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NOISE CONTROL FOR CARS AND TRAINS FROM AN ENGINEERING PERSPECTIVE

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ABSTRACT
The noise generated by transport systems has a twofold relevance: While exterior noise is proven to be a major issue for their environmental acceptance and compatibility, interior noise determines the comfort and thus the user acceptance and competitiveness. The paper compares and investigates various approaches used to predict and analyze important noise generating mechanisms by appropriate models for cars and trains. Special emphasis is given to rolling noise where mechanical differences of the elements involved require differing assumptions and thus have led to different levels of modeling and predicting accuracy. Based on recent results, a state of the art assessment of actual modeling tools and noise control measures is given. This general focus is completed by further methods of analyzing, modeling and controlling the noise caused by cars and trains. Among these, the benefits of statistical energy analysis and sound quality considerations are reviewed thoroughly. Finally, the use of active control measures is discussed together with recent examples of demonstrations and implementations in cars and trains.

1 - INTRODUCTION
Motivation for and interest in noise control is not restricted to acousticians and noise control engineers. On the contrary, their professional interest may even be justified socially by the fact that noise exposion has become a matter of high personal and social relevance, resulting in high interest of many affected non-acousticians.

More than three of four Europeans, for instance, are annoyed by unwanted sound, i.e. by noise. And, even worse, it was just in the last years that noise was proven to be a threat rather than an annoyance. Consequently, noise control turns out to be a natural and necessary defence measure for all being affected. This particularly holds for transport noise which is generated by continuously increasing traffic based on a strong and increasing desire of mobility as well as on increasing transportation needs between decentralized production places. Although substantial progress has been made over the last years, the benefits were compensated by the fact that increased transport volume resulted in more and more traffic and vehicles. Therefore, exterior transportation noise control definitely turns out to be an important task in order to establish and maintain the environmental compatibility of transportation and thus to preserve human health and welfare.

Besides environmental compatibility, the comfort offered by a transportation system plays a major role for its acceptance. As the subjective assessment of comfort crucially depends on the perception of the related sound, interior sound quality has become a major issue for the acceptance and thus the competitiveness of transportation systems. It is thus evident that exterior and interior transportation noise control appear to be a serious challenge to preserve the acceptance, competitiveness and environmental compatibility of transportation systems.

Because of its complexity, this challenge has to be met at various levels among which political and social measures may be equally important as traffic planning and technical measures. This paper only deals with the latter and is confined even more to those vehicles whose motion is based on a rolling mechanism instead of flying in air or moving in water: cars and trains.

Effective defence against unacceptable noise or unwanted sound and sound quality should first of all fight the evil at its roots, i.e. try to prevent the generation and propagation of noise and vibration at or nearby the source. This directly leads to the aim of doing proper design by minimizing noise generating mechanisms without restrictive cutbacks in functionality. This is designing for target sounds like silence (or others!) and this is what - for cars and trains - this paper deals with.
The basic elements of such a process are understanding and influencing the noise generating mechanism by

- predictive investigations leading to modeling and simulation,
- measuring analysis of prototypes, validation experiments and constructive realizations,
- evaluation of targeting goals and practical results for partial or final designs and realizations by appropriate metrics.

These are the topics which - to some extent - will be discussed further in the following sections. It is obviously impossible to consider all relevant methods and approaches. Instead, the paper will rather try to describe the currently most important and most promising approaches, demonstrate their usability and benefits for practical engineering work and prove their usefulness by giving illustrative and successful examples and by qualifying the influence of important constructive parameters.
All this will be presented for cars and trains and consequently will enable a comparison of system specific properties and tasks as well as assess the impact of these differences to the methods and approaches being preferable for each of the two systems.

2 - NOISE COMPONENTS AND LIMITING VALUES

There are three kinds of noise generating mechanisms which determine the overall interior and exterior noise levels and characteristics: driving train noise, rolling noise and aerodynamic noise. Their absolute as well as their relative (i.e. to what extent they contribute to the total noise) value depends on both, driving parameters like speed, gear or revolutionary speed and mechanical properties like material properties of the wheel and the underlying rolling surface, contact impedances or flow profile.
Without going to detail, it may be stated here that a global average over multiple driving conditions proves rolling noise to be the major exterior noise generating mechanism for both, automotive and rail-bound transport systems. Within a great speed range, noise emissions of cars and trains are determined by rolling noise. This range typically covers velocities from some 40 to approximately 150 km/h for cars and from some 50 to approximately 300 km/h for trains. As most passenger transport and all freight transport operate within this range, rolling noise in practice turns out to be the most dominant noise source. For this reason, the control of rolling noise stays to be necessary and promising.
This also holds for interior noise in trains, where structurally transmitted rolling noise mainly determines the sound and its quality inside trains, whereas in cars aerodynamic and - above all - power train noise can influence and dominate interior sound and sound quality. It thus can be stated that - for a wide speed range - an engineering perspective to sound control for cars and trains focuses on rolling noise and - to some extent - on drive train noise when noise reducing measures are to be considered in order to fulfil prescribed specifications in terms of limiting values or comfort characteristics.
For each transport system, these specifications - if they exist at all - reflect specific constellations, conditions and past histories. In cases where the procurement of vehicles is carried out by competent operating authorities assumed to insist in state of the art noise emission values, legal limits were established only occasionally. Thus, for railway vehicles, existing noise emission regulations in Switzerland and Austria were joined only recently by proposals in Italy and Germany, the latter thought to provide the basis for a German proposal to the European Commission ([1]).
In contrast, international emission limits were established long ago for automotive cars, whose procurement is left to masses of isolated purchase decisions which typically are indifferent towards the related impact on others affected. Here, the continuous adaptation of the limiting value, last defined in [2], has led to a reduction of 8 dB (and more, depending on the type of vehicle) over the last 25 years.
It should be mentioned here that continuing discussions deal with the question whether and to what extent current measurement procedures like accelerated pass-by for cars are representative for dominant traffic situations. In addition, effects of noise have started to be taken into account when the consequences of new or extended traffic planning are to be considered.
Global differences in assessing the noise caused by road and railbound traffic can be defined by fixed reductions like the so-called railway bonus which in Germany for instance is set to 5 dB. In a comprehensive dose effect study carried out by the German Railway Corporation DB AG the justification of

this bonus is investigated by differentiating the effects of typical railway noise to home living, sleeping and working or communication with special reference to high speed traffic ([3], [4]). It is hoped that this study brings further inside into the effects of annoyance and disturbance caused by railway noise.

