Investigation of Tyre Road Noise
Process and Analysis

A pleasant sound based on a low interior noise level is one of the main requirements for passenger cars. Because of the reduction of many single noise sources, tyre road noise is now becoming increasingly important. Manufacturers of luxury cars in particular are asked to accept this challenge. Daimler has developed a systematic method for the investigation of tyre road noise. The target is to identify the main principles of noise transmission in an efficient process.

1 Introduction

One of the main customer requirements for passenger cars is a pleasant sound based on a low interior noise level, especially for manufactures of luxury cars. For this reason, noise, vibration and harshness (NVH) development is now a central part of vehicle engineering with the highest priority. Over the last few years, the continuous optimisation of many single noise sources has led to a significant reduction in interior noise levels. Among the individual noise sources, tyre road noise has become more and more important, especially in view of the need to create a balanced and pleasant interior noise. **Figure 1** lists the main tyre road noise phenomena. The identification of noise sources (powertrain, components, wind, tyres, road contact, etc.) is a key part of NVH development. Numerous studies on the tyre as a source of noise have revealed the following results: In general, the difference between different passenger cars is greater than the difference between the tyres of two tyre manufacturers. However, in particular cases, the influence on specific noise phenomena can be much more important. Measurements with different tyres have clearly shown that there is no correlation between the measured levels for exterior and interior noise, but correlation may be possible for specific frequency ranges. **Figure 2** shows this relationship as a summary. The knowledge of noise sources and noise transmission behaviour is a fundamental aspect of the modern NVH development process. The method of Transfer Path Analysis (TPA) [1, 2] is one means of identifying noise sources and their main transmission paths. The application of transfer path analysis leads to an analytical model that is then used to calculate the single path contributions of the interior noise. For this case study of tyre road noise, both structure-borne noise and airborne noise are responsible for the total interior noise. **Figure 3** gives an overview of this transmission behaviour. At the beginning of a study of tyre road noise, the general noise transmission behaviour is not well known, and the application of TPA requires a lot of effort and cost. Therefore, an early estimation of the general noise transmission behaviour is useful because of the high number of possible transmission paths and the characteristics of the noise sources. One way of reducing the amount of effort and cost required is based on the application of a coherence analysis [3] as a preliminary investigation. Related to the measured interior noise, relevant frequency ranges for structure-borne noise or airborne noise transmission can be determined. Additionally, it is possible to separate noise transmission from the front or rear axle. In this way, a basic procedure for investigating tyre road noise can be found based on the application of a preliminary investigation, as described above. This procedure is characterised in **Figure 4**.

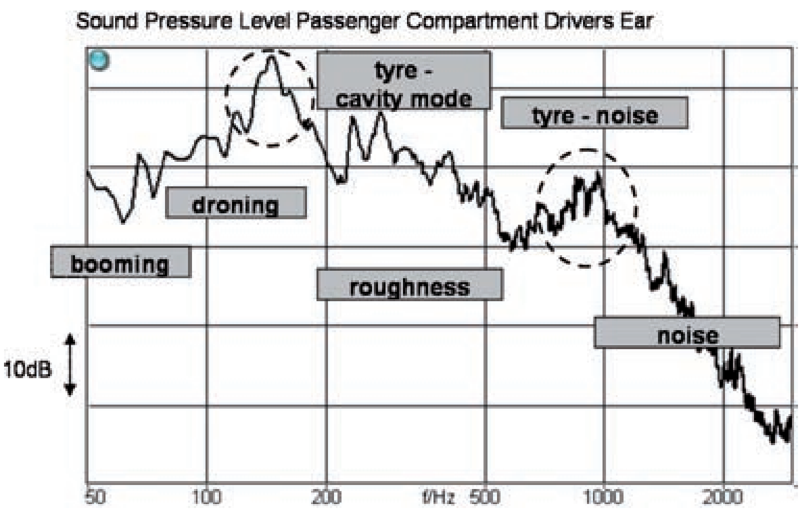
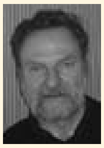


Figure 1: Tyre road noise phenomena

The Authors

Dipl.-Ing. (FH) Gregor Koners is development engineer, member of the team structural analysis in the NVH centre at Daimler AG, Mercedes Car Group in Sindelfingen (Germany).

