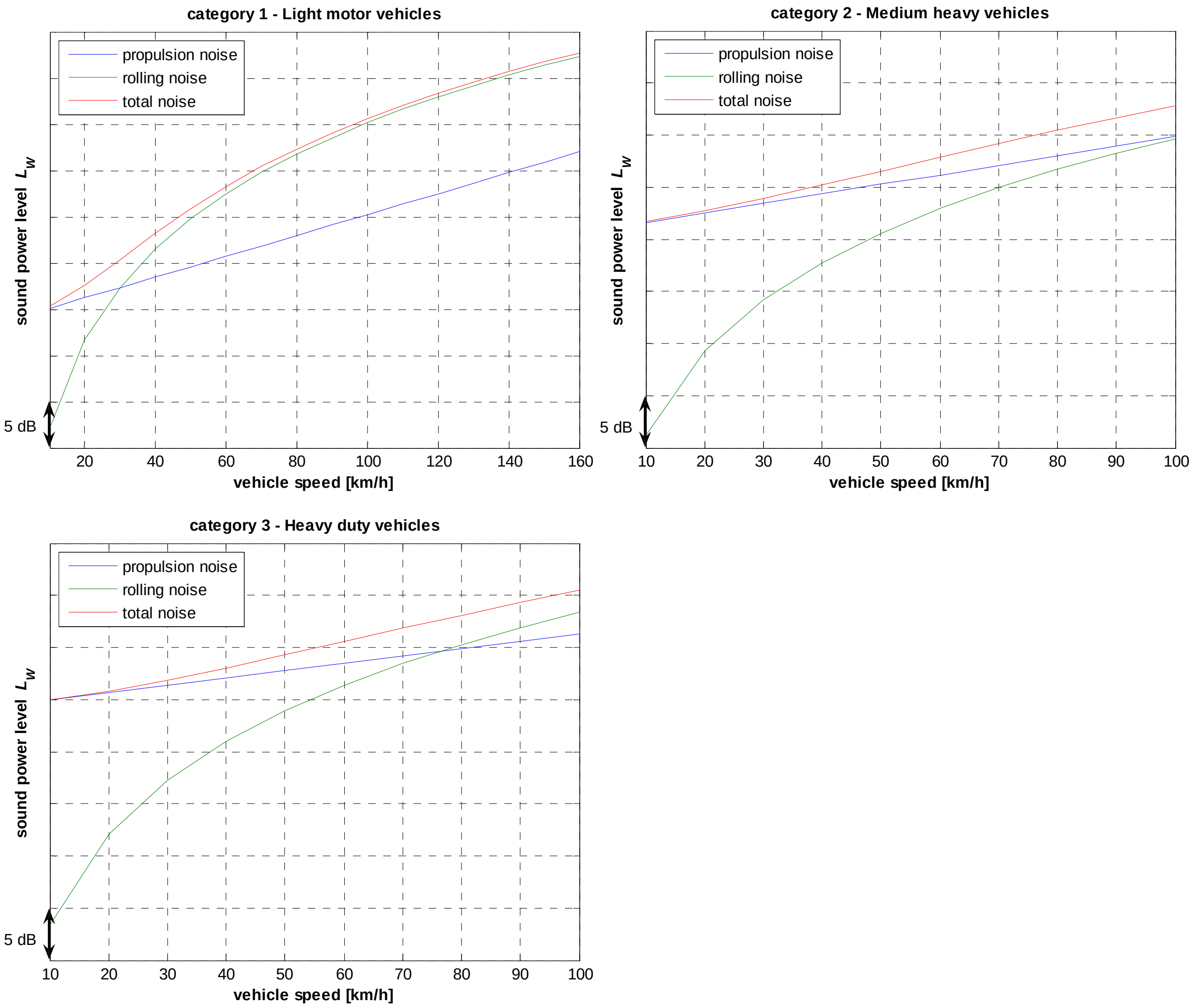


figure 25 – Rolling noise L_{WR} and propulsion noise L_{WP} vs. vehicle speed, for categories 1 to 3

4.3 Correction factors

Using the equations and coefficients of § 4.1 the noise emission of any road vehicle can be calculated, given its vehicle speed. In these basic equations, however, a large number of effects are not taken into account, which may result in noise levels not representative for the actual situation under investigation. Several correction factors are given in this section to include these effects in the model. Note that most of these corrections should be applied to the propulsion noise or rolling noise part only, before calculating the noise emission at the relevant source height (see section 2.1.3).

Furthermore, the actual noise levels at a certain location are influenced by deviations in the local vehicle fleet with respect to the current European average, which is the basis for the current model coefficients. Corrections for these deviations are described in paragraph § 4.4 below.

4.3.1 Propulsion noise correction – Vehicle acceleration / deceleration

For the propulsion noise accelerating and decelerating vehicles, a correction $L_{WP,acc}$ is developed based on the actual (instantaneous) vehicle acceleration in m/s^2:

$$\Delta L_{WP,acc} = \begin{cases} C_P \cdot a & \text{for } a \geq -1 \text{ m/s}^2 \\ C_P \cdot (-1) & \text{for } a < -1 \text{ m/s}^2 \end{cases}, \quad \text{with } |a| \leq a_{max}.$$

This correction is only valid for moderate acceleration values, as is expressed by the last expression. Here, a_{max} is equal to **2 m/s²** for category 1, **1 m/s²** for categories 2 and 3, and **4 m/s²** for category 4.

The coefficient C_P is given in the WP5 Excel database for each 1/3-octave frequency band and for each vehicle category, and is also plotted in figure 26. The coefficient is equal for categories 1 and 4, as well as for categories 2 and 3.

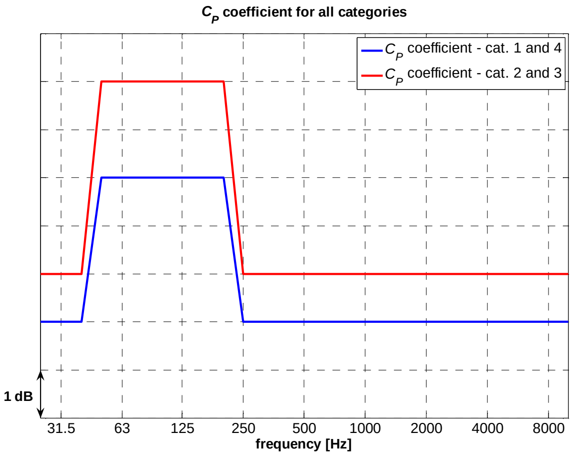


figure 26 – Acceleration coefficient C_P for vehicle categories 1 & 4 (blue line) and categories 2 & 3 (red line)

4.3.2 Propulsion noise correction – Uphill / downhill driving

For vehicles driving up- or downhill, the propulsion noise is corrected for the road gradient α because of the change in engine load. This correction $L_{WP,gradient}$ is derived from the $L_{WP,acc}$, using the downward component of the gravity force, $g \cdot \sin(\alpha) \approx g \cdot \alpha$, where g = 9.81 m/s² is the gravity constant.

For small downward gradients, the propulsion noise is decreased with respect to a flat road; for larger downward gradients the propulsion noise is increased because of engine braking. Engine braking will start much sooner for trucks, from around -2% gradient, than for cars, which generally do not use engine braking unless on very steep gradients of < -8%.

This effect is shown in figure 27; please note that the figure shows the approximate effect of gradients on the overall L_{WP} level in dB(A), whereas the actual coefficient is applied for each 1/3-octave band.

The frequency-dependent expression for the gradient correction is thus:

$$\text{for category 1 and 4:}\quad \Delta L_{WP,gradient} = \begin{cases} C_P \cdot g \cdot \dfrac{\alpha}{100\%} & \text{for } \alpha \geq -2\% \\ C_P \cdot g \cdot \dfrac{-2\%}{100\%} & \text{for } -8\% < \alpha < -2\% \\ -C_P \cdot g \cdot \dfrac{\alpha + 10\%}{100\%} & \text{for } \alpha \leq -8\% \end{cases}$$

$$\text{for category 2 and 3:}\quad \Delta L_{WP,gradient} = \begin{cases} C_P \cdot g \cdot \dfrac{\alpha}{100\%} & \text{for } \alpha \geq -2\% \\ -C_P \cdot g \cdot \dfrac{\alpha + 4\%}{100\%} & \text{for } \alpha < -2\% \end{cases}$$

where $g \approx 9.8\,\mathrm{m/s^2}$ and the coefficient C_P is given for each 1/3-octave band in the Excel database.