3 - ROLLING NOISE GENERATION AND MODELING

Like any noise control, efficient rolling noise control requires a thorough understanding of the generating mechanism: the better such a mechanism is understood, the better specific control measures may be planned and realized. It is thus useful to base any control of rolling noise on validated models which are able to describe the influence of constructive designs and materials by simulating their combined action. When rolling on a reinforced surface, both the wheel and the surface get excited by any deviations from steady evenness in relevant properties of the contact patch like compliance or smoothness. In spite of this general similarity, the details of noise generation differ essentially for wheel/rail and road/tire interaction and thus need specific modeling. A comparative summary of these models with respect to the basic source mechanisms, the mechanical properties of the components involved and their radiation properties was given by Heckl ([5]). In the following, some important features of the models for wheel/rail and road/tire noise generation will be shortly reviewed and completed by some recent developments.

For trains, it was Remington ([6]) who first added the roughness (geometrical deviations from smoothness) of wheel and rail to an effective roughness acting in the contact patch. Based on impedance descriptions of all components involved, it was possible to make reasonable predictions of the sound and vibrations generated by the rolling process.

Although this approach was subject of various subsequent comments, completions and even alternative proposals, it has proven to be a useful and reliable basis for modeling, understanding and predicting rolling noise ([7]-[9]). Of course, additional mechanisms and effects like parametric excitation by periodic and stochastic changes of the rail impedance or the consideration of couplings and transverse excitations may cause additional, important contributions. However, having been successfully added or included (e.g. as additional auxiliary sources) to the basic model, they showed to be compatible with the model rather than querying it ([10]).

For cars with soft tires instead of stiff steel wheels, the quantitative modeling of rolling noise lags behind wheel/rail simulations. This is due to the more complicated vibration behavior of tires, variations in their radiation efficiency, non negligible dimension of the contact area, lower wave speeds, great importance of tangential motion and - above all - non-linearity of the phenomena.

Unlike wheel/rail noise, where extended, physically well-founded impedance descriptions lead to useful simulative tools, the physical modeling of road/tire noise generation at present still is less meaningful. Based on a thorough compilation of physical effects contributing to the resulting noise by Heckl ([11]), Kropp has given a comprehensive theoretical description of those two mechanisms which generally are considered to be the most relevant ones: radial tire vibrations and aerodynamic phenomena, especially air-pumping ([12], [13]). Being rather complex, this model may be used to predict the influence of important parameters like speed, mass and stiffness of tire belt or surface roughness on the generated sound pressure.

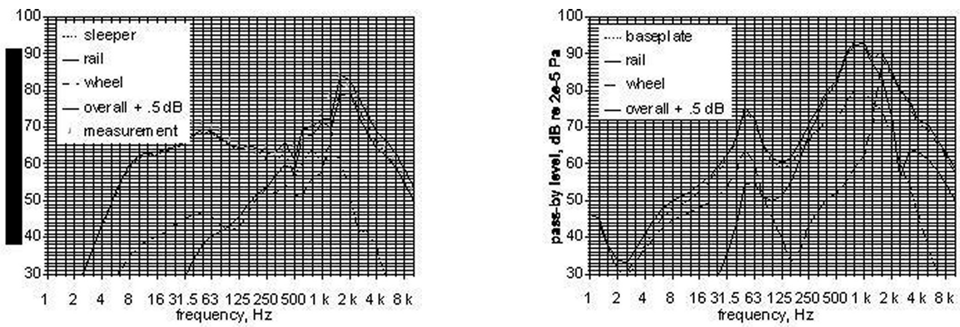
However, the difficulty of comprehensive modeling and the resulting limitations of manageable physical models have stimulated another rather descriptive approach. Based on multiple sound spectra for various tires and textures, a statistical analysis was carried out by Sandberg and Descornet [14] to investigate the correlation between the frequency spectra of the noise and the wavenumber spectrum of the texture. From the resulting statistical model it was concluded that the two most relevant noise generating mechanisms, tire vibrations and air-pumping, are closely connected to different texture properties. Road/tire noise thus was assumed to be completely described by geometrical properties of the road surface: short wave lengths determining the air-pumping contribution and long wavelengths being responsible for the mechanical excitation of tire vibrations.

In spite of such far reaching statements it should be stated that the empirical statistical model of road/tire noise generally is confined to qualitative conclusions.

4 - ROLLING NOISE MODELING AND EXTERIOR NOISE CONTROL FOR TRAINS

Powerful wheel/rail rolling noise simulations and predictions may be derived from an impedance model which is excited by the sum of wheel and rail roughness ([7]-[10], [15]). Basing the wheel model on modal parameters and modeling the rail as Timoshenko beam (with discrete or continuous support), the sleepers as simple masses (if bi-bloc) or continuously supported beams (if mono-bloc) and the remaining track elements together with contact elasticity and soil as suitably chosen two-poles allows to calculate the mean velocity of the wheel and the velocity distribution along the radiating elements of the track

like rail and sleepers. With these structural velocities the radiated sound and finally the pass-by levels can be predicted.
Fig. 1a shows a typical result of such a simulation using the RIM software (**RIM** (**R**ad/Schiene **I**mpedanz **M**odell) is a numerical prediction software tool developed by Müller-BBM in close cooperation with Deutsche Bahn (DB) AG) for a ballasted track. It can be seen that radiated sound is dominated below 250 Hz by the sleeper, from 500 to 1.2 kHz by the rail and above 1.2 kHz by the wheel. In addition, comparison of the calculated spectrum with the frequency distribution obtained from measurements shows excellent agreement of the simulation results with experimental experience ([9]). This agreement was equally reported by other comparable models and implementations ([16]).



(a): Ballasted track. **(b):** Non-ballasted track.
Figure 1: Computational analysis of noise contributions to the pass-by level.

