Sustainable Road Surfaces for Traffic Noise Control

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SILVIA PROJECT DELIVERABLE

Recommendations on Specifications for Tyre and Vehicle Requirements

E Pucher, TUW
J Litzka, TUW
J Haberl, TUW
J Girard, TUW
J Ejsmont, TUG
J Lelong, INRETS
J-F Hamet, INRETS
U Sandberg, VTI
H Bendtsen, DRI
G Watts, TRL
A Parry, TRL
G van Blockland, M+P
A Kuijpers, M+P

Silenda Via

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Executive Summary

This document is submitted in fulfilment of Deliverable 07 of the SILVIA EU research project. The goal of this document is to examine the parameters of tyres, vehicles and driving conditions in order to demonstrate the potential to further the noise reductions achieved by low-noise surfaces through a systematic optimisation of the vehicle, tyre and road surface. This work has been carried out as part of work package 5: Integration of Low-Noise Pavements with Other Noise Abatement Measures. This report gives an overview of the general effects of various tyre and vehicle parameters, a brief review of the SILVIA database, and analyses of the influences of various tyre and vehicle parameters on traffic noise. These analyses are based on data present in the SILVIA database, supplemented with results from relevant literature. Based on these analyses recommendations have been made concerning guidelines for vehicle and tyre manufacturers and legislators as a way to improve the performance of low noise surfaces through optimising the vehicle and tyres.

Proposed stronger guidelines have been given for “quiet vehicles.” Currently, the system to designate a “quiet vehicle” is fairly forgiving. In order to provide a stronger motivation to the consumer to purchase vehicles with improved noise performance, the requirements for designating a vehicle as a “quiet vehicle” should be more stringent. In this report it is proposed that:

- The vehicle should be tested with the tyres sold on the vehicle – each vehicle model should be tested for each set of tyres sold with it, and the vehicle noise rating should change accordingly if the tyres are changed prior to sale or at the time of sale.
- The rolling noise and the accelerated pass-by noise should be measured under real life conditions, i.e. road surfaces in common use instead on an ISO surface, which is only a test track and never used for public roads.
- The vehicle should show an improvement over the fleet average noise level from vehicles for the given model year of at least 3 dB(A).
- The vehicle testing should cover the range of typical driving conditions.
- When users change tyres, a tax incentive should be implemented encouraging them to use the quietest tyres.

Vehicle parameters were examined, in addition to driving conditions. The resulting recommendations included those listed below:

- Electronic slip control systems should be more widely adopted – reducing slip can lead to decreases of as much as 3 dB(A) for pass-by noise.
- Special regulations for alpine regions regarding speed and night driving, and introduction of 4-wheel drive systems, for example, for heavy vehicles, are potential means of reducing traffic noise in areas where substantial gradients occur.
- Improved power unit soundproofing on diesel engines can yield reductions in noise levels at low speeds.

Tyre parameters were also examined regarding their impact on traffic noise. Some recommendations of note resulting from the analyses of tyre parameters were as follows:

- Wider tyres should be required to meet the same noise level standards as narrow tyres for the same type of vehicle.
- Tyre material properties such as the hardness of the rubber and the thickness of the belts should be optimised for given size parameters of tyres – such an optimisation can lead to a noise reduction of as much as 2 dB(A).

By implementing these guidelines, the authors feel that the next generation of quiet vehicles would show a marked improvement in noise performance over the current fleet.

Contents

1. Introduction

1.1. The SILVIA Project

SILVIA is a collaborative RTD project supported by the European Commission under its Competitive and Sustainable Growth (GROWTH) programme. The project started in September 2002 and has a planned duration of three years. SILVIA aims at providing decision-makers with a tool allowing them to rationally plan traffic noise control measures. To this end, the work will aim at filling three major knowledge and technical gaps, namely by: setting up classification and conformity-of-production procedures of road pavements with respect to their influence on traffic noise, investigating and improving - based on existing data and laboratory and field testing - the functional and structural durability of low-noise pavement construction and maintenance techniques, and developing a full life-cycle cost/benefit analysis procedure for traffic noise abatement measures. The main final product of SILVIA will be a European Guidance Manual on the “Utilisation of Low-Noise Road Surfaces" integrating low-noise surfaces with other traffic noise control measures including vehicle and tyre noise regulation, traffic management and road and building noise protection equipment.

Road traffic noise has been and continues to be a problem in many European communities (EU, 1996, ACSO, 1992). In recent years, low-noise road surfaces have been introduced that can lead to substantial reductions in traffic noise. However, the overall benefits of these noise-reducing surfaces are influenced by other factors including the tyres of the vehicles, use of passive noise reduction measures such as barriers, and traffic control measures for noise reduction.

1.2. Description and Goals of SILVIA Work Package 5

Work Package 5 (WP5) of the SILVIA project studies in detail the effects of combining low noise road surfaces with other noise reducing measures. The work within WP5 is a research based on existing results, comprising the analysis of comparable data to obtain consistent European data structures.

The objectives of WP5 are:

- To describe noise reduction solutions taking into account the combination of pavement and tyre design.
- To address noise reduction possibilities by assessing other vehicle noise sources (e.g. reducing power unit noise).
- To discuss the acoustical optimisation of local conditions (urban, semi-urban and rural roads, crossings, roundabouts, etc).
- To consider traffic management measures for noise control and the effect of these on mobility.
- To estimate the noise reduction of low-noise pavements when combined with noise barriers and earth mounds, and when used on bridges.

The research in SILVIA WP5 is further sub-divided into 4 tasks. Task 5/1 of WP5 deals specifically with the combination of road and tyre design. Task 5/1 will look into acquiring experience and results from other research projects. The influence of operating conditions has also been studied as part of Task 5/1. This includes the vehicle operating parameters such as accelerated pass-by and rolling pass-by, and conditions like driving in a curve or gradient. Influence of traction force and slip on noise emissions have also been studied, in addition to examining noise spread among various tyres and road surfaces on the market. Finally Task 5/1 uses the results of this study to provide recommendations for tyre selection guidelines.

Task 5/2 of WP5 is focussed on the influence of local conditions on noise emissions. This research includes the specific problems associated with urban and semi-urban roads, and specific problems such as the influence of frequent road works for energy and water supply on vehicle noise emissions. Rural roads and highways are also covered in this research. Task 5/2 also includes such specific problems as noise at crossings and roundabouts and the alignment of roads in mountainous regions with steep slopes.

The topic of Task 5/3 is the influence of traffic management measures on noise emissions. Within Task 5/3 the effect of speed limits dependent on road design including the use of speed-reducing humps and bumps will be studied. Also, Task 5/3 will cover options such as traffic restrictions in special periods, and the concentration of traffic flow on main routes equipped with noise reducing surfaces in combination with traffic restrictions on parallel routes.

Task 5/4 continues the study of the combination of low noise surfaces with other noise reducing measures by looking at the combination of noise-reducing pavements with road and building equipment. This work will include investigations of noise-protecting barriers and earthworks in combination with low-noise surfaces, investigations on bridges (joints) and other passive noise protection such as building insulation.

1.3. Aims of this Report

This report will provide recommendations to policymakers and to those in the tyre and vehicle industry regarding possible measures for traffic noise reductions. To achieve this goal, an extensive analysis is performed regarding the influences of tyre parameters, vehicle properties and vehicle operating conditions on noise emissions. The analysis is based on results and experiences of the SILVIA partners from other projects as well as from literature. The general topics studied in this analysis were: the influence of vehicle operating conditions such as accelerated pass-by and rolling as well as driving in a gradient and curve on the noise, the influence of the traction force and slip on the noise emissions, the noise spread among various tyres on the market and the noise spread among various road surfaces on the market. Based on the analysis of results from SILVIA WP5 partners and on literature available on this topic, recommendations on vehicle and tyre requirements are provided.

Chapter 2 of this report describes the methodology for the analysis and resulting recommendations for tyre and vehicle parameters. This is followed by an overview of recent literature on the effects of vehicle and tyre parameters and operating conditions on traffic noise, given in Chapter 3. Chapter 3 also gives a general overview of the vehicle and tyre parameters of interest for traffic noise, and presents certain hypotheses regarding the influence of certain parameters on vehicle/tyre/road noise. Chapter 4 describes the SILVIA database of vehicle/tyre/road noise. The results stored in this database are used for the analysis of the influence of various parameters on noise levels. The structure of the database is briefly presented, and the datasets comprising the database are also described. Chapter 5 describes the analysis of the effects of operating conditions, tyre and vehicle parameters on noise levels. The hypotheses formulated in Chapter 3 are tested in the analysis of available data from the SILVIA database and relevant literature. Chapters 6 and 7 give the recommendations based on these analyses for tyre and vehicle requirements, respectively.

2. Methodology

2.1. Scope of Analysis

The analysis comprising this report will cover aspects of tyre and vehicle properties that influence traffic noise, as well as the dependence on the road surface. As mentioned in the description of WP5, in Chapter 1, tyre/road surface interaction is an important part of the research. The technical aspects covered in this field include the influence of the parameters of the tyre, the road surface, the vehicle and the driving conditions. Details of the parameters examined are provided in Tables 1 and 2 on the following page.

The way each of the parameters outlined in Tables 1 and 2 effects traffic noise depends on the type of road surface. Therefore, the analyses have been carried out for many types of road surfaces whenever the data was available.

A database of traffic noise results has been compiled as part of WP5. This database includes thousands of individual vehicle pass-by measurements from several of the SILVIA partners. This database has been used where data were available for the analysis work included in this report. For certain parameters where the database did not contain sufficient information, these results were supplemented by recent relevant studies in the literature.

Figure 1 shows the EU noise limit values required for type approval for various vehicle categories from 1970 to 2005. The result of the analyses in this report will lead to recommendations on guidelines for tyres and vehicles. One issue to be addressed is: are the limits shown in Figure 1 sufficient? Can further reductions be brought about through the optimisation of the entire vehicle/tyre/road system? Additionally, guidelines about specific tyre and vehicle parameters will be proposed.

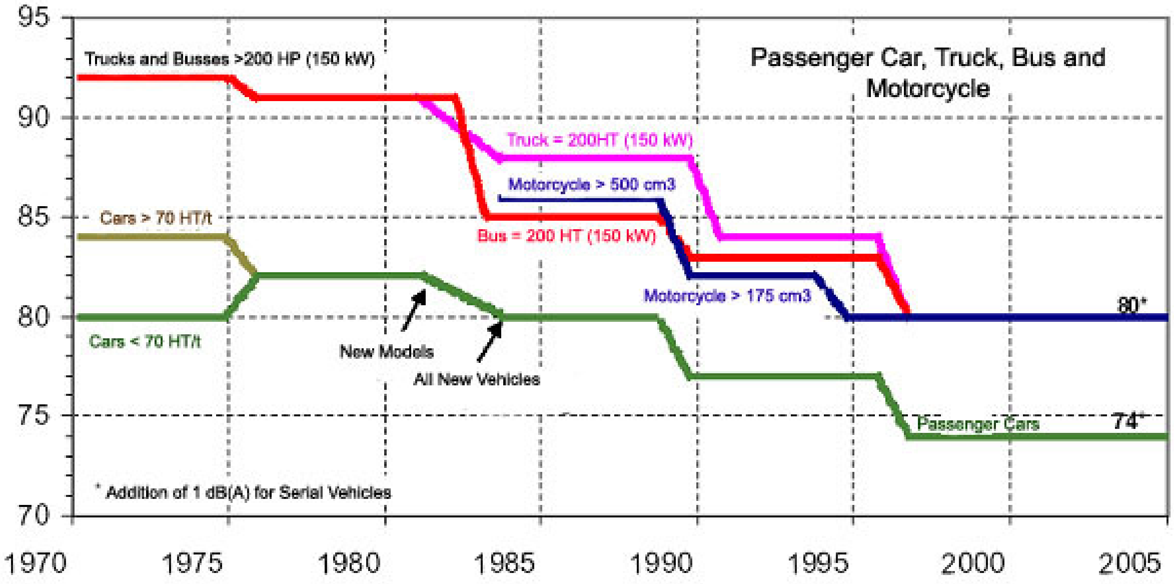


Figure 1: EU Noise Limit Values for Various Vehicle Categories as Required for Type Approval (EEC, 1992, Stenschke, 2003)

Table 1: General Parameters for Analysis of Vehicle/Tyre/Road Noise (Each on Various Road Surface Types)

Driving Conditions					**Vehicle Parameters (by Vehicle Class)**					**Slip & Traction Force**		**Tyre Parameters**				
Constant	Accel.	Coast (Roll)	Gradient	Curve	Power Unit Noise	Exhaust System	Vehicle Weight	Vehicle Power	Diesel vs. Petrol	Slip	Traction Force	HT Tyres Drive & Non-Drive	LT & SUV Tyres	PC Tyres	Re-inforced PC Tyres	M+S Tyres (with and without studs)

HT = Heavy Truck, LT = Light Truck, SUV = Sport Utility Vehicle, PC = Passenger Car

Table 2: Tyre Parameters For Each Given Tyre Type (i.e., Passenger Car Tyre, etc.)

General Tyre Parameters		**Dimensional Properties**			**Material Properties**	**Tread Pattern**			
Tyre Load	Tyre Inflation	Tyre Width	Tyre Aspect Ratio	Tyre Rim Diameter	Hardness	Circumferential Grooves	Profile Depth	Symmetry of Segments	Ventilation

2.2. Measurement Methods for the Available Data

The far-field measurements included in the database were primarily measured using an ISO measurement schematic, as can be seen in Figure 2.

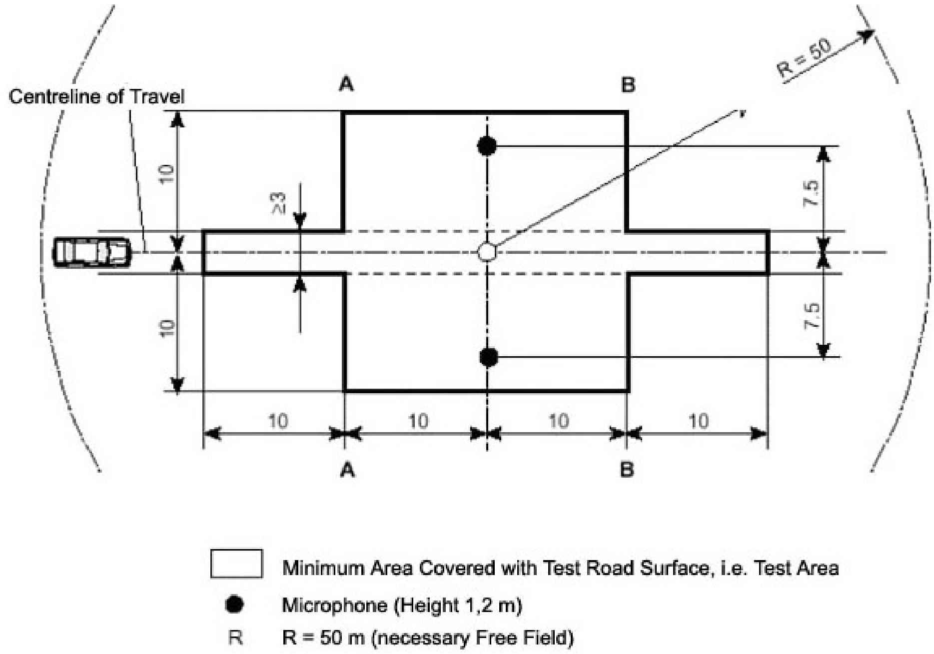


Figure 2: Sample Schematic of ISO Test Set-up for Pass-By Noise Measurements (ISO, 1994)

The area within the bold lines should be covered with a surface meeting the ISO 10844 standard, but the surface during the measurements might have been different due to the purpose of the measurements. It is also common that in measurements made on actual roads, the set-up is different, with a microphone on only one side, with a smaller area covered by the test surface, and with a radar device measuring vehicle speed.

Data available included pass-by measurements under the following driving conditions:

- Coast-By (Engine Turned Off, Free Rolling, Can also Constitute Engine Turned On, Free Rolling - Where Coast-by Results with the Engine Turned on are Given, this is Noted)
- Drive-By (Accelerated Pass-By)
- Decelerating Pass-By (Vehicle Decelerated, Either by Braking or by Engine with Clutch Engaged)
- Cruise-By (Vehicle Maintaining a Constant Speed)

2.3. Road Surface and Vehicle Terminology

The following lists the terminology for road surface types used throughout this report.

CC	Cement Concrete
DAC	Dense Asphalt Concrete
DPAC	Double Layer Porous Asphalt Concrete
EACC	Exposed Aggregate Cement Concrete
EP-GRIP	Epoxy-Bound Surface Dressing
GA	Gussasphalt
HRA	Hot Rolled Asphalt
ISO	Test Surface Conforming to Standard ISO 10844:1994
PAC	Porous Asphalt Concrete
STC	Surface Treated Concrete
SMA	Stone Mastic Asphalt
TSF	Thin Bituminous Surfacing - Microsurfacing

The vehicle categories used in this report follow the terminology below.

PC	Passenger Car
HV	Heavy Vehicle
HT	Heavy Truck
LT	Light Truck
M	Motorcycle

2.4. Analysis Procedure

As mentioned in Section 2.1, the analysis will be based on the results contained within the SILVIA database, supplemented where necessary with data from relevant literature. The analysis for operating conditions will be based on real life traffic data, including data from alpine roads for the influence of gradient on noise levels, and also on controlled test data, where the influence of vehicle acceleration and slip on noise levels can be quantified. The vehicle and tyre parameters will be based on real world and controlled test data. As the effects of the various parameters on the road surface type cannot be neglected, the analyses will be carried out on various road surfaces depending on the availability of the data.

When more than one set of measurements are available, the data sets are analysed separately. In this manner the influence of local conditions and other variables on the results are minimised. The majority of data available in the database consists of pass-by measurements. Thus, the analyses are based for the most part on far field measurements.

Based on these analyses, an overview of the importance of the various parameters on traffic noise is given, based on the possible reduction of noise level through optimisation of each of the given parameters. This overview is used in the formulation of recommendations on specifications for tyre and vehicle requirements.

3. Recent Work on the Influence of Tyre and Vehicle Characteristics on Traffic Noise

3.1. Introduction

As was mentioned in Chapter 1, road traffic noise is a problem for many communities in Europe. Tyre/road noise is of course an important part of the problem, and often dominates traffic noise. Figure 3 shows an example of the contribution of tyre/road noise in comparison to power unit noise for a vehicle with typical acceleration. In this report, the term "power unit" will refer to the engine, transmission and drive components of the vehicle. For constant speeds, on a typical vehicle, the tyre/road noise level can equal the power unit noise at a speed of 50 km/h (Cercle Bruit, 1998).

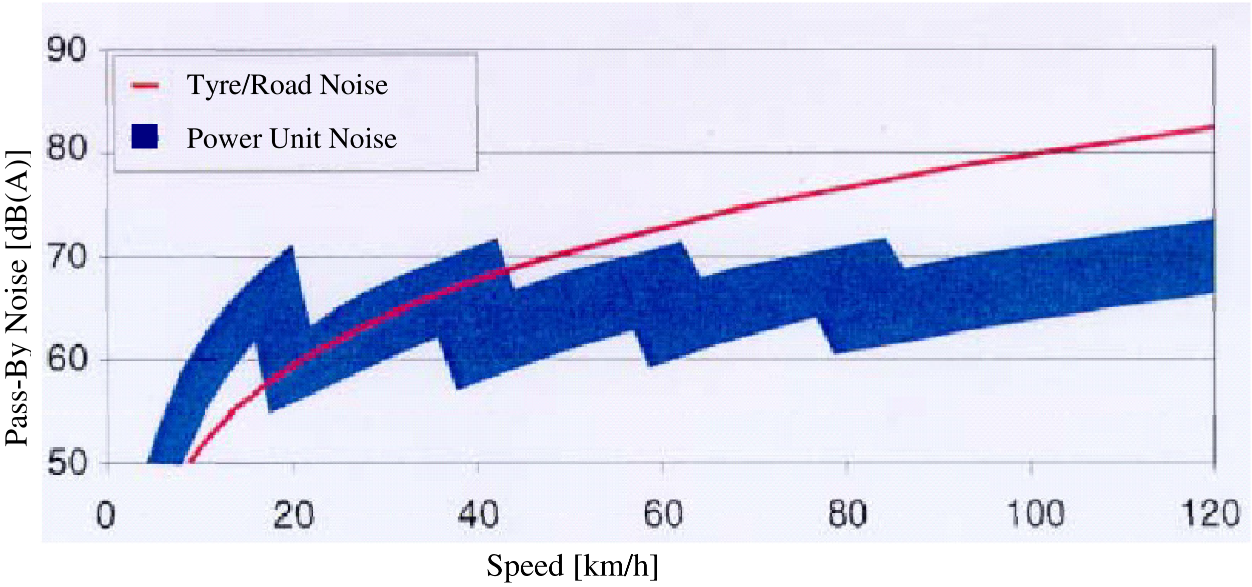


Figure 3: Example of Power Unit and Tyre/Road Noise for a Vehicle Under Typical Acceleration (de Graaff, 2001)

In this chapter, an overview of the mechanisms of tyre/road noise will be given based on standard literature, involving the influence of tyre characteristics and of vehicle parameters. The influence of road surface is noted where relevant, but not separately discussed in this document - this work is the focus of Work Package 4 of the SILVIA project. Then, hypotheses on the influences of various tyre and vehicle parameters and operating conditions on vehicle/tyre/road noise will be posed based on these mechanisms and characteristics. These hypotheses are tested based on a variety of experimental data in Chapter 5 of this report.

3.2. Influence of Tyre Characteristics

3.2.1. General Remarks

The contact of the tyre with the road leads to the generation of noise through several mechanisms that are known in general terms, although sometimes hard to describe in detail regarding the relation of these mechanisms to road surface and tyre properties.

3.2.2. Tyre Parameters and Terminology

Figure 4 gives a cut-away view of a standard tyre, showing the terminology of the various tyre components. This terminology will be used throughout this chapter and the remainder of the report for discussing the tyre properties. This is followed by Figure 5, which shows the various dimensions for a typical tyre.

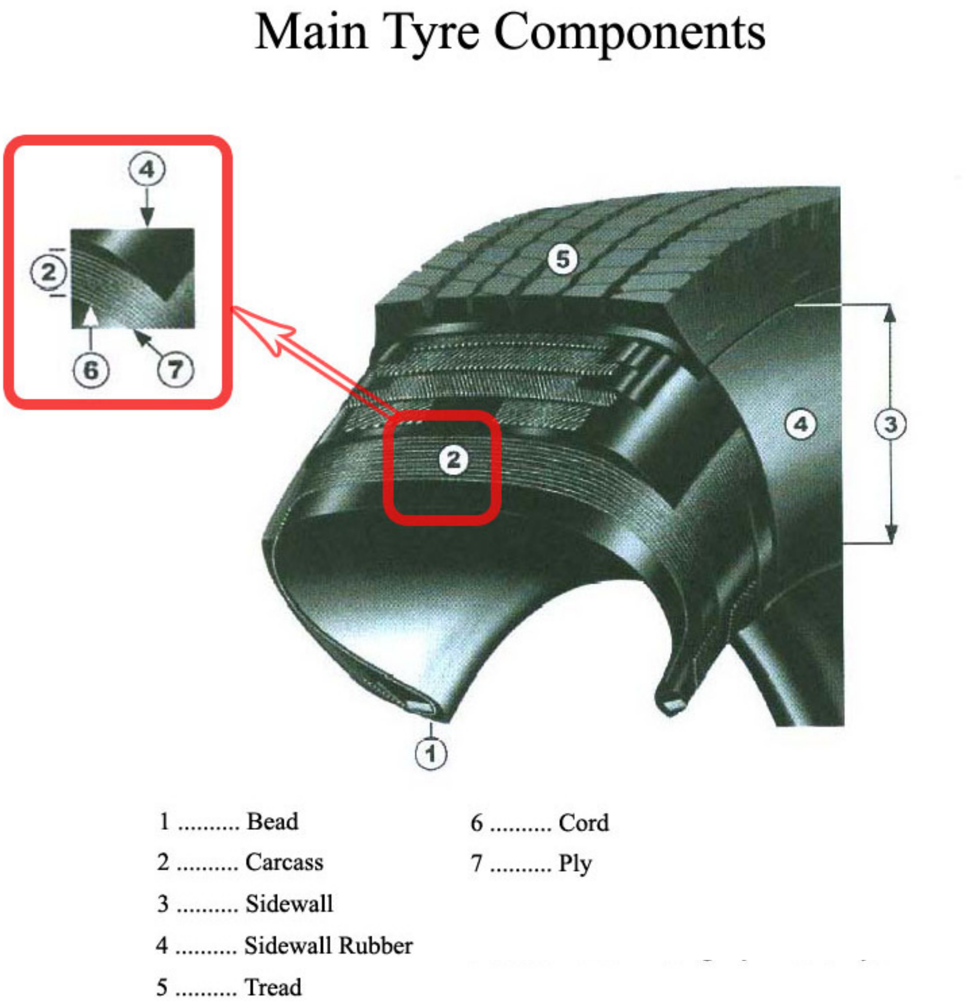


Figure 4: Cross Section of an Example Tyre Showing Terminology (ETRTO, 2004)

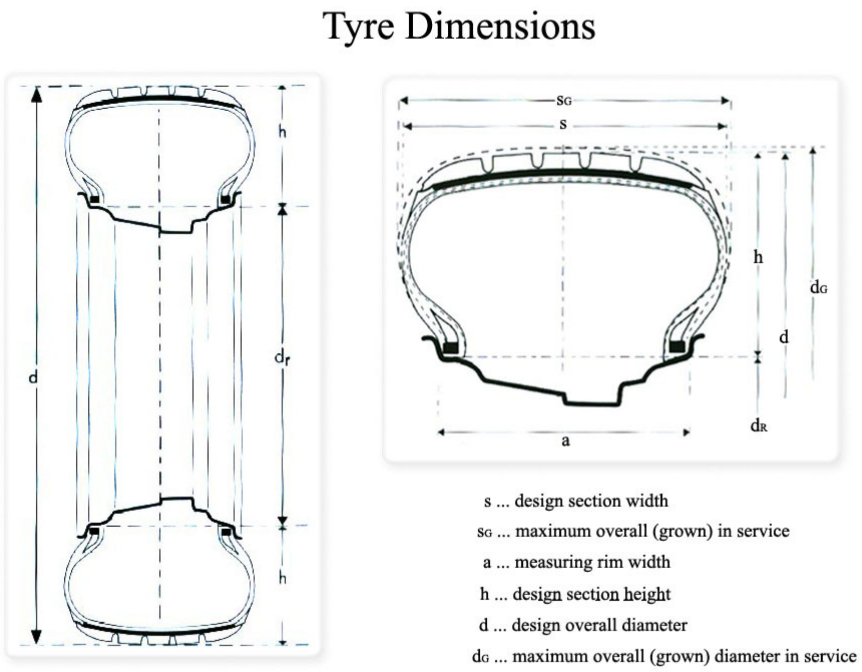


Figure 5: Terminology for Dimensions of Tyres (ETRTO, 2004)

The tyre parameters of interest for tyre/road noise include, but are not limited to:

Situation-Specific Properties:
- Tyre Load
- Tyre Inflation Pressure

Dimensional Properties:
- Tyre Width (W)
- Tyre Aspect Ratio (AR)
- Tyre Outside Diameter (OD)

Material Properties:
- Hardness

Tread Pattern:
- Pitch/Tread Randomisation (Note: Segment Length = Pitch)
- Symmetry of Segments
- Directionality of Segments
- Ventilation to the “Outside” of Grooves or Pockets of Air in the Tread
- Groove Width
- Groove Angle
- Existence/Extent of Circumferential Grooves
- Sipes (Very Prominent in Tyres for Winter Use)
- Studs

This is not an exhaustive list of tyre parameters effecting tyre/road noise. For a more thorough discussion of relevant tyre parameters, the reader is referred to a textbook on the subject, such as Sandberg and Ejsmont (2002).

3.2.3. Tyre/Road Noise Generation Mechanisms

Tyre/road noise or rolling noise are common names for all noise that is generated due to the rolling contact of road and tyre. The primary mechanisms for rolling noise are the tyre vibrations that are excited by road and tyre profile irregularities. The road surface texture or the tyre profile blocks excite radial and tangential vibrations in the tyre, and those vibrations radiate into the air as audible noise (see Figure 6). The vibrations in the tread are also transferred to the sidewalls, causing sidewall vibrations.

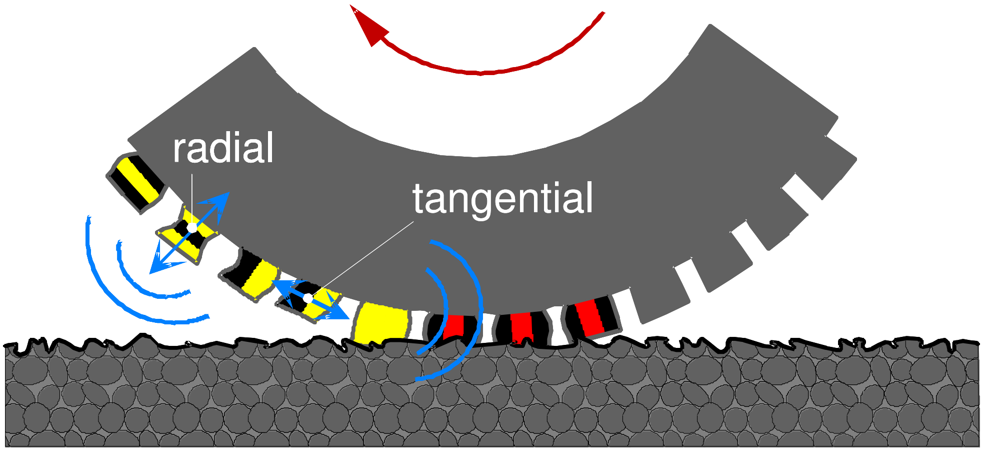


Figure 6: Radial and Tangential Tyre Vibrations through Impact of Tread Blocks and Rubber Deformation (Kuijpers and Van Blokland, 2001)

Besides the roughness induced vibrations, other mechanisms can play a role in the generation of tyre/road noise. For very smooth dense roads or for tyre tread profiles with closed pockets, air pumping noise can be generated by squeezing out, or sucking in of air in small pockets between the road surface and the tyre tread. Another mechanism causes the so-called stick/slip vibrations: the periodic sticking and slipping of the contact between tyre and road, which occurs particularly at cornering, braking or accelerating. However, also rolling at constant speed and no side forces causes tangential forces and slip of individual tyre tread elements against the road surface, and thus potentially may cause stick/slip noise. The stick/slip phenomena also result in tangential forces and hence tangential vibrations in the tyre. When a good cohesion between the tyre rubber and the road surface is present, then also stick/snap vibrations are excited, which cause radial vibrations.

Besides the generation mechanisms, there are acoustical processes that influence the amount of radiated sound or the efficiency of the radiation process. These processes are resonances and the so-called horn effect (see Figure 7).

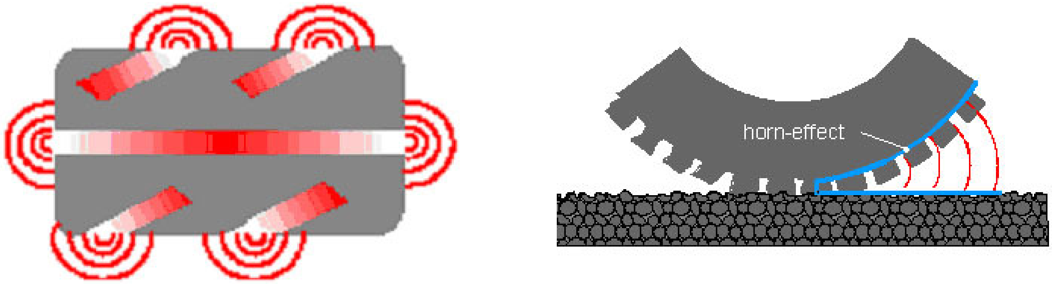


Figure 7: Amplification Processes: Pipe Resonances and the Horn Effect (Sandberg & Ejsmont, 2002, Beckenbauer, 2003)

Resonances correspond to a build-up of energy, which increases the amount of radiated sound. Pipe resonances can occur when closed tubes are formed in the contact area between tyre and road. The Helmholtz resonance is caused by the movement of air into and out of the air cavities in the tread pattern (see the left side of Figure 7), in which the air volume of the cavity acts as a spring which resonates with the mass of the air in the “throat”; similar to a mechanical spring-mass system.

Another amplification process is the so-called horn effect (see the right side of Figure 7). The tyre tread and the (dense) road surface form a horn that amplifies the noise generated in the tyre/road contact patch by as much as 20 dB. However, the effectiveness of the horn is influenced by the road surface type. For instance, a porous road with absorption will significantly decrease the efficiency of the horn.

3.3. Influence of Vehicle Parameters

The sound pressure level of a passing vehicle increases during the approach, reaches a peak at or rather near the closest position of the vehicle to the measurement point, and decreases when the vehicle has passed the location. Such a curve of the sound pressure level of a passing vehicle is called “time history” and is shown in Figures 8 and 9. The example in Figure 8 is for a case when the vehicle is driven at maximum acceleration past the microphone. It is merely a coincidence in Figure 8 that the engine noise and tyre noise have nearly equal contributions – this is by no means generally the case. In case of coast-by a typical time history is shown in Figure 9. Each group in Figure 9 is an average of a large number of individual vehicles cruising-by and with measurements being made with the SPB method.

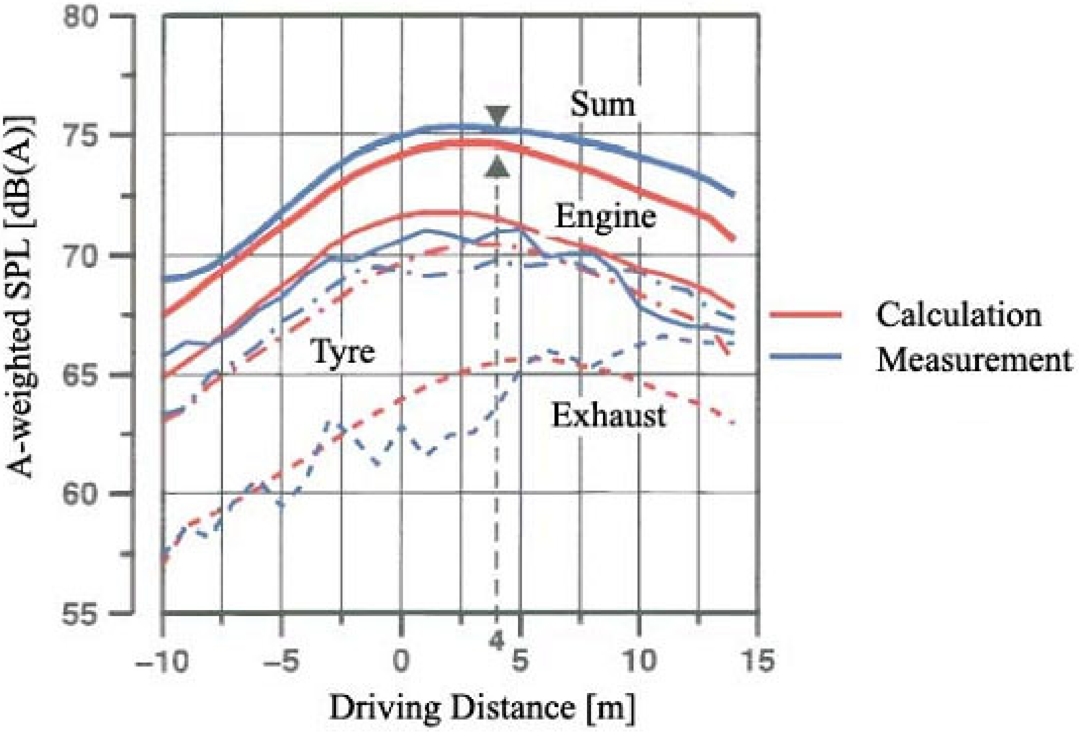


Figure 8: Comparison of Measurement and Calculation of Time Histories of an Accelerated Pass-By Measurement (Hofe et al., 1997)

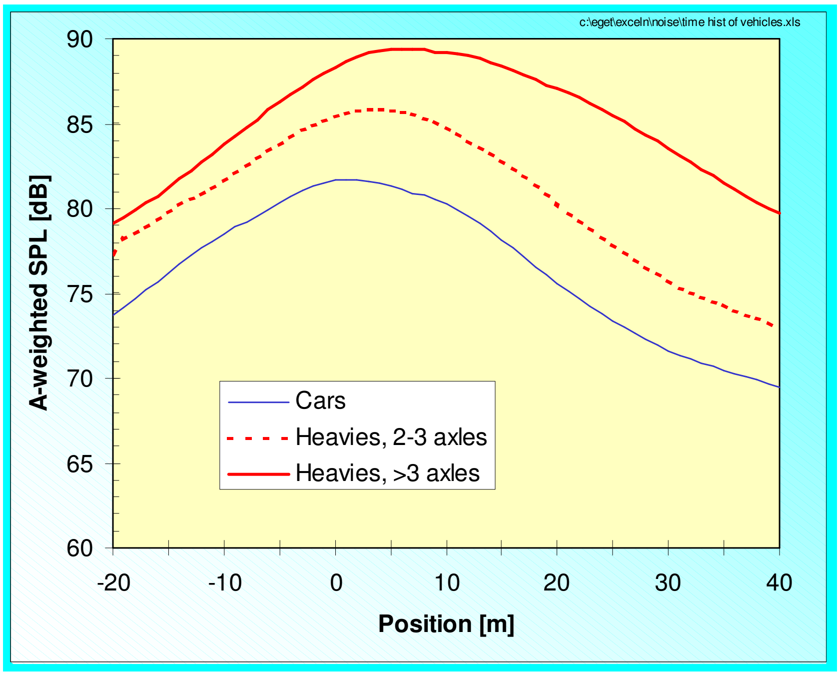


Figure 9: A-weighted Sound Level as a Function of the Vehicle Position During Cruise-By, for Three Different Groups of Vehicles (Sandberg & Ejsmont, 2002).

In general, noise emitted by a passing vehicle on the road is caused by many different factors, which could be divided into three main groups (see also Figure 10):

- Wind Turbulence Noise,
- Power Unit Noise and
- Tyre/Road Noise.

Wind Turbulence Noise could be defined as the noise emission due to turbulent airflow around and perhaps partly through the vehicle. This kind of noise emission is generally not an important factor for exterior vehicle noise (for low and moderate speeds). Power Unit Noise, the noise emission from the units of the vehicle that take part in the propulsion of the vehicle, includes noise from the engine, fan, exhaust and transmission system. The third group is related to the rolling of the tyres on the road surface, which was described in Section 3.2.

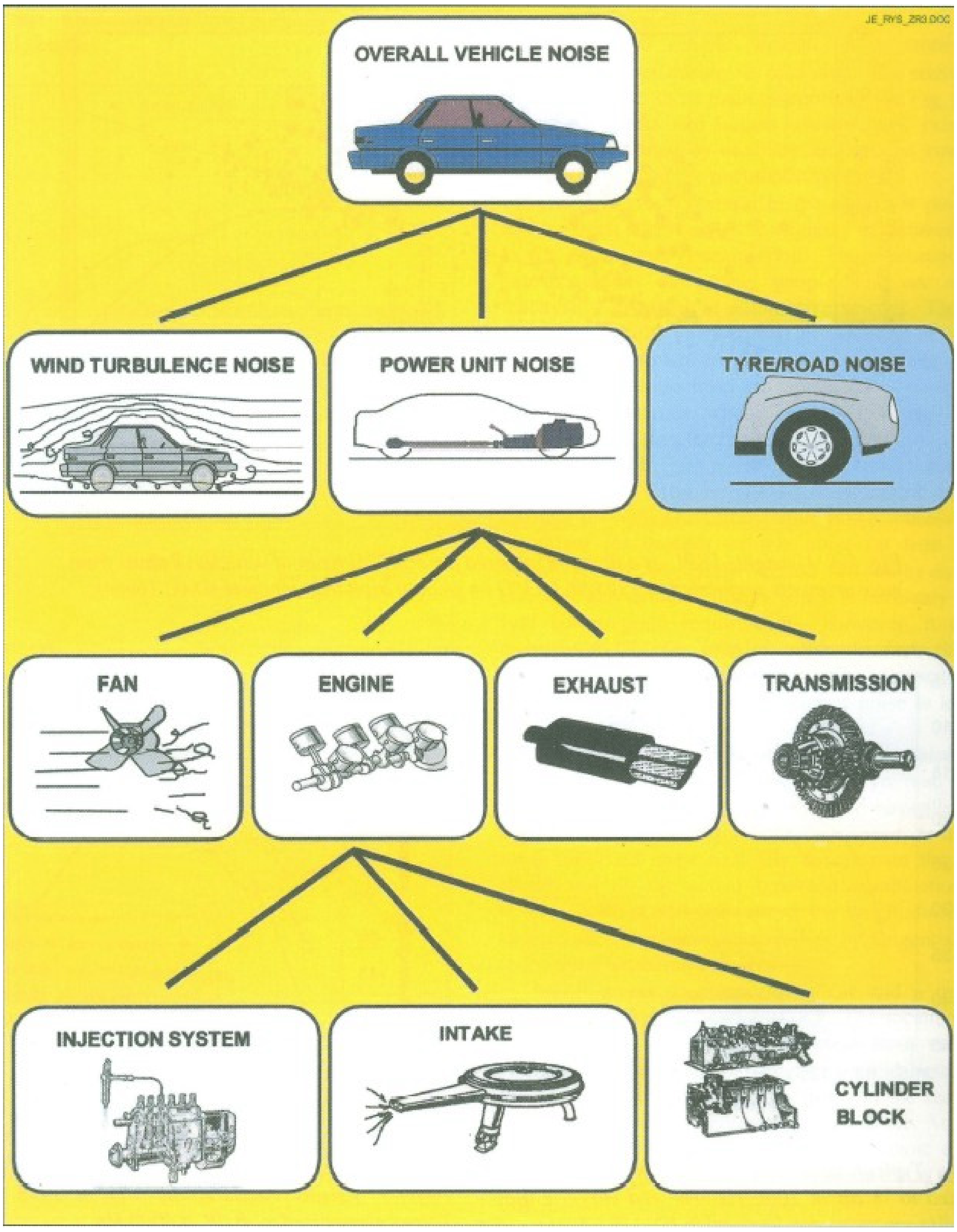


Figure 10: Noise Sources of a Passenger Car (Sandberg and Ejsmont, 2002)

The influence of the tyre/road noise on the overall noise emission of vehicles passing by increases with an increase of the driving speed. In urban regions with speed limits around 30-50 km/h the power unit of a vehicle is an important factor for driving noise, whereas at highway speeds it is mostly negligible.

Sandberg and Ejsmont (2002) give examples of noise reduction measures that have been applied so far. These are listed as follows.

