Reduction Potential of Road Traffic Noise

A Pilot Study

Wolfgang Kropp, Tor Kihlman, Jens Forssén and Lars Ivarsson

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Edited version

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Preface

In the past the Royal Swedish Academy of Engineering Sciences, IVA, has taken initiatives to promote the development of quieter industrial products. This pilot study is part of a new IVA study to reduce noise. A cooperative effort has also been initiated with other national academies. The United States National Academy of Engineering, NAE, is working on a project, ”Technology for a Quieter America,” covering noise at the workplace, community noise, and noise from products. The Engineering Academy of Japan, EAJ, has also expressed an interest in the noise issue. This issue will be presented in a convocation of the engineering academies to be hosted by EAJ in Tokyo during October 2007 – CAETS 2007.

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Thomas Beckenbauer, Müller BBM, Germany

These experts reported on relevant topics. Their reports as well as the full report are found at http://www.iva.se/trafficnoise

This shortened version of the report does not include discussions of the special problem in Sweden, Norway and Finland; the use of studded tyres. The use of studded tyres decreases substantially the possibilities to reduce road traffic noise emissions.

Göteborg in August 2007.

Wolfgang Kropp and Tor Kihlman

Abstract

This report concerns the technical potential to decrease noise emission from road traffic. The work is based on four reports by experts in the field supplying needed knowledge to discuss this question. Special focus is given on the need for coordination between the demands upon and actions by the three main actors; the car industry, the tyre industry and the road owner. The influence of the European noise policy (i.e. ongoing discussion concerning type approval for vehicles and tyre noise limits) with its positive and negative consequences is investigated. For vehicles, tyres and roads the available technical solutions are discussed to reduce their contribution to road traffic noise.

For Norway, a study is presented of different scenarios (concerning reduction of emission from vehicles including tyre/road noise) and their influence on an annoyance index during the next 10 to 15 years.

The report concludes that there is a technical potential to reduce the emissions substantially and proposes how to accelerate this process in a positive way. This includes political actions as well as research needs.

Contents

Conclusions from the Report

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For Norway, a study is presented of different scenarios (concerning reduction of emission from vehicles including tyre/road noise) and their influence on an annoyance index during the next 10 to 15 years.

The report concludes that there is a technical potential to reduce the emissions substantially and proposes how to accelerate this process in a positive way. This includes political actions as well as research needs.

The starting point for this study was the unbalance between the noise emissions from ordinary traffic and possibilities to achieve reasonable immission situations even with optimal use of measures on the immission side. This unbalance is about 10 dB, so the question asked was whether a source reduction of 10 dB could be achieved with today's technology.

Main results from the project

The findings of the report are that **5 dB(A) emission reduction can be achieved by utilising technology available today.**

However, in order to reach the needed reduction of about 10 dB, research and development is needed on tyres and road surfaces. A modified vehicle concept might be required to be adapted to an increased demand on exterior noise.

For the purpose of this study, we have to take into account the complex interaction between the tyre, road and vehicle designs with respect to traffic noise emission and especially immission at the people's living place. Although substantial work has been collected in this report, the work is far from being complete.

Considering the necessary lead times for industry and road owners to meet stricter noise limits and the additional time it takes until all vehicles, tyres and road surfaces fulfil lower limits, it takes decades to achieve a few dB lower equivalent levels also with high ambitions regarding sharpened limits. The scenarios studied in Norway illustrate this. See p.35 [and Berge 2007] for more details. On the other hand, if the process towards lower noise technology is not speeded up within the UNECE and among the road owners, the traffic noise situation will rather continue to get worse than better at all during the next 10 to 20 years.

We have the tools in the form of relevant technical test methods for vehicles, tyres and road surfaces. This means that noise limits can be set for the products. We also have good knowledge about lower noise technology. It is evident, however, that the political process towards sufficiently sharp noise limits in the UNECE regulations 51 and 117 is too slow. Instead of being slowly technology following as hitherto, the noise limits need to be technology driving. The coordination between the three parties (vehicle manufacturers, tyre manufacturers and road owners) needs to be much improved based on a holistic approach to the environment noise problem caused by the road traffic. Economic incentives could be a way to speed up the development.

The technical potential for road traffic noise reductions has to be discussed case specifically where driving cycle and traffic composition are defined. Reductions of different sources are not additive. The relative importance of different sources is different depending upon traffic situation and speed. Road traffic noise reduction needs a thoroughly planned holistic approach.

The results on p. 20 illustrate that to obtain a reduction of the total noise by 5 dB, it is necessary to reduce both the rolling noise and the propulsion noise. But the necessary reductions are case specific. To get a reduction of the total noise by 5 dB, one can see from these studies that tyre/road noise can be reduced by 6 dB, as one possible solution, and the needed reduction of propulsion noise is then around 4 dB for 30 km/h driving speed and around 2 dB for 110 km/h driving speed. These are averaged values representing all vehicle classes.

Our judgement is, that the potential for reducing the propulsion noise is sufficient to obtain these 2-4 dB. However, the necessary lead-time may be different for car manufacturers and heavy vehicles manufacturers. It is unlikely that manufacturers of passenger cars ever were forced to explore the real potential for exterior noise reduction. New platforms may need to be designed. The situation is somewhat different for heavy vehicles. There, encapsulation and screening have been used extensively to adapt to tightened limits and modified test procedures. Technology solutions are available, but might demand that exterior noise properties are taken into account in the very early design phase. Heavy vehicles are built in modular systems and stricter noise limits may necessitate basic changes in the components; engines, transmission gears, etc. Substantially stricter noise limits must therefore be set in a very long time perspective.

The potential for reducing tyre/road noise is distributed between tyre and road. For the tyre the following can be concluded:

- Exploiting the spread of noise emission from tyres on the market one might identify a potential for reduction of tyre noise by 2-3 dB.
- Although there is a potential, it might be difficult to utilise this, having in mind all the different properties required from tyre performance.
- Top speed limits and less focus on high performance with respect to handling as well as on fashion criteria will definitely open for the development of quieter tyres.
- Focus and resources should be given to develop quiet and safe tyres with low rolling resistance.

With 2-3 dB reductions for the tyres, 3-4 dB are required from the road surface. Already the optimisation of the road texture can give up to 2 dB in relation to an SMA 0/11 (the Swedish standard surface is SMA 0/16 which is even a bit louder than the SMA 0/11). Semi-dense surfaces can give a reduction between 2 and 4 dB. With increasing absorption of the surface the reduction can increase up to more than 6 dB. However, the use of such high absorbing surfaces (open porous asphalt) demands regular cleaning. In addition one has to cope with a loss of efficiency of about 1 dB per year, at least at the very beginning when the surface is newly laid.

An aspect, which is often neglected in this context, is the quality control of the manufacturing process. Carefully monitoring the properties of the road surface, which are related to its acoustical behaviour, can give a gain of several decibel of rolling noise reduction, even if the same type of road pavement is taken into account. Acoustic measurements of the finished road surface are essential.

The disadvantage of the low noise surfaces is the higher costs. It may well mean 4 times as high annual costs for the most advanced cases compared to the reference SMA 0/16. These costs, however, shall be compared to the economic evaluation of the noise reductions.

Proposed Actions

Based on the report it can be concluded that in order to reduce road traffic noise a series of measures and actions can and have to be taken. These proposed measures and actions are as follows:

- The traffic noise emission question demands a holistic approach. Not only is it necessary to coordinate measures on vehicles, tyres, roads and traffic management but also to seek such solutions that are of benefit also for air quality, traffic safety, energy efficiency and use of natural resources (not least land).

- There is a need for independent competence in the broad field of road traffic noise guarantying a holistic approach separated from the specialised interest of the individual partners; vehicle industry, tyre manufacturer and road authorities. Such a competence centre should be located at one or several universities with high reputation in the field, acting as an adviser for policy decisions.

- Acoustical requirements must be included in the contracts with those who lay road surfaces. The performance can be checked upon completion. Thereby, local actors can demand guarantees for the acoustic properties of road surfaces. Among the Nordic countries, this procedure seems to be best enforced in Denmark.

- Acoustic classification systems need to be worked out for vehicles (tested by the new ISO 362), for tyres and for road surfaces (tested by the CPX-method). This should be done on an international level, i.e. by UNECE. Differences in climatic conditions may have to be taken into account. The same tyre (or road surface type) may get a different classification in a colder zone than in a warmer. The steps in new versions of the UNECE regulations 51 and 117 could be chosen to correspond to such classes and thereby be technology driving.

- The acoustic classification needs to be included in the requirements for *Clean Vehicles*. (This is especially important for delivery vehicles used in urban areas during night.)

- The top speed limits of vehicles should be discussed in a broad context. Except for Germany, the State of Montana in the US and the North West Territories in Australia, there are speed limits of maximum 130 km/h on all roads in the world. Nevertheless, the German market appears to have a surprising effect upon car design and the car market; cars tend to have ridiculous top speeds. This fact is also reflected upon the tyres. They have to be safe for the top speeds of the cars. If no car could be driven at higher speed than an agreed top speed, say e.g. 130 km/h (rather than 250 km/h) this would have a very favourable effect upon increased safety and would promote better energy efficiency, less negative life-cycle environmental impact, including lower CO2-emissions. It would also make it much easier to design low noise tyres. It could therefore make it easy to introduce much lower noise limits than proposed by FEHRL for step 2. (See p. 29).

  But not only that: Such a top speed limitation would also have a major influence upon the car design. It should be discussed together with the car industry what such a limit would and could lead to.

- Economic instruments need to be developed in order to get a demand for quieter products. With generous economic benefits for owners of quieter vehicles and quieter tyres, the development could be speeded up.

- Economic instruments could also be in the form of quota for noise emissions. They should be set so that they push the development towards quieter vehicles, tyres and roads. Such quotas are now subject for research and discussion for air traffic noise. Quota for road traffic noise may be more complicated to use than for air traffic noise, but it should be subject for further study. A quota system for the noise emissions from vehicles and tyres and the noise properties of road coverings, could be a tool to coordinate the work by the three responsible parties.

- It is mainly the political decisions that are lacking. There is a demand for political leadership for lower noise emissions. It should be tried to join a number of European countries to demand that the EU Commission speeds up the work on noise emissions by UNECE.

  This list is not complete. However, to take up some of the proposed actions would be a big step towards a reduction of road traffic noise and it will help to overcome the years of stagnation in this question.

Research Needs

The work with this report has not only identified the potential for reducing road traffic noise but also areas where further work is needed. Some of these areas are listed in the following:

- In the report (Forssén, 2007) a pilot study is carried out to answer the question of how much propulsion noise and tyre/road noise has to be reduced in order to achieve a reduction of road traffic noise by 5 or 10 dB. This study should be carried out more thoroughly based on the new prediction models from the EC project IMAGINE, including different future scenarios and traffic situations. It should also include propagation effects due to meteorological conditions and ground influence as well as due to screening by noise barriers and high buildings.

- In the report (Berge, 2007) scenarios are studied for Norway concerning the consequences of different ambition in noise reduction from road traffic. Similar studies should be carried out for other countries as the conditions may vary from country to country.

- Economic models are needed to identify optimal reduction measures for road traffic noise. It should also be investigated how a quota system for noise emission could be introduced and how income from such a system could be used to support measures for road traffic noise reduction.

- The research on quiet and safe tyres with low rolling resistance should be given high priority. One might argue that this is the task of the tyre industry. However, independent research can contribute to explore the potential available under given constraints such as speed limits.

- There is a need to investigate solutions for road surfaces beyond today's technology. This might concern different materials for the surface, optimised textures, multifunctional road surface (e.g. used as sun collectors as discussed in some projects in Germany), and surfaces with low rolling resistance.

- A top speed limit is expected to affect tyre design, road design as well as complete vehicle design. The potential for lower noise emissions created by a speed limit should be studied. The effects on other emissions as well as on traffic safety should also be included.

Some of these research activities could give an immediate impact on the development of quieter road traffic. Other activities might take many years to lead to results. These activities, however, are therefore not less valuable. It just demonstrates the complexity of the problem and the urgent need to start now to attack the problem.

Introduction

In European cities, equivalent levels (LAeq,24h) outside dwelling windows frequently lie in the range 60-65 dB. Estimates indicate that more than 100 million Europeans are exposed to outdoor equivalent levels above 65 dB from road traffic. These levels, far above WHO recommendations, cause several adverse effects, among others sleep disturbance, speech interference, general annoyance and cardiovascular effects. Noise is one of few environmental problems which still shows a negative trend.

A common goal in a number of European countries is since many years an equivalent outdoor level in the order of 55 dB for dwellings. This level is a technical-economic compromise, it can be regarded as an acceptable goal, but it does not represent a good environment. The problematic noise situation is caused by normal traffic flows of vehicles fulfilling present noise emission requirements.

Measures to protect the environment have almost entirely been taken on the immission side through town and traffic planning, barriers and building design. In more recent time, soundscaping giving residents access to quietness and a quiet side of the dwellings has become an important tool to limit the traffic noise problems. But even with an optimal use of soundscaping, the traffic noise problem cannot be reduced to an acceptable level; the emissions are too high. There is an unbalance of 10 dB between the emissions from ordinary traffic and possibilities to achieve reasonable immission situations even with optimal use of measures on the immission side. The problem is still more severe in existing situations.

A severe obstacle for effective emission control is that the emitted noise comes from several sources and the responsibility for these sources is shared between several parties; the vehicle manufacturer, the tyre manufacturer and the road owner. There are, however, no regulations or other measures describing or even promoting any cooperation between the actors. A critical problem to solve is therefore to establish a system for consorted actions of the different actors. One step could be to set a common political goal to reduce the real emissions.

This report gives an overview of the present policy situation, the technological problem and the technological options. It also identifies the areas where further clarifications are needed. The shared responsibility is reflected in the disposition of the report.

European Noise Policy

Due to the complexity of the noise problem, policy aspects reach from local ordinances to global policy. With present technological knowledge the noise problem cannot be solved entirely neither by local measures on the immission side, nor by the manufacturers even with the most far-reaching source control. All parties have to cooperate at their best to reach an acceptable situation. Present market forces are insufficient. Ambitious national/local ordinances and very strict emission limits on tyres and vehicles are needed. Without an effective coordination between the three main bodies, little progress can be expected.

The EU policy is important both on the emission and immission sides. Emission regulations for type approval of road vehicles and tyres are set by UNECE, the *UN Economic Commission for Europe*. The present work within UNECE, described below, is however, intended to lead to a global standard. EU has a strong position within UNECE, and EU has, or is considered to have, very high ambitions when it comes to noise control of products.