It is obvious that this model can be refined according to specific demands by integrating additional effects like discrete sleeper support, parametric excitation etc. In summary, it may be stated that wheel/rail impedance models today are acknowledged as a valuable and handsome tool to predict noise and vibration generated by rolling railway vehicles ([17]) or to implement related estimates. Examples are the development of criteria for rail grinding using a roughness sensitivity analysis, insertion loss predictions for elastic mats on bridges or source modeling for vibration predictions in neighboring soil and affected buildings (see references in [15]).
To demonstrate the powerful capabilities of the model, a design example for acoustic track optimization shall be given. In recent years, ballastless track has attracted growing interest and this is mainly for maintenance reasons with high speed traffic. One major disadvantage of ballastless slab track, however, is its increased noise emission (typically 3 to 5 dB) with respect to ballasted track.
The effective reduction of this increased level by primary constructive means requires a thorough analysis of all relevant influential parameters. In analogy to Fig. 1a, Fig. 1b shows the contributions of various components to the overall pass-by level for a slab track as obtained from the predictive RIM simulation model. It can be seen that air-borne noise between 250 Hz and approximately 1.5 kHz is caused by the rail, above 1.5 kHz by the wheel. More important than the changes in limiting frequencies is that the overall level is no longer determined by the wheel contribution (as in Fig. 1a). For ballastless track, it is the rail determining the overall pass-by level instead.
As shown in [15] and [18] to [20], this analysis can be justified by further simulative insight. It is thus possible to determine optimum constructive designs and material properties by systematic parameter variations. Fig. 2 shows some results for different track constructions and parameters. While the cases 1, 10 and 11 refer to existing track realizations, 2 to 9 describe variations of ballastless track (FF), especially by using elastically supported bi-bloc sleepers (4-5), elastically supported mono-bloc sleepers with low (6-7) and with high (8-9) damping.
It can be seen that only elastically supported mono-bloc sleepers with high damping are able to suppress the track's contribution to the overall pass-by level. The wheel's contribution solely determines the level then and the reduction may be up to 6 dB. Another obvious conclusion is that the wheel's contribution is practically invariant against alterations of the track construction and may be reduced only by wheel alterations. Further track optimizations thus require accompanying measures at the wheels.
The above result was taken as the starting point for a new track design where highest priority was given to acoustical requirements as long as these were compatible with indispensable constructional, operational and maintenance needs at least ([20]).

5 - ROLLING NOISE MODELING AND EXTERIOR NOISE CONTROL FOR CARS

As mentioned earlier, existing models for road/tire noise generation are less specific and thus less powerful