Dr.-Ing. Marcus Hofmann is development engineer, member of the team advanced product engineering in the NVH centre at Daimler AG, Mercedes Car Group in Sindelfingen (Germany).



Dipl.-Ing. Heinz-Dieter Klein is development engineer, member of the team vehicle acoustics (exterior noise) in the NVH centre at Daimler AG Mercedes Car Group in Sindelfingen (Germany).

Dipl.-Ing. M.Sc. Joachim Mell is development engineer, member of the team vehicle acoustics in the NVH centre at Daimler AG, Mercedes Car Group in Sindelfingen (Germany).

Dipl.-Ing. (FH) Gerhard Schneider is development engineer, member of the team insulation systems in the NVH centre at Daimler AG, Mercedes Car Group in Sindelfingen (Germany).

2 Analysis of Noise Transmission Behaviour

2.1 Coherence Analysis: Basic Mechanism of Noise Transmission

Based on coherence analysis [3], the global mechanisms of noise transmission are first of all determined. By combining different reference channels to form groups of coherence, it is possible to differentiate between airborne and structure-borne noise transmission from the front or rear axle. For driving on real roads, reference sensors for acceleration and sound pressure are applied to the car. 3D accelerometers are fixed at the wheel centres and microphones are placed at the footprint areas. The accelerations, the sound pressure levels at the footprint and the interior noise are then measured at the same time. For a different coherence analysis, different reference signals are combined into groups, and the multiple coherence relating to the interior noise is calculated. The result of such a coherence analysis is shown in **Figure 5**. For the example shown in Figure 5, the result is clear:

1. For the frequency range from 100 Hz to 150 Hz, the interior noise is dominated by structure-borne noise transmission coming from the front axle.
2. In the frequency range around 1000 Hz, only airborne noise transmission is relevant. The airborne noise is radiated by the rear wheels.

With a view to the results of the coherence analysis, the further procedure is defined:

1. For the identification of noise transmission in the frequency range from 100 Hz to 150 Hz, TPA for structure-borne noise is used. Only noise transmission at the front axle is considered.
2. For the frequency range around 1000 Hz, the relevant airborne noise transmission paths should be identified. The application of a reduced transfer path analysis leads to the estimation of the single noise contributions. Only noise transmission from the rear wheels is considered.