European policy

Most environmental problems can be solved entirely by emission reductions. Emission regulation has been the general approach in the EU environmental legislation. But this approach is not sufficient to solve the traffic noise problem.

The shortcomings of noise emission legislation were the background to the EU Directive on environmental noise adopted in 2002 (Directive 2002/49/EC). The Directive emphasizes both the immission side and the emission side. The immission side is handled by EU DG Environment. It defines common indicators and methods and demands statistical data, noise maps and action plans to be worked out and sent to the Commission. It covers bigger agglomerations. It does not prescribe any common limit values or even guidelines for the immissions.

The emission side is handled by the EU *DG Enterprise*. This DG's mission is the free flow of goods and its ambitions when it comes to noise emission regulations appears very low.

The emission legislation has two parts; the tyre noise legislation and the vehicle type approval.

In 2001 the first EU Directive on tyre noise was adopted (Directive 2001/43/EC). This directive is identical with UNECE regulation 117. It was early shown, that practically all tyres on the market fulfilled this directive already when it was introduced so its effect in terms of reduced emission has hitherto been zero. Further, the spread in data is of the order of 10 dB indicating that tyres can be made comparatively quiet. According to the Directive, it should be considered for revision in 2004. This work has been delayed by at least two years due to slow action by the Commission. In the work finally initiated by the Commission, the organization FEHRL, *Forum of European Highway Research Laboratories,* in its report for the Commission has proposed substantially stricter emission limits in two steps, the first in 2008 and the second in 2012. (FEHRL 2006)

If adopted, the expected effect would be 2-3 dB in equivalent noise levels to be reached in 2020. The industry, through the organization ETRMA, is actively lobbying against the stricter limits. Relevant questions to ask and analyze in the discussions with the industry are the economic implications for the customers and if there are any cars to which no tyres on the market could be available if the stricter limits were adopted.

Tyre legislation may be regional for Europe. Vehicle legislation should be international. The organization through UNECE is described in next section. DG Enterprise has therefore left the vehicle legislation to UNECE but used its influence on that work rather to delay it than to speed it up. For reasons described below, it is critical with continued work to demonstrate the technical options for stricter legislation in parallel with concerted political actions. There is an important time perspective of two years for actions.

UNECE's work on noise emission legislation

UNECE, *United Nations Economic commission for Europe,* has for many years worked on common requirements for wheeled vehicles. The work started with the 1958 Agreement, which main purpose was to unify the requirements on vehicles to facilitate crossing national boundaries in Europe. The Contracting Parties, mainly countries in Europe, formed through their members an Administrative Committee that took the formal decisions on the requirements on the vehicles. Regulation 51 concerned noise emission limits. These limits were sharpened a number of times, as mentioned above without any real effect upon the noise emission from road traffic.

With the 1998 Agreement, the intention was widened to arrive at global technical regulations for wheeled vehicles. This agreement is signed by Contracting Parties also outside Europe. The purpose is to harmonize technical regulations and "to ensure that objective consideration is given to the analysis of the best available technology, relative benefits and cost effectiveness as appropriate in developing global technical regulations:" The decisions are taken by the Executive Committee which is formed by the representatives of Contracting Parties. It should be noted, that the agreement allows sub national, national and regional authorities to adopt technical regulations that are more stringent than those at the global level.

The technical work is performed in the working party, WP 29, *World Forum for Harmonization of Vehicle Regulations* and an under-group of technical experts on noise, GRB, *Group Rapporteur de Bruit.* These experts, who represent the Contracting Parties, develop the proposals to the Executive Committee but in their work they are much dependant upon contributions from industry that is also participating in the meetings through their organizations.

ISO develops the test methods, but UNECE sets the limit values to be fulfilled at type testing, so there is a close cooperation between GRB and ISO TC 43/SC1. Tyre noise is covered by UNECE regulation 117. Noise limits for four-wheel motor vehicles are addressed by the relevant European Directives and UNECE Regulation 51.

The Terms of Reference, TOR, for WP29 are:

> *"Initiate and pursue actions aiming at the harmonization or development of technical regulations or amendments to such regulations which may be accepted world-wide, and which are directed at improving vehicle safety, protecting the environment, promoting energy efficiency and anti-theft performance, providing uniform conditions for periodical technical inspections and strengthening economic relations world-wide, according to the objectives laid down in the respective Agreements."*

It could be noted that noise is not explicitly mentioned. The TOR includes no explicit incentive to decrease the noise emissions.

The test method ISO 362 dates back to the 60'ies. It has been heavily criticized since its introduction, see e.g. the Swedish Parliamentary Committee *Trafikbullerutredningen,* SOU 1974:60. Minor modifications of the standard have not solved the problems and strengthening the noise limits has not led to any corresponding reductions of the emission from individual vehicles in ordinary traffic except for heavy-duty vehicles at low speeds. Now ISO, in cooperation with GRB has arrived at a revised test method, which is supposed to be more relevant. It is intended to be representative for urban driving conditions with speed limits 50 km/h or less (ISO/FDIS 362-1:2005).

WP 29 adopted the new test cycle in November 2006. On demand from the EU Commission, the decision in the Executive Committee has been delayed by two years. During a transition period of two years, manufacturers have to test their vehicles according to the old measurement method in order to get type-approval and also, for monitoring purposes, in accordance with the new measurement method. By this monitoring procedure, the Commission says it will gain the necessary test data for an impact assessment and on that basis propose adequate limit values for the new test method to abolish the existing test protocol. In the first step, the limit values linked to the new test method are planned to be set such that the emissions will remain more or less unchanged. This will mean a further delay in the process of introducing more stringent noise levels for motor vehicles. A second step will then not come until a number of years later, 2014 or 2015. Then, we have had nearly 20 years without any real progress. Further, after decisions on stricter limits are taken, it lasts at least another 10 years until lower immission levels (L_{eq}-values) can be observed.

The Commission's position is said to take into account that setting new limit values for noise emissions will require a solid impact assessment, which can only be done on the basis of reliable and representative data. The Commission will ask an independent contractor to evaluate the type-approval data as soon as they become available and to provide the Commission with interim evaluations at regular intervals. As soon as the type-approval data have reached a sufficient degree of representation, the Commission will propose new limit values.

The regulations from UNECE are apparently slowly technology following, rather than technology driving. However, according to a discussion with a senior member of GRB, the term “best available technology” does not prevent the adoption of regulations that are technology driving. Participants in the GRB work have in oral communication expressed that they feel no pressure from the political side to speed up the work in order to decrease the traffic noise emissions. To achieve a change, it is evident that a clear political signal is needed telling that the noise emissions from the road traffic has to be substantially reduced as fast as possible.

Our judgement is that a political action from as many countries as possible for lower noise emissions should be launched now to prepare for an intervention in the process in good time before any further decisions are taken by the EU Commission so that already the first step would imply strengthening of the limits.

Road Traffic Noise – The Influence of Different Sources

Road traffic noise is typically characterised by the sound pressure levels on the immission side (e.g. in front of the window of a dwelling). Different measures are used such as the Lmax (maximum sound pressure level during a certain period), L_{eq} (the equivalent level as an integrated quantity over a certain time period) or L_{DEN}, where the L_{eq} for day evening and night are weighted by different penalties. In this way the need for quiet time periods in the evening and undisturbed sleep during night is accounted for. Typically recommended limits for traffic noise at the façade are $L_{Aeq,24h}$ values of 55 dB.

With respect to the characterisation of road traffic noise one can also conclude that neither the measurement procedure nor the recommended limits takes into account the type of sources and source characteristics in the case under consideration. The measure just describes the sum due to all sources involved in traffic work. This fact also makes the control of road traffic noise difficult as explained in the further text.

The Sources of Road Traffic Noise and Noise Limits

Three different types of sources can be distinguished:

- Contribution from engine, exhaust system, auxiliary equipment and power transmission
- Contribution from the interaction between tyre and road
- Contribution from aerodynamic sources

These three source types are distinguished by a complex dependence of source strength and source characteristics (e.g. frequency content, time behaviour) on load and speed parameters.

As a consequence there is no simple relation revealing which sources are responsible for the measured sound pressure levels at e.g. a façade directly. The amount of contribution from the different sources to the total level is case dependent. Models for the prediction of the contribution of individual sources as function of different parameters have been developed in the EC project *IMAGINE*. However, even these models are focusing on average behaviour of an ensemble of vehicles and cannot be used to predict noise immission from individual vehicles under certain load situations.

Let us take as an example the often-stated fact that "tyre/road interaction is the dominant source at speeds above 30 km/h for light vehicles and above 70km/h for heavy vehicles". This is correct when observing an average condition, but it will not hold for a noisy vehicle or a quiet road surface.

During the recent years models have been developed which are suitable for predicting traffic noise in typical situations. Although they use characteristic vehicle compositions they allow for defining traffic modus (speed or drive cycle) and the road texture. At the same time the influence of the road surface on the traffic noise might vary with the type of tyre used on the vehicle by a few dB.

To conclude, if we are interested in reducing road traffic noise by let us say 5 dB we need to investigate the potential in each individual area, but we also have to study the complex interaction between the changes in tyre, road and vehicle design with respect to traffic noise emission and especially immission at the people's living place. This has to be carried out case specific where driving cycle and traffic composition is considered as exactly as possible. In simple words: reductions of different sources are not additive and road traffic noise reduction needs a thoroughly planned holistic approach.

In this aspect it is surprising that up to now limits for the emission of the different road traffic noise sources/components were handled separately from each other if it all.

Vehicle noise limits

Limits for vehicle noise were first introduced 1970. The last modification entered into force 1996 (Directive 92/97/EEC), which sets the noise limit at 74 dB for cars and at 80 dB for heavy trucks. At that time, it was expected that noise limits would be reduced every 4-5 years in the same way as exhaust emission reductions. These expectations were not fulfilled. For 10 years now, the limits have been unchanged. One argument was that tyre/road noise is considered as the limiting factor and therefore a further tightening of the limits without reducing tyre/road noise is meaningless. In addition, the test method (the old standard ISO 362) was not well correlated with normal driving pattern in urban traffic. Since then, ISO has been working on revising the test method 362, which in principle has been adopted by the EC as the new test method in ECE regulation 51. The test method increases the influence of the tyres, which is in consistence with real traffic situations (tyres were up to now not included and the influence of roads will not be considered). In November 2006 a two years transition period has been introduced, where all vehicles shall be tested according to both the new and old test method. On basis of these measurements, new limits will be set. This decision will inevitably mean a further delay in the process of introducing more stringent noise levels for motor vehicles. It seems that no real tightening of the noise limits can be expected before 2014-2015. Then, we have had nearly 20 years without any real progress concerning more stringent noise emission limits for motor vehicles.

Tyre noise limits

Limits have been introduced 2001 by the EC (Directive 2001/43/EC). However, experts stated that less then 5 percent of the existing tyres at the time of introduction would be affected by the limits. This means that the limits did not have any impact on road traffic noise at all. Therefore a recent study by the *Forum of European Highway Research Laboratories* (FEHRL) for the EU Commission proposed a substantial tightening in tyre noise limits. The proposal is currently being reviewed by the Commission. However, it is uncertain whether these stricter limits will be adopted.

Noise emission limits for road surfaces

There are no limits defined for tyre/road noise due to road surface performance and it is very unlikely that limits will be set in the near future.

The question arises, how, in this situation of shared responsibilities and diverging procedures to define noise limits, a general reduction of traffic noise can be achieved in an economically efficient way. The logical answer is that the vehicles, tyres and roads as a complete system have together to fulfil demanded limits concerning the traffic noise immission at the people's living place. A shared responsibility has to be established to make the process towards lower traffic noise emissions effective.

The Physics behind the Sources of Road Traffic Noise

In the following a brief summary is given for the most important sources and their generation mechanisms.

Tyre road noise generation

Basically two different types of mechanisms can be distinguished, mechanisms exciting the tyre structure to vibrations, leading to radiation of sound, and aerodynamic effects. Sound radiation is mainly due to radial vibrations of the tyre structure as well as vibrations of the sidewalls, the latter in minor scale and mainly at low frequencies. The excitation of vibrations demands time varying forces acting between the tyre and the road. The changes of contact forces over time can be due to different effects: inhomogeneities (e.g. the tyre non-uniformity) and defects of the tyre structure, tread pattern geometry, road texture, processes in the contact such as stick slip and stick snap. First, the tangential and radial forces lead to friction mechanisms, which in turn lead to stick-slip when the tread blocks are in contact with the road. Secondly, when the tread blocks are on the way to loose contact with the road, some adhesive forces will tend to keep them in contact with the road. At the same time, stick-snap will appear. Figure 1 illustrates the different generation mechanisms of tyre vibrations.

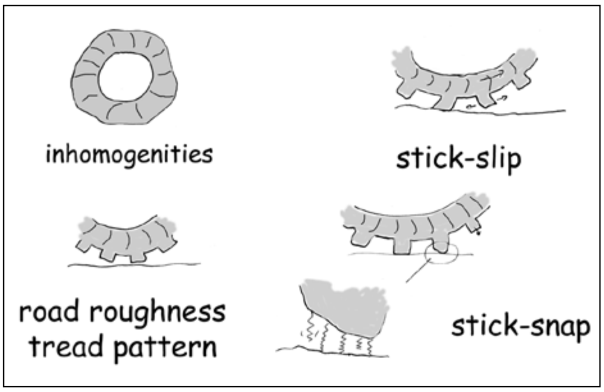


Figure 1. Generation mechanisms related to tyre vibrations.

Which of these mechanisms are dominating at which frequencies is not always easy to predict. As a rule of thumb one can expect tyre vibrations as the main source for frequencies below 1000 Hz. The wide range and complexity of different tyre/road combinations make a general answer difficult and might even lead to confusion. However, one can conclude that there is a general agreement on the mechanisms behind the generation of sound due to the vibration of the tyre structure.

The situation becomes more confusing considering aerodynamic sources. There is a general agreement that while the tyre is rolling, some air is pumped out at the leading edge and sucked in at the trailing edge. As long as the amount of the air flow is time invariant there will be no sound generation having in mind that it is the rate of change in the airflow which is responsible for the sound generation. In the German project "Sperenberg", Beckenbauer and his colleagues made a very thorough study of pass-by noise for different road and tyre combinations (Beckenbauer, 2001). For a number of these combinations – but not for all – the speed exponent (i.e. the change of the sound pressure amplitude as function of driving speed) changes from "3" indicating mechanical sources to "4-5" indicating aerodynamic sources when passing 1000 Hz. It could be interpreted as air-pumping. However, how the air pumping mechanisms work in detail is explained in different ways and, as often when disagreement occurs, the explanations might be correct for certain cases but they might not give a general answer.