Engine in general:

- Switchover to turbo-charged engines
- Optimisation of the engine combustion process
- Encapsulation or shielding of entire engines or especially parts of them
- Use of hood blankets or laminated covers
- Sound absorptive material in the engine compartment
- Optimisation of the stiffness of the cylinder block
- Use of structural-borne noise reducing material

Exhaust system:

- Minimization of outlet and mantle emission of exhaust silencers
- Introduction of more than one silencer
- Optimisation of pipes to or from silencer
- Dual-mode mufflers
- Use of absorptive materials
- Active noise control

Induction system:

- ¼-wave tuners or other resonators
- Thicker duct walls
- Increased volume of air cleaner
- Intake covers or shields
- Active noise control

Other vehicle components:

- Improvement of gearboxes, damped propeller shafts
- Improved rear axle transmission
- Shield of transmission components
- Regulation of the fan by thermostat
- Decreased speed of fan by using a larger fan or optimisation of fan shape
- Silencers for air compression outlet noise
- Improvements of brakes for reduction of break squeal
- Improved aerodynamics
- Selection of suitable tyres

The vehicle category can also have a substantial influence on the noise levels. In Vienna, Austria, SPB measurements according to the ISO standard ISO 11819-1 were performed on an urban road. These measurements were taken on a bituminous surface layer (DAC, maximum chipping size 11 mm). The typical difference in noise levels between passenger cars and heavy vehicles is demonstrated in Figure 11. As will be seen in later portions of this report, the differences in properties of passenger cars and heavy vehicles can mean that different methods need to be used for optimising the vehicle/tyre/road system for low noise from heavy vehicles vs. passenger cars.

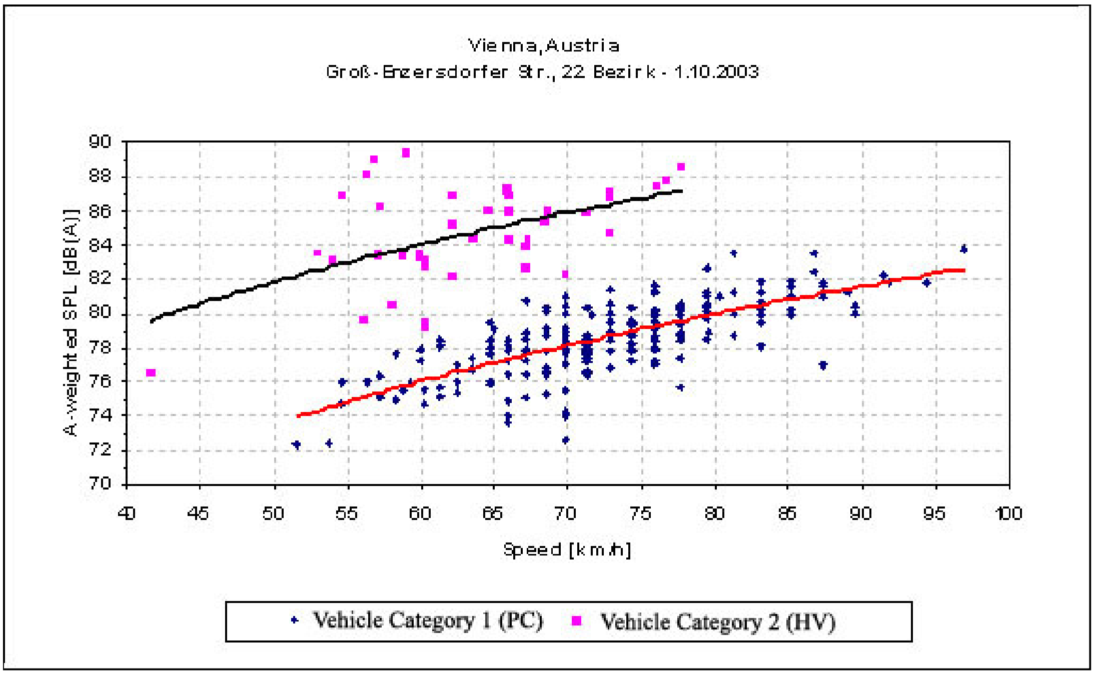


Figure 11: Maximum Noise Levels as a Function of Speed for Different Vehicle Types

3.4. Summary and Flow Diagram of Tyre and Vehicle Characteristics of Interest

Figure 12, below, gives a summary of the characteristics that affect vehicle/tyre/road noise. As can be seen from the figure, there are many parameters that need to be considered. In addition to the vehicle and tyre parameters discussed in Sections 3.2 and 3.3, the local conditions and the road surface also play an important role. In fact, as was mentioned for some parameters in Section 3.2, the properties of the road surface can lead to a completely different relationship between certain tyre parameters and traffic noise.

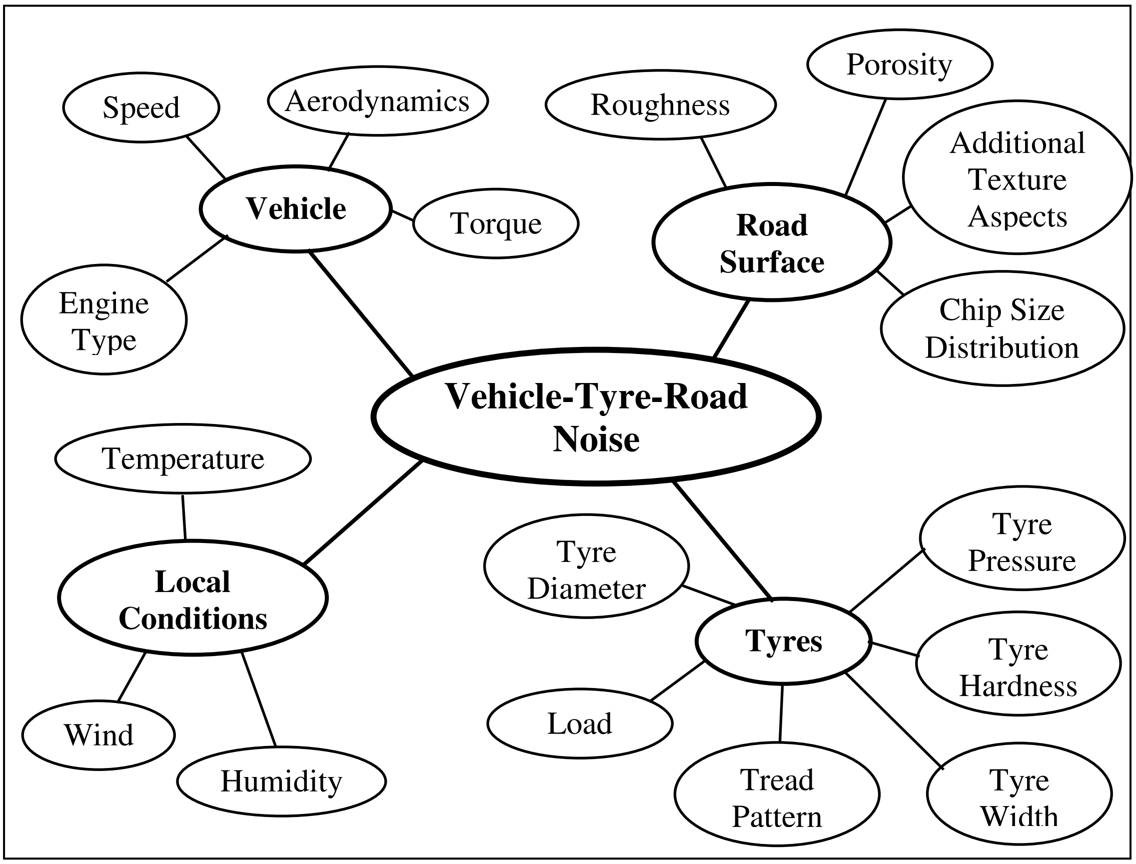


Figure 12: Influences of Tyre, Vehicle and Road Surface Properties on Traffic Noise (adapted from ASTRA, 2002)

3.5. Development of Hypotheses of Relations of Tyre and Vehicle Characteristics and Noise

3.5.1. General Remarks

Based on the results discussed in Sections 3.2 and 3.3, hypotheses are given here regarding the influences of various tyre and vehicle parameters and operating conditions on vehicle/tyre/road noise. These hypotheses will be tested with results from the SILVIA database, supplemented where necessary with experimental results available in literature. In addition to testing these hypotheses, the question as to the extent of influence of each of the parameters will be addressed as part of the analysis in Chapter 5.

3.5.2. Hypotheses Concerning Driving Conditions

- Acceleration will lead to an increase in noise levels, both for power unit noise and tyre/road noise (increased engine torque causing the power unit noise to increase, tyre slip and traction force causing an increase in tyre/road noise).

- Driving in a gradient will lead to an increased noise level versus an even road for a given speed, due to the increase in torque for driving on a positive slope, and due to possible braking noise on a negative slope.

3.5.3. Hypotheses Concerning Tyre Parameters

- A loaded vehicle will have a higher pass-by noise level than an unloaded vehicle (thus, increasing the load on tyres will lead to higher noise levels).

- Increasing the tyre pressure will possibly yield decreased noise levels due to the reduced contact area of the tyre and road surface.

- Increasing the tyre width will lead to an increase in noise levels.

- Increasing the tyre diameter will lead to an increase in noise levels for a smooth surface, and a decrease for a rough surface, due to the counteracting influences of tyre diameter on the horn effect and on the tyre tread impact.

- Variations in the tyre material properties, such as rubber hardness, will impact the noise levels. Increasing the tyre tread stiffness will lead to a reduction in noise due to reduced vibrations caused by reduced rubber deformation.

- Changes in the tread pattern can have a substantial effect on tyre/road noise levels, but depends on the type of road surface.

4. Vehicle/Tyre/Road Noise Database

4.1. Introduction

A database was created bringing together results of noise tests from the partners involved in SILVIA WP5. The database includes reports and results of experiments related to the combination of low noise road surfaces with other noise abatement measures. This chapter will briefly outline the structure of the database to be used in the analysis work described in Chapter 5. The database structure was described in further detail in SILVIA Deliverable D04: Report on Database Structure for Other Noise Abatement Measures. Because this database has been used in the analysis process for the current report, an overview of the database and the datasets that comprise it is given here.

4.2. Overview of the Database Structure and Functionality

The database itself is basically a storage and indexing system, designed to allow information to be stored with varied levels of detail. The goal of the database is to optimise the storage space of the results, and to store them in a coherent and consistent manner allowing for easy search and retrieval.

The database system optimises storage space in several ways. For one, the indexing system is set up such that when several sets of tests are performed on, for example, the same road surface, the road surface information is entered only once and an identification number is assigned to information on this particular road surface. For each set of tests using this road surface, the identification number for the road surface information is given so that all the road surface details do not have to be entered for each recorded test result. This same indexing technique also applies to local test conditions, vehicle information (if, for example the same vehicle is used for several sets of tests), measurement or modelling techniques, etc.

Microsoft ACCESS 2000 ™ has been used in compiling the database for the SILVIA project. Microsoft ACCESS 2000 ™ was chosen for several reasons, including the ubiquity of the software (bundled with MS Office), the compatibility with other Office applications, and the capability to use a separate programming language for accessing/interfacing the database.

Figure 13 lists the categories of information stored in the SILVIA database. The categories of information fall into two general groups: test parameters and test results. These two groups of categories are shown in the following figure.

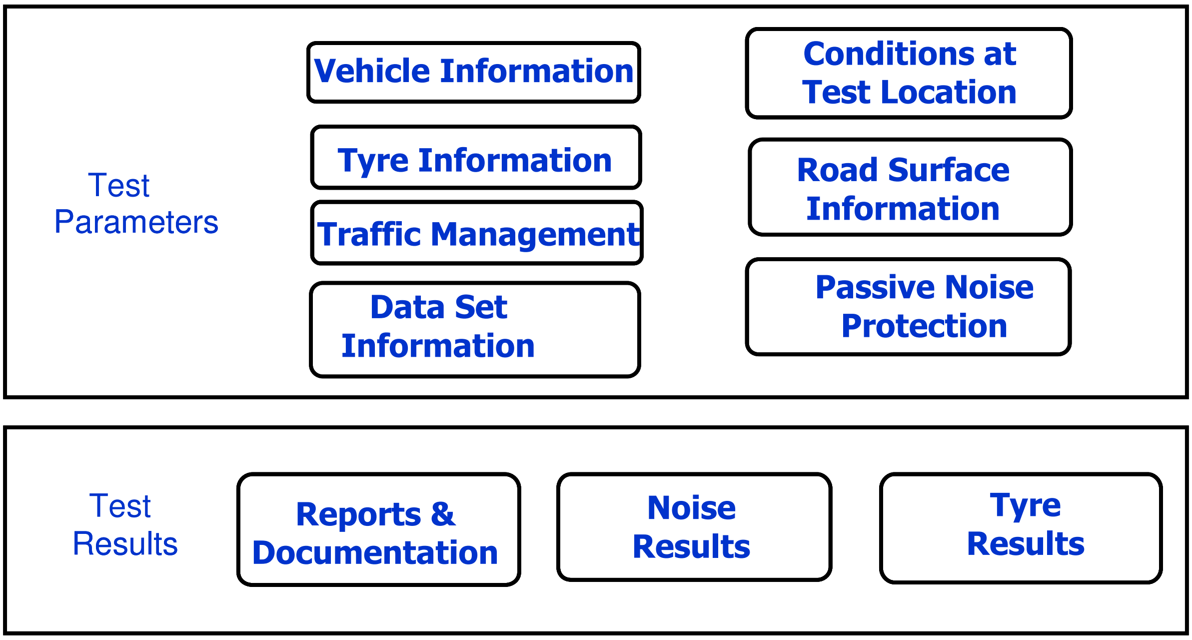


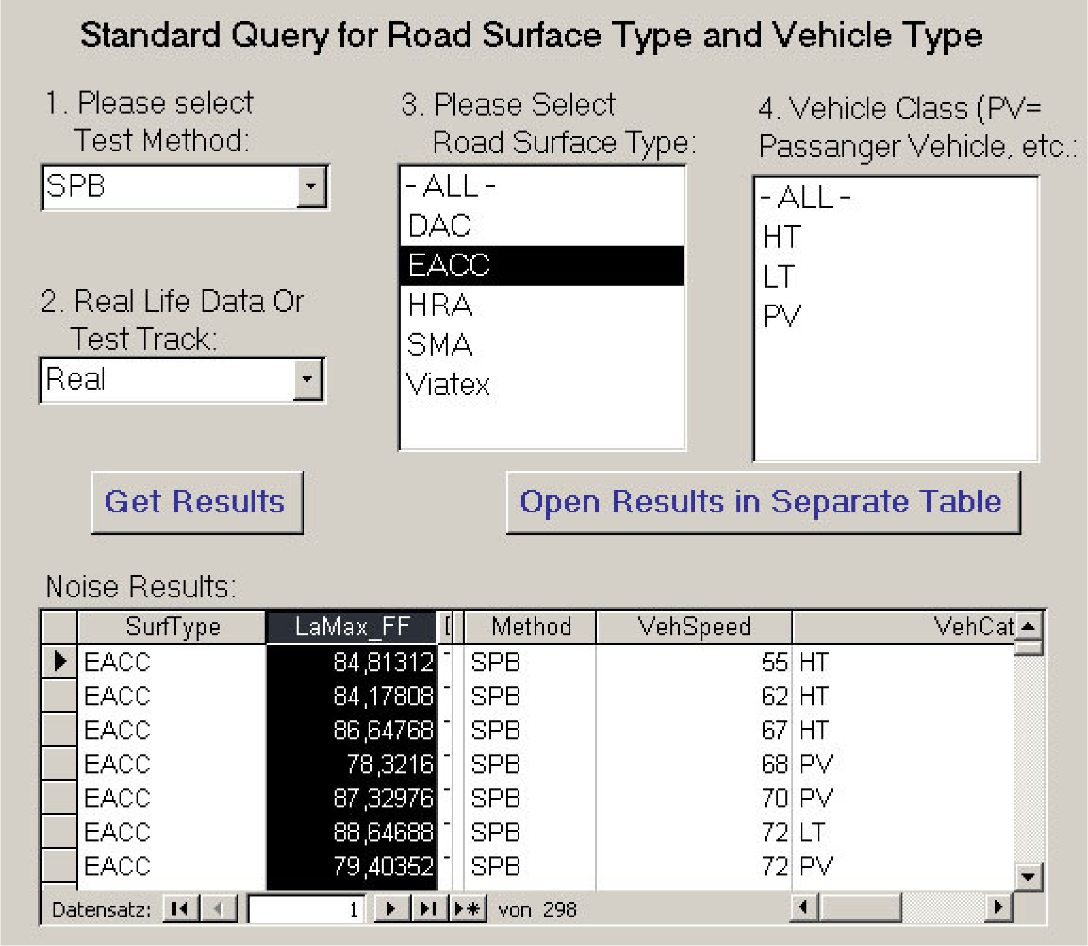
Figure 13: Database Categories

Test parameters in the database would include all relevant parameters for the experiment or simulation. The test results would include the noise measurements or simulation results, both A-weighted and frequency-dependent, where applicable.

Appendix A provides tables giving each of the parameters included in the database and descriptions of each of these parameters. The results to be included in the database will consist of reports and existing data from experiments and simulations. As can be seen in Appendix A, the list of parameters included is very detailed. It should be noted that when a researcher is filling in his results in the database, it is not expected that he have information for each available field. The number of fields was intentionally made large so that for very thorough datasets, all of the gathered information can be stored.

Data retrieval can be performed within MS ACCESS 2000 ™ using the “Query” function. This function takes you through steps where you select the fields of interest from the database categories.

Figure 14 gives the dialogue window the user would see when employing one of the standard queries designed as part of the SILVIA database. The shown query is designed for extracting data when the user is interested in the road surface and vehicle type, as well as whether the desired results should be from real traffic or from a test track. The query gives the option of multi-select for several of the parameters, and the user must always select the test method, so that it is not possible to unknowingly compare results from different measurement methods. After the user selects the parameters he seeks, the resulting data is displayed in the window. These results can also be displayed in a separate window.



Standard Query for Road Surface Type and Vehicle Type

1. Please select Test Method: SPB

2. Real Life Data Or Test Track: Real

3. Please Select Road Surface Type:
- - ALL -
- DAC
- EACC
- HRA
- SMA
- Viatex

4. Vehicle Class (PV= Passanger Vehicle, etc.:
- - ALL -
- HT
- LT
- PV

Noise Results:

SurfType	LaMax_FF	[	Method	VehSpeed	VehCat
EACC	84,81312		SPB	55	HT
EACC	84,17808		SPB	62	HT
EACC	86,64768		SPB	67	HT
EACC	78,3216		SPB	68	PV
EACC	87,32976		SPB	70	PV
EACC	88,64688		SPB	72	LT
EACC	79,40352		SPB	72	PV

Figure 14: Selection of Categories in Example of a Simple Query for Data Retrieval

It is important to note that in comparing different sets of results, the test method must be selected as one of the search criteria. Otherwise, one could be comparing, for example, near-field measurements obtained from trailers (CPX method, ISO/CD 11819-2) with results of SPB measurements. This type of comparison would lead to misleading and incorrect conclusions. Thus, all standard queries included in the database are designed such that the test method is already selected as one of the search criteria, and the user can add other fields of interest.

After having specified the parameters to be studied and the details of the analysis, the user can save the query. Then, one can later make slight modifications to the query, such as adding or removing one or more fields, rather than starting over.

The user can also design a separate query using the query wizard in MS ACCESS TM. The query function of MS ACCESS TM makes it simple to extract specific results from the SILVIA database. The query function is useful for simple analysis operations, or for extracting sub-sets of data matching certain criteria. These extracted data can then be analysed in a different data processing application such as MS EXCEL TM where more detailed analyses can be performed.

Alternatively, one can simply use an external program application to retrieve the data from the MS ACCESS TM database and perform the analysis. MS ACCESS TM is designed to be compatible with many types of software applications. The user can write a program in the language of their choice to retrieve data from the database and perform analyses on these results. Thus, more complex analysis can be performed either by using a data processing application on extracted results, or by writing a program to interface with the database that will perform both the data retrieval and data analysis steps.

4.3. Description of Data Sets Used in the Analysis

4.3.1. General Remarks

In preparing the structure of the SILVIA database, we have examined several databases held by contributing partners, not only to ensure that the database structure would be adequate to store all of these datasets, but additionally to review the advantages of the structures used in compiling these databases by the individual partners. At present five traffic noise databases that are included in the SILVIA database have been examined. These databases have been received from INRETS, TRL, the Vienna University of Technology (TUW), LCPC and from the Bundesanstalt für Strassenwesen (BASt) in a joint project with M+P and Müller-BBM. Some details about each of these datasets are given below, along with some of the aspects of their individual database structures that were noted when designing the SILVIA database structure.

4.3.2. BASt/M+P/Müller-BBM Dataset

The BASt/M+P/Müller-BBM dataset was collected as part of a research project initiated by the Federal Highway Research Institute of Germany (Bundesanstalt für Strassenwesen (BASt)) by order of the Federal Ministry of Transport (Beckenbauer et al., 2001).

The measurements were collected with the goals of developing:

- An acoustic model that quantitatively describes the effect of the surface texture on tyre/road noise.
- Strategies for the design of textures for low noise road surfaces.

A range of surfaces with specifically constructed textures that are suitable to excite or suppress specific mechanisms in a very controlled way were laid down and measured in terms of acoustic and texture parameters in order to accomplish these goals.

The surfaces were constructed at an out-of-use airfield in Sperenberg (in the federal state of Brandenburg, Germany). The site was chosen because of the free terrain and the absence of interfering noise. The test location is shown in Figure 15.

Figure 15: Test Site Location for BASt/M+P/Müller-BBM Dataset

Figures 16 and 17 show the test set-up for the BASt/M+P/Müller-BBM dataset, including the surface types.

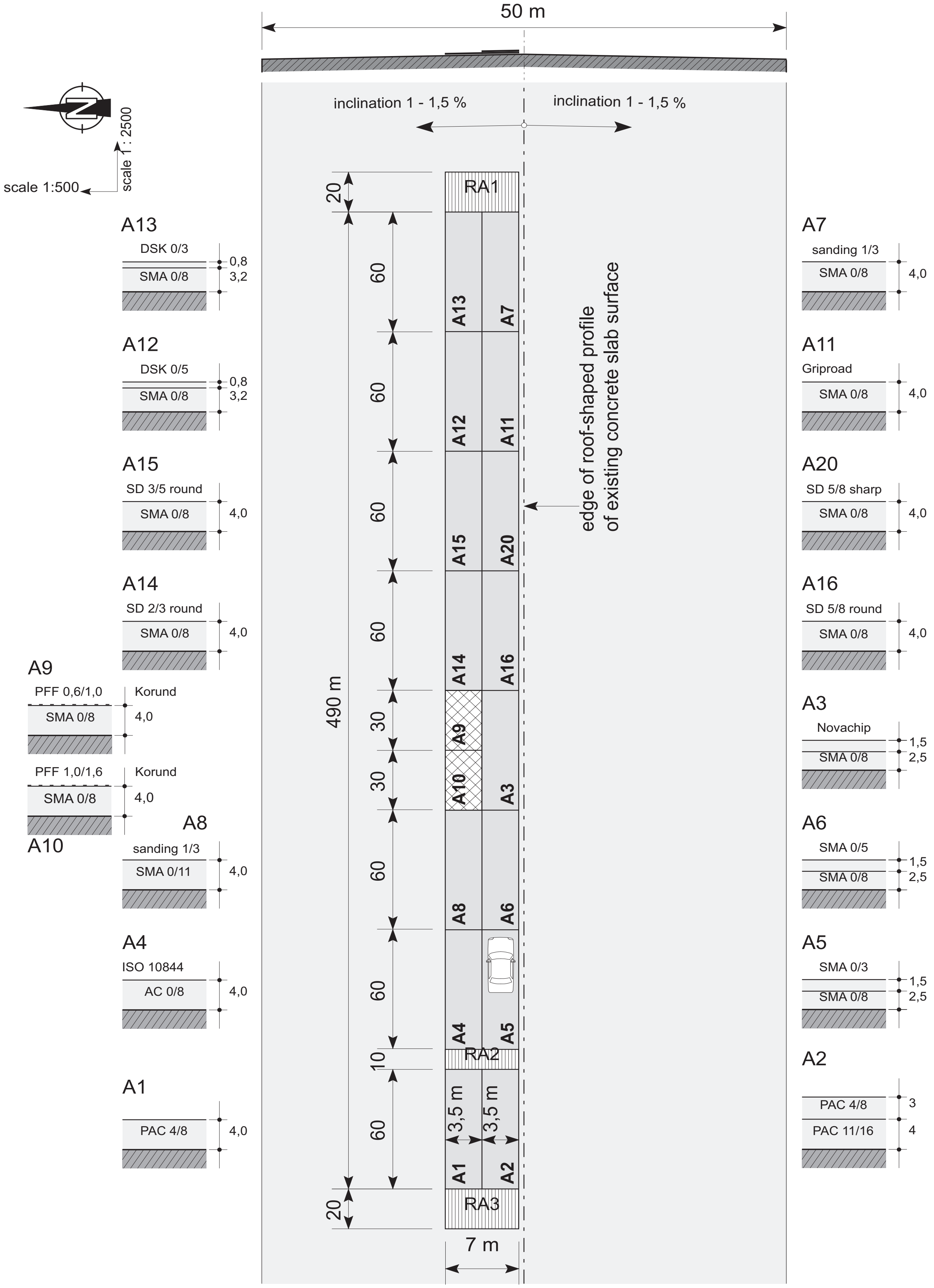


Figure 16: Partial Schematic of Test Layout for the BASt/M+P/Müller-BBM Dataset Showing the (Standard) Asphalt Surfaces

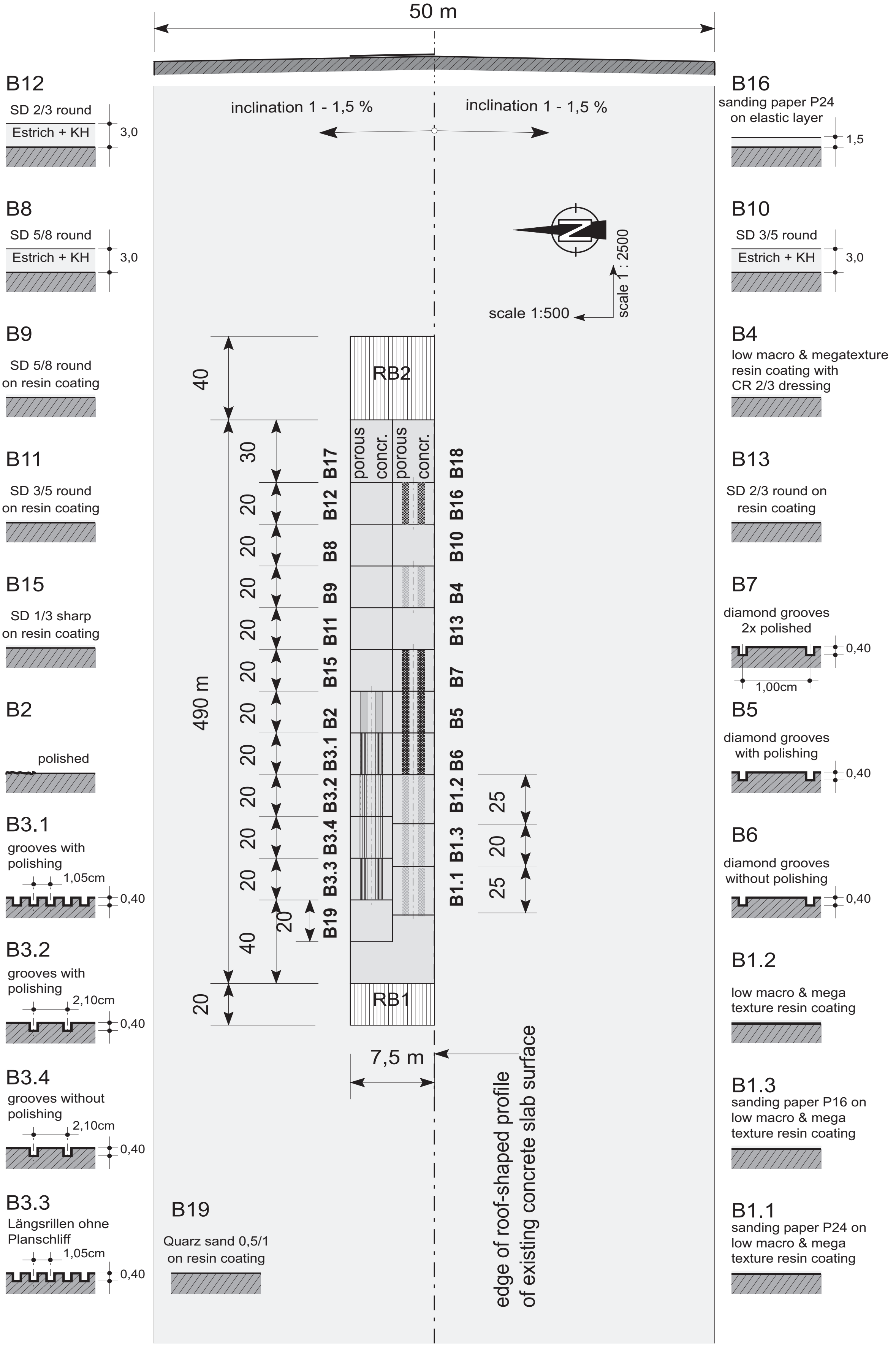


Figure 17: Partial Schematic of Test Layout for the BASt/M+P/Müller-BBM Dataset Showing (Standard and Additional Experimental) Concrete Surfaces

The surface parameters that were studied in the experiments are given in Table 3.

Table 3: Surface Parameters Studied in the BASt/M+P/Müller-BBM Dataset

Macro- and Megatexture	Texture wavelength in the range of 5 to 300 mm
Shape Factor of the Aggregate	Different spectra result from sharp and round particles of comparable size
Texture Orientation	Whether the orientation of the texture is positive or negative would cause the same wavelength spectrum, but would likely excite different tyre/road noise
Regularity of the Texture	Stochastic and deterministic texture patterns can lead to different characteristic noise
Directionality of the Texture	Surface texture directionality can be caused by certain methods of laying the surface, and may affect the noise production
Megatexture of the Subsurface	Underlaying surface texture irregularities may influence the finished textures of thin top layers
Surface Porosity	Air pumping noise is suppressed due to porosity because of the equalization of air pressure differences in the contact patch and additional acoustic properties irrespective of the texture
Acoustic Impedance of Porous Surface	Shape, coating and arrangement of concatenating voids in porous surface layers influence the sound absorption properties

The acoustic properties of the road surfaces are investigated with full-size vehicles. Vehicle pass-by measurements were made, in addition to trailer measurements.

The far field noise was obtained during coast-by measurements where 2 microphones were mounted at a distance of 7,5 m and a height of 1,2 m above ground on each side of the moving vehicles with the engine switched off. The maximum sound pressure levels L_{AFmax} and the single event levels (SEL) together with their spectral content were recorded.

Near field noise was measured using a trailer where 2 microphones were mounted in close proximity to the rolling tyres. The measurements were taken from tyres located within a sound absorbing box that is towed by a car with a silent motor. The equivalent sound pressure levels L_{AFeq} of the passages of single test surfaces were recorded. The set-up was based on the German measurement standard.

4.3.3. French Database

The French database addresses the acoustic emission of transport vehicles. It contains datasets from INRETS and LCPC. The data was collected in order to update previous values contained in the French “Guide du Bruit des Transports Terrestres”. The dataset consists of both near-field noise measurements using the CPB method, and far-field noise measurements using the SPB method (ISO 11819-1, 1997). This database contains a thorough set of standardised data: over 13 000 SPB measurements from heavy-duty and light-duty vehicles, and over 3000 CPB measurements. In addition to this thorough set of standardized data, the INRETS database also contains data focussed on specific problems. Pass-by measurements are included on uphill and downhill sections of road in order to assess the influence of the road gradient on noise levels. The dataset also includes measurements performed on a roundabout, pass-by measurements of vehicles under various acceleration and deceleration conditions, and noise measurements of heavy-duty trucks under various load conditions.

Figure 18: Noise Emission Measurement on the INRETS Test Tracks (Lelong et al., 1999)

The road surfaces included in the INRETS dataset are: Very Thin Bituminous Surfacing, Ultra Thin Bituminous Surfacing, Porous Asphalt Concrete and Dense Asphalt Concrete (Bar and Delanne, 1993). Several different tyre designs were used for comparison, with details of the individual tyre types given in the dataset. Direct measurements of the speed and acceleration of the vehicle, engine speed, were also taken. Table 4 summarizes the details of the data included in the INRETS dataset.

The INRETS database was stored in MS ACCESS^{TM}. The structure of the INRETS database consisted of three main tables. The first of these tables, labelled “Vehicles”, contains a description of the vehicle used for the relevant test. The second table is “Site of Measurement”, and gives information describing the measurement environment (location name, road number, nature of the road surface, grading, etc.). The third main table of the INRETS database is titled “Results”, and contains the measured parameters for each vehicle passing (kinematics, mechanical parameters and acoustical data). The INRETS database is used with a database interaction program that was written in a different programming language. Thus the MS ACCESS^{TM} program serves only as the storage and indexing system, while the data retrieval and analysis is performed separately.

Table 4: Summary of INRETS Dataset

Standardised Measurements	SPB Method (13 000 LV and HV Measurements) CPB Method (3000 Measurements)
Problem-Specific Data	Effect of Gradient Noise at Roundabouts Noise Under Accelerating/Decelerating Conditions Effect of Load for Heavy Duty Vehicles
Road Surfaces	Very Thin Bituminous Surfacing Ultra Thin Bituminous Surfacing Porous Asphalt Concrete Dense Asphalt Concrete
Tyre Specifications	Several Types of Tyres Used, Details Given in Dataset
Other Direct Measurements	Vehicle Speed and Acceleration/Deceleration Engine Speed (for a Few Vehicles – Usually Deduced from Gear Box Characteristics and Tyre Dimensions)

The general dataset from INRETS includes measurements designed to examine the influence of different power unit systems on traffic noise under various driving conditions. The method which was developed and used consists of reproducing the different kinematics on an asphalt concrete test track for the selected vehicles (see Figure 18). An appropriate measurement procedure has been defined especially for cases of transient conditions (acceleration/deceleration). This procedure is based on synchronised acquisition of the signals corresponding to the different measured parameters. Figure 19 shows the experimental set-up.

Three categories of parameters are measured :

- **Kinematics data** : Instantaneous speed and acceleration are measured using 5 emitting/receiving infrared-cells. A 10 meter interval separates two consecutive cells.[1]
- **Mechanical parameters** : The operator notes the engaged gear. In the case of Diesel-motorised cars, the engine speed has been also recorded.[2]
- **Acoustic data** : Three microphones are located in the acoustic field close to the track (7,50 m from the road axis and 1,20 m above the ground). A 10 meter interval separates two consecutive microphones. The maximum A-weighted sound pressure levels with fast-response time-weighting characteristics (LA_{max}) and the acoustic time-history (time-weighting: 30 ms) are recorded.

For each vehicle, the measurements carried out are as follows :

- **Pass-by (constant speed)**[3] : Ten vehicle pass-bys were recorded in neutral and for each engaged gear (1 to 5).
- **Acceleration**: For each engaged gear, 10 vehicle accelerated pass-bys were recorded. The amplitudes of the acceleration were chosen by the driver so as to reproduce driving behaviour situations. Extreme operating conditions as driving with the throttle full open (situation described by the ISO 362 homologation standard) are also considered.

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[1] The signal delivered by the cells located at the extremities is used for triggering the multi-channel acquisition system.

[2] This parameter is not used in the separate study on driving conditions.

[3] Making these measurements ensures credible comparisons with the accelerated pass-by measurements achieved the same day (thus with the same meteorological conditions).

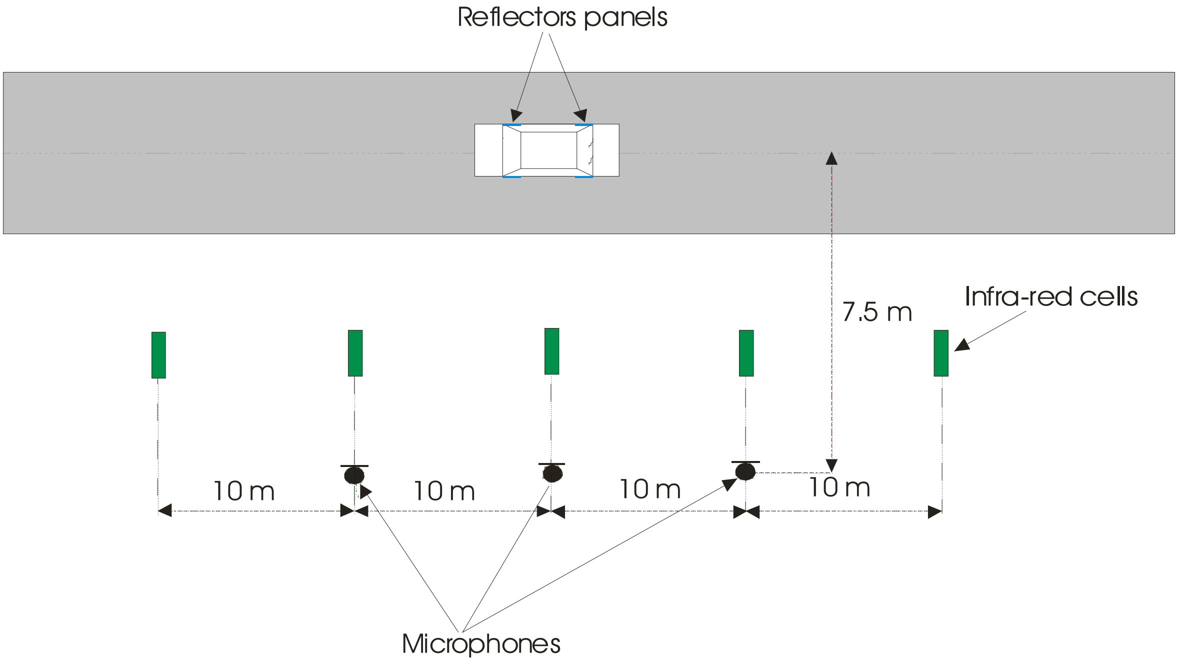


Figure 19: Experimental Set-up for the Study of Effect of Operating Conditions on Noise Levels by INRETS

4.3.4. TRL Dataset

Transport Research Laboratories, TRL, has provided results of measurements that they performed as part of the research project HARMONOISE. This dataset includes statistical pass-by noise measurements from passenger vehicles as well as light-duty and heavy-duty trucks. The data provided by TRL consists of over 25 000 individual pass-by measurements, covering a time span from 1993 to 2000. These measurements were taken on real, in-use road surfaces, and the surface types included Hot Rolled Asphalt, Exposed Aggregate Cement Concrete, Stone Mastic Asphalt, Porous Asphalt Concrete and Thin Bituminous Surfacing, as well as some other experimental surface types. The measurements all followed the standardized SPB method, according to ISO 11819-1 (1997). In addition to the noise measurements, TRL has provided surface texture depth measurements for many of the recorded datasets. Spectral data has been included in the range from 25 Hz to 8000 Hz.

In addition to the extensive data that will be very valuable in the later stages of WP5, in the analysis of the results, the TRL data has also been examined to ensure that the SILVIA database contains all the relevant fields for this type of database, so that no vital information is lost in converting the dataset into the SILVIA database structure.

4.3.5. TUW Dataset

The Institute for Internal Combustion Engines and Automotive Engineering and the Institute for Road Construction and Maintenance of the Vienna University of Technology (TUW), has contributed an extensive set of vehicle noise measurements. These data were collected as part of the Austrian “Low Noise Road” research umbrella (Pucher, 1998). The goals of this research were (Schwarz, 1998):

- The development and production of the test road track.

- The experimental determination of the quietest combination between of vehicle, tyre and road surface according to the state of the art on the basis of reference vehicles and reference tyres.
- The determination of the achievable outside noise level with trial tyres and reference vehicles, and with reference tyres and low-noise passenger car and truck prototypes.
- The modification of the tyres and vehicles based on the obtained results, followed by repeated measurements.
- The combination of all measures concerning vehicles, tyres and road surfaces with the objective of achieving the halving of the noise pollution followed by the initiation of a concrete implementation of the results.

The TUW data includes statistical pass-by measurements taken under varying conditions of acceleration and vehicle load for heavy vehicles and passenger cars. The road surfaces in this database include Porous Asphalt Concrete, Stone Mastic Asphalt, Thin Bituminous Surfacing, Exposed Aggregate Cement Concrete, Surface Treated Concrete and an ISO surface for comparison (Pucher, 1998). The testing was performed at the test ground~~s~~ of Semperit Reifen AG. The test track is shown in Figure 20 (Pucher, 1998, Schwarz, 1998).

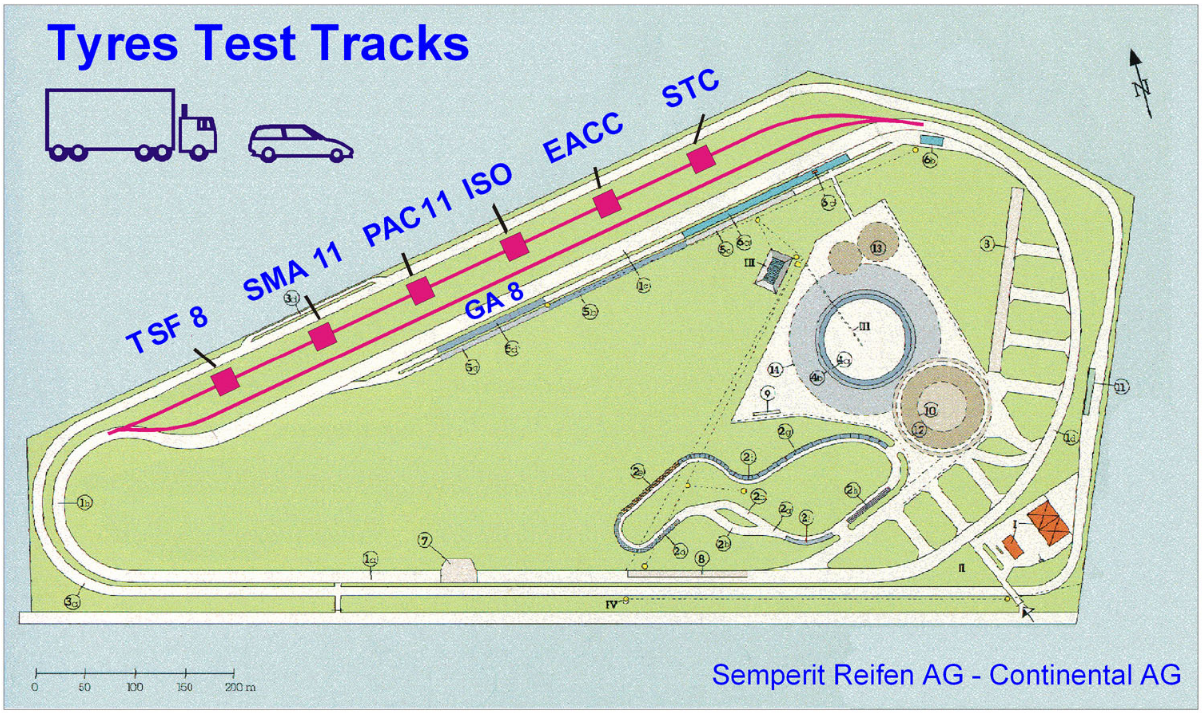


Figure 20: Test Grounds for TUW Dataset, TSF (Thin Bituminous Surfacing), SMA (Stone Mastic Asphalt), PAC (Porous Asphalt Concrete), EACC (Exposed Aggregate Cement Concrete) and STC (Surface Treated Concrete), (Pucher, 1998, Schwarz, 1998)

Tyre parameters studied include tyre tread mixture, tyre tread basic mixture, nylon position, belt angle, belt division, sidewall thickness, core profile height, high impact of carcass, layer number of carcass and profile design.