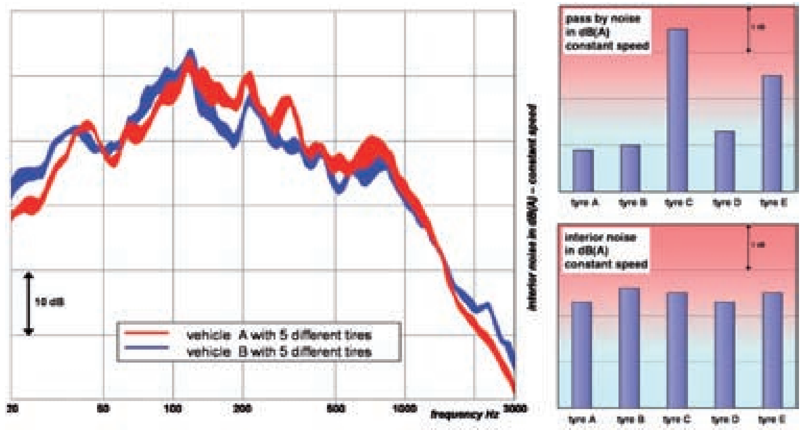


Figure 2: Correlation interior / exterior noise, influence of tyres

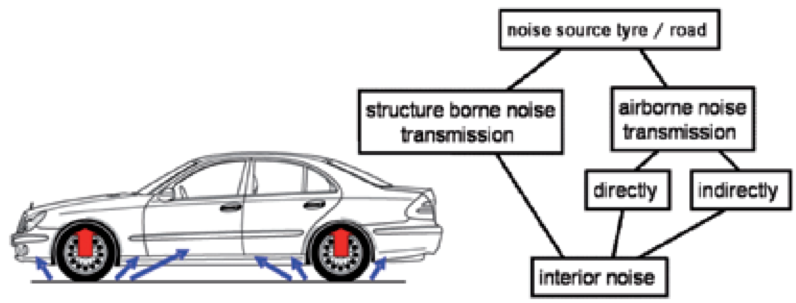


Figure 3: General noise transmission behaviour – tyre road noise

2.2 Coherence Analysis: Validation Process

The method is validated in two steps. First, an acoustic enclosure is applied to encapsulate the driven wheel on a dynamometer (only one wheel is driven). This modification reduces only the airborne noise transmission. The structure-borne noise is then calculated for the test with and without modification. If the measured reduction in the noise level corresponds to the reduction estimated via coherence analysis, it is possible to determine the interior noise path for structure-borne and airborne noise. The result of these investigations shows a good correlation between measurement and prediction. In a second step, the separation of noise transmitted from the front or rear axle is investigated. For this purpose, a car is rolled on a four-wheel dynamometer. The parts of the noise transmission for the front and rear axle are then estimated using coherence analysis. Following this, the axles are operated separately. The comparison of the results also shows a good correlation between measurement and prediction using coherence analysis. **Figure 6** shows a summary of the results. The comparison shows that, in each case, there is a good correlation between measurement and prediction. It is clear that it is possible to apply this method as a preliminary investigation. The target is the identification of the principal noise transmission behaviour. The applicability of the method in road operation was also demonstrated. For road measurements, however, the range of speed is reduced because the flow around the microphones produces inherent noise that can lead to falsifications in the results.

2.3 Transfer Path Analysis: Structure-Borne Noise Transmission

The noise transmission behaviour was to be identified for the frequency range from 100 Hz to 150 Hz, as shown in Figure 1. As a result of coherence analysis, it is known that only structure-borne noise transmission leads to the peak shown in the example. For the identification of the noise transfer paths, TPA has to be applied. The interior noise and the accelerations at relevant connection points of the suspension are measured in road operation. The acoustic mechanical transfer functions (p/F) together with the rele-