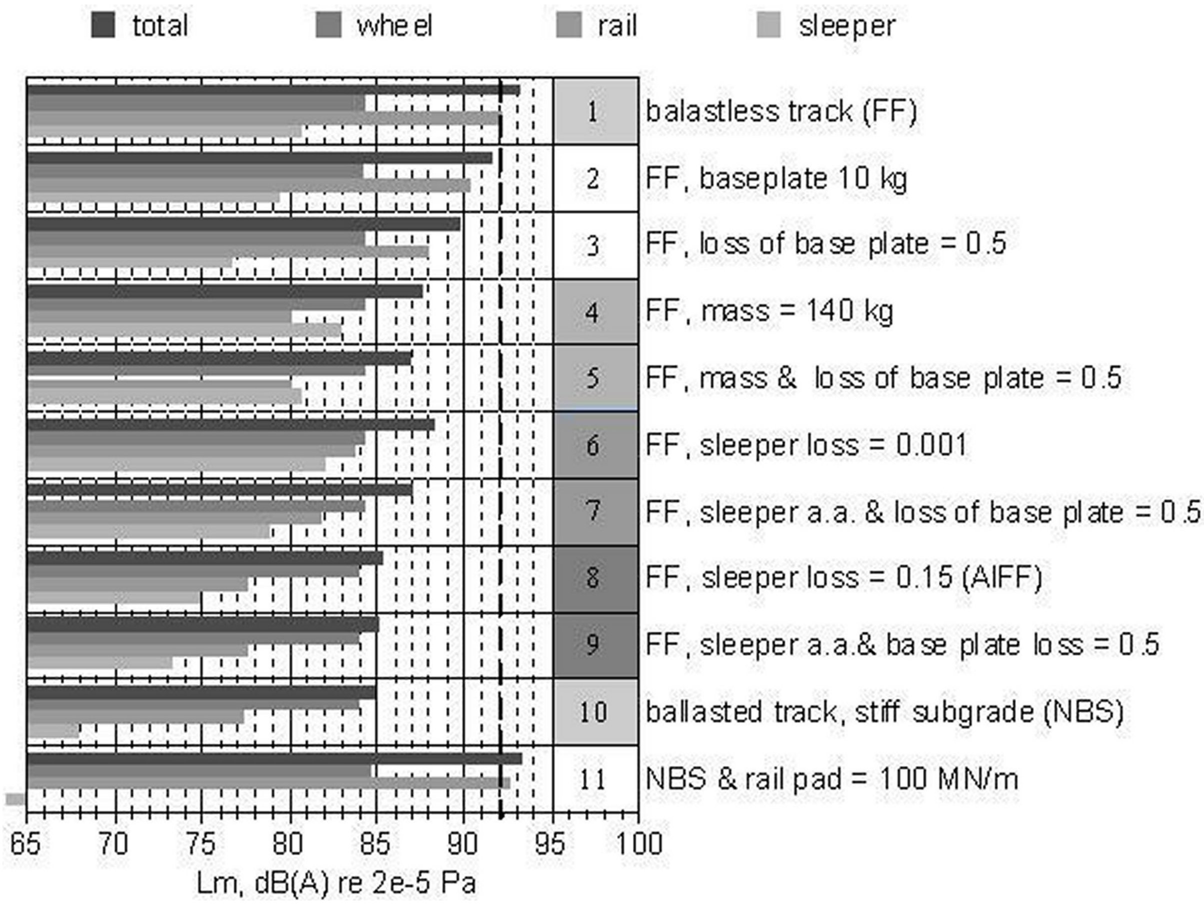


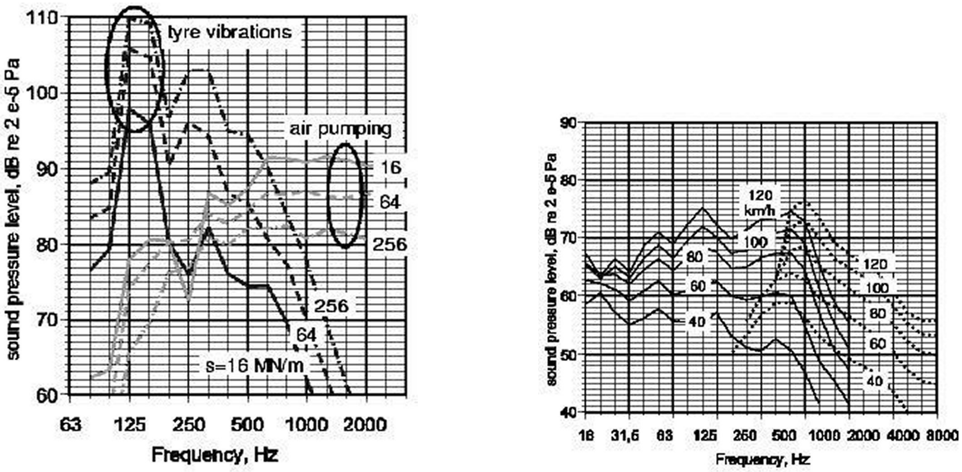
Figure 2: Predictive comparison of A-weighted pass-by levels for an ICE-train on different track constructions and parameters.

when used for predictive simulations of concrete noise control measures. However, recent investigations might open new perspectives for the modeling precision by adding two new extensions to previous approaches:

- a large new database of thorough coast-by measurement results obtained for 20 different types of tires and 43 different road surfaces with well-aimed variations of surface characteristics such as texture or sound absorption ([21]) and
- the integration of physical model elements into a new defined statistical model.

The elements of a physical model go back to the work of Kropp ([12], [13]) and are particularly given by an orthotropic plate approximating the tire and distributed springs whose stiffness is defined by tread elasticity and which represent the contact patch. Generated by rotating tire deformations, the tire represented by the orthotropic plate is excited to vibrations radiating sound to the surrounding medium. Together with the tire vibrations, the radiated sound, which depends on the wavelength of the tire vibrations as well as on the total geometrical situation, may be determined by doing appropriate calculations for the simplified elements. If air-pumping is modeled in parallel by taking into account local deformations as given by the road roughness, the resulting prediction is able to confirm basic observations. As an example, Fig. 3a shows the calculated frequency dependence of the radiated sound pressure generated by mechanical excitation and air-pumping for different stiffnesses representing different tires.

From these curves it can be stated that above a stiffness dependent frequency of almost some 1000 Hz air-pumping is clearly dominating the level of radiated sound while below the level is determined by mechanical excitation. This can be confirmed by results of Sandberg and Descornet ([14]) as shown in Fig. 3b, where low frequency (mechanical excitation) and high frequency (air-pumping) partial spectra are given for a typical tire at different speeds. Again, based on conclusions from previous correlation analysis, a clear distinction can be made between these effects and the frequency range where they determine the overall noise.



(a): Analytical model (for varying stiffness).

(b): Statistical approach (for varying speed).

Figure 3: Frequency dependence of the noise generated by mechanical and aerodynamic excitation.

The general assumption of uniquely relating the effects of mechanical excitation and air-pumping to different frequency ranges was the basis for various noise control measures and modifications of the texture of dense road surfaces, e.g. for obtaining well-aimed noise reductions above 1000 Hz by exclusively influencing air-pumping excitation. However, recent experiments with dense road surfaces were not able to confirm this. Instead, they rather increased the motivation for an improved road/tire noise generating model.

In recent work it was found that a physically supported statistical model might be a progressive approach to overcome obvious inconsistencies. By preprocessing the road roughness profile it is possible to determine a resulting equivalent contact pressure distribution which is used then to evaluate the radiated sound pressure. In addition the preprocessing avoids the inconsistency of representing non-linear physical dependences in a linear statistical model.

Superposition of these results with corresponding results from calculations of the noise generated by air-pumping may be used to reduce the parametric degrees of freedom in the remaining statistical model. Determination of these parameters by a thorough regression analysis leads to a novel model which seems to enable improved predictions with better agreements to measurements and observations.

As an example, it may be concluded from first evaluations that the speed exponent of the sound pressure above 1000 Hz differs from previous assumptions by clearly staying below a value of 4. This would strongly indicate the existence and importance of noise generating mechanisms by mechanical excitation which have been neglected in the past. As a consequence, this might point to new possibilities to influence and design roads and tires.

In addition, the improved reliability of quantitative predictive calculations would further improve the reliability of immediate conclusions and requirements, e.g. with respect to the texture of road surfaces. It should be noted, however, that the preliminary improvements outlined here incorporate important tire features like deformation of the tread but neglect some further features like detailed profile characteristics.

6 - INTERIOR NOISE CONTROL AND SOUND QUALITY FOR CARS AND TRAINS

While control of exterior sound mainly is aimed to reach acceptable values for those being affected but not involved, interior sound design immediately addresses users and operators or operating authorities. Especially in the case of automotive cars, where users normally correspond to buyers, this offers the possibility of brand identification and distinction from competitors. Consequently, from the automotive industry, sound design fitted to the emotionality of a car is seen to be a major motivation for any decision to buy. This trend, which gradually is followed by manufacturers of railway coaches, requires increased performance of predictive design and analysis tools for interior sound and vibration to meet targeted customer requirements.

For passenger cars, the necessary computing efforts to obtain useful results for interior sound and vibration limit the method of finite elements to predictions below 200 to 300 Hz. Even with this limitation the method does not allow for interactive design because of the long response time due to intensive calculations. This can be improved essentially by evaluating the effect of small modifications in the modal space which can be obtained from a modal transformation based on the results of a thorough FE-analysis. Numerical experience has proven that this approach worked satisfactory for a wide range of modifications which in most cases covered the physical range of possible modifications without recalibrating the modal space by a new, precise FE calculation.