The TUW database was stored in individual files, so that while quite extensive the data retrieval and analysis was not optimised. A benefit of the SILVIA database is that this extensive dataset will be converted to a more accessible structure, and that it will be available for analysis in the project.

5. Analysis Based on SILVIA Database Content

5.1. Introduction

This chapter will discuss the analysis of vehicle/tyre/road noise data available from partners in the SILVIA project. As mentioned in Chapter 2, the analysis is based on data available in the SILVIA database as described in Chapter 4, with supplementary results from relevant literature. The influence of operating conditions is examined first, including the influence of slip and traction noise. This is followed by the analysis of tyre properties and discussion of the spread in noise level of various tyres on the market. Next, the noise spread among different road surfaces is discussed. Finally the results of these analyses are summarised.

5.2. Effect of Typical and Extreme Operating Conditions on Noise Levels

5.2.1. General Remarks

The driving conditions can strongly influence the level of pass-by noise for a vehicle. This issue is addressed in the current section. First, the influence of acceleration will be analysed in comparison with constant driving. Acceleration is analysed from 3 sources: experimental results from INRETS and LCPC, and modelling results from TUG. This is followed by a discussion of the influence on noise of special conditions such as driving in a gradient or a curve. Then the topic of the influence of slip and traction force on noise is addressed.

5.2.2. Acceleration vs. Coasting and Cruising, Experimental

A vehicle under accelerating conditions will generally have increased noise at a given speed compared to a vehicle driving at a constant speed. This change in noise level will be partly due to the increased vehicle power unit noise, and partly to increased tyre/road noise caused by traction forces and tyre slip. This topic was studied separately by INRETS which tested 12 vehicles (see Table 5) selected in order to scan various power unit types, i.e. types of motorization. Measurements were made in CPB conditions.

Table 5: Main Specifications of the Selected Vehicles

PC[a]	Power Unit Type	km	Cyl. (l)	Tyre	PC[a]	Power Unit Type	km	Cyl. (l)	Tyre
A	Hybrid	--	--	165/65 R15	**G**	Gas	38000 km	1,171	155/70 R13
B	Gas	1400 km	1,998	195/60 R15	**H**	Gas	81300 km	1,564	155/70 R13
C	Gas	23200 km	1,998	195/55 R15	**I**	Diesel	21400 km	1,900	205/60 R15
D	Gas	32400 km	1,170	155/70 R13	**J**	Gas	7600 km	1,171	165/65 R14
E	Diesel	16800 km	2,100	185/65 R15	**K**	Electric	18200 km	--	155/70 R13
F	Gas	41000 km	1,391	165/65 R13	**L**	Diesel	26100 km	1,5	165/70 R13

[a]PC here designates Passenger Car

In the case of constant speed for each given configuration (vehicle/engaged gear) linear regressions have been calculated on the common range of speed (see Figure 21). The retained maximum and minimum levels of emitted noise are defined as follows:

$$L^r_{\min} = \min\left[A_{r,i} + B_{r,i}\log\left(v/v_{ref}\right)\right] \qquad L^r_{\max} = \max\left[A_{r,i} + B_{r,i}\log\left(v/v_{ref}\right)\right]$$

The constant speed results are given in Figure 21, looking at the noise levels from various vehicles on a Dense Asphalt Concrete.

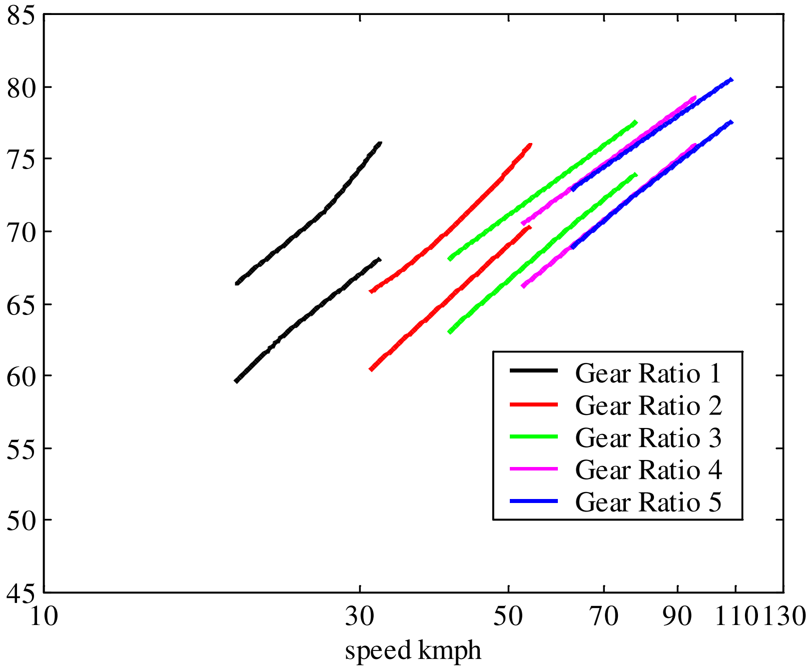


Figure 21: Effect of the Driven Gear by Driving from INRETS Data With Constant Speed on Dense Asphalt Concrete (Lelong, 1999)

In the case of acceleration for each given configuration [vehicle/engaged gear], the measured acceleration values are distributed by steps of 0,5ms^{-2} [$0<\gamma<0{,}5$ms^{-2} : γ_{min} = 0,5ms^{-2}; ….; $0{,}5.(k_{max}-1)<\gamma<0{,}5.k_{max}$: γ_{max} = $0{,}5.k_{max}$m.s^{-2}]. Linear or quadratic regression is calculated for each acceleration step. Maximum and minimum levels of noise are given by (Besnard et al., 1999):

$$L^r_{\min}(v) = \min\left[L^r_i(v, \gamma_{\min})\right] \qquad L_{\max} = \max\left[L^r_i(v, \gamma_{\max})\right]$$

The acceleration mainly affects the "mechanical" component of emitted noise, masked by the noise of tyre/pavement contact for passenger cars travelling at high speed. The effect of acceleration can reach 4 dB when 1st or 2nd gear is engaged. Figure 22 gives results similar to those shown in Figure 21, except for vehicles driving under accelerating conditions.

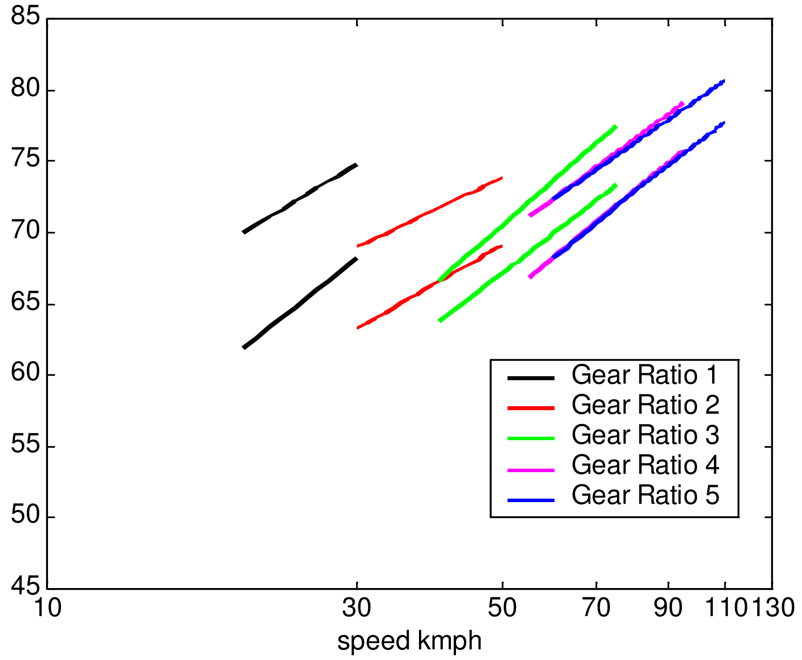


Figure 22: Effect of the Driven Gear by Accelerating from INRETS Data on Dense Asphalt Concrete (Lelong et al., 1999)

From a comparison of the data used in Figures 21 and 22, the effect of acceleration on the noise level over various speeds and in various gears can be obtained. Figure 23 is a result based on analyses of these data, looking at the noise levels from various vehicles under accelerating versus constant driving conditions on a Dense Asphalt Concrete. As can be seen in Figure 23, the sound level difference between the accelerating and non-accelerating measurements is approximately 1,5 dB(A).

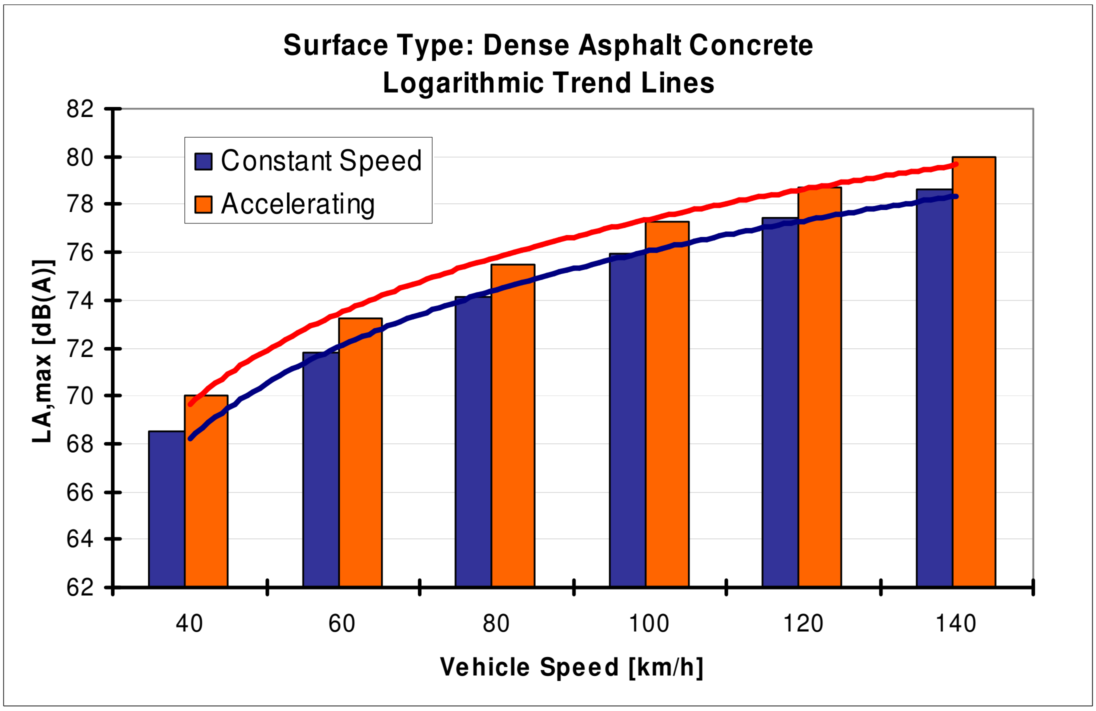


Figure 23: Comparison of Constant Speed Driving and Accelerating of INRETS Data on DAC - Various Vehicles (from data used for Figures 21 and 22)

Figure 24 shows SPB results for driving under accelerating and constant conditions, on Porous Asphalt Concrete (PAC) and a type of Thin Bituminous Surfacing (TSF) from the LCPC dataset. By looking at these results, one can see that the effect of the accelerating condition on the noise level also depends on the road surface. From these results, several interesting points emerge. First, it can be seen that the influence of speed on the difference between the constant driving and accelerating noise levels changes with road surface. At a nominal speed of 60 km/h, the difference in noise level between the accelerating and constant driving conditions ranges from 0,5 to 1,5 dB(A). In addition, it can be seen from Figure 24 that the difference in noise level due to accelerating is more pronounced at both at lower speeds (at and below 40 km/h) and at higher speeds (over 100 km/h) than at the nominal speed of 60 km/h for both surfaces. The higher influence of acceleration at the relatively low speeds is fairly straightforward, as the tyre noise contribution would be low here. The higher influence at the speeds at and above 100 m/h may be due to a higher vehicle torque necessary for accelerations at these high speeds.

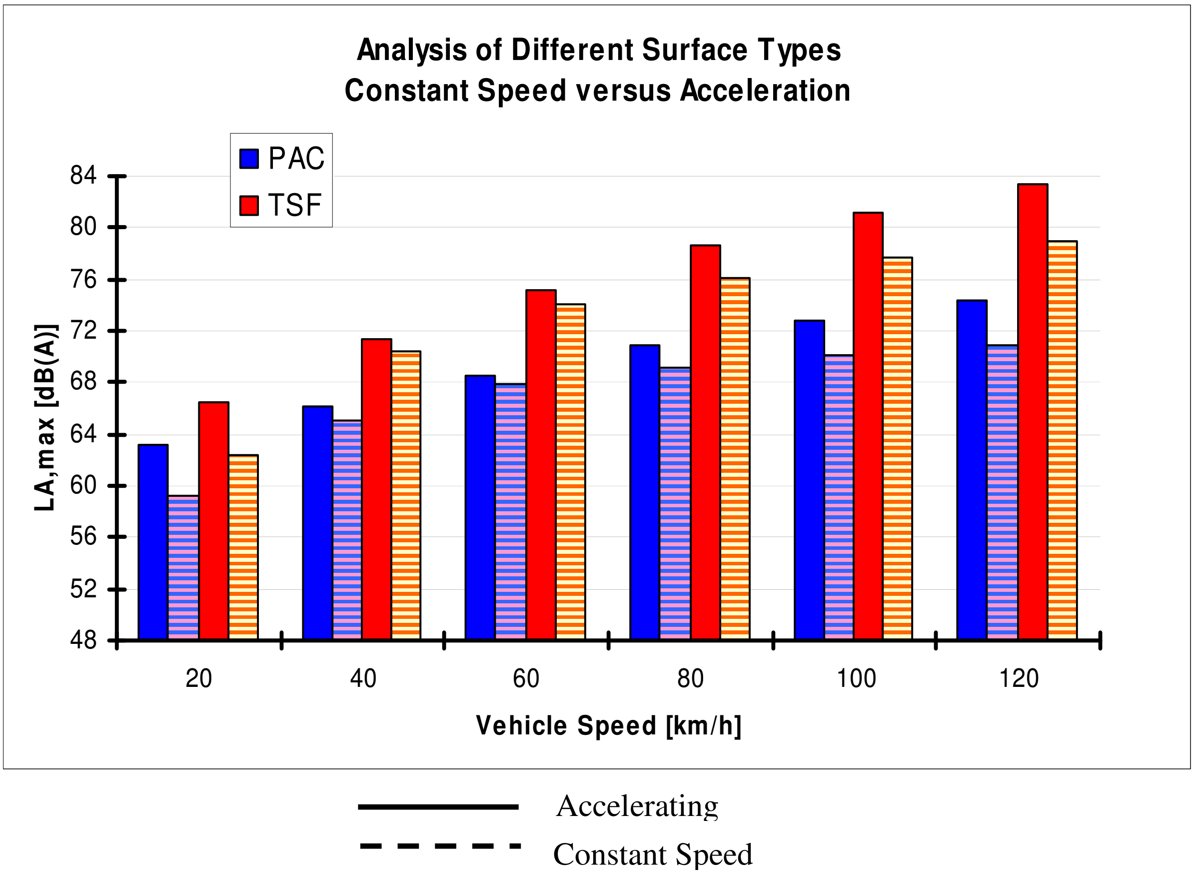


Figure 24: Analysis of Constant Speed Driving versus Accelerating of LCPC SPB Data on PAC and TSF – Various Vehicles (as Noted in Legend, Solid Bars are for Accelerating Conditions, Striped Bars for Constant Speed)

In summary, based on these results from the LCPC and INRETS datasets, the influence of accelerating on noise level is dependent on both the speed and the road surface, and can range from 0,5 to over 3 dB(A) (the higher values coming from results at speeds below 40 km/h and over 100 km/h).

5.2.3. Acceleration vs. Coasting or Cruising, Simulations

This section contains results of computer simulations of noise in different driving conditions prepared for 7 cars and 1 motorcycle. The simulation was based on the VENOM model developed by TUG and VTI. The model is based on actual measurements on a test track and may be used to simulate overall noise level at the distance of 7,5 m from the centre of the vehicle in the perpendicular direction for any driving conditions including coasting, cruising, acceleration, deceleration and braking. In most of the conditions the model has a precision of about 0,2-0,3 dB(A).

Description of the "VENOM" Model

The VENOM model is based on measurements on a test track of vehicle noise performed for many different driving conditions. The results were analysed and transformed to the equations that describe influence of speed, acceleration/deceleration and gear on overall vehicle noise for 7 cars and 1 motorcycle.

The vehicle noise tests were conducted on the Mantorp racing car test track (Sweden). The surface was a Dense Asphalt Concrete with 12 mm maximum chipping size, laid in the late 1970's. Its Swedish designation is MAB12T. The texture was such that it resembled a Stone Mastic Asphalt with max 12 mm chippings. Texture measurements were made with the VTI Mobile Laser Profilometer. A Mean Profile Depth (MPD) according to ISO 13473-1 of 1,16 mm was recorded. This may be considered as a "medium" texture on a smooth-rough scale encompassing common road surfaces. A photo of the texture is shown in Figure 25.

Figure 25: The Test Surface for Acceleration vs. Cruising Simulations

The data collected for the cars make it possible to develop a vehicle noise model for each car that predicts the noise emission (A-weighted sound level) for each gear as a function of vehicle speed and acceleration/deceleration. Data for each gear will normally comprise the following data (noise levels for both microphones):

- Constant speed, at 2-4 different speeds, 2-3 runs, 2 microphones, i.e. 8-24 points
- Moderate acceleration, 2-4 different speeds, 2-3 runs, 2 microphones, i.e. 8-24 points (but not on the 4th and 5th gears)
- Maximum acceleration, at 2-4 different speeds, 2-3 runs, 2 microphones, i.e. 8-24 points
- Deceleration (engine braking), at 2-4 diff speeds, 2-3 runs, 2 microphones, i.e. 8-24 points
- Braking (using brakes, engine idling), at 5 different speeds, 3-4 runs, 2 microphones, i.e. 30-40 points (same for all gears)
- Idling, one point only, but 2-3 measurements and two microphones; i.e. 4-6 points (same for all gears)

Thus, in total, each gear will comprise 66-142 data points. A special technique developed at the Technical University of Gdansk was used in order to convert the measured data to approximating equations. Separate equations were developed for various driving conditions, i.e. coast-by, constant speed, deceleration, acceleration and braking. When applicable, the equations were separately created for each gear. The following types of equations were found to fit the results well and were used:

Coast-by: $L_{CB} = A_{CB}*Ln(V) + B_{CB}$
Constant speed: $L_{CS(1)} = A_{CS(1)}*V+B_{CS(1)}$ for the 1st gear
$L_{CS(i)} = A_{CS(i)}+Ln(V)+B_{CS(i)}$ for the 2nd -5th gear

Deceleration: $L_{DC(i)} = A_{DC(i)}*V^2+B_{DC(i)}*V+C_{DC(i)}$

Acceleration: $L_{AC(i)} = A_{CB}*Ln(V) + B_{CB}+ (C_{AC(i)}*V^2+D_{AC(i)}*V+E_{AC(i)})*a^2 + +(F_{AC(i)}*V^2+G_{AC(i)}*V+H_{AC(i)})*a$

Braking: $L_{BR} = A_{CB}*Ln(V) + B_{CB}+ (C_{BR}*V^3+D_{BR}*V^2+E_{BR}*V+F_{BR})*a^2 + +(G_{BR}*V^3+H_{BR}*V^2+I_{BR}*V+J_{BR})*a$

where
L = Maximum A-weighted sound level during a pass-by
V = Vehicle speed corresponding to the recorded sound level
a = Acceleration (can be both negative and positive)
i = Gear number
A, B, C, D, E, F, G, H, I, J are constants

Figure 26 presents examples showing the fit between the model based on the equations and actually measured data.

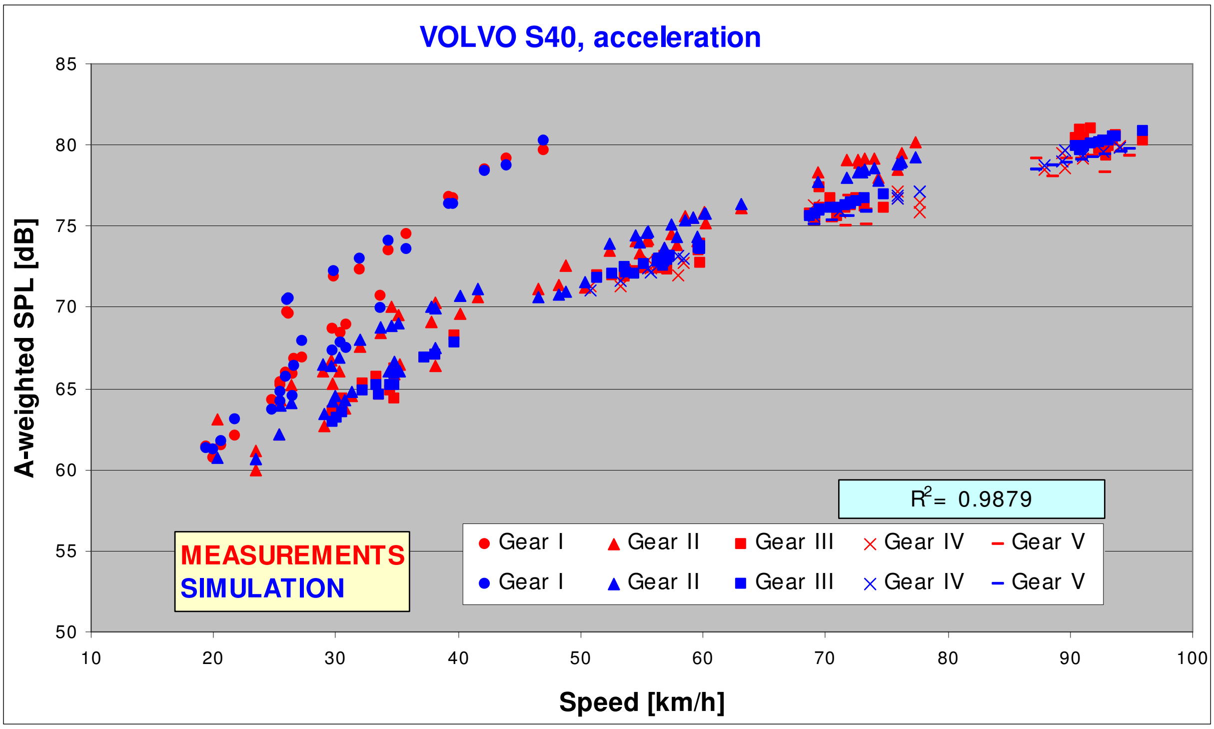


Figure 26: Simulated Sound Levels (Blue Symbols) Compared to Actually Measured Ones (Red Symbols) - Acceleration Mode for a Volvo S40

Results of the Simulation

For all vehicles that are integrated in the VENOM model several simulations were performed. They included: coasting and cruising for speeds 10 - 120 km/h, acceleration 1 m/s^2 and 2 m/s^2 on 1st to 4th gear and 3 m/s^2 on the 1st gear as well as moderate braking (-2 m/s^2) and hard braking (-6 m/s^2). This increased noise with harder braking is most likely primarily caused by stick-slip noise due to the increased forces on the tyres.

Figures 27-34 show the difference between given driving condition and corresponding coast-by. The difference is caused both by the power train noise and by the increase of tyre/road noise when considerable longitudinal forces are applied to the tyres.

Description of the abbreviations used in the Figures 27-34:

CS I, CS II, CS III, CS IV	**- Constant speed driving (cruising) at given gear (I-IV);**
ACC I (1m/s^2) ... ACC IV (1m/s^2)	- Gentle acceleration (1m/s^2) at given gear;
ACC I (2m/s^2) ... ACC IV (2m/s^2)	- Hard acceleration (2m/s^2) at given gear;
ACC I (3m/s^2)	- Very hard acceleration (3m/s^2) on the first gear;
BR (-2m/s^2)	- Gentle braking (deceleration 2 m/s^2);
BR (-6m/s^2)	- Hard braking (deceleration 6 m/s^2).

It must be noticed, that acceleration 2m/s^2 on IV-th gear is for most of the vehicles a result of extrapolation, as the vehicles are not powerful enough to reach such an acceleration. In most cases 1,2- 1,7 m/s^2 was the real live limit of the acceleration on the IV-th gear.

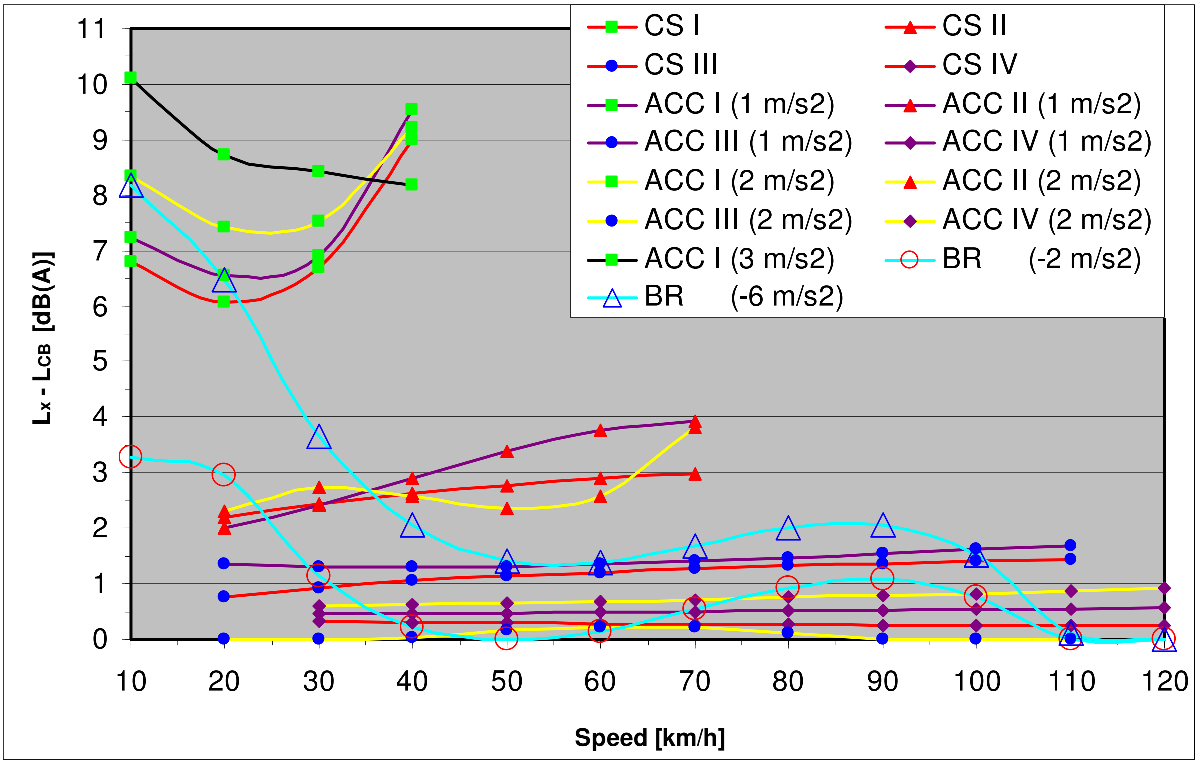


Figure 27: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: FORD Ka

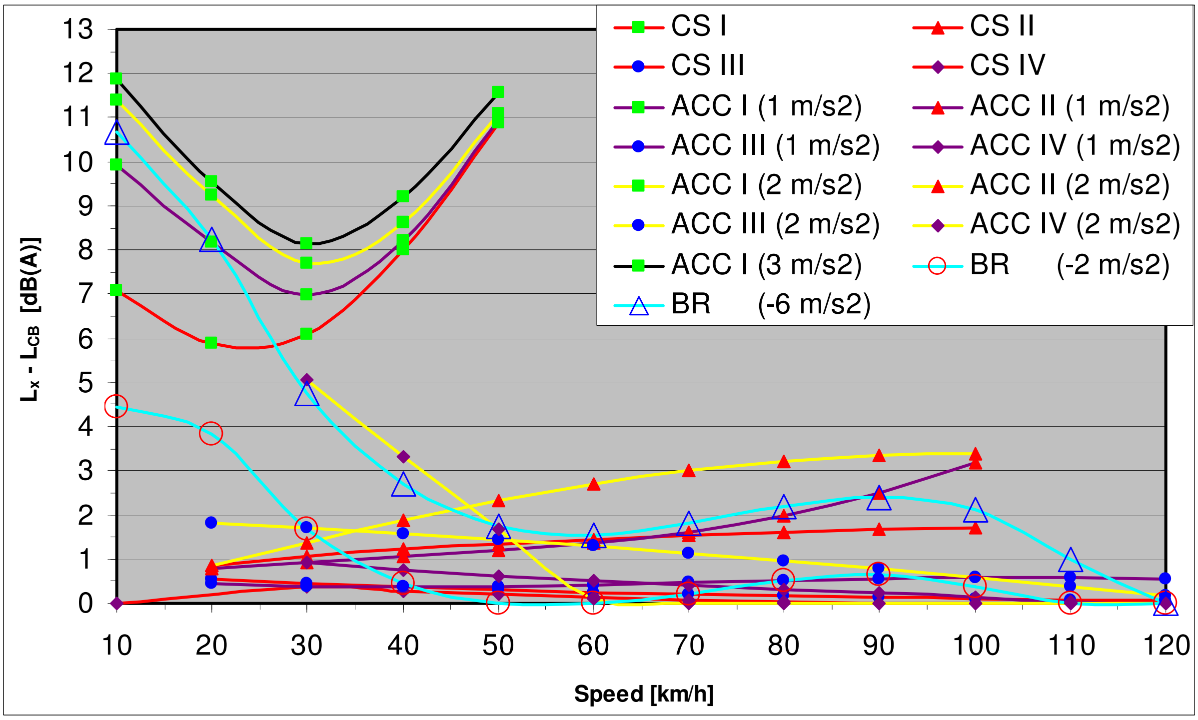


Figure 28: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: Toyota Previa

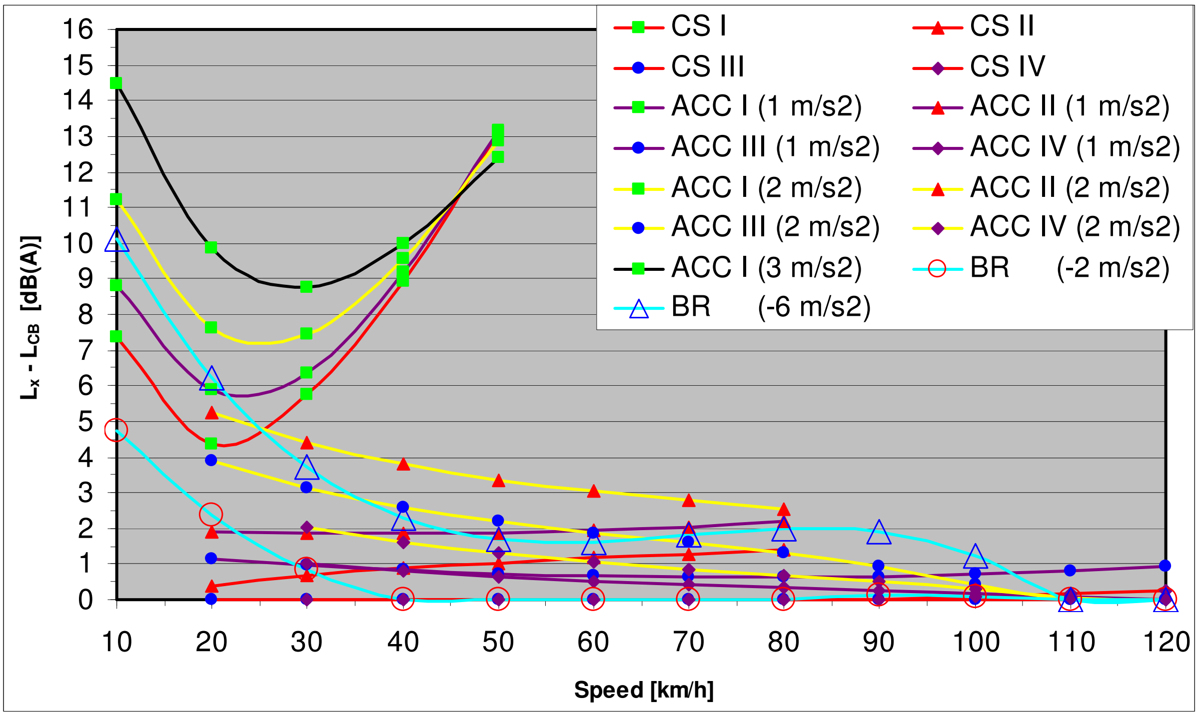


Figure 29: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: VOLVO S40

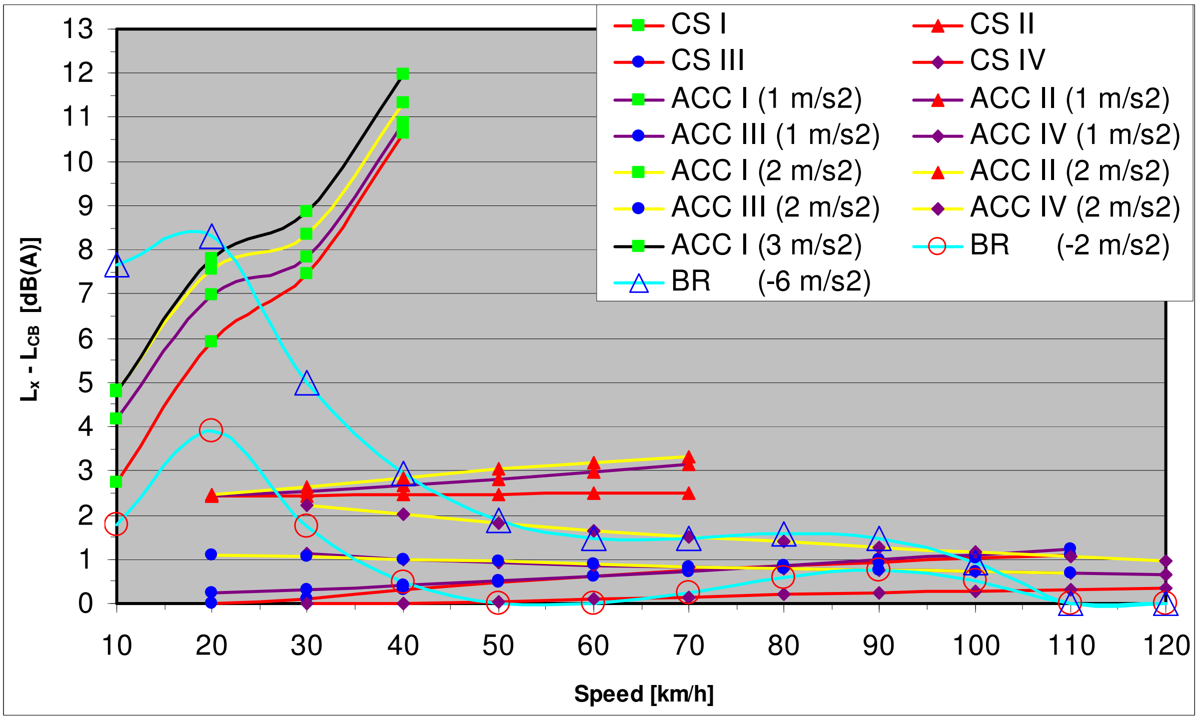


Figure 30: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: VOLVO S40 D

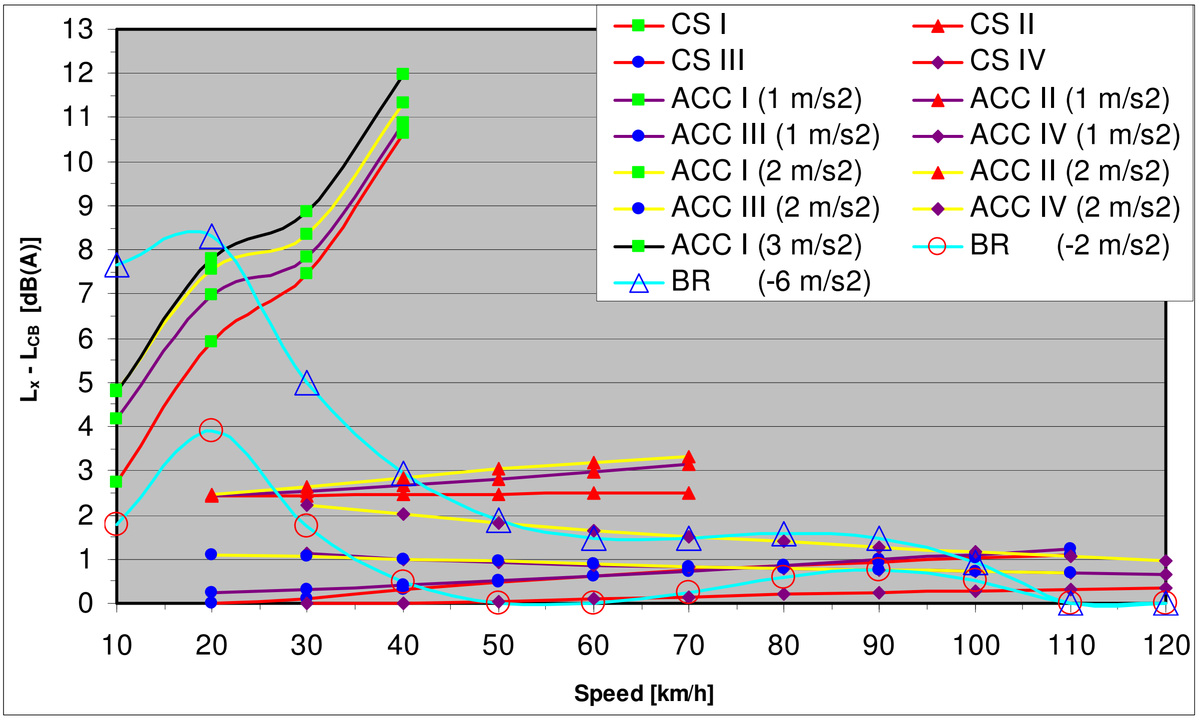


Figure 31: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: FORD MONDEO V6

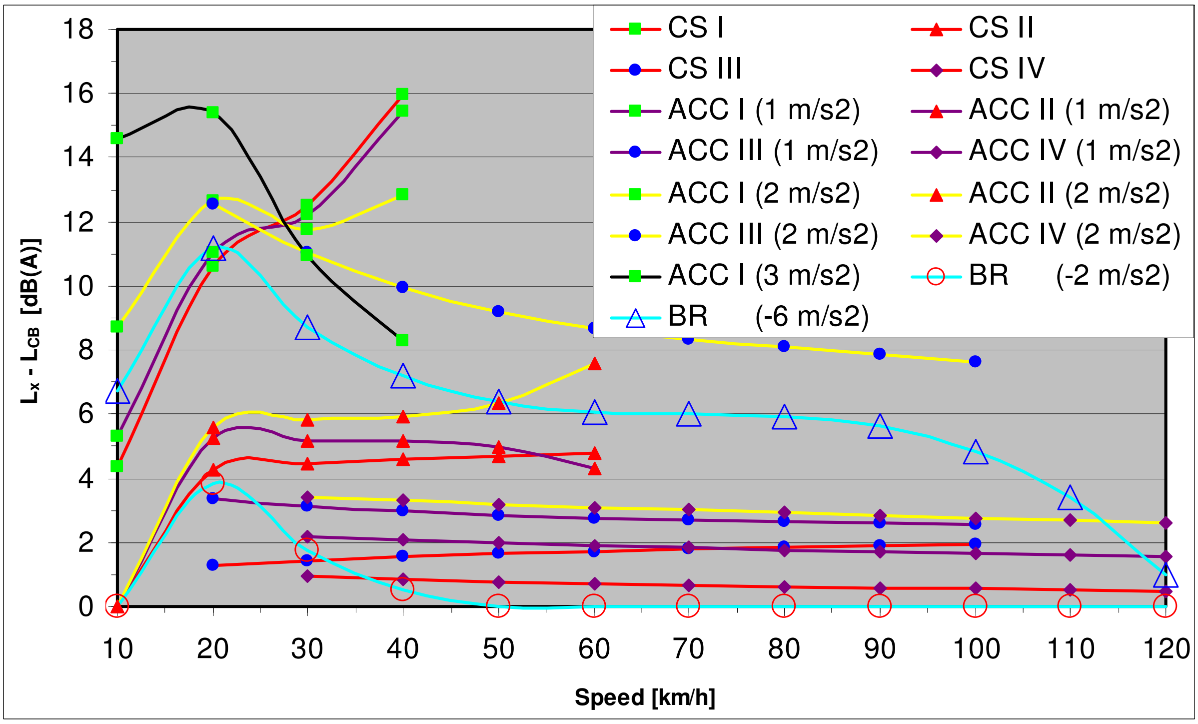


Figure 32: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: TOYOTA HiLux

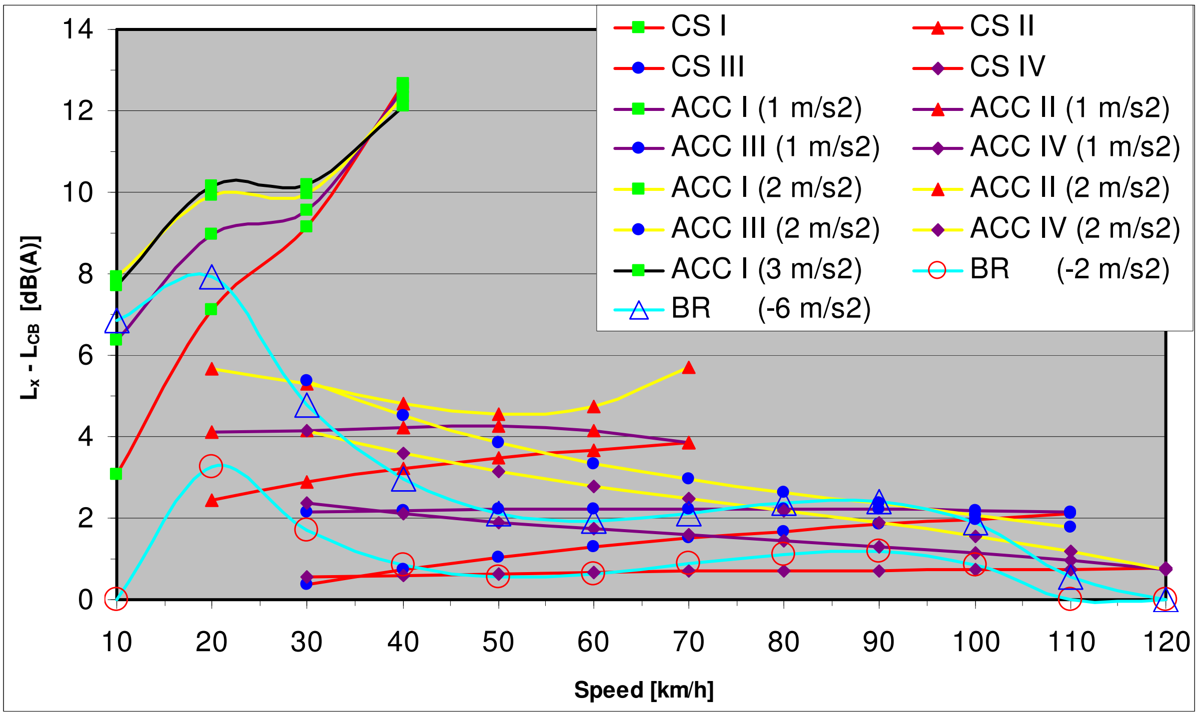


Figure 33: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: MITSUBISHI Pajero

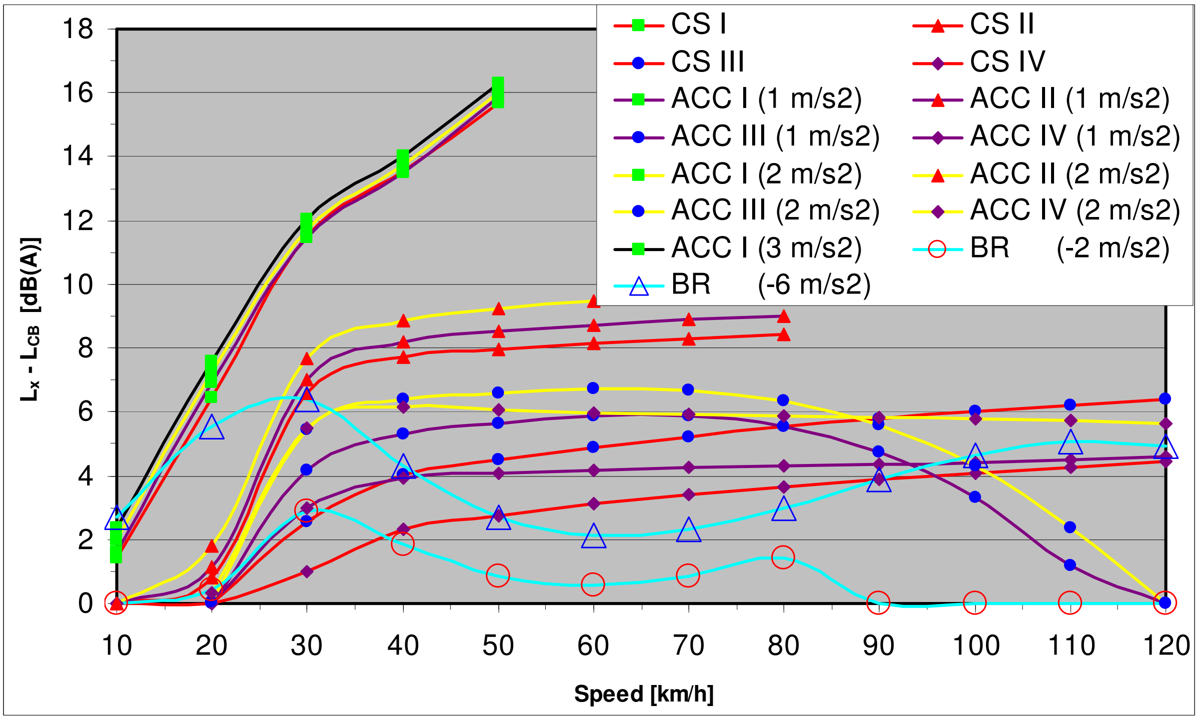


Figure 34: Difference in Noise Emission (expressed as LAmax at 7,5 m) for a Given Driving Condition Compared to the Corresponding Coast-By Levels. The Noise Levels are Calculated from the Model which was Constructed Based on all Measured Values. – Vehicle: Motorcycle BMW F650GS

The results presented in Figures 27-34 indicate, that if driving conditions are restricted to speeds over 50 km/h and 3rd or higher gear, the overall noise of cars accelerating, cruising or braking is higher at the most by 2 dB(A) in comparison to the coast-by (that is tyre/road noise in practice). For the motorcycle the increase may be up to 6 dB(A). If, however, the manoeuvres are performed on the 1st or 2nd gear, the increase may be much higher, up to 14 dB for the 1st gear and 4 dB(A) for the 2nd gear.

