CHALMERS

Developing measures against gravel noise in cars

Master's Thesis in the Master's programme Automotive Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The vehicle's tires pick up gravel which is tossed against the vehicle body. The impacts produce a disturbing noise in the interior which leads to a low quality perception. The so called gravel noise is a very specific acoustic phenomenon in automotive research and development. The complex subject matter is not much recognized by the average passenger, but almost every car manufacturer and several material and component suppliers are dealing with this disturbing noise.

After the introduction to the gravel noise several investigations in complete vehicle road testing are conducted on gravel test tracks. Once the boundary conditions of the driving tests are discussed, a sensitivity analysis is performed which reveals the, for the gravel noise relevant, surfaces at the vehicle. Benchmark measurements indicate how competitors perform acoustically in regards to gravel noise and give the basis to further discuss what a high-grade quality gravel noise is. A target value for the vehicle specifications is defined based on the findings.

Due to the high complexity and costs to achieve reproducible measurements in road tests, a suitable method to simulate the gravel noise is researched. Several approaches are investigated and evaluated. To reduce the interior gravel noise, the following section deals with the development of countermeasures. Potentials for improvements and materials are analyzed and evaluated. The identified weak spots are enhanced and a package of measures for a new vehicle is developed. The thesis is completed with a conclusion and a look into the prospects.

Keywords: gravel, disturbing noise, cars, countermeasures

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The mixture between theoretical analyses and practical testing made this thesis very interesting with time flying by. Especially the possibility to plan, perform and analyze the measurements, which means being responsible for the whole process, was challenging and interesting. Highlights were the road testing at the proofing ground in Nardò, Italy and, of course, being able to drive the unique Porsche vehicles and being allowed to participate in the product development.

Contents

1

Introduction to the gravel noise

In the premium car sector the overall driving impression is very important. A major contributor to a high quality impression is the acoustic cognition. Porsche and its customers make distinctive demands. On the one hand the engine sound should be present in certain situations to feel the sportive attributes of the cars. On the other hand the drive has to have a certain comfort which includes low rolling and disturbing noises. There, even relatively small effects like gravel noise can majorly reduce the valence and the customer's quality perception.

Gravel, chippings, stones and dirt on the street are picked up by the vehicle's tires and tossed against the body and other parts of the vehicle. The impact produces an unwanted and disturbing noise. Depending on material type and location at the body, a short impulse across the whole frequency range is the result. Especially the high frequency component is categorized as highly disturbing and imparts a degraded quality feeling. The global aim of this project is to reduce these sounds.

The complaints about a low quality interior noise caused by gravel excitation have its origin from the complete vehicle testing and introduction of new vehicles. Here the cars are evaluated down to the last detail and every drawback is revealed. The driving events either take place in Scandinavia or on racetracks in southern areas. In Sweden or Norway most times the roads are not evacuated from snow. Gravel is distributed onto the compacted snow to increase the grip. When not following the racing line on the racetrack, dirt is picked up by the car. The dirt consists of gravel, small stones and rubber debris from tires, so called pick-up. Under both driving conditions many objects impact the vehicle body and produce the disturbing noise.

1.1 Relevant frequency bandwidth

In order to analyze and work with the gravel noise it is important to understand the sound and determine the affected frequency bandwidth. Picture 1.1 shows a wavelet analysis of a vehicle driving into a gravel test track to detect the relevant frequency areas influenced by the stones colliding with the vehicle.

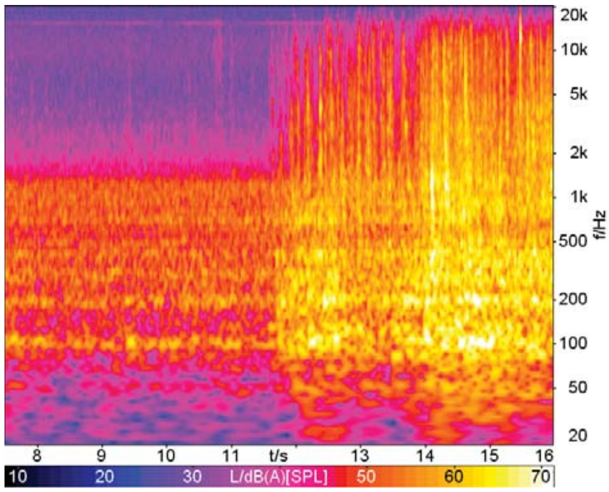

Fig. 1.1. Wavelet analysis of the gravel noise.

The microphone is located at the driver's left ear. The beginning of the gravel road is clearly visible at second 12, before a few stones already hit the vehicle. The single impacts leave impulses across the whole frequency range. The peaks are clearly visible from approximately 1.3 to 20 kHz. The base rolling noise is amplified in the lower frequency range. Visible due to the brighter colours at approximately 50 to 1000 Hz.

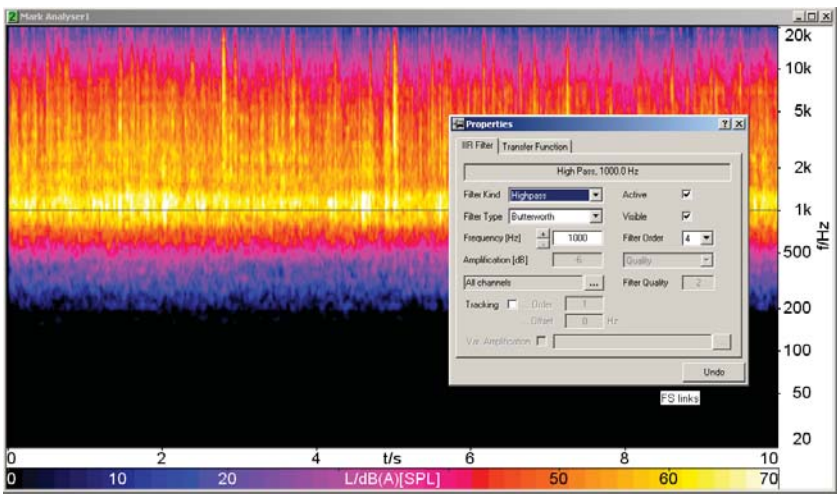

Fig. 1.2. Filtering the relevant frequency range.

In the Artemis Markanalyzer it is possible to apply filters online while listening to the recording. An example is shown in picture 1.2. By slowly moving a high pass filter up the frequency band, the disturbing sound is identified as the high-pitch part starting at about 1 kHz. The emphasized lower rolling noise frequencies are not as significant and are categorized as not disturbing.

1.2 Analysis method

The primarily used analysis method is an octave analysis with a Hanning window function, spectrum size of 4096 and an overlap of 50%. This configuration turned out to be a reasonable compromise between time and frequency resolution for the gravel noise application. Since a continuous excitation of the vehicle in the road tests is assumed, the focus is directed to the frequency resolution. The recordings are A-weighted. The relevant frequency bandwidth of 1 to 16 kHz is displayed. Depending on the application, e.g. benchmark measurements, a FFT analysis is used to get a better impression of the level differences and to achieve a clear comparison.

To further evaluate different vehicles or countermeasures and to generate a clear ranking, the arithmetic average is calculated of the 1 to 16 kHz octave levels. In contrast to the overall sound pressure level, the received singular value represents only the octaves reflecting the quality rating in regards to gravel noise and does not consist of the low frequency octaves which are determining the overall sound pressure level. The arithmetic average is illustrated in figure 1.3.

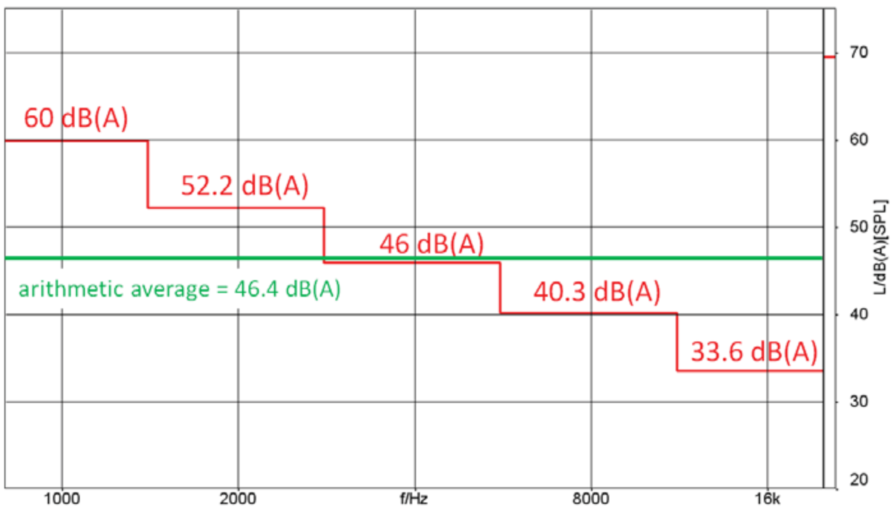

Fig. 1.3. The arithmetic average of the 1 to 16 kHz octaves.

Sound level difference

In order to emphasize the impact of the disturbing noise for example of gravel or splash water, the sound level difference between the rolling (base) and gravel noise is calculated. This evaluation approach displays directly where the sound level increases significantly or in which band width the intensification is negligible. Figure 1.4 shows the octave analysis of the two sound signals and their difference.

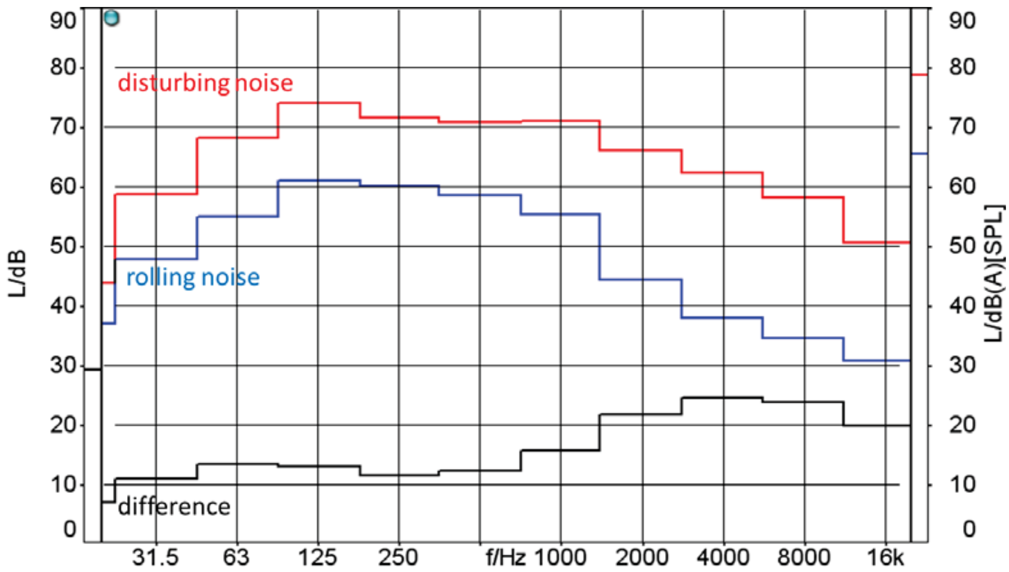

Fig. 1.4. Octave level differences.

But is this consideration valid? When driving over gravel or water the surface changes and consequently the emitted rolling noise. In this situation the disturbing noise consists of a different quantity of the base noise than measured before. Which would mean it is not reasonable to subtract the two sound levels. To justify the statement it is necessary to approach from a different point of view. The rolling noise is the noise level designed by development and expected and accepted by the passengers. Every additional sound can be regarded as unwanted and disturbing - regardless where its source is.

2

Road testing

In the following chapter the complete vehicle road testing is discussed. Picture 2.1 shows the Porsche Panamera on the gravel track at the test center in Nardò, Italy.

Fig. 2.1. The Porsche Panamera on the gravel track.

It is essential to achieve reproducible measurement results; hence the boundary conditions have to be constant. After the influences to the vehicle's interior gravel noise are looked into, a sensitivity analysis is conducted. It is determined where the gravel impacts the vehicle and what interior noise is generated. The comparison of competitors in different vehicle segments reveals the gravel noise performance of different cars. On the basis of the benchmark measurements it is discussed what a valuable gravel noise is.

2.1 Boundary conditions

The interior gravel noise is affected by several parameters. Described more precisely, the amount of stones that are thrown from the tires against the vehicle body depends on various influences. It is necessary to keep these conditions constant to produce reliable and reproducible measurements. The essential parameters are looked into more detailed.

Gravel type and grain size

Different stone types in various sizes are found on normal roads in real driving situations. However to create reasonable conditions a test track has to consist of one gravel type. But which gravel type is suitable? Several investigations, observations and video analyses have shown a crucial variance between different stones.

The test track at the test center in Nardò consists of stones with a size of 4 to 6 mm. The gravels used at the test track in Weissach are smaller and only have a grain size of 2 to 4 mm. Decisive for these choices was unfortunately the availability of the stones on location instead of prior research. The two types are shown in picture 2.2.

Fig. 2.2. The two different gravel types.

The two gravel types excite the vehicle in different ways. The bigger stones are catapulted more or less straight away from the contact area of the tire on the track. Instead the smaller stones are picked up further by the tire and released somewhere around the tire circumference. In addition, the lighter weight enables the stones to be reflected of a surface respectively to bounce between the road, tire and vehicle body. This hence leads to the excitation of different areas of the car and an altered cognition of the gravel impacts. It is assumed that the smaller stones represent the complaints from real driving situation closer. The sound is defined as sand trickling. The more distinctive impacts caused by the bigger gravels are defined as the classic gravel noise. As a conclusion, both excitation forms have to be considered which is unfortunately not always possible due to areal, time and cost restrictions. Figure 2.3 shows the interior noise level of the two different gravel tracks. The test vehicle is both times the limousine with a driving speed of 60 km/h and the shown microphone position is the driver's left ear. The effected frequency range is equal. However the excitation of the smaller stones result in higher levels except the 1 kHz octave which indicates the low pitch, hollow sound of the bigger stones.

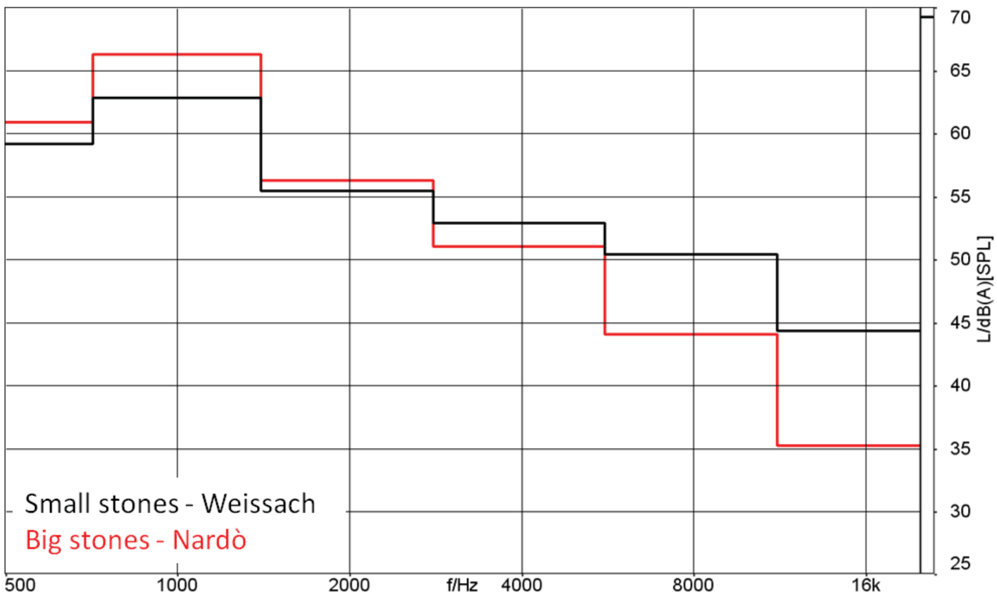

Fig. 2.3. The interior noise levels with excitation of the different gravel tracks.

Vehicle velocity

The amount of gravel and the velocity of the flying stones is coupled with the vehicle speed. To investigate the influence of the vehicle velocity to the gravel noise several tests are conducted. Below a vehicle velocity of 30 km/h stones are flying infrequently. Above a vehicle speed of 90 km/h, the safety is not assured since the track consists of a small bend where the car starts to get unstable. Figure 2.4 therefore shows the octave analyses of the gravel excitation with the vehicle velocities of 30 to 90 km/h. The illustrated microphone is located at the driver's left ear. The measurements at the positions at the driver's right ear, front passenger seat and rear right seat show analog results. To ensure the quality of the measurement results, four recordings at each speed are conducted and averaged.

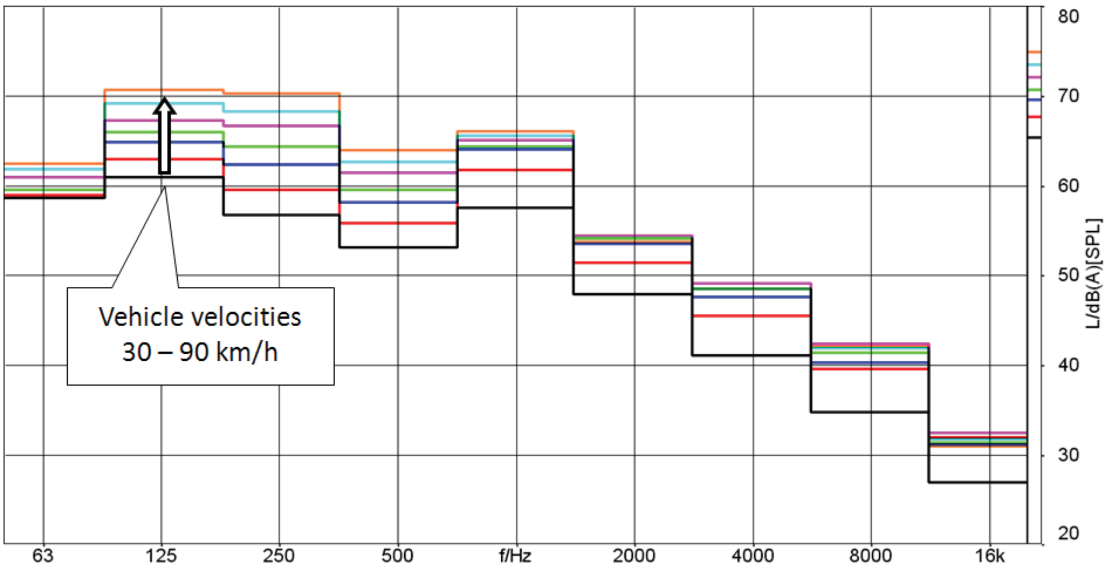

Fig. 2.4. The influence of the vehicle velocity to the interior noise level.

In the lower frequency range, specifically in the 125 to 500 Hz octaves, the differences of the vehicle velocities are clearly visible. The faster the car drives, the higher the interior noise levels result. The rolling noise caused by the rough gravel surface is steadily increased. In the relevant frequency bandwidth of 1 to 16 kHz, the differences between the velocities decrease. The velocities 50 to 90 km/h are situated very close together - approximately plus minus 1 dB per octave. Only the 30 and 40 km/h measurements are considerably lower.

60 km/h is defined as the vehicle speed for further testing on the gravel track in Nardò. It reaches same excitation levels as higher velocities and still is a safe and realistic compromise between city and overland driving speeds which means the gravels have realistic velocities.

Tires

The limousine is fitted with summer tires and winter tires to evaluate the influence of the tire type. Further in order to investigate the effect of the axles, the different tire types are afterwards fitted in mixed configuration to the front and rear axles. Figure 2.5 shows the measurement results at the driver's ear and the setup combinations. *ST* stands for summer tires and *WT* for winter tires.

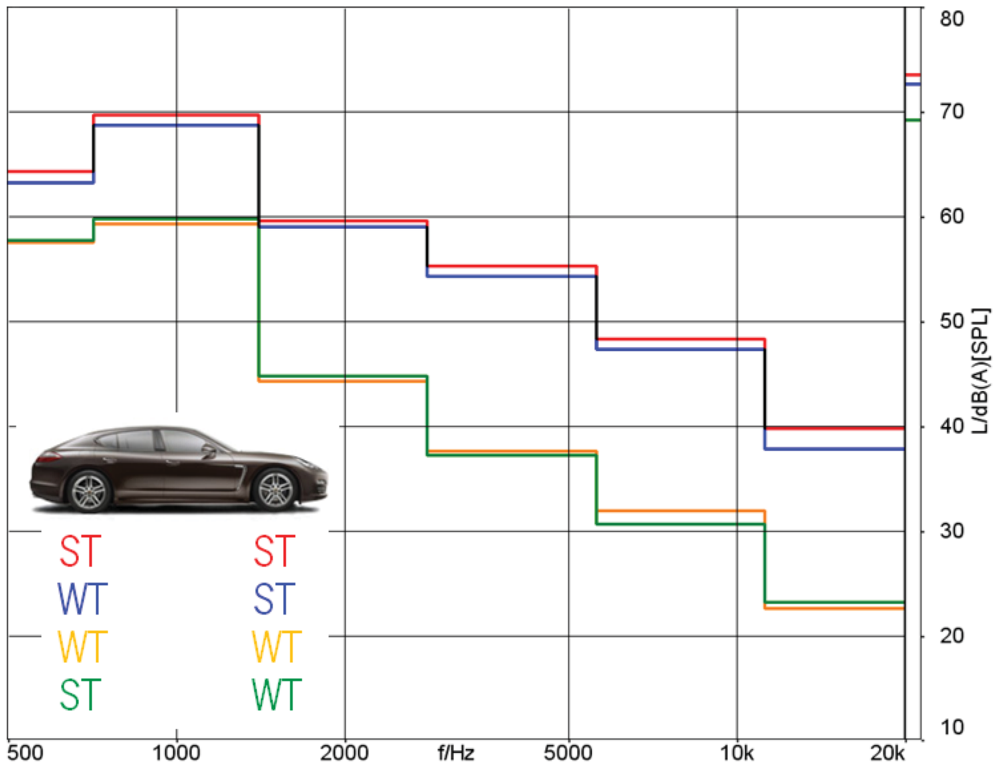

Fig. 2.5. The interior noise level in dependence of the tires.

The red graph represents the measurement on summer tires, respectively the orange graph the measurement on winter tires. The levels drop 10 dB in the 1 kHz octave and in the 2 to 16 kHz octaves about 15 dB per octave. This huge difference is easily perceptible inside the vehicle. Only a few stones impact the vehicle when the winter tires are mounted. The expectation that the structured profile of the winter tires picks up a greater amount of gravel is not fulfilled. It is assumed that the stones cut into the bigger surfaces of the summer tires which enable the stones to stick at the tire until released due to the centrifugal force. To achieve a maximum excitation of a vehicle for further investigations summer tires are used.

To identify which axles influence the gravel noise more, the front axle is fitted with summer tires and the rear axle is fitted with winter tires. The results only differ around 1 dB in the high octaves compared to the measurement with complete summer tires. When fitted the other way around, front axle with winter tires and rear axle with summer tires, the octave levels are equal to the measurement with only winter tires mounted.

As a conclusion it is possible to determine that the rear axle has an insignificant influence to the interior gravel noise. The stones tossed by the rear wheels do not impact the vehicle at acoustical relevant areas only on parts of the rear end body styling kit. The main contributor to the disturbing noise is the front axle.

2.2 Sensitivity analysis

A sensitivity analysis is performed in order to identify relevant surfaces that influence the interior gravel noise. It is necessary to find weak spots that afterwards can be treated with countermeasures. The tests are performed on the gravel track in Nardò which has a length of 300 m. With the vehicle speed of 60 km/h it is possible to receive a recording time of approximately 18 seconds per run. As mentioned before, each measurement is repeated 4 times. The average delivers reliable results with an adequate reproducibility. The vehicle is equipped with the standard measurement equipment and four microphone positions which are at the driver's right and left ear, the front passenger seat and at the rear right seat.

Fig. 2.6. The test vehicle masked with fleece.

To dampen the gravel impacting the vehicle body, the relevant surfaces are silenced with self-adhesive fleece. The material prevents an excitation of the vehicle. Picture 2.6 shows examples of the masked car.

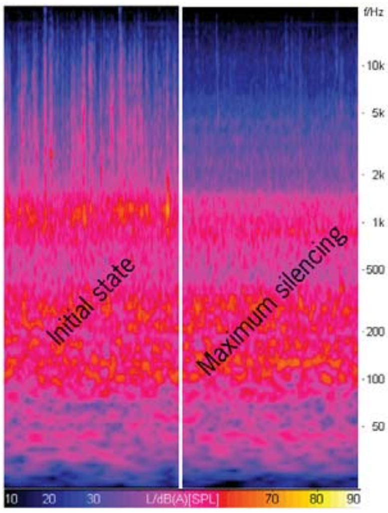

Fig. 2.7. Wavelet comparison between initial and silenced vehicle.

