DOI: 10.61782/fa.2023.0225

ADAPTING INTERIOR NOISE-BASED METHODOLOGY FOR PASS-BY NOISE TESTING

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ABSTRACT

Exterior pass-by noise (PBN) compliance is a seemingly simple topic governed by strict regulation from governing bodies. In recent years, an emphasis on the effect of noise pollution on health, particularly in urban areas, has led to stricter legislation. Traditional pass-by test methods can tell manufacturers if the vehicle has obtained a level lower than the stipulated value but is unable to provide insights into why a failure might have occurred.

Adler Pelzer Group has an existing test-based methodology called Acoustic DNA which can optimize NVH trim for interior noise problems through airborne source ranking and body panel contribution analysis. Following an extensive development project, carried out in conjunction with customers, this technology has been enhanced to identify which source and transfer path on a vehicle is causing peaks in the overall level during pass-by. In combination with advanced acoustic simulation, system targets and associated NVH trim for PBN can be optimized throughout the vehicle development cycle.

Keywords: *methodology, pass-by, acoustic.*

1. INTRODUCTION

The Acoustic Diagnostic Network Algorithm (DNA) is an experimental method combined with proprietary solvers for the measurement then determination of the isolated radiating sound power of airborne sources of a motor vehicle.

When combined with serial and parallel transfer functions, the contribution of each source to the cabin noise level is calculated both as a direct source-path-receiver response and via the parallel approach, of each body panel of the vehicle.

Whilst the source-path-receiver decomposition concept has been known for many years, there was no single test-based computer program that quickly answered typical NVH questions – what treatment needs to be installed to solve the noise problem or alternatively, what can be removed without making serious noise level increases? Acoustic DNA allows engineers to identify key sources on the vehicle, determine the major noise paths into the vehicle cabin, and then virtually optimize its NVH trim to attenuate cabin interior noise.

The main benefit of this technique is that using a set of acoustic transfer functions and proprietary algorithms, all crosstalk between the sources during vehicle operation is removed. In a similar fashion, the transmission loss of the vehicle's body panels can be quantified without requiring any destructive measurements.

Over the past 25 years this technique has been extensively validated through confidential customer projects and the methodology itself continues to evolve based on customer and market demands [1]. Due to the introduction of stricter PBN legislation in the EU [2], OEMs are now under pressure to make large reductions in pass-by noise levels. Due to the difference in noise source dominance compared to interior noise, and the difficulty in adding new NVH components to the exterior of the vehicle, a concentrated effort has been required by the industry to find the optimum approach to complying with the new legislation.

At the time of commencing our development of the Acoustic DNA PBN methodology around 2007, there were very few commercial offerings. Especially those that extended the direct overall measurement of PBN on the PBN track into a detailed understanding of the vehicles isolated noise sources and external transfer paths. This information is crucial to any optimization process concerning the NVH package. The companies first publication in 2009 [3] gave a detailed example of the technique and over the years this has been

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enhanced by the introduction of faster, adaptive, crosstalk isolation algorithms together with more powerful calibrated sources and vehicle location technology. This has enabled the method to progress from novel research into a day-to-day project-based activity.

Since the DNA method produces isolated airborne radiated source powers, the only requirement to adapt the method to PBN was to add a comprehensive set of spatial acoustic transfer functions relating to the vehicle's position on the PBN track. Combining the radiated sound powers with the spatial transfer functions and the correct vehicle location created a prediction of the PBN level together with information relating to the source ranking. If simultaneously the traditional response is measured at the left-hand and right-hand 7.5 m microphone locations, then the prediction could be validated accordingly. This paper is split into four subsequent sections. It introduces the concept of Acoustic DNA and the necessary data acquisition system. Then briefly discusses the proprietary process used to isolate each noise source on the running vehicle. Next it discusses the measurement of noise radiation into the far field using exterior spatial transfer functions. Once the complete dataset is obtained it is post processed in a bespoke cloud-based application where ranking of sources and transfer paths can be examined, and an optimization algorithm applied to create potential noise reduction solutions. The final section deals with transferring this knowledge to a particle tracing simulation application where detailed material modifications to NVH components can be assessed prior to validation testing.