5.2.4. Driving in a Gradient or a Curve

Driving in a gradient represents a completely different situation for the vehicle driver than driving on a straight, level road surface. The difference between a road in an alpine region and one with no gradient is due to the positive and negative gradients in the longitudinal direction of the roadway. Resulting from this, an alpine road leads to different driving conditions, due to the necessity of accelerating and braking on the slopes, even on straight sections an increased engine speed is necessary to hold the same driving speed than on a level surface. This condition leads therefore to an increase in engine noise and thus to an increase of the overall noise emissions of passing vehicles.

The influence of driving in a gradient on noise emissions is embodied in the standards of the European countries for the calculation of environmental noise due to passing vehicles. As an example the Austrian regulations (RVS, 1997) for calculating the Equivalent Sound Pressure Level ($L_{A,eq}$) is described in a few words. The Austrian model for the calculation of $L_{A,eq}$ includes a factor K_L, which takes into account the influence of driving in a gradient on the overall noise emission of a vehicle passing by. Looking at the general formula for calculating the equivalent sound pressure level in the Austrian regulations (see Figure 35), one sees three different additive correction factors, one factor regarding the influence of speed ($K_{V,PKW,F}$ and $K_{V,LKW,F}$), one concerning the influence of gradients ($K_{L,PKW}$ and $K_{L,LKW}$) and the third is focussing on the influence of the composition of the traffic (M_{PKW} and M_{LKW}).

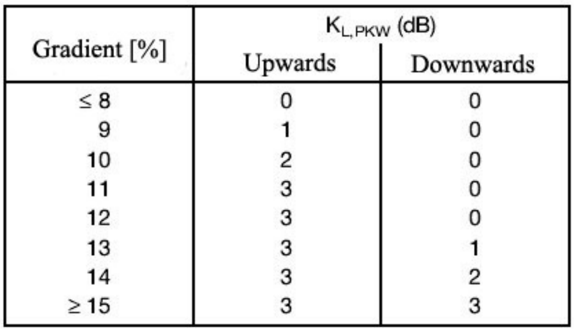
$$L_{eq,PKW} = L_{PKW,F} + K_{V,PKW,F} + K_{L,PKW} + 10 \lg M_{PKW} \text{ in dB}$$

$$L_{eq,LKWI} = L_{LKWI,F} + K_{V,LKW,F} + K_{L,LKW} + 10 \lg M_{LKWI} \text{ in dB}$$

$L_{eq,PKW}$ .... Equivalent Sound Pressure Level PC
$L_{eq,LKW}$ .... Equivalent Sound Pressure Level HV
$L_{PKW,F}$ .... Basis Factor of Noise Emission PC
$L_{LKW,F}$ .... Basis Factor of Noise Emission HV
$K_{V,PKW,F}$ .... Factor for the Influence of Speed PC
$K_{V,LKW,F}$ .... Factor for the Influence of Speed HV
$K_{L,PKW}$ .... Factor for the Influence of Road Geradient PC
$K_{L,LKW}$ .... Factor for the Influence of Road Gradient HV
M_{PKW} .... Number of Passenger Vehicles passing per hour
M_{LKW} .... Number of trucks passing per hour

Figure 35: Austrian Model for the Calculation of Leq for Passenger Cars (PC) and Heavy Vehicles (HV), (RVS, 1997)

Regarding passenger cars the influence of driving in a gradient starts from an upward gradient of approx. 8 - 9 % (see Figure 36), whereby regarding trucks an upward gradient from 4 % results to significant noise level increases (see Figure 37).



Gradient [%]	$K_{L,PKW}$ (dB)	
	Upwards	Downwards
≤ 8	0	0
9	1	0
10	2	0
11	3	0
12	3	0
13	3	1
14	3	2
≥ 15	3	3

Figure 36: Characteristic Value $K_{L,PKW}$ Describing the Influence of Gradients on the Calculation of $L_{A,eq}$ for Passenger Cars (RVS, 1997)

Gradient [%]	$K_{L,LKW}$ (dB)	
	Upwards	Downwards
≤ 2	0	0
4	2	0
6	4	1
8	5	2
10	6	3
12	7	3,5
≥ 14	8	4

Figure 37: Characteristic Value $K_{L,LKW}$ Describing the Influence of Gradients on the Calculation of $L_{A,eq}$ for Heavy Vehicles (RVS, 1997)

An overall view of the factor K_L in dependence on the gradient of the road is shown in Figure 38.

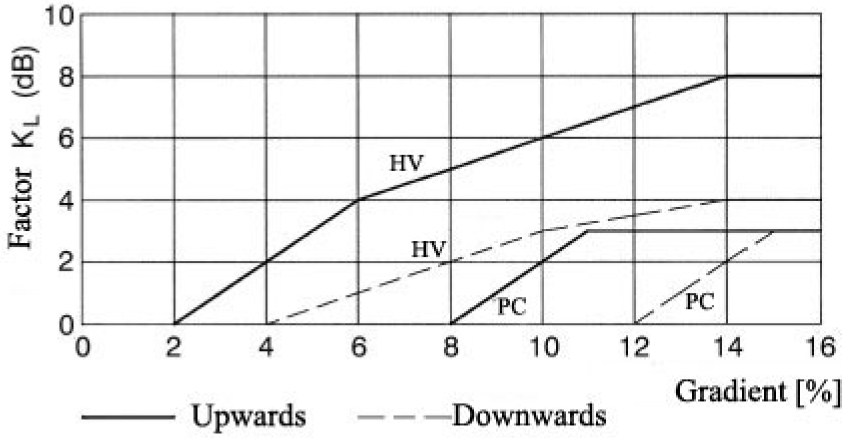


Figure 38: Influence of gradients on the calculation of $L_{A,eq}$

An Austrian research project (Pucher et al., 2003) dealt in part with the influence of driving in a gradient on motorways in Austria. Results from SPB measurements on different motorways with different road surfaces and different gradients were taken and analysed. For an average motorway in mountainous regions the speed ranges vary strongly from passenger cars to heavy vehicles. For passenger cars the range of speed is from 50 to 120 km/h, while for heavy vehicles this speed range is from 30 to 80 km/h. In addition to the speed range effect, all vehicles are often either accelerating or braking. The constant driving situation can essentially be disregarded for analyses of alpine roads. In comparison with the typical noise levels for a standard road with no gradient, the noise levels are higher on an alpine road (see Figure 39 and Figure 40). This difference is due in part to the increased influence of the engine noise, caused by road sections with positive slopes where an additional accelerating is necessary.

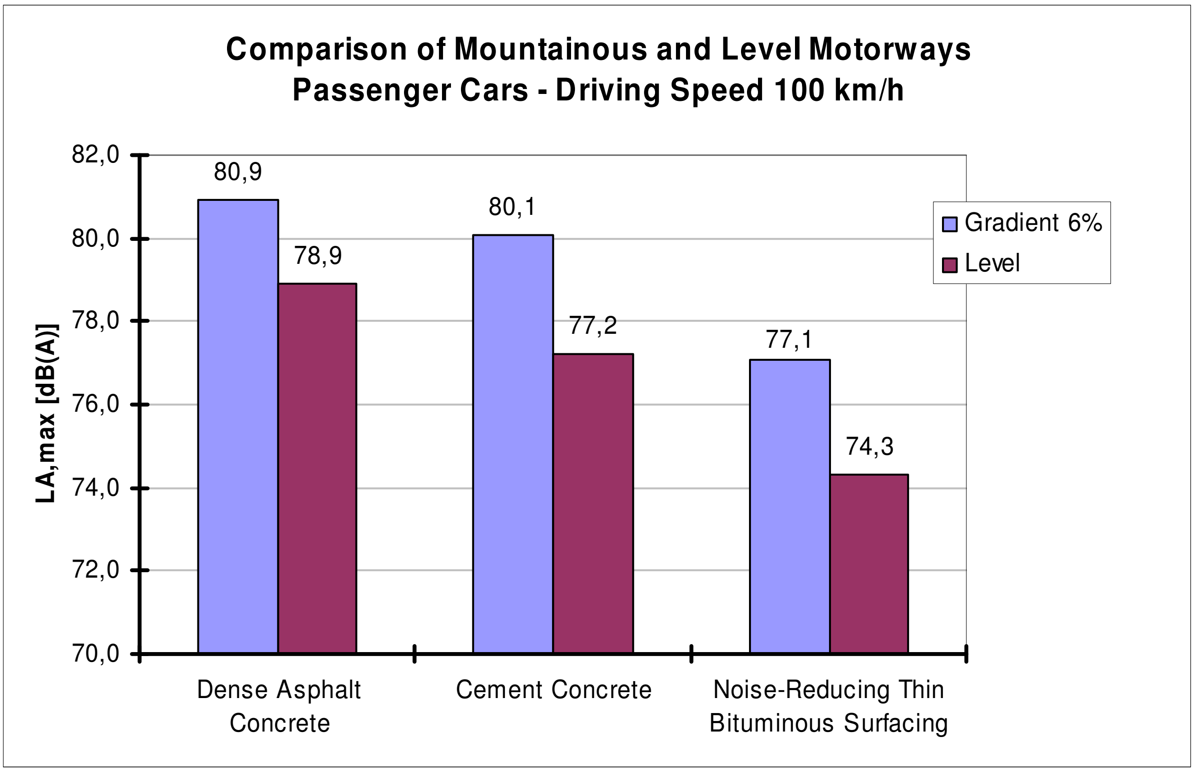


Figure 39: Model Output of Sound Pressure Levels on an Average Mountainous Motorway in Austria for Passenger Cars on different Road Surfaces

As is evident in Figure 39 motorways in mountainous regions are about 2 to 3 dB(A) noisier for passenger cars than motorways in level regions, always regarding the same speed situation. The range for heavy vehicles as to be seen in Figure 40 is almost the same (increases of SPL are about 2,0 to 3,5 dB(A)). But one has to consider that the driving speed of trucks on gradients is much slower than the speed of passenger cars. This means, regarding the same speeds for heavy vehicles and passenger cars, the increase of noise emissions by driving in a gradient is much higher for heavy vehicles than for passenger cars.

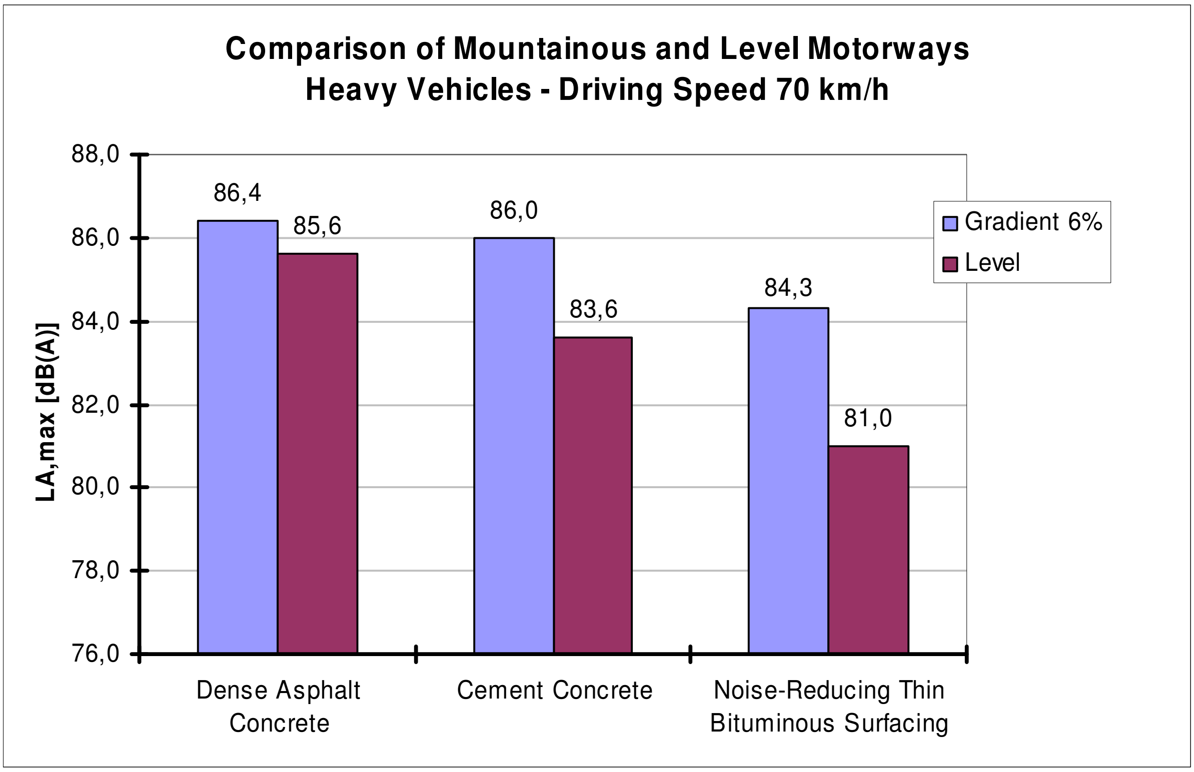


Figure 40: Model Output of Sound Pressure Levels on an Average Mountainous Motorway in Austria for Heavy Duty Trucks on Different Road Surfaces

Other Austrian measurement programmes were dealing with this problem. In 1984 (Rudelstorfer and Tiefenthaler, 1984) a large amount of measurements were taken on several roads (federal roads and motorways). On each site SPB measurements took place, with a microphone distance of 10 m and a microphone height of 3,0 m, the lane width of the selected sections is 3,5 m (see Figure 41).

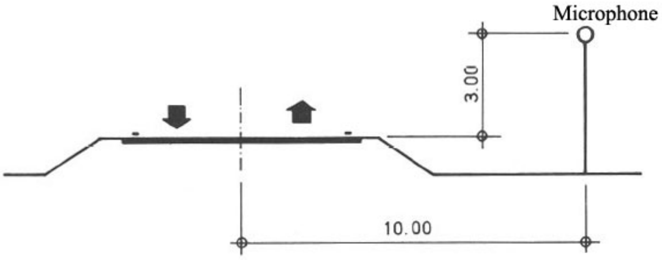
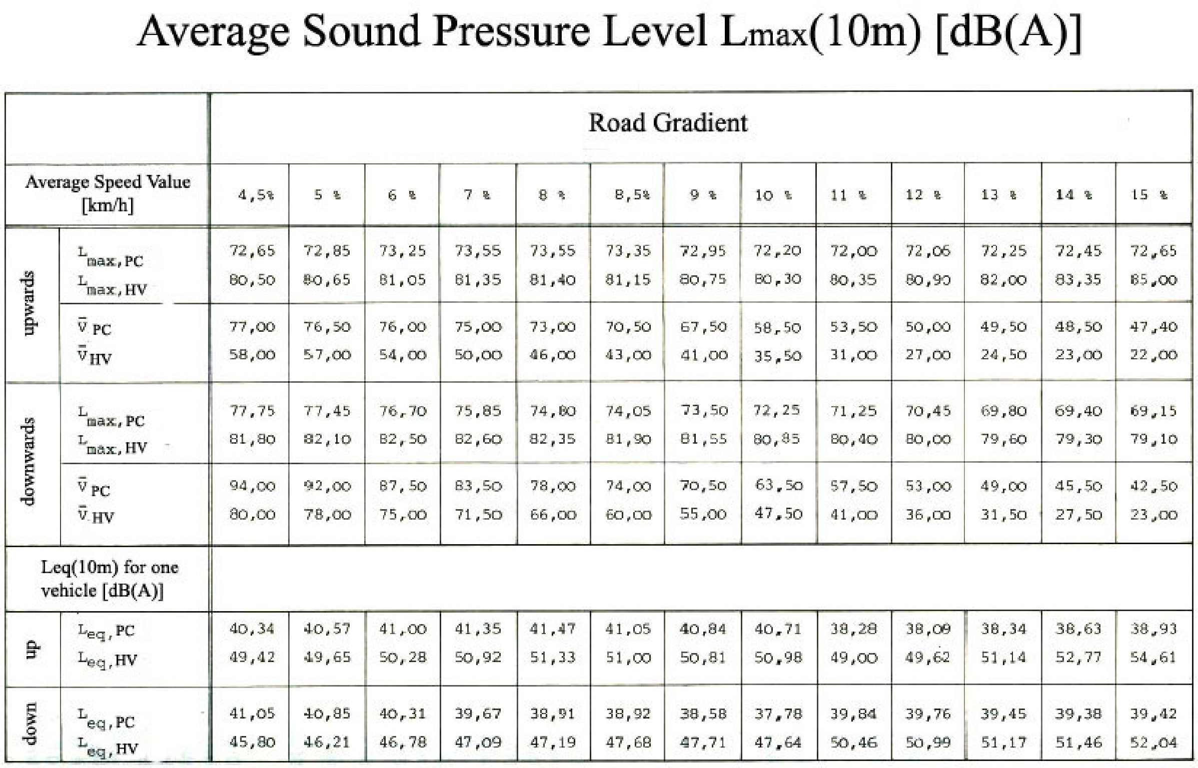


Figure 41: Cross Section of Federal Roads (Rudelstorfer and Tiefenthaler, 1984)

All results shown in the analysis are average values, meaning that the average value of the measured maximum sound pressure level at different measurement sites is taken with the associated vehicle speed (see Figure 42). Thus the results comprise the average over several sites. Analyses for passenger cars (see Figure 43) and for heavy vehicles (see Figure 44) are shown in the following figures.



Average Sound Pressure Level Lmax(10m) [dB(A)]

		Road Gradient												
Average Speed Value [km/h]		4,5%	5 %	6 %	7 %	8 %	8,5%	9 %	10 %	11 %	12 %	13 %	14 %	15 %
upwards	$L_{max,PC}$	72,65	72,85	73,25	73,55	73,55	73,35	72,95	72,20	72,00	72,06	72,25	72,45	72,65
	$L_{max,HV}$	80,50	80,65	81,05	81,35	81,40	81,15	80,75	80,30	80,35	80,90	82,00	83,35	85,00
	$\bar{v}_{PC}$	77,00	76,50	76,00	75,00	73,00	70,50	67,50	58,50	53,50	50,00	49,50	48,50	47,40
	$\bar{v}_{HV}$	58,00	57,00	54,00	50,00	46,00	43,00	41,00	35,50	31,00	27,00	24,50	23,00	22,00
downwards	$L_{max,PC}$	77,75	77,45	76,70	75,85	74,80	74,05	73,50	72,25	71,25	70,45	69,80	69,40	69,15
	$L_{max,HV}$	81,80	82,10	82,50	82,60	82,35	81,90	81,55	80,85	80,40	80,00	79,60	79,30	79,10
	$\bar{v}_{PC}$	94,00	92,00	87,50	83,50	78,00	74,00	70,50	63,50	57,50	53,00	49,00	45,50	42,50
	$\bar{v}_{HV}$	80,00	78,00	75,00	71,50	66,00	60,00	55,00	47,50	41,00	36,00	31,50	27,50	23,00
Leq(10m) for one vehicle [dB(A)]														
up	$L_{eq,PC}$	40,34	40,57	41,00	41,35	41,47	41,05	40,84	40,71	38,28	38,09	38,34	38,63	38,93
	$L_{eq,HV}$	49,42	49,65	50,28	50,92	51,33	51,00	50,81	50,98	49,00	49,62	51,14	52,77	54,61
down	$L_{eq,PC}$	41,05	40,85	40,31	39,67	38,91	38,92	38,58	37,78	39,84	39,76	39,45	39,38	39,42
	$L_{eq,HV}$	45,80	46,21	46,78	47,09	47,19	47,68	47,71	47,64	50,46	50,99	51,17	51,46	52,04

Figure 42: Detailed Results of the Measurement Series Described in Rudelstorfer and Tiefenthaler (1984)

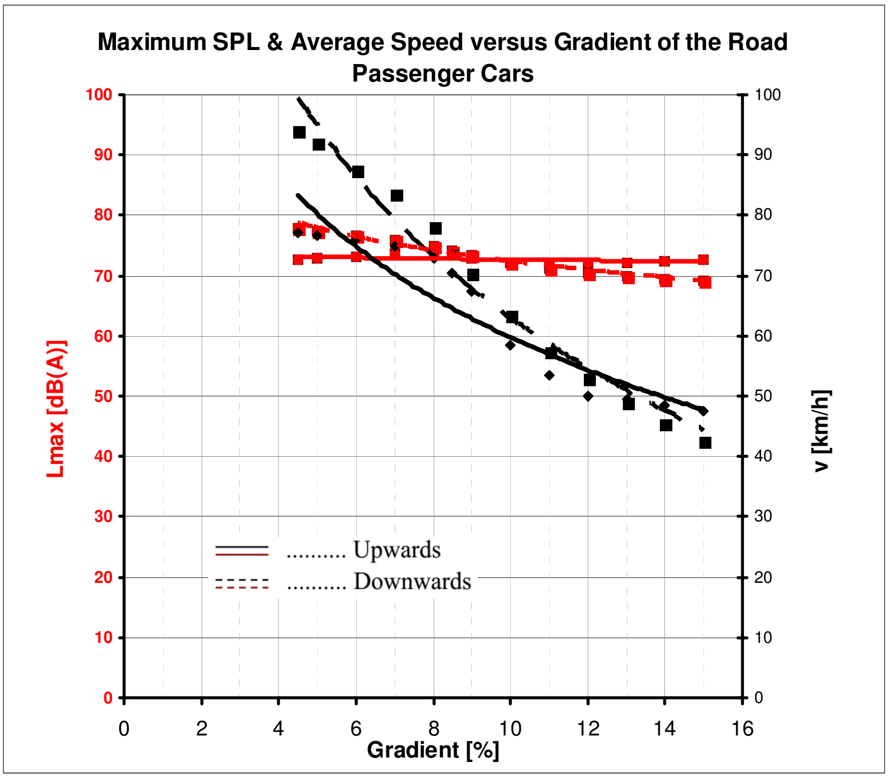


Figure 43: Measurement Results for Passenger Cars Driving on Gradients

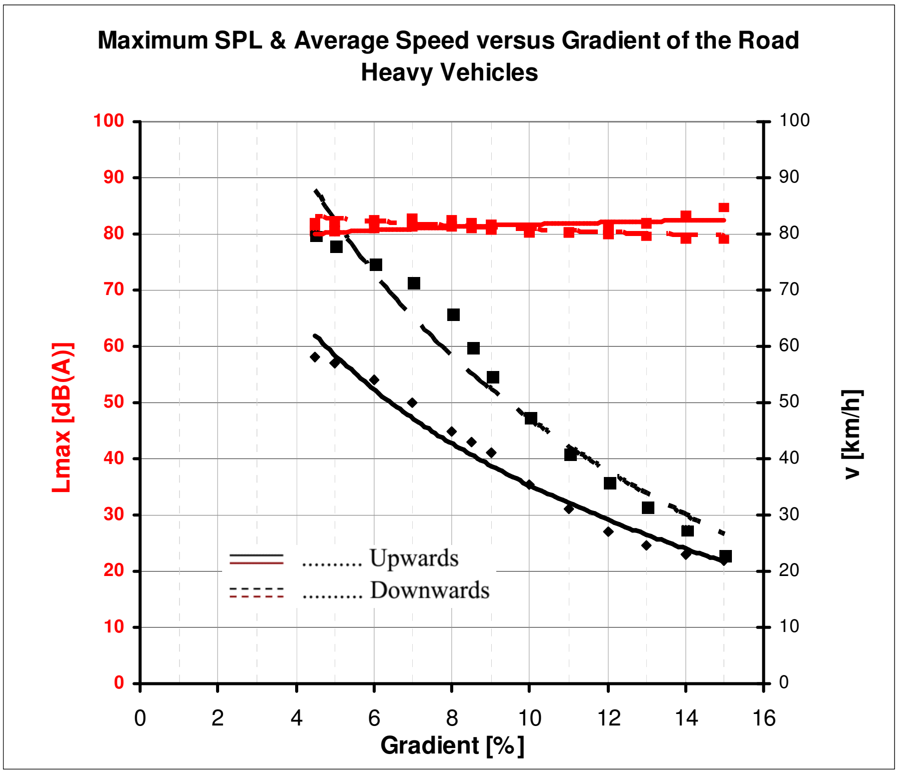


Figure 44: Measurement Results for Heavy Vehicles Driving on Gradients

If one regards the development of noise emissions both from passenger cars as well as from trucks, no significant rise of the noise levels are noticeable with rising gradients. The difference does not appear so significant because another speed condition prevails on each gradient. Therefore the influence of the speed seems to be a very important factor when looking at the effect of gradients on noise levels.

If one compares the situation of driving upwards with these of driving downwards, Figure 45 is showing the case for passenger cars and Figure 46 the case for heavy vehicles. Both figures are showing the same tendencies. Just in extreme situations like very steep roads with gradients over 12-13%, a steep rise of noise emissions from trucks is noticeable. This effect results on low driving speeds (around 22 km/h) and high engine speeds, which are leading to high engine noise emissions.

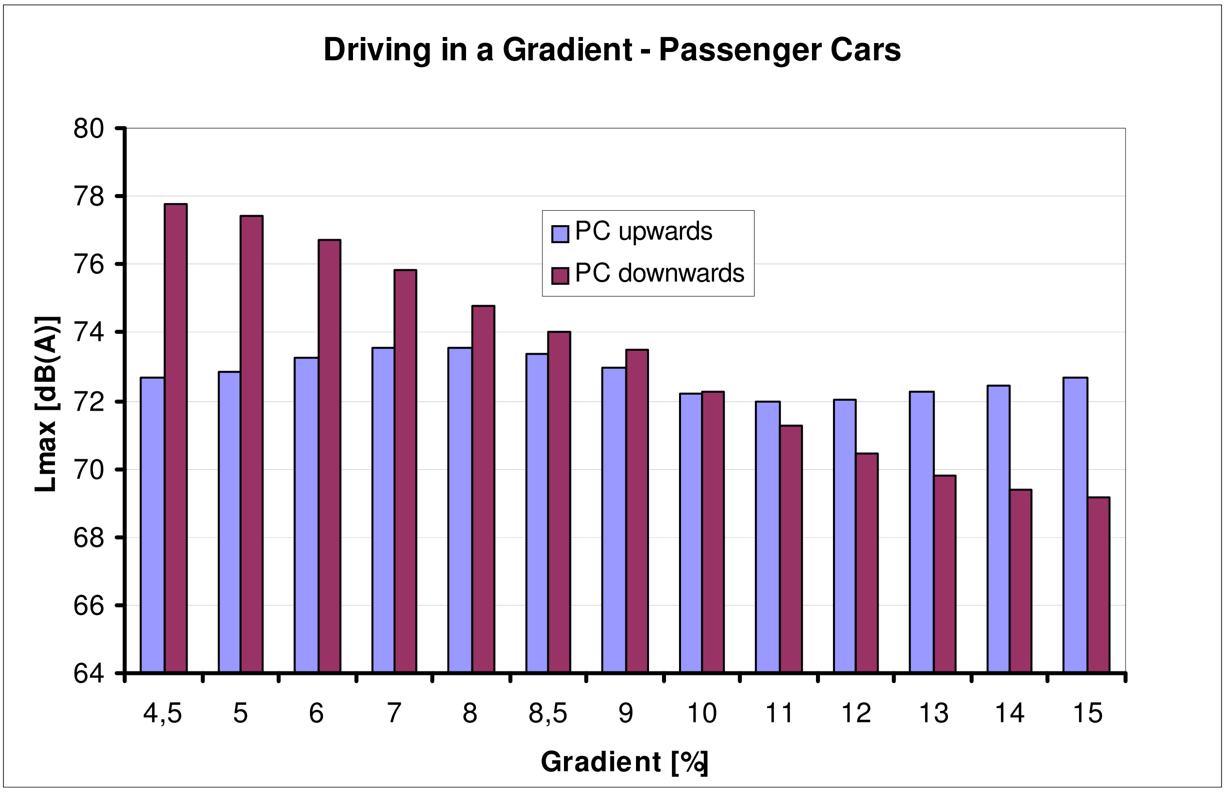


Figure 45: Comparison of Upwards and Downwards Driving of Passenger Cars

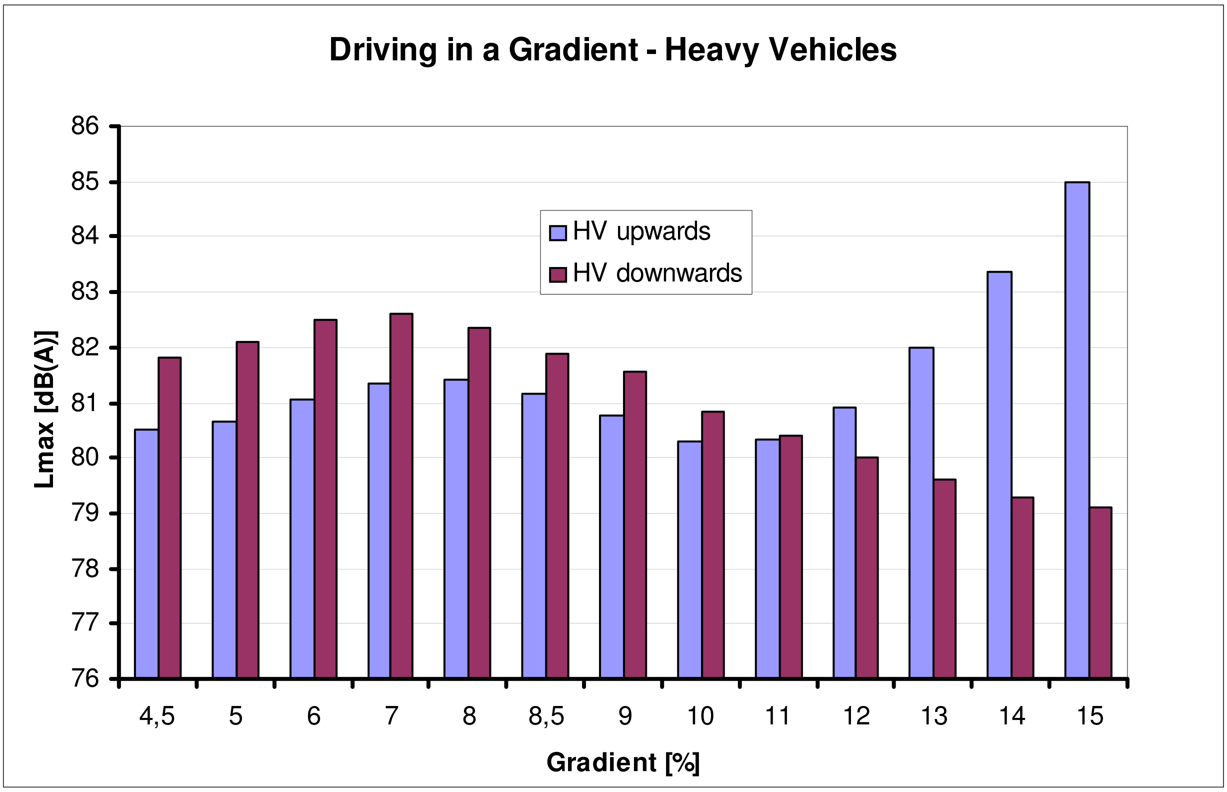


Figure 46: Comparison of Upwards and Downwards Driving of Trucks

Figures 47 and 48 show a comparison of the results for passenger cars and heavy vehicles on an upward and a downward slope, respectively. The results show that on a downhill gradient, heavy vehicles show less of a decrease in noise as the slope gets steeper than do passenger cars.

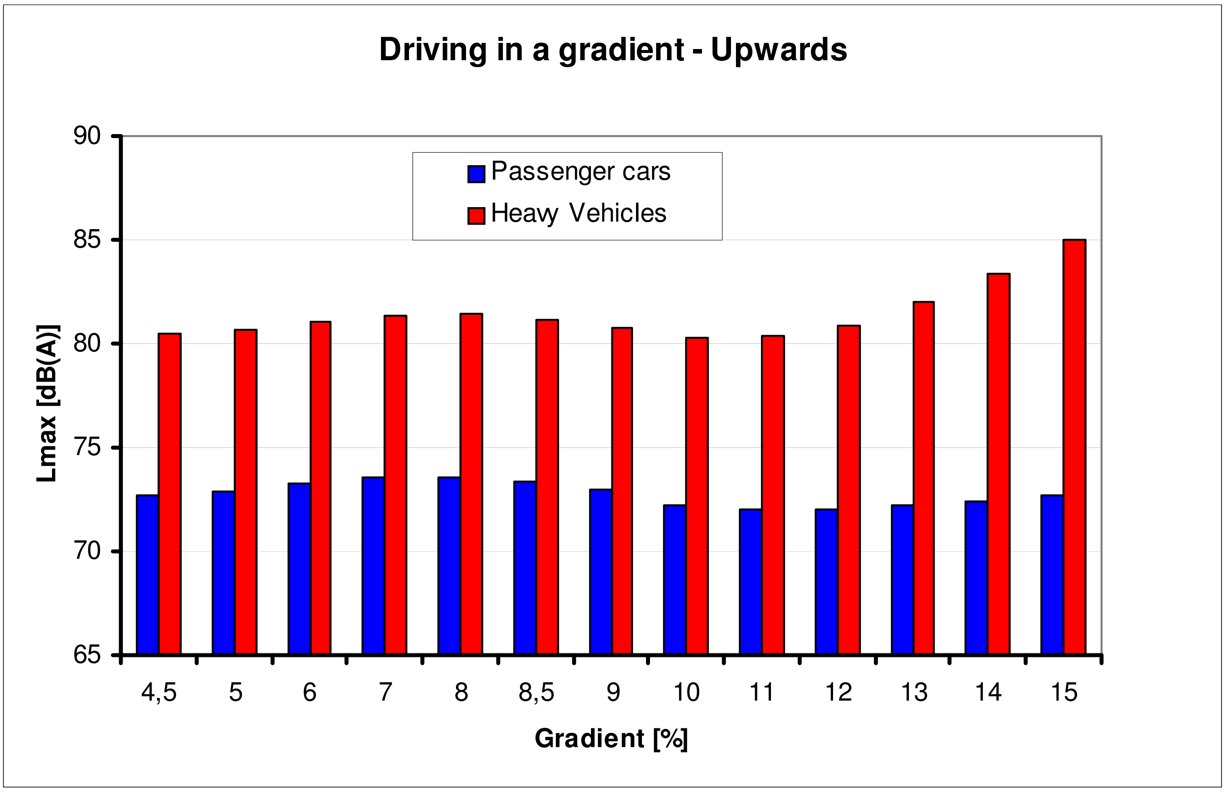


Figure 47: Sound Pressure Levels for Different Gradients Driving Upward Direction

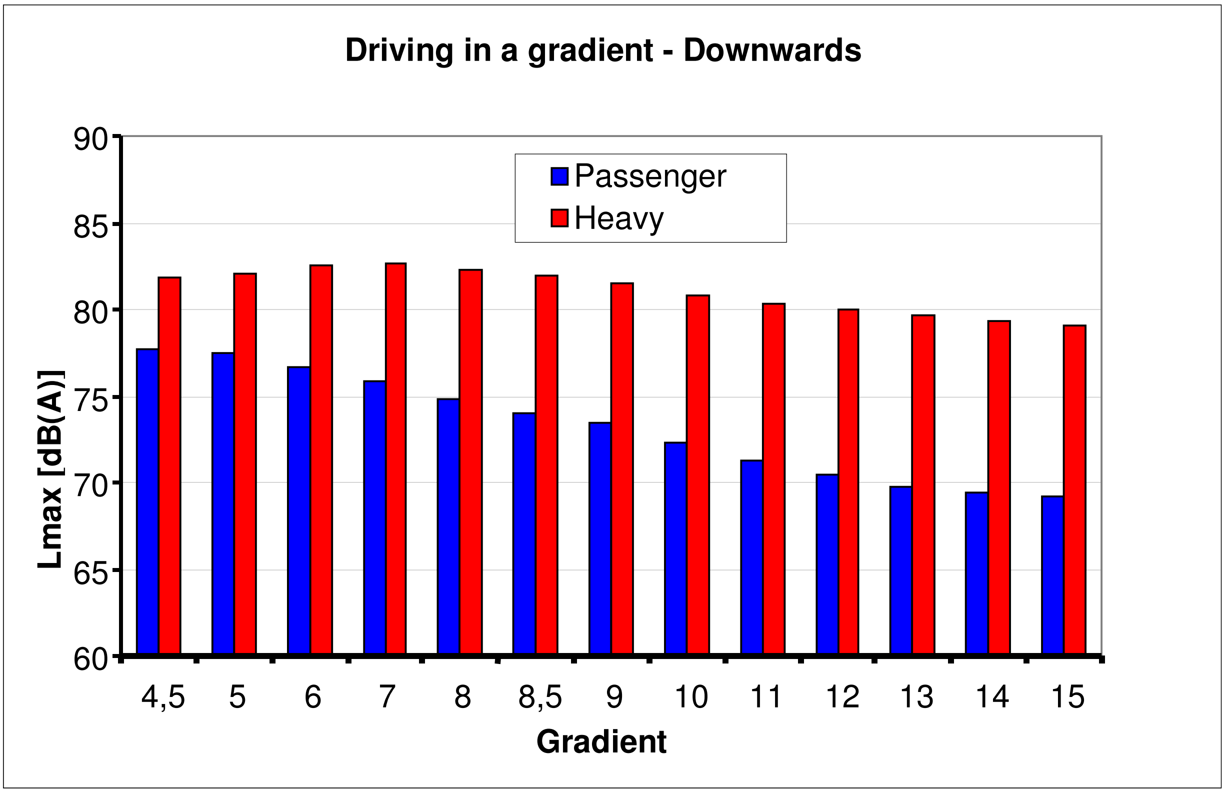


Figure 48: Sound Pressure Levels for Different Gradients Driving Downward Direction

5.2.5. Slip and Traction Force vs. Noise

Thus far in this section it is seen that accelerating and driving on positive and negative slopes results in an increase over constant driving when the same vehicle speed is used for comparison. The primary factors in this noise increase are additional power unit noise through increased engine torque, possible braking noise for deceleration, and the increased tyre/road noise due to tyre slip and due to the traction force on the tyre.

A separate analysis of the influence of tyre slip on pass-by noise is shown in Figure 49. Here it is seen that when the tyre slip goes up to 1% of the rotational speed of the tyres, the noise increase can be as much as 3 to 4 dB(A). It should also be noted that the spread in results is wide, demonstrating that there is not truly a linear relationship between tyre slip and noise.