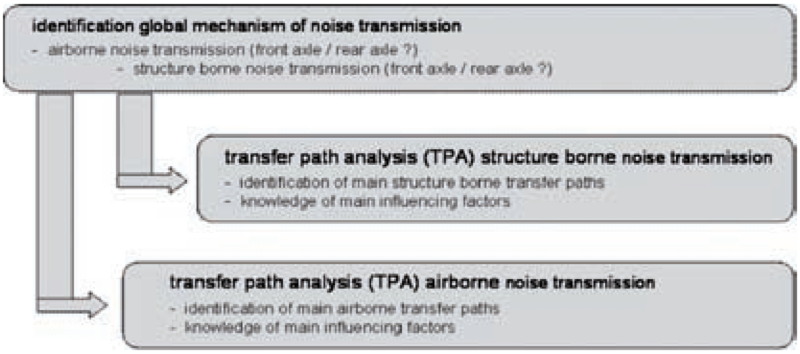


Figure 4: Investigation of tyre road noise – basic approach

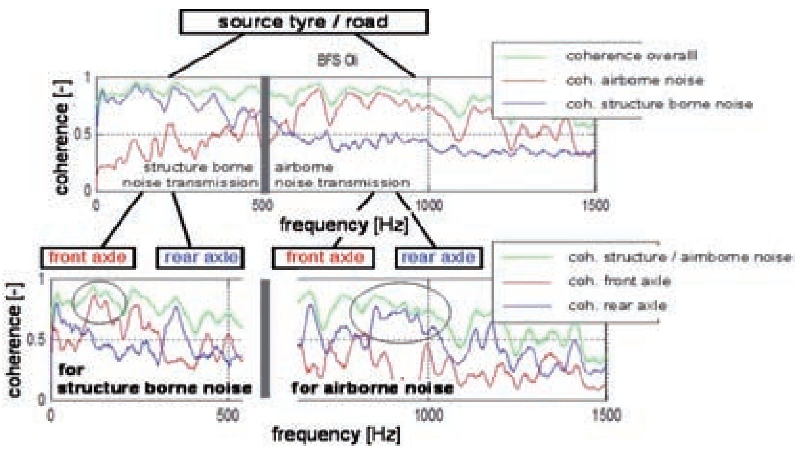


Figure 5: Result of coherence analysis

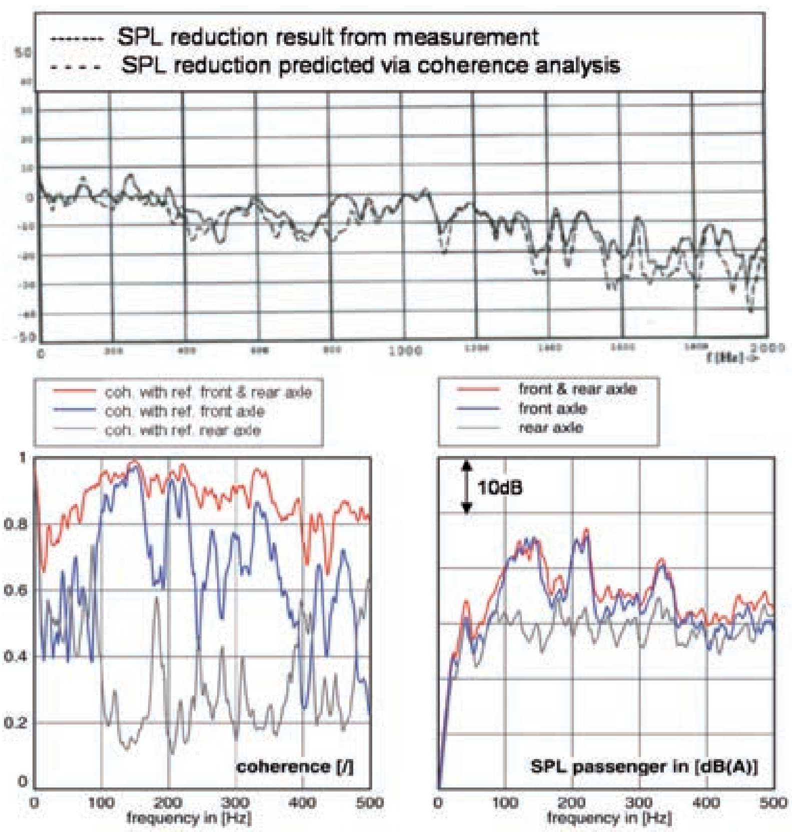


Figure 6: Validation of coherence analysis

vant frequency response functions are measured in the laboratory. Using TPA, the operational forces are calculated by means of the matrix inversion method [2, 5] and, together with the acoustic mechanical transfer functions, all possible noise path contributions of the front axle are determined. The correlation of the source signals, which is necessary for force calculation in the matrix inversion method, is guaranteed by means of Principal Components Analysis (PCA) [4]. The result of an interior noise measurement compared to the estimated sum of all single noise paths is shown in **Figure 7**. There is a good correlation between both curves for the frequency range of interest. A comparison of the results for all single noise paths shows that there are four main transfer paths that are responsible for the interior noise. For all paths, the combination of high operational forces together with high levels for the acoustic mechanical transfer functions p/F leads to high interior noise levels. **Figure 8** illustrates this relationship. The reduction in operational forces together with the reduction in the acoustic mechanical transfer function p/F is set as a target for reducing interior noise in the relevant frequency range. In particular, measures to reduce the operational forces often come into conflict with requirements for active safety.

2.4 Transfer Path Analysis: Airborne Noise Transmission

As shown in section 2.1, airborne noise from the rear axle is responsible for the interior noise in the frequency range around 1000 Hz. Therefore, the main airborne noise transfer paths have to be identified. In order to identify this transmission behaviour, a reduced transfer path analysis for airborne noise transmission is applied. The interior noise is measured in road operation. The radiated tyre noise is measured on the four-wheel dynamometer. Six microphones are used for each tyre. Four microphones are located close to the footprint (in and out, on the inner side and on the outer side) and two microphones are located in the wheelhouse. In the laboratory, the acoustic transfer functions p/Q (interior sound pressure level due to a volume velocity source excitation at the described locations) are measured. The measure-