2. BACKGROUND TO ACOUSTIC DNA

The sound pressure levels inside an operating motor vehicle cabin are generated by a combination of structural and airborne contributions. These originate at a variety of sources, travel along an assortment of paths, and are received at the ears of the occupants from several different directions. Whether the sound received is ultimately determined as noise, or unwanted sound, is dependent on the subjective appreciation of the occupants. The type of sound spectrum inside a vehicle cabin can also be a valuable sales attribute for a motor vehicle manufacturer, as it represents a vehicles' acoustic character which can be used to differentiate a mark or model from another.

In the 1990's NVH systems of prototype vehicles were generally developed using the "systems engineering approach" envisaged by the Ford Motor Company. This required each body system to be removed from a donor vehicle and installed in a transmission loss suite where various treatments were examined. This together with full vehicle SEA models enabled the NVH package to be optimized. Whilst this approach was successful, it was costly, time-consuming, and required actual vehicle hardware to be dismantled and consequently destroyed. The Acoustic DNA method was created by the authors in 2001 so that system engineering information could be obtained, quickly and accurately without the need to dismantle vehicle hardware. System acoustic performance from the DNA was originally fed into SEA full vehicle models but the latest application includes a virtual SEA model environment with a rapid optimization routine that uses a proprietary function called the "S-curve" which happens to resemble the "principle of least action" as described by the famous physicist Richard Feynman [4]. The DNA name was chosen to be easily remembered and derives from the term for the human genome and subsequently this term has been used by high brand OEMs in advertising campaigns ever since.

Unlike Transfer Path Analysis (TPA), Acoustic DNA provides the complete airborne breakdown of the source-path-receiver environment of a test vehicle and more importantly which component, or area, of the acoustic treatment package, body-in-white, or sub-system needs to be modified to produce improvements, either in noise or cost and weight.

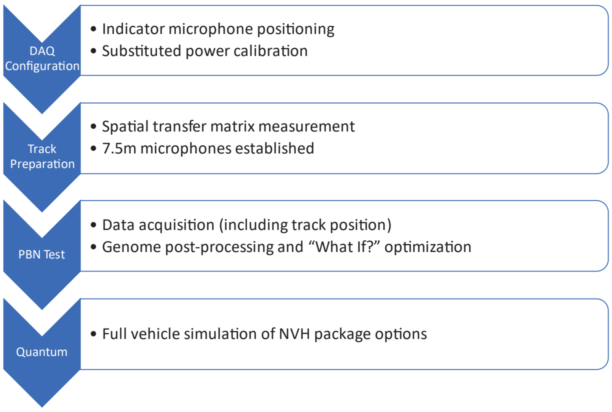
Acoustic DNA operates for airborne noise between the frequency range of 200 Hz – 10 kHz in third octaves. This apparent limitation doesn't restrict the effectiveness of the technique, from a component supplier point of view, as the specified frequency range relates to the typical expected performance of NVH components. When the technique was originally developed only internal combustion engine vehicles were available but due to the recent trend of electrification, and the presence of strong tonal noise, the method has been extended to examine fine frequency.

Modeling techniques such as Statistical Energy Analysis (SEA) have many similarities to Acoustic DNA testing. If required, all responses from Acoustic DNA can be input directly into mainstream SEA software to act as hybrid data. Also, our bespoke modeling technology, discussed later, takes advantage of data from Acoustic DNA testing. The main advantage of Acoustic DNA being the speed of testing and subsequent interactive optimization which is an order of magnitude faster than a full-vehicle SEA model whilst also being self-validating as the cabin noise prediction is solved twice, once for the direct component and a second time for the parallel transfer, mimicking an SEA model.