With subjective evaluation, it is tested if all vehicle parts have been treated. The following areas are modified with the fleece to achieve a maximum silenced car: sill panel, underbody parts, front and rear wheelhouse liner each divided into a front and rear part, rear door and rear end body styling kit behind the rear wheels. Figure 2.7 shows wavelet analyses of the initial vehicle state and the maximum silenced car. It is possible to see that the high pitch frequency parts which are relevant for the disturbing gravel noise are almost completely eliminated.

After the state of maximum insulation is achieved, each surface or so called window is opened. A measurement with the unmasked surface reveals its influence to the interior gravel noise. In order to minimize effects of the gravel track condition, each time the completely silenced vehicle is measured before a window is opened. This way a direct reference for each vehicle state is achieved. Figure 2.8 shows the influence of each window in relation to the maximum silenced vehicle. The measurement at the driver microphone position is displayed. The remaining microphones show similar results.

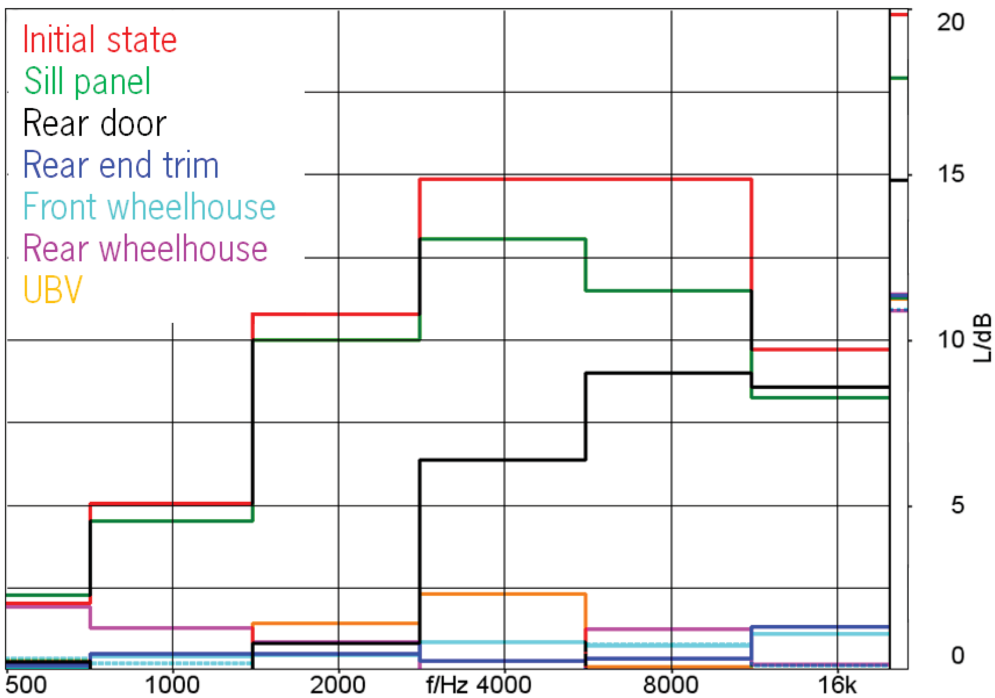

Fig. 2.8. The influence of the sections to the interior noise.

Each graph illustrates how much louder the interior noise spectrum is compared to the maximum masked vehicle. The red line represents the unwrapped vehicle in its initial series production state with the 4 and 8 kHz octaves almost 15 dB louder. The graph reveals that the sill panel is the main contributor to the interior gravel noise. The levels reach in the 1 and 2 kHz octaves nearly the height of the initial car without treatment. The gravels patter directly from the tire onto the lower sill panel area. In the 4 to 16 kHz octaves the influence of the rear doors is also significant. Not many gravels impact the rear doors, but the few ones impacting directly the sheet-metal influence the octave analysis and the aural impression immense. The remaining sections which are the front and rear wheelhouses, the underbody panel and the rear end trim are not of significant relevance. The level increase resides below 2.5 dB.

In order to examine the sill panel more detailed, it is divided into a front and rear part at the B-pillar. Measurements are performed with each section unmasked. The rest of the vehicle is still covered completely. Figure 2.9 shows the interior octave levels at the driver microphone position.

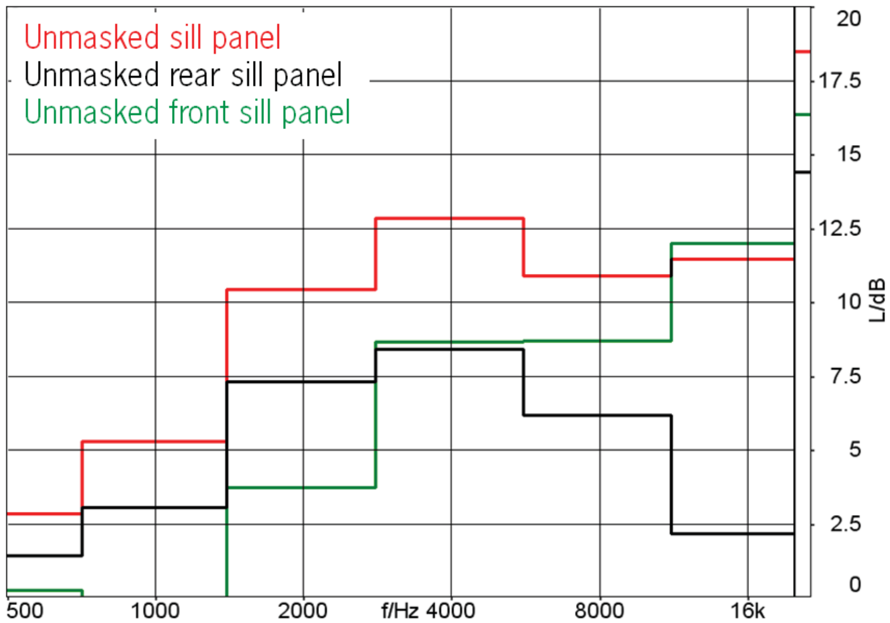

Fig. 2.9. The influence of the sill panel to the interior noise.

The graphs indicate that the rear sill panel causes higher interior noise levels in the 1 and 2 kHz octaves. Subjectively more impacts occur, but resulting in a rather low-pitch noise compared to the front part of the sill panel. Here the 8 and 16 kHz octaves are dominant and fewer stones hit the vehicle. The microphone at the rear passenger position shows analog results with an expected slight level increase of the rear sill panel. A possible countermeasure should hence treat the whole sill panel to lower all frequency bands.

With the excitation of the bigger gravel at the test center in Nardò, the sill panel and the rear door are the main contributors to the interior disturbing noise. But is this also applicable for the excitation with the small stones? Which differences occur and which gravel track rather reflects the complaints? Further investigations have to be conducted to receive a clear overview.

2.3 Benchmark

The Porsche brand has its origin in motor sport and the vehicles today are still highly connected to the racing background. The main focus is performance, agility and lightweight also in the rather new car segments of the sports utility vehicle Cayenne and the four-door sports limousine Panamera. In these automotive sectors the competitors usually have their main emphasis on different values. Attributes in directions of comfort are in focus.

In the following section, a comparison between several competing four dour luxury limousines is performed. The boundary conditions, measurement equipment and measurement procedure is equal to the one defined at the sensitivity analysis. The competitors are measured each time directly after a measurement with the reference vehicle. Figure 2.10 lists the participating vehicles. Due to time and matching issues it was not possible to use the same set of tires for each vehicle in order to eliminate the influence of the different rubber components and sizes. Otherwise, the tires belong to the complete vehicle and how it performs in regards to gravel noise, which allows the comparison between the vehicles with the different fitted tires. The tire sizes and types among the participants spread widely with no correlation to a certain brand standing out. Further it is stated that most vehicles are fitted with textile wheelhouse liners in the front and rear which gives acoustical advantages. This also indicates the luxury class since the material is more expensive than injection molding plastic parts.

Vehicle	Tires (Summer)		Textile WHL f/r
Audi S7	20“	Pirelli Pzero	X / X
Audi A8L W12	20"	Pirelli Pzero	X / X
BMW 640i Grand Coupé	20"	Dunlop SP SportMaxx GT	X / X
BMW 550i GT	19"	Dunlop SP SportMaxx GT	X / X
BMW 730d	19"	Pirelli Pzero	X / X
Mercedes-Benz CLS 350 Shooting Brake	18"	Yokohama AdvanceSport	– / X
Lexus GS450h	19"	Bridgestone Potenza	– / X
Bentley Mulsanne	21"	Dunlop SP SportMaxx GT	X / X
Reference II	20"	Michelin Pilot Sport	– / X
Reference	18"	Pirelli Pzero	– / X

Fig. 2.10. The benchmark vehicles.

The luxury class limousines are designed to chauffeur people in the rear seat; hence the following analyses are related to the rear right passenger seat microphone. The microphones in the front show analogous results in ranking, although the difference to the reference vehicle is smaller. This indicates that the insulation in the reference car tends to be better in the front. Figure 2.11 shows the interior octave levels in relation to the reference measurements.

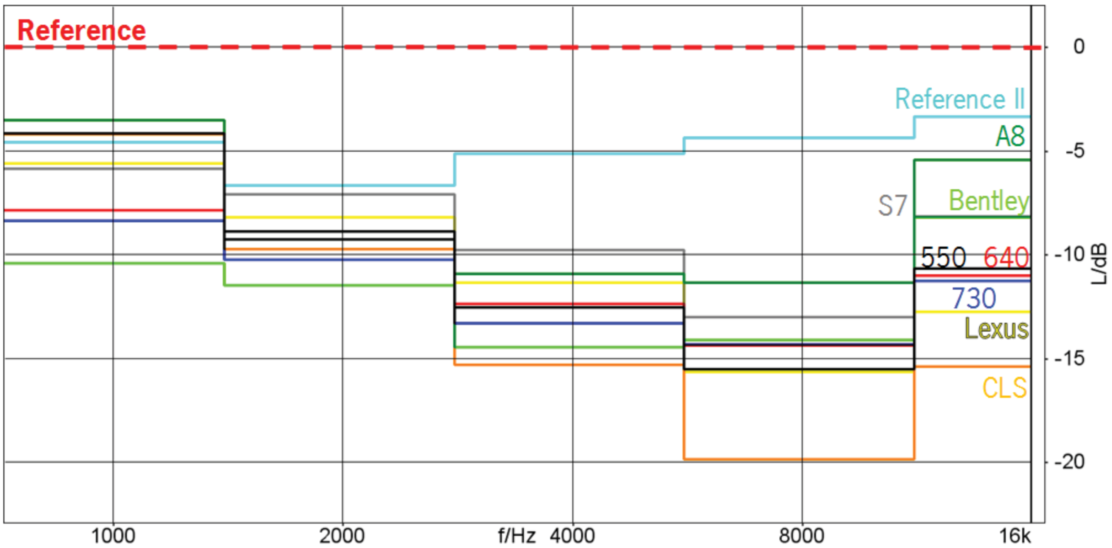

Fig. 2.11. The difference of the interior octave levels to the reference car.

The reference vehicle is represented by the x-axis at 0 dB. The octave levels of every participating vehicle are situated in the negative region which means that they are quieter. The 8 kHz octave level of competitor 6 is almost 20 dB lower than the reference. The reference vehicle number 2 is about 5 dB quieter through the relevant frequency range. The remaining vehicles position between these two examples. As explained in chapter 1.2, the arithmetic average of the 1 to 16 kHz octaves is calculated to achieve a clear ranking. Figure 2.12 shows the results.

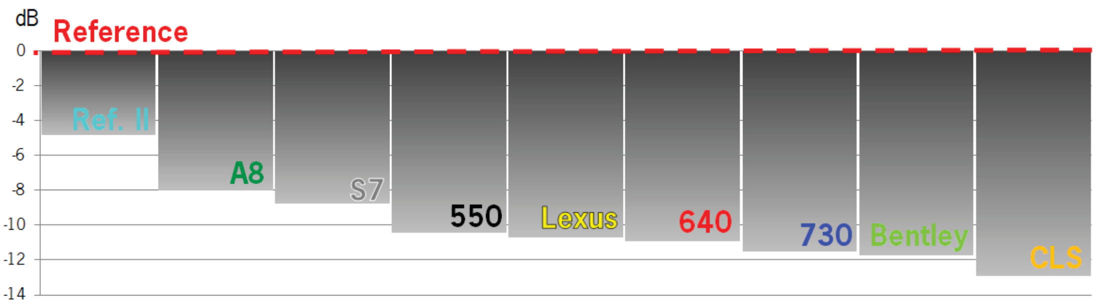

Fig. 2.12. The difference of the average octave levels to the reference car.

As indicated before, competitor 6 ranks best. Most of the competitors achieve a value around 10 dB lower than the reference vehicle at the microphone position at the rear passenger seat. Looking at the front microphone positions, the gap between the reference vehicle and participants is smaller, even with competitor 2 being 1 dB louder.

The question remains: Why do some vehicles perform acoustically much better in regards to gravel noise? Do less stones impact the body or are the damping and countermeasures more advanced? In order to find out the gravel impacts are counted manually with the help of the wavelet analyses. Picture 2.13 shows a wavelet analysis of each vehicle and the according percentage of gravel impacting the vehicle in relation to the reference vehicle.

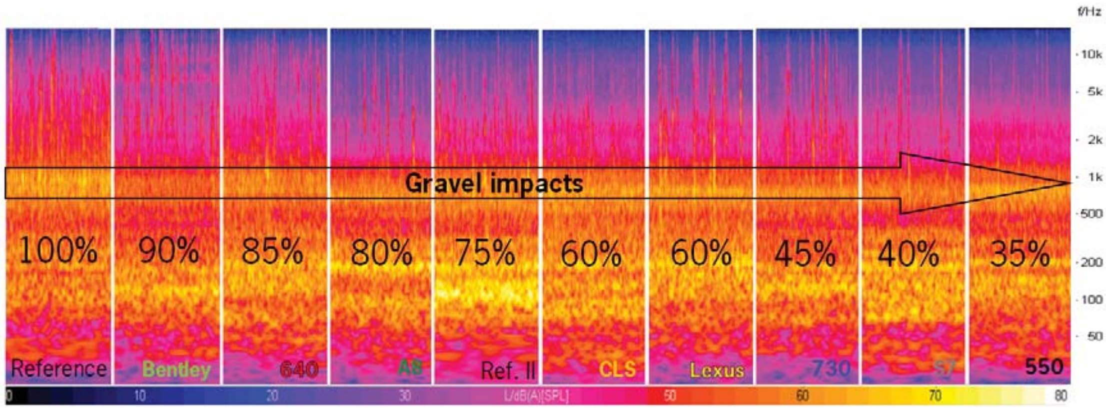

Fig. 2.13. The wavelet analyses and according number of gravel impacts.

The figure illustrates that all participating vehicles have fewer gravel impacts than the reference vehicle. The number goes down to approximately one third at competitor 4.

In correlation with the measured interior octave levels, figure 2.14 is generated. With the help of the graph, the participants are categorized. Cars achieve a low interior noise either because only a few stones impact the body, or although a lot of objects hit the vehicle, advanced insulation measures or acoustically favorable surfaces prevent the noise to propagate into the interior which also leads to a low interior noise level. On the other hand there are vehicles that throw a lot of gravel impacting itself which consequently leads to a loud interior noise or only a few stones impact unfavorable surfaces, in general sheet metal, which generates a high pitch, surrogating low quality interior gravel noise.

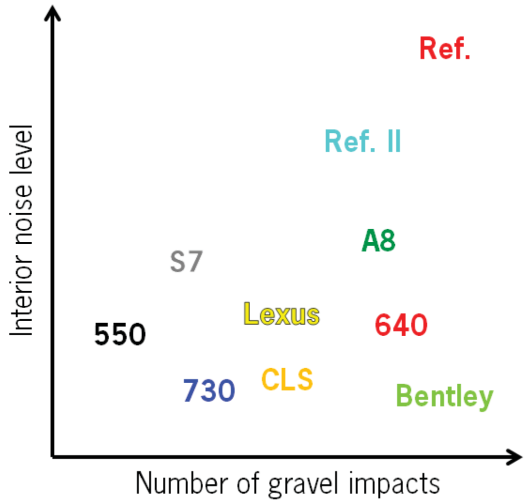

Fig. 2.14. The relation between gravel impacts and interior noise level.

But reflect these objective measurements the subjective passenger impression? In order to find out, the recordings are evaluated by acoustic experts. To prevent affection for a certain company influence the participants, the sound files are not labeled. The participants were asked to rank the cars from valent to not valent. Figure 2.15 shows the results. To achieve an easier overview and identify tendencies, lines connect the same vehicles.

	Participant 1	Participant 2	Participant 3	Participant 4
1	S7	S7	550	550
2	A8	CLS	S7	CLS
3	Bentley	550	Bentley	S7
4	550	A8	A8	Bentley
5	CLS	Bentley	CLS	A8
6	Lexus	640	Lexus	730
7	730	730	730	Lexus
8	640	Lexus	Ref. II	640
9	Ref. II	Ref. II	640	Ref. II
10	Ref.	Ref.	Ref.	Ref.

Fig. 2.15. Subjective evaluation of the benchmark vehicles.

The reference car is ranked last by every expert. The remaining vehicles alternate between different positions; however a car is either rated on position 1 to 5 or 6 to 10 so that tendencies are clearly visible. Considering the objective measurement results, it is noticeable, that the acoustic performance with gravel excitation is correlated to the amount of stones that impact the vehicle as well as to the interior noise level. Obviously if there is only little excitation, it is not possible to receive a high interior noise, followed by a bad evaluation. Further the acoustic analyses of several vehicles have similar results, but the aural impression is different. Competitor 1 is subjectively evaluated very well although the interior noise levels are relatively high. The gravel impacts are infrequent, which leads to the conclusion that the number of impacts is a decisive factor for the subjective gravel noise perception.

Consequently it has to be stated, that the objective measurements and subjective evaluation results are connected but not as a clear and continuous as eligible.

Defining a target value

In the technical specifications of a vehicle every possible target value is defined. These values lead a direction in the product development process and reveal in which engineering sections improvements have to be achieved and which vehicle properties are on target. The simple instrument directly exposes drawbacks and enables to steer resources and to focus on certain topics. Target values are derived from preceding models and competing vehicles.

The difficult controllable boundary conditions and hence the restricted reproducibility make it complicated to define an absolute target value in regards to gravel noise performance. The changing track conditions and vehicle properties, e.g. the tires, make it impossible to asses if a project reaches an absolute target value during the complete development process. In combination with another benchmark comparison in a different vehicle section, a draft of a target value definition for gravel noise performance is defined for the first time.

Each participating vehicle is measured on the prior defined gravel track directly after a reference vehicle to minimize the influence of the gravel track. The difference of the average of the 1 to 16 kHz octaves of the interior noise spectra is calculated, as explained in section 1.2. Figure 2.16 shows the measurement results for 6 competing SUVs for the front and rear microphone position.

Fig. 2.16. Defining a target value.

The reference vehicle equals the 0 dB line. The values show at the front microphone, that three competitors are louder, the VW Touareg is on the same level and the Range Rovers have lower interior noise levels. The reference vehicle performs worse at the rear recording position, which is indicated by the comparing levels shifting towards the negative respectively quieter range.

The target value at the front is defined as -1 dB respectively in the rear as -2 dB to the reference measurement, which means the acoustic performance has to be improved more in the rear compartment. The values are illustrated with the dashed blue line in figure 2.16. It has to be pointed out again, that these levels are differences to the reference vehicle of average octave levels. For reliable and comparable measurement results it is important that the reference vehicle remains the same for further evaluations.

3

Experimental simulation

The evaluation of complete vehicles or selective countermeasures in regards to gravel noise is complicated. The stones colliding with the vehicle in customer-close driving operation are random events and not continuous. The boundary conditions are very unstable and it is difficult to achieve the necessary reproducibility for objective measurements. The installation of a gravel stone test track with a reasonable length is connected with noticeable effort and costs. Due to areal limitations at the Porsche research and development center in Weissach it is not possible to set up a permanent gravel stone test track. The available test track at the test center in Nardo, Italy is far away and for a quick evaluation or comparison of vehicles or modifications connected with high effort and costs.

Therefore in this part of the thesis a suitable method to evaluate a vehicle's characteristic with gravel or gravel like excitation is researched. Several excitation methods are investigated and compared.

3.1 Excitation methods

In the following section the different excitation methods to simulate the gravel noise are described. Several experiments are conducted in order to assess the suitability.

3.1.1 Impulse hammer

To better understand the mechanism from the gravel impact to the noise at the driver's or passenger's ear and to evaluate the gravel noise critical areas, vibro-acoustic transfer functions are determined. The transfer path is a combination of structure-borne and air-borne paths which means the sound propagates through solid structure as well as through air. A transfer function, also known as frequency response function, describes the relationship between an input signal and an output signal. It is possible to assume that the vehicle is a linear and time invariant system.

Two microphones made by the company Bruel&Kjaer are installed inside the vehicle. One on the driver position and the other one on the left back seat since all measurements are performed on the left side of the car. An accelerometer made by the company Deltron is placed on the rail of the driver's seat. The data acquisition equipment consists of a Head Squadriga as frontend and measurement computer with the software Head Recorder and Head Artemis. To excite the vehicle, a PCB impulse hammer with an integrated force transducer is used. Figure 3.1 shows the microphone setup, measurement points and the accelerometer.

Fig. 3.1. Measurement setup.

The following procedure is defined for the measurements: For each test point 10 hammer hits are averaged. The recordings are automatically started when the hammer sends an impulse and are stopped after 0,185 seconds. This enables a continuous and constant hammering and leads to an easy to analyze recording. The vehicle parts of interest are analyzed; particular surfaces are rasterized more detailed.

The Software Head Artemis is used to analyze the measurements. The analysis tool *Transfer Function DFT* basically divides the sound pressure recorded inside the car (output signal) by the force detected by the impulse hammer (input source). After a Fast Fourier Transformation the frequency spectrum is shown. In order to get a clearer information, the signal is smoothened. Figure 3.2 shows the force signal from the impulse hammer, the sound pressure response signal and the calculated vibro-acoustic transfer function.

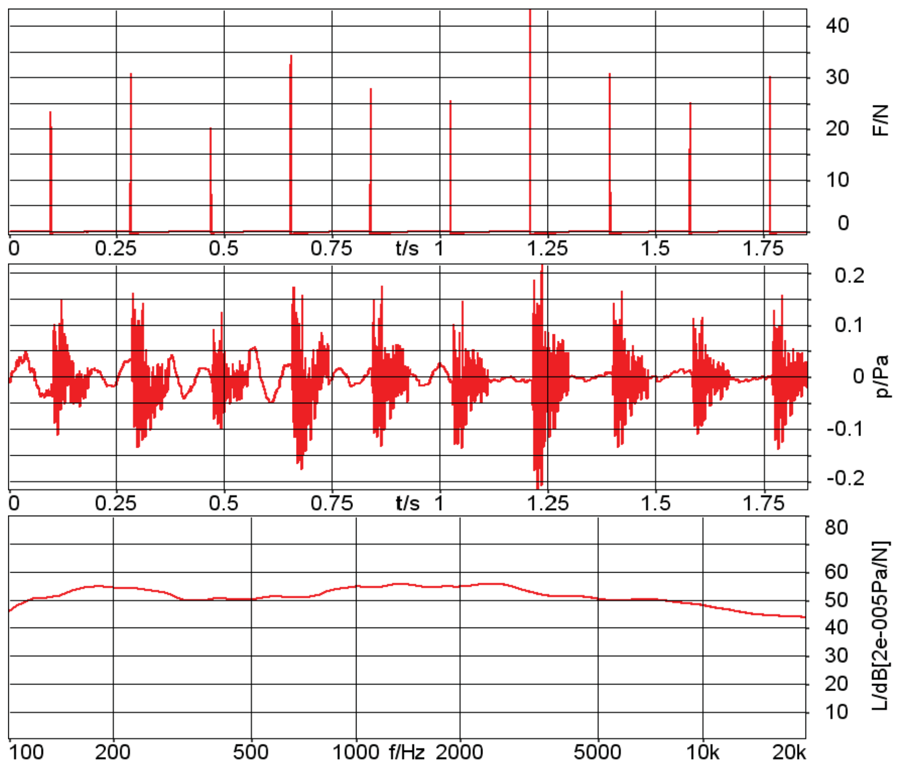

Fig. 3.2. Transfer function signals.

In a first assessment the impulse hammer method is tested of reproducibility, further the influence of magnitude and alternation of the hammer force is analyzed. Two test points at the wheel house liner are measured five times also with implicit alternated hammer force. The results are shown in graph 3.3.