In 1971 Hayden (Hayden, 1971) presented the first semi-quantitative model of tyre noise excitation, and this was based on air-pumping. Hayden proposed that, as the tread enters the leading edge of the road contact area, air is squeezed out as the tread is compressed and as it penetrates into the road surface. At the trailing edge, the tread is decompressed and lifts up from the road surface with the result that air rushes back to fill the voids.

Some investigations of a smooth tyre rolling over a cavity in the road were carried out at INRETS (Deffayet, 1989 and Hamet, 1990). They measured the pressure in cylindrical cavities of different dimensions as a slick tyre rolled over the opening. The internal pressure increased very rapidly at the approach of the tyre and remained at a constant high level as the tyre obtruded the cavity. External measurements at the entrance of the contact patch showed no acoustical signal during this phase. When the cavity opens, the pressure signal oscillates and decays more or less rapidly depending on the cavity dimensions.

Figure 2 summarises the both main ideas.

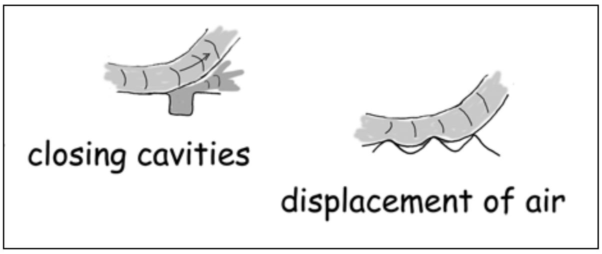


Figure 2. Aerodynamic sources in the contact area between tyre and road

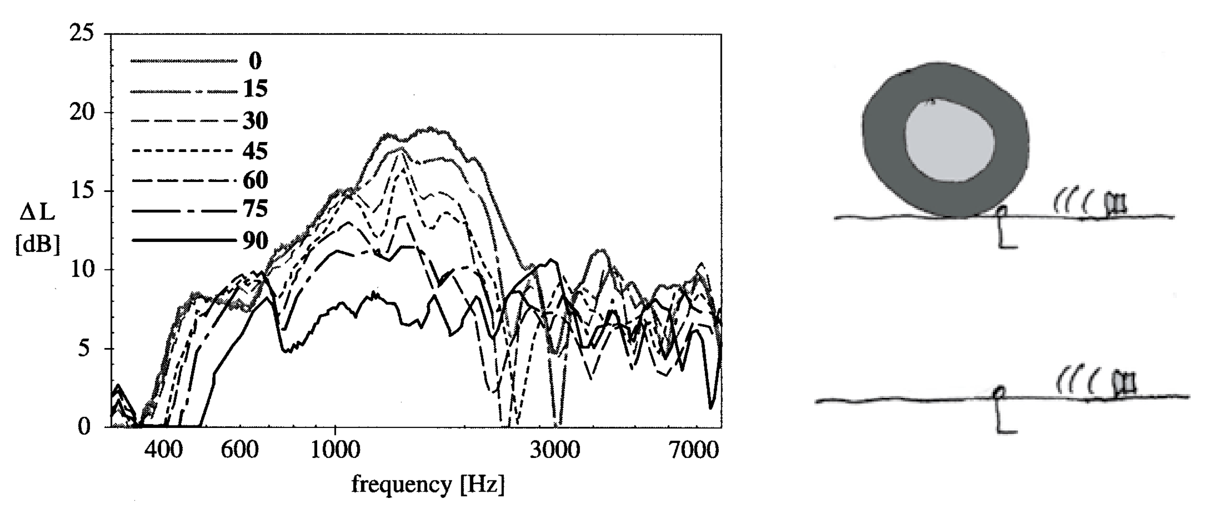


Figure 3. Amplification due to the horn effect for different angles (0 in the plan of the tyre, 90 perpendicular to the plane off the tyre) from (Kropp, 2000)

The multitude of generation mechanisms makes the picture of tyre/road noise generation diffuse and the decision for a modelling strategy rather difficult. The problem becomes even larger due to the complexity of the radiation conditions for both vibrations and aerodynamic sources.

The so-called horn effect as explained by Ronneberger in 1989 leads to an amplification of the radiation depending on geometry, source location and acoustic properties of the road surfaces. Further, resonance effects in the contact areas (e.g. resonances inside partly or fully open grooves) are identified as additional sources of noise generation in some publications. This is rather confusing and the effects are better considered as additional amplification effects for the radiation from the vibrating/moving tyre structure.

Propulsion sources

Three main sources can be distinguished (intake noise, exhaust noise and engine noise) In addition to this, auxiliary equipments (e.g. cooling fans) as well as transmission line and gearbox can be dominant under certain situations (e.g. idle condition or max load on the engine).

Intake and exhaust noise are mainly determined by the engine performance. Mostly, they are controlled by using mufflers (reactive mufflers in the form of expansion chambers, and also resistive absorption types) which have the task to reduce noise without reducing engine performance due to an eventual pressure drop created by the flow resistance of the devices. The muffler system can also radiate sound itself due to shell radiation and fundamental breathing modes of the muffler or intake walls. These types of radiation are taken care of by reinforcements and added structural damping. The needed volume of the muffler system is given by the needed amount of reduction level and the maximum allowed pressure drop in the system. The maximum volume of muffler system is then set by the engine which has the highest power of the family of engines in a carline.

Due to the fact that cars today are developed in platform strategies, it is difficult to increase volume in an exhaust system in a platform since a new floor structure is then needed. Therefore if more intake or exhaust volume is needed, it can take some time before this can be available in a new platform. A platform cycle can be 10 years. If an increased noise reduction is wanted in a short term the maximum engine power will probably be reduced.

The noisiest engines today are the diesel engines due to the fact that they have a harder compression ratio and combustion process compared to petrol engines. However, there is a lot of development going on in order to give smoother combustion pulses due to pre-injection strategies using fast injectors. In the same time the tougher emission requirements promote harder and noisier combustion processes. In a customer view it is preferred that the diesel engine noise is perceived the same as petrol engine noise. In order to please this demand a lot of work is done for the engine as source. First of all the sound radiation from the engine itself is minimised by structural optimisation. Secondly the engine bay is as sealed as possible for both external radiation and radiation to passenger compartment. Also the acoustical absorption material in the engine bay is maximized in order to reduce the diesel character of noise. However, in today's cars there are some holes to the surrounding area which are not sealed, typically for drive shafts and also for cooling of the engine. If the engine bay is to be more sealed than today, a new concept for the engine bay is probably needed in order to handle the heat exchange.

Moreover there are other sources on the engine such as auxiliaries like generators compressors and turbines. There is a trend to use more compressors and turbines today in order to make engines more fuel effective, so called "down sizing" (small engine but high power). The compressors and turbines also create sound and have to be optimised for noise emission. Also these "small" engines can potentially be a stronger noise source since they are operating in a higher rpm range compared to conventional engines.

A Brief Parameter Study – What is needed to Reduce Road Traffic Noise by 5 or 10 dB

Data on the separate contributions to traffic noise from rolling and propulsion can be used to investigate the effects of independent reductions of the two kinds of noise sources. Here, the *Nord2000 Road* source model (Jonasson, 2006) has been used to estimate Swedish conditions, and in addition measured data from a German project (Steven, 2003) have been explored. The strongest rolling noise is estimated for the Swedish conditions, as expected due to the difference in used road surfaces.

The results give an estimate of the needed reduction of propulsion noise to achieve a 5 or 10 dB reduction of the total noise (rolling and propulsion noise), assuming that a reduction of rolling noise is already in place by some given amount. Application to the reversed approach is also possible, i.e. with a given reduction of propulsion noise as starting point. See Forssén, 2007. Below, selected results are shown for cases of 5 dB total reduction from using the *Nord2000 Road* source model, which models the emitted noise from a representative ensemble of vehicles. The estimate is made under the simplifying assumption that the effects of sound propagation can be neglected, i.e. only the acoustic output power is used. In addition, a dry, flat and straight road is assumed, with vehicles driving with constant speed. For typical urban driving conditions, the acceleration of vehicles would lead to a

Table 1. Needed reduction of propulsion noise (in dB) to achieve a 5 dB reduction of the total noise (rolling and propulsion noise), for a rolling noise reduction already in place by an amount of ΔL=0, 2, 4, 6, 8 or 10 dB. (Nord2000 Road source model.)

ΔL [dB]		Passenger car	Medium heavy vehicle	Heavy vehicle	Combined
0	30 km/h	—	6.8	—	—
	50 km/h	—	15.8	—	—
	70 km/h	—	—	—	—
	90 km/h	—	—	—	—
	110 km/h	—	—	—	—
2	30 km/h	—	5.7	7.9	16.6
	50 km/h	—	7.4	—	—
	70 km/h	—	9.6	—	—
	90 km/h	—	11.0	—	—
	110 km/h	—	10.4	—	—
4	30 km/h	6.7	5.2	5.6	6.2
	50 km/h	—	5.5	7.3	9.0
	70 km/h	—	5.8	11.4	23.0
	90 km/h	—	5.9	—	—
	110 km/h	—	5.9	—	—
6	30 km/h	4.0	4.9	4.6	4.2
	50 km/h	2.1	4.6	3.8	3.3
	70 km/h	0.3	4.5	2.9	2.5
	90 km/h	-1.0	4.4	2.3	2.4
	110 km/h	-1.7	4.4	1.9	1.7
8	30 km/h	2.9	4.7	4.1	3.3
	50 km/h	-0.2	4.2	2.5	1.7
	70 km/h	-2.6	3.8	1.0	0.4
	90 km/h	-4.1	3.6	0.1	0.3
	110 km/h	-4.9	3.7	-0.5	-0.7
10	30 km/h	2.3	4.6	3.8	2.9
	50 km/h	-1.2	3.9	1.8	0.9
	70 km/h	-3.8	3.4	0.2	-0.6
	90 km/h	-5.4	3.2	-0.9	-0.6
	110 km/h	-6.2	3.3	-1.5	-1.8

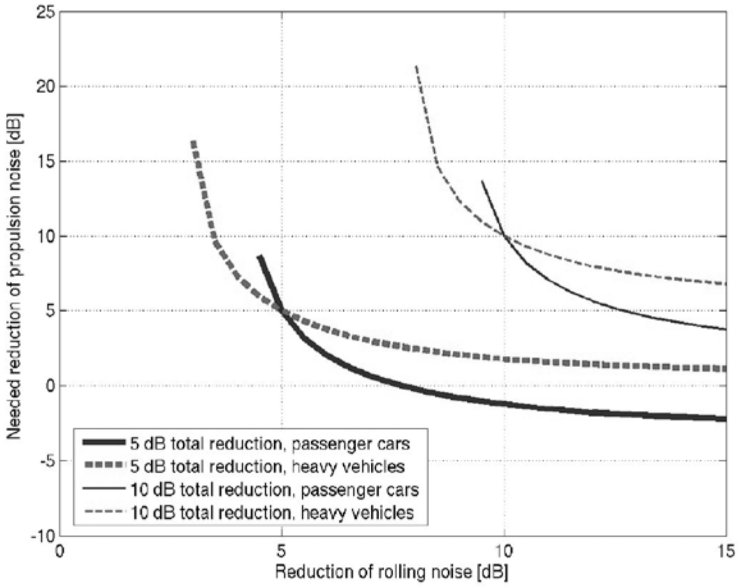


Figure 4. Needed reduction of propulsion noise to achieve a 5 or 10 dB reduction of the total noise (rolling and propulsion noise), for the Swedish case 50 km/h. On the horizontal axis is the rolling noise reduction that is already in place.

relatively stronger propulsion noise. The proportions of the different vehicle types used for the cases (passenger cars, medium heavy vehicles and heavy vehicles) are shown in the report (Forssén, 2007), as well as further modelling descriptions and results.

Table 1 shows the estimated reduction of propulsion noise needed to achieve a 5 dB reduction of the total noise (rolling and propulsion noise). It is then assumed that a reduction of the rolling noise is already in place by an amount of ΔL=0, 2, 4, 6, 8 or 10 dB. As an example, looking at the combined result (rightmost column) for a rolling noise reduction of 6 dB (ΔL=6 dB), one can see that the needed reduction of propulsion noise is around 4 dB for 30 km/h driving speed and around 2 dB for 110 km/h driving speed. (It could be noted that '—' means no solution, and a negative value means that an increased propulsion noise is allowed.)

Figure 4 shows a graphical display for the case *50 km/h*. The reduction of the rolling noise that is assumed to already be in place ranges from ΔL=0 dB to ΔL=15 dB (in steps of 0.5 dB), and the results for possible solutions are plotted. The results are displayed only for passenger cars and heavy vehicles. The two thinner curves show the analogous results for a total reduction of 10 dB.

From the results it can be concluded that there is a must to reduce the rolling noise, in order to reach a total reduction of at least 5 dB, i.e. a sole reduction of propulsion noise is not sufficient. (This can be seen in Table 1, in the rightmost column for the combined noise, where no possible solution is shown for ΔL=0 dB.)

This can be concluded also from the analysis of the German data. Even though this is a preliminary investigation the estimate has a margin large enough to enable the general conclusion that a sole reduction of propulsion noise is not sufficient. In addition, a sole reduction of rolling noise will also not be sufficient for reaching a total reduction of 5 dB or more if one looks at the lower driving speeds. In general, for heavy vehicles, a relatively larger part of the total noise is due to propulsion noise, compared with passenger cars. However, for urban driving conditions which includes lower driving speeds and significantly increased propulsion noise due to acceleration, the propulsion noise of both passenger cars and heavier vehicles need to be considered.

The aim of the study made here (Forssén, 2007) is not to produce final and quantitative results on the effects of separately reducing rolling noise and propulsion noise, but to show how such a detailed investigation can be made. The detailed results can be used to assess possibilities and costs related to different measures. Graphs such as in Figure 4 show points of possible solutions, whereby an optimal solution can be chosen, depending on prospects and costs of different measures.

For a detailed and accurate future study, different scenarios and traffic situations should be investigated by using not only the source model but including also the sound propagation. Such an investigation could be carried out by using the Nord2000 Road model for Swedish conditions and the Harmonoise/Imagine model for other European conditions (Jonasson et al., 2004 and Nota et al., 2005).