3. MEASURING PBN USING DNA METHODOLOGY

3.1 Typical Project Workflow

Table 1 shows a workflow for a typical PBN project from initial DAQ configuring through Genome optimization and further model simulation. These are discussed further below.



DAQ Configuration	Indicator microphone positioning Substituted power calibration
Track Preparation	Spatial transfer matrix measurement 7.5m microphones established
PBN Test	Data acquisition (including track position) Genome post-processing and "What If?" optimization
Quantum	Full vehicle simulation of NVH package options

Table 1. PBN Work Flow Diagram.

3.2 Data Acquisition System

The data acquisition system (DAQ) used for Acoustic DNA is a high channel count digital recorder and spectrum analyzer fully contained within the test vehicle cabin. The operating sound power of the various noise sources of the test vehicle, including the power unit and tyres are measured using proximity microphones, called indicators which are calibrated using the source substitution method via a powerful calibrated tube source [5]. However, this method has the disadvantage that each microphone can pick up cross talk from nearby sources making it difficult to isolate any noise source to a single indicator. To eliminate cross talk a cross transfer matrix SPTF is measured between all indicator microphones and source locations. Once the vehicle is operating, sound pressure levels are recorded from the indicator microphones. A cross talk removal algorithm calculates what the sound power level would have to be from each source to re-create the operational sound field whilst also accounting for the crosstalk factors between each source and each indicator microphone. Whilst a matrix inversion would appear to be the ideal solver for cross talk removal this was not the case as the solve can become unstable. A proprietary technique was developed to remove crosstalk rapidly and accurately, and this has become part of the author's company IP.

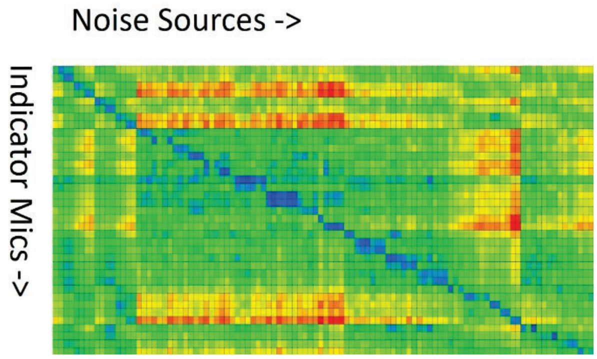


Figure 1. The diagonal component of Diagnostic Assurance Criterion (DAC) establishes the relationship between sources and indicator microphones.

The correct juxtaposition of each indicator microphone to each potential noise source is essential to an accurate result and to ensure the quality of this procedure, an analysis called the "Diagnostic Assurance Criteria" (DAC) is used which identifies problematic microphone positioning and enables microphones to be re-positioned as required. The DAC represents the sound propagation transfer function between each indicator microphone and each substituted source location and is required to have a strong diagonal sensitivity meaning that at least one indicator microphone is audibly "seeing" each source. This is calculated by examining the negative value of the SPTF which occurs when the SPL at an indicator is numerically higher than the input sound power level from the calibrated tube source. This shows that the indicator is sufficiently close to the noise source. A strong blue diagonal on the DAC, see figure 1, indicates a direct relationship between each source (on the horizontal axis) and its respective indicator microphone (on the vertical axis).

For PBN, separate microphones are required separated from the vehicle and placed at the 7.5 m pass-by measurement locations opposite the center of the track, see figure 2.

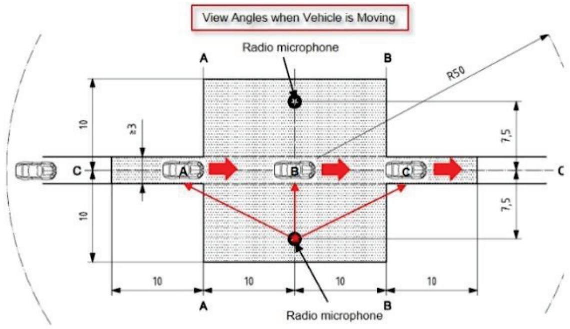


Figure 2. Pass-by track layout.