However, because of the computing effort involved and because of the difficulty to model all elements and substructures with sufficient reliability, hybrid methods combining experimental and numerical techniques are of great practical importance. As an example, the so-called transfer path analysis (TPA) predicts interior sound pressure based on numerical and experimental transfer characteristics from the excitation points, where the car body is excited by the chassis and driveline structures, to the interior sound field ([22], [23]). Fig. 4 gives a typical TPA result showing the relative contributions of the transfer paths from 8 different car body mounts to the driver's ear position by rough road excitation. Similar decompositions may be given for other positions, thus allowing the detection of predominant excitations and/or transmission paths and subsequent elimination of weaknesses.

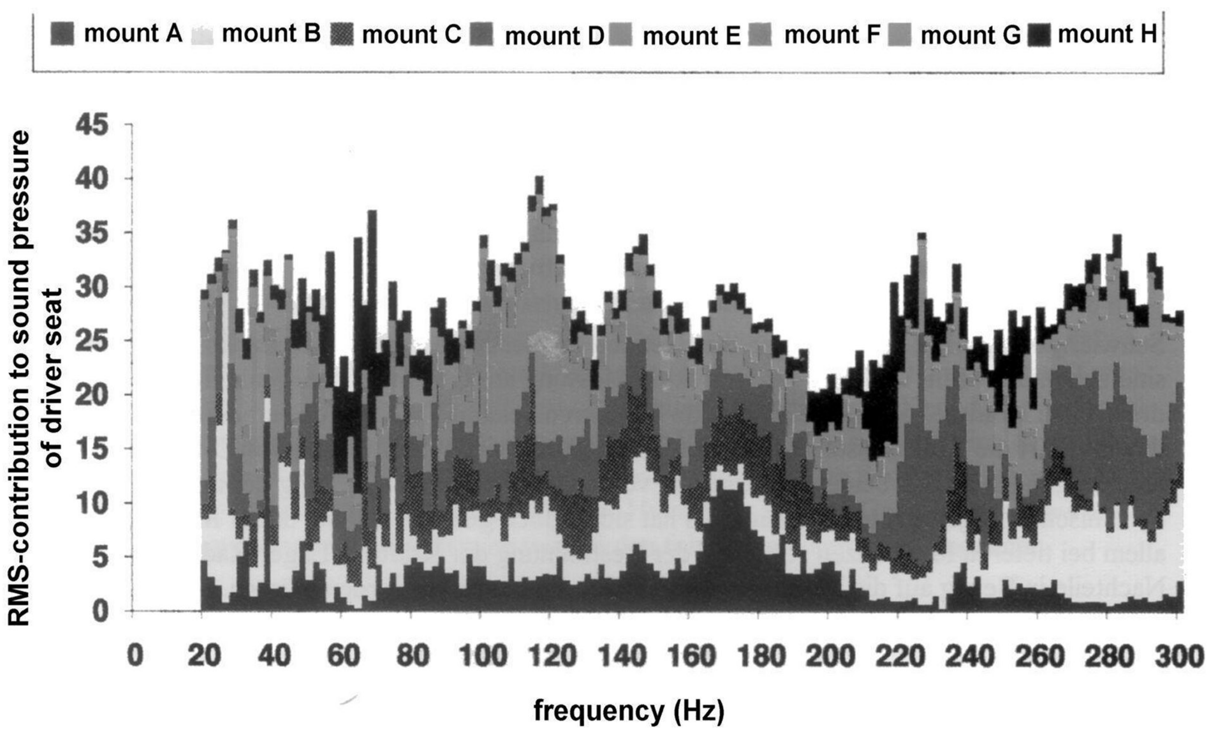


Figure 4: Acoustic contribution of different transfer paths to the driver's ear for rough road excitation of an automotive passenger car ([23]).

For railway coaches, the use of FE based predictions is more limited than for automotive cars. The dimensions and the material properties of the substructures involved limit the applicability of reliable FE calculations in the audio frequency range to bogie elements which, in the low frequency range, dominate the transmission of rolling noise into the compartment.

A typical example is given by increased sound and vibration levels in high speed trains caused by wheel harmonics (multiples of the rolling wheel's rotational frequency) and reinforced by coinciding resonances of the track and secondary bogie springs. This leads to raised noise and vibration levels around 90 Hz in high speed trains, particularly when they are running on new ballasted tracks with stiff subgrade ([15]). Although being easy to apply, decreasing the track resonance frequency by soft pads has the disadvantage of increased rail vibration and sound radiation around 1 kHz. For vehicles, work thus had to concentrate on avoiding the weak vibration attenuation of the bogie in the frequency range of interest. This led to the use of air springs and a thorough acoustic optimization of all flanking paths (dampers and stabilizers), resulting in a 20 dB improvement at the frequency of interest.

Unlike low frequency contributions, the overall noise is composed of many parts transmitted to the compartment via multiple paths. Well-aimed design therefore requires specific tools which fulfil the need for accurate predictions. Besides some forced attempts to use established techniques like finite (FEM) and boundary (BEM) element methods, reliable results are obtained from estimates based on simplified analytic models together with experimental data ([24]).

The availability of such noise transmission models permits conclusions on the sensitivity to both, excitation strengths and construction unit properties. This may be achieved by evaluating the differential changes of the target quantity (e.g. sound pressure in a compartment) caused by small changes of source strengths or parameters characterizing the transfer behavior from the source to the target. Within the scope of adequate modeling precision, this parametric sensitivity analysis may replace the method of transfer path analysis (TPA) by a very handsome and efficient approach.
As an example, table I shows this in a simplified but nevertheless meaningful manner by specifying to what extent exemplary noise sources and acoustical properties contribute to the interior noise level in various operating conditions. By balancing (and ranking) the relevance of sources, transfer paths and material properties, the method turns out to be an extremely valuable tool in designing vehicles for specified noise values.
By its very nature, this approach assumes some extension of the substructures involved and thus was used preferably for railway vehicles. However, it might be worthwhile to explore the potential of the method for higher frequencies in small passenger cars.