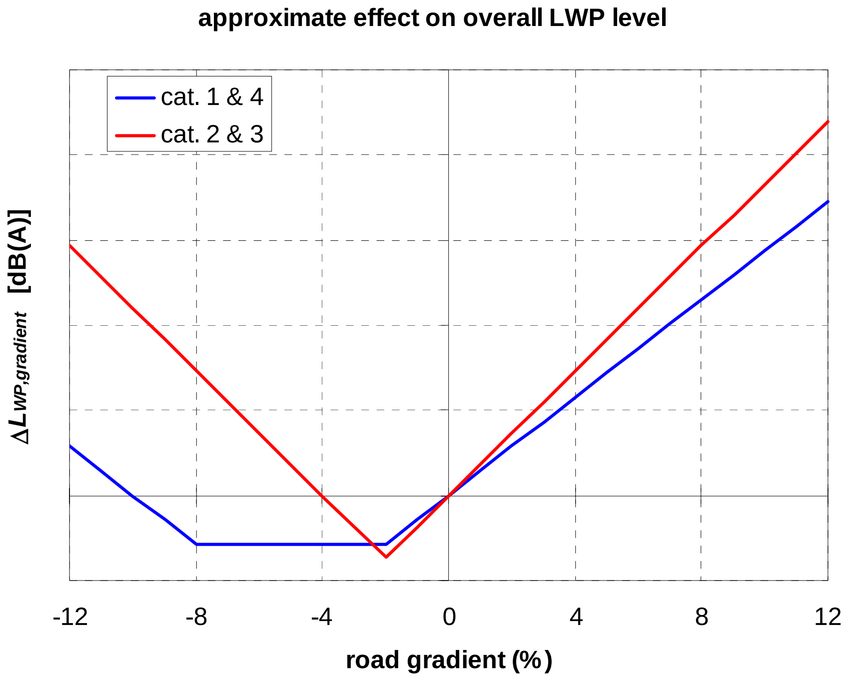


figure 27 – Approximate effect of road gradient on overall propulsion noise

It shall be noted that the effect of reduced or increased speed during uphill-downhill driving is not included in the correction: the vehicle speed may increase due to downhill driving, for instance, but it may also be intentionally decreased to be able to control the vehicle (mainly for trucks). For uphill driving, speed decreases may occur as well. These effects shall be applied separately through a modification of the speed profile. We refer to the work of WP2 [36] for more information on this effect.

4.3.3 Rolling noise correction – Air temperature

The rolling noise L_{WR} is corrected for the actual air temperature T by an amount $L_{WR,temp}$ given by:

$$\Delta L_{WR,temp} = K \cdot (20\ ^{\circ}C - T)\ ,$$

which means a positive correction, thus an increase of the noise levels, for temperatures lower than 20 °C, and a negative correction for higher temperatures. The coefficient K is defined for many different types of road surfaces [31], ranging from 0.03 to 0.12, and is listed in § A.2 of Appendix A of this report.

Heavy duty vehicles are assumed to exhibit a lower temperature effect on rolling noise. The coefficients K for categories 2 and 3 are therefore taken to be half the value of those for category 1, as indicated in the § A.2.

4.3.4 Rolling and propulsion noise correction due to road surface type

In § 4.1.2 the reference road surface is defined, which is a virtual road surface consisting of a mixture of DAC 0/11 and SMA 0/11 with an age of 2 years or more but not at the end of its life time [2]. The rolling noise coefficients of our model are based on this surface. Corrections for the actual road surface are given here for surfaces belonging to the "reference cluster" on which the virtual surface is based (SMA and DAC types), and for other surfaces as well.

Corrections for road surfaces within the reference cluster

Differences between surfaces within the reference cluster are handled by frequency and speed independent corrections as follows:

- *Light motor vehicles* (cat. 1):
  *S*ee table V below. The corrections are applied equally on the coefficient A_R for each frequency band. The validity of the table is restricted to chipping sizes between 8 and 16 mm.
- *Heavy and medium heavy vehicles* (cat. 2 and 3):
  No corrections within the reference cluster.

table V - Corrections within the reference cluster to be applied equally for each frequency band.

Road surface	Correction relative virtual reference
Virtual reference, chipping size: 11 mm, mean value of DAC and SMA	± 0 dB
DAC	-0,3 dB
SMA	+0,3 dB
Chip size (Validity restricted to 8-16 mm)	+0,25 dB/mm above 11 mm -0,25 dB/mm below 11 mm

Note: As an example a 2 years old SMA 0/16 road surface will have a correction of 0,3 + 5·0,25 = 1,55 dB.

Corrections for other road surface types

The effect of the road surface on rolling and propulsion noise is based on the acoustic classification and labelling of road surfaces as developed within the SILVIA project method (ref. [16]). The effect of the road surface on the rolling noise levels is given by:

$$\Delta L_{road,rolling} = \alpha_{i,m} + \beta_m \lg\left(\frac{v}{v_{ref}}\right)$$

with α: spectral reduction at reference speed of 70 km/h for category m (1 or 3) and spectral band i (1/3rd octave bands from 250 to 4000 Hz). For other spectral bands the value is zero.

β: Speed effect on rolling noise reduction.

For propulsion noise the surface effect is defined as a spectrum reduction only (see § 3.6.1). The correction is depending on vehicle category and on spectral band as:

$$\Delta L_{road,propulsion} = \max\{\alpha_{i,m}, 0\}$$

The SILVIA method is quite new and not many surface are characterized by it. However, the SILVIA method is largely based on the Netherlands method C_{road} and the values obtained through this method can be used. In the figure below some examples are given. In the appendix A the numerical values are presented.

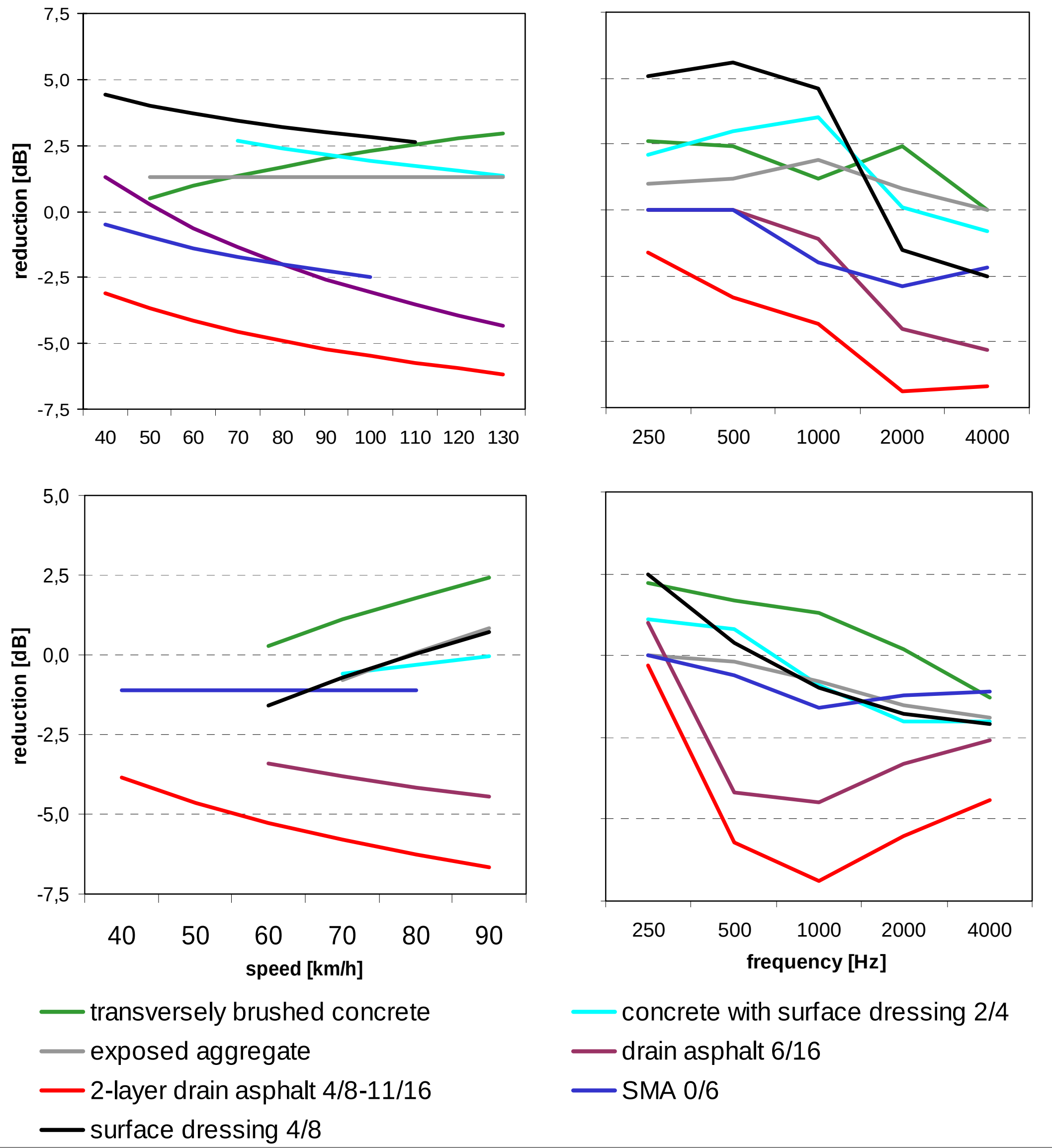


figure 28 – effect of road surface on the rolling noise emission of road vehicles. Examples for some common porous and dense surfaces for passenger cars (upper graphs) and for heavy duty vehicles (lower graphs).