Initially, these were fitted with radio transmitters sending signals to the on-board DAQ but later this was changed to having a separate DAQ placed on the roadside which was time synchronized with that on-board. It was found that for larger vehicles the reception of the radio signal could be problematic at the extremes of the PBN track causing drop-outs due to aerial placement issues.

The cabin noise version of the Acoustic DNA technique performs analysis at both discrete road speeds within an operating condition and throughout the whole operating range during an acceleration or deceleration. Data measured using a DAQ front-end is discretized in terms of vehicle speed or engine speed using information obtained from the vehicle's Controller Area Network (CANBUS) system. However, PBN measurement requires engine speed, vehicle speed, and the vehicle's location along the PBN test-track.

There exists a plethora of different approaches to reliably obtaining this data ranging from GPS satellite positioning, time synchronization, and laser tracking, but during the development phase of the project it was found that none of these methods would work reliably. Due to the strict time constraints typically found when working on customer locations or rented test tracks, the reliability of the measurements and accuracy of the results was the top priority for the project. This was solved by the combination of a laser trigger placed at the start gate of the track, a received GPS location, and data from the CANBUS which was post-processed to create a time versus position reference function, see figure 3.

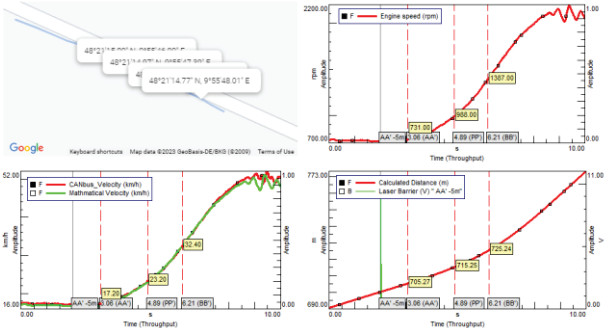


Figure 3. The measured vehicle velocity was integrated in order to calculate the vehicles location through the test track.

3.3 Spatial Transfer Function Measurement

With the DAQ configured, and the indicator microphones in their correct locations juxtaposed to each source via the use of the DAC the next step is to measure a comprehensive set of spatially varying acoustic transfer functions between each radiating sound source on the vehicle and the measurement microphone placed at 7.5 m from the traveling center line. These need to be measured progressively as the vehicle travels across the track. An effective method to obtain this dataset is to use a reciprocal sound source placed at the 7.5m microphone location and record the acoustic transfer function response simultaneously on all the DAQ channels. The vehicle is either positioned stationary along the centerline at 1 m intervals from location -15 m to +15 m and transfer function recordings made, or if the track is sufficiently uniform over a 50 m radius, the reciprocal source can be moved as shown in figure 4 with the vehicle remaining at the center.

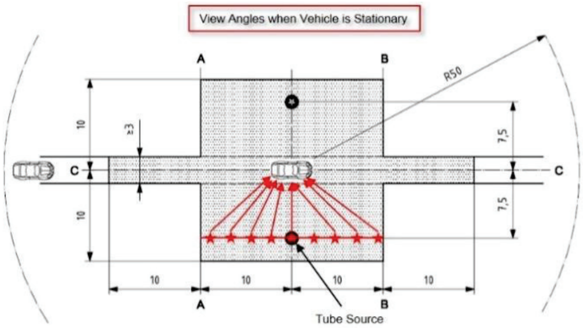


Figure 4. Reciprocal transfer function measurement.

Initially the reciprocal source used for vehicle cabin noise DNA was used but it was found that even on a certified PBN track the low frequency background noise contaminated the measured reciprocal transfer function. The source was modified to include a bass speaker, see figure 5.