Noise source or construction unit	Pass-by level v = 160 km/h	Acceleration level	Standstill	Interior noise open track v=160 km/h	Interior noise tunnel v=160 km/h
Track	o	−		++	++
Wheels	++	o		−	−
Converter incl. Cooling	−	−	++		
Traction motor incl. Gears, air-borne noise	+	++		o	+
Sound insulation floor				++	−
Sound insulation roof				−	+

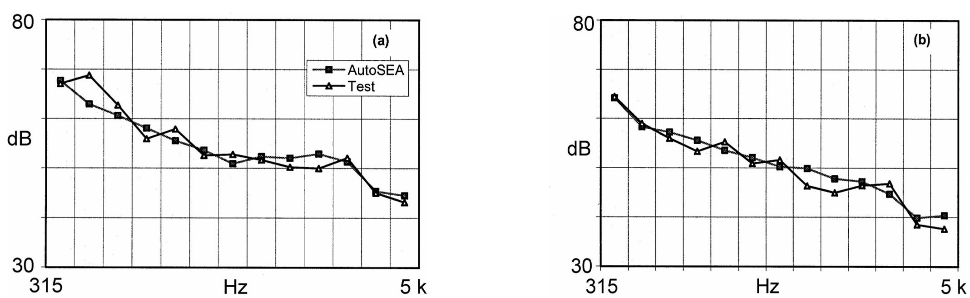
Table 1: Noise management analysis for exemplary sources and transfer paths.

Predicting, measuring and influencing sound and vibration field quantities lacks final justification if the target is not clearly defined. Depending on the state-of-the-art sound levels achieved in the past, these targets have started to be set in terms of additional descriptors completing the use of minimal sound levels only ([25]). Aimed to incorporate metrics for subjective or adequate impressions, it is quite natural to base these targets on the well established psychoacoustic quantities loudness, sharpness and roughness or fluctuation strength or even to combine these with appropriate weights in some single-valued index.
Also, instead of being used directly, these quantities may be used indirectly by deriving, specifying and justifying spectral targets in the frequency domain. This is an important practical issue and may include reasonable rules how deviations from frequency dependent specifications should be handled: Quantitative knowledge about the consequences of spectral fluctuations on acoustic comfort would allow for balanced design efforts, thus avoiding over-design.
To illustrate this, the results of some experiments shall be shortly described here. They were defined and carried out to allow quantitative statements on admissible deviations from a spectral distribution as typically found in high speed trains. As a qualitative result it may be stated globally that broad band deviations were assessed proportionally, i.e. more pleasant for reduced and less pleasant for increased broad band levels. On the contrary, narrow band deviations always were perceived as less convenient, even in the case of a reduced narrow band level. From this it may be concluded that deviations from the spectral specification should stay within tolerable deviations, e.g. +5/-10 dB.
Besides precise quantification of the subjective impressions, the study enabled additional investigations on criteria of speech intelligibility and privacy in passenger compartments of railway coaches. As a matter of fact, the criteria for defining sound quality in cabins and compartments simultaneously used by several passengers may be conflicting. A typical example is given by comfort (increasing with decreasing noise) and privacy (decreasing with decreasing noise). So, when properly designing vehicles, noise control measures should be thoroughly matched with room acoustic measures to get an optimal trade-off between comfort and privacy [26].

For automotive sound assessments, the above mentioned attempts to define suitable sound quality indexes are accompanied by defining and implementing rules for the evaluation of psychoacoustic quantities from measurement data. Following the ISO standard for stationary loudness, standardizing of non stationary loudness has entered (national) discussions to avoid the irreversible establishment of various, incompatible implementations in the market.
Although partially implemented in various labs, evaluation of roughness still seems to be at an early stage. This similarly holds for sharpness. However, since a new, improved procedure to evaluate the roughness of (rotational-) speed dependent noises with special ear-related characteristics is urgently needed, previous work of Müller-BBM is continued and will come up soon with further results of practical relevance.

7 - STATISTICAL ENERGY ANALYSIS

Besides the predictive simulation tools described in previous chapters, Statistical Energy Analysis (SEA) has become an important tool in the design and analysis of noise and vibration control components used in vehicles [27]. This is particularly true for passenger cars, where SEA may provide a framework for analyzing complex multi-source and multi-path noise and vibration transmission problems.
Compared to other general tools like Finite and Boundary Element Methods (FEM and BEM), SEA by its very nature inherently overcomes their principal limitation in modeling for high frequencies. Thus, for frequencies above 100 Hz in railway coaches and some 200 to 300 Hz in automotive vehicles (depending on the vehicle characteristics and dimensions, of course), SEA has proven predictive potential and benefits, especially for the analysis of interior rolling noise.
As an example for automotive applications, Fig. 5 gives the results of validating the full vehicle SEA model of a minivan by a semi-anechoic room speaker test simulating road/tire noise transmission ([28]). For a given sound power generated by two loudspeakers under the front wheel at the driver side, the diffusion of energy in the model was tracked all the way from the tire-patch location to the vehicle structure and the interior volume. It can be seen from the comparison of predicted and measured responses in Fig. 5 that the predictions closely follow the measured values. Similar results were obtained for structure-borne transmission of road/tire excitation to different car-body locations ([29]). Comparing these results confirms the fact that in most cases SEA models for air-borne sound transmission tend to be slightly more precise than for structure-borne applications.



(a): Front seat ear position. **(b):** Low cargo space position.

Figure 5: SEA model validation for road/tire noise in a semi-anechoic room.

SEA models can also be used effectively in the evaluation and optimization of design alternatives. As shown in [28] and [29], the evaluation of various component level design changes may result in fractional-dB differences. This is due to the statistical nature of SEA models which enables them of following even small changes which generally are very difficult - if not impossible - to measure because of the great variability associated with component or assembly characteristics and tests. This relative precision of SEA calculations preserves their value even in such cases where the prediction of absolute values lacks precision.
For interior noise analysis and control in railway coaches, a specific difficulty of modeling the commonly used extruded profiles has to be overcome. Fundamental investigations have shown that the characteristics of such profiles may be successfully modeled by equivalent sandwich constructions ([30]), thus reducing the modeling task to the use of known SEA substructures. Satisfying validation results were obtained for typical coach-like structures and coaches showing very good agreement for air-borne and good agreement for structure-borne sound prediction. Again, the slight superiority of air-borne predictions could be observed.