The tyre noise level increase due to tangential forces is calculated from measured noise levels as follows:

$$L_{TangForce} = L_{TyreTorque} - L_{Roll}$$

Where $L_{TangForce}$ is the noise due to tyre tangential forces, $L_{TyreTorque}$ is the total noise attributed to the tyres under a loaded condition, and L_{Roll} is the rolling noise measured under similar conditions and speed.

The value $L_{TyreTorque}$ is calculated from measured values from:

$$L_{TyreTorque} = L_i - L_{drive}$$

Where L_i is the measured pass-by noise under the operating conditions of interest, and L_{drive} is the power unit noise. The power unit noise L_{drive} is found from:

$$L_{drive} = L_{i(slick)} - L_{Roll(slick)}$$

Where $L_{i(slick)}$ is the measured pass-by noise under the operating conditions of interest using a slick, or tyre with no profile, and $L_{Roll(slick)}$ is the rolling noise using a slick measured at the same conditions and speed.

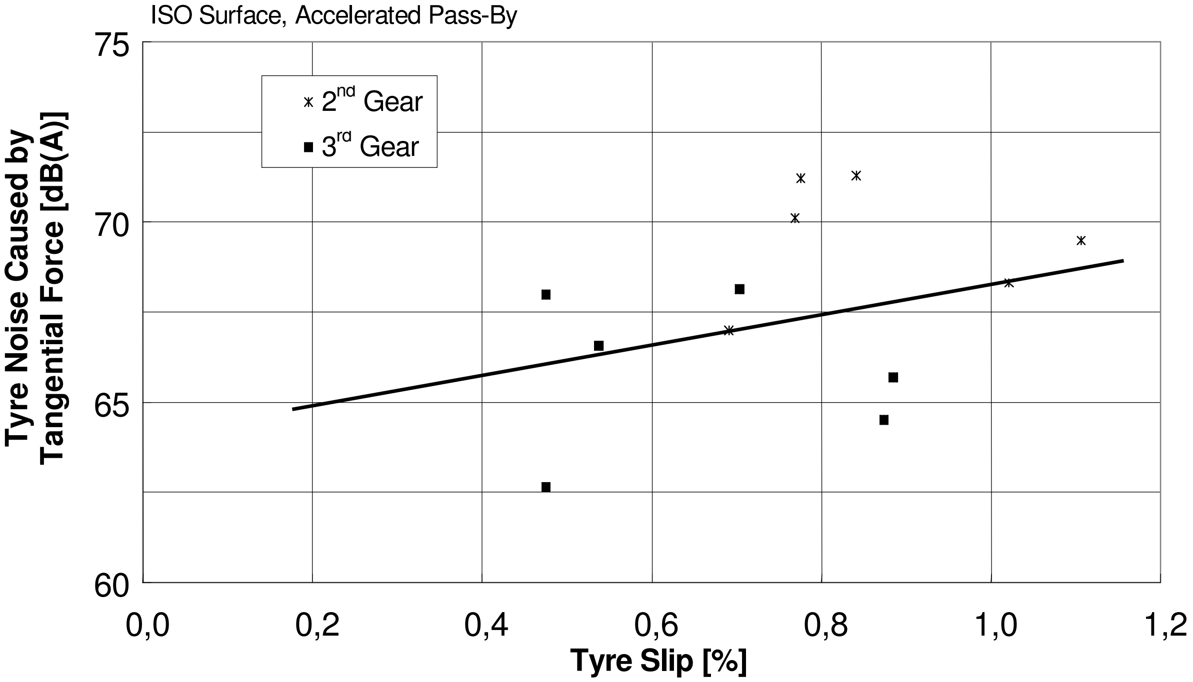


Figure 49: Tyre Noise Caused by Tangential Force Versus Tyre Slip for 6 Tyre Types (Adapted from Schwarz, 1998)

In general however, it is seen that as the tyre slip increases, the road/tyre noise increases. Thus, the increase in noise from extreme driving is not only due to the power unit noise but also to increased noise caused tyre slip.

The influence of torque on tyre/road noise is an important factor for an accelerating vehicle. In Figure 49 we saw the relation between the portion of tyre noise due to torque and the amount of tyre slip. Figure 50 gives the tyre noise under torque $L_{TyreTorque}$ vs. vehicle speed and tyre torque. The Tyre noise $L_{TyreTorque}$ is calculated from measured values as shown above.

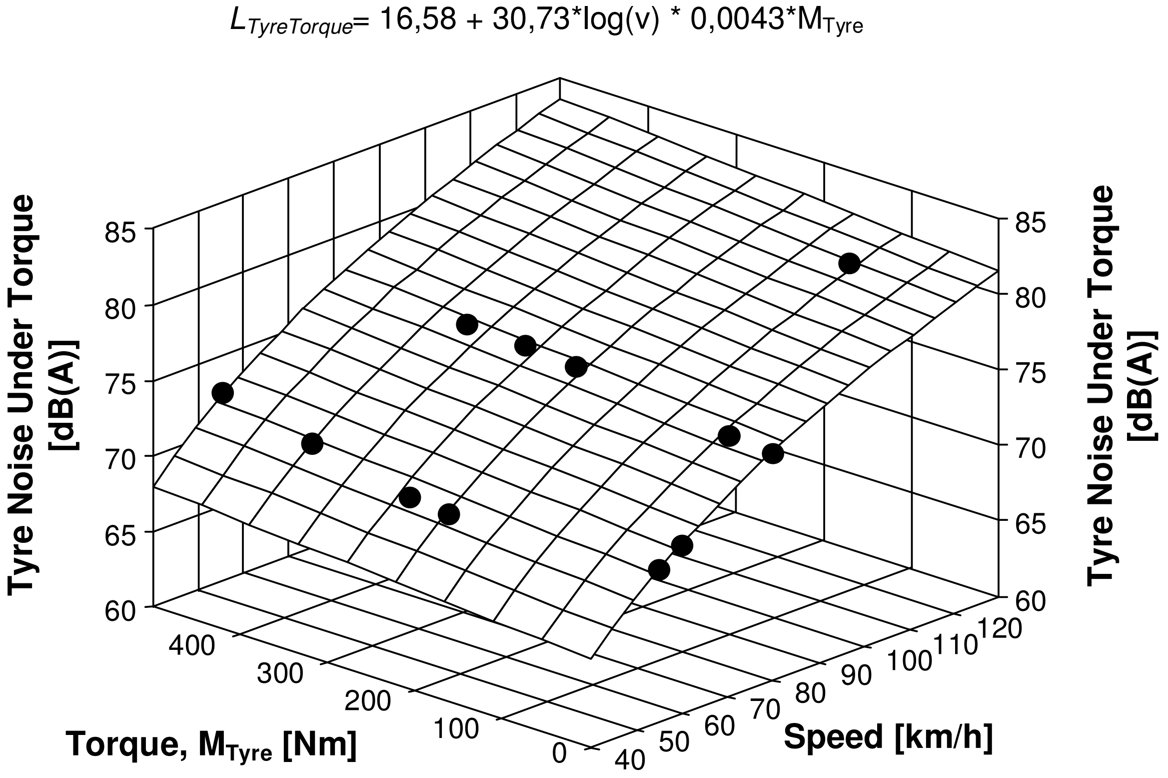


Figure 50: Calculated Tyre Noise Under Torque vs. Tyre Torque and Vehicle Speed for a Passenger Car on an ISO Surface (Adapted from Pucher, 1998)

The results of slip and traction force shown in Figures 49 and 50 would account for a part of the difference in pass-by noise from vehicles accelerating vs. those driving at a constant speed, seen in Section 5.2.2.

5.3. Effect of Vehicle Parameters on Noise

It is also important to look at differences in the vehicle parameters and how they influence the noise levels. One potential difference is the type of power train. The two most common types of power units for passenger cars are diesel and petrol internal combustion engines. The INRETS dataset had several measurements for both diesel and petrol engines. In addition, the LCPC dataset had results for different vehicle types. These two datasets have been drawn upon for the results shown in Figures 51 to 56 of this section of the report. The results seen previously from the INRETS dataset for accelerating and non-accelerating vehicles (Figure 23) also included the power unit type. Figure 51 shows these results subdivided into the engine type.

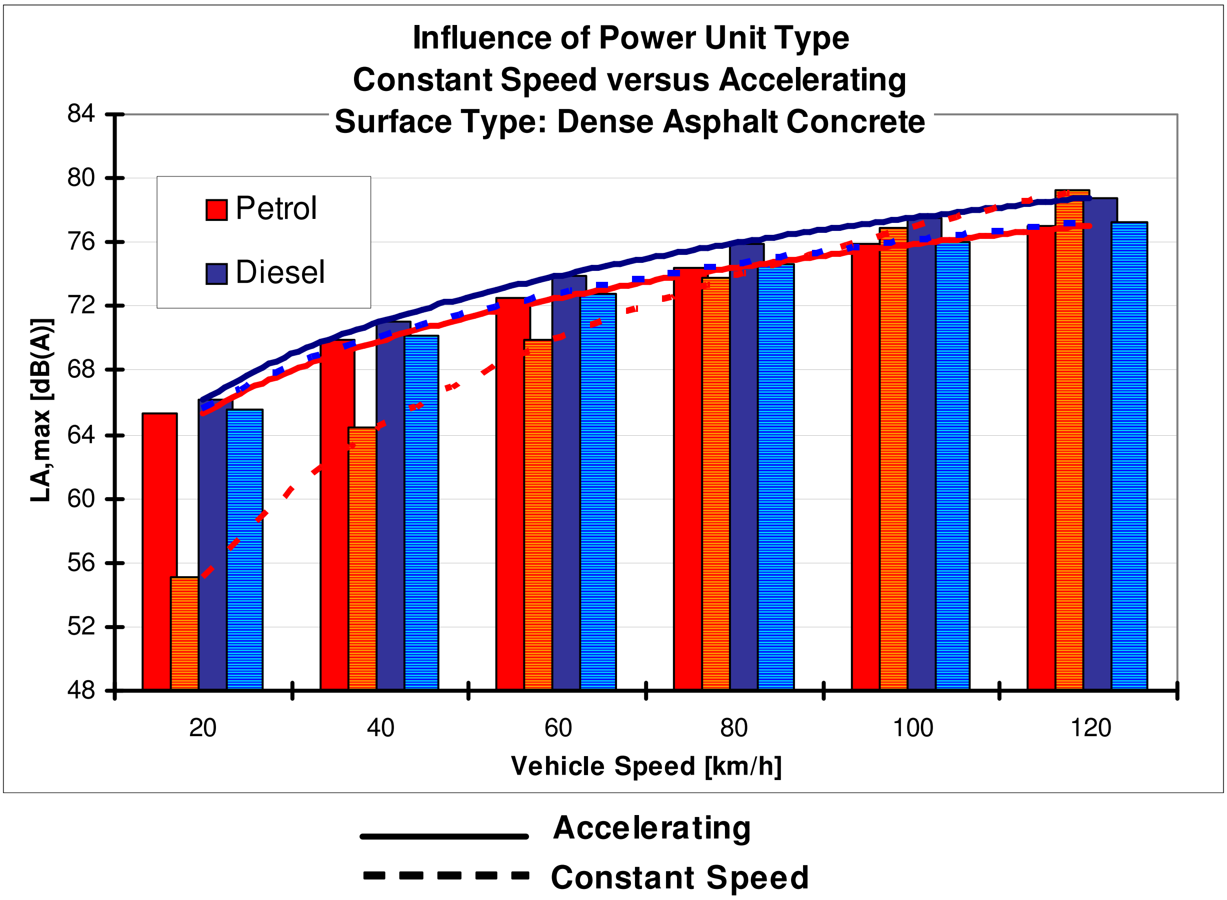


Figure 51: Comparison of Different Power Unit Types (Petrol versus Diesel) of INRETS Data at Constant Speed Driving and Accelerating on Dense Asphalt Concrete

From Figure 51, it is seen that the difference between constant speed and accelerating for petrol vehicles is very high; on the other hand, the difference concerning diesel engines is not so substantial.

Figure 52 shows regression analysis under constant speed for several vehicle types, including diesel, electric and hybrid electric vehicles. The results are summarised in Table 6.

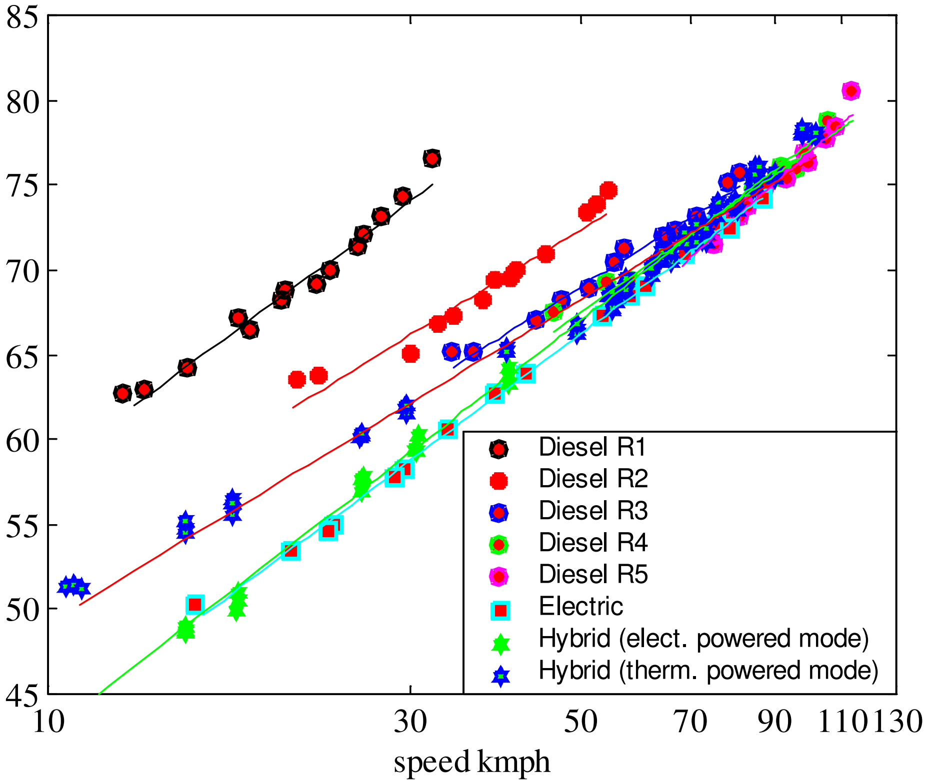


Figure 52: Cruise-By Noise Levels of Passenger Cars with Diesel, Hybrid or Electric Motorisation - Regression Analysis of INRETS Data on Dense Asphalt Concrete

Table 6: Passenger Cars Running at Constant Speed, Influence of the Type of Motorisation

Engaged Gear	**Gas & Diesel**		**Hybrid & Electric**	
	Main noise source	Bracket (dB)	Mode electric	Mode thermal
1	Motor	7	Reduc. > 10 dB	Reduc. > 5 dB
2	Motor	5	Reduc. > 3 dB	Reduc. > 2 dB
3	Equivalent	4	Reduc. > 2 dB	=
4	Tyre/road	3	=	=
5	Tyre/road	3	=	=

In the case of petrol and diesel powered vehicles, the contributions of motor and tyre/road noise to the total emitted noise have been determined (Lelong, 1999). At low ("urban") speeds, a diesel powered vehicle is in many cases the noisiest. Hybrid and more significantly electric powered vehicles bring substantial noise reductions. Concerning the influence of tyres, the results obtained when the vehicles are running in neutral show that the dispersions do not exceed 3 dB (see Figure 53).

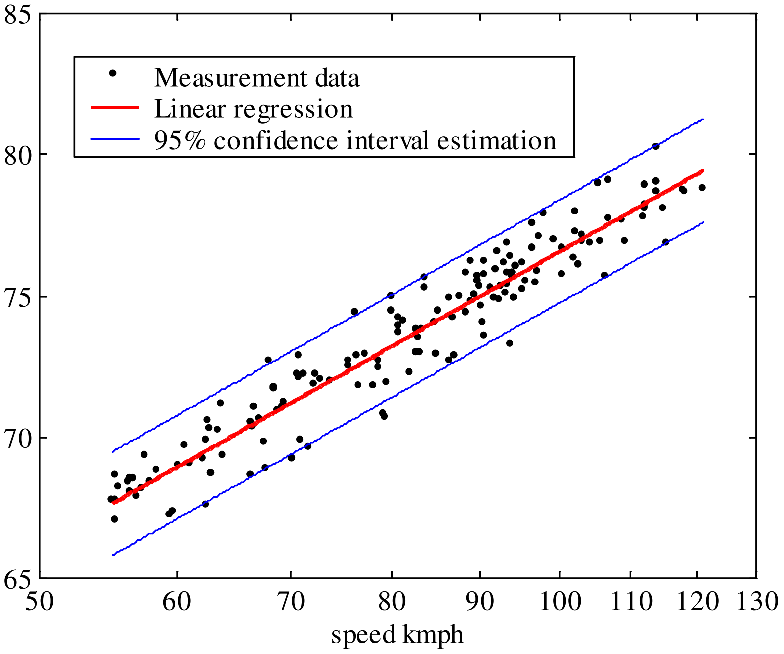


Figure 53: Tyre Noise – Dispersion of Measured Noise Levels (Vehicles Rolling in Neutral)

The results seen in Figure 52 were for vehicles driving at a constant speed. Figures 54 and 55 give similar results, but for vehicles under accelerating conditions.

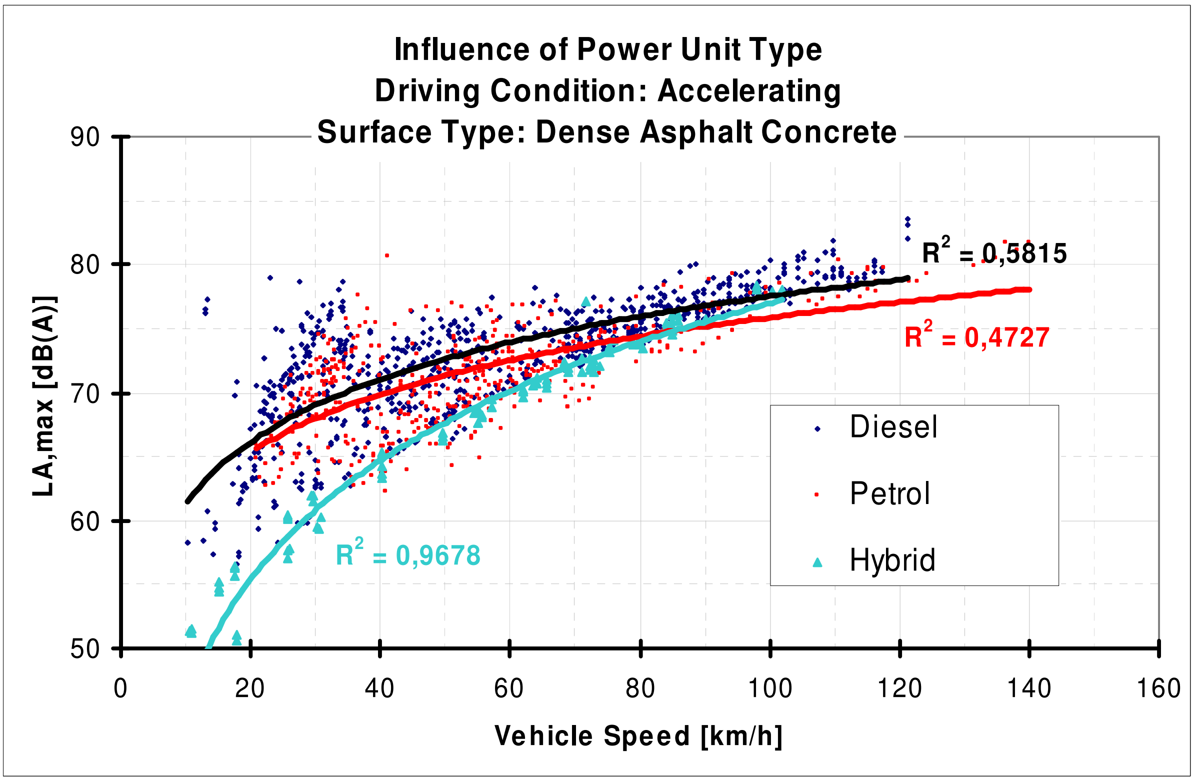


Figure 54: Comparison of Different Power Unit Types of INRETS Data Accelerating on Dense Asphalt Concrete

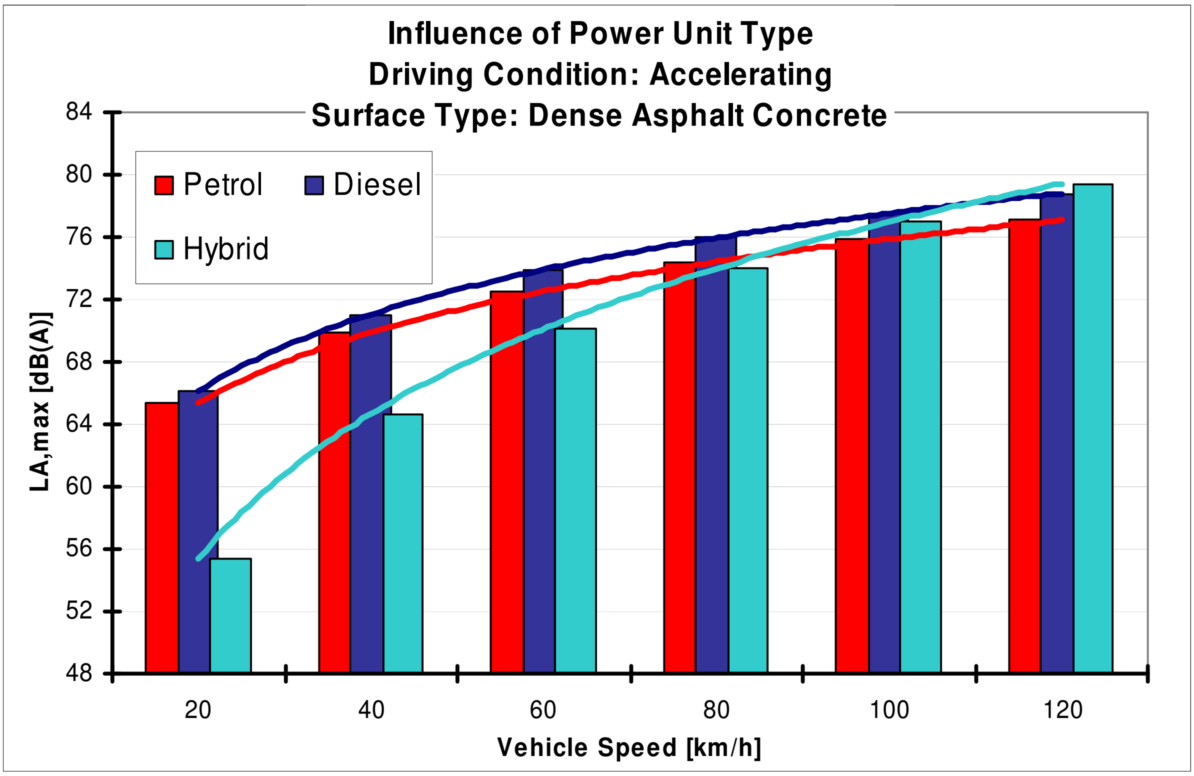


Figure 55: Analysis of INRETS Data of Different Power Unit Types Accelerating on Dense Asphalt Concrete

When comparing Figure 55 to Figure 52, the main difference seen is that the difference between the petrol and diesel vehicles at low speeds is not so noticeable. The hybrid still has quite low noise at low speeds, most likely due to assist from the electric motor and battery power for acceleration.

Figure 56 shows similar results to Figure 55, but based on results from the LCPC dataset. The same trend is seen for the petrol and diesel vehicles.

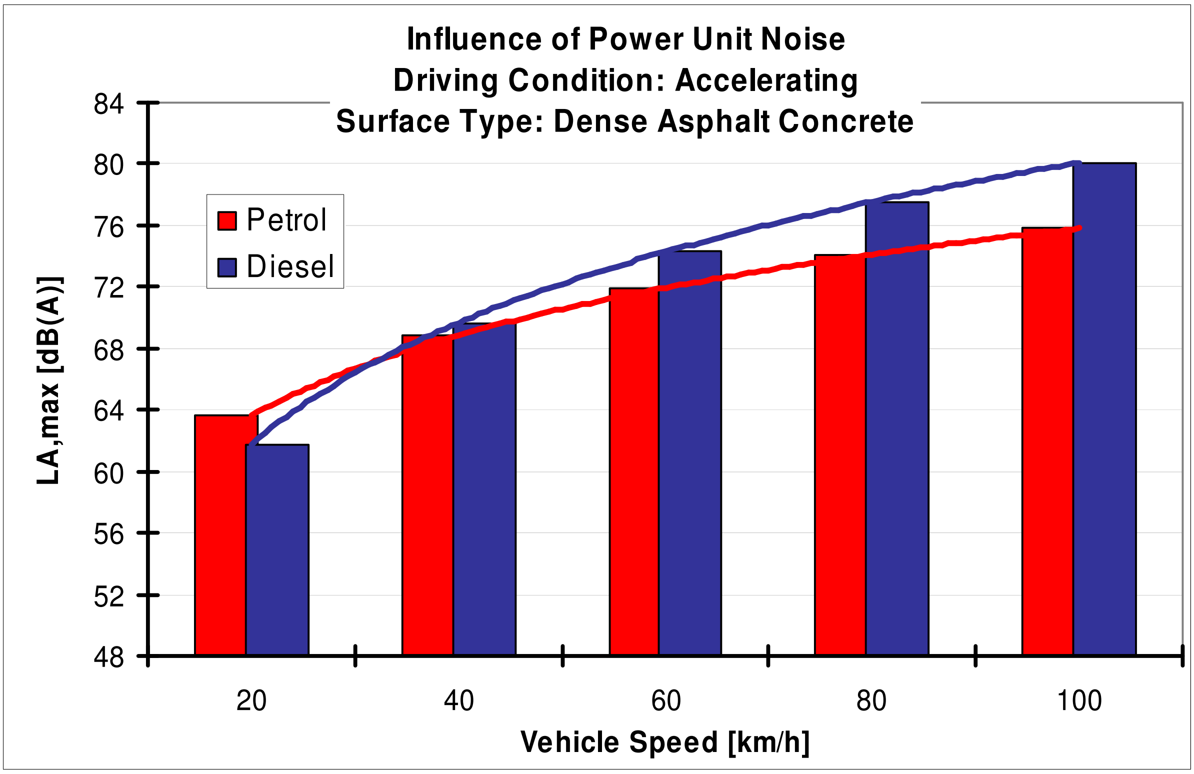


Figure 56: Analysis of LCPC Data of Different Power Unit Types Accelerating on Dense Asphalt Concrete

Figure 57 is a result based on the TUW dataset, where various road surfaces, tyre types and vehicles were tested. The results include an optimisation for passenger cars and for heavy vehicles. The stock passenger car shown in Figure 57 was equipped with a direct injection diesel engine. The "low-noise" passenger vehicle prototype in Figure 57 was the same vehicle type as the stock vehicle, but with the engine and transmission better encased for soundproofing, and included modifications to the air intake and exhaust systems. Additionally, the tyres for the passenger car were optimised based on the tread parameters and material properties (details on these experiments are available in Schwarz, 1998).

For the heavy vehicle comparison shown in Figure 57, a similar procedure was followed. The "low noise" heavy vehicle included better sound insulation of the engine and drive-line as well as covering of the top and bottom of the framework of the truck cab. The quieter truck tyres involved traction tires with increased tread stiffness in peripheral direction, a continuous central groove in the tread pattern, diagonal transverse grooves and a unidirectional tread pattern (details on these experiments are available in Polt, 1998).

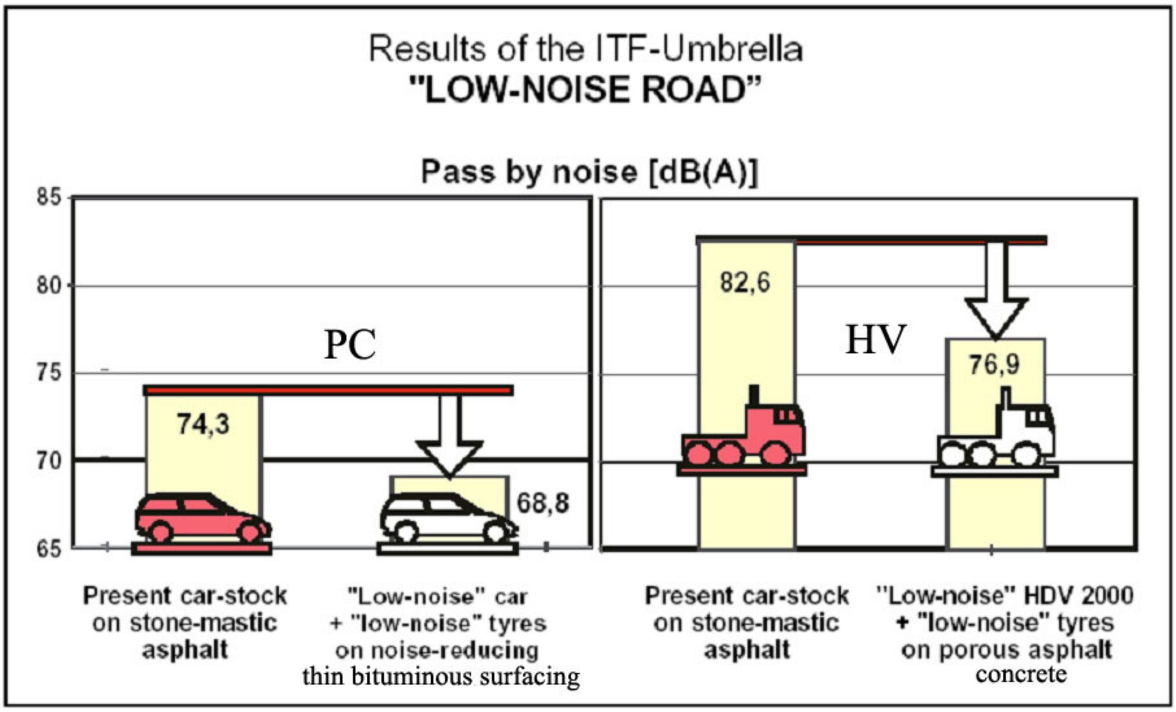


Figure 57: Possible Improvements for Passenger Cars and Heavy Vehicles in the Accelerated Pass-By (Pucher, 1998)

A complete system optimisation of the road surface, the tyres and the vehicle can result in roughly a 5 dB(A) reduction in noise levels. The vehicles used in these analyses were all diesel and petrol vehicles, no hybrid or electric vehicles were included in this dataset. Thus, the results in Figure 57 are for vehicle types commonly available on the market.

5.4. Effect of Tyre Parameters on Noise

5.4.1. General Remarks

The tyre parameters can substantially influence the levels of traffic noise. It is not only of interest to examine the role that the various tyre parameters play, but in addition to see how these tyre parameters affect the road noise on various types of road surfaces. As was seen previously (Figure 53), the results obtained when the vehicles are running in neutral show that the dispersions from the influence of tyres are in the range of 3 dB or less, so this would be an indicator of the potential improvements through tyre optimisation. This section will review the individual effects of some tyre parameters.

5.4.2. Influence of Tyre Load

The vehicle load can influence the pass-by noise of vehicles, and this difference can depend on the type of surface and the tyre type. Experiments done by the Vienna University of Technology (TUW) looked at this particular issue. Testing was performed on a vehicle under loaded and unloaded conditions to determine the effects of vehicle load on the pass-by noise. Experiments were performed on several tyre tread variations so that the influences of the tyre tread pattern could be seen.

All tyre variations for the TUW experiments on vehicle load had dimensions 175/70 R13 82T. Noise measurements were carried out in accordance with the measurement standard 92/23/EWG. This meant that when the tests were carried out for the unloaded vehicle, the tyre inflation pressure ranged from 1,9 to 2,1 bars, while when the test vehicle was loaded, the tyre inflation pressure was between 1,6 and 1,7 bars. For the loaded condition the tests were carried out with the vehicle at 70% to 90% of the rated load.

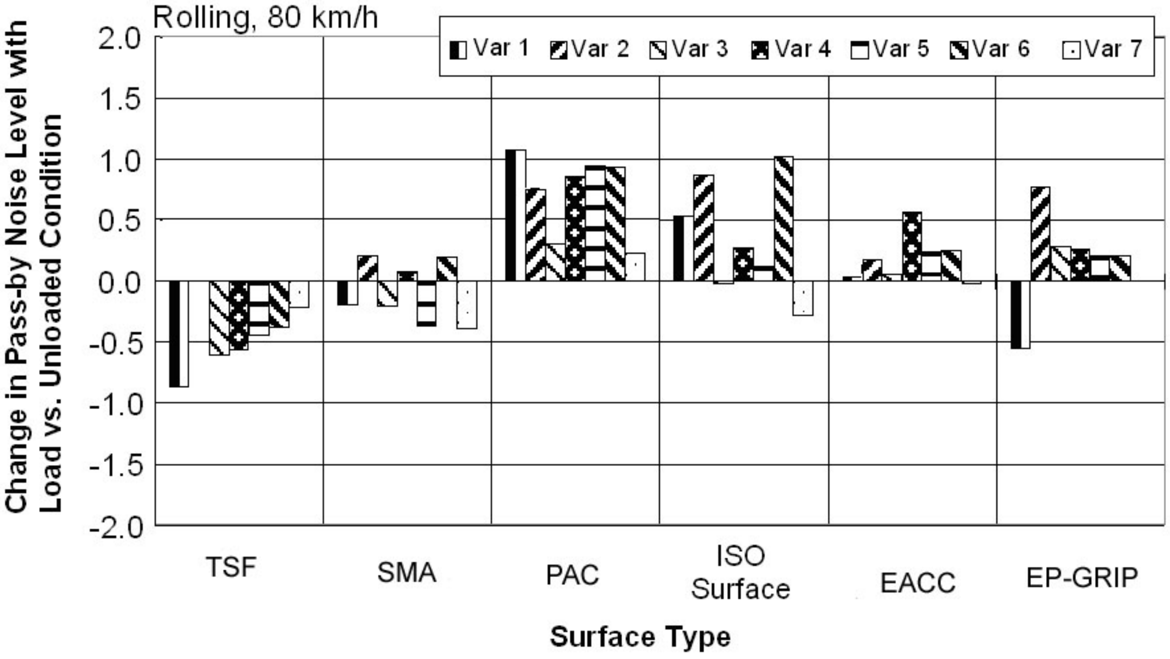


Figure 58: Difference in Rolling Noise from a Vehicle Under Loaded to Unloaded Conditions for 7 Different Tyre Tread Pattern Variations on 6 Surface Types

The effect of vehicle load, in combination with a reduction in the tyre pressure, on the rolling noise is small, and depends on the road surface. On Stone Mastic Asphalt there is essentially no change, on Porous Asphalt Concrete, EP-Grip, Exposed Aggregate Cement Concrete and the ISO surface there is an increase in the pass-by noise of up to 1,1 dB(A). On Thin Bituminous Surfacing there is a reduction in the noise level when the vehicle is loaded.

On an ISO surface from M+P (Roovers, 2003) the results were similar to those from the TUW experiments, as can be seen in the following table. Loading of the vehicle resulted in an increase of 1,7 dB(A) when the tyre pressure was changed vs. the unloaded condition (from 2,4 bars to 1,8 bars). For a constant tyre inflation pressure the noise increase with loading of the vehicle was lower, giving an increase of 1,4 dB(A). The results of these two data sets is in reasonable agreement for the ISO surface, showing an increase in noise level (of from 1 to 1,7 dB(A)) for an increase in load with a decrease in tyre inflation pressure.

Table 7: Influence of Tyre Load and Pressure on Coast by Noise (dB(A)) for an ISO Surface (Roovers, 2003)[a]

Tyre Type and Usage	Noise Level Loaded 1,8 bars	Noise Level Unloaded 1,8 bars	Noise Level Unloaded 2,4 bars
Goodyear Eagle NCT 2 175/65 R14T 7000 km	-	-	71,5
Pirelli P3000 Energy 175/70 R13T 100 km	72,9	71,5	71,2
Michelin Energy XT-1 175/65 R14T 100 km	72,0	70,9	-
Pirelli P 5000 Drago 195/50 R15V 100 km	-	72,0	-

[a] Experiments performed using a Peugeot 206 test vehicle at 80 km/h

5.4.3. Influence of Tyre Inflation Pressure

Figure 59 shows the effect of tyre inflation pressure on pass-by noise levels from the TUW dataset. The results show the difference in sound levels versus a tyre with no load and a standard tyre inflation pressure. The effects of increasing the inflation pressure, of decreasing the inflation pressure, and of decreasing the inflation pressure and increasing the load are given.

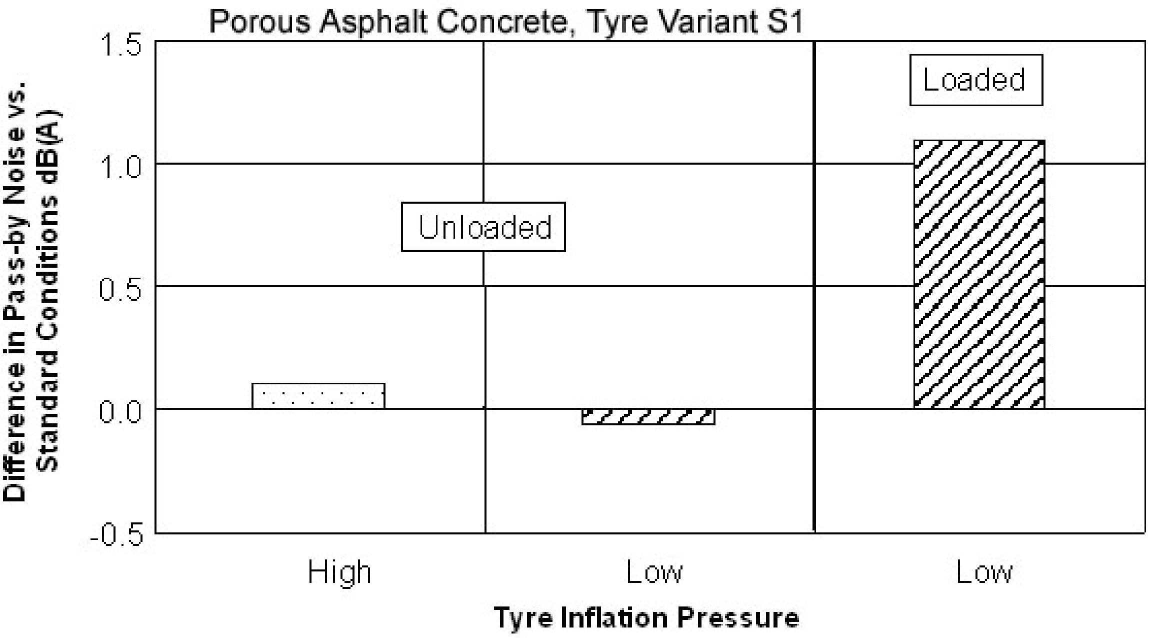


Figure 59: Difference in Rolling Noise from an Unloaded Vehicle with Tyre Inflation Pressure Increased and Decreased vs. the Standard Level, and for a Loaded Vehicle

From the figure, it can be seen that the effect of the tyre inflation pressure for the given tyre on Porous Asphalt Concrete was essentially negligible. This is in modest agreement with the results obtained by M+P (Roovers, 2003) as seen in Table 7 in Section 5.4.2. The M+P results showed a pass-by noise increase of about 0,3 dB(A), while the results in Figure 58 from TUW showed a decrease of around 0,2 dB(A), when the tyre inflation pressure was lowered. Note that the M+P data were from cruise-by (engine on) tests and on an ISO surface while the TUW results in the figure were from roll-by (engine off) tests and on a Porous Asphalt Concrete surface.

5.4.4. Influence of Tyre Width

The effect of tyre width on noise levels has been extensively studied. From the literature, it was seen in Chapter 3 that to some extent the consensus is that the noise level increases with tyre width. This is not always the case, however, and the effect depends upon the vehicle load, tread pattern and other variables.

The results of measurements by INRETS included measurements of tyres with various widths, all taken with the same measurement method and similar conditions. These experiments were performed for 34 different tyre types. Data were extracted for tests done with varying tyres on the same surface. These results are shown as Figure 60. The tyre widths shown in the figure are based on the individual tyre specifications. There was not sufficient data on varying tyres for the same vehicle, so the results are for multiple passenger vehicle types. Thus, the loading on the tyres presented in the results varies for the data shown, possibly explaining part of the wide spread in the results. The varying tread patterns and other tyre properties would also contribute to the spread in the data. Nonetheless, for this general survey of results, the trend is that the tyre width increases the pass-by noise - in a range of tyre width from 155 mm to 205 mm at 80 km/h, the average increase in noise level is approximately 1,5 dB(A).

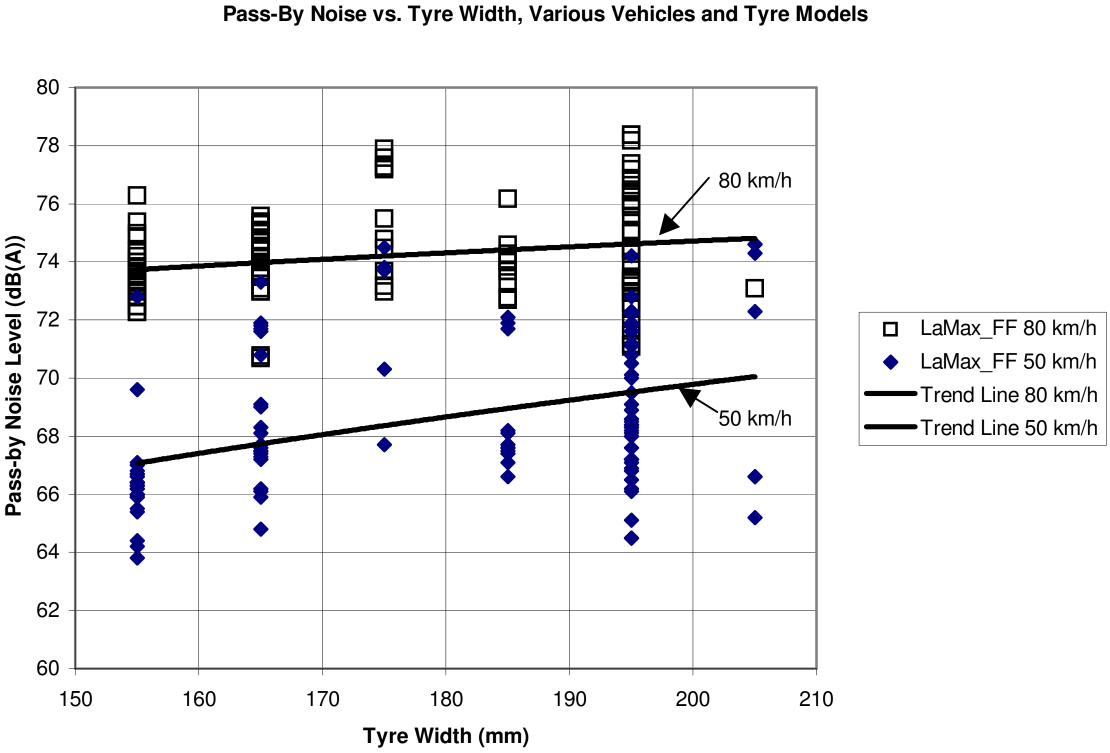


Figure 60: Cruise-By Noise Levels for Vehicles with Various Tyre Widths at Speeds of 50 and 80 km/h on Dense Asphalt Concrete

The influence of tyre width on tyre/road noise was investigated by Roovers (2002). From a collection of measurement results for 138 tyres, measured by M+P, TüV, TRL, and ADAC following the EU directive, a positive correlation was found between tyre width and the rolling noise on the ISO-10844 surface. The correlation is displayed in Figure 61.