4.3.5 Rolling noise correction – Road surface wetness

The increase of noise emission by wet surfaces for category 1 vehicles (water layer thickness 2 mm) is taken into account by the following formula:

$$\Delta L_{wetness} = \max\{(15.\lg(f) - 12.\lg(v/v_{ref}) - 48), 0\}$$

with *f*: Centre frequency of 1/3rd octave band.
v: Speed of the vehicle .

4.3.6 Rolling noise correction – Truck tyre configuration

For category 3 vehicles a default axle configuration of 4 axles is assumed: one steer axle with two single tyres, one driven axle with four single block tyres, and two trailer axles with two super-single trailer tyres each (10 tyres in total). From analysing the truck tyre measurements for a typical "composite truck" (see [24] and § 3.2.1), but using different tyre and axle configurations, we have developed some correction factors.

Some trucks may be equipped with trailer axles carrying double mounted “steer axle”-type tyres. This would lead to a slight increase of rolling noise.

$$\Delta L_{WR,doublemounting} = +0.8\ \text{dB}\ .$$

Finally, the total number of axles may be different from the default of 4. A correction $L_{WR,axle}$ may therefore be used, given by

$$\Delta L_{WR,axle} = \begin{cases} 6.8 \cdot \log\left(\frac{\#\,axles}{4}\right) & \text{for supersingle tyres} \\ 9.1 \cdot \log\left(\frac{\#\,axles}{4}\right) & \text{for double mounted tyres} \end{cases} .$$

4.3.7 General correction – Directivity of the point sources

Detailed formulation of the directivity of the noise emitted by a rolling vehicle can be found in [2] and [28]. For general modelling the complicated directivity functions are approximated as follows:

1. horizontal directivity is neglected since it does not affect L_{eq} noise levels, apart from in cases of strong non-homogeneities in horizontal propagation along the road (such as ending barriers); however, if the source model is to be used to calculate maximum sound pressure levels (L_{max}) the horizontal directivity has to be taken into account; we recommend then to use the corrections proposed in [2] or [28].
2. no frequency dependence is assumed for vertical directivity and the relation is approached by the following linear function:

$$lmv\acute{}s : \Delta L(\psi) = -\frac{\psi(\text{deg.})}{20}$$

$$hdv\acute{}s : \Delta L(\psi) = -\frac{\psi(\text{deg.})}{30}$$

   Leading to a maximum reduction at an angle of 90° of -4,5 dB for cat 1 and of -3 dB for category 2 and 3. No directivity for cat 4.

For low frequencies, strongly deviant behaviour can be expected due to interference effects, but for L_{Aeq} estimation this effect can be neglected.

4.4 Regional and vehicle fleet corrections

4.4.1 General remarks

In this paragraph, all corrections that can be applied to account for vehicle fleet variations, either to address regional variations, variations in time, or action planning purposes, are given. Each correction is zero by default, meaning that if they are not applied, the results conform to the European average.

The default source coefficients given in the Excel sheet are recommended values that are to be used to create noise maps that comply with European average vehicle and road parameters. Using these values assures that the maps created are comparable to those created in other countries where the same coefficients are used. Some of the regional deviations that are known to exist are included in correction factors described here. To allow a fair comparison between noise maps from various countries, it should be clearly stated which correction factors were used to create the map.

Finally, we would like to point out that other regional corrections to the default coefficients, not listed in this section, may be used if accurate information is available. Local measurement results can be used if they are based on sufficient and reliable data (a few hundred vehicle pass-by's measured on different locations), and if deviations from the default values can be reasonably explained. And again, it should be clearly documented which adaptations were made to create the noise map.

Although they are corrections for variations in a larger, general vehicle fleet, these corrections are designed to be applied on a single-vehicle level, i.e. they should be applied to the noise emission levels before aggregating to a traffic flow (see chapter 6).

4.4.2 Engine fuel type

For category 1 vehicles, a distinction can be made between Diesel engines and other ("Otto") engines, the latter of which contains petrol, LPG, and other engine fuel types. Diesel engines tend to be noisier than other engines, though the difference is growing smaller with time. Type approval tests currently have a 1 dB(A) higher limit value for Diesel cars.
Based on the M+P measurements on accelerating traffic and other sources, such as [19], an effect of +3 dB(A) on the propulsion noise of a single vehicle is introduced in our model. Due to the substantial presence of rolling noise above 20 km/h, the effect on overall noise will be smaller and decrease further with increasing vehicle speed.
The propulsion noise emission L_{WP} of the average category 1 vehicle can therefore be corrected for the local or national % of Diesel engines, with respect to the total number of light motor vehicles, using the following linear $L_{WP,Diesel}$ correction:

$$\Delta L_{WP,Diesel} = 3.0 \cdot \frac{\%\ Diesel - 19\%}{100\%}.$$

Hybrid vehicles are a special case since the engine operates in special mode, and its emission cannot directly be connected to the vehicle speed and acceleration. As first approach one can model hybrids by assuming that the engine is active about 50% of the time, equivalent with a reduction of propulsion noise with 3 dB.

4.4.3 Vehicle weight / tyre width

The increase of rolling noise with tyre width for passenger cars was found to be 2 dB(A) between a 155 mm tyre from 1970 and a 195 mm tyre from 2000, or 0.5 dB(A) per 10 mm width increase [32]. From M+P test track measurements on a series of modern passenger car tyres in Kloosterzande (NL), an increase of 0.36 dB(A) per 10 mm increase of tyre width was found. For our model, we therefore propose a correction, for passenger car tyres only, of:

$$\Delta L_{WR,tyrewidth} = 0.04 \cdot (tyre\ width - 187\,\text{mm}).$$

If no tyre width statistical data are found the following relation between vehicle weight and tyre width, for passenger cars, can be used:

$$tyre\ width \approx 0.062 \cdot vehicle\ weight + 118\,\text{mm}.$$

For truck tyres, no correction is proposed; statistical variations of truck tyre widths over different regions are assumed to be negligible.

4.4.4 Vehicle age

No significant effect of vehicle age on the average vehicle noise emission is expected, since:

- statistical differences in vehicle age were found to be small (see [1]), and
- the noise effect of ageing vehicles is smaller than 1 dB(A) per 10 years (see f.i. [19]).

4.4.5 Delivery vans

Vehicle category 1 (Light motor vehicles) contains mostly passenger cars, but a certain amount of delivery vans (3500 kg) are also present. The amount of delivery vans within this category varies quite much over Europe, and their contribution to the total noise emission is significant. The average category 1 delivery van is assumed to have 5 dB(A) more propulsion noise and 1 dB(A) more rolling noise than a passenger car. A linear correction to both noise sources for the percentage of delivery vans within the total number of light motor vehicles is therefore to be applied:

$$\Delta L_{WP,vans} = 5.0 \cdot \frac{\%\ vans - 10.5\%}{100\%}$$

$$\Delta L_{WR,vans} = 1.0 \cdot \frac{\%\ vans - 10.5\%}{100\%}$$

4.4.6 Illegal replacement exhaust silencer systems

Illegal replacement exhaust silencer systems (IRESS) are quite popular in some countries, mainly for Powered two-wheelers (category 4a and 4b), but are found also for passenger cars and even for trucks. The effect of an IRESS system on the overall propulsion noise is assumed to be 12 dB(A) on average (see [11], [12], [13]). A correction for the percentage of IRESS in the total number of vehicles per category is given by:

$$\Delta L_{WP,IRESS} = 29 \cdot p_{IRESS} - 24 \cdot p_{IRESS}^2$$

$$p_{IRESS} = \begin{cases} \dfrac{\%\ IRESS - 1\%}{100\%} & \text{for category 1, 2 and 3} \\ \dfrac{\%\ IRESS - 35\%}{100\%} & \text{for category 4} \end{cases}$$

4.4.7 Winter tyres and studded tyres

In the Nordic countries the use of studded tyres on passenger cars is common and even obligatory in winter time. The influence of studded tyres on the rolling noise L_{WR} for category 1 vehicles can be accounted for using a correction $L_{WR,\mathrm{stud}}$. This speed-dependant correction is taken from the interim model for Nordic countries [28], and is given by:

$$\Delta L_{WR,stud} = \begin{cases} a + b \cdot \log(v/70) & \text{for } 50 \le v \le 90 \text{ km/h} \\ a + b \cdot \log(90/70) & \text{for } v > 90 \text{ km/h} \\ a + b \cdot \log(50/70) & \text{for } v < 50 \text{ km/h} \end{cases}$$

where coefficients *a* and *b* are given for each 1/3-octave band in table IX in Appendix A of this report.

Studded tyres for trucks are not very common, though they may exist. A correction is therefore not included in our model. We do not propose a correction for snow chains: no data on the noise effect on snowy roads are available, and the use of chains is limited to certain areas and certain periods of year only.