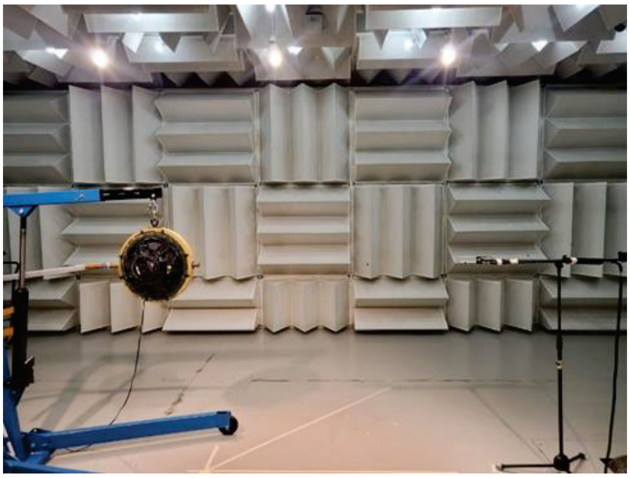


Figure 5. First version of reciprocal transfer function measurement kit incorporating a tube source and bass loudspeaker pair.

Whilst this solved the problem of background contamination, only having one source meant that the measurements had to be repeated for the microphone at 7.5m on the other side of the track. After a detailed investigation of suitable replacement reciprocal sources, a pair of powerful dodecahedrons was obtained, and testing conducted serially between the LHS (P1) and RHS (P2) 7.5m positions.

4. POST-PROCESSING

4.1 Cloud-based "Genome" Application

In compliance with company innovation procedures proof-of-concept studies of PBN Acoustic DNA have been extensively validated. To progress the method from interesting research to project-based activity the authors implemented a comprehensive analysis application inside our cloud-based "Genome" platform. Genome not only applies the crosstalk removal algorithms to raw data from the DAQ indicator microphone recordings but also applies the relevant spatial transfer functions and assesses the test quality interactively with the user including validation against the official 7.5 m microphone responses. Through this tool it is possible to perform the complete analysis outlined in the previous sections and perform optimization studies.

4.2 Correlation of Measurement vs Prediction

An example of the high accuracy of the method for a large commercial vehicle is shown in figure 6. This compares the measured SPL dBA at P1 (LHS) against the Acoustic DNA PBN predicted value. As an indication of the accuracy available and error bar of +/- 1 dBA has been applied to the measured curve inline with the accepted ISO standard.
Comprehensive information relating to each noise generating source is also available as required.

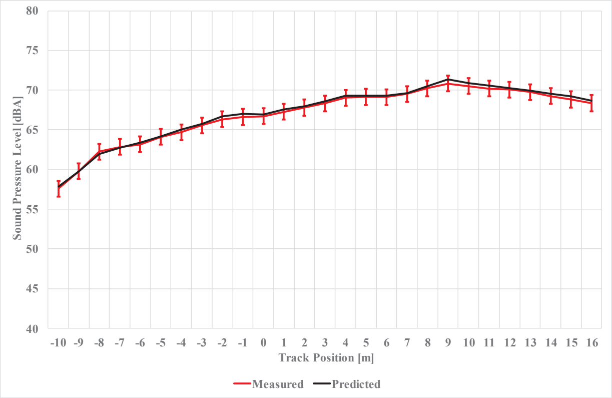


Figure 6. Overall measured SPL at 7.5m vs predicted against track location.

In figure 7, the 3rd octave spectra from 200 Hz to 10 kHz can be seen for both the measured and predicted data at the peak PBN location. This shows the good correlation of spectral shape giving confidence to any further analysis.