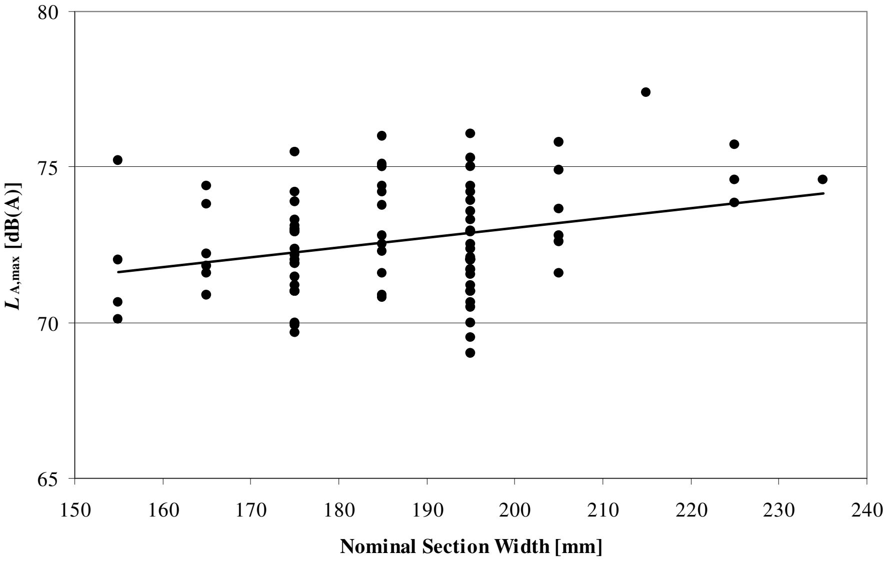


Figure 61: Correlation Between Tyre Width and the Rolling Noise Level on the ISO-Surface, (from Roovers, 2002)

The data in Figure 62 show further evidence of an increase in noise level with tyre width. These data are for passenger vehicles taken on an average road surface (Kemper, 1989).

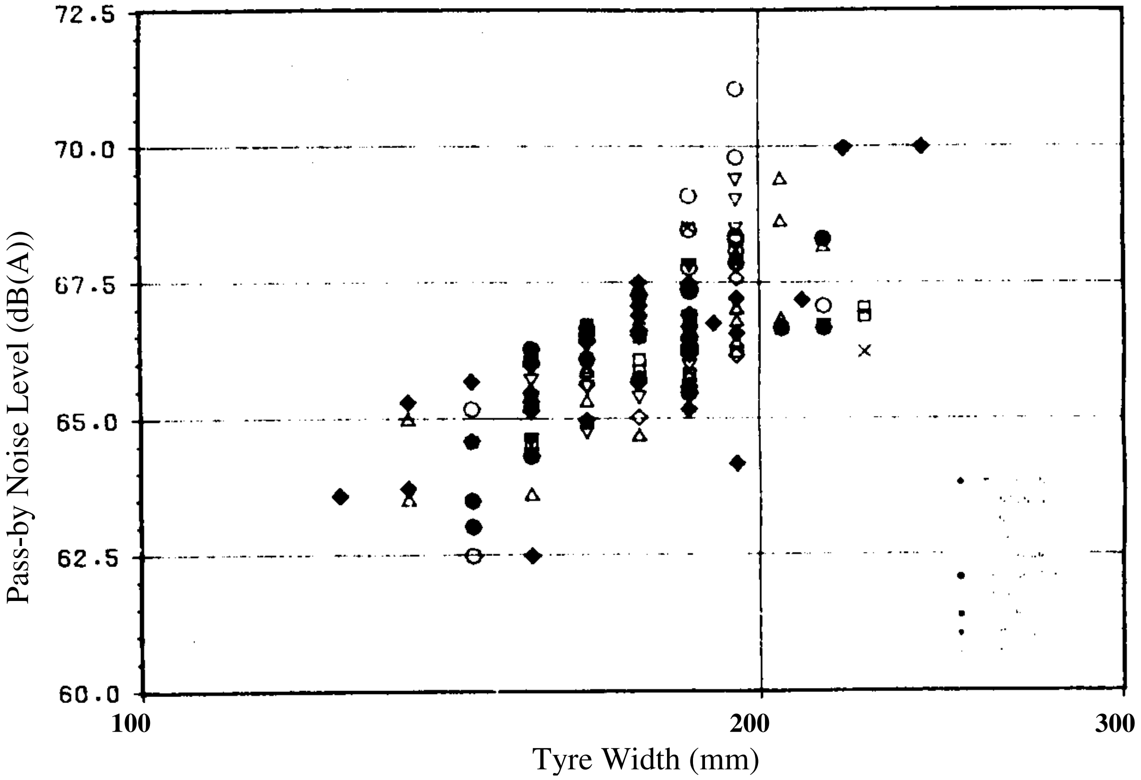


Figure 62: Effect of Tyre Width on Pass-By Noise from Passenger Cars on an Average Road Surface (Adapted from Kemper, 1989)

Figure 63, adapted from Stenschke (2003), shows further evidence of this general trend toward an increase in pass-by noise with increasing tyre width. Interestingly, the trend seems to reduce itself for tyres over 215 mm in width. These results were found from measurements following the EU directive and with 82 different tyres.

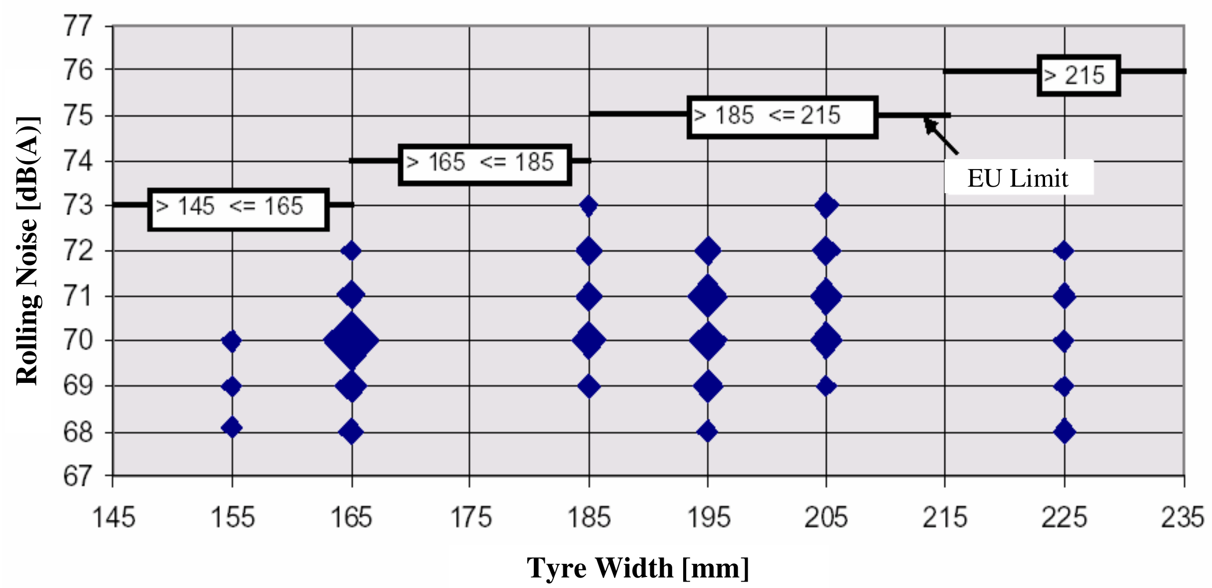


Figure 63: Relation Between Rolling Noise and Tyre Width for 82 Tyre Types – Data Rounded to 1 dB(A) (Stenschke, 2003)

Figure 64, taken from Sandberg (2000), gives an overview of tyre width effect for several datasets. The data is for a total of 276 passenger car and truck tyres, and is for pass-by measurements either taken at or corrected to 80 km/h. While the noise spread among various tyres is noticeable, the noise increase with increasing tyre width is apparent.

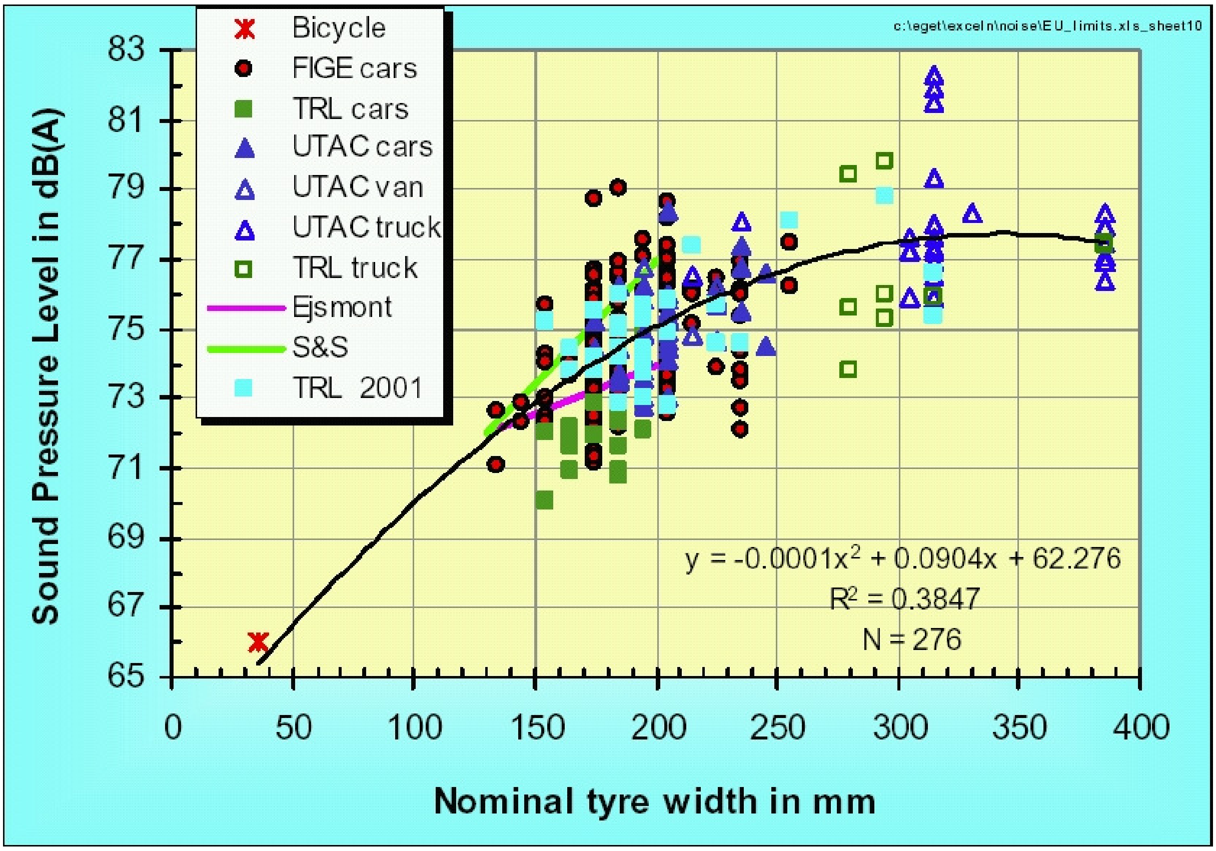


Figure 64: Noise vs. Tyre Width for a Full Range of Tyre Sizes (Sandberg, 2000).

The Transport Research Laboratory (TRL) in England has also performed experiments evaluating the effects of tyre width of the noise emission levels. They have found a correlation between the noise, tyre width and tyre diameter as follows on an SMA surface:

$$L_{SMA,100} = 92.8 + 0.033 * WIDTH \, ,$$

where $L_{SMA,100}$ is the noise level on the SMA surface at 100 km/h for a passenger car (Abbot and Watts, 2003). Thus, the noise level for this particular example increased by approximately 0,3 dB(A) for every 10 mm increase in tyre section width in the range from 145 to 235 mm.

For truck tyres, the same study by TRL found that the noise level increased by approximately 0,1 dB(A) for every 10 mm increase in tyre section width in the width range from 255 to 495 mm, fairly independent of the road surface type (Abbot and Watts, 2003).

Figure 65 shows the effects of tyre width on vehicle noise from several measurements taken by TRL (Phillips, 2001). These results are for near-field measurements, so that while the trends can be observed, the noise levels will of course be higher than the far-field results seen in the previous figures.

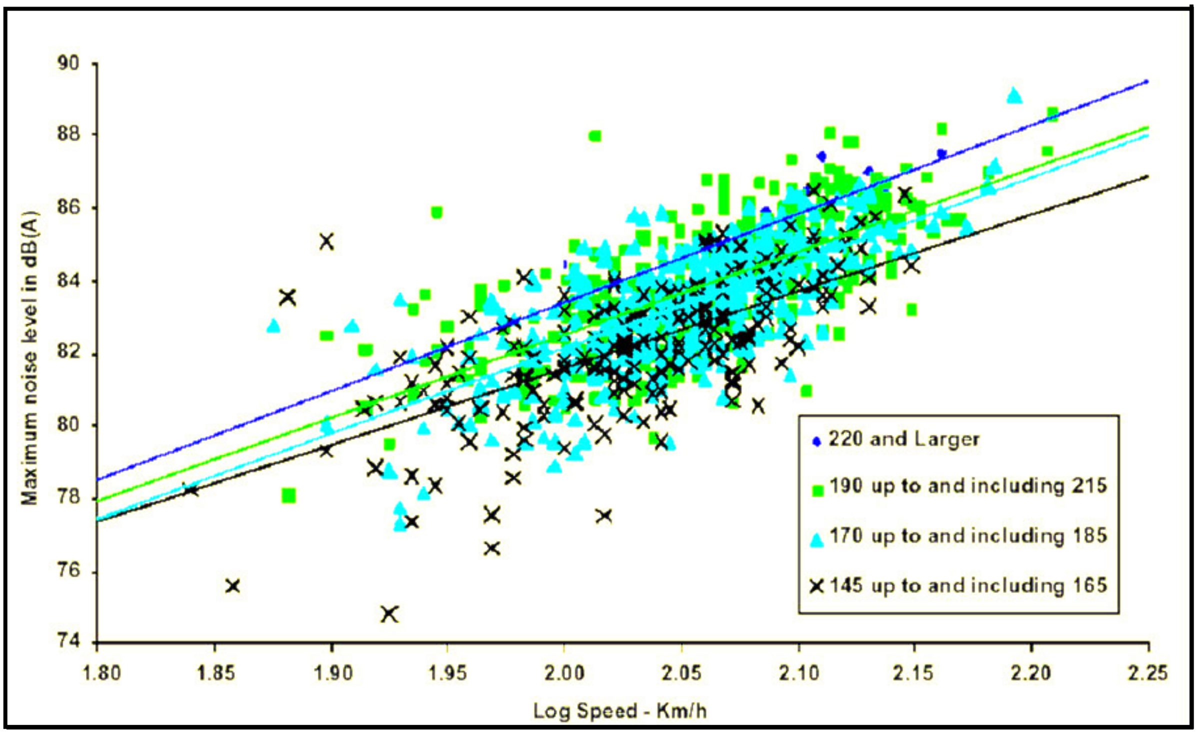


Figure 65: Influence of Tyre Width On Near-Field Noise for Various Road Surfaces (Phillips, 2001)

The data from Phillips (2001) shows a trend of increasing noise level with increased tyre width, over the speed range studied. Figures 64 and 65 combine to show that the trend of increasing noise with tyre width is consistent among various tyre types.

As can be seen, there is much data available on the influence of tyre width on tyre/road noise. The general trend based on all these data (weighting of separate results according to level of detail in the results) is that an increase in the tyre width of 25 mm results roughly in an increase of 1 dB(A) in the noise level below, say, 200 to 215 mm.

5.4.5. Influence of Tyre Diameter

The diameter of the tyre also plays a role in the tyre/road noise. The diameter can influence the noise emission through the horn effect and through the tread impact on the road surface.

Sandberg and Ejsmont (2002) showed that increasing the tyre diameter led to an increase in noise for tyre widths below 195 mm. They mention that this may be due to the horn effect becoming more efficient at the smaller angle of attack that a larger tyre diameter would produce. However, they also mention that a smaller angle of attack has the opposite effect on tyre tread impact noise. Thus, a logical conclusion would be that on a rough surface, where the tread impact would have a larger effect and the horn effect would be somewhat minimised due to the large texture providing air pockets, the increase in tyre diameter would lead to a decrease in tyre noise. On the other hand, for smooth surfaces, the tread impact effect would be lessened, and the increase in tyre diameter could lead to an increase in noise due to the increased efficiency of the horn effect with the smaller attack angle.

Abbot and Watts (2003), measuring the correlation coefficients of various tyre parameters on noise levels, found that the tyre diameter had a slight negative correlation coefficient for two road surfaces, Hot Rolled Asphalt and Porous Asphalt Concrete, meaning that as the tyre diameter increases, the noise level is decreased.

Figure 66 shows results from some analyses on the relation between rim diameter (which is closely related to tyre diameter) and rolling noise level on the ISO-surface. These data were taken from the combined dataset from M+P, TüV, TRL, and ADAC (Roovers, 2002). A small positive correlation was found between rim diameter and rolling noise level. However, this might be due to the correlation between rim diameter and tyre width, because in general wide tyres are mounted on large rims with a low aspect ratio.

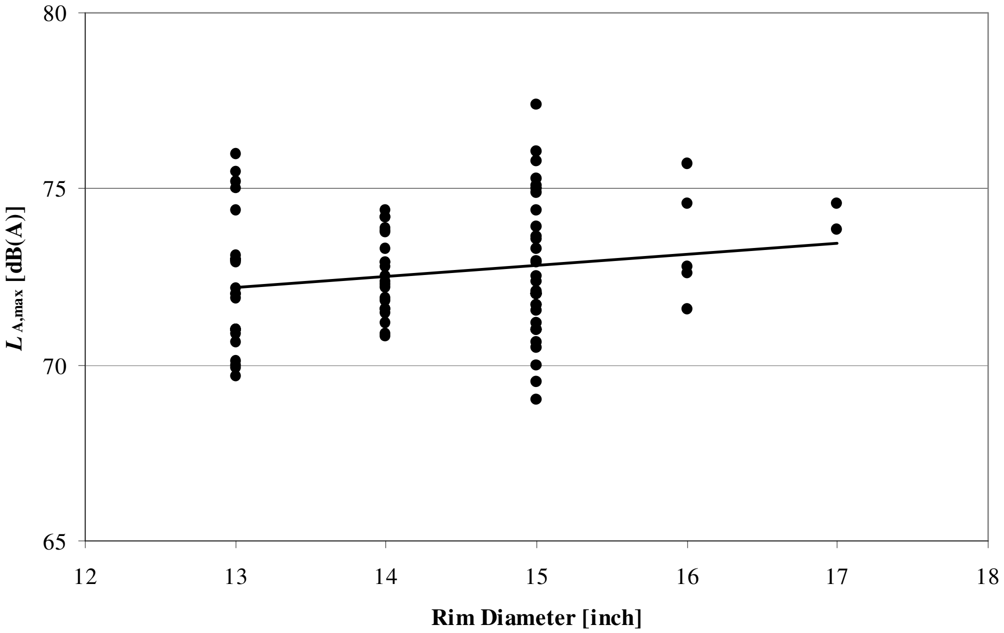


Figure 66: Correlation Between Rim Diameter and Rolling Noise Level on an ISO-Surface (Roovers, 2002)

The INRETS dataset also included data on tyre properties, so that a simple analysis of the tyre diameter effect on noise levels could be performed. Figure 67 shows the overall effect of tyre diameter for a variety of vehicles and tyre types. Note that the tyre width also varied in these results. The results shown were taken on a Dense Asphalt Concrete surface, at a constant speed of 80 km/h.

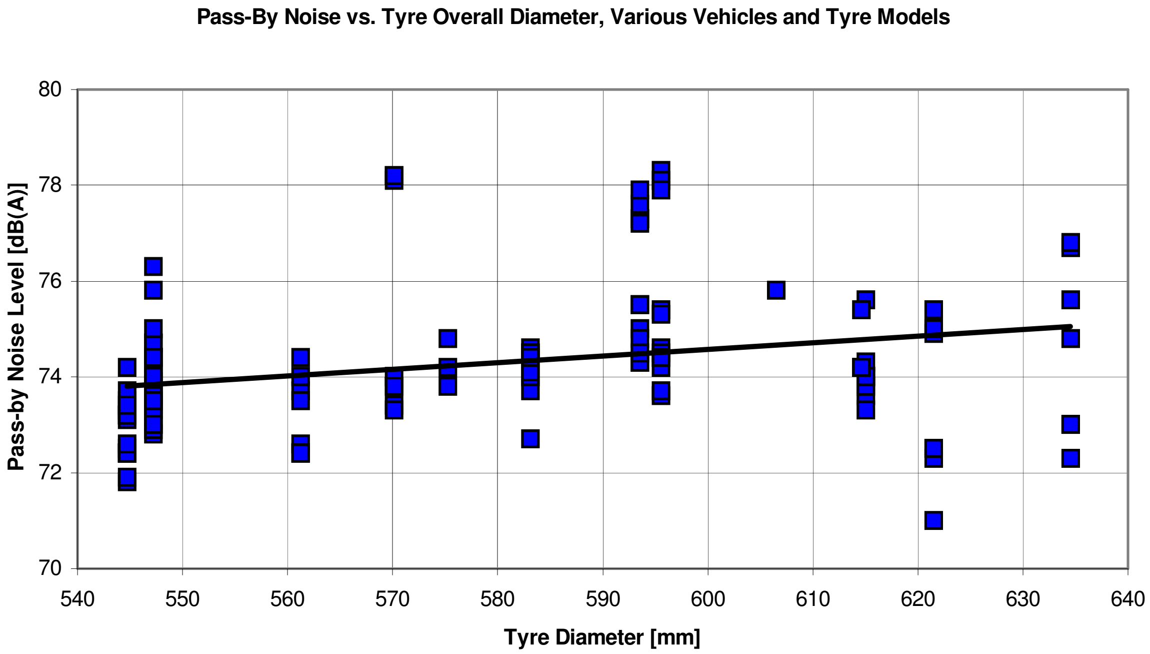


Figure 67: Influence of Tyre Diameter on Pass-By Noise for Dense Asphalt Concrete, for Tyres with Various Tread Patterns and Tyre Widths, 80 km/h

The results show that, while in some cases a slight trend toward an increase in tyre noise with increasing tyre diameter exists, the range of values depending on other tyre parameters makes quantification of the effect of tyre diameter difficult. In summary, the results observed tend to indicate that the influence of tyre diameter on pass-by noise is small, as the effect on the tread impact mechanism and on the horn effect seem to counteract each other to some extent.

5.4.6. Influence of Tyre Material Properties

The Shore Hardness of the tyre will also have an effect on the noise level. Results from the TUW dataset included a study of the influence of various tyre material properties on tyre/road noise. The following table shows the parameters varied as part of this study.

Table 8: Parameters varied in TUW dataset for evaluation of tyre material properties on Noise Levels. The changes are all vs. a reference tyre of size 195/65 R15 91H (Schwarz, 1998)

Tyre Variant	Sidewall Reinforced	Belt Angle [deg]	Belt Thickness	Tread Layers	Base Rubber Thickness [mm]	Base Mix
SA1	Yes	Ref. tyre	Ref. tyre	Ref. tyre	Ref. tyre	A
SA2	No	Ref. tyre	Ref. tyre	Ref. tyre +2	Ref. tyre +1,5	B
SA3	No	Ref. tyre +4	Ref. tyre	Ref. tyre	Ref. tyre +1,5	A
SA4	Yes	Ref. tyre +4	Ref. tyre	Ref. tyre +2	Ref. tyre	B
SA7	Yes	Ref. tyre +4	Increased	Ref. tyre	Ref. tyre +1,5	B
SA8	No	Ref. tyre +4	Increased	Ref. tyre +2	Ref. tyre	A
SA9	No	Ref. tyre	Increased	Ref. tyre +2	Ref. tyre	A
SA10	No	Ref. tyre +4	Increased	Ref. tyre +2	Ref. tyre	A
SA11	Yes	Ref. tyre	Increased	Ref. tyre	Ref. tyre	B

Table 8 describes the manner in which several material properties of the tyre were varied. These tyre variants were all based on a standard reference tyre of size 195/65 R15 91H. The base mix Variants A and B had varied Shore Hardness values, Variant B being a harder rubber than Variant A.

Figure 68 shows how changes in these tyre properties effected the pass-by noise on the various surface types. Of the properties varied, the increased base rubber thickness had the most noticeable influence on the noise levels. On all road surfaces there was a reduction in noise from 0,7 to 2,0 dB(A). This can be seen by comparing tyres SA2, SA3 and SA7 with the reference tyre S2 in Figure 68. The difference was most noticeable on the surfaces with larger textures, such as EP-GRIP, Stone Mastic Asphalt and Porous Asphalt Concrete. Increasing the belt thickness resulted in a noise decrease ranging from 0,2 to 1,2 dB(A) depending on the road surface. Reinforcing the sidewall had an influence of around 0,2 to 0,7 dB(A). Increasing the tyre hardness did not result in a measurable change in the pass-by noise for the two tyre hardness values tested. Unfortunately, the actual shore hardness values for the two rubber compounds used were not available, so the amount of change in the rubber hardness for these tests is not quantified.

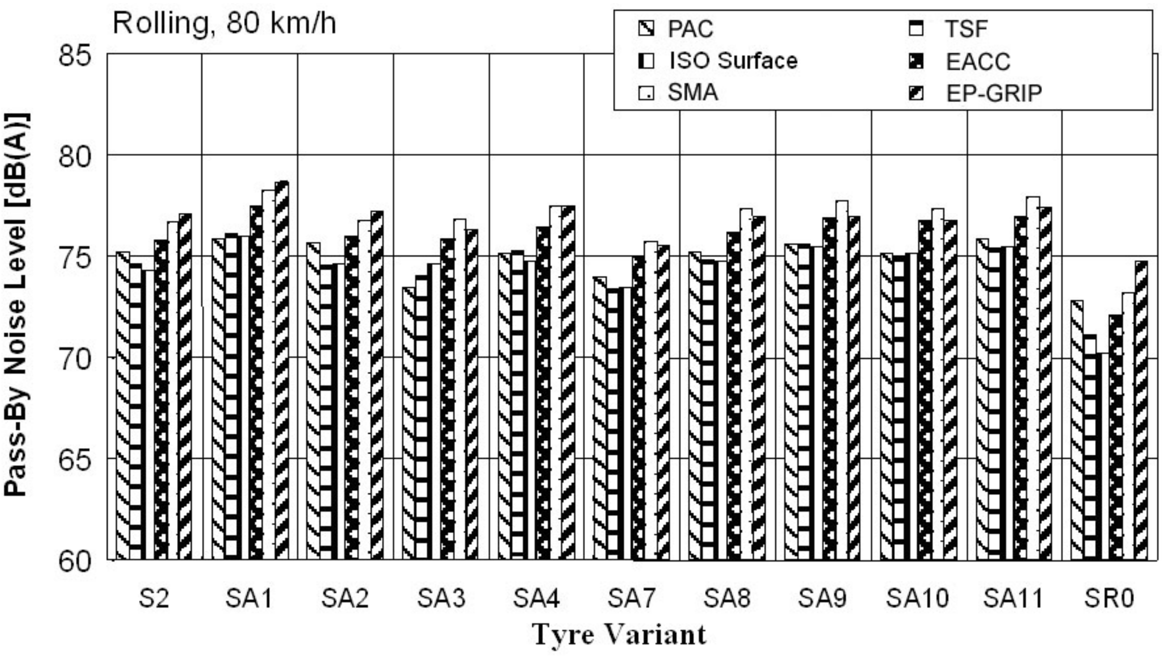


Figure 68: Effect of Tyre Base Construction Properties on Pass-By Noise for Various Surfaces, Tyres Based on Reference Tyre S2 with Size 195/65 R15 91H – SR0 is a Slick

Based on the results shown in Figure 68, a theoretical tyre with optimised material properties (called variant SAFL) was compared with the basis tyre. The results of this comparison for the various road surface types are given in Figure 69.

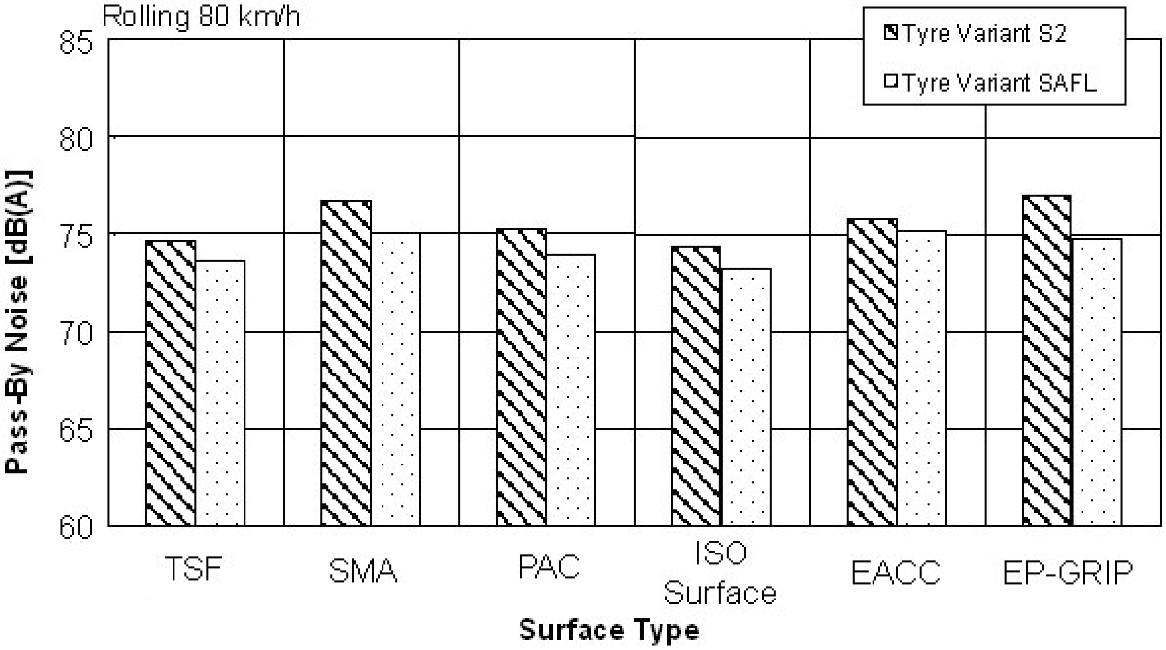


Figure 69: Comparison of a Tyre with Optimised Base Construction Resulting from Results of Figure 68 versus the Standard Reference Tyre S2 on Various Surfaces, both Tyres had Dimensions 195/65 R15

Figure 69 demonstrates that an optimisation of tyre material properties can result in a noise reduction of 0,5 to 2 dB(A), depending on the road surface type. Once again, this is only for the range of material property values used in the study. It is possible that a further reduction in noise level could be achieved by wider variations in the various tyre material properties.

5.4.7. Influence of Tyre Tread Pattern

There are several properties of interest regarding the tyre tread pattern. While this report will not go into all tyre tread pattern parameters, a few of those thought to be more influential will be examined.

Circumferential Groove Orientation

The arrangement of the circumferential grooves, also known as longitudinal or rib grooves, on tyres can influence the tyre road noise. The TUW dataset includes measurements on several test tyres where the orientation of the circumferential grooves was varied while holding the other tyre properties constant. Figure 70 shows the circumferential groove patterns of the test tyres.

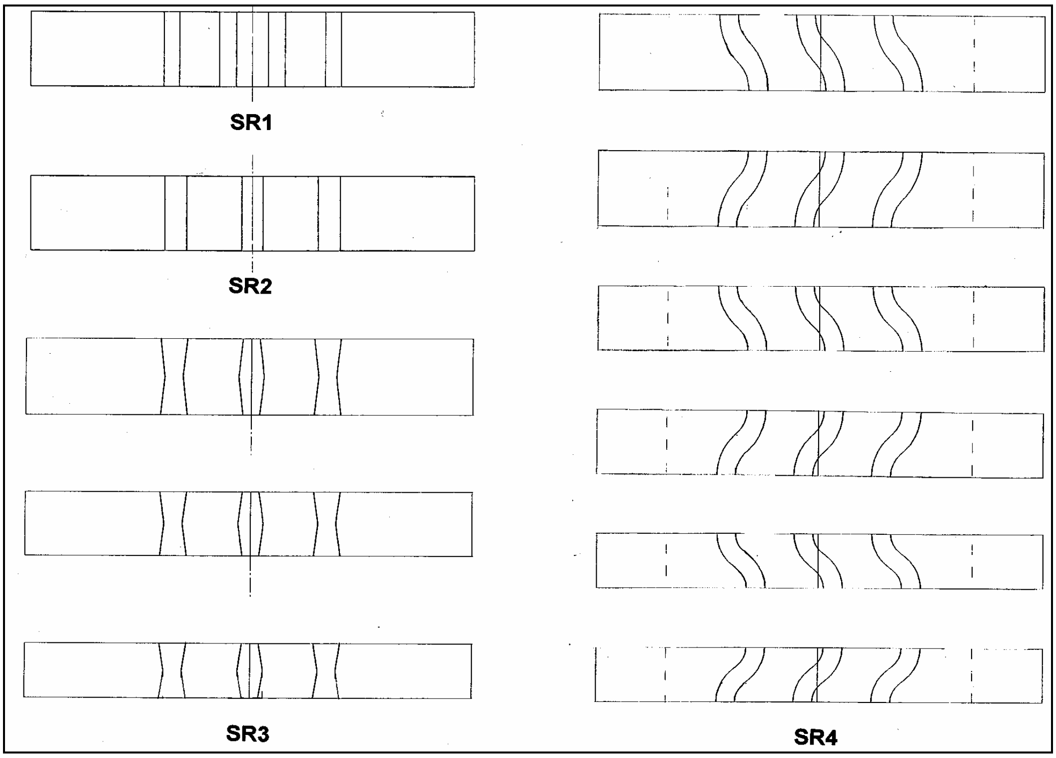


Figure 70: Arrangement of Circumferential Grooves of the Various Test Tyres. All Test Tyres Shown Were Sized 195/65 R15 91H (Schwarz, 1998)

The tyre variant SR1 consisted of 4 longitudinal grooves, while the SR2 variant had 3 grooves. The profile of tyre variant SR3 had angled grooves. There were 3 versions of tyre variant SR3, where the types of angles in the grooves was varied. The change in the groove cross section was expected to reduce the resonance of vibrations. The variant SR4 consisted of s-shaped grooves. Six versions of variant SR4 were used, consisting of six different pitches in the grooves. The cross section of the curving longitudinal grooves varied for the SR4 tyres.

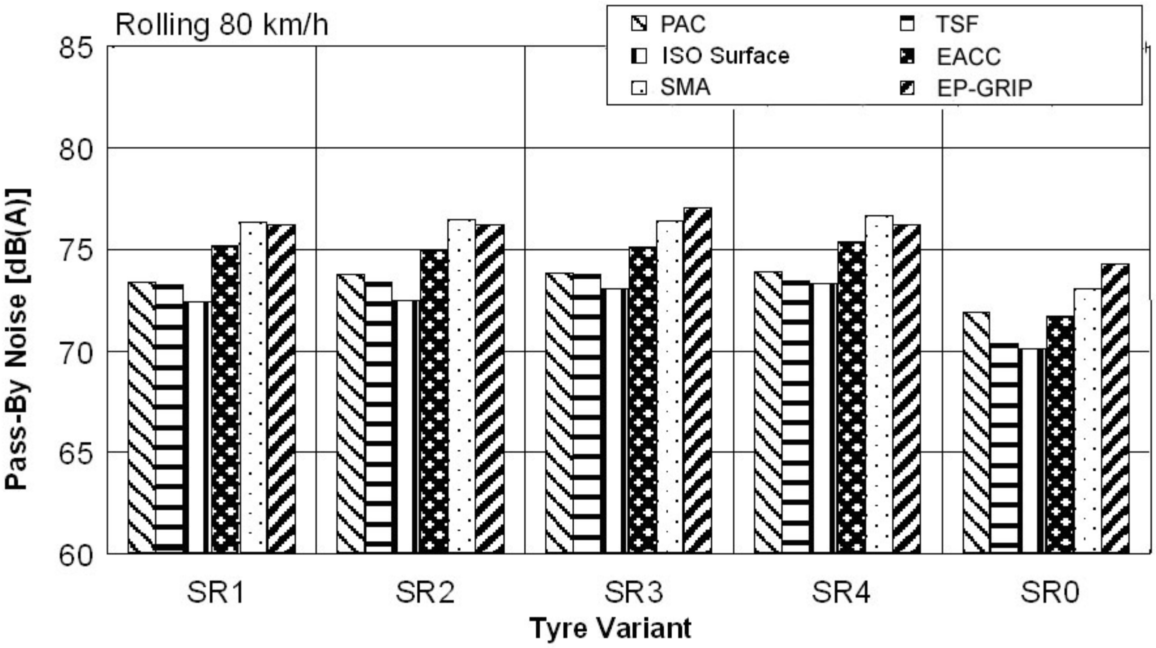


Figure 71: Rolling Noise at 80 km/h for Several Tyre Longitudinal Groove Orientations on Various Surfaces – Refer to Figure 70 for the Tyre Variant Descriptions, SR0 is a Slick

The TUW dataset shows that introducing longitudinal grooves on a smooth tire leads to an increase in the pass-by noise on all surfaces tested. The execution of the groove form with a variable cross section does not show a reduction of the groove resonance. It should however be noted that the introduction of cross-ways grooves in addition to the longitudinal grooves, to allow better ventilation, would most likely reduce the effect of adding the longitudinal grooves.

Tread Pitch, Number of Treads

The TUW dataset also included a study of the influence of various tread patterns. Figure 72 shows 8 experimental tyres for which all properties except for the tread pattern were held constant. The number and pitch of the treads was varied for these 8 tyres to see how these parameters would influence pass-by noise.

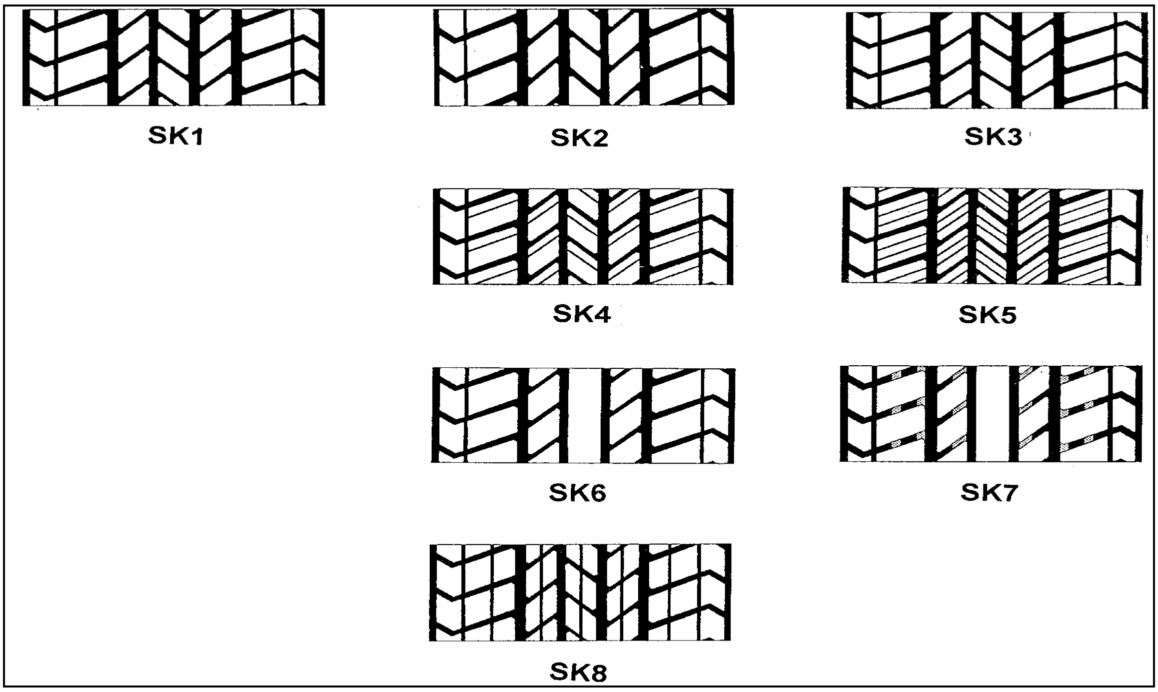


Figure 72: Tread Arrangements for TUW Dataset Study on Tread Pattern Effects for Noise Levels… all Tyres of Size 195/65 R15 91H

Pass-by noise measurements were performed using these test tyres on various surfaces. The results of these experiments are given in Figure 73.

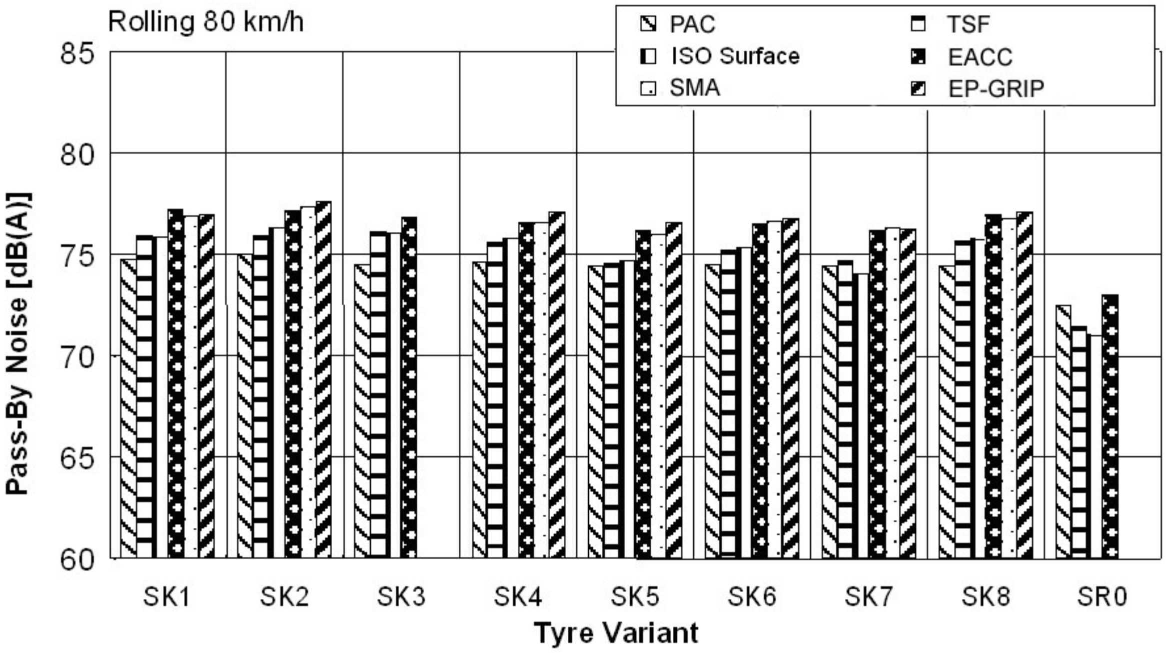


Figure 73: Effect of Tread Pattern Variations on Various Surfaces - All Tyres of Size 195/65 R15 91H, SR0 is a Slick, for Tread Types see Figure 72

As can be seen from Figure 73, the tread pattern can have a substantial influence on the pass-by noise level. For an accelerating vehicle, the tread pattern may play a more important role, as there will be more tangential torque on the tyre treads. Figure 74 shows results for the tyre tread variations given in Figure 72, but for accelerated pass-by measurements. The noise levels shown in Figure 74 are higher than for the rolling noise measurements in Figure 73 even though it is accelerated pass-by results because the vehicle speeds in Figure 74 start at 50 km/h, while the results in Figure 73 were measured at 80 km/h.