4.5 Uncertainty

4.5.1 General remarks

It is quite difficult to give any estimation of the accuracy, or uncertainty, of our model. The road noise emission model is dependant on too many parameters to obtain a reliable answer. The only reliable answer could come from validation of our model results versus actual noise measurements of traffic flows. There is no direct way to measure the sound power level of a traffic flow, however: measuring roadside noise always includes a transfer from the source to the receiver, and is dependant on the speed and acceleration of the vehicles, the values of which can only be determined with a certain uncertainty as well. Combining the uncertainties of these different sources is not trivial: in Appendix B of this report, a mathematical description of the total uncertainty of traffic noise is given.
The validation of our model versus measurements is described in chapter 5, and an estimation of the deviations is given.

4.5.2 Uncertainty ranking of model elements

It can be stated that the accuracy of our model increases with the importance of the parameters. We have spend most of our data acquisition effort and analysis time on gathering reliable spectra for the *A* coefficients, which represent the noise spectrum of each vehicle category at the reference speed of 70 km/h, with no acceleration and further reference conditions. The total of rolling noise and propulsion noise at this speed as been validated against many measurements. We believe that these values are an accurate representation of the European average vehicle, for each main category.
Second are the *B* coefficients, representing the influence of vehicle speed, also per 1/3-octave band. The speed dependence of the total noise has been validated against roadside measurements and corresponds to values found in other national and interim calculation methods.
The distinction between rolling and propulsion noise is based on dedicated measurement campaigns on test tracks, or on specific vehicles, but cannot be measured on large quantities of vehicles. The fact that propulsion noise dominates for lower vehicle speeds and higher accelerations, and dominates more for heavy vehicles than for passenger cars, is represented by our model, and the vehicle speeds at which the “break-even” point between the two occurs is in agreement with our experiences.

In § 0, several corrections are given to account for other parameters to increase the validity of the model calculations for the specific situation that is to be modelled.
Correction factors for vehicle acceleration and road gradients have been developed from a limited amount of measurements. The effect on overall noise is determined from these measurements, whereas the spectral shape of the acceleration effect is based more on an engineering estimate. The acceleration effect for light motor vehicles and powered two-wheelers relies on more measurements than that for categories 2 and 3.
Correction factors for road surface and tyre effects mainly come from previous knowledge from several of the partners. The effect of road surfaces on the vehicle noise has not been extensively studied within the scope of this project, but has been under investigation for many years. The corrections and values presented here are therefore considered to be reliable.

Finally, we have developed a set of vehicle fleet corrections, presented in § 4.4. These correction factors are all based on overall dB(A) noise levels, since the amount of available noise data is too small to generate reliable frequency dependencies. Most of these effects are based on combinations of results from third-party studies, type approval standard and related research, and other literature. The order of influence of these corrections agrees with other investigations, though the exact values of these corrections are difficult to validate. We have only included effects that have been verified from multiple independent sources, therefore the corrections presented in this report are considered reliable enough to be used.

5 Validation

5.1 Model results vs. roadside measurements

To validate the road noise model, we have compared it to the measurements conducted in June – September 2006 in the Netherlands, Poland, Italy and UK, and to the predictions of the Nord2000 model that has been updated with new measurements in the last year. All of these measurement sets are based on at least 150 vehicles each, therefore they are considered statistically reliable for each measurement location.

To obtain the model results at the roadside (7.5 m from the centre of the road lane, 1.2 m height), a series of transfer functions have been calculated to derive the roadside sound exposure level (SEL) from the $L_{W,tot}$ at the appropriate source heights of 0.01 and 0.3 / 0.75 meters. These are given in figure 33.

In figure 29 to figure 32 below, the measurement results at 70 km/h are plotted vs. frequency together with the model results (black line with circles), in one separate graph for each vehicle category. For category 4a (mopeds), no measurements were available for validation besides the data set the model is based on.

From these graphs, it is clear the model is a good estimation of the average between the measurements from different European countries. An increase of the Nord2000 predictions with respect to the other measurements can be seen for all vehicle categories in certain frequency ranges (mainly 50 – 400 Hz and > 2500 Hz). This is a distinctive deviation that could not be fully explained. A correction for the road surfaces does not improve things much; the road surfaces should be approximately the same on all locations. It could be, however, that road surfaces in Nordic countries are more damaged than on the European mainland because of the use of studded tyres in winter time. This could imply that an SMA surface in Nordic countries makes more noise than a similar SMA surface in other countries.

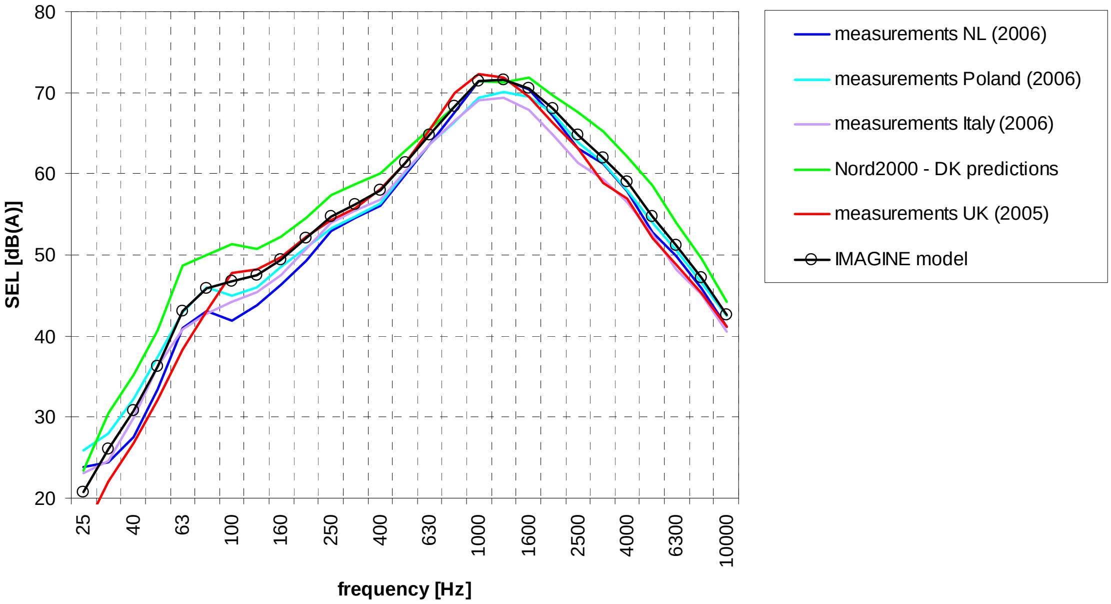


figure 29 – IMAGINE model predictions vs. roadside measurements at 70 km/h – category 1

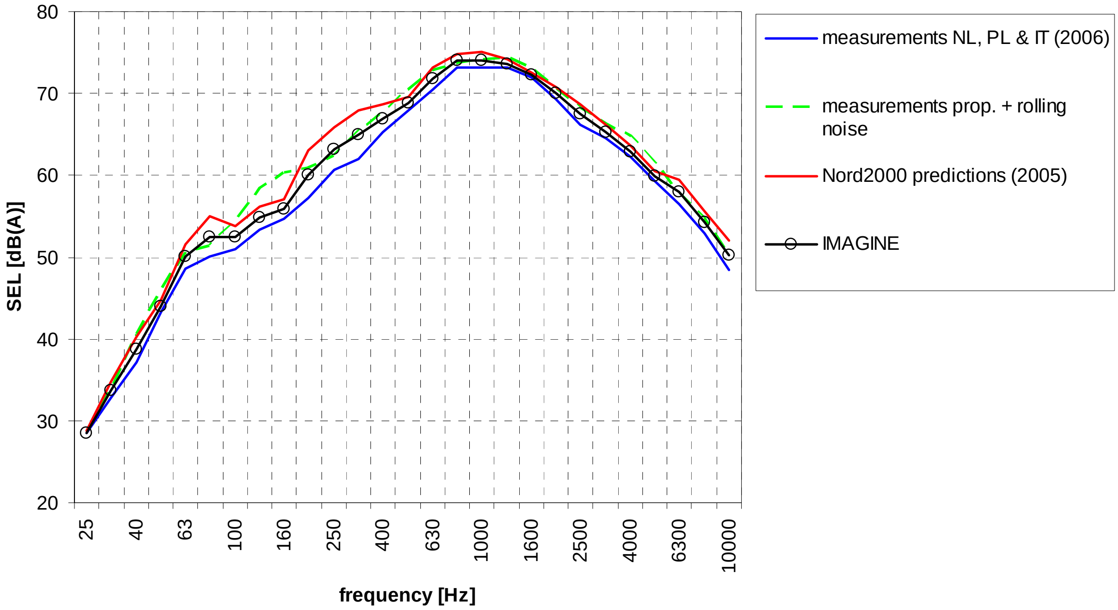


figure 30 – IMAGINE model predictions vs. roadside measurements at 70 km/h – category 2