Noise Reduction Potential for Road Surfaces

The following section is a summary and excerpts of the contributions by Thomas Beckenbauer on the state of the art on low noise road surfaces (Beckenbauer, 2007) but with some added comments. The focus is on road surfaces as used for instance in Germany.

First, a brief introduction is given into the basics of road engineering. Thereafter, the main parameters that influence the acoustic performance of the road surface in relation to the tyre/road noise generation mechanisms are discussed and an overview about the use of absorbing surface is given. Finally, the question of maintenance and quality control is discussed.

A Short Introduction into Road Surface Engineering

Based on the void content, road pavements can be classified in four groups:

Void content	Pavement group	Noise reduction (re. SPB_{cars}, 120 km/h, reference pavement SMA 11)
0 ... 7 %	dense surface	0 – 2 dB
7 ... 12 %	semi dense surface	2 – 4 dB
12 ... 18 %	semi porous surface	4 – 6 dB
> 18 %	(open) porous surface	>6 dB

Both dense and porous road surfaces can be produced based on cement and bituminous binders. The stone size distribution of the mineral aggregate as well as the percentage and kind of the binder affect the acoustical behaviour of the road surface. Shape and kind of the minerals play a minor role for dense road surfaces. Concerning porous road surfaces they affect the void structure and the achievable void content of the pavement, which is acoustically meaningful. This means that producing porous road surfaces is restrictive and requires a more careful acceptance testing with respect to the choice of the material.

For safety reasons the road pavement must also show a good skid resistance. Often good skid resistance is not only the result of choosing appropriate material but also a matter of treating the surface in the right way. This concerns surface dressings and all kinds of dense cement concrete pavements. Figure 5 summarizes the systematic of acoustically relevant civil engineering properties of road pavements.

In Table 2 common types of road pavements that are in use on most of the European roads are given. In Sweden less than 0,1 percent of the national road network consists of concrete pavements. Most of the roads are made of asphalt concrete or stone mastic asphalt.

Figure 5. Systematic of acoustically relevant civil engineering properties of road pavements.

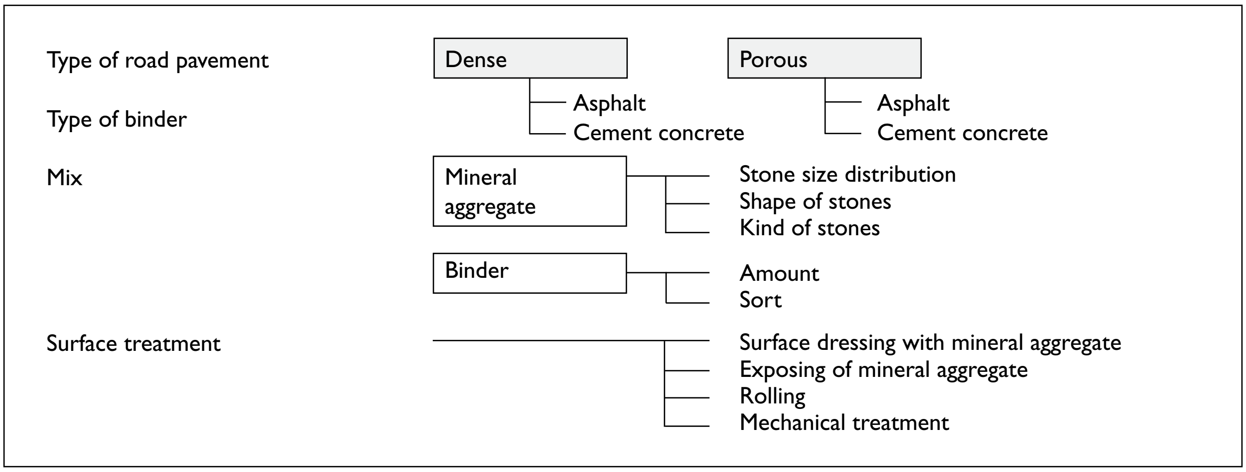


Table 2. Examples for various types of road pavements.

Pavement group	Asphalt	cement concrete
dense	- surface treatment on asphalt - asphalt concrete - stone mastic asphalt - Gussasphalt	- burlaped or brushed concrete - exposed aggregate
semi dense	- thin layers	None
semi porous	- drainage asphalt	None
open porous - two layer porous asphalt	- porous asphalt - porous cement concrete	

Basic Parameters Influencing the Acoustics Performance of Road Surfaces

Independent from the type of road pavement and its civil engineering properties there are three characteristics, which are suitable to describe the acoustical behaviour of the road surface:

- surface roughness
- porosity
- elasticity

These parameters influence the excitation of tyre vibrations, air-pumping and sound radiation from tyres. All three characteristics can be qualified and quantified by a set of parameters, which influence the acoustical behaviour of a road surface independently from each other. These parameters are given in Figure 6.

It is important to have in mind that roughness depth and roughness wavelength are not sufficient parameters to describe road surfaces. It is also essential to describe the shape of the roughness.

Figure 7 shows the difference in the pass-by levels (average over 12 different tyres at a speed of 80 km/h) for two surfaces, which only differ on how the surface is shaped.

Surfaces with concave structure (SMA 0/8) are clearly quieter then surfaces with convex

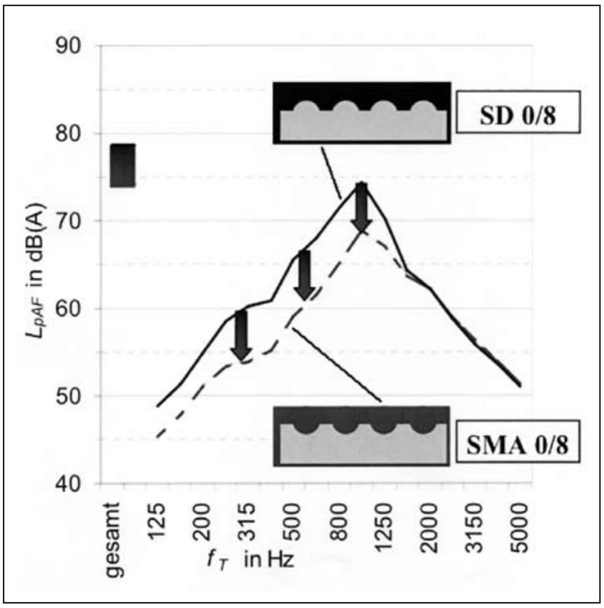
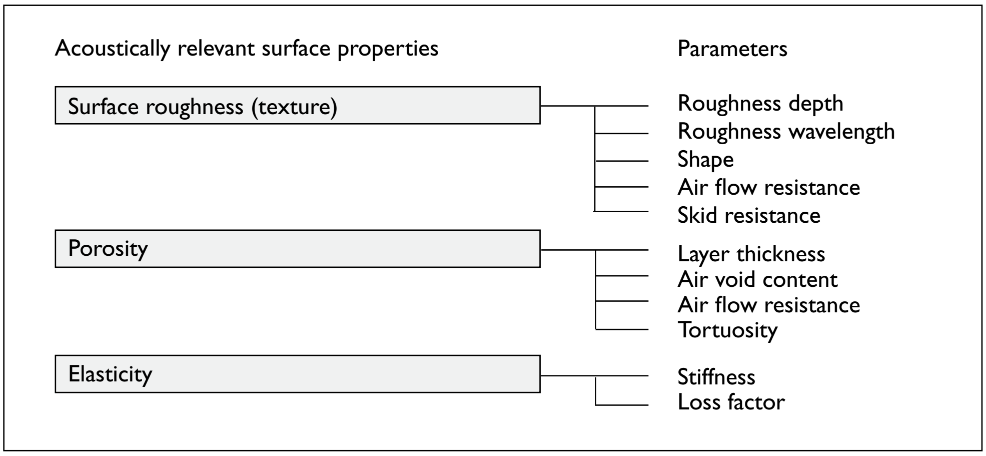


Figure 7. Two surfaces with identical grains size but different surface treatment.

Figure 6. Characteristics and parameters that help to describe the acoustical properties of road pavements.



structure. In addition there is no linear relation between surface roughness and generated noise. Figure 8 summarizes texture magnitude spectra of the roughness for typical dense road surfaces tending to more convex (a) or more concave (b) texture shapes. On the right hand side, the corresponding spectra of the coast-by noise for an average passenger car tyre can be seen. The acoustical level difference at 1 kHz is not more than 5 dB in both cases whereas the maximum roughness differs by 15 dB on a logarithmic scale for the surface dressings and by 9 dB for the hot rolled surfaces. Only a small part of the pavement roughness is acoustically effective.

One could also say that the tyre is only observing a portion of the roughness when rolling on the surface. For air-pumping it is even so that increasing roughness is of advantage.

Acoustically Absorbing Surfaces

Acoustically absorbing surfaces have the main function to reduce the amplification due to the

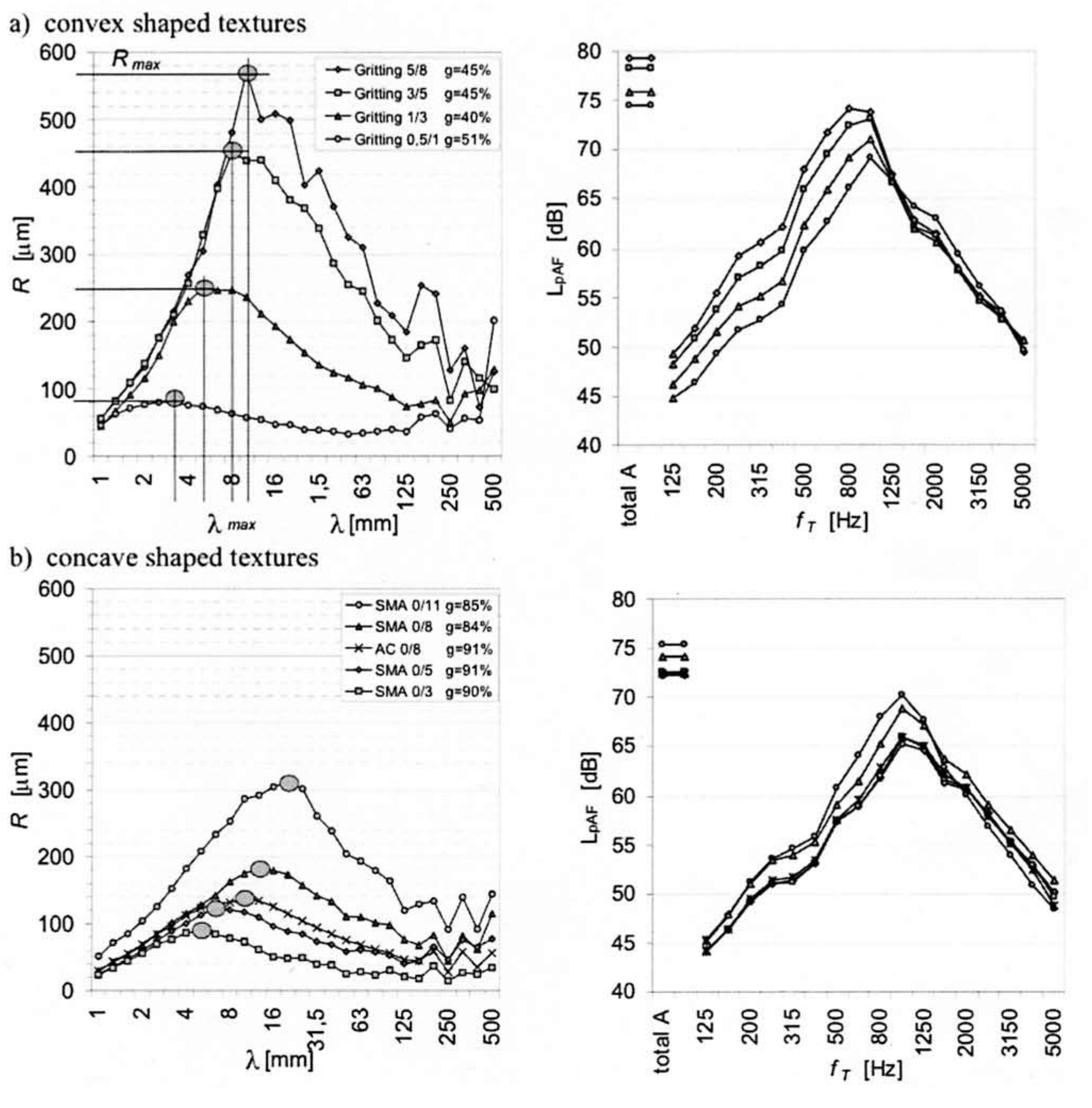


Figure 8. Typical texture magnitude spectra (left) and coast-by level spectra in third octave bands (right) for dense road surfaces and average passenger car tyres; a) surface dressings on stone mastic asphalt 0/8, b) SMA: stone mastic asphalt, AC: asphalt concrete. Shape factors g as indicated in the legends.

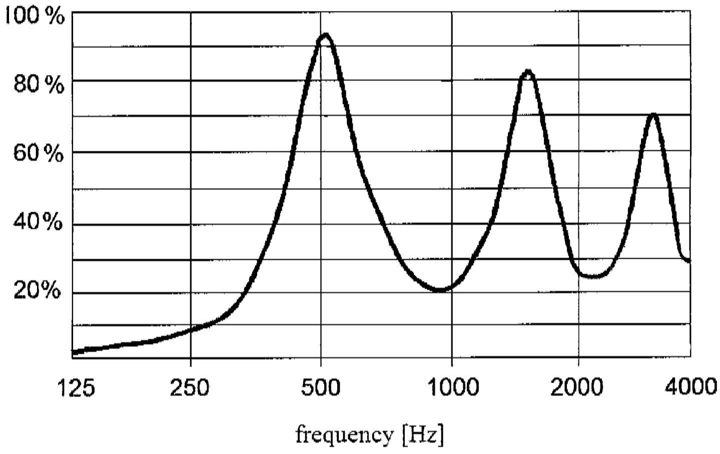


Figure 9. Spectrum of a well built open porous asphalt.

horn effect and in this way to reduce sound radiation from the area close to the contact patch. In order to achieve this, surfaces have to be designed which give high absorption. Figure 9 shows a typical frequency response of the absorption coefficient. It typically shows pronounced maxima between 200 Hz and 4000 Hz. The maxima are characterized by

- their position along the frequency axis
- their magnitude
- their width

These characteristics depend strongly on civil engineering parameters. Spectral position and height of the maxima are mainly affected by the layer thickness and the maximum absorption coefficient. Width and also spectral position are affected by the airflow resistance. The airflow resistance depends on shape, dimensions and consistency of the voids which are affected by the maximum aggregate size, the stone size distribution and the binder content in the asphalt mix

Decreasing void content yields lower absorption maxima. Bigger layer thickness is necessary to shift the absorption maxima towards lower frequencies. This is important for the damping of low frequency tyre road noise, which is related to low speed traffic conditions and/or the percentage heavy vehicles of the traffic volume.