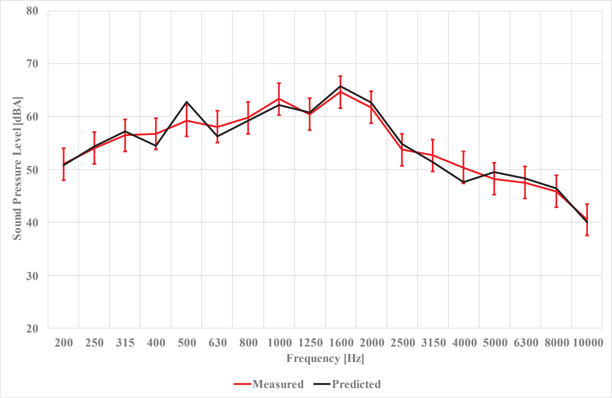


Figure 7. 3rd Octave spectra measured vs predicted at the peak location.

5. COMBINING ACOUSTIC DNA WITH SIMULATION

5.1 Pass-by Optimization Using Full-Vehicle Hybrid Modelling

The test based PBN technique using Acoustic DNA, described above, provides a comprehensive set of the noise source generators and spatial transfer functions as the test vehicle travels across the test track. Genome then provides an interactive toolbox to determine which components of the system require improvement to achieve the target peak pass-by level. Whilst Genome indicates what needs to be changed and by how much, proving and optimizing these scenarios usually involves prototype part construction and multiple test-runs in various build conditions. Apart from the time and cost involved in this procedure the full potential of any solution, in particular innovative designs, is rarely pursued, especially when extreme options are to be considered.

An alternative to this is acoustic modeling and simulation and there are numerous software packages and methodologies available for this endeavor. A considerable effort was expended by the authors to find an application, or group of applications that would fulfill the objective of a relatively easy to use, medium computationally intensive procedure that produced accurate validated simulations within acceptable tolerances and timescales. Software involving FEM, BEM and SEA were examined and trial projects carried out, in some cases together with the software developer company. The conclusion from this work being the use of open-source particle tracing technology (SPPS) combined with CAD imported from all the major software formats and tetrahedral volumetric meshing in a user-friendly GUI together with user defined post-processing plugins. To simplify the description of this combination it was called "Quantum" [6].

5.2 Description of code

The SPPS (Simulation de la Propagation de Particles Sonores) code [7] is based on both energetical and probabilistic approaches to sound particle tracing within a pre-defined, perfectly closed, geometrical 3D meshing domain created using a tetrahedral mesh generator. For pass-by simulation each hybrid source from the Acoustic DNA is represented as an omni-directional virtual sound source, located appropriately in the imported full-vehicle model. Source directionality can be included, if measured, but it was found that omni-directional sources gave a suitable response. Each source radiates 15 million virtual sound phonons which propagate temporally along a straight line between successive time steps (0.01 seconds) until they collide with a surface of the model, the road surface, or the receiving microphone array. As the real-life spatial transfer functions in PBN can be affected by the ambient conditions this is also accounted for. The PBN track was modeled as a closed semi-anechoic chamber of 125,000 m^3 with the road surface absorption set as per ISO standard 362.

The vehicle model sits in the center line in the middle of the chamber so representing an indoor pass-by setup, with a microphone array offset 7.5 m either side of the center line and microphones spaced as 1 m intervals from the zero-distance reference location, as shown in figure 8.

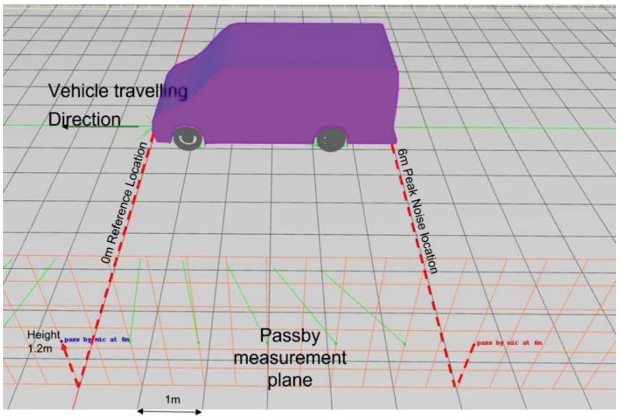


Figure 8. Pass-by chamber layout.