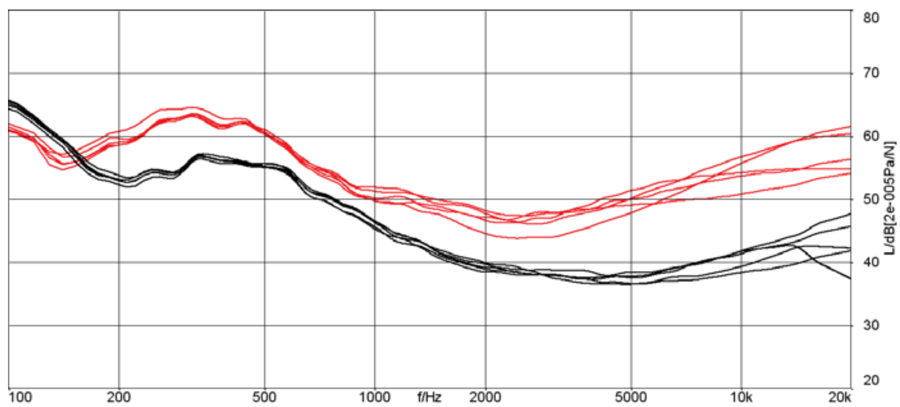

Fig. 3.3. Transfer functions reproducibility.

The characteristic of the transfer functions remains equal, although level deviations in a range of plus minus 3 dB can be recognized in higher frequency areas. It is possible to assume that the reproducibility with constant boundary conditions is given. An influence of the hammer force is not detectable. This further confirms the assumption that it is dealt with a linear time invariant system.

The transfer functions of the areas of interest are determined. The front and rear wheelhouse, body sill and underbody are analyzed closely. Figure 3.4 shows the front wheel house divided into sections with the corresponding vibro-acoustic transfer functions. The green part is the edge of the outer front fender. Blue and yellow, not to be mistaken with the yellow brake caliper, represent areas direct on the chassis. The red part is the wheelhouse liner, made out of plastic. The transfer function of each measuring point is shown in the upper graph in figure 3.4. The graphs of each surface spread widely, influenced for example if the position is located near a mounting point or further to the center of a part. Still it is possible to recognize curves with the same characteristic. To be able to easier analyze and evaluate the different areas, the energetic average is calculated and displayed in the lower graph of figure 3.4.

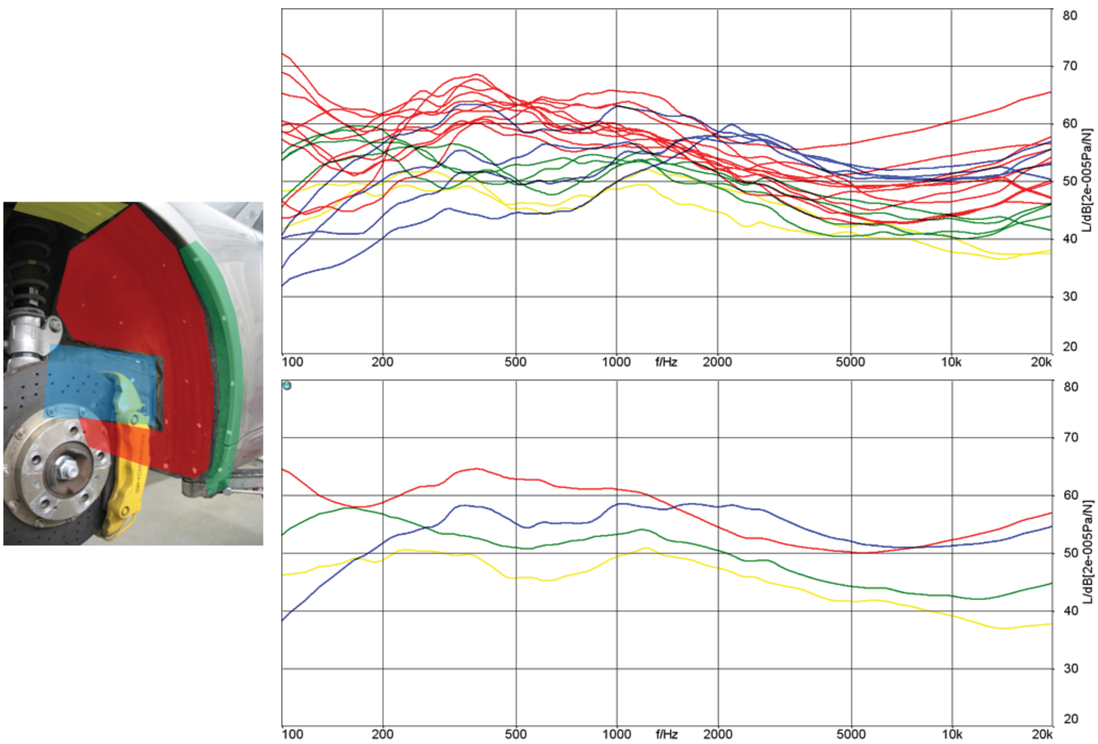

Fig. 3.4. Front wheelhouse transfer functions.

The plastic wheelhouse liner represented by the color red is prominent in the lower frequency range and on the same level as the blue chassis part in higher frequencies. The edge of the outer front fender and the upper, yellow chassis part follow in importance. It has to be taken into account, that the probability of gravel hitting the upper area and the small edge of the outer front fender is smaller than the central liner and chassis area. Further, the possibilities to implement measures within these parts are more likely and more realistic.

The sill, as one of the main contributor to the gravel noise, is divided into several areas to evaluate their contribution. The side of the sill is separated into the sections with and without antichip coating. As shown in figure 3.5 colored in blue and red. The area on the outer fender panel which already is covered by a foil against gravel damage is marked in green. The part of the sill on the underbody is colored in black. Again, the different measuring points on each surface vary. Tendencies, for example that sill side and underbody is prominent in transmitting high frequencies, are noticeable. A clear comparison and evaluation is only possible when calculating the average.

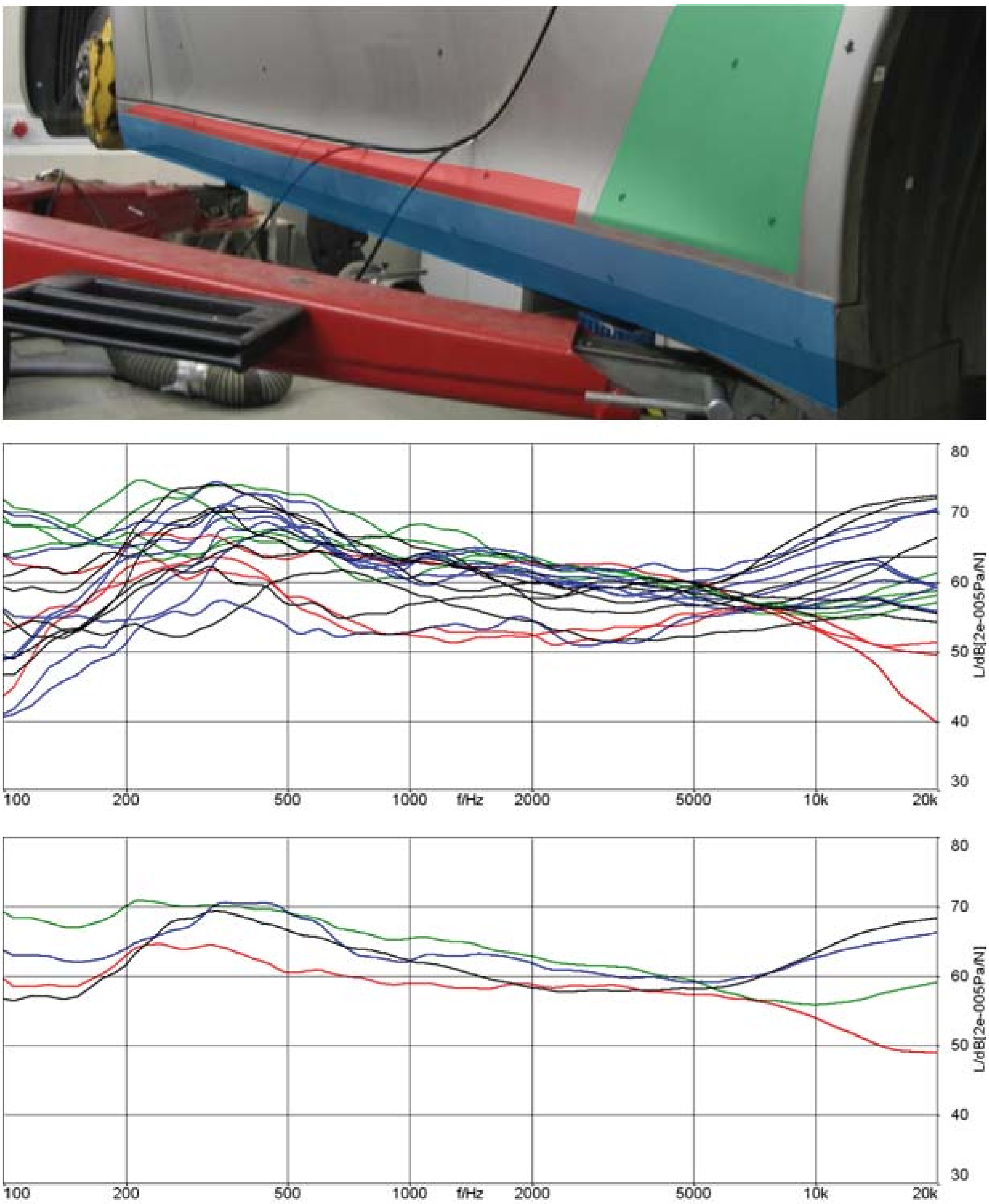

Fig. 3.5. Sill panel transfer functions.

The rear wheelhouse is fully open. Due to missing necessity, lightweight design and cost reasons there is no wheelhouse liner in the test vehicle with rear engine. Main parts of the exhaust system are directly behind the wheel and exposed to water and dirt which leads to the assumption that this is a main contribution to the gravel noise. Figure 3.6 shows the rear wheelhouse and the related vibro-acoustic transfer functions. The wheelhouse is divided into the following sections: edge of rear-end trim in green, mount of rear-end trim in red, rear muffler colored in black, several exhaust parts and mounts in yellow and upper chassis area represented by blue.

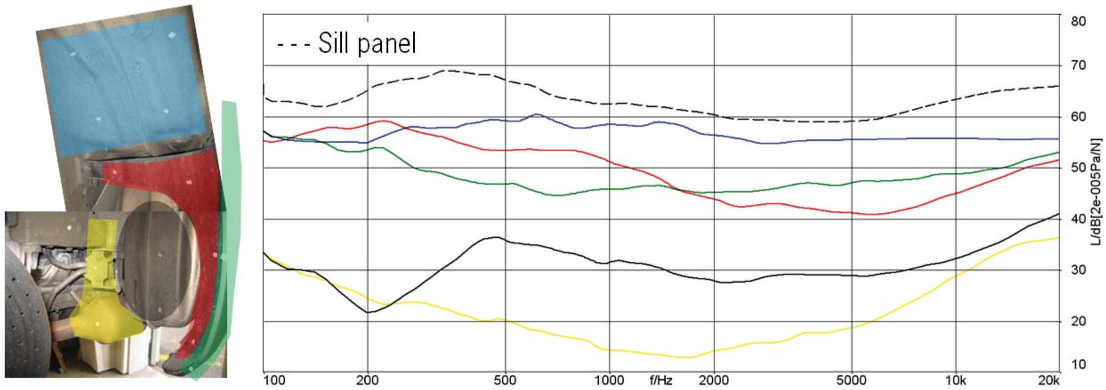

Fig. 3.6. Rear wheelhouse transfer functions.

The diagrams show that the exhaust parts including the rear muffler transmit clearly less sound, about 10 to 20 dB over the whole frequency range, than the other areas. The reason for this is the support of the exhaust system which acts as an acoustic encapsulation. The most dominant transfer path in the rear wheel house is the upper chassis part with its direct connection to the passenger cabin.

The last area which is looked at is the underbody. Most of the underbody is covered with panels because of aerodynamics and corrosion protection. The different sections are selected after these covers. The seat pan, where the chassis has only a coating and no cover panel, and the underside of the sill are separately measured. Figure 3.7 shows the different sections and their transfer functions. The rear panel transmits mostly lower frequencies in contrast to the plastic cover at the end of the sill which contributes more in the higher frequencies. The almost directly exposed seat pan is apparent in the mid frequency range.

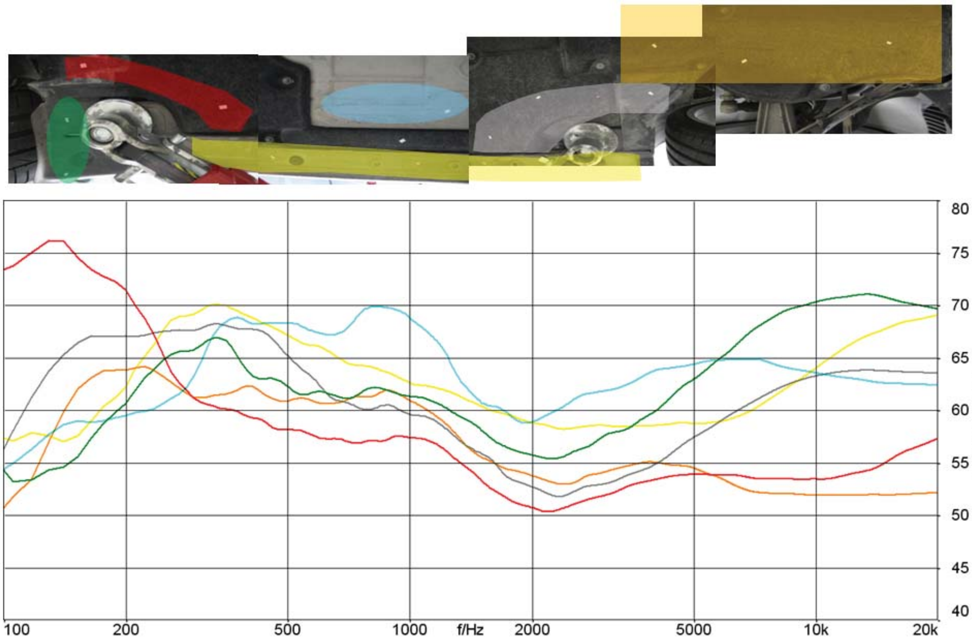

Fig. 3.7. Underbody transfer functions.

As mentioned before, the open rear wheelhouse leads to the assumption that stones are able to impact directly the exhaust system. In order to clarify the contribution of the exhaust system to the gravel noise, several measurements are conducted. Further the vibro-acoustic transfer function of the exposed rear axle transverse link is measured. Figure 3.8 shows the link, exhaust system and corresponding transfer functions. As a reference the average transfer function of the sill sections is drawn in blue. The transfer functions from the exhaust system and link are more than 20 dB lower than the ones from the sill and it is possible to conclude that the influence to the gravel noise inside the vehicle is low.

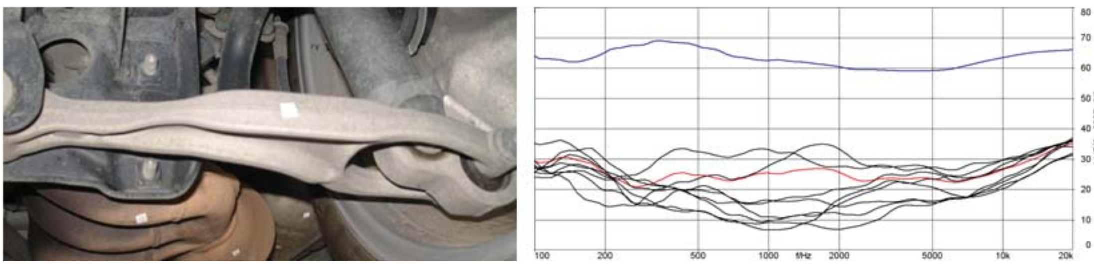

Fig. 3.8. Exhaust system and link transfer functions.

After regarding the vehicle's parts which contribute to the gravel noise each for its own, a general comparison is carried out. Figure 3.9 shows the average of each section.

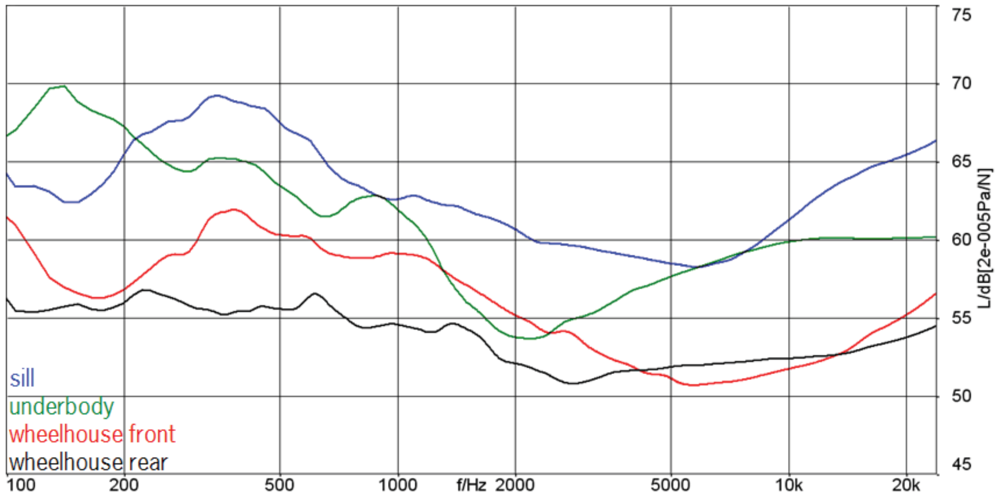

Fig. 3.9. Comparison of the transfer functions.

The measurements show that the sill has the most dominant transfer function followed by the underbody. Situated below are the front and rear wheel house. It has to be noted that in these comparisons the probability of a stone impacting each surface is not considered. Thus the actual influence of the regarded areas to the gravel noise can differ from this ranking.

In order to test if the vibro-acoustic transfer functions determined with the impulse hammer are suitable to detect and evaluate vehicle modifications to alternate the gravel noise, the following experiments are conducted. The front wheel house cover is fitted with an Aluminum-Butyl layer with the weight of 2,4 kg per m^2. This countermeasure is not realistic and suitable for production because of weight and cost reasons. It is only to achieve a measurable delta and enable an evaluation of this method. The transfer functions are determined before and after the modification. Figure 3.10 shows the original and modified front wheel house cover, the test marks and the corresponding transfer functions.

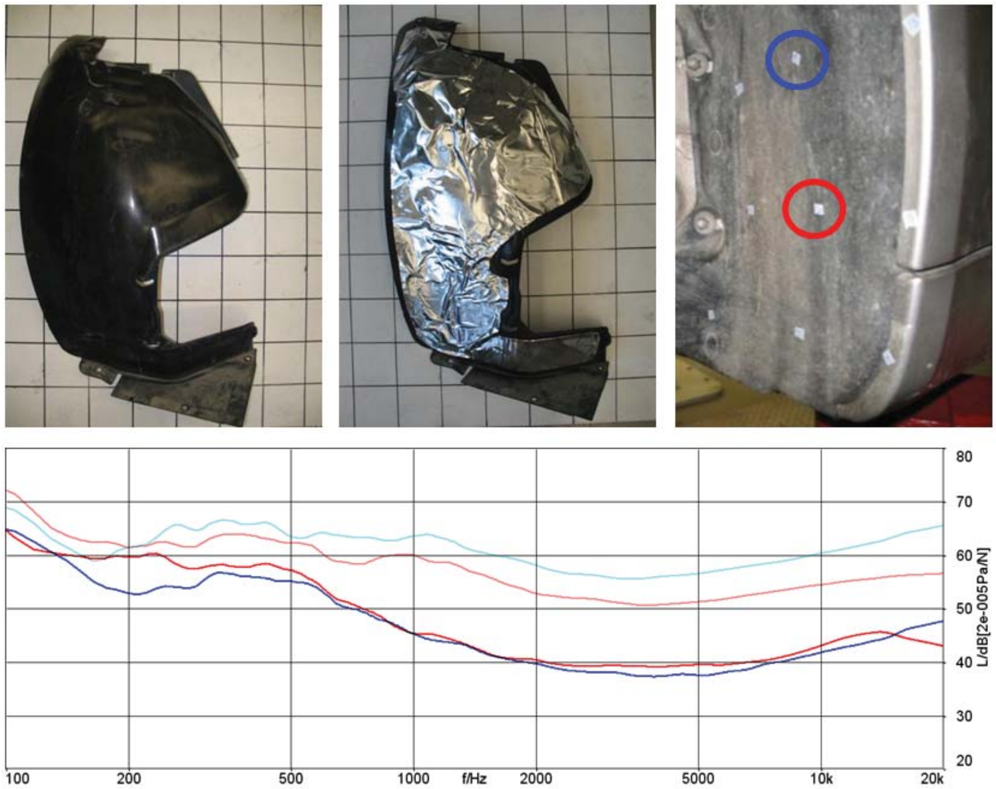

Fig. 3.10. Modification of front wheelhouse liner.

The lighter color shades represent the initial state, the deeper color shades the modification. The transfer functions of the two measured points on the wheel house cover have a similar characteristic with an almost constant delta of 4 to 6 dB in the frequency range of 1 kHz to 18 kHz. With the modification the transfer functions drop about 10 dB respectively 15 dB in the mentioned frequency bandwidth. It is assumed that the Alubutyl achieves the maximum possible damping and thus the transfer functions of the two measuring points move closer together.

In order to assess the influence of the Alubutyl beneath the wheel house liner, which is almost the maximum potential of a countermeasure in this vehicle area, the modified car is subjectively evaluated. Driven on normal roads, it has to be stated that there is only a minor effect to the whole interior noise and the driver's gravel noise perception. It must be considered that as always in automotive acoustics the whole system has to be looked at. A single countermeasure most times has only a small influence.

3.1.2 OmniSound source

The following section deals with the reciprocal determination of the vibro-acoustic transfer functions. The tests are performed with a Bruel&Kjaer OmniSource Type 4295 and Polytec Laser-Doppler-Vibrometer PSV400.

The Laser-Doppler-Vibrometer enables a contactless detection of vibration of objects with the help of the Doppler Effect. A helium neon laser beam is divided. One part remains inside the scanning head; the other part is reflected by the measuring object where the frequency is modulated in relation to the object's motion. A time-dependent interference pattern is generated when superposing the two beams which allows the conclusion to the object's displacement respectively velocity and acceleration.

The vehicle is excited with the OmniSource; a sound source with a certain orifice to emit the sound equally in all directions. A pink noise that covers the whole frequency range is used as a signal. The sound source is placed inside the vehicle at the driver's ear position to assure to determine a matching vibro-acoustic transfer function. A reference microphone is positioned 10 cm away from the orifice in the middle of the driver's seat.

In a first experiment the power of the OmniSource is analyzed and evaluated. Therefore two microphones are placed in front of the sound source - one directly aiming onto the orifice, the other aligned in 90°. Picture 3.11 shows the test setup in a semi-anechoic chamber.

Fig. 3.11. OmniSource test setup.

The microphones are moved away from the source in steps of 10 cm. Each time a measurement is done. A pink noise with the frequency range of 20 to 20.000 Hz is used as signal. The top graph in figure 3.12 shows the octave spectra. The black lines are the two reference microphones build inside the sound source. Red represents the 0° microphone and blue the 90° microphone with the distance 0 cm, 10 cm, 20 cm, 30 cm, 40 cm and 50 cm beginning with the top line. The graph below illustrates the octave band differences between the 0° and 90° microphone for each measured distance.

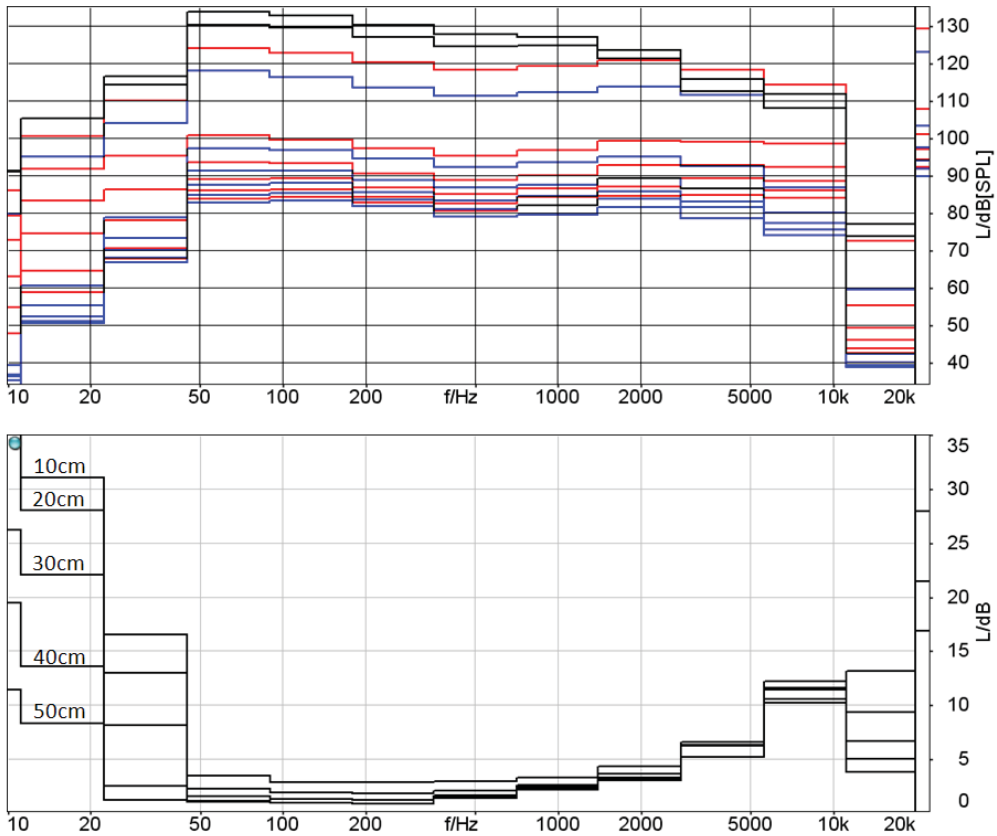

Fig. 3.12. OmniSource test measurement results.