8 - ACTIVE NOISE CONTROL AND SOUND DESIGN

For suitable, "fitting" applications, active control of noise and vibration was shown to be an efficient tool to reduce undesired field components to an acceptable level. Examples for successful test applications may be found in vehicles including ships and aircraft, the latter even with a series implementation. However, although having been a subject of considerable research and development efforts, active noise control in cars and trains has not succeeded yet in being implemented on a large scale. This is only partially due to technical shortcomings like insufficient actuator capabilities or long-term robustness and reliability. More relevant seems to be that the related cost could not be reduced to an acceptable level. Nevertheless, in the long term, especially for problematic cases like low frequency rolling noise, infrasound generated by ventilation systems or poor sound insulation of light-weight structures and car-body elements, the implementation of active control systems should have serious potential. The related interest definitely will be intensified by the attractive possibility of rather changing the sound characteristics instead of just reducing or cancelling them.

Apart from some special cases, active sound control means generating additional sound interfering with the original sound pattern. This concept includes the possibility of deliberate sound alterations by allowing non interfering superposition of new sound components. By combining these newly generated field elements with cancelling components, almost arbitrary modifications of the sound field can be achieved. This approach extents the possibilities of traditional Active Noise Control (ANC) techniques and thus may be described appropriately by Active Sound Design (ASD).

As mentioned above, psychoacoustic quantities may be used to characterize subjective assessments of arbitrary sounds which - of course - may include sounds generated by active control measures too. This immediately creates the reverse idea of using active control to approximate sounds with prescribed, aurally adequate perception characteristics. In this case, the common goal of minimizing some mean square error function would be replaced by an error function using the relevant sound parameters and characteristics.

However, non-linear and thus irreversible computation rules prevent a unique assignment of temporal sound characteristics to perception related sound descriptors. For repetitive components of engine and rolling noise a more pragmatic approach may be used instead. By prescribing well defined amplitude values of a given set of harmonics (engine orders or wheel harmonics), subsequent approximation of these order-related amplitudes will vary the resulting noise together with the associated subjective parameters ([31]).

Practical measures of active control shall be represented here by two examples demonstrating their state-of-the-art potential as well as current limitations for cars and trains. The first example refers to a high speed ICE rail-way coach, where active means were considered to reduce the low frequency noise components described in section 4.

Although direct sound cancellation by a set of loudspeakers was proven to successfully compensate the tonal noise in the compartments, a thorough analysis of the transfer paths from vibration generation to sound radiation showed that applying forces to the vehicle body close to the secondary springs would be the most efficient way of reducing the interior noise.

After a successful case study, the concept was tested for a vehicle running on the rolling test rig of the German Railway Corporation, DB AG [32]. Fig. 6 shows the result for four piezo-ceramic actuators (two on each side) being arranged in parallel to the secondary springs of a bogie at a speed of 200 km/h. The actuators were driven by a reference signal derived from the wheel's rotation and thus determining the frequencies to be considered.

It can be seen from the spatial sound pressure distribution of Fig. 6 that the sound field generated by the bogie on the left side of the figure was essentially reduced in the whole volume of the compartment. At critical speeds, these reductions were up to 20 dB for predominant wheel harmonics at specific seats and up to 12 dB when averaged over an ensemble of typically 6 seats. It should be noted, however, that the realization of such measures on an industrial scale would require improved actuators with respect to power, linearity and cost.

The second example will prove the feasibility of Active Sound Design in a small size 4 cylinder car (new beetle). To demonstrate the capabilities of such a system, it was used to realize the sounds of different engines from other cars ([31], [33]). The targeted sounds were obtained from measurements in these cars and then stored for use in the signal processing device. Based on the error signals from six error microphones and appropriate information on revolution speed and engine load, six secondary loudspeakers were fed such that the resulting sound field was an optimal approximation of the prescribed sounds.

Fig. 7 gives some typical examples by showing the time-dependent frequency spectrum at the driver's

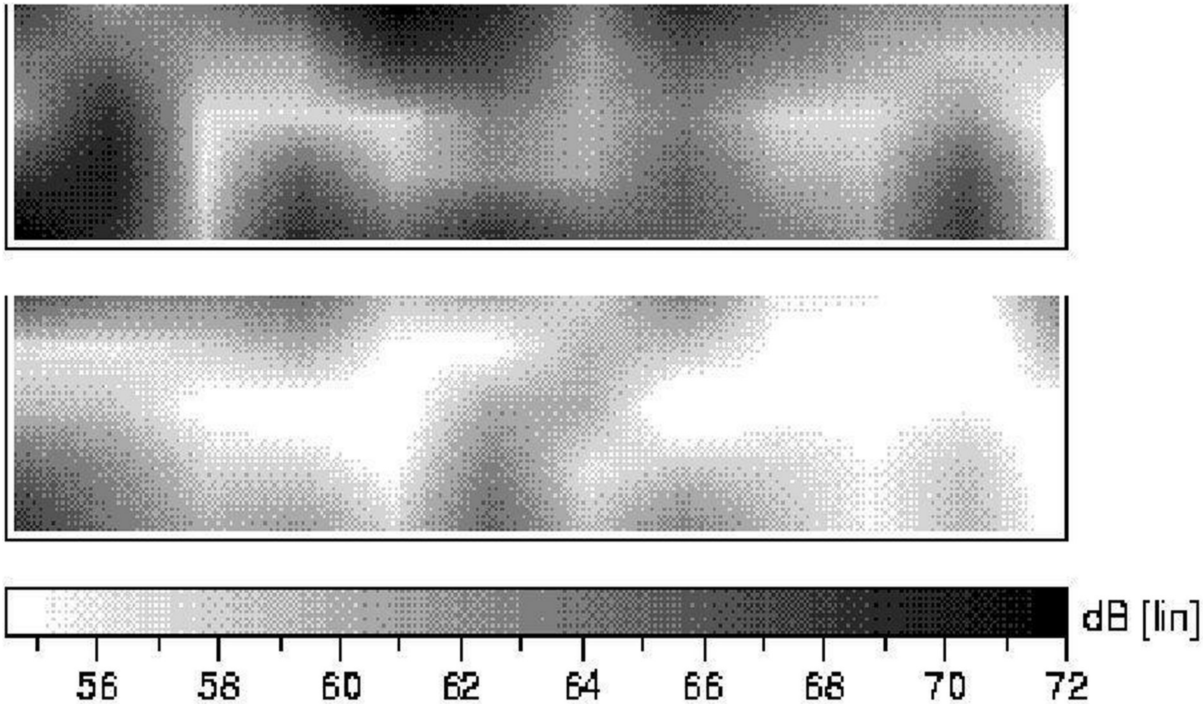


Figure 6: Spatial distribution of the sound pressure level in the compartment of an ICE high speed coach with (below) and without (above) active control.