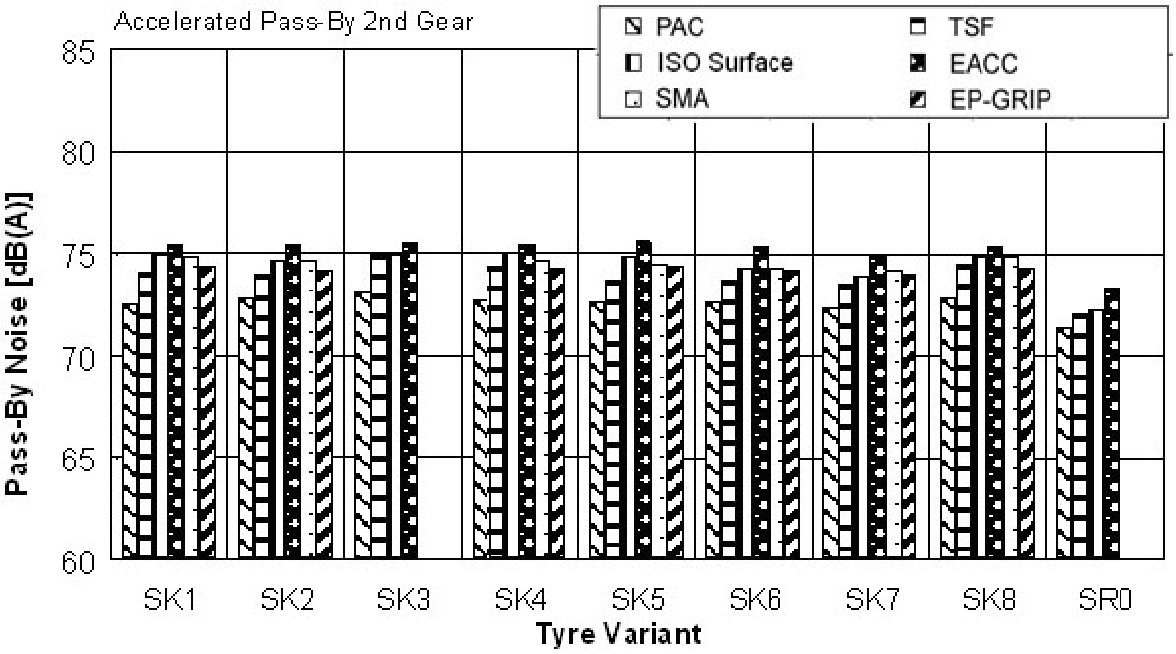


Figure 74: Accelerated Pass-By Noise for 8 Tyres with Varying Tread Patterns on Several Road Surfaces and the Reference Tyre SR0 (Slick)

A reduction of the depth of tread, achieved by increasing the pitch, resulted in an increase in the noise levels on all surfaces (seen by comparing tyre SK3 with the basis tyre SK1). Following the same trend, the tyre having the lowest pitch number and the increased depth of tread, tyre SK2, gave the largest reduction in noise levels vs. the basis tyre.

It can also be seen that a reinforcement of the overall tread surface area by introducing a solid longitudinal tread in the centre of the tyre resulted in a reduction in accelerated pass-by noise on all road surfaces. The tyres having this closed centre tread were SK6 and SK7.

Overall, for the tyres tested, the variations in tyre tread pattern resulted in a noise effect in the range of 1 dB(A). It should however be noted that the tread pattern can also increase or decrease the effects of varying other tyre properties.

Profile Properties

The reference tyre that was the basis of the profile variation tyres was the tyre tread SM7. The size dimensions of all these tyres were 175/70 R13 82T. The inner and outer shoulders of the tyre were rotated outward vs. the SM7 tyre to produce the SM6 tyre. By making the shoulder tread blocks on the inner and outer edge of the tyre equal and aligned in the circumferential direction, the SM8 tyre was made. With the profile SM9 the two longitudinal grooves are widened in each case by 1 mm in relation to the profile SM7. All blocks remain the same size, so that the distance between the individual blocks of the centre area was reduced accordingly. Also with the profile SM10 the longitudinal grooves were widened by 1 mm, however the distances between the blocks within the centre area were kept constant and the blocks within this range were made smaller. Further, as with the variant SM6, the shoulder area was modified in such a way that all tread block edges were aligned. For the increase of the block rigidity reinforcement bars were also inserted in the tyres. The results of these modifications to the tyre profile are given in Figure 75.

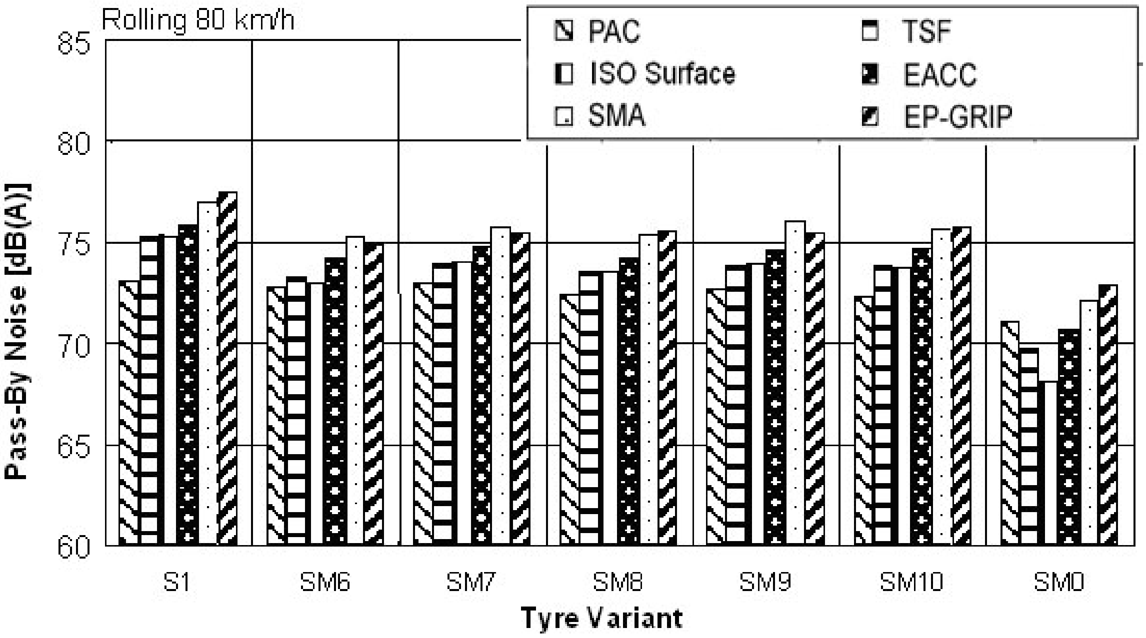


Figure 75: Influence of Profile Depth for Several Experimental Tyres - Tyres were Based on the Reference Tyre but With Varied Profile Properties

The tyre variant SM6, where the inner and outer shoulders of the tyre were rotated outward, showed the most substantial reduction in noise levels for all road surfaces tested. Overall, the variations in the tyre profile properties resulted in possible pass-by noise reductions ranging from 0 to 2 dB(A), depending on the surface type.

It has been shown that several tyre parameters have an influence on tyre/road noise. Analyses as part of this research included tyre pressure and load, tyre width, diameter, material properties and tread pattern.

5.5. Noise Spread Among Various Tyres

Many of the results shown in Section 5.4 demonstrated the range of noise levels based on variations in the tyre parameters. TÜV Automotive has done a series of tests under the same conditions for various tyre types available on the market (TÜV, 2003). As a summary of the discussion on the noise spread among tyres on the market, results from these experiments are given in Figures 76 and 77. Figure 76 shows the minimum and maximum noise levels for the tyre size ranges tested. Additionally given in the axis is the number of tyres tested for each size range. Figure 77 shows the range of the noise levels based on the results of Figure 76.

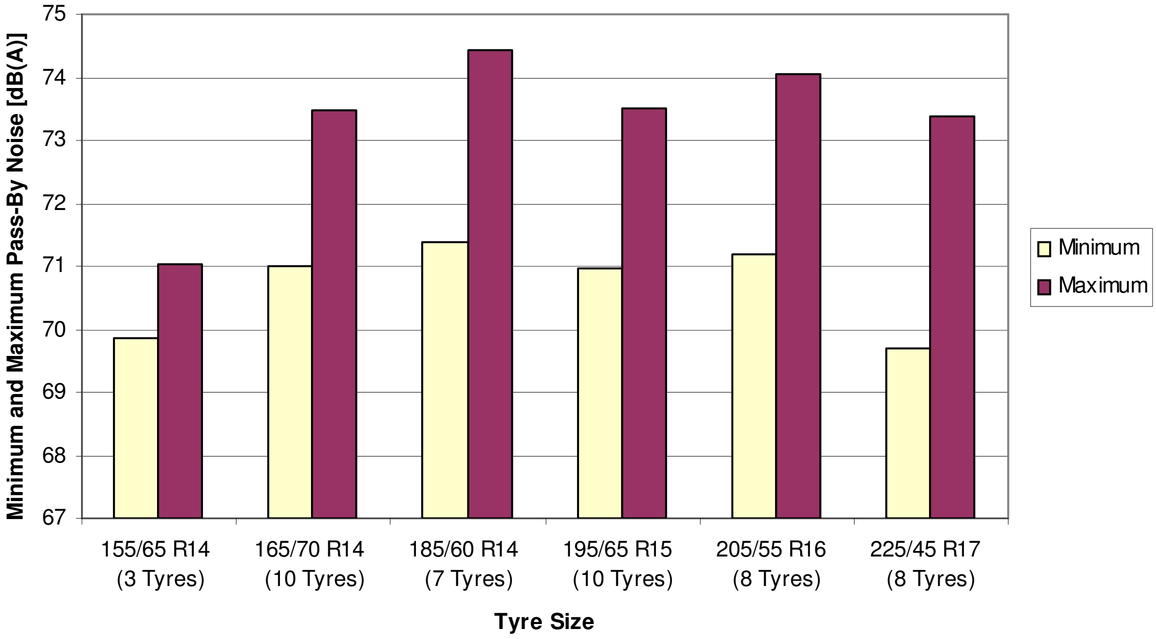


Figure 76: Maximum and Minimum Pass-By Values for Various Tyres of Similar Size (Data from TÜV, 2003)

From Figure 77, it can be seen that, even for relatively small tyre groupings, the noise spread can be as high as 3,5 dB(A) for the same tyre size. These results underscore the importance of the various tyre construction parameters such as the tread pattern when the vehicle/tyre/road system is to be optimised for low noise. It should be noted that the tyre size class may not influence the range of noise levels as starkly as Figure 77 indicates, as the results for the smallest tyre class, 155/65R14, are based on only 3 tyres and thus are too few to be representative. It is also interesting to note that the overall range of noise variations in Figure 77 is coherent with the results seen from the INRETS dataset (Figure 53), as both show this range to be roughly 3 dB(A).

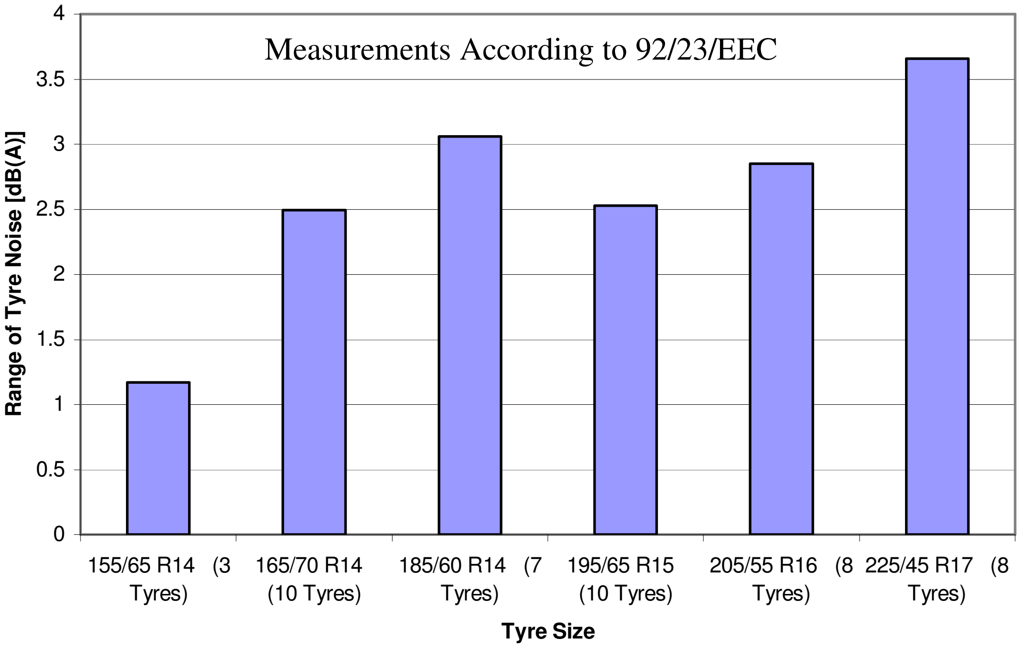


Figure 77: Range of Pass-By Noise Levels for Various Tyres of Similar Size (Data from TÜV, 2003)

Figure 78 gives the summarised results of the 18 vehicle/tyre combinations of the TUW dataset. The results shown are for rolling noise at 80 km/h and 55 km/h, and for full acceleration in 2nd and 3rd gear. In the figure, the "most silent" vehicle/tyre combination and the range of noise levels are shown for every road surface.

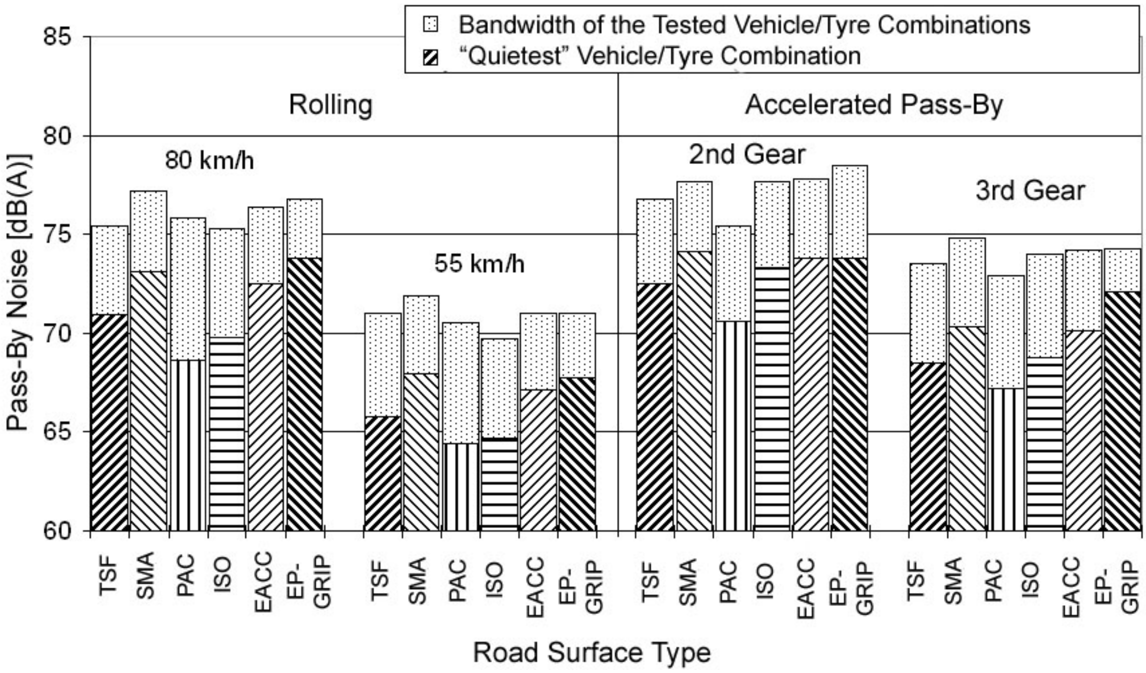


Figure 78: Pass-by Noise from 18 Tyre/Vehicle Combinations on 6 Different Road Surfaces (Schwarz, 1998)

For a reference vehicle, Volkswagen Golf III, 1,8 litre petrol engine, 37 different tyre variations were tested on 6 road surfaces. The results of these experiments are given in Figure 79. The "most quiet" combination for Porous Asphalt Concrete resulted in a noise reduction of approximately 2 dB(A) compared with Stone Mastic Asphalt.

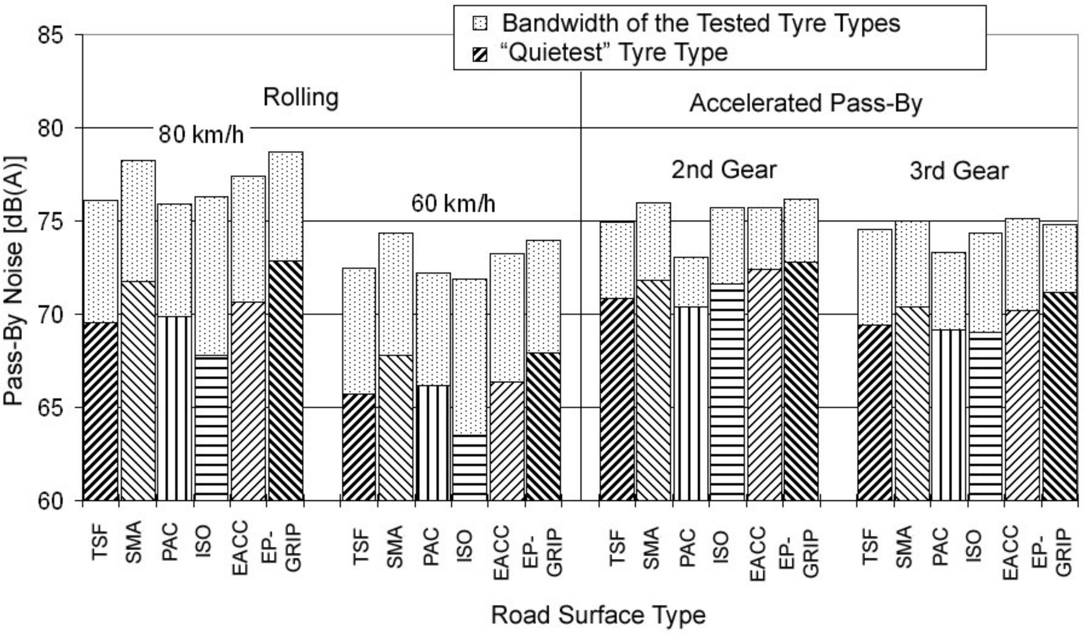


Figure 79: Pass-By Noise from 37 Tyre Variations Using a Reference Vehicle, for Various Driving Conditions (Schwarz, 1998)

5.6. Noise Spread Among Various Tyres on Different Surfaces

As has been seen in many of the results thus far in Chapter 5, the road surface type is important in the extent of influence for many tyre parameters. The road surface type will also strongly influence the overall noise levels. This topic is being investigated in detail under SILVIA Work Package 4: Low-Noise Durable Pavements. The objective of SILVIA WP4 is to investigate effective technologies for durable low-noise road surfaces; on the basis of which design, construction and maintenance guidelines for low-noise, durable road pavements according to the most advanced technology will be established. The key deliverable from SILVIA WP4 will be the development design guidelines and functional specifications for durable noise-reducing road surfaces and maintenance operations. This section of the current report is intended only to give an overview of this topic to demonstrate the importance of the road surface type in the vehicle/tyre/road surface system.

Figure 80, below, shows an overview of the influence of various road surface characteristics on tyre/road noise (Sandberg and Ejsmont, 2002). From the figure, it can be seen that a range of 17 dB(A) in the near-field noise is possible by varying the surface type. The broad range in noise levels is of course caused by some road surface types designed to produce high noise levels as a means of speed control, such as paving stones on some city streets.

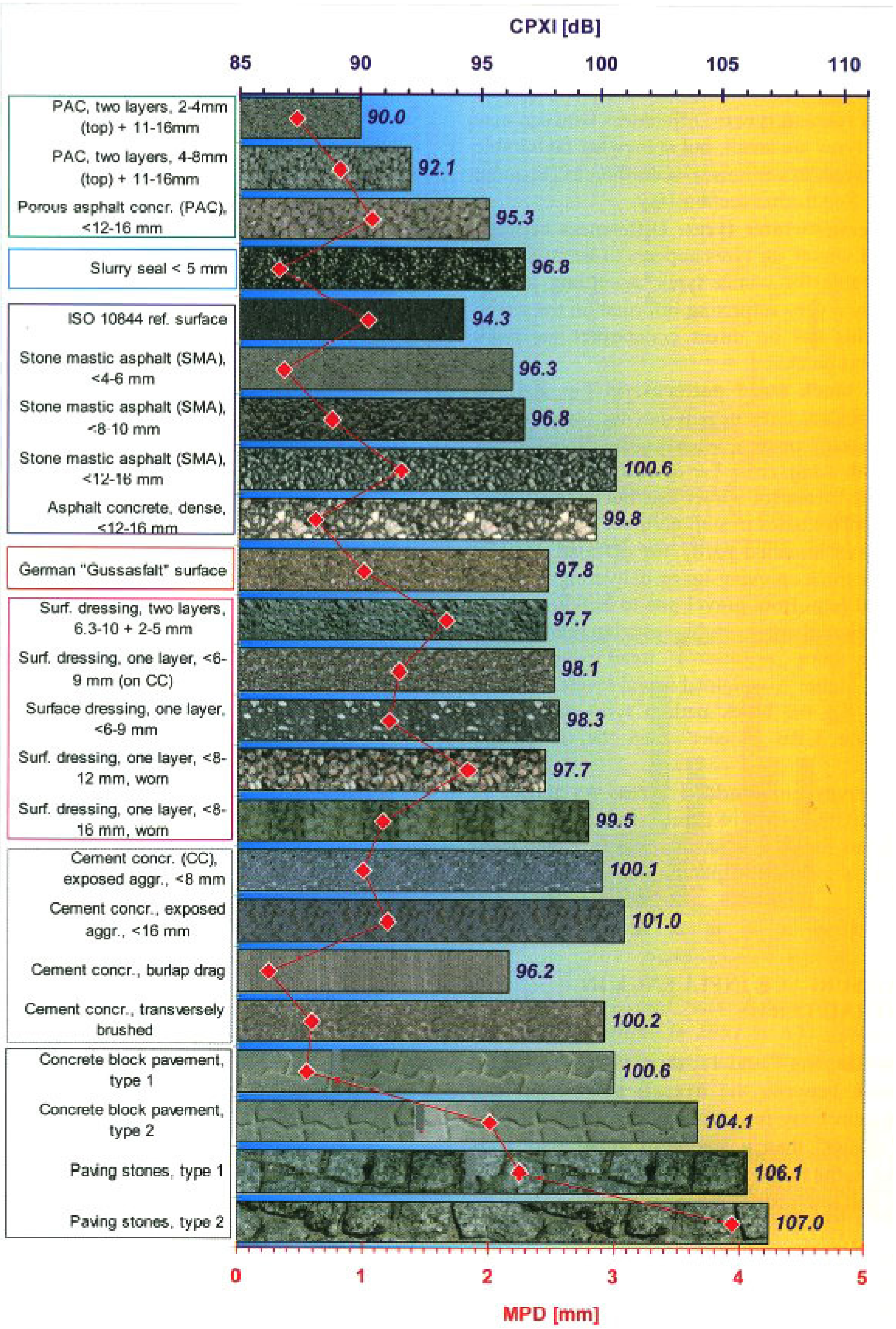


Figure 80: A-Weighted Near-Field Sound Levels (Sandberg and Ejsmont, 2002)

To illustrate the noise spread among various tyres on different surfaces, the Sperenberg dataset was analysed. From the dataset, the noise level of each tyre/road combination at 80 km/h was determined by regression analysis. In Figure 81, the minimum, average, and maximum noise level on 25 asphalt and concrete surfaces is displayed. The figure is based on the results for 12 different passenger car tyres.

In general, a finer grading results in a lower rolling noise level. Furthermore, the noise spread among the tyres is smaller on porous surfaces than on dense surfaces. The noise spread on the ISO surface is rather large, compared to the other silent road surfaces.

Figure 82 shows the results for each tyre/road combination. This figure shows that the ranking from silent to loud tyre does not depend much on the road surface type: A silent tyre on a quiet surface is also a relatively silent tyre on a noisy surface.

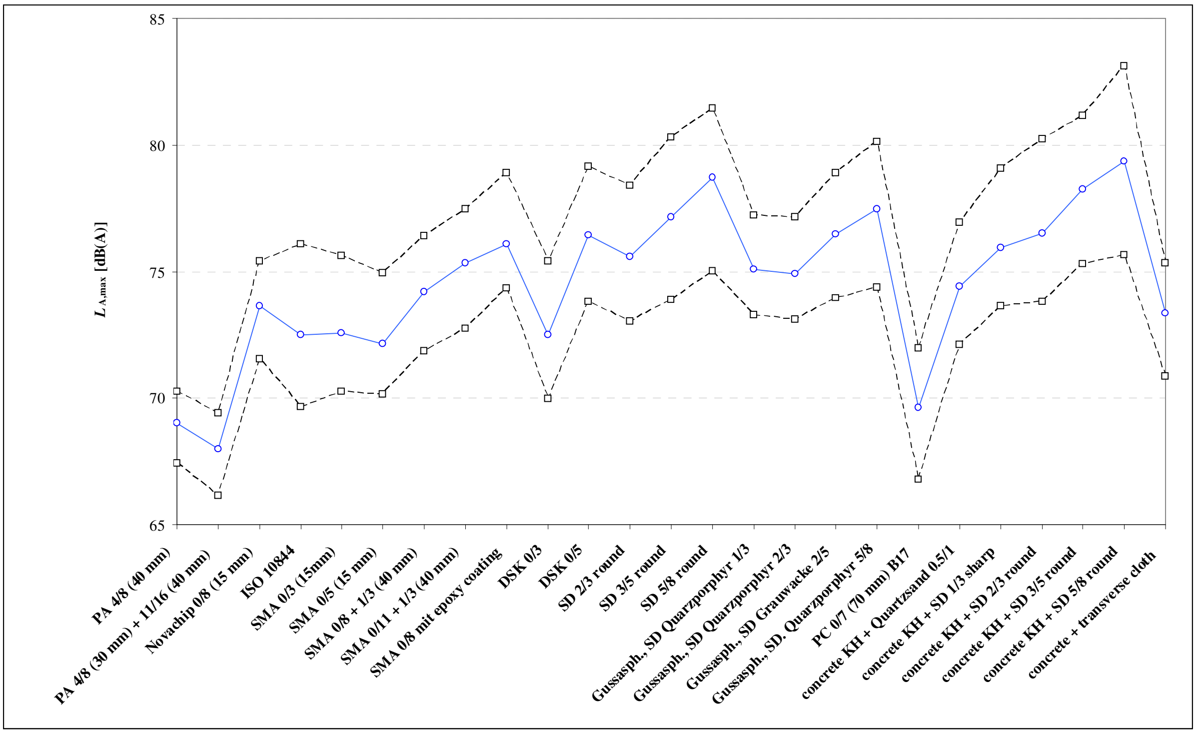


Figure 81: Average and Spread of Rolling Noise Level on Various Road Surfaces at 80 km/h

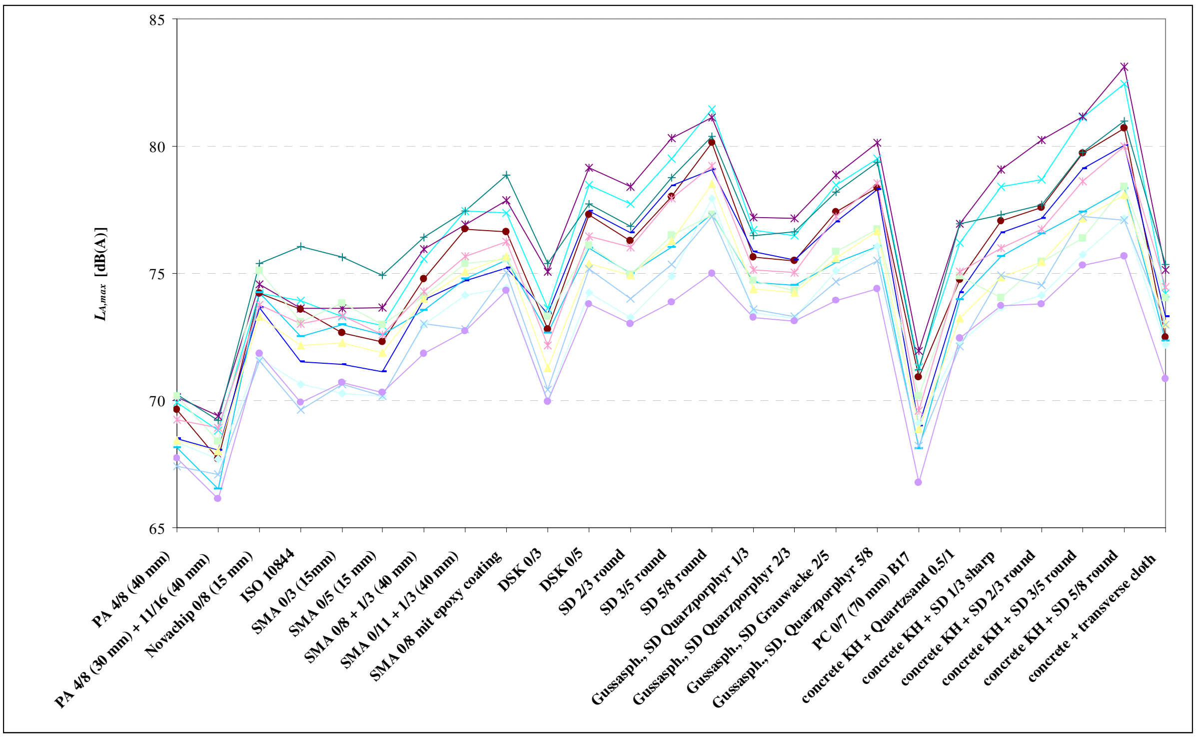


Figure 82: Rolling Noise Levels of 12 Passenger Car Tyres on Various Road Surfaces at 80 km/h

The observations described above are only valid for passenger car tyres. For truck tyres, the influence of the road surface on the tyre noise is less clear. This is illustrated in Figure 83 for three truck tyres from the Sperenberg dataset with respectively a steering, traction and M+S profile. A few observations can be made. Firstly, the noise spread between tyres depends on the road surface type. For instance on the SMA surfaces, there is a big difference between the steering and the other tyres, whereas for the surface dressings (SD) and Gussasphalt surfaces, the difference between steering and the others is small. Secondly, the rolling noise level depends on the stone grading in a complex way: on SMA, for increasing stone grading, the traction and M+S tyre become smaller whereas the steering tyre becomes noisier! Thirdly, the noisiness ranking of the tyres depends on the type of road surface. This all indicates that the observations for passenger car tyres should never be applied to truck tyres as they behave completely different.

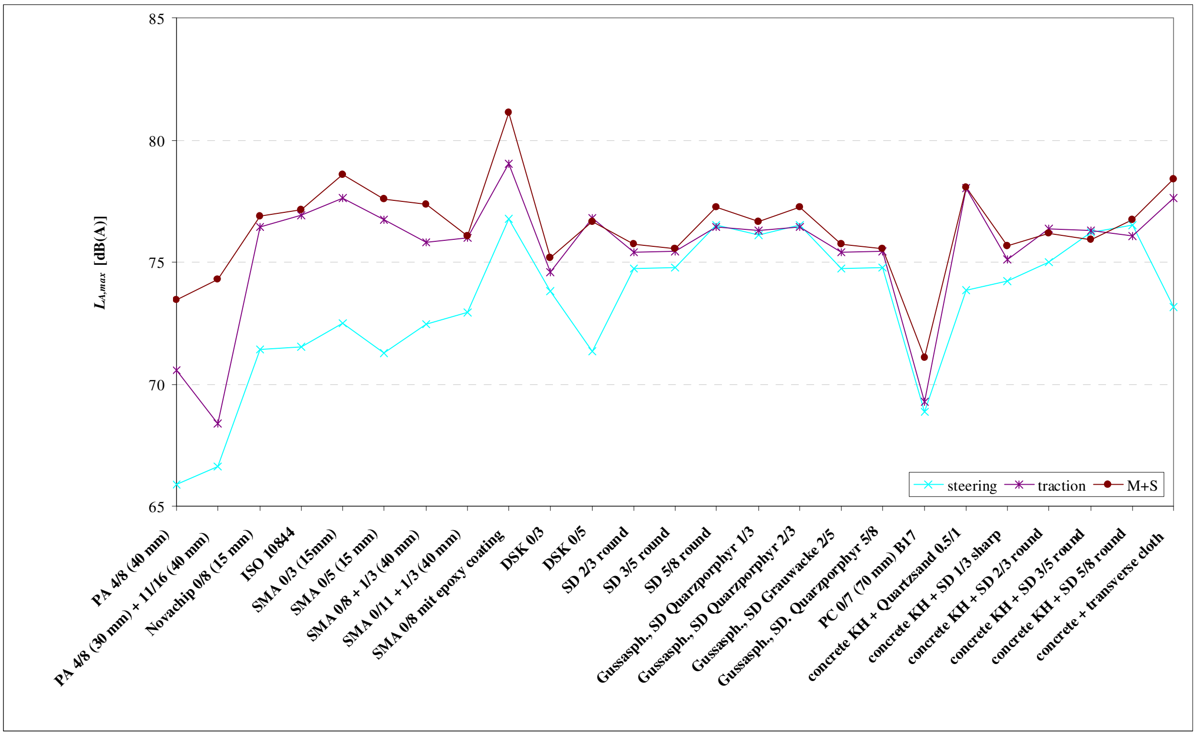


Figure 83: Rolling Noise Levels of 3 Truck Tyres (Steering, Traction and M+S Profile) on Various Road Surfaces at 80 km/h

The recommendation for designing *quiet roads* from the analyses described above is: For passenger car tyres, a road can be designed to be quiet irrespective of the tyre to some extent, but for truck tyres, the quietness of the surface depends on the tyre (profile) type.

The recommendation for designing *quiet tyres* from the analyses described above is: Passenger car tyres can be made quiet irrespective of the road surface to some extent, but for truck tyres, the quietness of the tyre depends on the surface.

Additionally, SPB results from French tests were also obtained (CTFR4, 2001). The SPB results are shown in Figures 84 (passenger cars) and 85 (heavy vehicles). In these figures, the road surface type is given. Additionally, several types of TSF surfaces are distinguished as TSF-1 through TSF-5. The definitions of these surface types are as follows: TSF-1 = ultra thin bituminous surfacing (less than 20 mm thick), TSF-2 = very thin bituminous surfacing (20-25 mm thick) with less than 18 % voids, TSF-3 = very thin bituminous surfacing (20-25 mm thick) with more than 18 % voids, TSF- 4 is a standard thin bituminous surfacing and TSF-5 is a very thin bituminous surfacing (20-25 mm thick). These results also demonstrate the range of noise spread among road surfaces, and the differences for passenger cars and heavy vehicles.

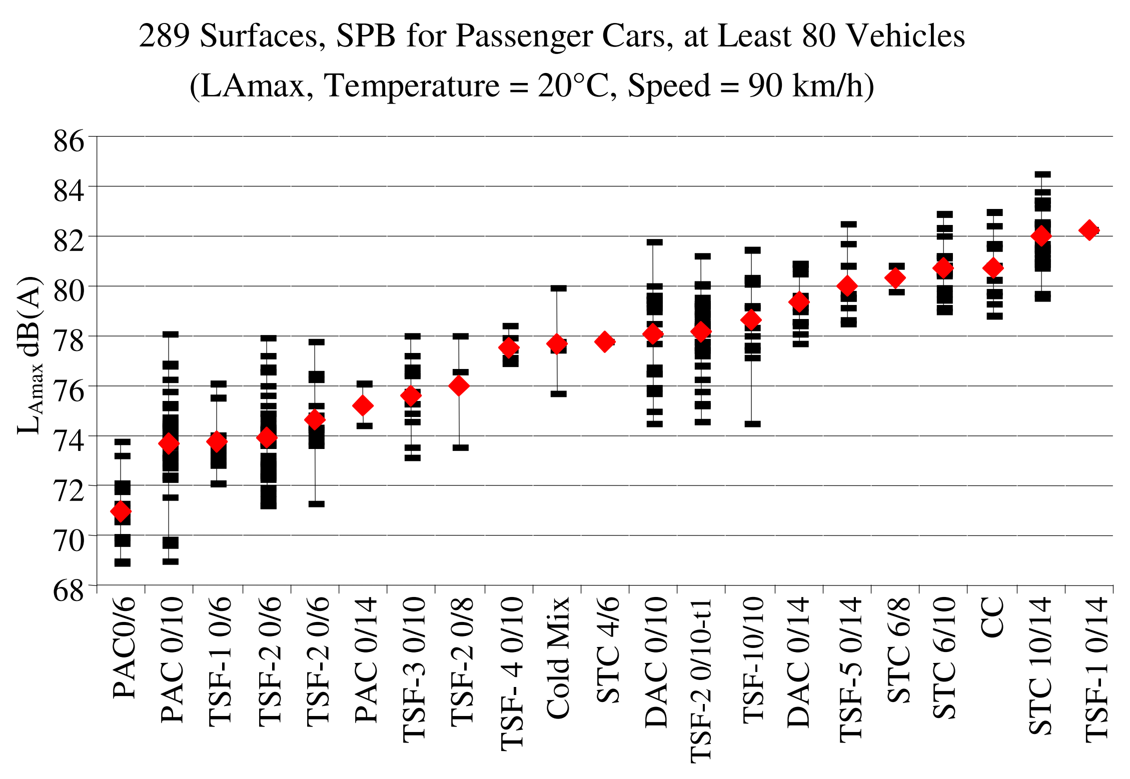


Figure 84: SPB Results for Passenger Cars for Various Surfaces (CTFR4, 2001)

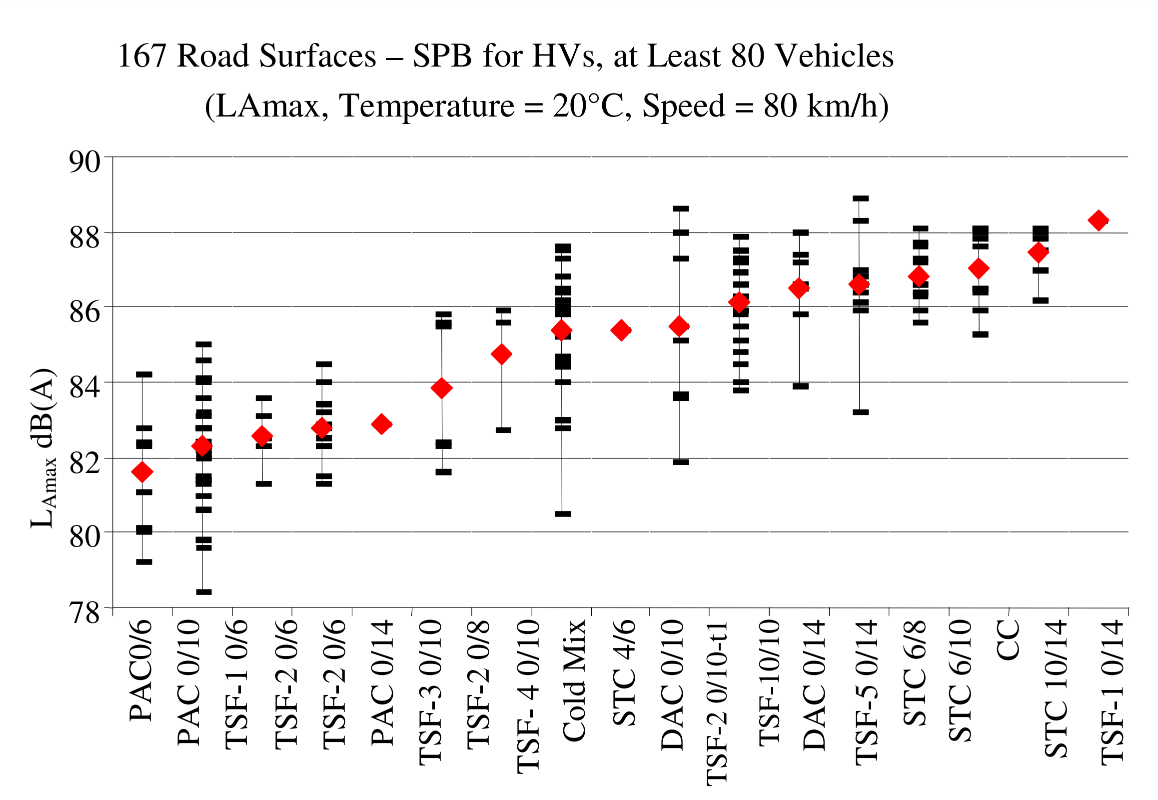


Figure 85: SPB Results for HVs, at Least 4 Axles, for Various Surfaces (CTFR4, 2001)

5.7. Overview of Analysis Results

5.7.1. General Remarks

In this chapter, an analysis based on the SILVIA dataset has been performed to determine the vehicle, tyre and driving style parameters of interest for tyre road noise, and to estimate the potential noise reductions through optimisation of these individual parameters for various road surfaces. As has been mentioned, the analysis based on the SILVIA dataset has often been supplemented by analyses from results reported in literature.

5.7.2. Overview of Influence of Various Parameters

Table 9 gives an overview of the results based on analyses of the SILVIA dataset and the relevant literature for various parameters.