As expected, the levels decrease with increased distance. The levels of the octaves drop from approximately 130 dB to 80 dB in the frequency range of 60 Hz to 10 kHz within the distance of 50 cm. More important is the difference between the two microphones. The results show a small deviation between 50 and 5000 Hz between the 0° and 90° microphones in the distances of 10 to 50 cm. The source emits the sound equally in this frequency range. The deviation in the 4 kHz octave is with 5 dB just acceptable. Below and above this bandwidth the deviations are too immense to achieve reliable measurements conditions. It has to be considered that if the excitation frequency range is already restricted, the receiving frequency response cannot exceed these limitations. The gravel noise relevant bandwidth of 1 to 16 kHz is not covered completely with the capacities of the sound source. It has to be evaluated if the method is still applicable.

In a first setup the Laser-Doppler-Vibrometer is directed to the driver's side window. To improve the reflection of the laser beam, the window is sprayed with chalk. Since the sound source is directed towards the window, this setup should show the maximum possible excitation of the vehicle. Picture 3.12 shows the Laser-Doppler-Vibrometer, the OmniSource and reference microphone and the laser beam aimed at the chalked window.

Fig. 3.13. Laser-Doppler-Vibrometer test setup.

Figure 3.14 shows the measuring points at the driver's window and the results. For each point three measurements are performed and the average is calculated. The green points indicate a valid measuring; the grey ones an optimum measurement result. The sound pressure level of the reference microphone is plotted against the frequency in the upper graph. The graph below shows the acceleration over the frequency at the driver's window.

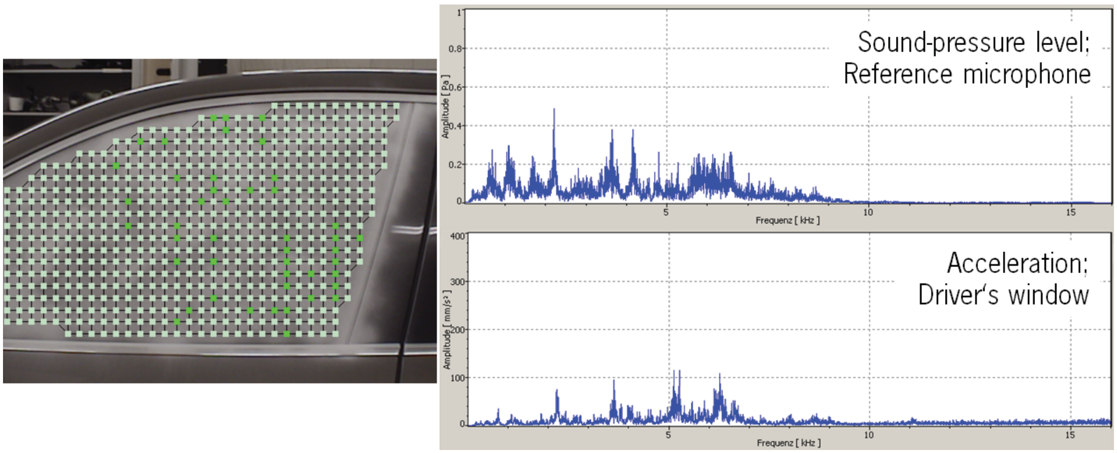

Fig. 3.14. Laser-Doppler-Vibrometer measurement results.

The deviation respectively acceleration of the windows is relatively small and only, as expected, in the frequency bandwidth up to 7 kHz. In order to get more energy into the vehicle body, the sound source is replaced by a Pioneer amplifier and JBL loudspeaker placed onto the passenger seat and rear right seat pointing to the window. Again the window is in the direct sound propagation paths. The speakers, the sound-pressure level of the reference microphone and the acceleration is shown in figure 3.15.

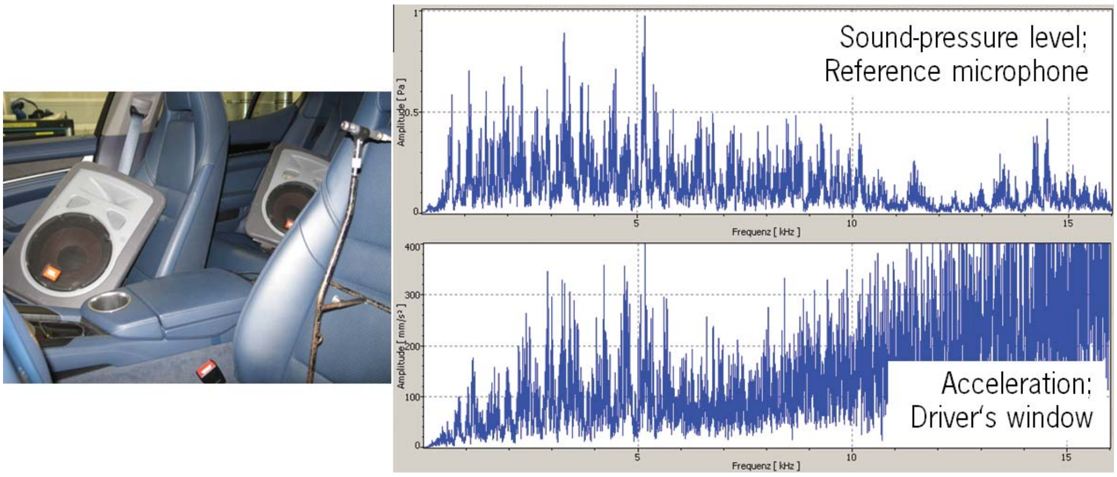

Fig. 3.15. Alternative soundsource.

The excitation with the second sound source results in higher amplitudes and an extended frequency range at the reference microphone. Consequently the amplitudes of the acceleration of the window grow. The oscillations above 7 kHz are not valid; the signal turns into noise.

In order to analyze if it is possible to detect vibrations at gravel noise relevant vehicle parts, the Laser-Doppler-Vibrometer is aimed at the sill panel. The measurement results are shown in figure 3.16. The picture on the left shows the illustrated measuring results in the Polytec measurement software. In the graphs on the right again the sound pressure level of the reference microphone and the acceleration of the object are shown. The sound signal is too weak to excite the sill panel. No vibration is detected. The signal turns into noise at 5 kHz.

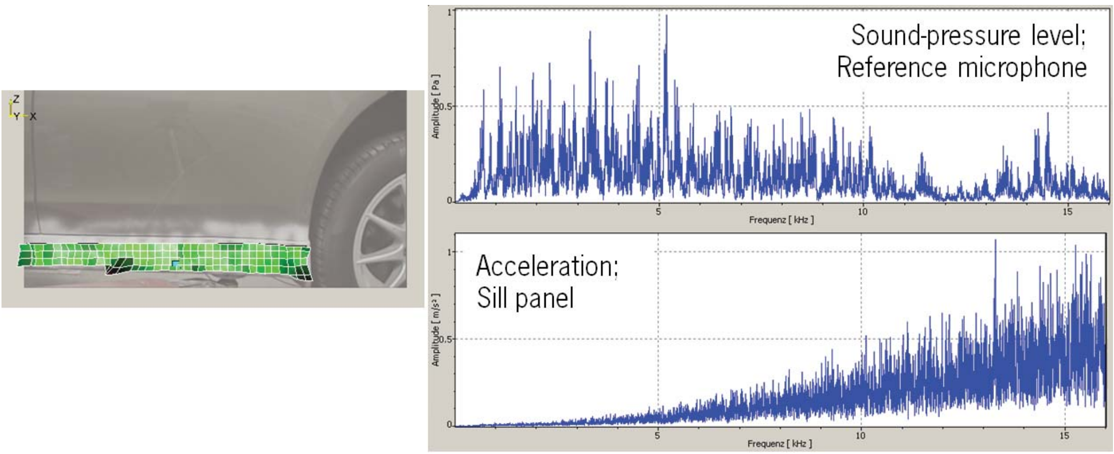

Fig. 3.16. Sill panel measurement.

The reciprocal determination of the vibro-acoustic transfer functions with the help of the Laser-Doppler-Vibrometer is not suitable for gravel noise related investigations. The structure-borne sound excitation of the body with a sound source from the inside of the vehicle is too weak. It is not possible to detect vibrations at gravel noise relevant vehicle areas in a reliable way.

3.1.3 Splashwater

In the following section the correlation between gravel noise and noise resulting from driving through water, known as splash water, is investigated. Further it is analyzed if it is possible to use the water excitation in order to evaluate vehicles and countermeasure in regards to gravel noise. The motivation is to achieve a similar excitation of the vehicle with easier controlable boundary conditions and thus a better reproducibility. The analyses consist of road tests with drive through water with the complete vehicle as well as local excitation with a water jet.

Fig. 3.17. Water drive trough.

Road test

The test area of Porsche's research and development center in Weissach includes a skidpad with the possibility to flood a part of the outer driving lane. As shown in picture 3.17, the water runs over the lane and gets banked up on the inner side of the circle until a part of the inner lane is flooded approximately 20 mm high. The rest of the circle is only run over by water which results in a water level lower than 10mm. The vehicles are equipped with a microphone on the passenger seat and on the rear right seat. In addition, the driver is wearing a head bow microphone which binaurally records the noise level at the driver's left and right ear.

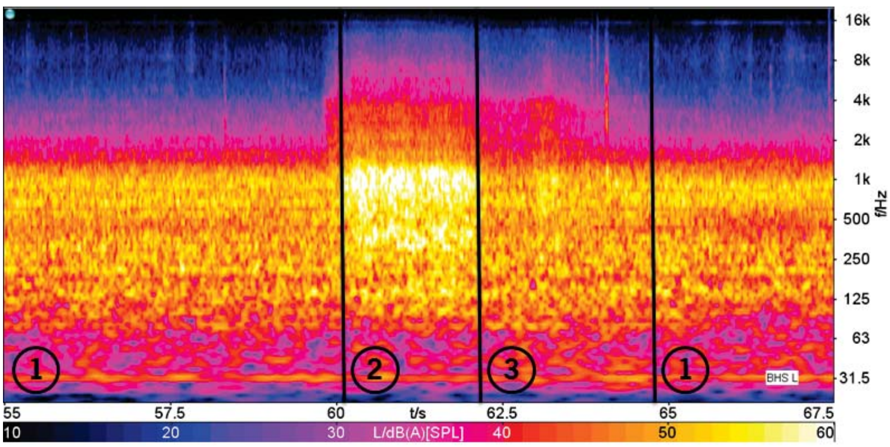

Fig. 3.18. Wavelet analysis of the drive through water.

The wavelet analysis, shown in figure 3.18, displays the interior noise while driving through the water. After the base rolling noise (point one) the impact of the water is clearly visible (point two). The frequency bandwith between 125 Hz and approximately 8 kHz is intensely amplified. The splash water noise is then followed by water hissing noise (point three) when the car drives over the wet surface at the end of the water area. The low frequency parts caused by the water hitting the vehicle body dissapear. Only the high frequency noises when the tire displaces the water film remain.

In the direct comparison to the gravel noise it is possible to see that the patterns are different. The excitation from the splash water is lower than the one from the gravel. Further the splash water noise is a continuous disturbance compared to the the short single events evolved from the gravel that also spread into a higher frequency range. Figure 3.19 shows the wavelet analysis of the two disturbing noises (point two) each shown in relation to the base rolling noise (point one).

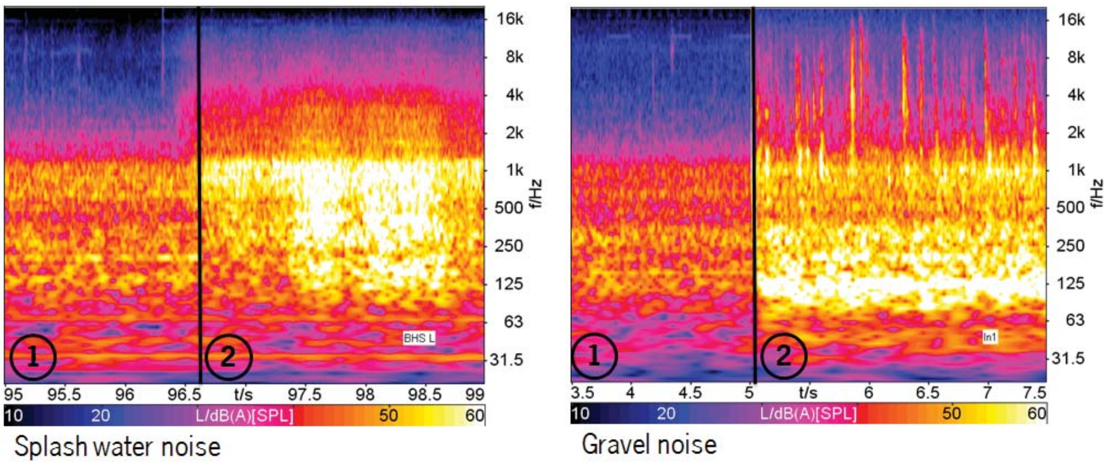

Fig. 3.19. Wavelet comparison.

Subjective evaluation also categorizes the splash water noise as much less disturbing than the gravel noise because of reasons mentioned earlier. Further the splash water noise is expected when driving in rain or over a wet surface and is not a sudden event as picking up gravel from the road.

Graph 3.20 illustrates the FFT analysis of the difference between the splash water noise (both levels) and the rolling noise. In addition the FFT of the difference between the gravel noise and rolling noise recorded on the gravel track in Nardo is shown. The vehicle speed is 60 km/h both times. The microphone position is at the driver's left ear. It is possible to see that the splash water noise is related to the water level. A peak at 250 Hz to 500 Hz and 4000 Hz and 8000 Hz is perceptible. In comparison, the distinctive part of the gravel noise appears in a wider peak from 1 kHz to 16 kHz. The growth in the lower frequency bandwidth with approximately 12 dB is also immense but not significant for the gravel noise.

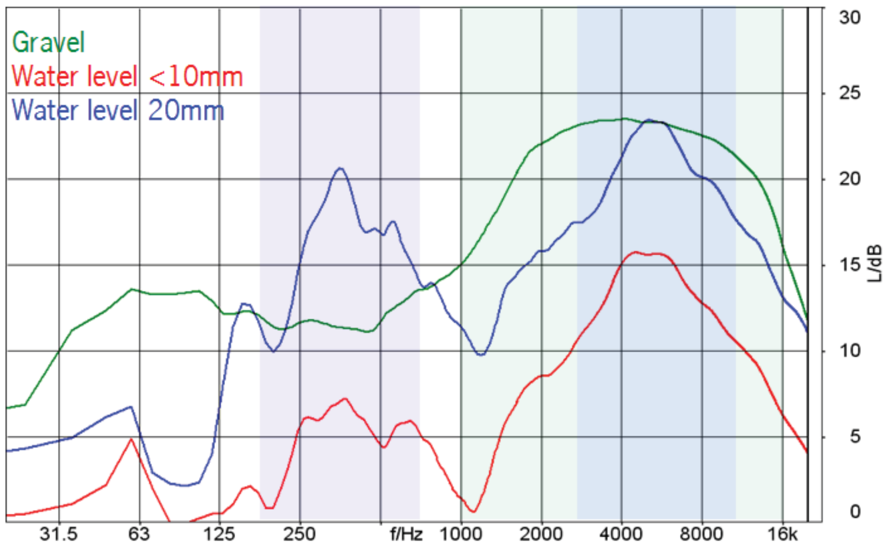

Fig. 3.20. Interior noise spectra excited by gravel and splash water.

In a first test run, the splash water noise in relation to vehicle velocity is investigated. The limousine is driven at 50 km/h, 60 km/h, 70 km/h and 80 km/h through the different water levels. Due to safety reasons it is not possible to drive with 80 km/h through the deep water since the vehicle starts aquaplaning. Figure 3.21 shows the octave analysis results.

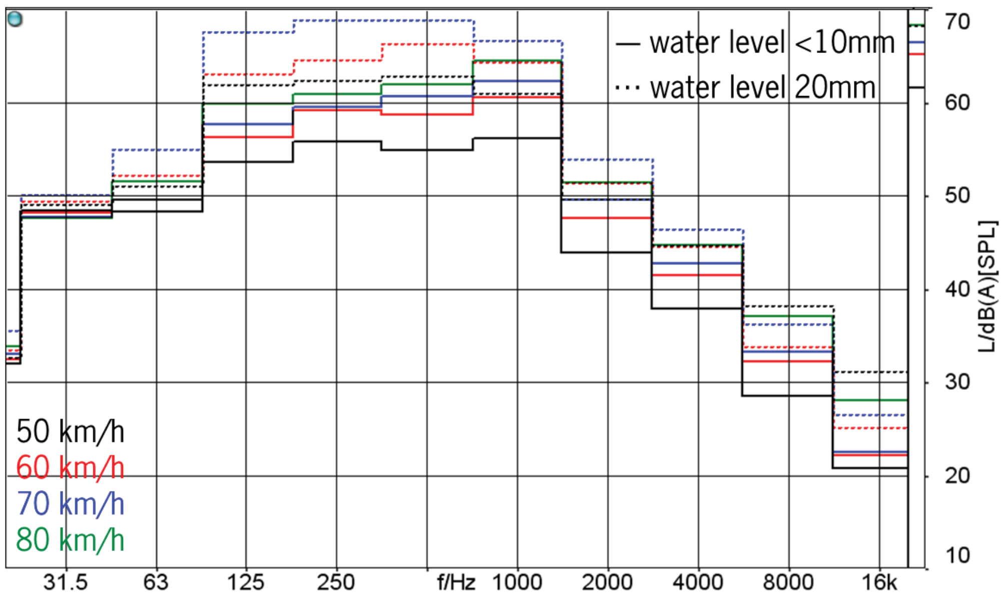

Fig. 3.21. Influence of the water level and velocity on the interior noise octave levels.

The water level of 20 mm is represented by the dotted lines respectively the water level of approximately 10 mm by the solid lines. The graphs show following: the higher the velocity, the faster the water is displaced, the more water impacts and excites the vehicle body, the louder the interior noise results. Although the increase is not linear. The frequencies between 100 Hz and a 1000 Hz are influenced the most. A significant increase in the octave levels is observable from 50 to 60 km/h driving through the shallow water. 60 km/h is defined as the velocity for the further tests.

In order to investigate if it is possible to evaluate measures on the vehicle to decrease the interior noise due to splash water, modifications are conducted to the vehicle. In a first test the sill panel including the part at the underbody is lined with self-adhesive fleece of 20 mm which prevents an excitation of the vehicle body. Picture 3.22 illustrates the modification and the resulting octave analyses. The vehicle speed is 60 km/h and the shown measurements are recorded at the driver's left ear. The measurements at the remaining microphone positions have analog results.

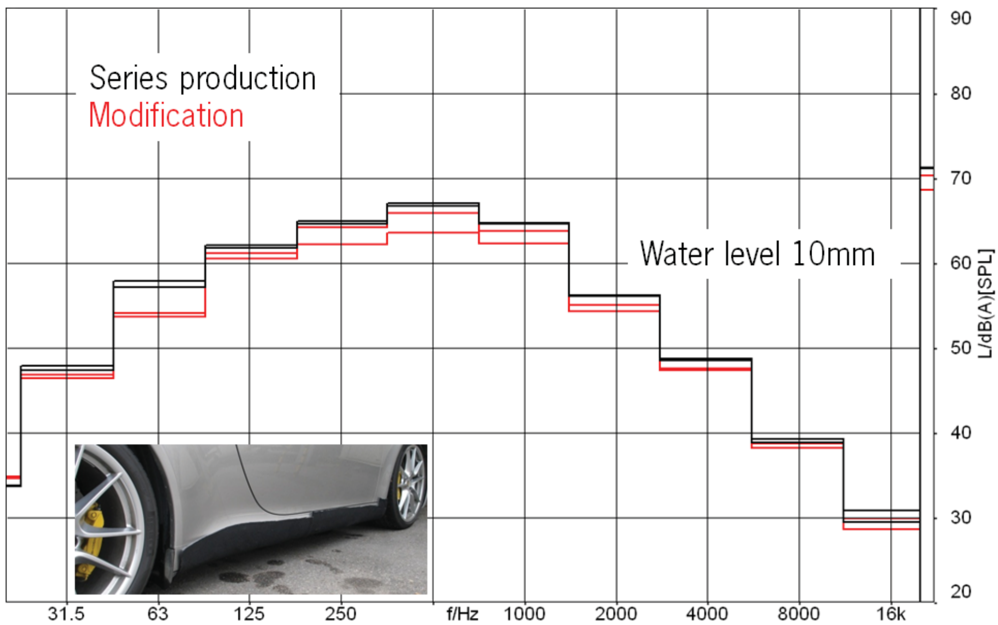

Fig. 3.22. Modification of the sill panel.

The two separate lines indicate the repetition of a measurement which show that the recordings with the modified vehicle scatter in the 250 Hz and 500 Hz octave about plus minus 1dB. The reason for this deviation is not obvious. It has to be assumed that, for example, different vehicle parts have been excited. The reproducibility across the frequency range is given except for this outlier.

The graphs indicate a slight level decrease across the whole frequency range, but no significant change is visible. In order to compare the influence of the sill panel at gravel and water excitation, in picture 3.23 both graphs are plotted. The effect of the sill panel is much greater with the gravel excitation. Further the effected frequency bandwidth is different. With the covered sill panel the level drops in the 2 to 16 kHz octaves up to 8 dB. The sill panel has much less influence when excited with splash water. The octave levels at the splash water are only higher at the 250 to 1000 Hz octaves. This is caused by more mass exciting the vehicle body than the light impulse from a stone.

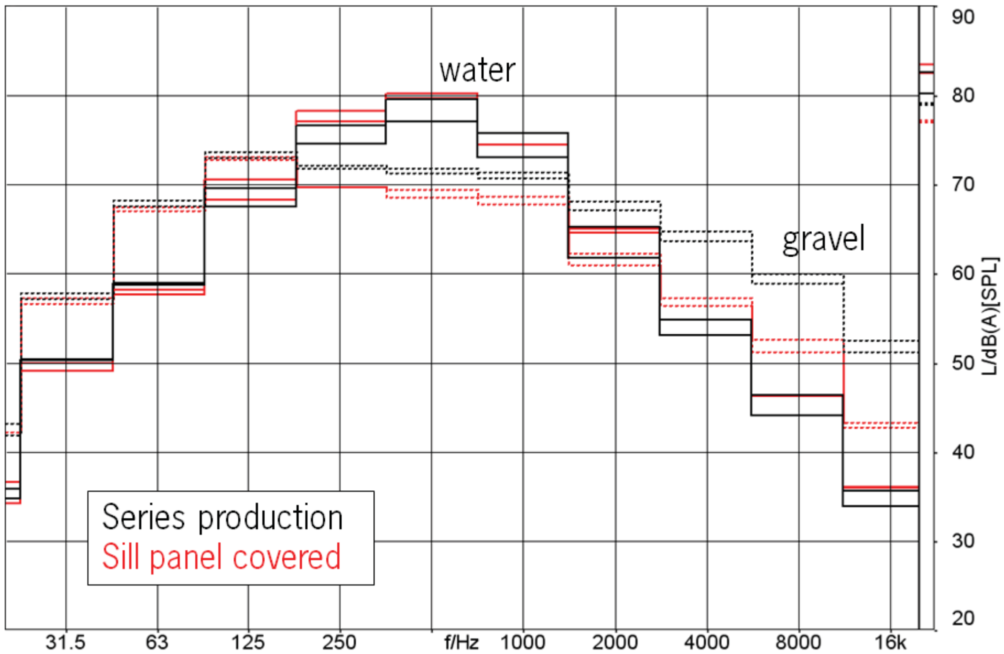

Fig. 3.23. Comparison gravel and water excitation.

The boundary conditions are not perfect. The length and consistency of the water area has to be improved for further investigations. The excitation of the vehicle is much weaker than the one from stones. In addition, the concise frequency bandwidths are different compared to the gravel noise which results in a different type of disturbing noise - the continuous low pitch splash water noise versus the high frequency gravel noise. The performed examinations show that different vehicle parts are relevant. It has to be investigated if a sensitivity analysis has to be conducted for the splash water noise in order to determine the acoustic weak spots.