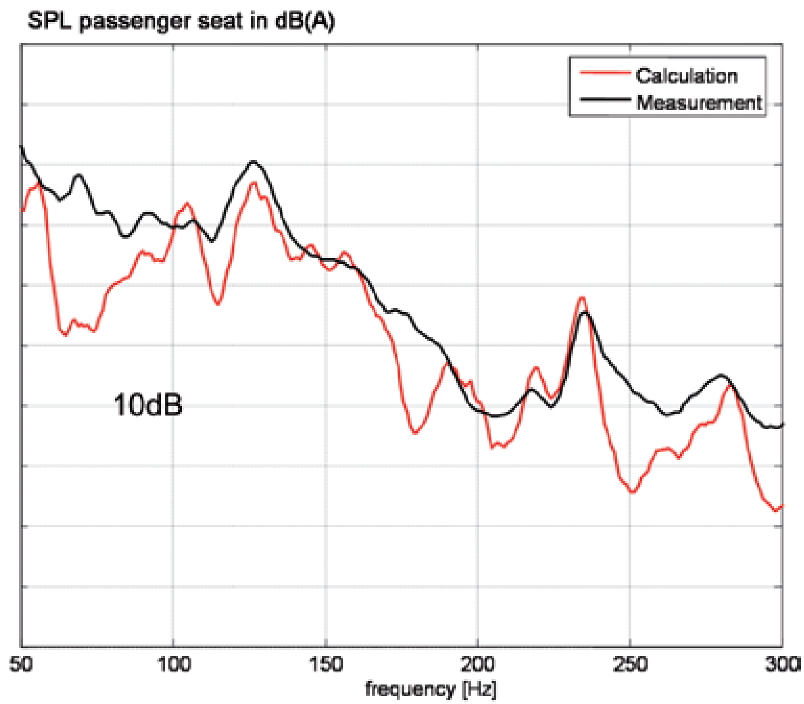


Figure 7: Result of structure-borne noise TPA

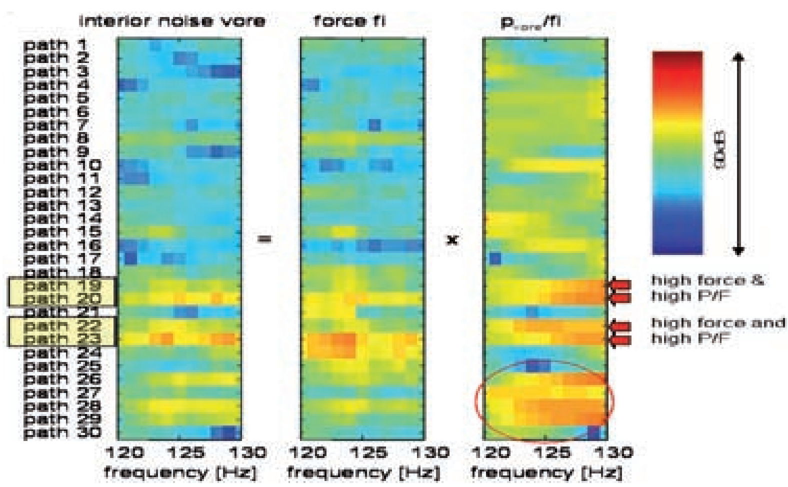


Figure 8: Structure-borne noise TPA – result of single path contributions

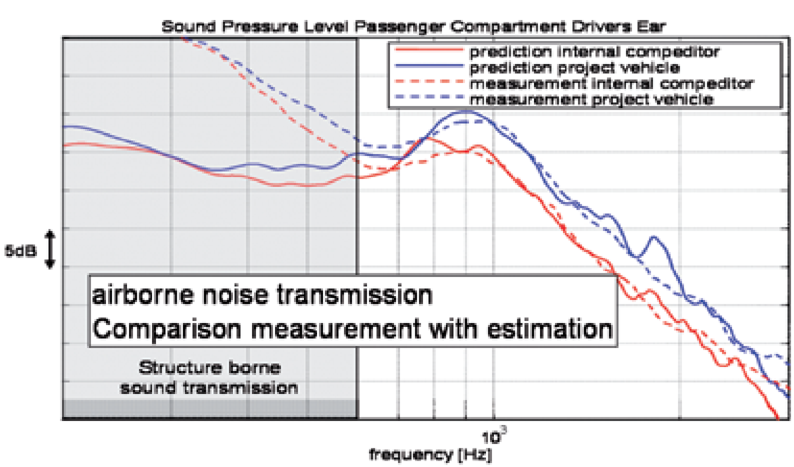


Figure 9: Result of airborne noise TPA

ments are performed reciprocally. The measured sound pressure levels radiated from the tyres are weighted by multiplication with the acoustic transfer functions p/F. The total interior noise level (for airborne noise transmission) is estimated as the summation of all single transfer paths. The result of this analysis is shown in **Figure 9**. The differences between the two cars are identified by comparison with a second car. Above 600 Hz, the characteristics of the measured curves are well represented. Below this frequency range, structure-borne noise transmission dominates over the interior noise. The analysis of all single paths is illustrated in **Figure 10**. It shows that, for the frequency range of interest around 1000 Hz, only noise transmission from the "in footprint" position is responsible. All other airborne noise transfer paths are not relevant. With regard to the measured sound pressure levels radiated from the tyres, the radiated sound is responsible for the high levels in the frequency range around 1000 Hz. The difference between the two cars is then a result of the different noise transmission behaviour of the cars, as the same levels of noise excitation are assumed for both cars. To confirm the results from this study, some encapsulation measures were applied to the wheel. The outcome of this investigation shows a good correlation between this measurements and the knowledge gained from transfer path analysis.

3 Summary and Outlook