In practice void content and airflow resistance

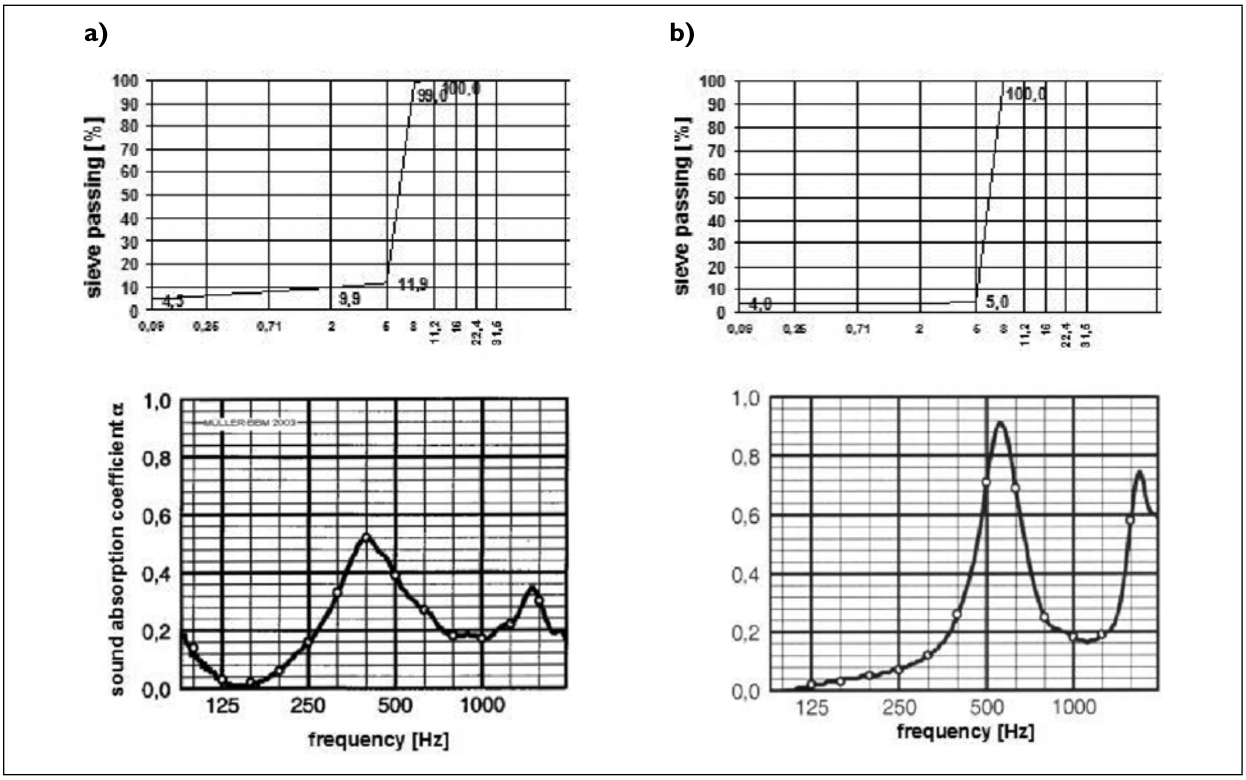


Figure 10. Example of an acoustical acceptance test for a single layered open porous asphalt 0/8, grading curve variation; binder in both cases the same. a) grading curve V6, b) grading curve V7.

are not independent from each other. Lower void contents are connected to higher airflow resistances.

For making target oriented mixes and attaining good final absorption coefficients it is absolutely necessary to carry out the process of choosing suitable materials, running multiple acceptance tests in the laboratory and controlling the laying, especially temperatures of the asphalt mix and compaction during the laying very carefully. In Figure 10 can be seen that the wrong gradation curve of the mineral aggregate causes a poor absorptive behaviour of the specimen with absorption coefficients not more than 0,52 at maximum. In contrast, a target oriented gradation curve yields a maximum absorption coefficient which is close to the optimum of 1,0. This result is typical for the laboratory situation where specimens are taken out of small asphalt plates that are compacted by means of a roller device. The ready made porous asphalt on a real road typically shows not more than 0,8 for the maximum absorption coefficient.

Quality assurance

Up to now, quality assurance with respect to noise related properties of the road pavement is not much an issue in road construction. In spite of comprehensive research and development work there is no standardized and mandatory procedure which would help to check the acoustical behaviour of the road pavement in public road laying projects. Due to this situation cases of pavement laying works with inadequate or even unacceptable acoustical result are still quite often occurring. In Figure 11 a recent case is shown yielding a rolling noise level, which is about 6 dB above the value, which can be expected. The reason is the coarse texture of the surface whose parameters totally exceed the recommendable values. The roughness depth adds up to about 5 000 µm and the texture wavelength is about 20 mm. The surface roughness is spread out across the driving lanes and shows a periodical structure.

The negative situation described above concerning acoustical approval and acceptance testing is true for all types of road pavements. The common pavement type stone mastic asphalt 0/8 has been investigated concerning differences in its acoustical behaviour depending on surface properties. The two examples for realized stone mastic asphalts 0/8 (SMA) shown in Figure 12 are part of two different contract sections. The road surface on the left hand side yields a pass-by level of passenger cars 2,6 dB above the value measured for the road surface on the right hand side (83,9 dB(A) re. 120 km/h compared to 81,3 dB(A) re. 120 km/h). The texture spectra show two clear differences. The roughness depth of the left hand SMA in the wavelength range around 10 mm does not exceed 100 µm. Due to the choice of the materials the surface is very smooth, thus enhancing the air pumping effect within the tyre road contact patch. On the other hand, the acoustical behaviour is affected by pronounced roughness waves with more than 100 mm wavelength, which is due to some imperfections in the laying process and intensifies the tyre's vibrations. Both peculiarities of the surface compared to the right hand SMA, one related to the mixture and the other one related to the laying process, caused the level difference of some 2 dB.

This means, carefully observing the proper-

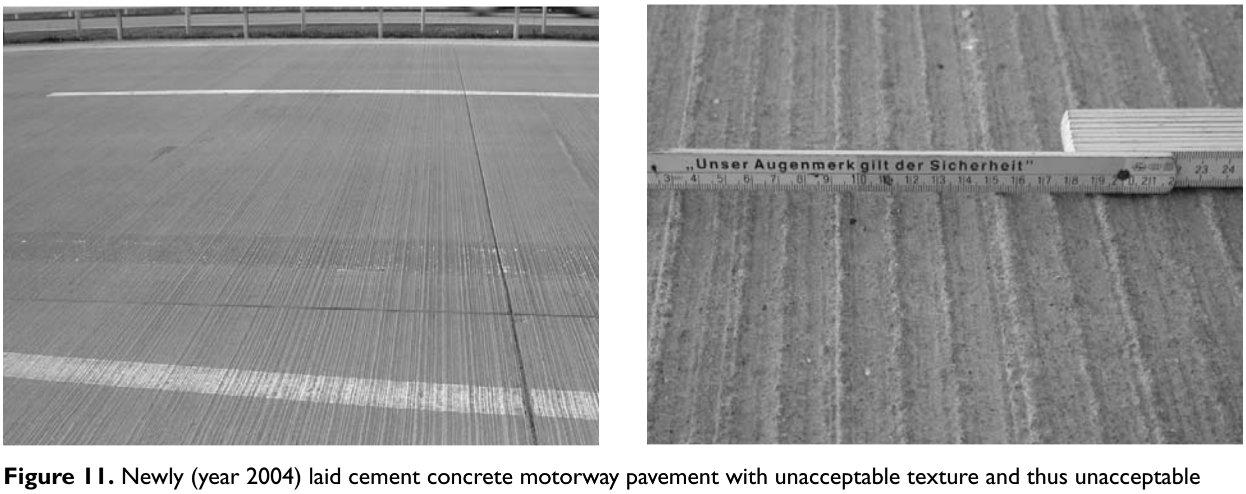


Figure 11. Newly (year 2004) laid cement concrete motorway pavement with unacceptable texture and thus unacceptable tyre road noise level (photos: Volker Schäfer, Brake).

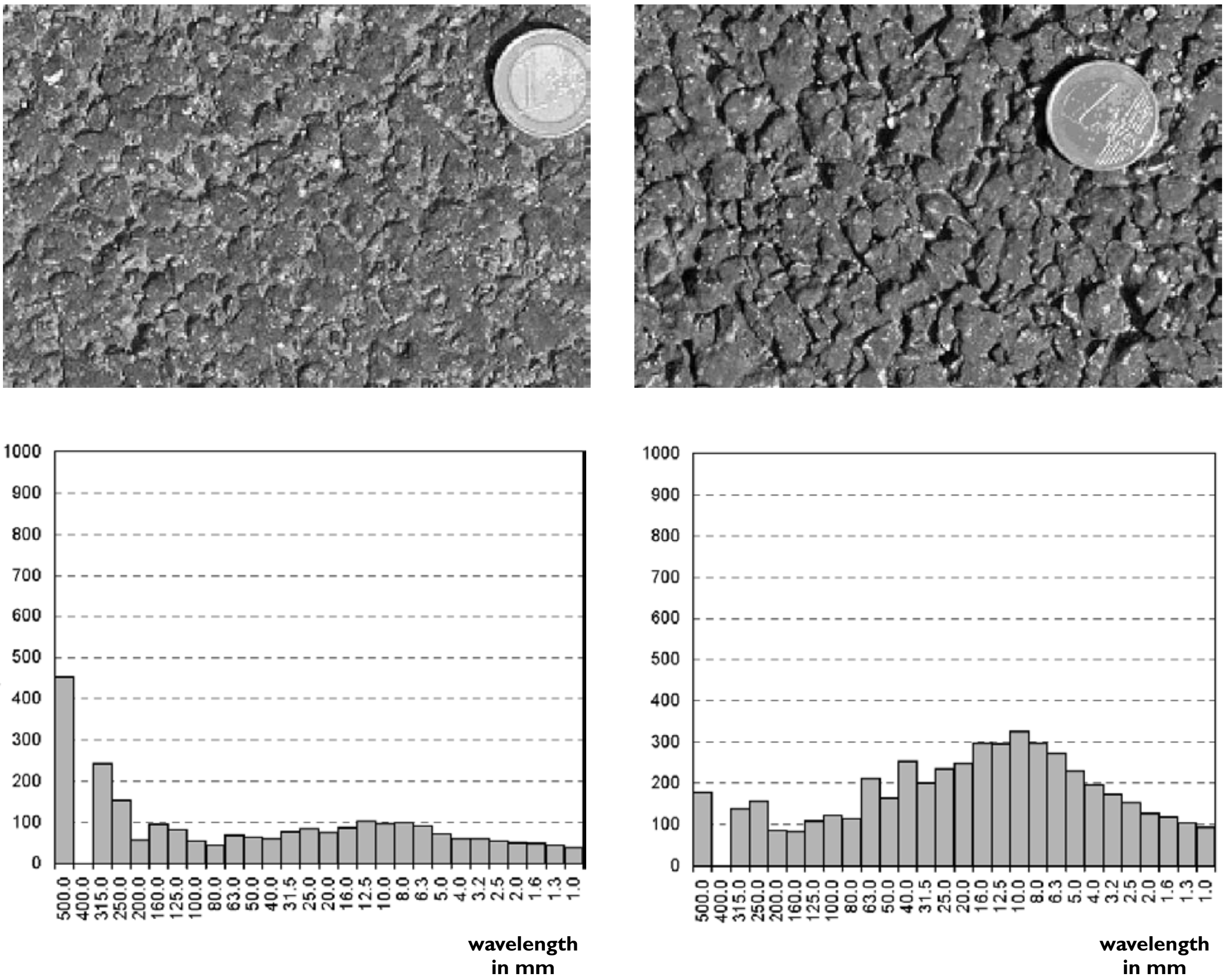


Figure 12. Sections of stone mastic asphalt 0/8 with different acoustical behaviour. Upper row: photographs of the road surface; lower row: texture spectra

ties of the road surface, which are related to its acoustical behaviour, can gain several decibels of rolling noise reduction, even if the same type of road pavement is taken into account. The acoustical monitoring must be part of performance tests in the civil engineering laboratory as well as final acceptance tests at the end of the laying process. Texture and sound absorption are of main concern.

Maintenance

Clogging of porous road surfaces is still a matter of fact. Clogging may cause two different effects. On the left picture in Figure 13 the absorption spectrum changes are shown if dirt particles accumulate between the upper and the lower layer of a two-layered porous road surface.

The porosity of the lower layer stays basically at the same level, the airflow-resistance, however, is rising dramatically. Thereby, the lower maximum is shifted to lower frequencies and so leaving the ideal range. In the mid frequency range, there is nearly no absorption left. In the right picture, the shift of the local maxima of the absorption coefficient is shown, which is due to accumulating dirt at the bottom of the porous layer. The porosity is still preserved, but the effective layer-thickness is clearly reduced. This yields a shifting of the maxima up to higher frequencies.

Therefore, maintenance of porous road surfaces is an important issue. Maintenance means cleaning of the voids. However, up to now there is only one procedure available for practical situations. The cleaning procedure consists of water, which is pressed into the voids with about 60 to 80 bar by means of a spray bar with static or rotating valves. At short distance to the spray bar, the water is sucked out of the porous surfaces by means of a vacuum cleaner.