Local excitation with water jet

To excite the vehicle body locally, water is applied with a standard hose. The continuous water flow enables a continuous excitation of the vehicle with reproducible boundary conditions. Picture 3.24 shows the water stream directed onto the sill panel. The standard measurement equipment is used with the microphone positions at the driver seat and rear left seat. The vehicles investigated are the sports car and the limousine.

Fig. 3.24. The water jet directed at the sill panel.

Different vehicle parts are sprayed onto in order to evaluate the excitation method. The sill panel, front and rear wheelhouse and the gravel protection foil which is located at the rear door at the limousine and on the rear wheel case at the sports car are excited at both vehicles. The measurement results are shown in figure 3.25. The sports car is represented by the dashed line respectively the limousine by the solid.

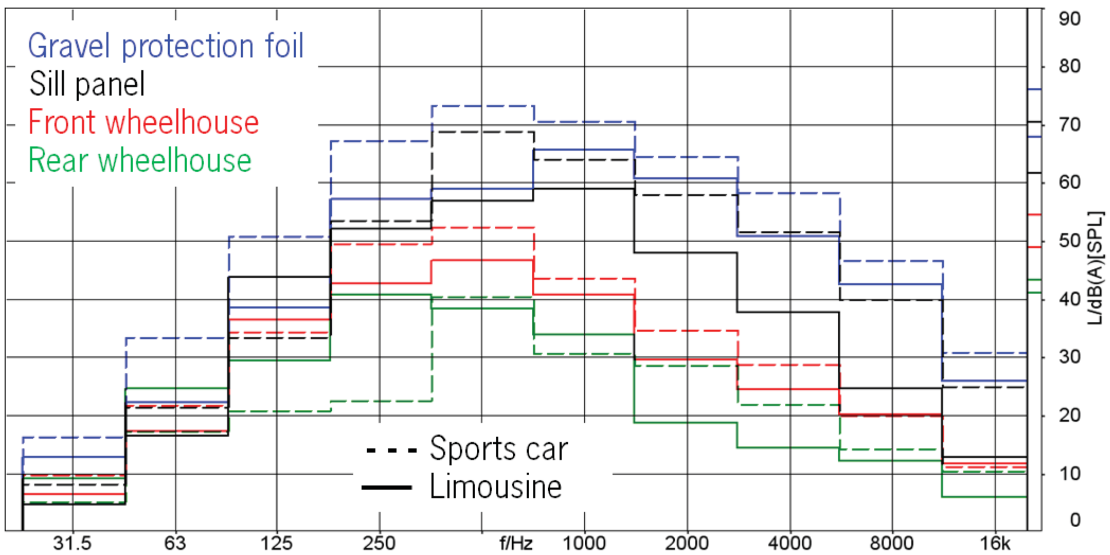

Fig. 3.25. Excitation of vehicle parts with water.

The octave analyses illustrate the different influence of each vehicle area. The water impacting the vehicle body directly, at the sports car sill panel and the gravel protection foil at both vehicles, result in a much louder interior noise level. The transmission path from the wheelhouses is more extensive plus the different additional parts prevent direct sound communication to the passengers' ears. Although the sports car is missing a rear wheelhouse liner and the water stream is able to hit directly metal parts of the exhaust system, the octave analysis show a significant collapse at the 125 and 250 Hz octaves. Due to the decoupling of the exhaust system only airborne noise is transmitted to the vehicle interior. Overall it is evident that the excitation of the sports car result in higher octave levels because of the mentioned reasons.

The sill panel is modified with self-adhesive fleece in order to evaluate the excitation method with water. Picture 3.26 shows the modified sports car and the resulting octave analyses for the front area and the rear area of the sill panel with the fleece applied and without. The measurements at the driver seat position are displayed.

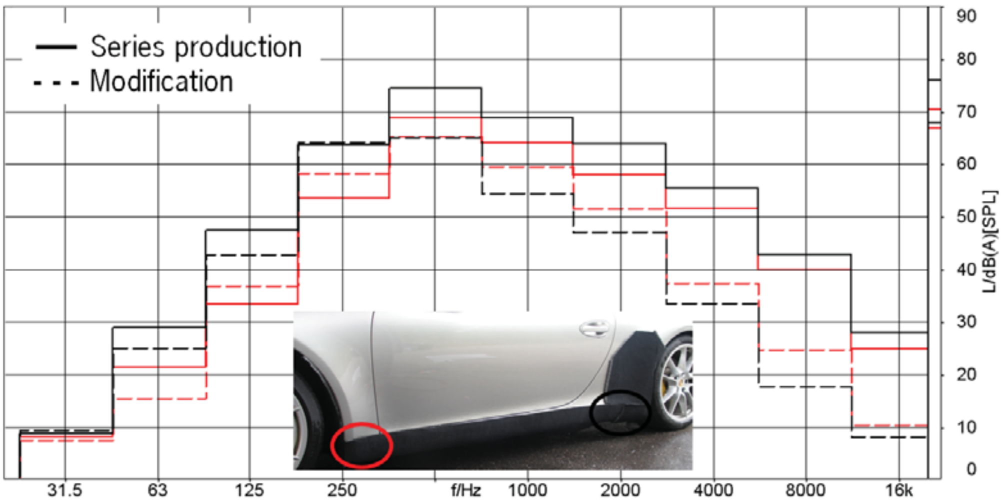

Fig. 3.26. Modification of the sill panel.

The graphs show significant level drops in the high frequency ranges from 500 Hz to 16 kHz. The level decrease at the rear sill is bigger than in the front. Due to the shorter transmission path to the vehicle interior, the adjustment made to the sill has a bigger influence. Further the path directly through the B-pillar to the driver's ear is blocked.

To determine what parts of the interior noise is caused by airborne and which by structure-borne noise, the following experiment is conducted. In a first recording the limousine is excited with a water hose at the front sill in series production status. Afterwards a separate panel close to the before excited vehicle part is sprayed on in order to prevent the structure-borne excitation of the vehicle body but still have the airborne sound of the water impacting the surface. Picture 3.27 shows the test setup and the results.

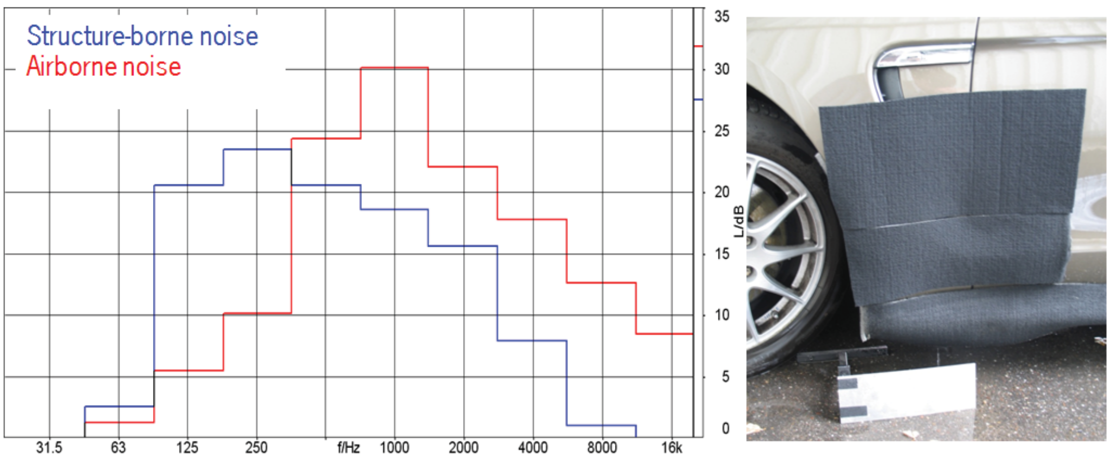

Fig. 3.27. Separation of air- and structure-borne sound.

With the two recordings it is possible to calculate the structure- and airborne parts of the interior noise. The octave analyses show that the airborne sound is dominant in the high pitch frequencies. As expected, the lower frequency levels are caused by structure-borne noise. Since the high frequencies are relevant for the gravel noise, the results lead to the assumption that the impact of an object on the vehicle body and the resulting airborne noise is the main contributor to the disturbing interior noise. It has to be further investigated if this is applicable to the excitation with stones.

The complete vehicle driving through water is not target-orientated. The noise transfer from the source to the passenger's ears and the relevant frequency bands are different to the gravel noise. In order to further investigate and improve the splash water noise, the boundary conditions, e.g. length of test track, water depth, have to be optimized. The local excitation with a water jet is promising due to the good reproducibility, although it has to be considered that it is a continuous excitation of the vehicle body which could influence the vehicle body oscillation in contrast to the short impulse of the gravel.

3.1.4 Plastic granulate

A different approach to simulate the gravel impact on the vehicle body is the use of plastic granulates. The small pieces of PVC, shown in picture 3.28, are used in insulation material production and have a grain size of one to two millimeters. The granulate is thrown by an electrical blower and directed via various outlet orifices.

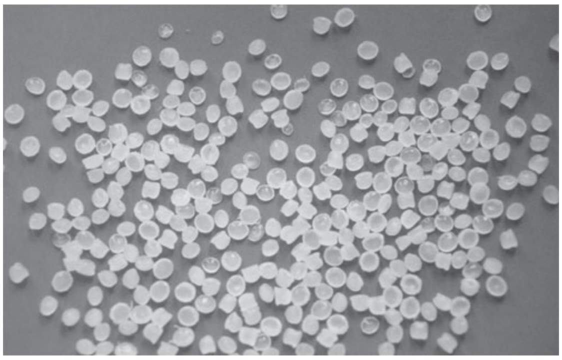

Fig. 3.28. The plastic granulate.

The vehicle is equipped with the standard measurement equipment with the microphones on the driver seat and on the rear left seat. The blower is directed to the vehicle areas which are relevant for the gravel noise. Additional to the objective airborne sound level measurements the granulate impact is evaluated subjectively.

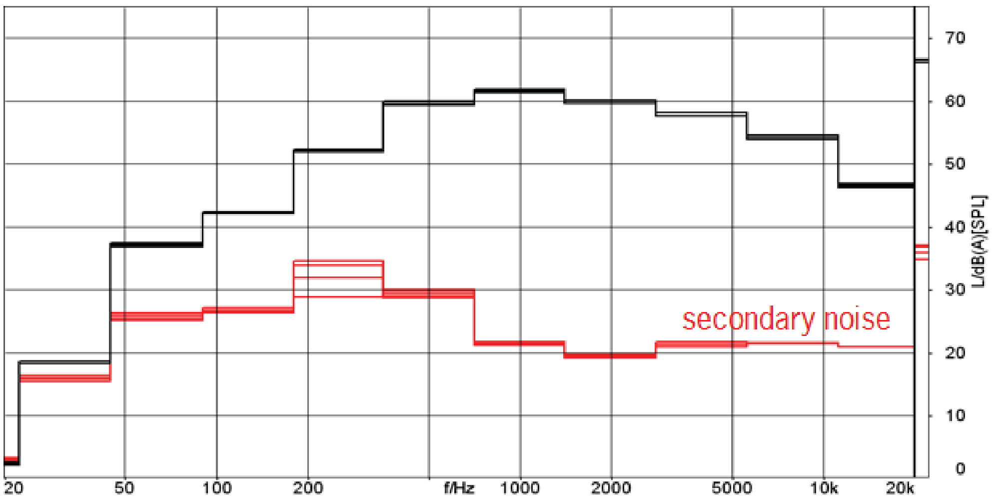

Fig. 3.29. Reproducibility of the plastic granulate.

In a first measurement run the reproducibility is investigated. Therefore the same excitation is repeated five times. Further a measurement is taken at rest without any excitation of the car but with the running blower to evaluate the effective measurable range. The results are shown in figure 3.29. The octave levels deviate plus minus 0.3 dB. The difference between excited vehicle and surrounding noise is approximately 30 dB in the gravel noise relevant frequency range of 1 to 16 kHz. These results imply a high reproducibility and a high excitation of the vehicle despite the disturbing noise of the electrical blower.

Different areas of the vehicle which are considered of interest for the gravel noise are blasted and compared among each other. The following areas shown in picture 3.30 are taken into account: the front wheelhouse liner, the underbody shield, the sill panel and the rear wheelhouse.

Fig. 3.30. The analyzed vehicle areas.

Graph 3.31 shows the octave levels of the microphone at the driver's position. Since the excitation is exactly the same at each measuring point it is possible to regard the octave analysis as a sort of transfer function and therefore compare the levels directly. In the relevant gravel noise frequency bandwidth the excitation of the sill panel results in the highest octave levels. The level drops from 64 dB(A) at the 2 kHz octave to 52 dB(A) at the 16 kHz octave. The granulate directly impacts the sheet metal body which results in a high pitch noise. A high amount of airborne noise is transported through the close by door sealing and windows. Additional the direct transfer path through the hollow B-pillar to the passenger's ear contribute to a high influence to the disturbing gravel noise.

The interior noise induced by the excitation of the front wheelhouse liner resides approximately 5 dB below the level of the sill panel. Although the transfer path into the passenger cabin is short, the influence of the wheelhouse is minor because of the softer material - PVC instead of sheet metal - which dampens the gravel impact. Another 8 to 10 dB lower situated is the rear wheelhouse. Even though there is no wheelhouseliner and the granulate hits directly parts of the exhaust system and body made of metal which suggests a high pitch impact noise, the effect onto the interior noise is relatively small. The transfer path is rather long and the mounting of the exhaust system prevents structure borne sound to convey to the passenger cabin. The underbody shield has the least influence. In the 4 to 16 kHz octaves the interior sound is more than 5 dB lower than the noise from the rear wheelhouse. The textile material of the underbody shield can be taken into account for this effect.

The measurements at the rear seat microphone show similar results. Due to the changed transfer paths from excitation point and microphone position the rear wheelhouse liner and sill panel gain in influence to the interior disturbing noise whereas the underbody shield and front wheelhouse setback.

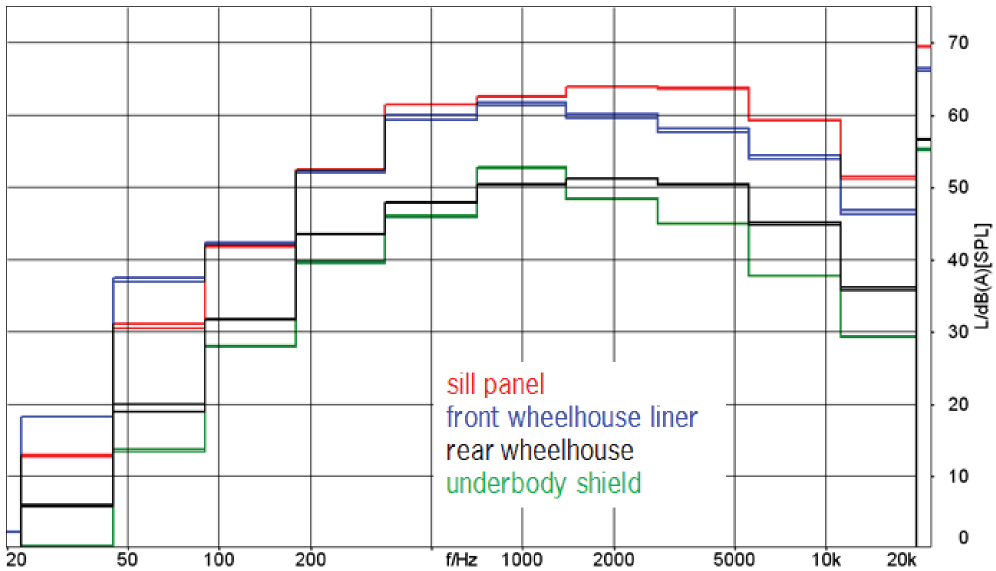

Fig. 3.31. Interior noise octave spectra with plastic granulate excitation.

The use of the plastic granulates provides a high excitation of the vehicle, a very good reproducibility and a realistic gravel noise simulation while subjectively evaluated. Despite the advantages a few drawbacks have to be mentioned. Like every artificial excitation method, this technique does not consider the probability of a stone hitting the corresponding part of the vehicle. This means that the areas of a car that are affected by gravel impact have to be known. Further the granulates spread out vastly when leaving the orifices so that it is not possible to excite only a small area of the vehicle.

3.1.5 Solid carbon dioxide snow

A suitable substitute for gravel in artificial excitation is solid carbon dioxide snow. The pellets have approximately the same size and weight as stones picked up on a road and are machine made. Further after reaching a certain temperature, the pellets dissolve into gas with no debris which gives a great advantage because no cleaning of the test bench is necessary.

In a first investigation the electric blower used in chapter 3.1.4 with plastic granulate is filled with the CO2-pellets. The advantage of having no waste after the tests is accompanied by the side-effect that the solid carbon dioxide is pulverized in the machine which leads to a too slight excitation of the car. Picture 3.32 shows the C02-pellets, the electric blower facing the front wheelhouse and the dissolving dry carbon dioxide snow.

Fig. 3.32. The CO2 pellets and the electric blower.

The advantages of the solid carbon dioxide snow still convince. In order to excite a vehicle with the pellets, a spray gun is modified to catapult the dry ice with the help of compressed air. Several test runs show that the pellets do not fly out of the blast pipe constantly. Further the compressed air and the pellets leaving the orifice generate a high secondary noise. To evaluate the actual sound level caused by objects hitting the vehicle, measurements with the spray gun aimed onto the front wheelhouse and passing beneath the vehicle are compared. 5 measurements of 10 seconds are recorded each time. Figure 3.33 shows the modified spray gun and the measurement results.

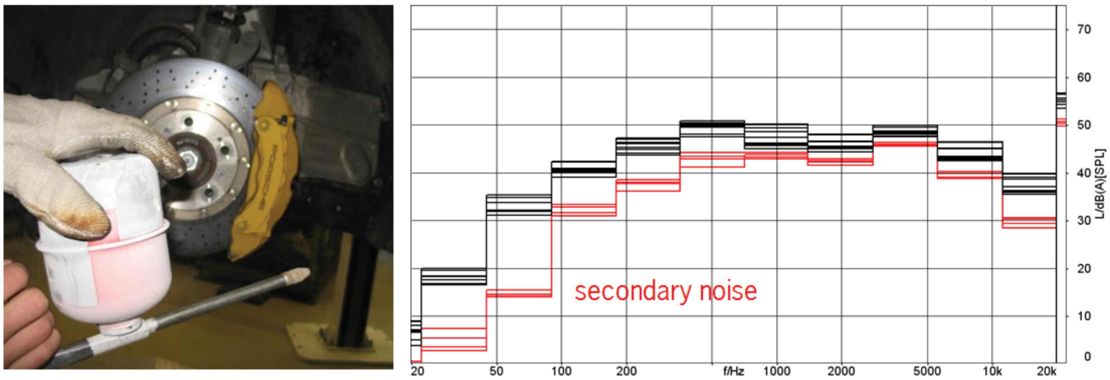

Fig. 3.33. Interior noise octave spectra with CO2 pellets excitation.

Each curve in diagram 3.33 represents one measurement. Each measurement is performed with the same boundary conditions. The high dispersion of up to plus minus 4 dB per octave indicate the insufficient reproducibility due to the inconstant amount of pellets impacting the vehicle.

The secondary noise is close to the sound level of the actual excited vehicle, especially in the high frequency areas of 1 to 16 kHz which are relevant for the gravel noise perception. This margin is too small - the effective measuring range is not sufficient which leads to the conclusion that the excitation with the spray gun and CO2 pellets is not a suitable method.

3.1.6 Slingshot

With the complex air-borne and structure-borne transmission paths it is difficult to determine the gravel impact location at the vehicle by the resulting interior noise. In order to detect the spot where an object hits the body and to investigate how the different vehicle areas sound in the inside by themselves and not superposed with several events, the relevant parts are catapulted with a slingshot and small gravel stones. Further it is analyzed if the slingshot is a suitable method to subjectively evaluate measures against gravel noise.

Fig. 3.34. The slingshot.

The slingshot, shown in picture 3.34, which is normally used for fish fodder, gravel of different size and weight, is catapulted against the vehicle. The resulting interior noise is recorded with the standard setup with the microphone positions on the driver seat and on the rear left seat. The impulses of the single stones are compared to the difference between rolling and gravel noise of an actual driving situation. The wavelet analyses are shown in picture 3.35.

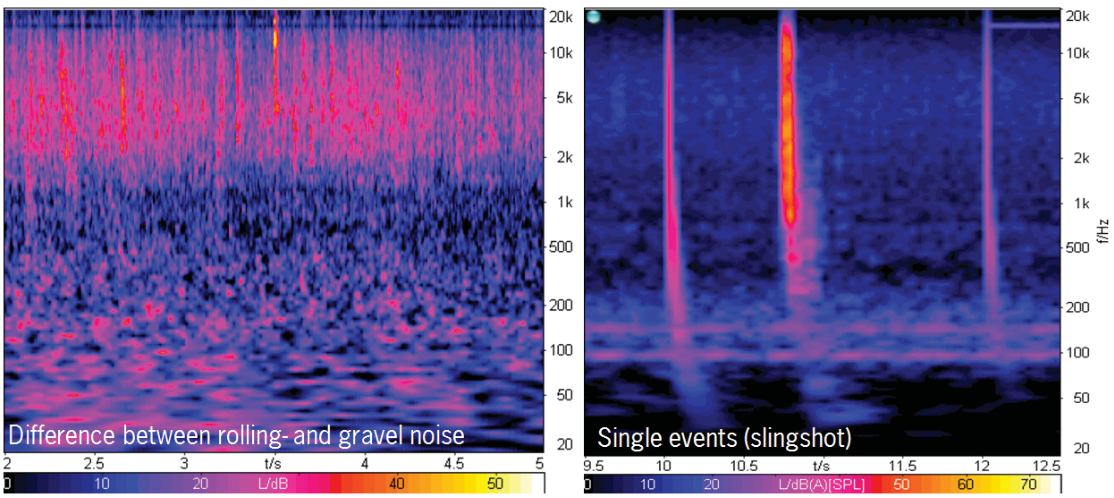

Fig. 3.35. Wavelet comparison.

As described in chapter 1 the gravel noise has its biggest influence in the frequency ranges between 1 and 20 kHz. The purple areas represent an intensification around 20 dB. Lower frequencies are amplified as well but are not considered disturbing since they are masked by rolling noise. The single events of a stone impacting the vehicle clearly show the impulses across the frequency range from approximately 100 Hz up to 20 kHz. Depending on grain size, distance to the vehicle and drag force of the slingshot, the intensity of the impulses alternates. With the short impulse due to the high velocity of the stone, a high amount of energy is transmitted to vehicle. This results in an excitation of the body in a frequency bandwidth even wider than compared to the impulse hammer which has been investigated in chapter 3.1.1.

Graph 3.36 shows the octave analyses of various single gravels impacting the sports car and the limousine each time at the rear end of the sill panel. The microphone position is at the driver seat. The scattering of the octave analyses shows the difficulties to reproduce an impulse. Comparing the two vehicles, tendencies are noticeable. The sports car shows higher octave levels than the limousine. This reflects the impressions and measurements obtained before. The extensive insulation package of the limousine and the plastic-covered sill panel result in a transmission path with more advantages than at the sports car.

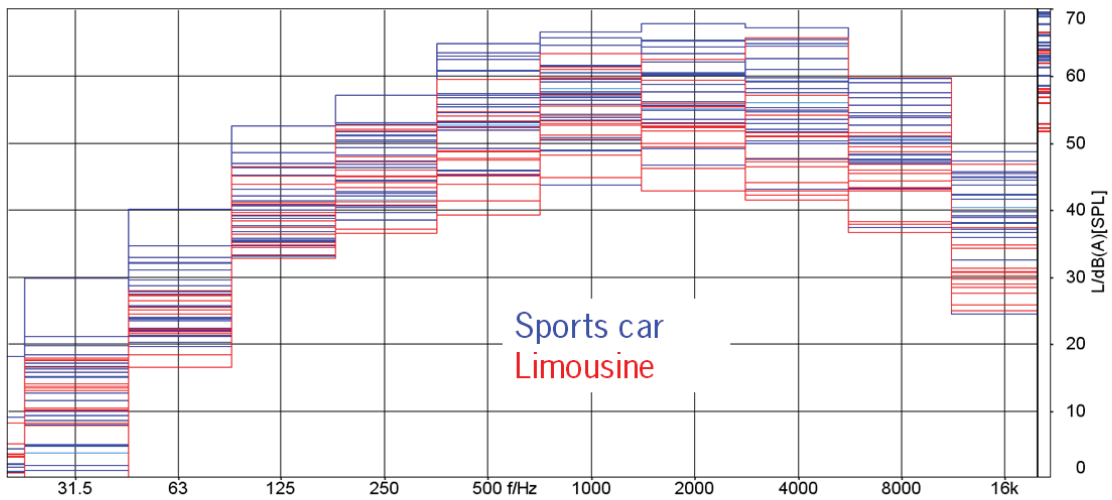

Fig. 3.36. Octave analyses of stone impacts.