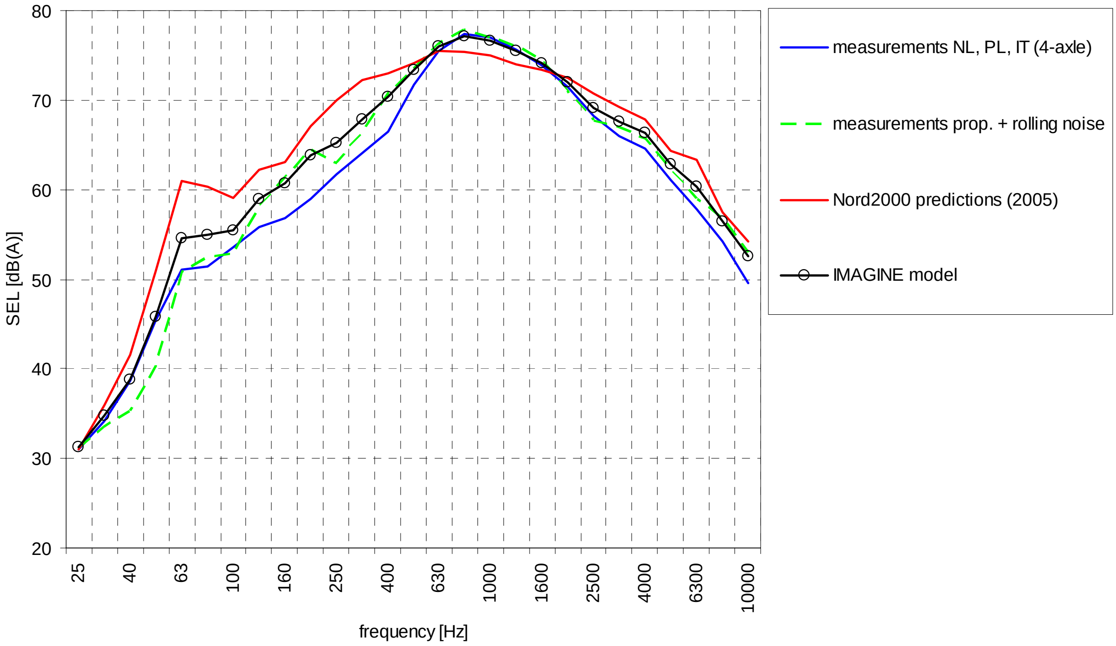


figure 31 – IMAGINE model predictions vs. roadside measurements at 70 km/h – category 3

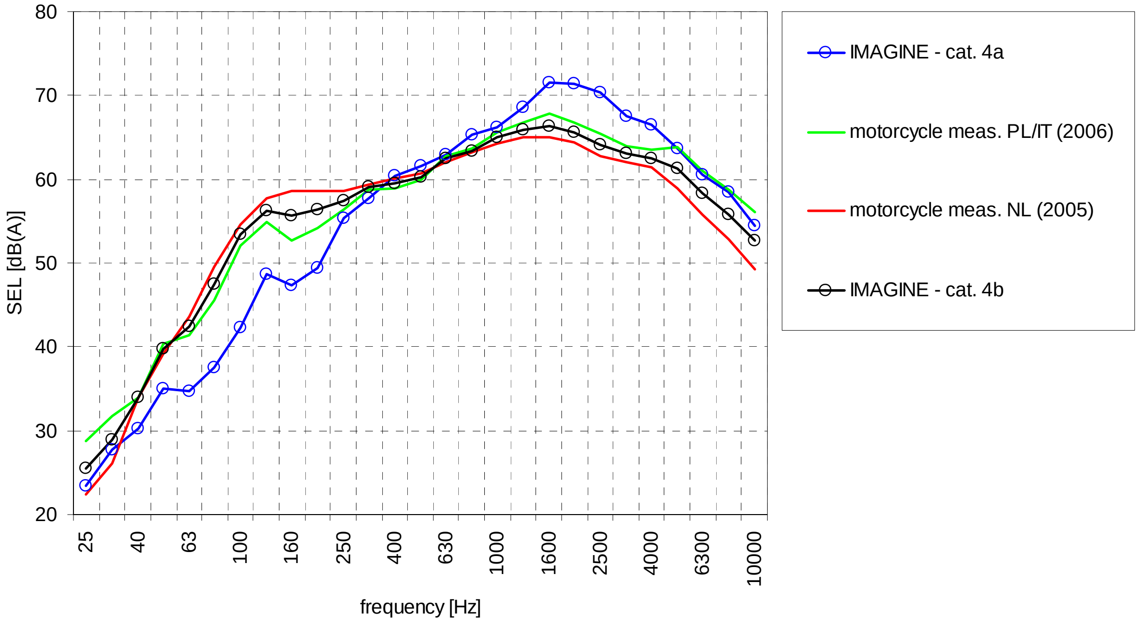


figure 32 – IMAGINE model predictions vs. roadside measurements at 70 km/h – categories 4a and 4b

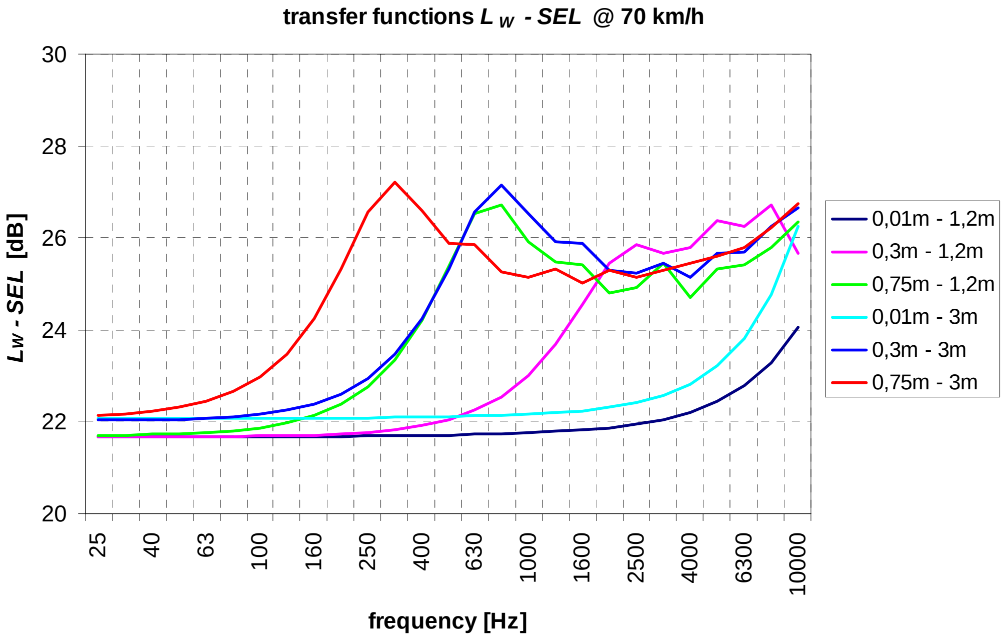


figure 33 – Transfer functions (calculated difference between L_W at the source and *SEL* at the receiver), for all three source positions (0.01, 0.3 and 0.75 m) to two roadside receiver positions (1.2 and 3.0 m height)

5.2 Estimation of uncertainty

5.2.1 Uncertainty under reference conditions

figure 34 – Uncertainty as a function of frequency, estimated from measurements vs. model calculation, for each vehicle category

From the comparison of measurements and model results in the previous section, we try to estimate the accuracy of our model. In figure 34 above, the expanded uncertainty estimated from these data is plotted vs. frequency, and the uncertainty estimated for the overall SEL level in dB(A) is given at the left side of the graph. This graph gives an indication of the accuracy of the model predictions under reference conditions, at the reference speed of 70 km/h.

The uncertainty given here is not a very exact value, but merely an estimation of the order of magnitude. The uncertainty for the overall level thus lies in the order of 0,5 – 0,6 dB(A). Looking at the spectral shape, we have divided the uncertainty roughly in four ranges. We see that the largest uncertainties arise at low and high frequencies; since the overall level is mainly determined by the mid-frequency range (800 – 2000 Hz), it can be expected that the uncertainty of the SEL levels about the same as the average uncertainty in this frequency range.

The deviations between measurements and model calculations do not only include an inaccuracy in the calculated sound power level L_W, but also an inaccuracy in the measured values and an inaccuracy in the transfer functions used to calculate the roadside *SEL*.