Figure 14 shows a typical result for the time history of the noise reduction of a two-layered

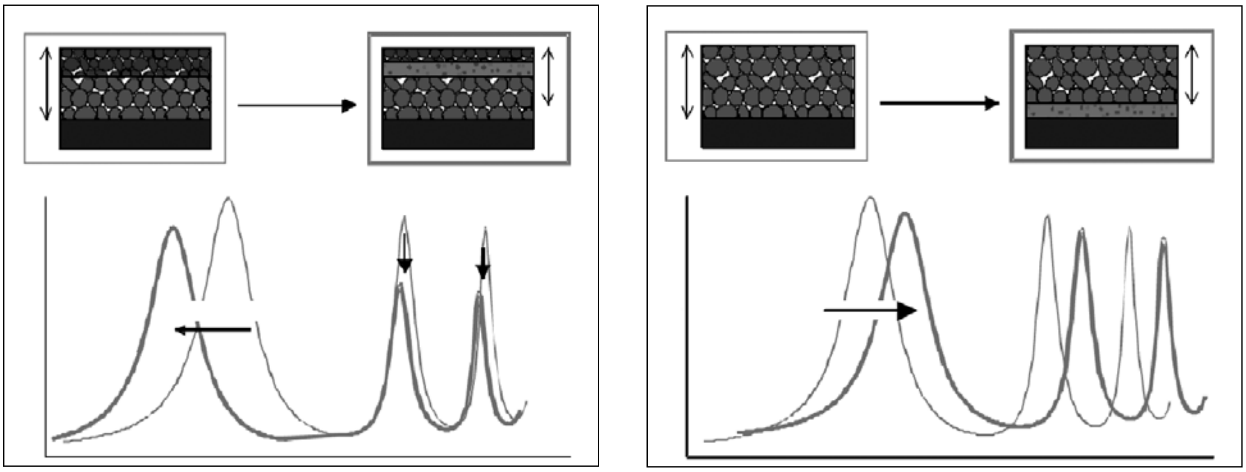


Figure 13. Impact of clogging on the sound absorption coefficient of porous asphalt. Left: particle accumulation between the porous layers, right: particle accumulation at the bottom.

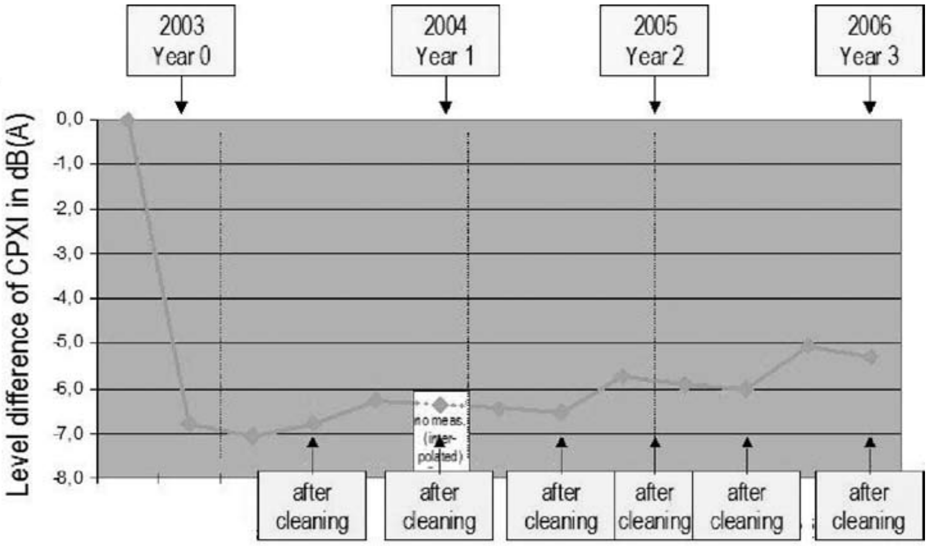
porous asphalt which has been proven on several road tracks. Starting at an initial value of -7 dB the noise reduction decreases by about +1 dB per year and is improved by -0,5 dB per year due to the cleaning. Finally, the noise reduction is deteriorated by +0,5 dB per year. So cleaning helps to double the acoustical life cycle of porous asphalt with respect to the clogging effect.

Conclusions – Potential for Quieter Road Surfaces

There is a substantial potential for noise reduction. Already the optimisation of the road texture can give up to 2 dB in relation to an SMA 0/11 (the Swedish standard surface SMA 0/16 will even be a bit louder than the SMA 0/11). Already some absorption will decrease the horn effect substantially. Therefore semi dense surfaces can give a reduction between 2 and 4 dB. With increased absorption of the surface the reduction can increase up to more than 6 dB. However, the use of such highly absorbing surfaces like open porous asphalt demands regular cleaning. In addition one has to cope with a loss of efficiency of about 1 dB per year, at least at the very beginning when the surface is newly laid.

An aspect, which is often neglected in this context, is the quality control under the manufacturing process. Carefully observing the properties of the road surface, which are related to its acoustical behaviour can gain several decibels of rolling noise reduction even if the same type of road pavement is taken into account. The acoustical monitoring must be part of performance tests in the civil engineering laboratory as well as final acceptance tests at the end of the laying process.

Figure 14. History of level differences of CPX measurements in terms of the CPX index CPXI.



Noise Reduction Potential for Tyres

In order to clarify the potential of noise reduction for tyres, one could start from a technical point of view and investigate the influence of different tyre parameters (e.g. geometry, tread pattern design, material selection, internal structure of the tyre, etc) on the noise generation mechanisms. Although one can find key parameters applicable to reduce noise such as mass or tread stiffness it is often a fact that such solutions are not applicable due to other properties tyres have to fulfil. Tyres have to fulfil a multitude of functions such as safety, rolling resistance, handling, mileage, design, interior noise, etc.

Exterior noise has a minor priority in tyre development. An alternative to exploring the potential might be to investigate the group of existing tyres on the market. This is discussed in the following section which is based on the work by Sandberg 2007. Making use of the substantial spread with respect to noise emission in the group of existing tyres, one could of course utilise tyre noise limits in a more efficient way than done up to now. An alternative would be to develop instruments, which allow the consumer to make decisions in favour of quieter tyres (see Sandberg 2007). The question however arises, if these tyres (the quietest one) really fulfil the customers' (e.g. the vehicle industry) demands.

In the third section the possibilities to reduce noise emission by improved tyre technology is discussed. This section is partly based on Sandberg 2007, partly on work carried out by one of the authors to this report in various projects on tyre/road noise interaction modelling. The last section gives the conclusions on the potential for reducing tyre/road noise by modifying tyres.

Variation in Noise Level between Current Tyres

The variation in noise level within various tyre classes was studied in Sandberg, 2006a. The data compiled there seemed to be rather consistent, suggesting that if one includes several hundreds of tyres in the tests, the variation (range) will be 6-8 dB within a certain sub-category of car tyres and about 10 dB within the total car tyre category (category C1 in formal tyre terminology). Generally, tyres are not interchangeable between the subcategories, which mean that the range a vehicle manufacturer or owner can "play with" is 6-8 dB.

For truck tyres (category C3), it was concluded that the range was about 10 dB considering the total truck tyre category. However, much of this range is the difference between drive axle tyres and tyres for steering and trailer axles. If one would look at only one of these two categories, the range seems to be about 5 dB within the steering and trailer axle category (tyres for steering and trailer axles do not differ much) and about 7 dB within the drive axle category.

Assuming that all European tyres are safe, this of course suggests that there is quite a potential to reduce noise emission without obtaining unsafe tyres simply by trying to apply the best currently available technology. The entire range of variation cannot be utilized for this, since within each subcategory there are tyres optimized for various purposes, but a major part of it should be available.

Tightening the EU Tyre Noise Limits

A study by FEHRL for the EU Commission proposed a substantial tightening in tyre noise limits (Directive 2001/43/EC); see Table 3 and Table 4.

Based on the variation within tyre categories, the following noise reductions seem to be technically possible. First, one scenario is outlined in which the tyre noise limits are tightened:

Scenario 1: Tightening the EU tyre noise limits (Directive 2001/43/EC) as proposed by the FEHRL study (step 2) [FEHRL, 2006] and assuming that the road surface is an ISO 10844 surface or another surface for which tyres are ranked in a similar way. In the assumption it is included that retreaded tyres are treated in the same way (today, retreaded tyres are not subject to any noise limits).

Reduction in maximum noise levels, car tyres: 3 dB
Reduction in equivalent noise levels, L_{den}, car tyres: 1,5 dB
Reduction in maximum noise levels, truck tyres: 4 dB
Reduction in equivalent noise levels, L_{den}, truck tyres: 2 dB

Table 3: Proposed tyre noise limits for C1 (car) tyres (rounding to nearest integer). Note: Darkness of shade is proportional to the expected number of tyres in the category around 2010

New tyre category	Nominal section width (mm)	First step (2008)	Relative decrease compared to current limit value	Second step (2012)	Relative decrease compared to current limit value
C1a_new	≤ 185	73	0.5 - 2.5	71	2.5 - 4.5
C1b_new	> 185 ≤ 215	74	2.5	72	4.5
C1c_new	> 215 ≤ 245	74	3.5	72	5.5
C1d_new	> 245 ≤ 275	75	2.5	73	4.5
C1e_new	> 275	77	0.5	75	2.5

Table 4: Proposed noise limits for C2 (van) and C3 (truck) tyres (rounding to nearest integer)

New tyre category	Nominal section width (mm)	First step (2008)	Relative decrease compared to current limit value	Second step (2012)	Relative decrease compared to current limit value
C2	Normal	73	3.5	71	5.5
	Snow (M+S)	74	4.5	72	6.5
	Special	76	3.5	74	5.5
C3	Normal	73	4.5	71	6.5
	Snow (M+S)	75	4.5	73	6.5
	Special	77	3.5	75	5.5

It may seem to some that these reductions are disappointingly low. One of the major reasons is that many of the present tyres (at least 50 percent) already meet the new and tighter limits; thus not all tyres need to be exchanged. The above noise reductions are valid for the case when most of the old tyres have been exchanged to the new ones, which will happen around 2020. In the meantime the noise will be reduced gradually down to the new levels.

Another scenario can be outlined in which one is consistently using the best available tyres; i.e. these with the lowest noise emission:

Scenario 2: Using only the tyres with the lowest noise emission among the present ones (within 1 dB of the quietest tyre) and assuming that the road surface is an ISO 10844 surface or another surface for which tyres are ranked in a similar way. In the assumption it is included that retreaded tyres are treated in the same way (today, retreaded tyres are not subject to any noise limits).
Reduction in maximum noise levels, car tyres: 5 dB
Reduction in equivalent noise levels, Lden, car tyres: 2,5 dB
Reduction in maximum noise levels, truck tyres: 7 dB
Reduction in equivalent noise levels, Lden, truck tyres: 3,5 dB

It is assumed in all the calculations above that tyres do not change their noise emission significantly with age. This is in practice not true. However, we do not presently know if they are becoming quieter or noisier with time and if the ranking between them is unchanged with wear and ageing. Whatever it is likely that the effects above will be lower rather than higher when considering tyres in various conditions. This has not been taken into account here.

Possibility to Reduce Noise Emission by Improved Tyre Technology

Tightening the tyre noise limits might have a disappointingly small effect in real traffic as shown in the previous section. However, it might also lead to required technology development toward quieter tyres. When working with modelling and prediction of tyre road/noise one learns rather soon that reducing tyre/road noise is a difficult task in itself, but the complexity is increased substantially when other tyre properties are of higher priority.

Typical tyre properties of higher priority are:

- Handling. Handling properties are demanded by the vehicle industry to fit the tyre to high performance cars.
- Rolling resistance. The discussion concerning CO2 reduction makes fuel consumption due to rolling resistance to an important issue.
- Mileage. This especially is an important competitive factor for truck tyres.
- Design. Tyres are a part of the design concept of a vehicle. Visual impression is often of higher priority to the customer than the functioning.
- High-speed performance. Tyres have to be safe up to the top speed of the vehicle which may be 250 km/h.
- Hydroplaning and braking performance. Safety is self-evident an important issue.
- Costs. Any technological solution has to be cost efficient to be able to compete on the market.
- Interior noise performance. Interior noise is a main competitive feature and the vehicle industry will select tyres with care to avoid road noise in the vehicle compartment.

The list could certainly be extended. To our knowledge, none of these properties is directly in conflict with lower noise emission from the tyres. When for instance measuring the rolling resistance of a sample of tyres and at the same time their noise emission, one will not find a correlation between these both properties. However, single measures in tyre design to achieve reduced noise emission, might be in conflict with some of the properties in the list. For example, one could easily reduce noise from traction tyres for trucks by tread pattern optimisation. This however has to be paid with higher wear and therefore lower mileage performance.

One can state that engineers in the NVH departments of tyre manufacturers have the tools and understanding to reduce tyre noise as long as they have free hands. As soon as other properties than noise are of higher priority, these tools will be less applicable.

As a consequence, the spread of emission values for tyres, as shown in the previous section, might not be freely available in tyre design when vehicle industry and customers formulate very specific demands.

Parameters for a quiet tyre design

By means of experimental and theoretical studies as well as engineering design experiences a number of key parameters have been identified during the years such as:

- Tread stiffness. A lower tread stiffness leads to a reduced excitation of tyre vibrations. This could be achieved by smaller tread elements, more frequent siping and softer rubber compounds.
- Tread pattern optimisation. Most of the tyres have well optimised treads avoiding periodicity in the pattern and smoothening the temporal variation of contact forces. Exception might be traction tyres for trucks.
- Mass. Increased mass of the tyre structure will lead to reduced vibrations of the tyre structure and also to a reduced radiation efficiency, which means less noise generation.
- Geometrical parameters. By curvature in lateral direction the contact geometry can for instance be influenced. This will for instance lead to a reduced horn effect on the noise generation.
- Void contents (i.e. volume of groves in relation to volume of rubber blocks in the tread). This influences mainly the air-pumping but might also influence the tyre vibrations.

For some of these key parameters some more detailed examples are given in Appendix 3.

Setting the boundaries

The possibility to construct quieter tyres will improve substantially if an agreement on reasonable maximum speed limits of the order of 130 km/h could be reached. This must be combined with technical devices preventing vehicles to be driven at much higher speeds. It would then not be demanded that tyres should function well up to present top speeds.

Ulf Sandberg estimates the potential noise reduction of a speed limit. See (Sandberg 2007). This would make it possible to optimize tyres in a more environmentally friendly way. Measured on an ISO surface, Sandberg estimates that an additional noise reduction of 2 dB could be obtained.

A global top speed limit for cars would probably reduce the incentives of offering ultra-high performance cars (with “high performance” in commercial arguing is generally meant extreme power, extreme acceleration and high-speed road-holding). This is related to the fashion and visual appearance of tyres since the industry and various journalists have deceived the public that high safety performance by tyres can be met only by wider tyres.

But there are also other tyre trends related to fashion and visual appearance, as reported (Sandberg, 2006a), and which are generally in conflict with noise reduction efforts. If these trends can be broken and optimization of tyres only need to be based on technical performance such as noise, rolling resistance, wear and safety (at speeds up to 130 km/h) without limitations caused by visual appearance or fashion, Sandberg estimates that there is an increased potential for tyre noise reduction by perhaps 1 dB, on top of the other possibilities mentioned above.