A systematic procedure for the investigation of tyre road noise based on coherence and transfer path analysis is presented. For some specified frequency bands, the noise sources and mechanisms for airborne and structure-borne noise transmission are identified via coherence analysis. This makes it possible to narrow the scope of the phenomena and to reduce the effort required for transfer path analysis. Transfer path analysis is an efficient tool for the identification of some noise phenomena. For structure-borne noise transmission, the relevant transfer paths for the frequency range from 100 Hz to 150 Hz and the airborne noise transmission paths for fre-

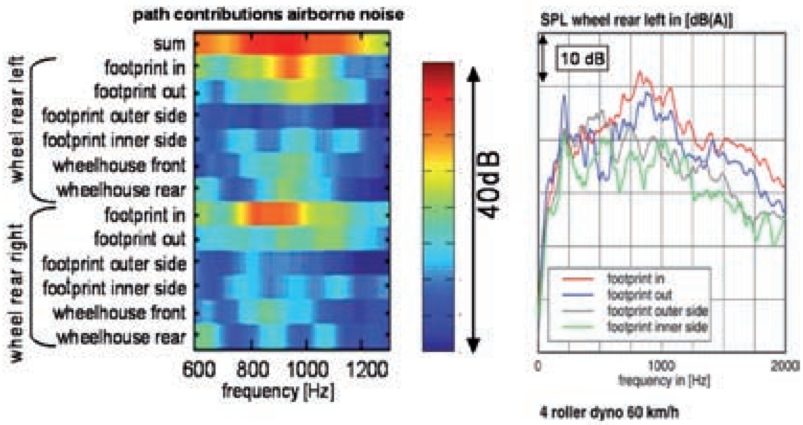


Figure 10: Airborne noise TPA – result of single path contributions

quencies around 1000 Hz can be identified. TPA is also applied for airborne noise transmission, but with a modified and simpler procedure. With regard to airborne noise, we were able to investigate some measures in the laboratory. It is possible to predict the effect of physical modifications based on FRF measurements without driving the car on real roads. Additional investigations should be carried out for the purpose of validating this method. Some interesting new applications may be possible, also in combination with other numerical, experimental and hybrid methods such as Panel Contribution Analysis [5], Statistical Energy Analysis (SEA), the Finite Element Method (FEM), and others.

References

[1] Wyckaert, K.; Hendricx, W.; van der Linden, P. J. P., LMS International: Noise and Vibration Transfer Path Analysis, Application Note, 1998

[2] Koners, G., DaimlerChrysler AG: Application of TPA including structure-borne and airborne noise, ISMA 21, Belgium, 1996

[3] Nettelbeck, C., Head acoustic GmbH: BTPA for road Noise, DAGA 2004

[4] Deges, R., Ford Werke AG; Gielen, L.; van der Linden, P. J. P., LMS International: Design implementation and validation of noise reduction on a midsize car, ISMA 21, Belgium, 1996

[5] G. Koners, DaimlerChrysler AG: Untersuchung tieffrequenter Fahrzeuginnengeräusche, 6. Int. Stuttgarter Symposium für Kraftfahrzeugwesen, 2005