Because of the various parameters that are not possible to keep constant, the reproducibility is not given. Therefore the excitation of the vehicle with a slingshot and single gravel is not a suitable method to evaluate actions against gravel noise.

The subjectively evaluation of the different single gravel impacts allows a categorization of the different vehicle areas in rank of importance corresponding to their acoustic pattern in the inside of the vehicle. The conclusions drawn in former investigations are confirmed. Especially impacts on metal surfaces result in a not valuable interior noise quality. Plastic surfaces dampen the impact; the resulting noise is hollower which leads to a valent interior noise perception. In addition stones that hit the vehicle further in the rear have less influence to the disturbing noise due to greater transmission paths.

3.2 Evaluation of the simulation methods

In the following section, the prior presented excitation methods to simulate the gravel noise are compared and evaluated.

An important point to assess the usability of a gravel impact simulation method is the covered frequency bandwidth. A suitable method has to meet the gravel noise relevant frequency range of 1 to 16 kHz. With each method the sports car is excited at the rear sill panel. The microphone position is at the driver seat. Since the transmission path remains constant, it is possible to directly compare and evaluate the received source signals. Figure 3.37 shows the measurement results as octave analyses.

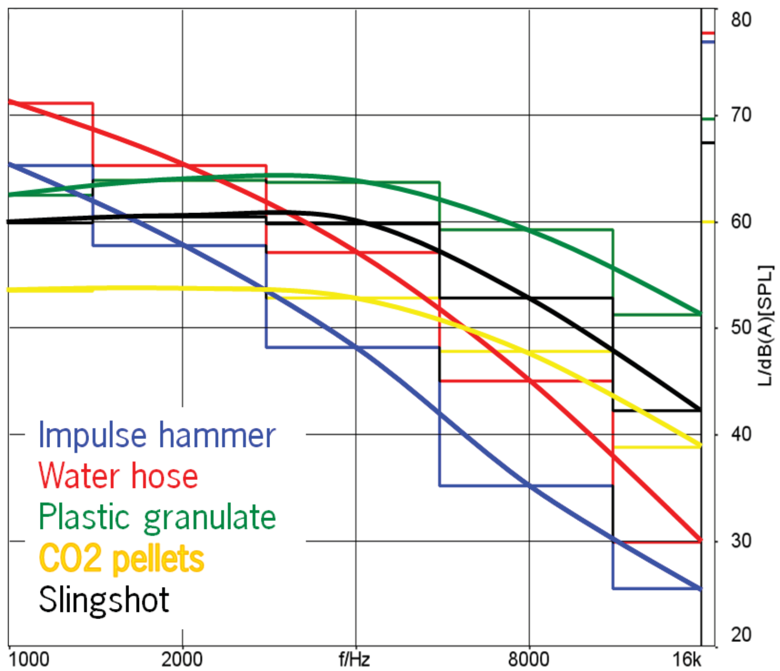

Fig. 3.37. The frequency response characteristics.

Curves are drawn into the octave analyses in order to evaluate the frequency-response characteristic. Further the octave levels are observed since it is necessary to place enough energy into the system with the excitation method.

The frequency level of the impulse hammer and water hose steadily drop through the frequency range of 1 to 16 kHz from 65 to 25 dB(A) respectively 70 to 30 dB(A) which reveals that the high frequencies are not induced into the vehicle enough. The plastic granulate, slingshot and CO2 pellets deliver a constant frequency level up to the 4 kHz octave. Afterwards the frequency drops. The frequency-response characteristic of the CO2 pellets and plastic granulate show a slightly smaller slope from 53 to 39 dB(A) respectively from 64 to 52 dB(A) in the 4 to 16 kHz octaves than the frequency-response characteristic of the slingshot.

In regards to the height of the octave levels the excitation with the plastic granulates has to be ranked best. The high amount of objects and the relatively high velocity when impacting the car enable a high energy induction into the vehicle which results in the high levels even in the high frequency ranges. The water flowing against the vehicle and the impulse hammer even applied with high force are not able to achieve a satisfying frequency-response characteristic. The induced energy and thus received frequency spectra in the interior is strongly related to the objects' mass and velocity.

Despite the frequency-response characteristic further properties of the excitation methods are evaluated. As important as the ability to achieve the relevant frequency range is the reproducibility. If the measurements are not reproducible, it is not possible to compare different countermeasures or complete vehicles. The criteria realism reflects how close the artificial excitation method is to the actual gravel noise. The subjective auditory impression is very helpful and important when assessing acoustical difficulties. The method's complexity is graded in the next column to discuss how easy a test procedure is performed and how much time is necessary. Last point in the matrix is the costs. Table 3.38 shows the evaluation results.

	Frequency	Reproducibility	Realism	Complexity	Costs
Impulse hammer	0	++	0	+	+
Water hose	-	+	-	+	+
Plastic granulate	++	++	+	- -	- -
CO2 Pellets	+	- -	+	-	-
Slingshot	++	- -	++	+	+
LDV	- -	+	- -	-	-

Fig. 3.38. Evaluation of the simulation methods.

Since the force transducer at the impulse hammer tip measures the applied hammer force and the vibro-acoustical transfer function can be calculated, the reproducibility is very good. The complexity and costs are low. A measurement is easily performed, but is not close to the actual gravel noise. As discussed earlier, the frequency level drops too quickly in the high octaves. The water jet has similar properties. The excitation method has advantages in reproducibility, complexity and costs. Due to the continuous water flow the excited frequency range and realism is rated as not suitable.

The plastic granulate thrown by the electric blower achieves a very good frequency-response characteristic and reproducibility. The interior aural impression is quite close to the actual gravel noise which gives a further advantage. Since the company does not own the blower it has to be rented. This leads to a disadvantage in complexity and costs.

The reproducibility for the CO2-pellets is not given. This disqualifies the method as a suitable procedure. The advantages in regards to realism and no effort with cleaning cannot convince. The slingshot enables to simulate one stone impact very accurately and with the resulting original frequency-response characteristic. The complexity and costs are of course low. Due to not definable force and size of the gravel, it is not possible to achieve the same impact energy reproducible.

The attempt to measure the reciprocal vibro-acoustic transfer function with the help of an omnidirectional sound source and a Laser-Doppler-Vibrometer was not successful. The excitation of the vehicle from the inside with the sound source is too low. The resulting frequency-response function is not applicable.

When overlooking the different excitation methods, each one has advantages and disadvantages. No excitation method is fulfilling all requirements and convincing in every criteria. Further the complete aural impression has to be considered. Evaluating and improving a certain vehicle area or part is definitely leading into the right direction to decrease the gravel disturbing noise. But the influence of a single countermeasure also has to be assessed in the complete vehicle. The conclusions drawn from a single countermeasure could not be applicable when evaluating the complete vehicle because of earlier discussed reasons. It has to be further investigated how far laboratory gravel noise simulation can be improved to represent the complaints in regards to gravel noise.

4

Countermeasures

The possibilities for countermeasure against gravel noise are restricted. As in most areas of automotive development, there are strict limitations due to design, package, weight and costs. A major part of acoustic issues is only evaluable in the complete vehicle, which also means in a late development phase. The more advanced the development of the vehicle is progressed, the more complicated and expensive are implementations of design changes and additional parts.

In a first step potentials of improvement are researched and the transfer path of the forced venting to the seatbelt outlet is analyzed. Afterwards, parts suitable for series production are developed and evaluated on the basis of hand-made prototype parts. In the last section, an upcoming vehicle in a prototype phase is improved in regards to rear compartment transparency and gravel noise performance.

4.1 Evaluating potentials for improvement

Several modifications are implemented in order to evaluate the potential of improvement at the considered vehicle areas. The investigations are performed with the plastic granulate, introduced in chapter 3.1.4. The measures applied are not applicable in series production cars due to costs, weight and package.

Fig. 4.1. Front wheelhouse liner modifications.

The front wheelhouse liner is made of PVC with relatively poor damping and absorption properties. Since the area was identified as a considerable contributor to the gravel noise, it is investigated how these properties can be improved. To increase the absorption the inside of the part is lined with self-adhesive micro fiber-fleece with a thickness of 10 mm. Further the hollow areas between the wheelhouse liner and vehicle body are filled with polyurethane (PUR) foam. The damping ability is amplified by aluminum-butyl with an area weight of 2.4 kg per m^2 which replaces the fiber-fleece. The different modifications are illustrated in picture 4.1.

The applied variations are analyzed and the results are shown in figure 4.2 for the driver microphone position. The fiber-fleece decreases the level in the frequency octaves 1 to 4 kHz by 2 to 4 dB. The additional PUR foam in the hollow areas does not increase the absorption. The damping with the help of the aluminum-butyl has a greater effect. The mentioned octave levels are reduced by 3 to 8 dB. The octave levels 8 and 16 kHz are slightly effected with a reduction of approximately 1 dB. The deviations at the lower frequency bandwidth can be neglected since they are disguised by rolling noises and not relevant for gravel noise, as discussed in the introduction.

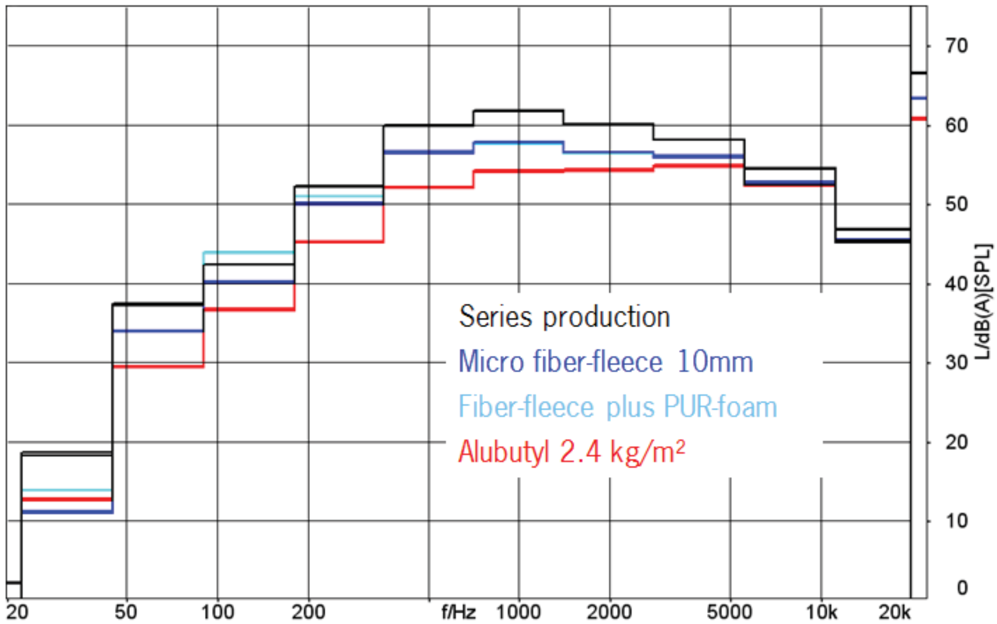

Fig. 4.2. Front wheelhouse liner modifications measurement results.

The forced venting is necessary to prevent an overpressure in the passenger compartment to occur with closed windows. Without the outlet it would neither be possible to close the doors, nor could the ventilation deliver fresh air into the cabin. Normally the orifice is located at the rear end. With the engine in the back at the sports car, the outlet is located inside the front wheelhouse to prevent fumes and noise from the engine to be transmitted into the vehicle. The forced venting is directly behind the wheelhouse liner and only covered with a flap gate made of thin plastic. This design enables airborne noise to enter straight into the vehicle body where it can migrate through the sill into the B-pillar forward to the passenger's outer ear. To prevent this effect, the outlet is closed with a heavy layer with the weight per unit of 4 kg per m^2 for a principle investigation. The modification is shown in picture 4.3.

Fig. 4.3. The forced venting.

The measurement results, illustrated in graph 4.4 for the microphone at the driver position, show only slight improvements in the significant frequency bandwidth. The airborne noise transmission path through the forced venting has to be evaluated as not as important as expected with the excitation of the front wheelhouse. The influence of the outlet of the forced venting with excitation of the sill has to be clarified.

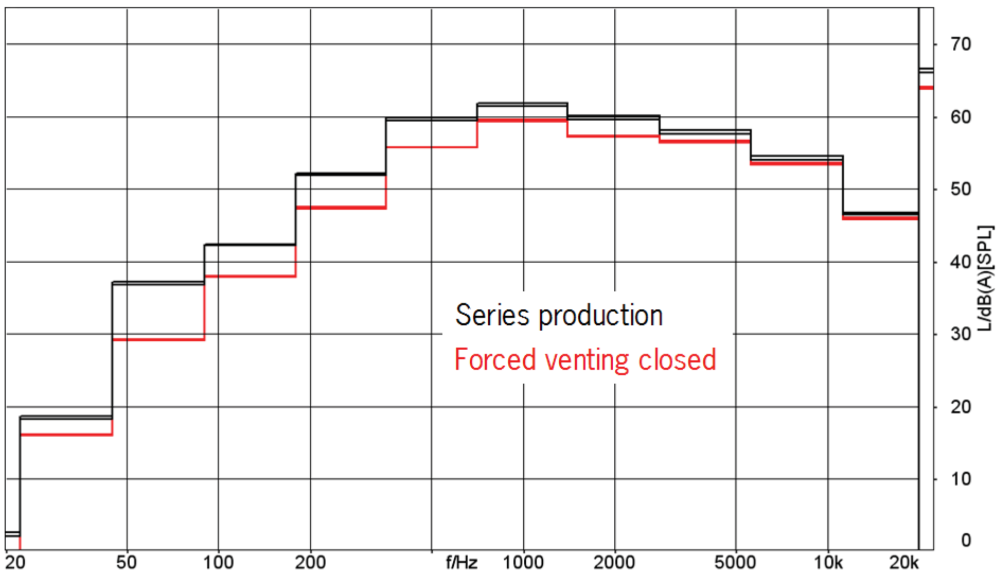

Fig. 4.4. Forced venting measurement results.

Due to a direct transfer path, the excitation of the sill panel, especially the underbody part which is directly in the trajectory of the gravel thrown by the front wheels, has a vast impact to the interior noise. In order to investigate the potential of a possible countermeasure applied to the outer surface, a mixed fiber-fleece with a thickness of 10mm is applied. The modification is shown in picture 4.5.

Fig. 4.5. Sill panel modification.

The fiber-fleece dampens the impact of the granulate and reduces the excitation of the vehicle body vastly. The octave analyses, shown in graph 4.6, indicate level reductions in the relevant frequency bandwidth up to 20 dB.

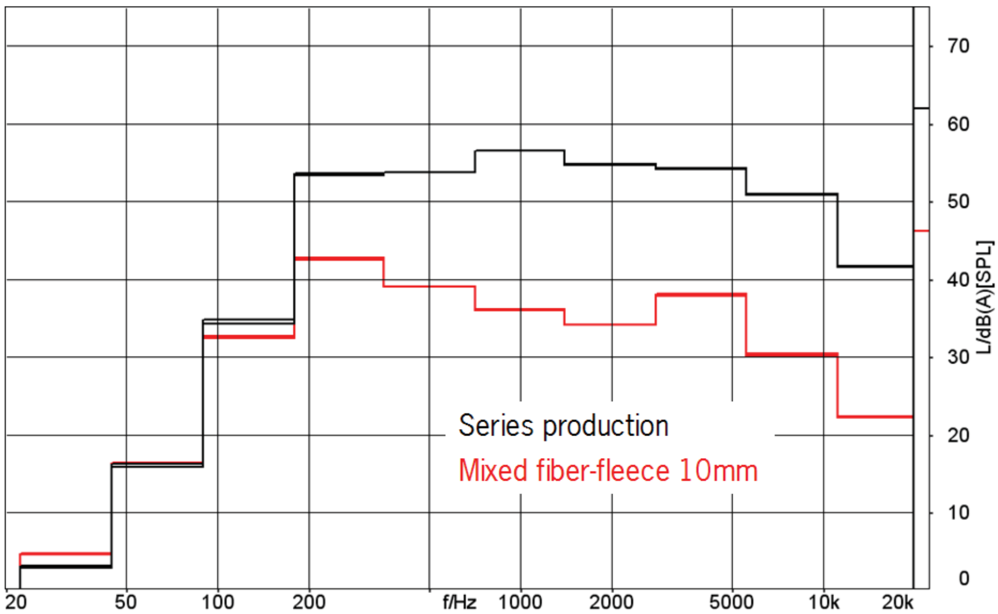

Fig. 4.6. Sill panel measurement results.

To finalize the investigations a micro fiber-fleece is positioned between the front underbody panel and the vehicle. The increased absorption is perceptible in the higher frequency ranges of 5 to 16 kHz. In these regions the levels drop about 3 to 5 dB per octave. The modification is shown in picture 4.7. The results are displayed in graph 4.8.

Fig. 4.7. The underbody panel.

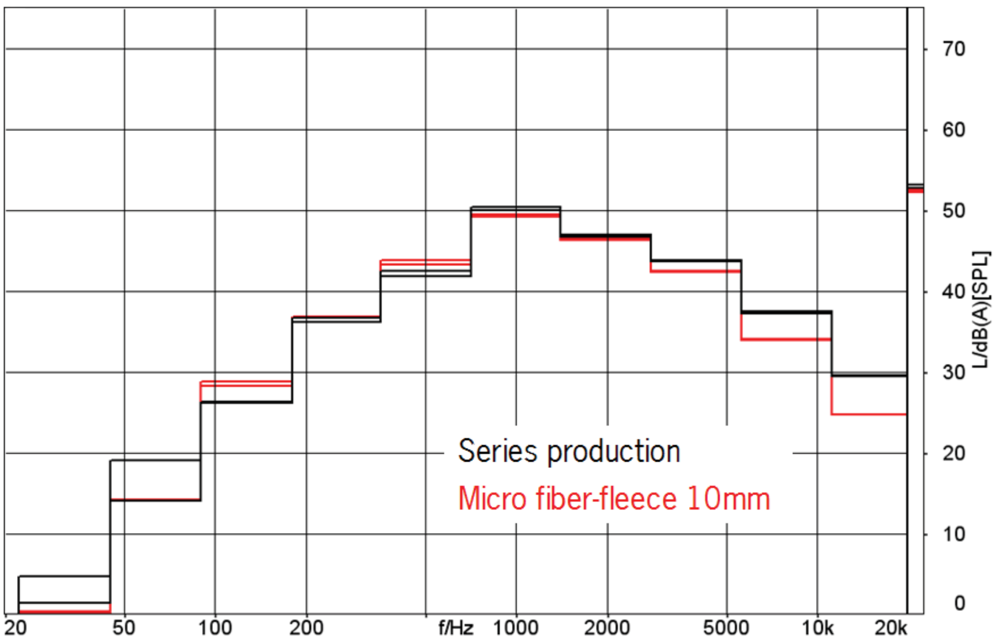

Fig. 4.8. Underbody panel measurement results.

Most of the considered vehicle areas show high potential to improve the interior noise in regards to gravel impact when investigated separately - though it is difficult to draw conclusions to the complete vehicle aural impression. In the next step realistic countermeasures are applied to the sill panel and wheel house liner. The modifications are then evaluated in the complete vehicle.

4.2 Analysis of the transmission path of the forced venting to the seatbelt outlet

Even with the forced venting at the rear end at the small sports utility vehicle, instead of located behind the wheelhouse liner at the sports vehicle, the sound transmission path has to be evaluated as critical since airborne sound is able to propagate almost freely from the outside to the inside. Gravel noise as well as rolling noise is able to directly emit out of the rear seatbelt outlet which is located very close to the rear passengers' ears, as shown in picture 4.9.

Fig. 4.9. The seatbelt outlet with attached microphone.

In the following investigation several measures are applied to reduce the noise intrusion through the closed venting orifice. In order to evaluate the influence, the sound pressure levels at the seatbelt outlet and forced venting outlet are measured. The left side of the vehicle is modified. To have a direct comparison, the right side remains in its initial state. The vehicle is excited by the gravel track with a velocity of 60 km/h.

Figure 4.10 shows the third octave analyses. The microphones at the forced venting outlet are represented by the dashed lines, respectively the ones at the seatbelt outlet by the solid lines. The black measurements are recorded at the left, modified side. The red ones are located on the right, initial side. In the shown example, the left forced venting is closed with a heavy layer. The modification is clearly visible at the microphones at the flap gates in the frequency range of 200 up to 20000 Hz because the intrusion of wind noises is prevented. The levels at the seatbelt outlets are very similar. Only in a few third octaves a level difference is visible. It has to be stated, that the influence of the airborne noise intrusion through the forced venting outlet has to be evaluated as not critical with gravel noise excitation. Subjectively evaluated the high pitch noises are lowered but an influence to the gravel noise is not noticeable.

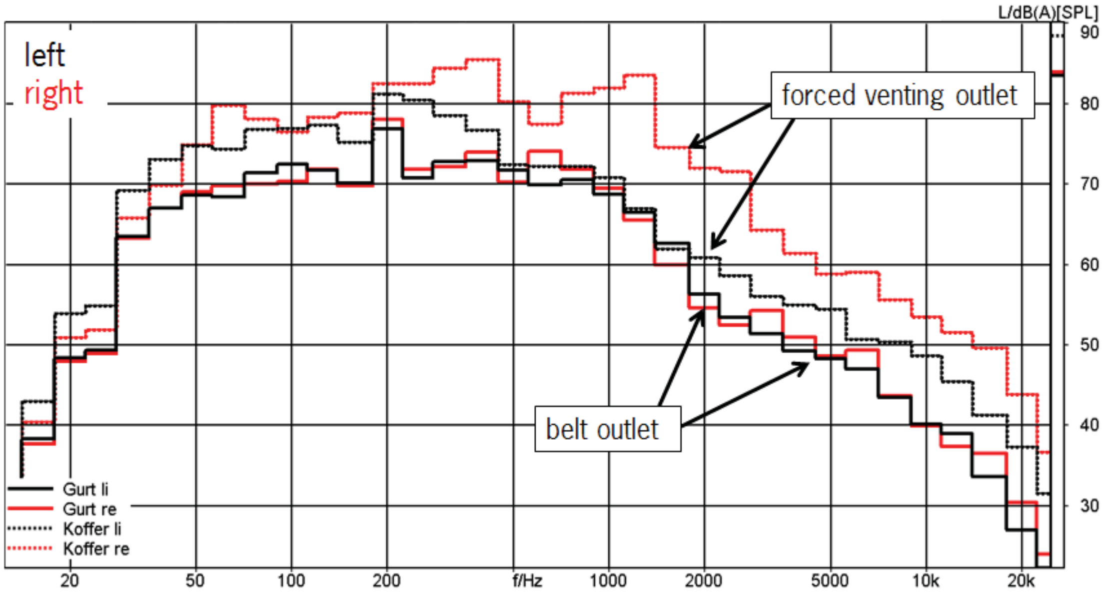

Fig. 4.10. Analysis of the transfer path forced venting to seatbelt outlet.

As further alternations, the hollow cavities behind the interior trim are filled with foam to increase the acoustical absorption and the seatbelt outlet is closed. Both measures have little to none effect to the gravel noise. The subjective impression at the rear seats is that the reverberance is lowered in regards to rolling noise.

The severe influence of the forced venting onto the interior gravel noise is not confirmed. The transmission path from the orifice to the seatbelt outlet has to be rated as not important. The drastic measures have only small influences to the passenger's disturbing noise perception. In regards to the gravel noise, it has to be assumed that the airborne sound is not relevant in this vehicle area. As soon as the vehicle body is excited by structure borne sound, the noise is present in the complete vehicle interior. The conclusion that the excitation of the vehicle has to be prevented instead of treatments of sound transmission paths is targeting.

4.3 Improving the acoustic performance of the wheel house liner

To improve the acoustic performance of the wheel house liner, several materials and material compositions are developed in cooperation with material suppliers. First the material characteristics are determined. The samples are analyzed with the *Apamat* which combines structure and airborne excitation. In addition, the absorption is measured in the alpha cabin. The influences of the materials are then evaluated with prototype wheelhouse liners in road tests.

Materials

The front wheelhouse liner of the current series production vehicle is made of polypropylene injection molding; the rear liner consists of a textile material. The higher damping and absorbing capabilities of the textile material is desirable. Several materials consisting of fibers are selected to increase these properties. In addition, combinations with foil, foam and fleece are investigated. Table 4.11 lists the designed materials and material compositions.