ear if the car is consecutively run up (to 6000 rpm) and down with four different sound implementations. The first run-up (lowest part of Fig. 7) shows the typical spectrum of a 12 cylinder sports car, then followed by an 8 cylinder sports car, a six cylinder sports car and, finally, by the original 4 cylinder engine sound (system switched off).
The effect was - objectively (by measurement) and subjectively (by ear) - striking. The various sounds were immediately able to generate the acoustic illusion of driving a different car. Thus, the system might be more than just a toy: it could equally be used - and should turn out to be extremely useful - as an experimental tool to determine and test optimal sounds for given cars.
Finally, it should be mentioned that Active Sound Design recently was used to reduce and/or modify the noise of air intake systems of car engines. Experimental results from test set-ups ([34]) were quite promising and seem to have found serious interest of experts. It thus can be stated that - in spite of some uncertainty about the acceptance of sounds forged by electroacoustic means - the prospect of deliberately designed sound realizations is highly attractive.

9 - SUMMARY AND CONCLUSIONS

Although being limited in scope, the foregoing sections have tried to give a rough overview on actual problems and methods in controlling noise and vibration for cars and trains. It is obvious that - within the limitations given here - this attempt was confined to be a sample survey only. The multiplicity of tasks together with the corresponding multiplicity of mathematical, physical and engineering approaches prevents any summarizing overview from being compact. It is hoped, however, that the focus chosen here was able to attract attention and to create further motivation.
In the introduction it was stated that vehicle acoustics has two major motivations: a social one to maintain and improve the environmental compatibility of a traffic and transport system and an economic/competitive one to find and increase its market acceptance and attractivity. For engineers, this motivation should be exceeded by the technical enthusiasm originating from the rapid development of tools to simulate, predict, analyze and solve the many interesting problems related to noise and vibration control for vehicles.
This motivation is needed, of course, because new and higher demands require improved tools and know how. Thus, besides the social and the competitive challenge, a continuous technical challenge addressing the ingenuity and creativity of engineers may be stated and confirmed. This should help to apply the many new methods and strategies to find appropriate solutions to actual problems. Moreover, it should guarantee further methodological developments meeting the needs of future problems.

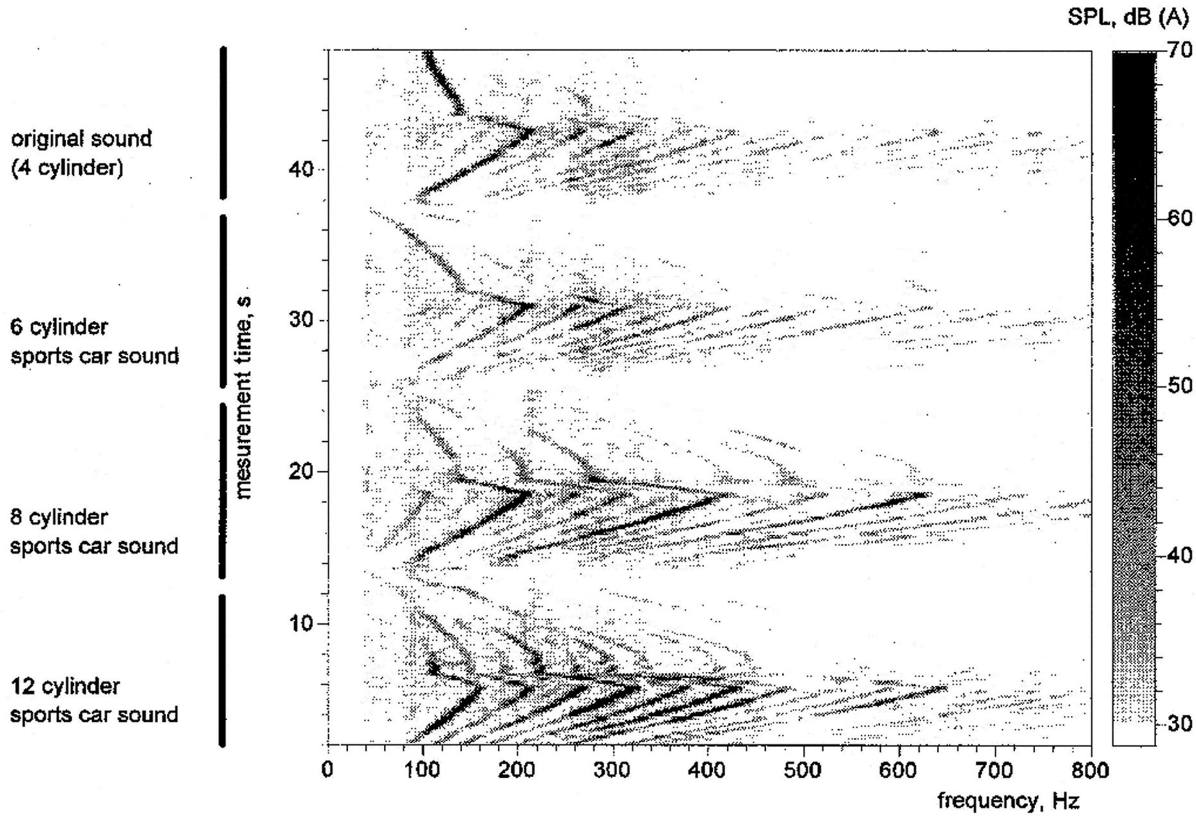


Figure 7: A-weighted sound pressure spectra at the driver's ear for four consecutive run-ups with different engine sounds.

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