5.2.2 Uncertainty at high and low speeds

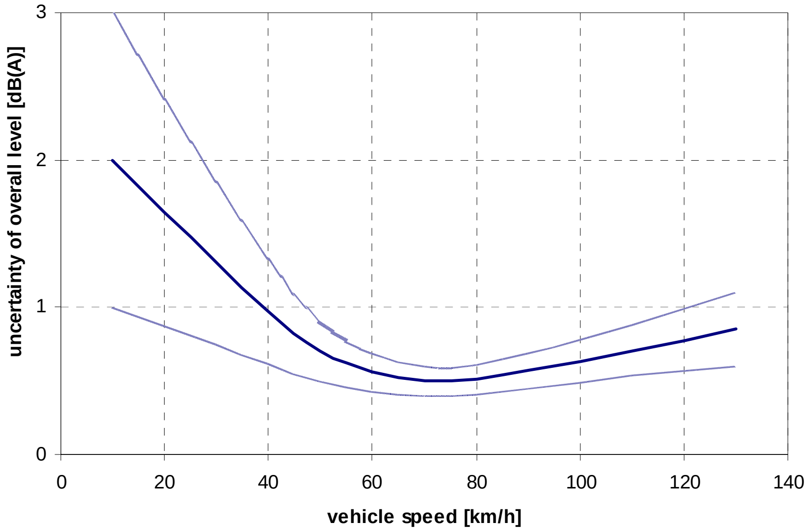


figure 35 – Estimated trend of model uncertainty versus vehicle speed

Unfortunately, there are not enough measurements available at low or very high speeds to be able to correctly validate our model outside the reference speed range around 70 km/h. It is clear, however, that the uncertainty of our model increases the farther the speed deviates from the reference speed. Our engineering guess on the uncertainty are expressed by the curve of figure 35, where the actual value could lie anywhere between the thin lines. We lack the experimental data to distinguish between vehicle categories, but the presented thick line can be used for a typical mixed vehicle fleet of 85% light and 15% heavy vehicles.

Especially at low speeds, where propulsion noise is dominant, the uncertainty is expected to increase more significantly, since the propulsion noise contribution is based mainly on single-vehicle measurements or quite limited amounts of statistical pass-bys. Furthermore, propulsion noise is more scattered by nature because of the driving behaviour and specific vehicle influence.

At higher speeds, the uncertainty will increase as well; however, rolling noise is dominant in this region, and our rolling noise model is based on more measurements and expertise. The $a + b\cdot\log(v)$ relation is widely accepted and has been validated on many occasions, for high vehicle speeds as well. Some uncertainty in the rolling noise speed coefficients still exists, however, therefore the uncertainty of the model will increase somewhat.

5.3 Comparison with Harmonoise

As was stated in the introduction to this report, the IMAGINE project was mainly meant to develop new model coefficients for the road noise emission model developed in Harmonoise, based on more extensive measurement sets and analyses. The main results of Harmonoise was the shape of the model coefficients and correction factors, which were filled with reliable coefficients within IMAGINE.

We do realize, however, that the Harmonoise model with its temporary coefficients has been used by the public in several cases already. We want to point out here, therefore, some significant changes that have been made with respect to the Harmonoise model.

- The shape of the main equations for rolling and propulsion noise has *not* changed, nor has the point source model.

- The contribution of propulsion noise has significantly decreased for all vehicle categories, which is justified by the fact that:
    - the Harmonoise coefficients were based on data sets of 4 – 10 years old, and a continuous decrease of propulsion noise of all road vehicles is observed since then, mainly because of the vehicle customers demands;
    - the type approval noise limits for road vehicles were decreased in 1996, and a large number of older, more noisy vehicles, has disappeared since then.
- The vehicle category for “Other heavy vehicles” has been removed.
- Data for the vehicle category for “Powered two-wheelers” have been added.
- The correction factor for vehicle acceleration is different, it is now kept constant below a certain deceleration.
- Directivity, road surface age and wetness correction have been somewhat simplified for user-friendliness.
- Regional corrections have been added.

6 The road noise model in practice

6.1 Using traffic models for road noise modelling

6.1.1 General

The road noise emission model described in this report allows for the calculation of the instantaneous noise emission levels of a single road vehicle at a certain speed and acceleration. For the creation of noise maps as required by the END, the noise impact of the entire road network of an agglomeration has to be assessed. To go from the noise emission of one single vehicle to that of a traffic flow on a road network, and how to properly assess all relevant road sections in a city, a traffic model is needed.

Guidelines on how to use traffic models for this purpose have been designed within the IMAGINE project by Work Package 2. Their results and conclusions have been written down in the IMAGINE Deliverable 7 [36]. Continuous deliberation between both Work Packages has taken place throughout the project.

In this section, the main procedure to calculate the noise emission on a certain road link is summarized. For more details on how to gather the appropriate input data from different levels of available traffic models, and where a currently available traffic model should best be improved to give more accurate and representative results, see the WP2 Deliverable.

6.1.2 Aggregation to a traffic flow (from [36])

The source emission model, as described above, gives the instantaneous sound power level for a single vehicle at a specific point, given the vehicle class, and its speed and acceleration. To calculate the noise emission of a vehicle flow on a network link, the instantaneous, single-vehicle sound power level L_W needs to be translated to an *equivalent sound pressure level*, L_{eq}, which is the sound pressure level at a receiver position averaged over a certain time period.

In order to execute the above mentioned computation in principle one should carry out the following steps:

- Compute the noise impact of each individual vehicle at the receiver point as a function of time while the vehicle passes along the network link;
- Integrate the contribution of each vehicle over time;
- Sum the contribution of all vehicles passing over the network link during a certain time interval;
- Determine the average noise impact of the vehicle flow during the specified time interval.

If one assumes a steady flow of vehicles on the network link with an average speed v at each moment in time there will be a number of Q/v vehicles per unit length, where Q is the number of vehicles passing per unit time. Instead of integrating over time one may also integrate over the length of the network link and obtain an equivalent result for the noise impact. Therefore it may be useful to express the noise emission of the vehicle flow in terms of an equivalent line source strength (average sound power per unit length) $L_{W,\,line,\,eq}$, as follows [33] [34]:

$$L_{W,line,eq} = L_{W,0} + 10 \cdot \lg\left(\frac{Q}{v}\right),$$

where $L_{W,0}$ is the instantaneous sound power level of the rolling noise or the propulsion noise of a single vehicle according to the formulae in 2.2.1. $L_{W,\,line,\,eq}$ is expressed in dB (re. 10^{-12} W) per m, Q in vehicles per second and *v* in m/s. This may be converted from other units by introducing conversion constants; if *Q* is given in vehicles per hour and *v* in km/h, then divide *v* by 1000.

Using this formula, the L_{WR} and L_{WP} contributions for rolling and propulsion noise should be calculated separately, and the two should be distributed over the vertical source positions as described in § 2.1.3. The result is then the $L_{W,line,eq}$ for the entire vehicle stream, divided over two different source heights.

For noise impact computations the sound emission of the moving vehicles on the network link may be represented by a series of incoherent point sources, distributed evenly over the network link. The sound power of each of these point sources must be equal to: $L_{W,\,line,\,eq}$ + 10 lg *l*, where *l* is the length of the network section that is represented by the point source. Usually two series of incoherent point sources at different heights will be used to represent the rolling noise as well as the propulsion noise of the vehicle flow on one traffic lane. Traffic lanes may be added together into composite driving lines and, consequently, composite series of point sources.

It should be noted that this definition of *equivalent* line sound power levels thus includes the influence of the pass-by time of the vehicle. Thus, a vehicle passing by at a lower speed will be heard longer, which has an increasing effect on the *equivalent* sound power level $L_{W,line,eq}$. This will thus raise the sound levels of slow traffic relative to those of fast traffic. Since fast vehicle produce higher *instantaneous* sound power levels the two effects are opposing, resulting in a minimum in the $L_{W,line,eq}$ vs. *v* curve around 20 km/h.

Using the equation above, the equivalent line sound power levels for different groups of vehicles (e.g. by vehicle or speed class) or different lanes can be mutually compared and summed. The summation of equivalent line sound power levels is calculated as follows:

$$L_{W,eq,total} = 10 \cdot \lg\left[\sum_{i=1}^{N} 10^{L_{W,eq,i}/10}\right],$$

where $L_{W,eq,i}$ are the *N* separate equivalent line sound power levels to be added. Similarly, the average equivalent line sound power level of multiple $L_{W,eq,i}$ values is calculated by:

$$L_{W,eq,avg} = 10 \cdot \lg\left[\frac{1}{N}\sum_{i=1}^{N} 10^{L_{W,eq,i}/10}\right] = 10 \cdot \lg\left[\sum_{i=1}^{N} 10^{L_{W,eq,i}/10}\right] - 10 \cdot \lg N .$$

6.1.3 Required input parameters

From the model, as described above, it is made clear that various input parameters are necessary. Some of these parameters (such as road surface, % studded winter tyres, etc.) will have to be supplied directly by the local or national authorities. From the traffic modelling, the main parameters that have to be delivered are the speed and acceleration per vehicle class, and the number of vehicles in each class. A more specific and full list of required traffic variables is given in table VI below.

table VI - Traffic parameters required by the road noise source model.

parameter	description	unit
vehicle flow (intensity): - for passenger cars - for light trucks - for heavy trucks - for powered two-wheelers	the total number of vehicles per vehicle class, per time unit, for the entire road or road lane; time unit is usually one hour, note that a separate vehicle flow number is needed for light and heavy trucks	h^{-1}
vehicle speed: - for passenger cars - for trucks - for powered two-wheelers	the driving speed of the vehicles per vehicle class, which can be given as: - one “spot” speed value for each single vehicle - a speed distribution, where an average speed value is given for successive speed ranges, and the % of vehicles for each range[8] - an average speed for the whole vehicle class	km/h
vehicle accel./deceleration: - for passenger cars - for trucks - for powered two-wheelers	the acceleration value per vehicle class, being negative for decelerating vehicles, which can be given as: - one value for each single vehicle - a distribution, where an average acceleration is given for successive ranges, and the % of vehicles for each range[9] - an average acceleration for the whole vehicle class	m/s^2

6.1.4 Using speed and acceleration data

Due to the logarithmic nature of noise, vehicles with higher noise emission will contribute more to the total emission than vehicles with lower noise emission. Furthermore, the dependence of the road noise emission on vehicle speed is non-linear (see 2.3.1). Both these factors require some care in calculating the total noise emission of a vehicle flow: the total noise emission of a vehicle flow with 1000 vehicles driving at different speeds from 60 to 80 km/h is *not* the same as that of 1000 vehicles driving at 70 km/h.