Sample	Description	Company	Thickness [mm]	Weight [g]	Surfacew. [kg/m²]
1	Monolaminate 1200, 3mm	A	2,7	840	1,19
2	Monolaminate 1200 + 2-layer foil, 3mm	A	3,8	1020	1,45
3	Monolaminate 1200 + 3-layer foil + cover fleece, 3mm	A	2,8	1030	1,46
4	Monolaminate 1200 + foam thick, 3mm	A	3,5	1075	1,52
5	Monolaminate 1200 + foam thin + cover fleece, 3mm	A	3,5	1215	1,72
6	additional to sample 1: 3-layer foil + microfiber fleece + 2-layer foil, 3mm	A	2,7+3=5,7	840+465=1305	1,85
7	additional to sample 1: 3-layer foil + microfiber fleece + 2-layer foil, 5mm	A	2,7+5=7,7	840+410=1250	1,77
8	additional to sample 1: 2-layer foil + microfiber fleece + 2-layer foil, 10mm	A	2,7+8,3=11	840+440=1280	1,81
9	additional to sample 1: microfiber fleece, 10mm	A	2,7+8=10,7	840+325=1165	1,65
10	Monolaminate 1200, 5mm	A	5	785	1,11
11	Monolaminate 1200 + 2-layer foil, 5mm	A	5,5	950	1,35
12	Monolaminate 1200 + 3-layer foil + cover fleece, 5mm	A	5,2	1240	1,76
13	Monolaminate 1200 + foam thick, 5mm	A	4,7	1020	1,45
14	Monolaminate 1200 + foam thin + cover fleece, 5mm	A	5,1	1240	1,76
15	additional to sample 7: microfiber fleece, 10mm	A	5+8=13	785+325=1110	1,57
16	additional to sample 7: 2-layer foil + microfiber fleece + 2-layer foil, 10mm	A	5+8,3=13,3	785+440=1225	1,74
17	additional to sample 7: 3-layer foil + microfiber fleece + 2-layer foil, 5mm	A	5+5=10	785+410=1195	1,69
18	additional to sample 7: 3-layer foil + microfiber fleece + 2-layer foil, 3mm	A	5+3=8	785+465=1250	1,77
19	Polyester + Propylate + foam, 1300, 3mm	B	4,5	1015	1,44
20	Polyester + Propylate + foam, 1300, 5mm	B	3,1	985	1,40
21	Propylate 1200, 3mm	B	4,8	1055	1,50
22	Propylate 1200, 5mm	B	3,15	1050	1,49
23	Propylate 800, 3mm	B	2,95	700	0,99
24	Polyester + Propylate + polyester 1300, 3mm	B	4,65	1005	1,42
25	Polyester + Propylate + polyester 1300, 5mm	B	3,3	1000	1,42
26	Propylate NVH 1100, 3mm	B	4,6	695	0,98
27	Propylate NVH 1100, 5mm	B	2,8	670	0,95
28	Sample 28	C	5,5	900	1,28
29	Reference: sheet metal		0,8	4403	6,24
30	Reference: polypropylene		4,3	3020	4,28

Fig. 4.11. The Material properties.

A sheet metal sample and a polypropylene sample which is currently used at the front wheelhouse liner are measured as a reference. In addition the current production series material is shown. The material ingredients are not further described due to confidential information. The samples have a size of 840 mm x 840 mm.

Air- and structure-borne excitation with the *Apamat*

In order to determine the material characteristics, the samples are analyzed in the *Apamat*. The *Apamat* developed by the company *Autoneum* is a window test bench with simultaneous excitation of air- and structure-borne sound which enables an evaluation of the overall effectiveness of acoustic measures. The test bench, shown in picture 4.12 consists of two chambers which are separated by the material sample. Inside the lower chamber two coils catapult standardized metal beads against the material sample. The sound pressure level resulting from the structure- and airborne excitation is measured in the top reverberation chamber. The original measurement procedure was modified. The metal beads impact directly the sample in order to simulate the gravel impact more realistic.

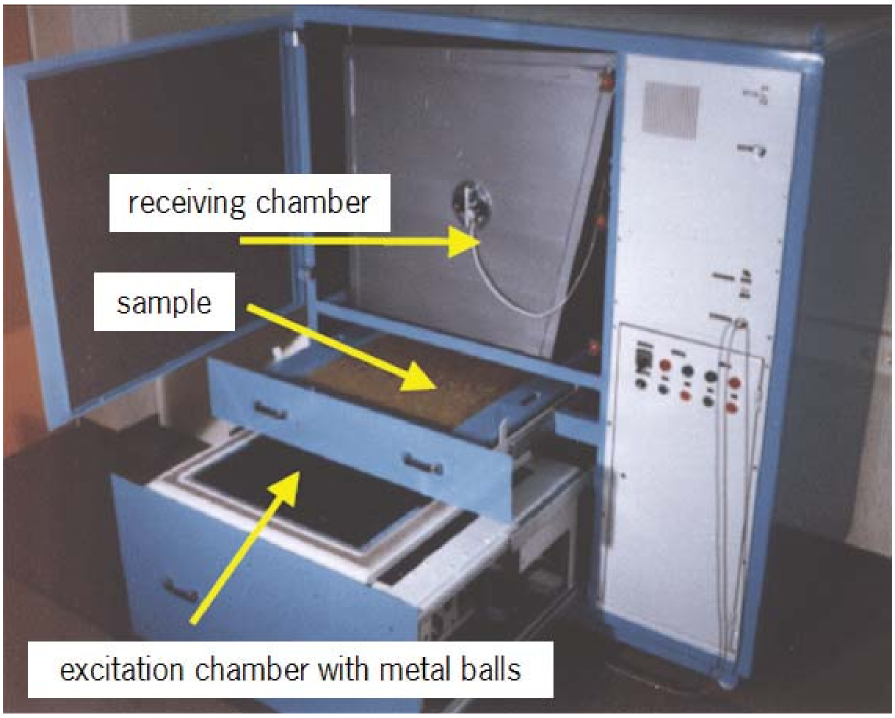

Fig. 4.12. The *Apamat* test bench. [Pel 12]

The materials are divided into the samples with 3 mm and 5 mm thickness to achieve a clearer overview. Figure 4.13 shows the sound pressure levels in the receiving chamber of the *Apamat* in the measurement range of 100 to 10000 Hz of the 3 mm materials.

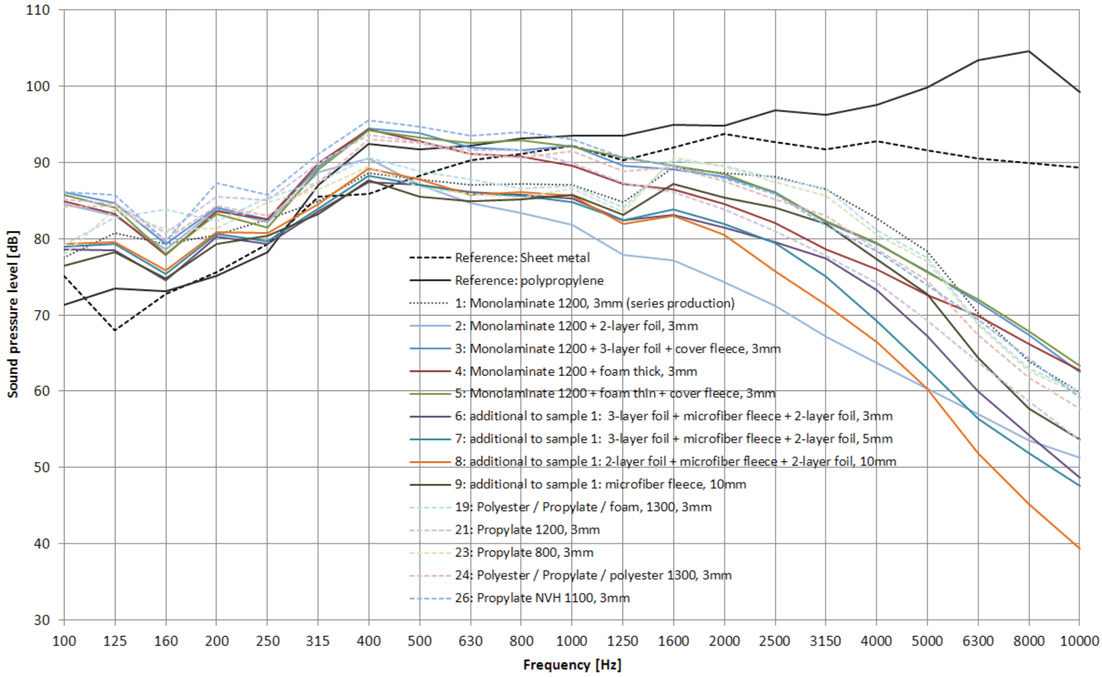

Fig. 4.13. The sound pressure level in the *Apamat* (3 mm samples).

The current series production material is represented by the dotted line. In the high frequency range of 1 to 10 kHz, almost every sample achieves a lower sound pressure level. In the lower bandwidths the samples of company B reach higher levels. Improvements around 20 dB compared to the series production are visible in the high frequency areas. The sheet metal and the polypropylene samples show extensive disadvantages upwards 1250 Hz - the bandwidths which have been identified as relevant for the gravel noise. Sample number 2, the series production material with an attached foil, stands out in the range of 800 to 5000 Hz. Further, sample number 8, which consists of the base material and a wrapped microfiber fleece of 10 mm, achieves low levels from 1600 to 10000 Hz.

Figure 4.14 shows the measurement results for the 5 mm materials. The increased thickness gives an advantage in most cases compared to the 3 mm materials.

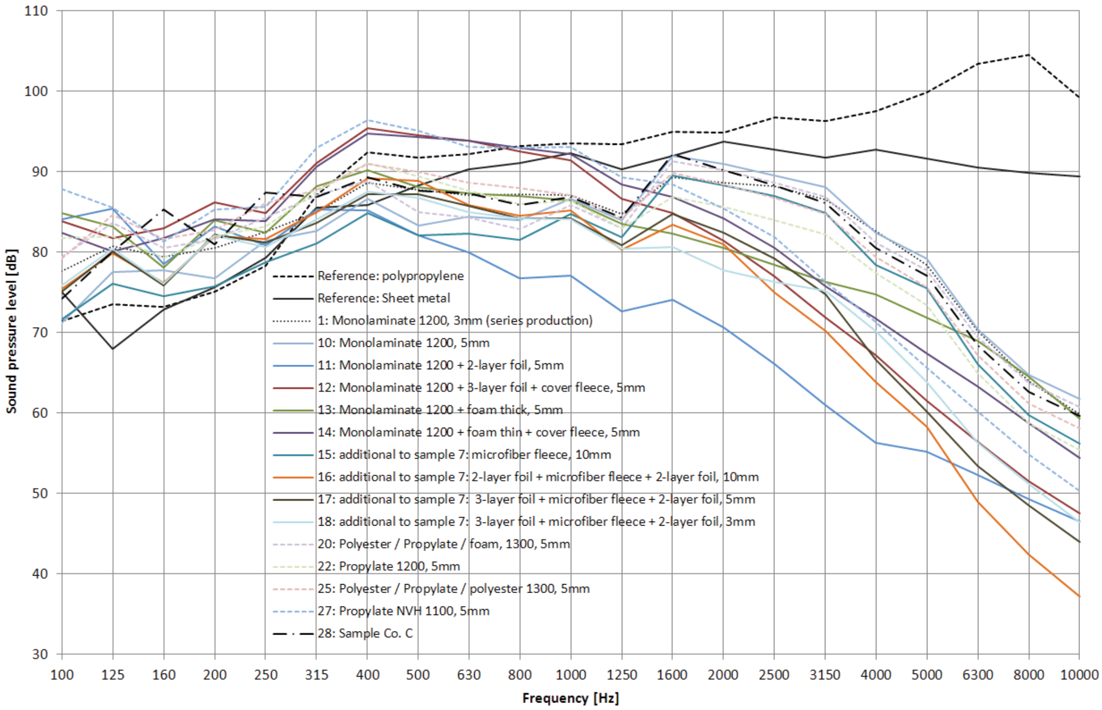

Fig. 4.14. The sound pressure level in the *Apamat* (5 mm samples).

Both graphs show that a combination of a base material with a foil or fleece can have a greater impact onto the sound pressure level than a different fabric material. It must be considered that the restrictions in regards to package and costs are very strict which basically eliminates the 5 mm variants and the samples with a thick additional absorber.

The absorption capabilities

The absorption capability of a material or part is a crucial property in automotive acoustics. The sound energy is transformed into heat energy due to the friction between the air and the material. The higher the absorption the less noise is able to reach the passengers ears. In case of the wheel house liner, the material absorbs rolling noises at the outer side. In the inside, the part absorbs sound energy in the transmission path to the vehicle interior. Due to different specifications to the outside, e.g. resistance to corrosion and abrasion, several materials consist of different layer. In the inside, an additional fleece is able to increase the absorption capabilities.

Fig. 4.15. The alpha cabin.

The Alpha cabin, shown in picture 4.15, is used to determine the absorption characteristics. Sounds in the frequency range of 400 to 10000 Hz are played with three loudspeakers in 15 steps. A rotating microphone measures the sound pressure levels on 4 positions which enables determining the reverberation time. The reverberation time T_{60} is defined as the time in seconds the sound intensity level is reduced by 60 dB which equals the level reached one millionth of its initial value [Sch 96]. The absorption coefficient 4.3 is then calculated with the help of the Sabine absorption formula 4.1 and the complete absorption area 4.2 with V the volume of the chamber, S the area of the sample and T_0 the reverberation time without the absorbing material [Zel 09].

$$T_{60} = 0.161 * \frac{V}{A_S} \tag{4.1}$$

$$A_S = \alpha * (A - S) + \alpha_d * S \tag{4.2}$$

$$\alpha_d = \frac{0.161 * V}{S} * \left(\frac{1}{T} - \frac{1}{T_0} * \frac{A - S}{A} \right) \tag{4.3}$$

The samples are measured in a steel frame with a height of 25 mm to cover the sides of the samples and guarantee that only the surface absorbs energy. The materials are situated directly on the ground. Both sides are measured. A setup with a cavity between sample and ground, which equals the assembly in the vehicle, could be discussed for further evaluation of the materials. The samples are divided into the 3 mm and 5 mm base materials for a clearly arranged comparison.

As mentioned before, the side directed to the wheel and road absorbs emitted rolling noises which otherwise are transmitted via several transfer paths into the vehicle interior. Figure 4.16 shows the absorption coefficient over the frequency range for the road side of the 3 mm samples; respectively figure 4.17 for the 5 mm materials.

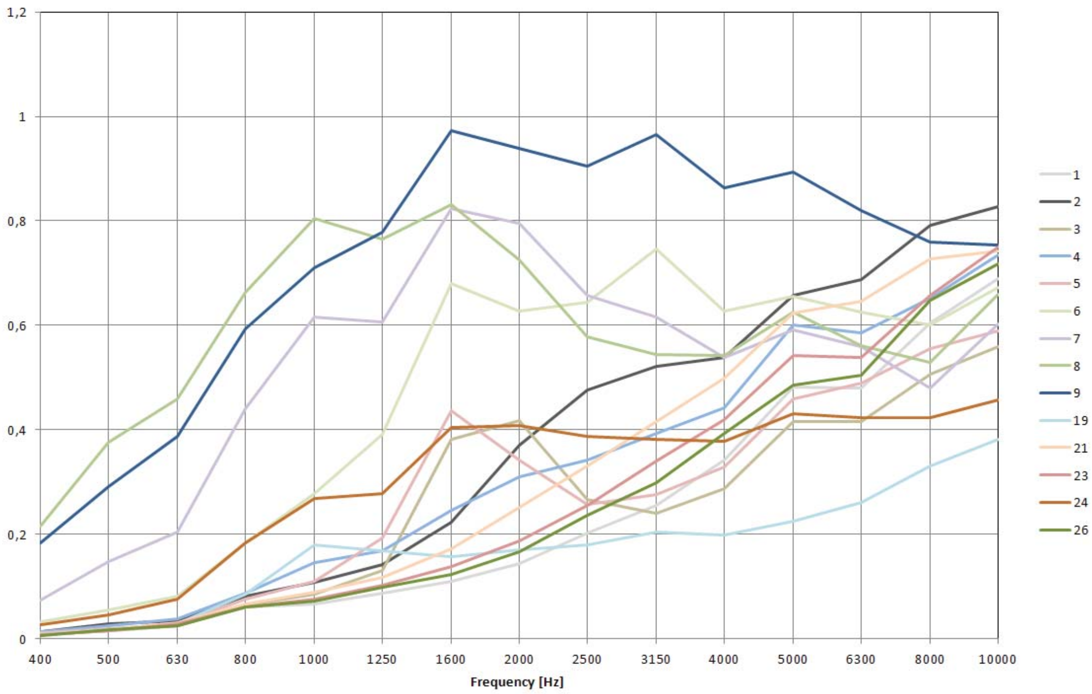

Fig. 4.16. The absorption coefficient of the 3 mm samples (road side).

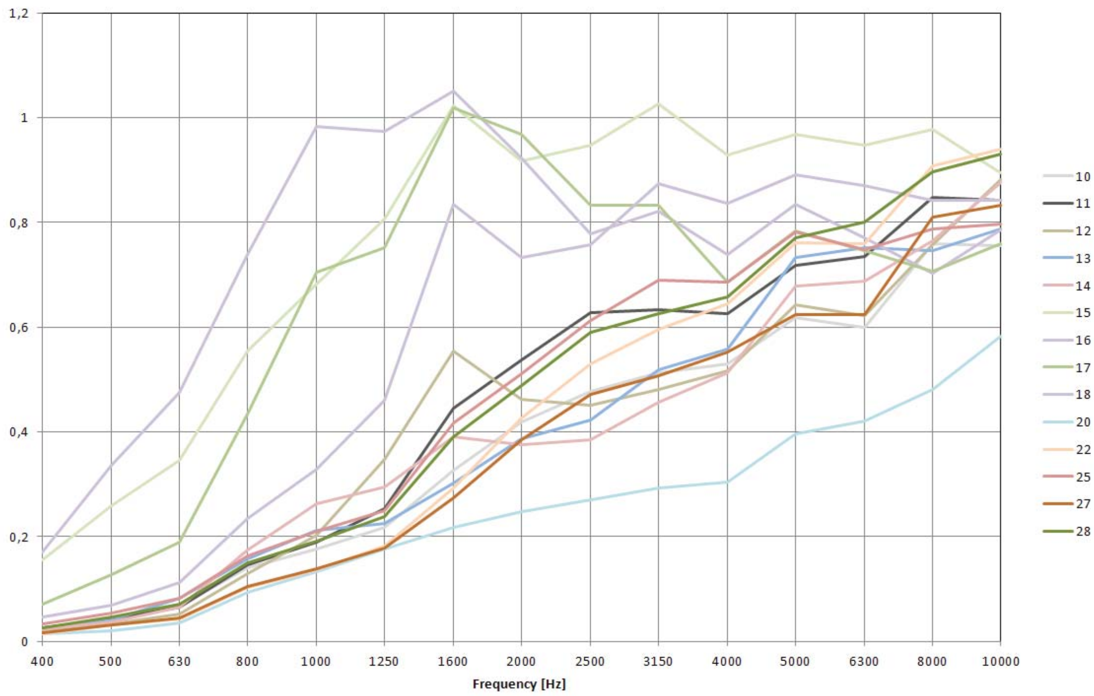

Fig. 4.17. The absorption coefficient of the 5 mm samples (road side)

The graphs show that the additional soft fleeces increase the absorption immense, especially in the lower frequency bands. This indicates that the sound interfuses the base material. The 5 mm samples show increased values. Generally a thicker material results in a greater absorption since the sound waves passes more surfaces which enables more energy to dissipate into heat.

The side directed to the vehicle body absorbs noise energy on the transfer path to the passengers ears. Figure 4.18 shows the absorption coefficient over the frequency range for the road side of the 3 mm samples; respectively figure 4.19 for the 5 mm materials.

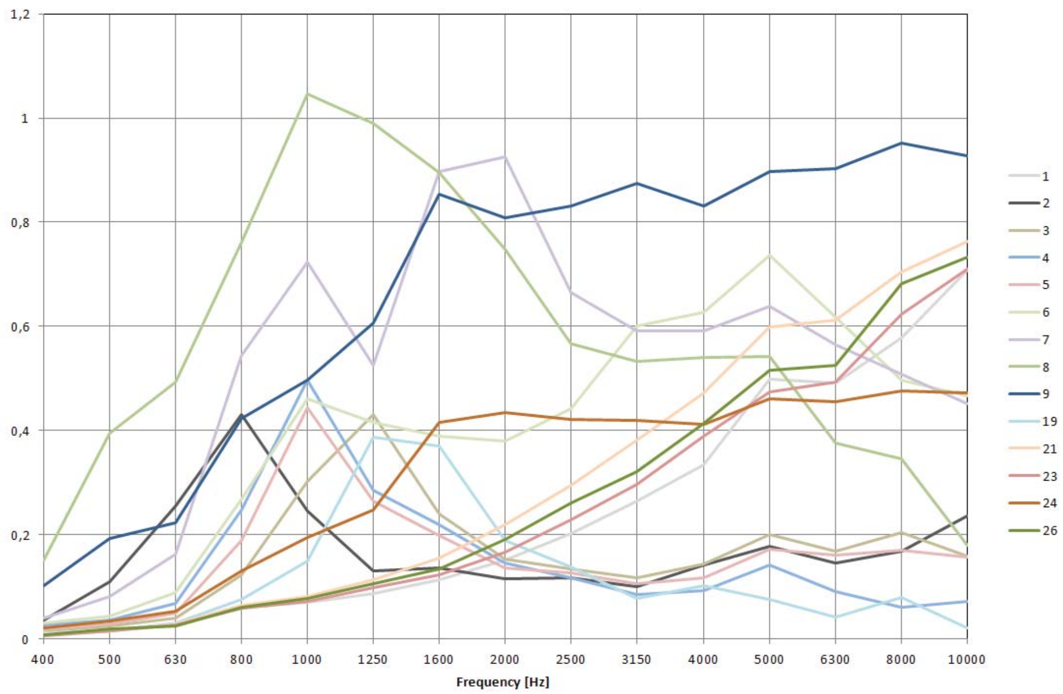

Fig. 4.18. The absorption coefficient of the 3 mm samples (road side).

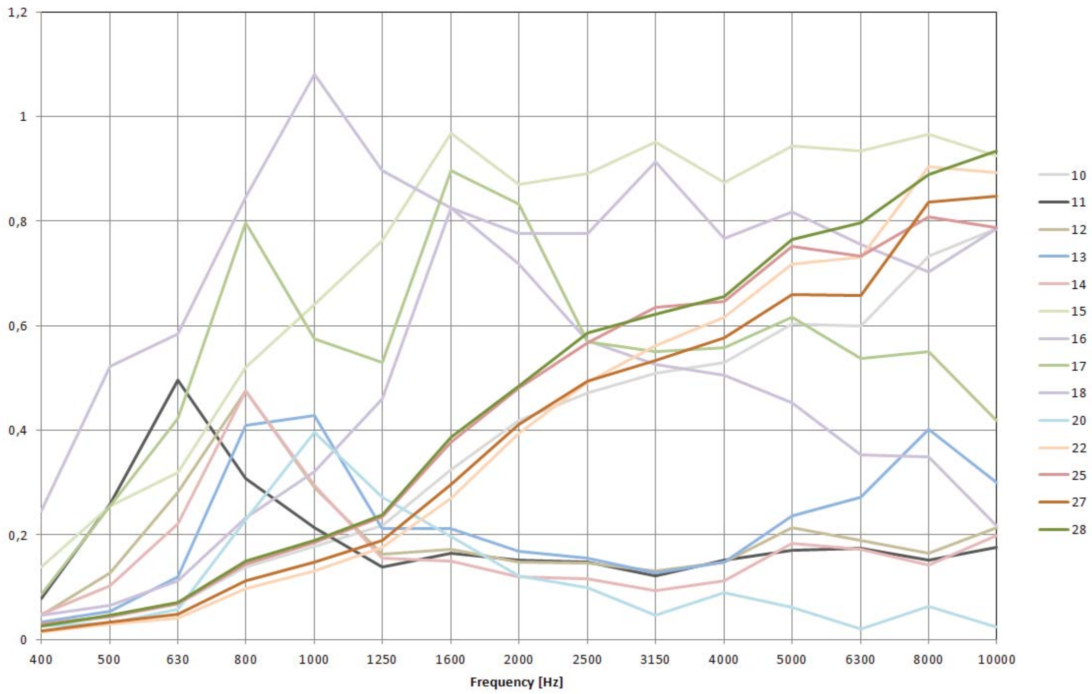

Fig. 4.19. The absorption coefficient of the 5 mm samples (road side).

The additional foils or foams close the pores of the base material and prevent the sound waves to intrude, which hence prevents the reduction of the sound energy. This effect is visible for sample numbers 2 to 5, 11 to 14 and 19 to 20. After a slight peak around 800 to 1250 Hz, the absorption drops again under 0.2. As seen on the side directed to the road, the additional absorber increases the absorption massively. The absorption of the series production material, sample 1, rises steadily over the frequency range 400 to 10000 Hz. Similar materials compositions show the same absorption behavior with slightly increased values. Again, the increased material thickness, e.g. 3 to 5 mm, results in an increased absorption due to the before explained mechanism.