Table 9: Overview of Noise Reduction Potential of Various Tyre, Vehicle and Driving Parameters Based on the Analyses in this Chapter

Parameter		Potential Effect [dB(A)]	Relative Importance
Driving Conditions	Constant vs. Accel.	Up to 3 dB(A), Depending on Road, Vehicle and Tyres – at Low Gear Can be as High as 5 dB(A)	Need for Quiet Power Unit and Reduced Traction Force Noise
	Gradient	Up to 3 dB(A) Passenger Cars, 6% Gradient vs. Level at Same Speed	Special Regulations for Alpine Regions, Because of the High Influence of Drive Train Noise
Slip and Traction Force	Slip	Up to 3 to 4 dB(A) for 1% Increase in Slip	Factors into Driving Conditions
	Traction Force	Up to 2,5 dB(A) for a 10 Nm increase in Torque	Factors into Driving Conditions
Vehicle Parameters	Power Unit Type	1 to 2 dB(A) Increase for Diesel over Petrol at 80 km/h for a Group of Vehicles, Hybrid Gives Substantial Low-Speed Noise Reductions	Vehicle Guidelines
General Tyre Parameters	Tyre Load	Up to 1,5 dB(A), Depending on Surface	Moderate Importance
	Tyre Inflation	0 to 0,3 dB(A)	Low Importance
Tyre Dimension Properties	Tyre Width	Roughly 1 dB(A) Increase for every 25 mm Increase in Width for PC's –Trend stops for Tyre Widths Over 215 mm , Lower Sensitivity for HV's	Moderate to High Importance
	Tyre Diameter	No Clear Trend Based on Our Data	Depends on Road Surface, Difficult to Quantify
	Tyre Rim Diameter	Not Separately Analysed	Can Have Effect Through Increased Overall Tyre Diameter, and Reduced Profile
Tyre Tread Material Properties	Tread Stiffness and Other Material Properties	Up to 2 dB(A) Noise Reduction Through Optimisation of Tyre Material Properties	Moderate to High Importance
Tyre Tread Pattern	Circumferential Grooves	Increase over Slick, 0 to 0,5 dB(A) Range for Modification of Groove Pattern	Low Importance of Circumferential Groove Pattern Optimisation
	Profile Depth	0 to 2 dB(A) for PC's	Moderate to High Importance
	Tread Pattern (Tread Pitch, # of Treads)	Up to 1 dB(A) for Randomised Patterns	Moderate Importance

5.7.3. Overview of Hypotheses of Chapter 3

The hypotheses formulated previously in Chapter 3 will now be reviewed based on the results of the analyses performed in this chapter.

Hypotheses Concerning Driving Conditions:

- Acceleration will lead to an increase in noise levels, both for power train noise and tyre/road noise (increased engine torque causing the power train noise increase, tyre slip and traction force causing increase in tyre/road noise)

Result: Correct, the overall noise increase was seen consistently, although the extent of the increase depended on the vehicle type, tyre properties and road surface type. The difference was larger at low gears. The tyre noise increase due to traction force was demonstrated as well.

- Driving in a gradient will lead to an increased noise level versus a flat road for a given speed, due to the increase in torque for driving on a positive slope, and due to braking noise on a negative slope.

Result: Correct, as data on alpine motorways demonstrated.

Hypotheses Concerning Tyre Parameters:

- A loaded vehicle will have a higher pass-by noise level than an unloaded vehicle (thus, increasing the load on tyres will lead to higher noise levels)

Result: Correct, tyre load was shown to increase noise by up to 1,5 dB(A) for a rolling vehicle, and in addition, the increased vehicle load would most likely result in higher power unit noise for maintaining a constant speed.

- Increasing the tyre pressure will possibly yield decreased noise levels due to the reduced contact area of the tyre and road surface.

Result: Partially correct, but depends strongly on the load on the tyres. For an unloaded tyre changing the pressure over a range from 1,8 to 2,4 bars resulted in a very small change in rolling noise. However, for a loaded vehicle decreasing the tyre pressure can be more substantial in terms of pass-by noise.

- Increasing the tyre width will lead to an increase in noise levels.

Result: Correct, for the data analysed (weighting of separate results according to level of detail in the results), a 25 mm increase in tyre width led to roughly a 1 dB(A) increase in pass-by noise. Interestingly, the trend seems to be less clear, and possibly even to reduce itself, for tyre widths over 200 or 215 mm.

- Increasing the tyre diameter will lead to an increase in noise levels for a smooth surface, and a decrease for a rough surface, due to the counteracting influences of tyre diameter on the horn effect and on the tyre tread impact.

Result: No consistent relationship between diameter and noise level was seen for the data analysed.

- Variations in the tyre material properties, such as rubber hardness, will impact the noise levels. Increasing the tyre tread stiffness will lead to a reduction in noise due to reduced vibrations, reduced rubber deformation.

Result: An optimisation of tyre material properties showed a reduction in noise levels of 2 dB(A) on an SMA surface, and of 1 dB(A) on a PAC surface. The extent to which the material properties were changed for these experiments were unfortunately not given in great detail.

- Changes in the tread pattern can have a substantial effect on tyre/road noise levels, and depends on the type of road surface.

Result: Correct, changes in the tread pattern for the data studied resulted in up to a 1 dB(A) change in pass-by noise.

The results of the work done in this chapter have been used to compose recommendations on tyre and vehicle guidelines in Chapters 6 and 7.

6. Recommendations on Specifications for Tyre Requirements

6.1. Introduction

The results in Chapter 5, as well as the information from general literature summarised in Chapter 3, have shown the results of the extent of influence of various tyre parameters on noise. It was however seen that, for one, the road surface type has a strong influence on the relationship between many of the tyre parameters and the resulting tyre/road noise.

Proposing guidelines based on vehicle class is relatively straightforward, in that one can place the certain tyres on the given vehicle types, and be confident that the match between tyre type and vehicle class will remain relatively unchanged. With the road surface, however, the situation is more complex. If one creates guidelines for tyre properties based on a given road surface, it is of course natural that the vehicle with these tyres will also drive at least occasionally on other types of road surfaces, where the tyre parameters have not been optimised for low tyre/road noise. Some tyre parameters depend on the road surface, while others do not. One way to minimise this potential problem is to propose guidelines based on road surface, where the road surface that is most common in the given country is used as the basis. In addition to this precaution, one can set guidelines for the tyre noise performance in such a way that, while they are optimised for the road surface type that is most common in the region, they are also designed to minimise at least to some extent the tyre/road noise on other common road surface types. It is important that safety not be sacrificed in implementing measures for noise reduction.

The recommendations given in this chapter are made with the goal of optimising the tyres for low noise on all common road surfaces. When a parameter has a substantial effect on a given road surface type, it is noted.

6.2. Proposed Guidelines Concerning Given Tyre Parameters

Table 10: Recommendations for Various Tyre Parameters

Parameter	Potential Effect [dB(A)]	Relative Importance	Recommendation
Tyre Load	Up to 1,5 dB(A), Depending on Surface	Moderate Importance	Vehicle Noise Testing Should be Performed for Loaded Vehicles as has been Proposed
Tyre Inflation	0 to 0,3 dB(A)	Low Importance	Should Be Monitored Especially for Loaded Vehicles
Tyre Width	For Passenger Cars Roughly 1 dB(A) Increase for every 25 mm Increase in Width, Appears Non-Linear at Widths Over 200 mm Lower Sensitivity for Heavy Vehicles	Moderate to High Importance	Wider Tyres Should Meet the Same Requirements as Standard Tyres; Use of Lighter Vehicles is Encouraged so that Narrower Tyres can be Used
Tyre Diameter	No Clear Trend Based on Our Data	Depends on Road Surface, Difficult to Quantify	The Influence was Seen to Be Rather Small, as the Effect on the Tread Impact Mechanism and on the Horn Effect Seem to Counteract Each Other
Tyre Rim Diameter	Not Separately Analysed	Can Have Effect Through Increased Overall Tyre Diameter, and Reduced Sidewall	Further Research is Recommended
Tread Material Properties	1 to 2 dB(A) Noise Reduction for SMA, 0,5 to 1 dB(A) for PAC	Moderate to High Importance	Optimisation of Tyre Tread Material Properties for Given Size Parameters
Circumferential Grooves	Increase over Slick, 0 to 0,5 dB(A) Range for Modification of Groove Pattern	Low Importance of Circumferential Groove Pattern Optimisation	A Closed Central Rib with Narrow Circumferential Grooves Showed the Best Noise Performance of the Groove Variations Tested
Profile Depth	0 to 2 dB(A) for Passenger Cars	Moderate to High Importance	Shown to Be Relatively Unimportant for PAC, but Substantial Effects on Other Road Surfaces, Where a Decrease of Profile Depth Led to a Noise Reduction
Tread Pattern (Tread Pitch, Number of Treads)	As Much as 1 to 2 dB(A)	Moderate Importance - An Optimisation Can Lead to a Marked Improvement on TSF, but on PAC the Change Was Small	Reduction of the Pitch and Reinforcement of the Tread Surface Area Were Shown to Produce Noise Reductions

7. Recommendations on Specifications for Vehicle Requirements

7.1. Introduction

As demonstrated from the results in this report, optimisation of the vehicle can lead to substantial traffic noise reductions. Quieter vehicles in combination with low noise tyres and road surfaces are necessary to achieve the full potential for low-noise traffic. One possible method of speeding the introduction of quieter vehicles would be to introduce a noise-related vehicle tax. A tax incentive encouraging vehicle owners to use the quietest tyres when replacing their tyres would also help to reduce traffic noise. In order to make any policies on incentive for quieter vehicles, a better, more rigid definition of a quiet vehicle would be beneficial. This chapter first gives recommendations on guidelines for vehicles, then discusses the possibilities of a more regulated “quiet vehicle” rating.

7.2. Recommended Vehicle Specifications

Table 11 gives recommendations on vehicle parameters based on the analyses of this report.

Table 11: Overview of Noise Reduction Potential of Various Vehicle and Driving Parameters Based on the Analyses in this Chapter

Parameter	Potential Effect [dB(A)]	Relative Importance	Recommendations
Constant vs. Accel.	Up to 3 dB(A), Depending on Road, Vehicle and Tyres	Need for Quiet Power Unit and Reduced Traction Force Noise	Expand Type Approval Testing to Cover More Realistic Driving Conditions, and Controlling Measures for Accelerations in Urban Areas
Gradient	Up to 3 dB(A) Passenger Cars, 6% Grade vs. Level	In Alpine Regions of High Importance	Special Regulations for Alpine Regions Regarding Speed, Night Driving; 4-Wheel Drive Systems, for Example, for Trucks
Slip	Up to 3 to 4 dB(A) for 1% Increase in Slip	Factors into Driving Conditions	Tyre Traction Standards; Encourage Use of Electronic Traction Control Systems
Traction Force	Up to 2,5 dB(A) for a 10 N*m increase in Torque	Factors into Driving Conditions	Limiting the Maximum Force by Electronic Control Systems
Power Unit Type	1 to 3 dB(A) Increase for Diesel over Petrol at 80 km/h for a Group of Passenger Cars	Vehicle Guidelines	Improved Power Unit Soundproofing on Diesel Engines for Low Speed Noise Level Reductions

7.3. New Specifications with Minimum Requirements for Low-Noise Vehicles and for Test Procedure

Currently, the system to designate a “quiet vehicle” is fairly forgiving. This means that consumers purchase a vehicle thinking that it is leading to a vast improvement regarding traffic noise, when in reality in some cases the resulting pass-by noise of this vehicle can be only marginally better than the fleet average over the vehicle driving cycle.

In order to provide a stronger motivation to the consumer to purchase vehicles with improved noise performance, the requirements for designating a vehicle as a “quiet vehicle” should be more stringent. It is proposed that:

- The vehicle should be tested with the tyres sold on the vehicle – each vehicle model should be tested for each set of tyres sold with it, and the vehicle noise rating should change accordingly if the tyres are changed prior to sale or at the time of sale.
- The rolling noise and the accelerated pass-by noise should be measured under real life conditions, i.e. road surfaces in common use instead on an ISO surface, which is only a test track and never used for public roads.
- The vehicle should show an improvement over the fleet average noise level from vehicles for the given model year of at least 3 dB(A).
- The vehicle testing should cover the range of typical driving conditions.

It should be noted that the test procedure for vehicle noise levels is currently being studied. By implementing these guidelines, the authors feel that the next generation of quiet vehicles would show a marked improvement in noise performance over the current fleet.

8. Summary

Low noise surfaces have been shown in recent years to provide a strong potential for traffic noise reduction. However, unless the other parameters of the tyre and vehicle are also improved, the full potential of these low noise surfaces cannot be realised. The goal of this document has been to examine the parameters of tyres, vehicles, and driving conditions in order to demonstrate the potential to further the noise reductions achieved by low-noise surfaces through a systematic optimisation of the vehicle, tyre and road surface. This work has been carried out as part of work package 5: Integration of Low-Noise Pavements with Other Noise Abatement Measures. This report gives an overview of the general effects of various tyre and vehicle parameters, a brief review of the SILVIA database and the datasets that comprise it, and analyses of the influences of various tyre and vehicle parameters on traffic noise. These analyses are based on data present in the SILVIA database, supplemented with results from relevant literature. Based on these analyses recommendations have been made concerning guidelines for vehicle and tyre manufacturers and legislators as a way to improve the performance of low noise surfaces through optimising the vehicle and tyres. It is important that safety not be sacrificed in implementing measures for noise reduction.

Stronger guidelines have been proposed for a vehicle to be designated as a “quiet vehicle.” The current requirements for a quiet vehicle rating are not stringent enough, and in some cases the resulting pass-by noise of current “quiet vehicles” can be only marginally better than the fleet average noise level over the vehicle driving cycle. By strengthening these requirements, newer quiet vehicles would result, as consumers would have a more clear motivation to purchase vehicles with improved noise performance.

In this report it has been proposed that:

- The vehicle should be tested with the tyres sold on the vehicle – each vehicle model should be tested for each set of tyres sold with it, and the vehicle noise rating should change accordingly if the tyres are changed prior to sale or at the time of sale.
- The rolling noise and the accelerated pass-by noise should be measured under real life conditions, i.e. road surfaces in common use instead on an ISO surface, which is only a test track and never used for public roads.
- The vehicle should show an improvement over the fleet average noise level from vehicles for the given model year of at least 3 dB(A).
- The vehicle testing should cover the range of typical driving conditions.
- When users change tyres, a tax incentive should be implemented encouraging them to use the quietest tyres.

Vehicle parameters were examined, in addition to driving conditions. The resulting recommendations included those listed below:

- Electronic slip control systems should be more widely adopted – reducing slip can lead to decreases of as much as 3 dB(A) for pass-by noise.
- Special regulations for alpine regions regarding speed and night driving, and introduction of 4-wheel drive systems, for example, for heavy vehicles, are potential means of reducing traffic noise in areas where substantial gradients occur.
- Improved power unit soundproofing on diesel engines can yield reductions in noise levels at low speeds.

The tyre parameters have also been studied. The general results found that the tyre width, tyre material properties, tyre profile depth and tyre tread pattern had moderate to strong influences on the noise level. The most notable recommendations resulting from the analyses of tyre parameters were as follows:

- Wider tyres should be required to meet the same noise level standards as narrow tyres for the same type of vehicle.
- Tyre material properties such as the hardness of the rubber and the thickness of the belts should be optimised for given size parameters of tyres – such an optimisation can lead to a noise reduction of as much as 2 dB(A).

The authors feel that the recommendations put forth in this report would lead to further improvements in traffic noise than those achievable by use of low-noise road surfaces alone. It is only in examining and optimising the entire system of the vehicle/tyre/road surface that the possible further reductions in traffic noise can be achieved.

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10. Appendix A: Field Descriptions for the SILVIA Database (Taken from SILVIA Deliverable D04)

Tbl_DatabaseKeyTable

ResultDataID	Text	ID Number for Each Set of Conditions for a Given Test Site. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
ExistingReportsID	Text	ID for Reports Based on this Set of Data. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
TyreMeasID	Text	ID Number for Specific Tyre Result Data. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
DataSetID	Text	ID Number of the Existing Data Set given by the Partner. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
RoadSurfaceInfoID	Text	ID Number for Specific Road Surface Parameters. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
CondAtTstPtID	Text	ID for Specific Conditions at the Test Points. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
TyreInfoID	Text	ID Number for Specific Tyre Information. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
VehicleID	Text	ID Number for Specific Vehicle Information. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
PassiveMeasuresID	Text	ID for Data on Specific Traffic Management. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
TrafficManID	Text	ID Number for Specific Details on Passive Measures. Please Begin ID With Initials of Your Group (e.g.: TUW10011)

tbl_DatasetInfo: Data Set Information Table

DatasetID	Text	ID Number of the Data Set given by the Partner. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
DatasetName	Text	Name of the given Dataset
DatasetPartner	Text	Name of Partner giving the Data, e.g.: TUW, Vienna University of Technology
ContactPersonName	Text	Name of Contact Person
ContactPersonPhone	Text	Phone Number of the Contact Person
ContactPersonEmail	Text	Email Address of the Contact Person
DatasetInfo	Text	Brief General Description of the Dataset
Publications	Text	Primary Publications that Used These Data
Simulation	Yes/No	Please mark YES, if these Results are from a Simulation
Method	Text	Test Method (CPX, SPB,...) or Simulation Method
Standards	Text	Which Testing Standards Were Followed, If Any
SchemMeth	OLE-Object	A Schematic of the Method If a Standard Method Was Not Used
TestEquipment	Text	Type of Test Equipment
EquipCertification	Text	Reference to the Certification of the Test Equipment
Date	Date/Time	Date of Experiments
Time	Text	Time Of Day
LocationGeneral	Text	Location of Experiments (e.g., Town or Test Track Location)
FreeField	Yes/No	Was The Testing Performed in a Free Field?
RoadName	Text	If Test Section Is a Real Road, Please Give Official Name of Road
Length	Number	Length of the Test Section [km] - for Stationary Tests, the Length of the Test Section, for Trailer Tests, the Length of the Road Surface Over Which Tests are Taken
TrafficDirection	Text	Direction of the Vehicles on the Test Section, e.g. next Town

tbl_ RoadSurfaceInfo: Road Surface Information Table

RoadSurfaceInfoID	Text	ID Number for Specific Road Surface Parameters. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
SurfType	Text	TSF = Thin Surfacing, SMA = Stone Mastic Asphalt, PAC = Porous Asphalt Concrete, DPAC = Double-Layer Porous Asphalt Concrete, DAC = Dense Asphalt Concrete, EACC = Exposed Aggregate Cement Concrete, STC = Surface Treatment Concrete,….
SurfTypeDescription	Text	Brief Description of the Surface
SurfAge	Number	Age of Surface [years]
MaxChip	Number	Maximum Chipping Size [mm]
ChipSizeDistr	Text	Distribution of the Chipping Size
SurfPorosity	Number	Porosity of Road Surface [%]
SurfWavSpect	Number	Wavelength Spectrum
SurfAbsorption	Number	Absorption Coefficient of the Road Surface
SurfPermeability	Number	Coefficient of Permeability [m/s]
SurfElasticity	Number	Youngs Modulus for Elastic Surfaces [MPA]
SurfThickness	Number	Road Surface Thickness [cm]
SurfWear	Text	Extent of Wear of the Road Surface
SurfTextureDepth	Number	Texture Depth [mm]
Real/Test	Yes/No	Please mark YES if the Surface is Real (for Public Use)
SurfPhoto	OLE-Object	Photo of Surface

tbl_CondAtTestPoint: Local Conditions Table

CondAtTstPtID	Text	ID for Conditions at the Test Point. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
DrivingConditions	Text	Driving Conditions at Time of Test: ACC = Accelerating, COA = Coasting, CON = Constant, STA = Stationary, DEC = Decelerating
RoadConditions	Text	Road Condition at Time of Test: W=Wet, D=Dry
RoadOrientation	Text	S = Straight, T = Turn (If Turn, Specify Arc of Curve)
RoadGradient	Number	Gradient of the Road (Slope), [%]
TraffVol	Number	Volume of Traffic, Expressed as Average Annual Daily Traffic, AADT [# vehicles/24h]
HDVShare	Number	Share of Traffic that is Heavy Duty Vehicles [%]
WindSpeed	Number	Wind Speed at Test Location [km/h]
WindDir	Number	Angle Relative to Car Driving Direction [degrees]
AirTemp	Number	Ambient Air Temperature at Test Location [K]
AirHumidity	Number	Relative Air Humidity [%]
RoadTemp	Number	Temperature of the Road Surface at Test Location [K]
SpeedCat	Text	Road Speed Category For SPB Tests (Low, Medium or High Road Speed Category)
Crossing	Yes/No	If the Tests Were Performed at a Road Crossing, Please Indicate it Here
Crossing	Text	Brief Description of Crossing, if Relevant
Roundabout	Yes/No	If the Tests Were Performed at a Roundabout, Please Indicate it Here
RoundaboutDesc	Text	Brief Description of Roundabout, if Relevant
Roadworks	Yes/No	If There Is Road Work in the Vicinity of the Tests, Please Indicate it Here
RoadworksDesc	Text	Brief Description of Road Work near Test Section, if Relevant

Tbl_TyreInfo: Table of Information on the Vehicle Tyres

TyreInfoID	Text	ID Number for Specific Tyre Information. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
TyreMake	Text	Tyre Make
TyreModel	Text	Tyre Model
TyreSpeedIndex	Number	Tyre Speed Index
TyreLoadIndex	Number	Tyre Load Index
Wint/Sum	Text	Winter Tyres or Summer Tyres [W/S]
TyreSize	Text	Manufacturer's Specification Code
TyreWidth	Number	Width of Tyre [mm]
TyreAspectRatio	Number	Tyre Aspect Ratio (Height to Tread Width Ratio)
TyreSurface	Text	Description of Tyre Surface Structure,e.g.: Tread Style, Depth of Treads, etc.
TyreRimDiam	Number	Tyre Rim Diameter [inches]
TyreWeight	Number	Tyre Weight [kg]
TyrePressure	Number	Inflation Pressure of Tyre [bar]
TyreDOT	Text	DOT Code of the Tyre, giving Manufacturer and Age (stamped on the tyre)
TyreProfile	Number	Average Tread Depth [mm]
TyrePhoto	OLE-Object	Photo of the Tyre
TyreShoreHard	Number	Tyre Shore Hardness

Tbl_VehicleInfo: Test vehicle Information Table

VehicleID	Text	ID Number for Specific Vehicle Information. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
VehCat	Text	Vehicle Category: PV = Passenger Vehicle(Cat. 1a), LT = Light Truck(Cat. 1b), DHV = Dual-Axle Heavy Vehicle, MHV = Multi-Axle Heavy Vehicles
VehMake	Text	Vehicle Make
VehModel	Text	Vehicle Model
VehYear	Number	Year of Construction
VehKm	Number	Vehicle Lifetime Distance driven [km]
VehEmiss	Text	Vehicle Emission Standard, e.g.: EURO3
VehTrans	Text	Type of Transmission: A = Automatic, M = Manual, O = Other (Please Provide Description for Other)
VehGears	Number	Number of Gears of Vehicle Transmission
VehLength	Number	Length of the Vehicle [m]
VehWidth	Number	Width of the Vehicle [m]
VehHeight	Number	Height of the Vehicle [m]
VehWeight	Number	Weight of the Vehicle [kg]
VehPhoto	OLE-Object	Photo of the Vehicle
VehVmax	Number	Maximum Speed of the Vehicle [km/h]
EngDisp	Number	Engine Displacement [ccm]
EngCyls	Number	Number of Cylinders in Engine
EngPmax	Number	Maximum Engine Power [kW]
EngN	Number	Rated Engine Speed [RPM]
VehSFC	Number	Vehicle Brake Specific Fuel Consumption [g/kWh]
VehFuel	Text	Vehicle Fuel Type, e.g. Diesel

tbl_TrafficManagement: Traffic Management Details Table

TrafficManID	Text	ID for Data on Traffic Management. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
SpeedLimit	Number	Give Speed Limit Here [km/h]
SpeedRedPavement	Yes/No	Please Indicate Yes if There Are Speed Reducing Measures in the Pavement Design (e.g., Speed Bumps)
SpeedRedDesc	Text	Please Describe Speed Reducing Measures in the Pavement Design (e.g., Speed Bumps) Here, if Relevant
PeriodicRestrictions	Yes/No	Are There Traffic Restrictions in Special Periods? If so Please Indicate Here
PerRestDesc	Text	Please Describe the Traffic Restrictions in Special Periods, if Relevant

Tbl_PassiveNoiseRedInfo: Passive Noise Reduction Information Table

PasssiveMeasuresID	Text	Table with Details on Passive Measures. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
Barriers	Yes/No	If There Are Noise-Reducing Barriers Near Measurement Point, Please Indicate it Here
BarriersDesc	Text	Please Describe Noise-Reducing Barriers Near Measurement Point, if Relevant
Earthworks	Yes/No	If There Are Noise-Reducing Earthworks Near Measurement Point, Please Indicate it Here
EarthworksDesc	Text	Please Describe Noise-Reducing Earthworks Near Measurement Point, if Relevant
Bridge	Yes/No	If the Testing Was Performed on a Bridge, Please Indicate it Here
BridgeJoints	Text	Please Describe the Joints on the Bridge Here, if Relevant
OtherPassive	Text	Please Describe Any Other Passive Noise Reducing Measures Near Test Location Here, if Relevant

Tbl_NoiseResults:

NoiseResID	Text	ID Number for Noise Result Data. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
ResultDataID	Text	ID Number for Each Set of Conditions for a Given Test Site
NoiseBase	Number	Value of the Background Noise Level [dB(a)]
NoiseInVeh	Number	Value of the Inside Vehicle Noise Level [dB(a)]
Laeq_NF	Number	Emission Noise Level of the Near-Field Noise [dB(a)]
HeightMicro_NF	Number	Height of Microphone from Ground for Near-Field Tests [cm]
LengthPos_NF	Number	Microphone Forward (Forward = Vehicle Driving Direction) Distance from Centre of Tyre for Near-Field Tests [cm]
DistMicro_NF	Number	Tangential Distance of Microphone from the Tyre for Near-Field Testts [cm]
LocTrailer	Number	The Lateral Trailer Position on the Road Surface
TrailerTstLength	Number	The Length Over Which the Trailer Test is Taken
VehSpeed	Number	Speed of Vehicle at Time of Test [km/h]
CPXI_TCor	Number	Close Proximity Index [dB(a)], Corrected for Temperature (According to ISO 11819-2)
CPXL_TCor	Number	Minimum Close Proximity Index [dB(a)], Corrected for Temperature (According to ISO 11819-2)
CPXH_TCor	Number	Maximum Close Proximity Index [dB(a)], Corrected for Temperature (According to ISO 11819-2)
CPXI	Number	Close Proximity Index [dB(a)], Uncorrected for Temperature (According to ISO 11819-2)
CPXL	Number	Minimum Close Proximity Index [dB(a)], Uncorrected for Temperature (According to ISO 11819-2)
CPXH	Number	Maximum Close Proximity Index [dB(a)], Uncorrected for Temperature (According to ISO 11819-2)

SpectrumID	Text	ID Number for a Spectrum (1/3 Octave Bands) of Sound Levels at Frequency Intervals. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
SPBVehNum_Cat1	Number	Number of Tested Vehicles in Vehicle Category 1 (According to ISO 11819-1)
SPBVehNum_Cat2a	Number	Number of Tested Vehicles in Vehicle Category 2a (According to ISO 11819-1)
SPBVehNum_Cat2b	Number	Number of Tested Vehicles in Vehicle Category 2b (According to ISO 11819-1)
SPBW1	Number	Special Weighing Factor W1 for Vehicle Category 1 (If not in Accordance to ISO 11819-1)
SPBW2a	Number	Special Weighing Factor W2a for Vehicle Category 2a (If not in Accordance to ISO 11819-1)
SPBW2b	Number	Special Weighing Factor W2b for Vehicle Category 2b (If not in Accordance to ISO 11819-1)
SPBLveh_TCor_Cat1	Number	Vehicle Sound Level for Vehicle Category 1 [dB(a)], Corrected for Temperature (According to ISO 11819-1)
SPBLveh_TCor_Cat2a	Number	Vehicle Sound Level for Vehicle Category 2a [dB(a)],Corrected for Temperature (According to ISO 11819-1)
SPBLveh_TCor_Cat2b	Number	Vehicle Sound Level for Vehicle Category 2b [dB(a)], Corrected for Temperature (According to ISO 11819-1)
SPBLveh_Cat1	Number	Vehicle Sound Level for Vehicle Category 1 [dB(a)], Uncorrected for Temperature (According to ISO 11819-1)
SPBLveh_Cat2a	Number	Vehicle Sound Level for Vehicle Category 2a [dB(a)], Uncorrected for Temperature (According to ISO 11819-1)
SPBLveh_Cat2b	Number	Vehicle Sound Level for Vehicle Category 2b [dB(a)], Uncorrected for Temperature (According to ISO 11819-1)
SPBI_TCor	Number	Statistical Pass-By Index [dB(a)], Corrected for Temperature (According to ISO 11819-1)
SPBI	Number	Statistical Pass-By Index [dB(a)], Uncorrected for Temperature (According to ISO 11819-1)

Laeq_FF	Number	Immission Noise Level of the Far-Field Noise [dB(a)]
LaeqMax_FF	Number	Maximum Immission Noise Level of the Far-Field Noise [dB(a)]
LaeqMin_FF	Number	Minimum Immission Noise Level of the Far-Field Noise [dB(a)]
HeightMicro_FF	Number	Height of Microphone from Ground for Far-Field Tests [cm]
DistMicro_FF	Number	Tangential Distance of Microphone from the Tyre for Far-Field Tests [cm]
Lday	Number	Day-Time Noise Indicator [dB(a)] - According to the European Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise
Levening	Number	Evening-Time Noise Indicator [dB(a)] - According to the European Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise
Lnight	Number	Night-Time Noise Indicator [dB(a)] - According to the European Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise
Lden	Number	Day-Evening-Night-Noise-Level [dB(a)] - According to the European Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise
MicroBackCalc	Yes/No	If the Reported Microphone Distance is from Back-Calculated Values, and the Actual Microphone Distance was Different, Please Note Yes Here
GroundSpecs	Text	Specifications of the Surface Between the Edge of the Road Surface and the Microphone: Soft Ground, Reflective or Same as Road Surface
NoiseRoadTyre	Number	Contribution of Road-Tyre Noise to Total Noise [dB(a)]
CalcMethRoadTyre	Text	Calculation Method for Road-Tyre Noise
NoiseDriveTrain	Number	Contribution of Drive Train Noise to Total Noise [dB(a)]
CalcMethDriveTrain	Text	Calculation Method for Drive Train Noise
NoiseTyreTang	Number	Tyre Noise from Tangential Force [dB(a)]
CalcMethTyreTang	Text	Calculation Method for Tyre Tangential Force Noise
NoiseAero	Number	Aerodynamic Noise [dB(a)]
CalcMethAero	Text	Calculation Method for Aerodynamic Noise

tbl_Spectrum: Table of Spectral Noise Data

SpectralID	Text	ID Number for a Spectrum (1/3 Octave Bands) of Sound Levels at Frequency Intervals. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
25Hz	Number	A-Weighted Noise Level, Frequency = 25 Hz [dB(a)]
31,5Hz	Number	A-Weighted Noise Level, Frequency = 31,5 Hz [dB(a)]
40Hz	Number	A-Weighted Noise Level, Frequency = 40 Hz [dB(a)]
50Hz	Number	A-Weighted Noise Level, Frequency = 50 Hz [dB(a)]
63Hz	Number	A-Weighted Noise Level, Frequency = 63 Hz [dB(a)]
80Hz	Number	A-Weighted Noise Level, Frequency = 80 Hz [dB(a)]
100Hz	Number	A-Weighted Noise Level, Frequency = 100 Hz [dB(a)]
125Hz	Number	A-Weighted Noise Level, Frequency = 125 Hz [dB(a)]
160Hz	Number	A-Weighted Noise Level, Frequency = 160 Hz [dB(a)]
200Hz	Number	A-Weighted Noise Level, Frequency = 200 Hz [dB(a)]
250Hz	Number	A-Weighted Noise Level, Frequency = 250 Hz [dB(a)]
315Hz	Number	A-Weighted Noise Level, Frequency = 315 Hz [dB(a)]
400Hz	Number	A-Weighted Noise Level, Frequency = 400 Hz [dB(a)]
500Hz	Number	A-Weighted Noise Level, Frequency = 500 Hz [dB(a)]
630Hz	Number	A-Weighted Noise Level, Frequency = 630 Hz [dB(a)]
800Hz	Number	A-Weighted Noise Level, Frequency = 800 Hz [dB(a)]
1000Hz	Number	A-Weighted Noise Level, Frequency = 1000 Hz [dB(a)]
1250Hz	Number	A-Weighted Noise Level, Frequency = 1250 Hz [dB(a)]
1600Hz	Number	A-Weighted Noise Level, Frequency = 1600 Hz [dB(a)]
2000Hz	Number	A-Weighted Noise Level, Frequency = 2000 Hz [dB(a)]
2500Hz	Number	A-Weighted Noise Level, Frequency = 2500 Hz [dB(a)]
3150Hz	Number	A-Weighted Noise Level, Frequency = 3150 Hz [dB(a)]
4000Hz	Number	A-Weighted Noise Level, Frequency = 4000 Hz [dB(a)]

5000Hz	Number	A-Weighted Noise Level, Frequency = 5000 Hz [dB(a)]
6300Hz	Number	A-Weighted Noise Level, Frequency = 6300 Hz [dB(a)]
8000Hz	Number	A-Weighted Noise Level, Frequency = 8000 Hz [dB(a)]
10000Hz	Number	A-Weighted Noise Level, Frequency = 10000 Hz [dB(a)]

tbl_Reports: Table with Details of Publications Concerning to these Data

ExistingReportsID	Text	ID for Reports Based on this Set of Data. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
ReportName	Text	Name of the Report
ReportDate	Date/Time	Date of the Report
ReportContent	Text	Content of the Report in a Few Words
ReportRef	Text	Full Bibliographical Reference for the Report

Tbl_TyreResults: Table of Measured or Simulated Tyre Data

TyreResID	Text	ID Number for Tyre Result Data. Please Begin ID With Initials of Your Group (e.g.: TUW10011)
RotTyre01	Number	Rotational Speed of the Vehicle Driver Side Front Tyre [rev/min]
RotTyre02	Number	Rotational Speed of the Vehicle Driver Side Rear Tyre [rev/min]
RotTyre03	Number	Rotational Speed of the Vehicle Passenger Side Front Tyre [rev/min]
RotTyre04	Number	Rotational Speed of the Vehicle Passenger Side Rear Tyre [rev/min]
SlipTyre01	Number	Slip of the Vehicle Driver Side Front Tyre (difference between the vehicle speed and the tyre speed) [%]
SlipTyre02	Number	Slip of the Vehicle Driver Side Rear Tyre (difference between the vehicle speed and the tyre speed)[%]
SlipTyre03	Number	Slip of the Vehicle Passenger Side Front Tyre (difference between the vehicle speed and the tyre speed) [%]
SlipTyre04	Number	Slip of the Vehicle Passenger Side Rear Tyre (difference between the vehicle speed and the tyre speed) [%]
Torque01	Number	Torque on Driver Side Drive Tyre [Nm]
Torque02	Number	Torque on Passenger Side Drive Tyre [Nm]
TempTyre01	Number	Surface Temperature of the Vehicle Driver Side Front Tyre [K]
TempTyre02	Number	Surface Temperature of the Vehicle Driver Side Rear Tyre [K]
TempTyre03	Number	Surface Temperature of the Vehicle Passenger Side Front Tyre [K]
TempTyre04	Number	Surface Temperature of the Vehicle Passenger Side Rear Tyre [K]
ThrottleValvePos	Text	Position of the Throttle Valve at Time of Test
TorqueDriveshaft	Number	Driveshaft Torque at Time of Test [Nm]
VentilatorCond	Text	Ventilator Condition at Time of Test (On/Off)
LoadTyre01	Number	Actual Load on Vehicle Driver Side Front Tyre [N]
LoadTyre02	Number	Actual Load on Vehicle Driver Side Rear Tyre [N]
LoadTyre03	Number	Actual Load on Vehicle Passenger Side Front Tyre [N]
LoadTyre04	Number	Actual Load on Vehicle Passenger Side Rear Tyre [N]

11.Appendix B: Vehicles Tested and Included in the “VENOM” Model

Following vehicles were tested and included in the model:

Volvo S40 Diesel

Car model:	Volvo S40 1.9D
Year model:	2000
Accumulated driving distance:	5000 km
Power:	85 kW
Gearbox:	Manual 5-speed
Gearbox ratios:	1: 3.39, 2: 1.90, 3: 1.19, 4: 0.87, 5: 0.65
Final gear ratio:	3.77
Length:	4.55 m
Width:	1.72
Curb weight:	1370 kg
Exhaust system outlet:	Rear right
EU/ECE noise levels:	73 dB(A) (stationary 76 dB(A))
Tyre type:	Continental EcoContact CP
Tyre dimensions and speed class:	195/60 R15 88V (same on all 4 wheels)
Tyre production week:	Week 14 2000, except rear left which was week 4 1999
Tyre condition:	Worn by approx. 25 %.
Inflation pressure:	220 kPa, except rear left which was 200 kPa (cold)
Loads (incl driver):	LF 475 kg, RF 440 kg, RR 310 kg, RL 340 kg, total 1565 kg

Volvo S40 1.8

Car model:	Volvo S40 1.8
Year model:	2000
Accumulated driving distance:	12 000 km
Power:	90 kW
Gearbox:	Manual 5-speed
Length:	4.50 m
Width:	1.72
Curb weight:	1370 kg
Exhaust system outlet:	Rear right
EU/ECE noise levels:	73 dB(A) (stationary 80 dB(A))
Tyre type:	Goodyear Eagle Touring
Tyre dimensions and speed class:	195/55 VR15 85V (same on all 4 wheels)
Tyre condition:	Worn by approx. 25 %.
Inflation pressure:	255 kPa,
Loads (incl driver):	LF 445 kg, RF 410 kg, RR 330 kg, RL 335 kg, total 1520 kg

Ford KA

Vehicle model:	Ford RBT KA

Year model: 2001
Accumulated driving distance: 10600 km
Power: 44 kW (@ 5000 rpm)
Gearbox: Manual 5-speed
Length: 3.65 m
Width: 1.64 m
Curb weight: 1020 kg
Exhaust system outlet: Rear right
EU/ECE noise levels: ???

Tyre type: Kleber Viaxer
Tyre dimensions, load/speed class: 165/65 R 13 77T (same on all 4 wheels)
Tyre production week: Front: Week 40 2000. Rear: Week 41 2000
Tyre condition: Worn by approx. 25 %
Inflation pressure (at 40^{o}): LF 160 kPa, RF 185 kPa, RR 140 kPa, RL 145 kPa
Loads (incl driver): LF 350 kg, RF 300 kg, RR 185 kg, RL 220 kg. Total 1055 kg

Toyota Previa

Vehicle model: Toyota Previa (Luna)
Year model: 2001
Accumulated driving distance: 34200 km
Power: 115 kW (@ 5600 rpm)
Gearbox: Manual 5-speed
Length: 4.75 m
Width: 1.79 m
Curb weight: 1780 kg
Exhaust system outlet: Rear right
EU/ECE noise levels: ???

Tyre type: Michelin Energy GreenX – XH1 Radial XSE
Tyre dimensions, load/speed class: 205/65 R 15 94H (same on all 4 wheels)
Tyre production week: Week 11 2000
Tyre condition: Worn by approx. 25 %
Inflation pressure: 245 kPa (@ 40^{o})
Loads (incl driver): LF 535 kg, RF 465 kg, RR 405 kg, RL 445 kg. Total 1850 kg

Mitsubishi Pajero

Vehicle model: Mitsubishi Pajero D1-D (Pinin)
Year model: 2000
Accumulated driving distance: 55400 km
Power: 121 kW @ 3800 rpm
Gearbox: Automatic, 5-speed ("INVECS-II Sports Mode 5 AT")
Length: 4.30 m
Width: 1.85 m
Curb weight: 2020 kg ("Total weight" 2510 kg)
Exhaust system outlet: Rear right

EU/ECE noise levels: ????
Others: Sports utility vehicle (SUV), diesel, engine displ. 3.2 l
4-wheel drive (low and high) available

Tyre type: Bridgestone Dueler H/T
Tyre dimensions, load/speed class: 265/70R16 112S (same on all 4 wheels)
Tyre production week: Week 04 2000 for all, except rear left week 03 2000
Tyre condition: Worn by approx. 60 %
Inflation pressure: Front 195 kPa. Rear 205 kPa
Loads (incl driver): LF 625 kg, RF 595 kg, RR 535 kg, RL 550 kg, total 2305 kg

Toyota light truck

Vehicle model: Toyota HiLux 2.4 TD – Challenger
Load compartment type: X-Cab SR5
Year model: 2001
Accumulated driving distance: 5300 km
Power: 66 kW @ 3500 rpm
Gearbox: Manual 5-speed
Length: 5.10 m
Width: 1.69 m
Curb weight: 1830 kg ("Total weight" 2510 kg)
Exhaust system outlet: Rear left
EU/ECE noise levels: ????
Others: 4-wheel drive (low and high) available
Diesel engine

Tyre type: Bridgestone M723 M+S
Tyre dimensions, load/speed class: 225/75R16 121/120 N (same on all 4 wheels)
Tyre production week: Week 29 2000
Tyre condition: Worn by approx. 20 %
Inflation pressure: 270 kPa
Loads (incl driver): LF 615 kg, RF 595 kg, RR 505 kg, RL 490 kg, total 2205 kg

Ford Mondeo 2.5 l V6

Vehicle model: Ford Mondeo 2.5 l
Year model: 1997
Accumulated driving distance: 85 000 km
Power: 126 kW
Gearbox: Manual 5-speed
Length: 4.556 m
Width: 1.749 m
Curb weight: 1490 kg
Exhaust system outlet: Rear left and right, spots type
EU/ECE noise levels: 71 dB(A), Standstill 82 dB(A)

Tyre type: Nokian NRV
Tyre dimensions, load/speed class: 195/60R15 88V

Tyre production week: Week 09 1999
Tyre condition: Worn by approx. 20 %
Inflation pressure: 220 kPa
Loads (incl driver): LF 530 kg, RF 480 kg, RR 330 kg, RL 360 kg, total 1700 kg

BMW Motorcycle

Vehicle model: BMW F 650 GS
Year model: 2001
Accumulated driving distance: 1300 km
Power: 37 kW
Engine speed at max. power: 6500 rpm
Gearbox: Manual 5-speed
Length: 2.20 m
Width: 0.88 m
Curb weight: 185 kg
Exhaust system outlet: Two at rear, medium height
EU/ECE noise levels: 79 dB(A) (stationary 88 dB(A))
Others: Cylinder volume 652 cm^3

Tyre type: Bridgestone Trail Wing 101
Tyre dimensions, load/speed class: Front: 100/90-19 57H. Rear 130/80R17 65H
Tyre production week: Front: Week 08 2000. Rear: week 43 2000
Tyre condition: Worn by approx. 30 %
Inflation pressure: Front 165 kPa, rear 175 kPa
Loads (incl. driver): Front: 115 kg. Rear: 180 kg. Total: 295 kg.