When solving using the authors preferred probabilistic method, called "Random", a Monte-Carlo routine defines what happens to each Phonon whether it is absorbed, transmitted, or reflected, so that the number of Phonons decreases over time and the density of sound energy at a location in the mesh is proportional to the number of Phonons at the same point. Since the probability of a Phonon passing through a discrete point receiver, representing a microphone, is zero it is necessary to model the receiving microphone array as a series of small spheres and count the number of Phonons that pass through each sphere to deduce the sound energy density, hence the sound pressure level at each time step and frequency band. The code then calculates the overall sound pressure level by summing each Phonon contribution.

Post processing was conducted using bespoke plugins, written in Python 3, from which the peak noise level was extracted, the source contribution ranking evaluated together with the spatial transfer function matrix and various holographic displays created. Depending on the amount of detail included in the vehicle model some of the spatial transfer functions predicted can vary from their measured equivalent. These were examined and a "Bonding" function applied which effectively created a hybrid solution. This was especially useful when accommodating variations in track conditions.

5.3 Model validation

For the example shown in figure 9, of a commercial panel van, compares the overall dB linear and dBA noise levels between the measured, Genome predicted, and Quantum predicted peak noise level.

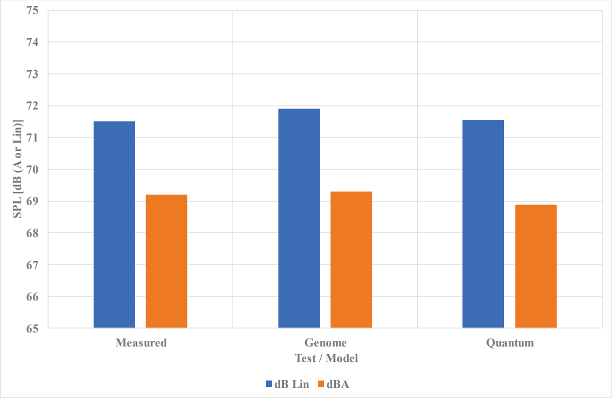


Figure 9. Comparison of pass-by peak level.

In each case, the comparison of level and peak location was satisfactory. This accuracy was further confirmed by comparing the spectral content of the peak level, shown in figure 10.

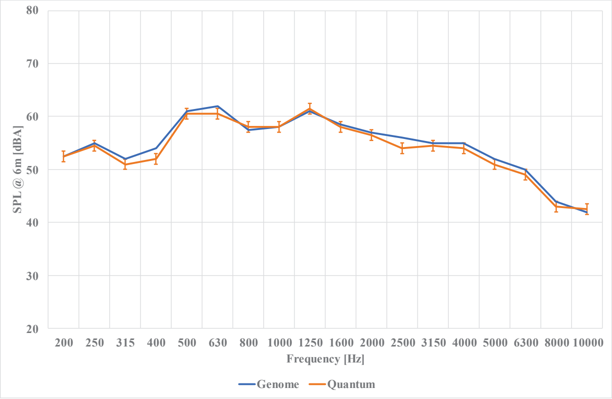


Figure 10. Spectral content comparison.

The Quantum models allow the effect of trial palliative treatments to be studied where their inclusion on the real-life test vehicle may be problematic. Items such as ground hugging acoustic curtains and full-wheel arch liners being examples of tricky items for prototype testing. Whilst extreme solutions may not be viable for production, they do provide a limiting solution for any type of potential palliative. Such a set of treatments was introduced to the van model as shown in figure 11.

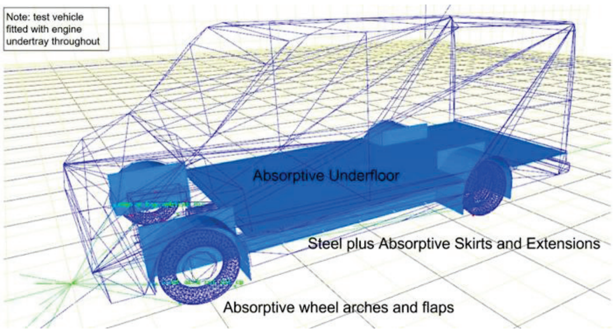


Figure 11. Diagram of potential treatments.