The advantages of the combinations of the conventional wheel house liner materials and a foil or foam measured with the structure- and airborne excitation in the *Apamat* have disadvantages at the absorption capabilities. In regards to gravel noise, the insulation function is favorable. To reduce rolling noises an absorbing effect has to be achieved, hence a compromise between the insulation and absorption function has to be met. A composition with a foil and an additional absorbing material at the inside is recommended. Though, specifications as stiffness, resistance to abrasion, corrosion and absorption of water are decisive criteria for the selection of the materials for wheelhouse liners or underbody covers and will most certainly eliminate several material samples.

From material level to the complete vehicle

In order to investigate the influences of the differences on material level at the complete vehicle, wheel house liner prototypes are manufactured and measured in road testing. Only the left rear wheelhouse liner is available in selected material samples due to restrictions at the suppliers. To be able to evaluate only the influence of one wheelhouse liner, the gravel noise relevant surfaces at the test vehicle are masked and the left rear passenger microphone position is regarded.

Prototypes of material sample number 20 and 27 are tested. Sample number 20 is a combination of polyester, propylate and foam. Material number 27 is made of a very soft propylate and originally designed for maximum advantages in gravel noise performance. In addition the maximum possible acoustic potential of the single wheel house is measured with the foam also masking the rest of the car. Picture 4.20 shows the different wheel house liners, prototype number 27 mounted at the test vehicle and the masked side of the car in order to prevent single stone impact events bias the measurement results.

Fig. 4.20. The wheelhouse liner prototype investigations.

Figure 4.20 shows the measurement results for the microphone position on the rear left seat - the closest position to the altered wheel house. The tests are performed at the gravel track in Weissach. The vehicle speed is 60 km/h. Four measurement runs are recorded and averaged.

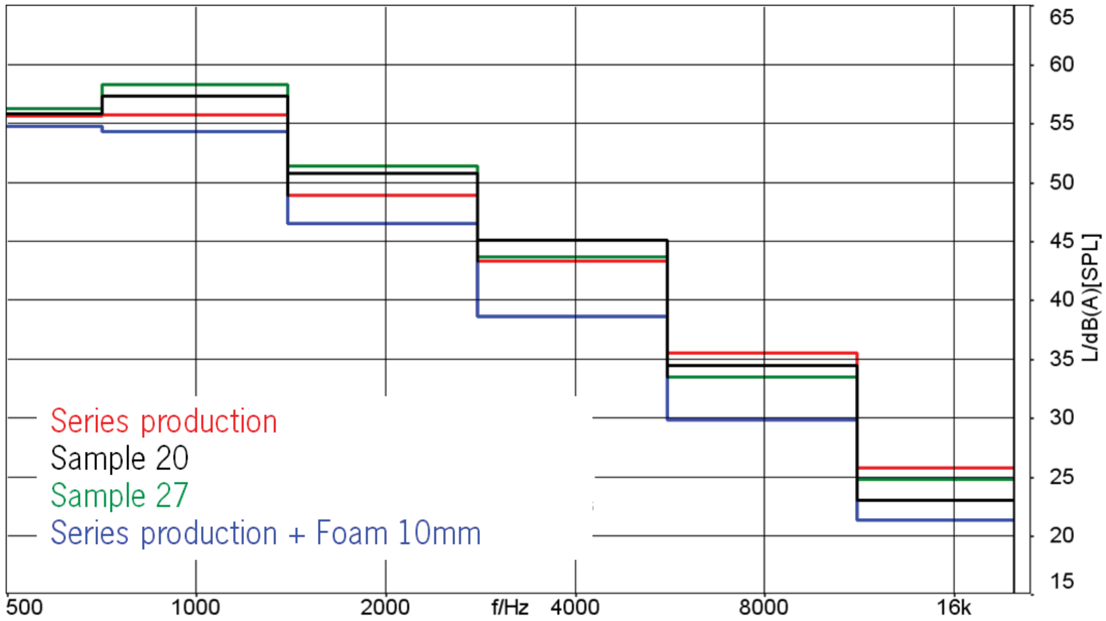

Fig. 4.21. The interior noise levels with altered wheelhouse liner.

The interior noise levels show differences around 5 dB in several octaves between series production and the foam added as maximum acoustic potential. This improvement has to be evaluated as crucial. The octave levels of the vehicle with the wheelhouse liner prototypes reside around the levels of the series production part. No real advantage can be determined which is underlined by the subjective driving impression. It has to be stated that the boundary conditions with only one available prototype are not optimal and that the influence of both liners might be greater and detectable.

The advantages of the developed materials proven on material level with structure- and airborne noise excitation in the Apamat as well as in regards to the absorption measured in the Alpha cabin could not have been confirmed on complete vehicle level. But the promising approaches have to be followed up to improve the properties of single parts step by step in order to influence the total vehicle performance.

4.4 Developing a countermeasure for the sill panel

The crucial influence to the gravel noise of the sill panel has been proven in the sensitivity analyses. Especially the location directly in the stone trajectory path of the front wheels which results in a high excitation identifies the sill panel is a main contributor to the disturbing noise. Hence, in the following section the sill panel is investigated and approaches to reduce the noise are evaluated.

To identify which parts of the disturbing noise are caused by structure-borne sound and which ones are airborne sound, the sill panel is decoupled from the vehicle. This is achieved with a foam between the plastic sill panel and the sheet metal body. The panel is then attached with tape to prevent excitation through the mounting points. In regards to series production countermeasures, the decoupling could be realized with decoupling mounting elements made of rubber components.

In addition, to evaluate the acoustic potential, the sill panel is masked completely and only the part which is located under the body e.g. the part which is not seen by the customer and therefore is more suitable for countermeasures. All other surfaces at the test vehicle which are relevant for the gravel noise are masked. The vehicle velocity is 60 km/h at the gravel test track in Weissach.

Figure 4.22 shows the interior noise levels at the front left microphone position of the earlier described variants.

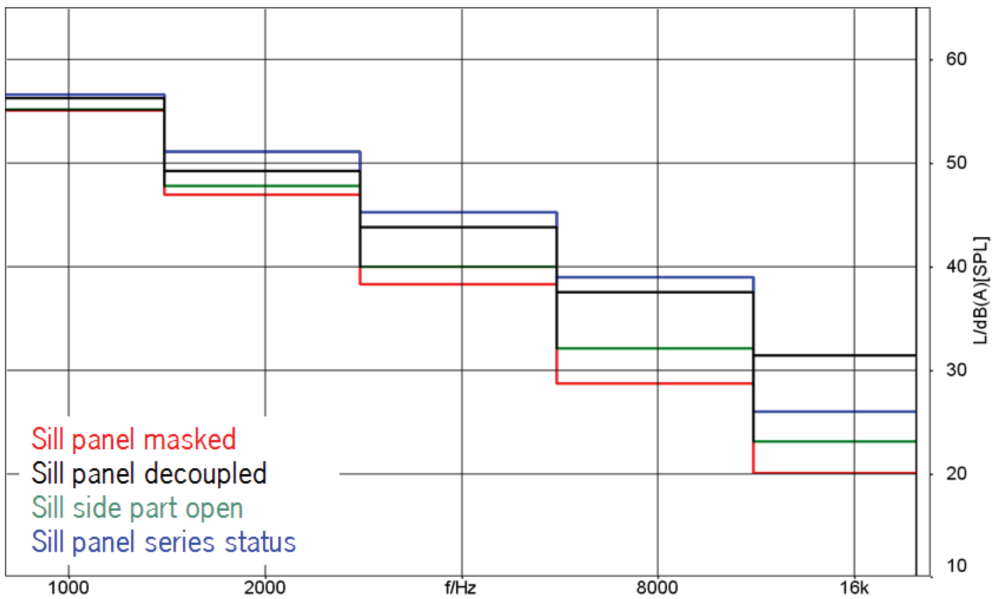

Fig. 4.22. The interior noise levels of the different sill panel variants.

The octave levels of the decoupled sill panel resides only slightly lower than the ones with the series production vehicle mounted panel which indicates most of the disturbing noise resulting from airborne sound. The impact of the gravel and small stones on the plastic surface produce the sound which than is transfered through acoustic weak spots, e.g. door seals and windows, into the vehicle interior. The enhancement in the 16 kHz in regards to the standard panel was subjectively noticeable but the reason could not be clarified.

The difference between the sill panel in series status and in completely masked condition is considerable. The 8 kHz octave is 10 dB lower respectively the 4 and 16 kHz octave 6 db and the 2 kHz octave about 2 dB. Opening the visible part of the panel at the side of the vehicle the octave levels rise about one third in relation to the completely covered part. This means the major part comes from the underbody, which, as mentioned before, is treatable more easy with measures.

Picture 4.23 shows the modifications at the sill panel as a first step to develop a countermeasure feasible for series production. The left picture shows an applied foam in the not visible area beneath the car. The width has been reduced to a size of 45 mm to just cover the indention. The right picture shows a taped Ethulene Propylene Dien Monomer rubber band with the same width but only a hight of 2,5 mm.

Fig. 4.23. The sill panel with countermeasures.

Figure 4.24 shows the reductions of the interior noise levels at the rear right microphone position of the two described variants. Both modifications result in level decreases in the 2 to 8 kHz octaves around 4 to 5 dB with the rubber showing only a slightly less reduction. This indicates that the stones have to be prevented from impacting the hard plastic of the sill panel which results in the disturbing noise.

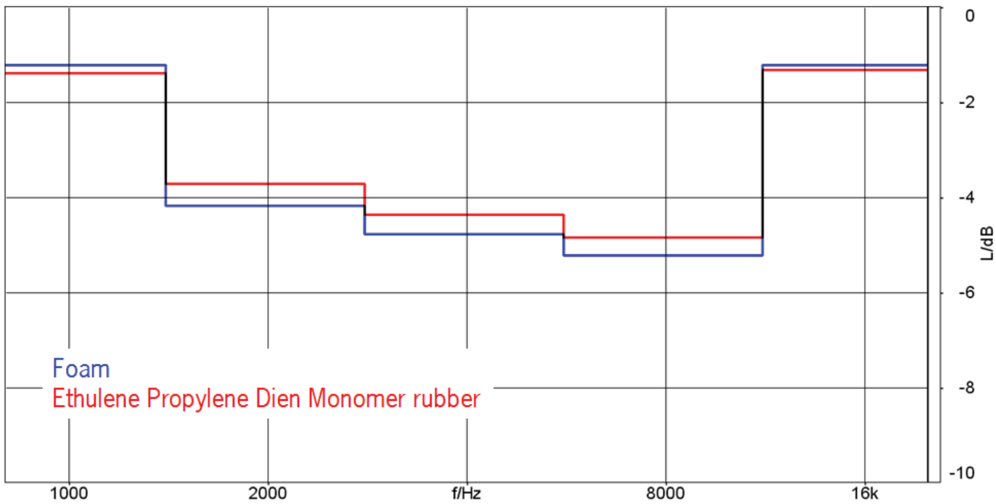

Fig. 4.24. The interior noise level reductions of the sill panel countermeasures.

Also in regards to package and ground clearance acceptable, since located in the indention, the EPDM rubber band is a suitable countermeasure for series production. The mounting could be realized with a powerful adhesive.

4.5 Developing countermeasures for a new vehicle

A not valuable gravel noise performance and an increased rear-compartment transparency lead to complaints in a concept phase of an upcoming vehicle. A package of measures is developed to achieve a higher quality interior noise. The process is accompanied up to production line level parts.

After the discoveries in the road test, described in chapter 2, the investigations are based on a combination of the different gravel excitations. In addition, subjective evaluation on distributed sand is a very crucial tool to develop the countermeasures.

A similar sensitivity analysis, as described in chapter 2.2, is conducted. In addition to the surfaces, which are relevant for the gravel noise and have been identified on the gravel track, areas are subjectively recognized in normal driving conditions with removed interior trim. Without the interior covers, it is possible to locate gravel impacts at the vehicle. The following segments are defined: sill panel, battery compartment, rear door, fuel tank, rear strut and rear axle carrier. All effected parts of the vehicle are masked with self-adhesive fleece. Further, the cutout in the rear wheelhouse liner is closed to prevent gravel tossing against the exhaust system and a separation is implemented into the rear end body part to build a maze towards the forced venting outlet.

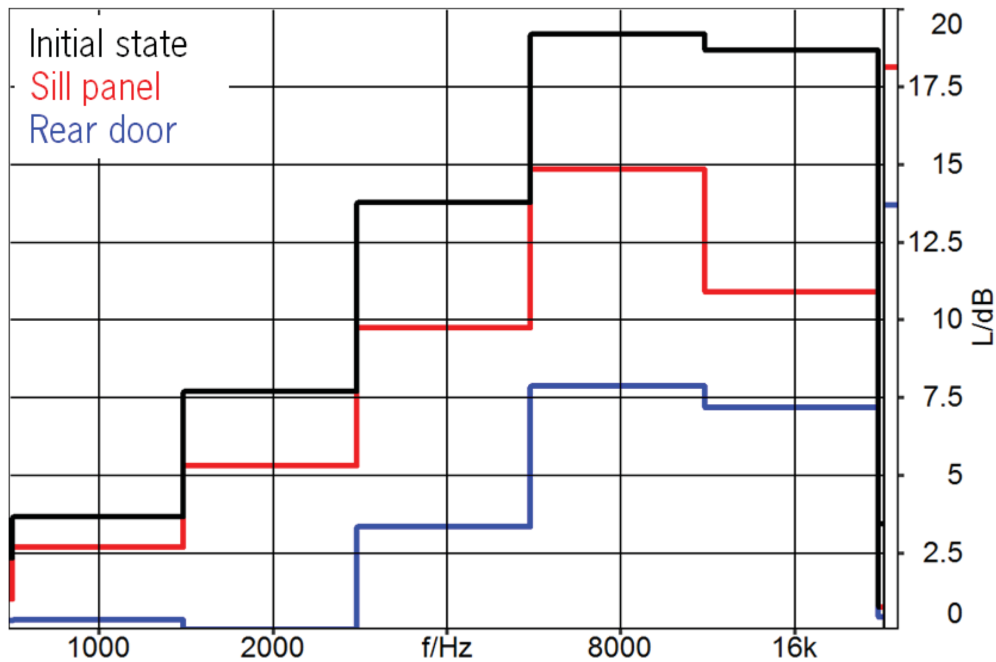

Fig. 4.25. The interior noise levels of the unmasked sections.

With the excitation of the larger gravel at the test track in Nardò at a velocity of 60 km/h, the windows are unmasked and the influence on the interior noise level of each section is measured. Figure 4.25 shows the interior noise octave levels at the rear right passenger position in relation to the levels with the completely masked vehicle. Again, each window is measured in direct comparison to the fully covered vehicle in order to minimize influences of the gravel track condition. The average of 4 test runs is calculated.

The black graph illustrates the difference between all segments masked with the fleece and the vehicle in its initial state. The interior noise level is lowered up to 19 dB in the 8 kHz octaves. The measurements indicate a high influence of the sill panel. The second and only further objective measurable segment is the rear door. The impact of the remaining sections to the interior gravel noise is not noticeable with the excitation at the gravel track in Nardò. It has to be assumed that the bigger stones are catapulted tangential away from the tire contact patch which automatically leads to a primary excitation of the sill panel and rear door.

The existing gravel track at the test center in Nardò imposes majorly the excitation of the sill panel and rear door which does not completely represent the excitation in real driving situations. The mixture of small stones, gravel and sand excites further and different parts of the vehicle. To finish the development of a suitable, functional package of measures, the subjective evaluation in normal driving conditions is used to verify the prior established measures.

Fig. 4.26. The preliminary realization of the countermeasures.

The determined measure package has to be defined under acoustic, realizable and economic reasons. A compromise has to be found. The final package consists of a fleece inside the sill panel, the closed rear wheelhouse liner, the covered battery compartment and an additional absorption above the exhaust system.

Picture 4.26 shows the preliminary realization of the countermeasures. The closed wheelhouse liner is shown in the upper left picture, the absorbing fleece which is attached above the exhaust system and the covered battery compartment on the upper right. The fleece inside the sill panel is shown in the picture below.

The final measure package is compared to the initial status of the vehicle. In addition three competing cars are measured. Graph 4.27 shows the interior noise spectra at the gravel track in Nardò. The measurement velocity is 60 km/h. Since the rear transparency is in focus, the recordings of the microphone located at the rear right seat is pictured.

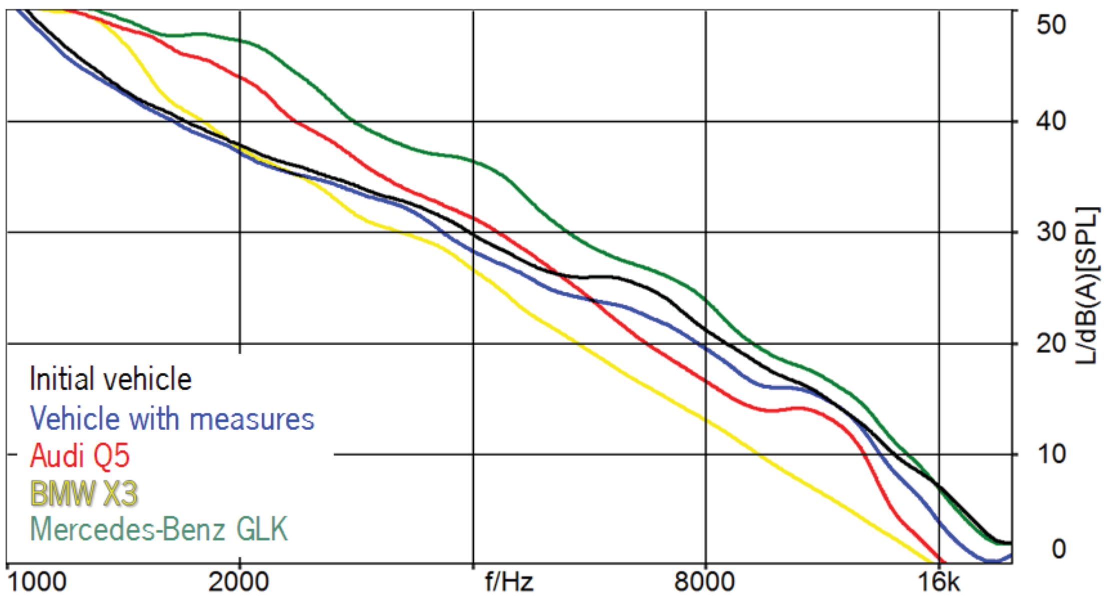

Fig. 4.27. The interior noise spectra at the gravel track.

The graphs indicate only a small improvement between the initial vehicle and the vehicle with applied measure package. As discovered before, the bigger gravel primarily excites the sill panels, which leads to the assumption that on this test track the only effective measure is the fleece inside the sill panel. Competitor 3 tosses the most stones which is reflected in the highest interior sound level. In opposite competitor 2 has the lowest level, due to only a few gravels impacting the vehicle.

Since the gravel track with the bigger stones has proven to be not optimal and not completely covering the complaints regarding rear-compartment transparency and sand trickling, a provisional test track is installed. With the small stones from Weissach, a track of approximately 50 m is dispersed. To achieve an increased measurement time, the velocity is reduced to 40 km/h which still leads to a sufficient excitation. With much effort and labor with the broom, a reasonable reproducibility is achieved. Graph 4.28 shows the measurement results at the rear right passenger position.

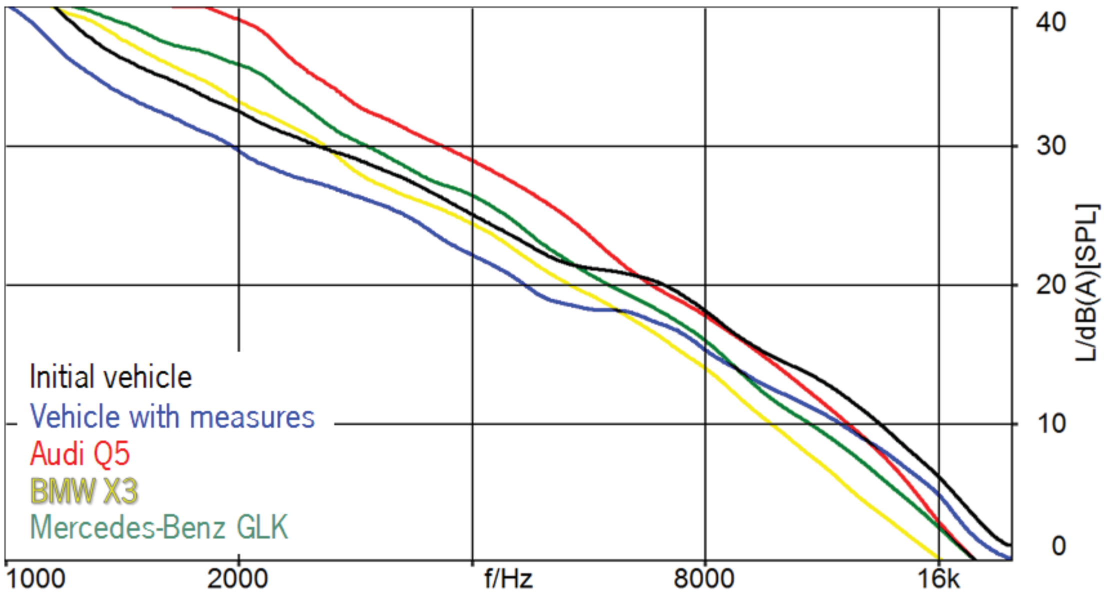

Fig. 4.28. The interior noise spectra at the provisional track.

The distance between the initial vehicle and the modified one increases. With the excitation of the small stones, the countermeasures take expedient effect. The interior noise level is lowered across the whole relevant frequency bandwidth with approximately 3 dB. In the range of 1 to 6 kHz, the new vehicle with measures clearly sets the benchmark. Competitor 1 achieves the highest interior levels here. From 6 to 16 kHz competitor 2 performs best.

The success of the development of the measure package can be proven with the objective measurements and subjective evaluations. The initial state is improved significantly. In some disciplines, the benchmark in the according vehicle segment can be set. The further steps are to estimate the possibility to implement these parts into series production and, equally important, the costs.

5

Conclusion und prospects

The simple sounding issue of gravel noise has shown to be a very complex and specific topic. In the introduction to the gravel noise, the problem is described and the relevant frequency bandwidth of 1 to 20 kHz is determined. Hence, the following analyses are concentrated towards this range.

The extensive road testing brought insights about what parts and surfaces of the vehicle influence the gravel noise at most. With the preceding investigations of the boundary conditions it was possible to ensure the reproducibility and accuracy of the measurements. The benchmark measurements revealed the acoustic performance of competing vehicles. With the different gravel noise behavior of the vehicles, which were objectively and subjectively evaluated, a discussion was conducted. A vehicle where only a few stones impact the body, which means there is almost no excitation, is rated well. But it is also possible to achieve a high quality interior sound with gravel hitting the vehicle and countermeasures and / or enough damping to reduce the disturbing noises. Further, with the help of the benchmark measurements, a procedure for a target value definition for vehicle specifications in regards to gravel noise is defined. Due to the fluctuations of the boundary conditions and hence influence to the interior noise levels, it is stated that it is necessary to refer to a reference vehicle to ensure that the target values are valid for following models and with different boundary conditions, e.g. on a different track. It is not possible to define an absolute value.

Due to the costs, effort and difficulties with reproducibility of the complete vehicle road tests, a method to experimentally simulate the gravel excitation is researched. Different approaches are evaluated. Each methods has its advantages and disadvantages. The determining of the vibro-acoustic transfer functions with the impulse hammer delivers a good reproducibility with only slight disadvantages in the frequency range. Further the excitation with the electric blower and the plastic granulate is promising to simulate the gravel noise realistically.

The excitation with the electric blower and the granulate also lays the fundamentals for the developing of countermeasures. The maximum potentials of improvements of the identified weak spots are determined with drastic measures.

The thesis that the transmission path of the forced venting to the seatbelt outlet has an immense influence to the gravel noise was disproved. Several concept tests showed that the direct connection between the outside and vehicle interior is not as important as expected. More important is the prevention of the impact of the stones and hence the excitation of the vehicle body, wherefore the following countermeasures aim in this direction. The material analyses showed potentials for improvements for the wheel house liners. Recommendations for material selection for upcoming vehicles were given. A measure for series production to reduce the excitation of the sill panel was presented. A new vehicle type was improved by several countermeasures. The success was proven in a benchmark where the vehicle could achieve the best ranking.

Although the limitations from design, function and costs are very strict, the project improved the gravel noise behavior of the vehicles and gave impulses to further improve the acoustic performance in regards to the disturbing noises. But improvements are still requiered. Each affected part of the vehicle has to be further improved step by step to achieve a high quality interior gravel noise. It has to be stated, that so far only the complete vehicle testing enables to evaluate vehicles and countermeasures concerning gravel noise and hence the experimental simulation has to be further investigated. The excitation of a local area at the vehicle does not represent the overall acoustic impression in the complete vehicle.

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List of Figures