The noise model assumes that the speed values used in the calculation are the instantaneous “spot” speeds (as if measured by a speed radar at the point of interest) for each single vehicle. If a model is available that can deliver such data, the best way to go is always to calculate the equivalent noise level for each vehicle or smallest group of vehicles <u>first</u>, and <u>then</u> calculate the energy sum of these noise levels to acquire the total noise emission.

If a less detailed model is available, i.e. only average speed values for groups of vehicles or for an entire vehicle flow, an error of 0 – 1 dB(A) is introduced with respect to the actual total noise emission of all the separate vehicles. The real noise emission will generally be underestimated by the model, unless the vehicle speeds are below 20 km/h.

For acceleration, the same can be said: less detailed or averaged data will introduce an error with respect to modelling individual vehicles.

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[8] for example: 5% of the vehicles drive at an average of 5 km/h, 15% at 15 km/h, 20% at 25 km/h, etc.

[9] for example: 15% of the vehicles accelerate at an average of 2 to 1 m/s^2, 45% from 0,5 to 1 m/s^2, 40% at 0 to 0,5 m/s^2

6.2 Integrating road surface correction

In § 4.3.4 the correction factors for the road surface type have been presented, with some default values for common road surface types. These values may be used and are a reliable representation of the average road surface of that particular type. The road surface type correction can be considered to be the most important correction on the overall vehicle noise, and more silent road surfaces are an increasingly important and popular in noise mitigating.

Strong deviations from the average road surface may arise, however, due to deterioration and local pollution of the surface, specific ageing effects for absorbing surfaces, certain aspects of the road surface construction in the first place, etcetera. Furthermore, the variety of road surface types is large, and it is often difficult to know exactly what surface type is currently laid down on every piece of road network.

Measurement methods exist and are described in the SILVIA deliverable [4], for instance, that can aid the user of our model to determine the road surface correction directly while driving over the road network. By combining this CPX method [6] with GPS data, the road surface corrections of an entire city road network could be measured in a single day. Examples of the results are given below.

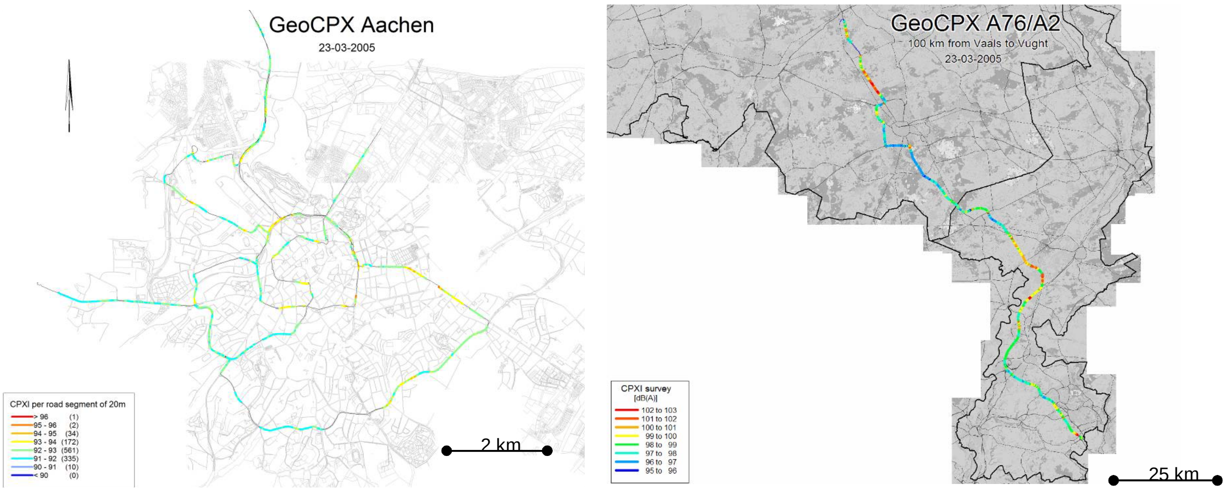

figure 36 – Measurement of road surface correction in Aachen, DE (left) and on the Dutch A76/A2 motorways (right); colours denote the standardized CPX tyre/road noise level

6.3 Action plans and what-if scenarios

6.3.1 Accessible to effect of measures

The model presented here is defined, not only with the objective to improve precision, but also with the objective to be accessible to the effect of technical measures on the vehicle and infrastructure. It makes this model an excellent tool for analyzing the effect of these types of measures on the overall noise emission of the vehicle population and on the noise levels in all types of circumstances. For instance, widespread use of hybrid vehicles in a certain urban area can be accounted for by reducing the propulsion contribution with $10 \cdot \log_{10}$ of the duty cycle of the combustion engine. The same applies to in- or decreasing the fraction of diesel engine vehicles versus Otto engines, shifts in vehicle weight, reduction of the % IRESS, etc….

6.3.2 EU and ECE type approval regulations

A special type of measure are those taken to meet EU type approval directives (and its related ECE regulations). The present regulation for the vehicle refers to the noise emission of the total vehicle under conditions of wide open throttle acceleration at speeds around 50 km/h. In addition there is a regulation for tyres that refers to the noise emission under condition of coasting-by at speeds around 70 to 80 km/h. The shift in noise emission of the tyre and the drive train, resulting from meeting the regulatory requirements can be directly implemented in the noise emission modelling and leads therefore directly to possible effects in noise exposure of the population.

When implementing the effects of shifts in tyre emission care must be taken to include the road surface effect. Not only does the road surface shift the total noise emission, it also affects differences between tyres. That means that on a rough surface no effect from shifts can be found, while on smooth surfaces, the effect is identical to that found in the test procedure. On road surfaces found in practice, the best estimation is to take 50% of the shift found on test tracks (ref . [35]).

6.3.3 Effect on the level of infra structure

Control of traffic noise by measures on infrastructure and vehicle flow are attractive, since they can be taken by local authorities and have an effect over-night. Changing road surfaces is simply implemented in the model through application of the surface correction (see section 4.3.4). Also effects of traffic calming, banning HDV´s and similar is easily implemented in the model presented here.

6.3.4 Future developments

It is known that the noise characteristic of vehicles changes in future. Over the last years we have seen that drive line contributions reduce and rolling noise contributions increase. For a part the underlying mechanisms can be modelled with the present model. Tyres get noisier due to increase in width. Drive line noise slightly increase due to diesel engines, but decrease under pressure of vehicle regulation and consumer requirements.

7 Recommendations for further investigations

Integration with air quality modelling

The model presented here distinguishes between the contribution of the power train and the contribution of the tyre. The power train contribution is based on vehicle driving conditions in such a way that a nearly direct link to the engine performance can be made. This, together with the available data on engine type and vehicle age composition allows the prediction of the exhaust air quality. Since both noise and air quality can be regarded as directly caused by road traffic and exhibit similar propagation modeling, integration of prediction methods for both components shall be very advantageous for users.

Direct linking with type approval

The presented model allows implementation of the effect of regulatory activities on the vehicle noise characteristics, a direct link is not reliable on the level that decision on regulatory modifications can be based on it. With some further study, such a reliable link is feasible and will therefore establish a direct link between the level of decisions on noise from vehicles and the resulting effects on population and on area affected by the noise.

Traffic situations

The model presented here relies on know-how of the vehicle driving status when crossing junctions and other flow inducing geometries. Such information will not be available in general, so we recommend that for a series of typical situations distance-speed relations are calculated, for instance through dynamic traffic modeling and that these graphs are made available to users.

Link with annoyance/specific annoyance

Implementation of the dose-effect relations, available through the work of EU noise working group 2, allows direct assessment of the fraction of people annoyed and highly annoyed. It is known that certain traffic conditions raise more annoyance then can be understood from the equivalent level, this aspect is referred to as specific annoyance, that will appear mostly at situations were traffic is accelerating and decelerating. Unambiguous relations of specific annoyance with either noise characteristics or vehicle driving characteristics would enable this aspect to also be taken into account.