Futuristic Designs

In the following two more futuristic design solutions for tyres are presented to give examples for innovative solutions, although they might not be usable yet:

- Tyre with porous tread: 3 dB on an ISO surface and similar smooth surfaces, and 5 dB on rougher surfaces such as the present dominating surface on Swedish roads. Such tyres could perhaps be on the market within 5-8 years.

- Tyre composite wheel or the Michelin TWEEL: 6 dB on an ISO surface and similar smooth surfaces, and 10 dB on rougher surfaces such as the present dominating surface on Swedish roads. Such tyres and wheels could perhaps be on the market earliest within 10-15 years.

Conclusions

From the previous section the following conclusions can be drawn:

- Exploiting the spread of noise emission from tyres on the market one might identify a potential for reduction of tyre noise by 2-3 dB.
- Although there is a potential it might be difficult to utilise this, having in mind all the different properties required from tyre performance.
- Tyres only optimised with respect to noise performance might even have higher potential.
- Tightening the tyre noise limits according to the FEHRL proposal (step 2), will give a reduction of 2-4 dB. The action is definitely necessary to accelerate technology development toward quieter tyres and to increase the priority of noise performance when designing tyres.
- Speed limits and less focus on high performance with respect to handling as well as on fashion criteria will definitely open for the development of quieter tyres.
- Focus and resources should be given to develop quiet and safe tyres with low rolling resistance.

Noise Reduction Potential for Vehicles

Contrary to the situation with roads and tyres, it is somewhat difficult to estimate the potential in reduction for the propulsion noise of vehicles. This is mainly due to three reasons:

- First, while acoustic properties of tyres and roads are subject to industry independent research, it is very unlikely that an acoustic research group at a university ever had the task to deal with exterior propulsion noise from vehicles in a systematic and holistic way. Research might instead have focused on details, such as radiation from the engine block, acoustic performance of the exhaust system or screening of the engine compartment.
- A second reason might be that the potential for noise reduction is strongly dependent upon which technology solution is chosen for the vehicle. Cars are built on platforms which are kept identical over many years and which are expensive to exchange. Based on these concepts, for instance enough space for a modified exhaust system might be difficult to create without changing platform.
- Third, it is very unlikely that a vehicle platform ever in the past has been designed with a main focus to meet demands for exterior noise formulated in regulations.

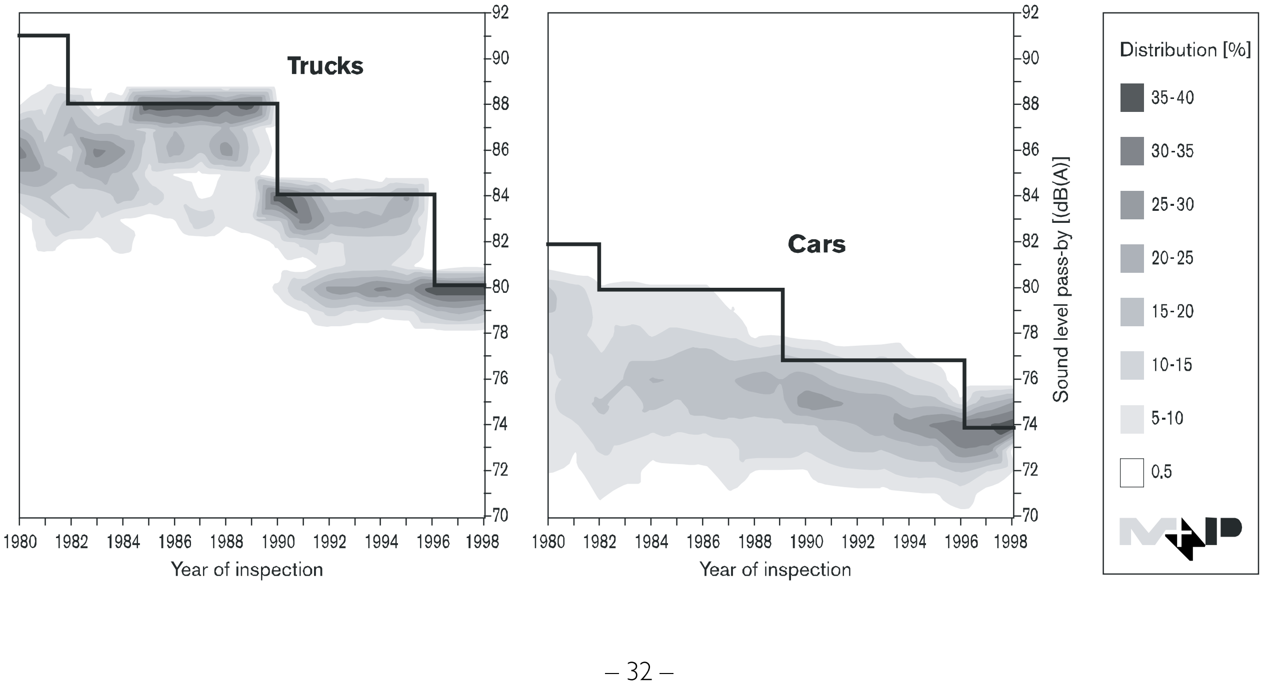
Figure 15 shows as summary of type approval measurements for passenger cars and heavy vehicles. It is clear from the distribution that the tightening of the limits for passenger cars (right side of the figure) did not create a severe problem before maybe 1990.

The cars produced before 1990 met with good margin the limits. Even after 1990 there is only a small trend in average performance visible, caused by the intention to be on the safe side when releasing a new series. Another interesting fact is that the lower bound of the distribution in Figure 15 is almost unchanged over the years. It might indicate that without any effort with respect to technology, 5-10 percent of the vehicles were about 2 dB quieter in the type approval than demanded by the limits introduced 1996.

For heavy vehicles this picture is somewhat different and it appears that the development may have been much more driven by legislation for exterior noise emission. The vehicle industry, however, managed up to now by secondary noise control measures to meet all demands. Change in technology (e.g. quieter engines, platforms or design philosophies) cannot be observed.

A consequence of the settings of the limits

Figure 15. Statistical distribution of type approval results between 1980 and 1998.



is that the emission from passenger cars in real traffic has not changed at all during the recent years. For heavy vehicles, however, a substantial reduction can be observed for low and medium speeds, but even here it can be concluded that the intended reduction in real traffic has not been achieved as shown in Figure 16.

The discrepancy between emission values in real traffic and limits in the type approval is often explained by the influence of tyre/road noise as a limiting factor for improvement. However, this can only be part of the explanation. Based on Figure 15 and Figure 16, one might also conclude that the vehicle noise limits at least for passenger cars did not create a real challenge for a technology development. This also means that the question concerning the potential for quieter vehicles has never really been seriously raised. Consequently, it is also difficult to answer this question. Despite this difficulty an attempt is made in the following section.

Future Trends and Potential to Reduce Noise from Vehicles

Trends in vehicle and engine design will result in future challenges for noise control engineers. Examples of such trends are:

- Increasing portion of diesel driven vehicles (it might be difficult to encapsulate the engines more than today due to heat problems and due to necessary openings for drive shafts etc.)
- Harder combustion processes needed for lower CO2 emissions (e.g. HCCI), which is in conflict with slower combustion processes to achieve quieter engines.
- Improved engine performance. The market has accelerated substantially with respect to engine power, although there are few places in the world where such cars can be driven at maximum speed.
- Less space in engine compartment. Increased engine performance leads to bigger engines and less space which can be used for noise reduction purposes.
- Reduction of total vehicle weight will put high demands on acoustic design to avoid poor acoustic performance with respect to sound insulation and to sound radiation.
- Sound quality and branch specific sound profiles are main values for customers, which have to conform to demands concerning exterior noise properties.

However, without regulations that motivate vehicle designers, it is unlikely that these questions will be tackled in the future in an appropriate way.

Figure 16. Comparison of the results of noise emission measurements from 1974 and 1999 (individual vehicles in normal traffic) from Graaff (2001).

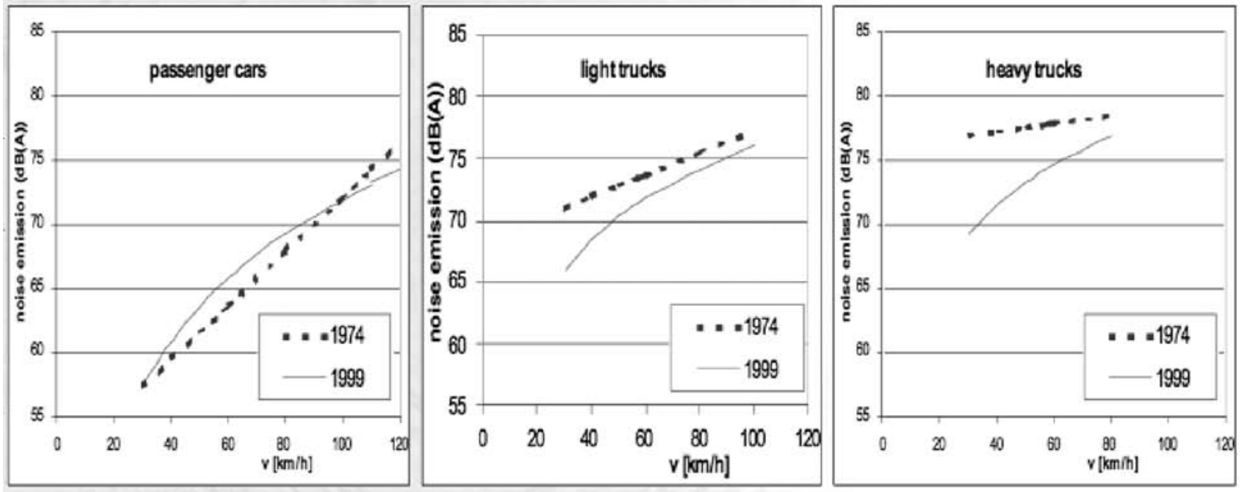


Table 5. Requirements for Noise and Vibration Harshness (NVH) and Thermodynamic requirements

NVH Requirements	Thermodynamic Requirements
Low Cylinder Pressure Excitation	High Engine Performance (Torque)
Low Dir./Indir. Combustion Noise	Optimized Peak Pressure Position
Low Cylinder Peak Pressure	**High Cylinder Peak Pressure**
Low Pressure Gradient	**High Pressure Gradient**
High Combustion Regularity	High Combustion Regularity
Low Gas Exchange Noise, (Intake, Exhaust)	High Cylinder Fill, Low Gas Exchange Losses
Valve Timing	**Valve Timing**

Although vehicle manufacturers seem never in the past have been forced to explore the potential for exterior noise reduction to any larger extent, one can at least give hints for solutions to reduce the different main sources.

- For the intake system the main potential is given by the design of the air filter volume. Either an increase of the volume (5-10 dB reduction would mean 3-6 litres increase) or an increase of the flow resistance in the air filter is needed. The latter, however, will lead to a reduced power of the engine. In addition, the radiation from casing surfaces has to be reduced.
- Similar actions can be taken for the exhaust system. There, an increase of the volume by 5-10 litres is needed to achieve a noise reduction between 5 and 10 dB.

Both measures will need space if one does not want to reduce engine performance. However, in vehicle design, space is a precious value. It might mean that new vehicle platforms have to be designed with sufficient space for increased volumes for intake system and exhaust system.

Regarding engine noise, there is very little possible to achieve with additional encapsulation. Noise emission has to be part of engine design in parallel with an optimisation of the combustion process. Table 5 shows requirements for both noise emissions and CO2 emissions.

Bold text indicates conflicts between both requirements.

The conflicts are mainly due to the fact that a good acoustic performance demands slow and smooth processes (e.g. slowly opening or closing of valves) while the combustion process has demands on sudden action well timed. The problem description for heavy-duty vehicles contains many similarities to that of passenger cars.

Conclusions

It is difficult to answer the question concerning reduction potential of vehicle noise. It is unlikely that manufacturers of passenger cars ever were forced to explore the potential for exterior noise reduction. The situation is somewhat different for heavy-duty vehicles. There, encapsulation and screening have been used extensively to adapt to tightened limits and modified test procedures.

Technology solutions are available, but might demand that exterior noise properties are taken into account in the very early design phase. The requirements on cleaner combustion can lead to conflicts with demands on quieter engines. It is certainly important to optimise combustion and noise in parallel.

Future Development

Lower noise emissions demand decisions on stricter limits. No such decision has yet been made in later years, but there are some proposals. After decisions are made, industry must be given some time until new limit values shall be implemented. After that, the full effect in equivalent noise levels is not obtained until the old tyres and vehicles have been shifted out. To begin with, the change to lower noise levels is slow.

For tyres, the organization FEHRL *(Forum of European Highway Research Laboratories)* in its report for the Commission has proposed substantially stricter emission limits in two steps, the first in 2008 and the second in 2012. If adopted the expected effect would be 2-3 dB in equivalent noise levels to be reached in 2020. The strengthening of the tyre directive is especially important for roads with speed limits above 50 km/h.

For vehicles, a new and apparently more relevant test method (ISO 362-1) has in principle been adopted but its introduction has been delayed by two years. According to what is suggested so far, limits implying a minor step towards quieter vehicles cannot be expected until 2014 or 2015. The expected lifetime of vehicles is longer than that of tyres, so the full effect will not be encountered until around 2030.

Considering the present discussions concerning new fuels and new propulsion systems, any discussion about vehicle propulsion noise around the year 2030 appears uncertain. If we for instance will get a rapid introduction of hybrids and the typical commuting traffic in the cities may be with electric motors, the picture could be more favourable as the propulsion noise from electric motors could be set lower than that from combustion engines. If the solution on the other hand will be combustion engines with high compression and low weight, the noise from the propulsion system may become more problematic.

Having the extreme slow pace in mind, one might wonder if there is any meaning in working for a reduction of road traffic noise at all. The question arises what are actually the consequences of no reduction at the source or some small reduction in accordance with the time schedule described above. What are the consequences of this extremely slow pace in progress for the people being exposed to road traffic noise? In the following sections a study is presented which has been carried out for Norway (Berge, 2007). It is concentrated on the development of the annoyance situation. It would be very helpful to carry out similar studies for other countries. However, the Norwegian example gives us indications of what we can expect in the future assuming different scenarios of development.