A “job list” that automatically runs multiple solvers was created that started with the full palliative set, called overall then “windowing” of each part to rank their individual effectiveness, see figure 12.

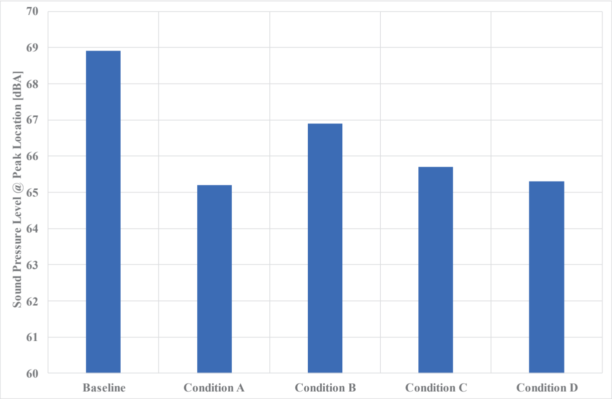


Figure 12. “Windowing” of potential treatments.

Optimization of a treatment package can be carried out in two ways. The most obvious being a “brute force” approach, by building a comprehensive “job list” of all package combinations and sifting through the results. This method can be useful for projects with restricted potential options and solving using multiple, powerful PCs reduces the overall time to solution significantly. An example of this is shown in figure 13 where a 2 dB reduction was achieved by 3 different package solutions.

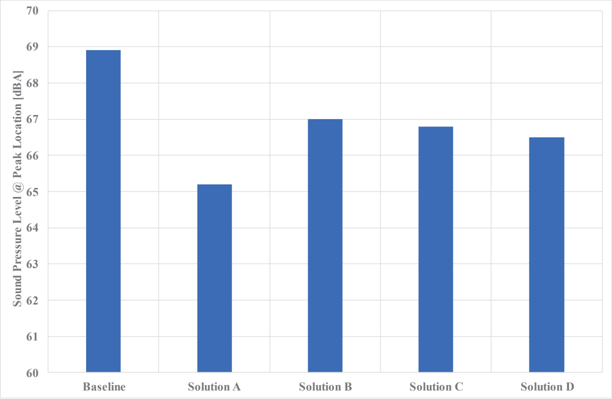


Figure 13. Optimized solutions using "brute force" solving.

Current development involves an alternative approach which combines the windowed data from the Quantum model and its associated changes in spatial transfer functions with the Genome software so providing an interactive optimization experience.

6. CONCLUSION

After an extended development cycle, a robust measurement based PBN technique has been created that allows for the identification of problematic noise sources and their peak locations during PBN testing. This data, combined with simulation, can allow for detailed analysis and component optimization to help OEMs achieve certification for exterior pass-by noise.

By tightly integrating the Acoustic PBN technique with simulation, we use a hybrid-approach that can aid OEMs at every stage of the vehicle development cycle.

Extending this technique to electric vehicles, in line with current automotive trends, should be a relatively simple process as any tonal characteristics typically found with EVs is not considered in PBN which only looks at a single A-weighted SPL value.

Developing NVH packages towards PBN has led to an increased investment in components such as full-engine encapsulations which previously were rarely used.

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8. DEFINITIONS / ABBREVIATIONS

PBN = Pass by Noise
EV = electrical vehicle
OEM = Original Equipment Manufacturer
SPL = Sound Pressure Level
SWL = Sound Power Level
NVH = Noise Vibration and Harshness.
SPTF = Sound Propagation Transfer Function (SWL-SPL)
CAD = Computer Aided Design
DAQ = Data Acquisition System
IP = Intellectual Property
SEA = Statistical Energy Analysis