Databases with known information on vehicle composition

The model presented here requires specific information of the characteristics of the vehicle fleet. This type of information has to be gathered at regional or country level, but is required on the level of a city or a highway. It will be advantageous when such information is made available from a central point that not only every user can refer to, but can also check for consistency of the used figures.

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APPENDIX A – Coefficients for rolling noise corrections

A.1 Correction for road surface type

table VII - Coefficients *a* and *b* for road surface type based on SILVIA method. Only octave band figures are given. In first approximation they can be applied to each 1/3[rd] octave band within it. Positive values indicate increase, negative values decrease of sound levels. Figures coming from Netherlands based research. More figures are available on www.stillerverkeer.nl (in Dutch only). No correction for category 4.

category 1	250	500	1 kHz	2 kHz	4 kHz	speed index (β)	A-weighted effect at 70 km/h
transversely brushed concrete	2,6	2,4	1,2	2,4	0	6	1,4
concrete with surface dressing 2/4	2,1	3	3,5	0,1	-0,8	-5	2,7
exposed aggregate	1	1,2	1,9	0,8	0	0	1,3
drain asphalt 6/16	0	0	-1,1	-4,5	-5,3	-11	-1,4
2-layer drain asphalt 4/8-11/16	-1,6	-3,3	-4,3	-6,9	-6,7	-6	-4,6
SMA 0/6	0	0	-2	-2,9	-2,2	-5	-1,7
surface dressing 4/8	5,1	5,6	4,6	-1,5	-2,5	-4	3,4

categories 2 and 3	250	500	1kHz	2 kHz	4 kHz	speed index (β)	A-weighted effect at 70 km/h
transversely brushed concrete	2,2	1,7	1,3	0,2	-1,3	12	1,1
concrete with surface dressing 2/4	1,1	0,8	-0,9	-2	-2	5	-0,6
exposed aggregate	0	-0,2	-0,8	-1,5	-1,9	15	-0,8
drain asphalt 6/16	1	-4,2	-4,5	-3,3	-2,6	-6	-3,8
2-layer drain asphalt 4/8-11/16	-0,3	-5,7	-6,9	-5,5	-4,4	-8	-5,8
SMA 0/6	0	-0,6	-1,6	-1,2	-1,1	0	-1,1
surface dressing 4/8	2,5	0,4	-1	-1,8	-2,1	13	-0,7

A.2 Correction for temperature

table VIII- Coefficients for temperature correction $\Delta L_{WR,T} = K(20°C - T)$, T in °C for category 1. For category 2 and 3 50% of the value applied for cat 1 can be used. Refer to ISO TC43 WG 27 for updated figures.

	generic correction factors for cat 1		
	porosity class		
texture class (MPD)	**< 5%**	**5<porosity<15**	**>15**
<0,5 mm	0,04	0,06	0,08
0,5< text< 1,5 mm	0,08	0,07	0,06
>1,5 mm	0,12	0,08	0,03

A.3 Correction for studded tyres

table IX- Coefficients *a* and *b* for studded tyres correction $L_{WR,stud}$ = *a* + *b*·log(v/70), for 50 v 90, for category 1 only

frequency [Hz]	*a*	*b*
25	0	0
31.5	0	0
40	0	0
50	0	0
63	0	0
80	0	0
100	0	0
125	0.3	-4.1
160	1.4	-6
200	1.5	-8.5
250	0.9	-4.1
315	1.2	1.7
400	1.5	0.6
500	1.9	-4.6
630	1.8	-3.9
800	0.8	-2.7
1000	0.5	-4.2
1250	0.2	-11.7
1600	-0.2	-11.7
2000	-0.4	-14.9
2500	0.5	-17.6
3150	0.8	-21.8
4000	0.9	-21.6
5000	2.1	-19.2
6300	5	-14.6
8000	7.3	-9.9
10000	10	-10.2

APPENDIX B – Uncertainty calculations

This paragraph is adapted from information for the Nord2000 project [37].
If the quantity to be calculated is L_{calc}, which is a function of the quantities x_j the principal equation becomes:

$$L_{calc} = f(x_j) \quad (1)$$

If each quantity has the standard uncertainty u_j the combined uncertainty is given by

$$u(L_{calc}) = \sqrt{\sum_{1}^{n} (c_j u_j)^2} \quad (2)$$

where the sensitivity coefficient c_j is given by

$$c_j = \frac{\partial f}{\partial x_j}\,. \quad (3)$$

For the roadside sound exposure level $L_{eq,T}$ we can write, for one vehicle type

$$L_{eq} = L_E - 10\lg(T) + 10\lg(N) = L_W + \Delta L_{tf} - 10\lg(v) + 10\lg(\frac{N}{T}) \quad (4)$$

where L_W is the total sound power level, ΔL_{tf} the total transfer function between L_W and sound exposure level, v = the speed, T = the time and N = the number of vehicles during the time T. Here, we do not explicitly state any speed effects in the propagation and transfer from L_E to L_W, these are implicitly included in the ΔL_{tf}.

As is shown in the source modelling report the speed dependence of L_W, if we focus on tyre/road noise, is approximately 35 lg(v), that is we get

$$L_{eq} = L_W(v = v_{ref}) + \Delta L_{tf} + 25\lg(\frac{v}{v_{ref}}) + 10\lg(\frac{N}{T}) - 10\lg(v_{ref}) \quad (5)$$

Thus the sensitivity coefficient, c_v, for speed is

$$c_v = \frac{\partial L_{eq}}{\partial v} = 25\frac{1}{v}\lg(e) = \frac{10{,}9}{v} \quad (6)$$

and for traffic flow

$$c_N = \frac{\partial L_{eq}}{\partial N} = \frac{10}{N}\lg(e) = \frac{4{,}3}{N}\,. \quad (7)$$

The total standard uncertainty of eq. (5) is the given by

$$u(L_{eq}) = \sqrt{(c_W u_W)^2 + (c_{tf} u_{tf})^2 + (c_v u_v)^2 + (c_N u_N)^2} \quad (8)$$

The total uncertainty is determined by these four different contributions $c_i \cdot u_i$, We do not now all of these contributions. As both L_W and ΔL_{tf} are very complicated quantities we cannot put up their equations. In stead we will have to assign them the sensitivity coefficient 1. The standard uncertainty of the transfer functions is determined by the IMAGINE P2P model. From ISO 1996-2, under favourable propagation conditions, u_W is estimated to be 1.5 dB.

The standard uncertainties for speed u_v and traffic flow u_N are dependant on too many factors to make any guess. Traffic models are generally built to give good estimations of the traffic flow *N*, and less on providing accurate vehicle speeds *v*. Traffic models exist in many forms with different levels of detail, and their accuracy and representativity depends on the amount of calibration and validation input. Furthermore, traffic on main roads with high traffic flows is easier to calibrate and model than traffic on smaller suburban roads. And finally, it may be possible to obtain good estimations for the total traffic flow *N*, but it may be quite difficult to obtain these values separately for each of the vehicle categories; a distinction between categories 2 and 3 is not often made, and powered two-wheelers are hardly ever addressed in traffic modelling.

Eq. (5) is valid for one category of vehicles. We could either assume that all categories have the same uncertainty and then the result will not change. However, if the uncertainties are very different between the categories we have to add them up. We then get

$$L = 10\lg\left(10^{L1/10} + 10^{L2/10} + 10^{L3/10}\right) \tag{10}$$

where $L1$, $L2$ and $L3$ are the calculated L_{eq}:s for the 3 categories of vehicles.

The sensitivity coefficient c_{Li} is then given by

$$C_{Li} = \frac{\partial L}{\partial L_i} = 10\lg(e)\frac{10^{Li/10}\ln(10)\cdot 0{,}1}{10^{L1/10} + 10^{L2/10} + 10^{L3/10}} = \frac{10^{Li/10}}{\sum 10^{Li/10}} \tag{11}$$

The standard uncertainties are given by eq. (8) applied on all vehicle categories and the total uncertainty is then given by

$$u(L_{eq,tot}) = \sqrt{(c_{L1}u_{L1})^2 + (c_{L2}u_{L2})^2 + (c_{L3}u_{L3})^2} \tag{12}$$

In case we want to add results from different weather conditions the following is useful:

L_{eq} for condition *i*, which lasts for p_i of the total time is denoted L_i. The total L_{eq} for the whole time interval is denoted *L*. We then get

$$L = 10\lg\left(p_1 10^{L1/10} + p_2 10^{L2/10} + \ldots + p_n 10^{Ln/10}\right)$$

For c_{pi} we get

$$c_{pi} = \frac{\partial L}{\partial pi} = \frac{10^{Li/10}}{\sum p_i 10^{Li/10}} \tag{13}$$

L_i is determined with the standard uncertainty σ_{Li} and p_i with the standard uncertainty σ_{pi}. The standard uncertainty of *L* is then given by

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{\partial L^2}{\partial L_i^2}\sigma_{Li}^2 + \sum_{i=1}^{n} \frac{\partial L^2}{\partial p_i^2}\sigma_{pi}^2} \; . \tag{14}$$