Scenarios of the Future

In Norway, in 2000, the Parliament decided on a national environmental noise target; the noise annoyance, SPI (national noise annoyance index, Stöyplageindeks), shall be reduced by 25 percent in 2010, compared to the reference year 1999. Road traffic noise is the main contributor to the SPI-number (80 percent).

In 2005, an evaluation was performed, to see the progress in different areas (road traffic, aircraft, rail, industry, etc). It was then clear that, except for road traffic noise, all other sources had reduced their SPI-values compared to 1999, but SPI from road traffic had increased, mainly due to increased traffic volume.

The 2010-goal is presently under revision and 2020 is becoming a more likely target year for achieving a reduction of SPI.

As part of the evaluation, SINTEF was engaged to make calculations for different scenarios. The aim was to be able to predict the effect of different noise reduction measures at the source. A calculation model based on TraNECam (see Berge 2007) was applied for this study.

Test Cases and Scenarios

Reducing the sources (engine, tyres) will have different effect for different traffic composition and speeds. As test cases, the following were chosen:

- Averaged Daily Traffic (ADT) = 10 000
  Portion of Heavy Duty Vehicle (HDV) = 10 percent
  Posted speed = 50 km/h
- Averaged Daily Traffic (ADT) = 20 000
  Portion of Heavy Duty Vehicle (HDV) = 15 percent
  Posted speed = 80 km/h

The following scenarios were chosen:
Basic trend-scenario:
The current trend continues, without any further reduction of engine or tyre noise.

GRB/Germany-scenario:
Based on a German proposal to UNECE GRB on new limits for vehicles and the new measuring method. Table 6 shows the estimated source reduction in dB for light and heavy vehicles and the year of introduction, as a calculated effect of the German proposal for new limits and measuring method.

Table 6. The GRB/Germany-scenario

Year	Light vehicles		Heavy vehicles	
	Engine noise	Tyre noise	Engine noise	Tyre noise
2011	-1,5	- 1,5	-1,8	-0,9
2015	-0,75	- 0,75	- 0,9	-0,5
Total	- 2,25	-2,25	-2,7	-1,4

Low ambition scenario:
Table 7 shows the low ambition scenario.

Table 7. Low ambition scenario

Year	Engine noise	Tyre noise
2011	-1	-1
2015	-1	-1
Total	-2	-2

High ambition scenario:
Table 8 shows the high ambition scenario.

Table 8. High ambition scenario

Year	Engine noise	Tyre noise
2008	-1	
2011	-1	-2
2015	-1	-2
Total	-3	-4

Very high ambition scenario:
This scenario was chosen, not to be realistic, but to see the effect of a large total source reduction (6 dB for engine noise and 4 dB for tyre noise), where the main focus is on further reduction on engine noise.

Table 9. Very high ambition scenario

Year	Engine noise	Tyre noise
2008	-2	
2011	-2	-2
2015	-2	-2
Total	-6	-4

Prediction Results

The effects of the different source reductions were calculated as reduction of Leq-levels (L_{tot}) at 10 meter from a centreline of the road. Separate results are available also for engine/propulsion noise (L_{prop}) and tyre/rolling noise (L_{roll}), but are only briefly presented here. The results are summarised in Table 10 for test case 1 (*10000 ADT, 10 percent HDV, 50 km/h*) and in Table 11 for test case 2 (*20000 ADT, 15 percent HDV, 80 km/h*).

For the ***Basic trend*** scenario, the reference year is 1999. For all the other scenarios, changes in the levels are calculated in the years 2015 and 2020, assuming no effect in 2010. The results are given in table 12.

Table 10. Calculated reductions of Leq-levels. Reference year 1999.

Year	Basic	GRB/G	LOW	HIGH	VERY HIGH
2010	- 0,9	-	-	-	-
2015	-0,9	-0,1	-0,5	-0,8	-1,1
2020	-0,9	- 0,8	-1,3	-2,2	-2,8

The table shows that for the basic trend, a reduction of 0,9 dB is predicted in 2010, but no further reduction is expected (due to a small increase in rolling noise levels).

For all the other scenarios, the reductions are in addition to what the basic trend indicates. Example: compared to 1999, the basic trend gives a reduction of 0,9 dB in 2020. The GRB/German scenario gives an additional – 0,8 dB in 2020, thus a total of – 1,7 dB compared to a reference year of 1999.

Table 11. Test case 2 .Calculated reductions of Leq-levels. Reference year 1999.

Year	Basic	GRB/G	LOW	HIGH	VERY HIGH
2010	- 0,3	-	-	-	-
2015	-0,3	0	-0,4	-0,8	-0,8
2020	-0,3	- 0,6	-1,2	-2,1	-2,4

Figure 17. Test case 1. "Very high ambition" scenario, compared with the" Basic trend"-scenario

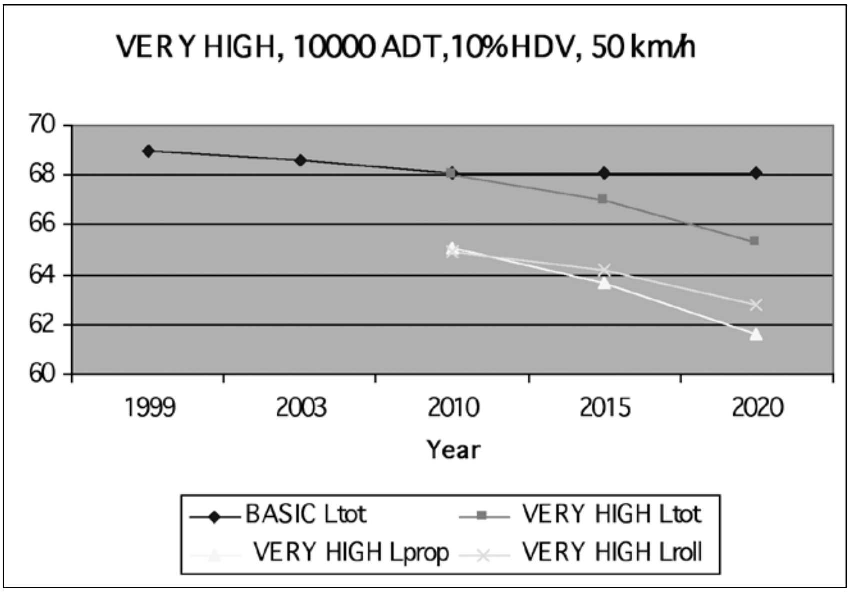


Figure 18. Test case 2. "Very high ambition" scenario, compared with the" Basic trend"-scenario

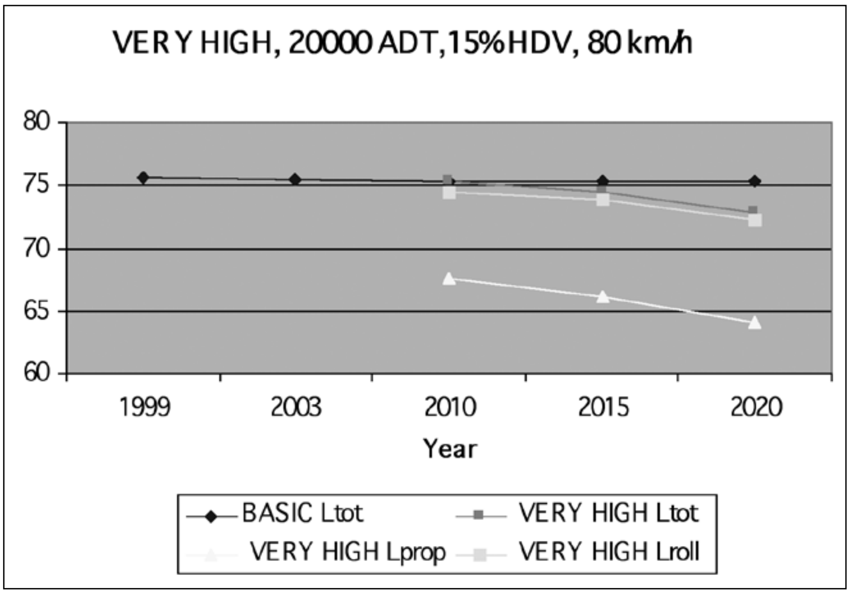


Figure 17 and Figure 18 show a graphical presentation of the effect of the "Very high ambition"-scenario, including the calculated changes in the engine noise and tyre noise levels.

It is interesting that the large source reduction (4-6 dB) for both test cases ("Very high ambition") only gives an effect of in the order of 2,5-3 dB on the Leq-levels in 2020. The main reason for this is of course that it takes a long time to replace older vehicles in the fleet (the average age of passenger cars in Norway is almost 11 years).

Conclusions on the Annoyance of People by Road Traffic Noise

The Statistics of Norway has been calculating the effect of some of the above scenarios on the noise annoyance index in Norway (SPI). In the calculations, the reduction of tyre and engine noise has been separated somewhat. In addition to the above mentioned scenarios, a few other options were introduced:

- The effect of introducing road surfaces that are on the average -1,5 dB more quiet than the normally used surfaces in Norway, and a low and a high replacement rate of existing road surfaces
- A slow and a very high replacement rate for low noise tyres
- A general speed reduction on a selection of roads

The results are given in Table 12. The percentage changes are relative to Basic 1999.

Table 12 SPI- calculations for different scenarios

Scenario	1999	2010	2020	2020 %
Basic trend	429 626	492 338	563 809	+ 31
Basic with speed reduction		489 635	560 896	+ 31
High amb. tyres (2012), incl. speed reduction		478 509		
Basic, with low ambition road surfaces			542 888	+ 26
Basic, with high ambition road surfaces			535 315	+ 25
High amb. tyres (-4 dB) (slow replacement rate)			460 063	+ 7
High amb. tyres (very high replacement rate)			407 992	- 5
High amb. tyres (very high replacement rate) high ambition repl. rate of road surfaces)			388 344	- 10
Low amb. engine (-2 dB), low amb. tyres (-2 dB) (slow repl. rate tyres)			463 972	+ 8
Very high amb. engine (-6 dB), high amb. tyres (- 4 dB) (slow repl. rate)			364 054	- 15
Very high amb. engine, high amb. tyres (very high repl. rate)			328 973	- 23
Very high amb. engine, high amb. tyres (very high repl. rate), speed reduction, high amb. road surface			297 652	- 31

The calculations are based on a dynamic model that takes into account an increase in the traffic, and in demographic parameters (increasing number of people living in densely populated areas). The table shows that if nothing is done towards reducing the traffic noise, we will have an increase in the noise problems: SPI increase of +31 percent in 2020 compared to 1999 instead of the national goal of -25 percent within 2010.

One can conclude that a substantial reduction of the sources is needed, together with the introduction of low noise road surfaces, if the political goal in Norway of 25 percent reduction of the annoyance index (SPI) due to road traffic shall be achieved, even in 2020.

References

Beckenbauer, T. (2007) *Pilot study. Noise reduction potential. Road surfaces,* Müller-BBM, 2007. Available at http://www.iva.se/templates/page.aspx?id=4354 as appendix 2.

Beckenbauer, T. & Kuijpers, A. (2001) *Prediction of Pass-by Levels Depending on Road Surface Parameters by Means of a Hybrid Model,* Internoise 2001, The Hague, the Netherlands.

Berge, T. (2007) *Noise reduction potential: The Nordic situation and future development,* SINTEF, Trondheim, Norway. Available at http://www.iva.se/templates/page.aspx?id=4354 as appendix 4.

Deffayet, C. (1989) *Bruit de contact pneumatique/chaussée – Emission acoustique d'une cavité de chaussée – Résultats expérimentaux,* Satolas INRETS NNB 8907.

FEHRL 2006. contract 802-10-06:1 http://ec.europa.eu/enterprise/automotive/projects/report_tyre_road_noise2.pdf

Forssén, J. (2007) *Effects of separately reducing rolling noise and propulsion noise – a preliminary investigation,* Applied Acoustics, Chalmers University of Technology, Göteborg, Sweden. Available at http://www.iva.se/templates/page.aspx?id=4354 as appendix 1.

Graaff, D.F. de (2001) *A speed and acceleration limit in the noise type approval of vehicles will enable silent cars to reveal their silence,* Internoise.

Hamet J.-F., Deffayet C,. Pallas M.-A. (1990), *Air-Pumping Phenomena in Road Cavities, International Tire/Road Noise Conference 1990 August 8-10 1990 Gothenburg,* p. 19-29.

Hayden, R. E. (1971) *Roadside Noise from the Interaction of a Rolling Tire with the Road Surface, Proceedings of the Purdue Noise Control Conference,* Purdue University, West Lafayette, IN pp. 62-67.

H. Jonasson (2006). *Acoustic Source Modelling of Nordic Road Vehicles.* SP Rapport 2006:12, 2006.

H. Jonasson, U. Sandberg, G. van Blokland, J. Ejsmont, G. Watts, M. Luminari (2004). *Source modelling of road veihcles,* Harmonise report HAR11TR-041210-SP10, 2004.

Kropp W., et al. (2000) *On the sound radiation from tyres, Acustica – acta acustica,* Vol 86 No5, p. 760.

Nota, R., Barelds, R. and van Maercke, D. (2005). *Engineering method for road traffic and railway noise after validation and fine-tuning.* Technical Report HAR32TR-040922-DGMR20, Harmonoise WP 3. (See http://www.imagine-project.org/).

Ronneberger, D. (1984) *Experimentelle un theoretische Untersuchungen spezieller Mechanismen der Rollgeräusche",* Mitteilungen des Instituts für Straßen,- Eisenbahn- und Felsbau an der ETH Zürich, 57, 55.

Sandberg U. (2001) *Noise emissions from road vehicles,* Final report. I-INCE working party on noise emissions of road vehicles. Convenor Ulf Sandberg. International Institute of Noise Control Engineering.

Sandberg, U. (2006a) *Tyre/Road Noise, Volume 2 Appendices – Appendix A: Literature Survey,* Final Report SI2.408210, FEHRL, Brussels.

Sandberg, U. (2007) *Possibilities to reduce noise emission from the tyre/road interaction with emphasis on the Swedish situation.* Swedish Road and Transport Institute (VTI) and Chalmers University of Technology, Göteborg, Sweden. Available at http://www.iva.se/templates/page.aspx?id=4354 as appendix 3.

H. Steven (2003). Ermittlung des weiteren Lärmminderungspotentials bei Kraftfahrzeugen, Forschungsvorhaben 205 05 809, by order of the German Enviromental Agency (UBA), July 2003.

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