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A Pass-By Noise Prediction Method Based on Source-Path-Receiver Approach Combining Simulation and Test Data

Massimiliano Calloni and Chadwyck Musser ESI Group

Alexis Castel ESI North America

Abderrazak Mejdi and Augusto Medeiros ESI Group

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Abstract

Optimizing noise control treatments in the early design phase is crucial to meet new strict regulations for exterior vehicle noise. Contribution analysis of the different sources to the exterior acoustic performance plays an important role in prioritizing design changes. A method to predict Pass-by noise performance of a car, based on source-path-receiver approach, combining data coming from simulation and experimental campaigns, is presented along with its validation. With this method the effect of trim and sound package on exterior noise can be predicted and optimized.

Introduction

The evolution of Pass-by noise legislation, as planned today according to ECE.R51.03 [1], will result in more stringent noise level thresholds and in more focus on component contribution, especially for tires. Contribution analysis will be crucial to understand which components are influencing the Pass-by noise performance and will help engineers in subsystem target settings.

Furthermore, when executing Pass-by noise test with the outdoor procedure, it's difficult to get dependable results because physical test equipment is mostly deployed on test tracks with changing environmental conditions.

The method based on source - path - receiver approach, combining test and simulation data allows costs to be diverted from inflexible full test procedures performed late in the design cycle to upfront decision making based on contribution analysis.

In this paper a Pass-by noise simulation case study on a vehicle and its validation, performed in conjunction with General Motors and based on this approach, is presented.

Pass-By Noise Simulation Process

Source-Path-Receiver Approach

The Pass-by noise simulation process used in this study and validation case is based on the "source-path-receiver" [2] approach (Figure 1), a very well-known and accepted method by the NVH community, used to predict and analyze noise and vibration levels of complex mechanical systems. In this method the evaluation of the "receiver" is based on the combination of sources and paths levels. The big advantage of this approach is that simulation data, test data or a combination of both can be used to predict NVH performances.

In this case study it has been decided to develop a hybrid model using test data for the sources and simulation data for the paths. It is also useful to underline that it's possible to use pure simulation data for the sources if reliable and available.

In the mathematical model used in this work for the Pass-by noise source - path - receiver approach [3], given a monopole source radiating with sound power W_j, the acoustic pressure at a specific position caused by this source is given by

$$P_{ij} = H_{ij}\sqrt{W_j}, \tag{1}$$

where H_{ij} is the transfer function (or Frequency Response Function, FRF) between the source and the receiver locations. Eq. (1) can be rewritten in decibel form as

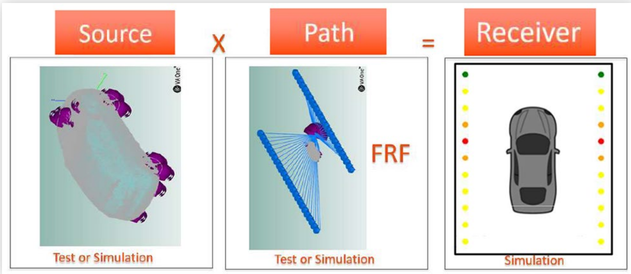
$$SPL_{ij} = H_{ij}^{*} + SWL_j, \tag{2}$$

where the sound pressure level SPL and the sound power level SWL are given by their classical definition:

$$SPL_{ij} = 20log_{10}\left(\frac{P_{ij}}{P_{ref}}\right), \tag{3}$$

$$SWL_{ij} = 10log_{10}\left(\frac{W_j}{W_{ref}}\right), \tag{4}$$

FIGURE 1 Source-path-receiver approach method.



while H_{ij}* the FRF in decibels, is given by

$$H_{ij}^{*} = 20log_{10}\left(\frac{H_{ij}}{H_{ref}}\right). \quad (5)$$

The dB-reference for (5) is given by the ratio of the two previous references, i.e.:

$$H_{ref} = \frac{P_{ref}}{\sqrt{W_{ref}}} \quad (6)$$

which for the pressure and power references in SI units of, respectively, 2×10^{-5} Pa and 1×10^{-12} W results in 20 Pa/$W^{1/2}$.

Pass-By Noise Case Study Outline

Pass-by Noise levels can be evaluated in two different ways:

- Vehicle outdoor Pass-by.
- Vehicle indoor Pass-by.

In this work it was chosen to use the outdoor approach to measure the total sound pressure level versus position for overall levels correlation and the indoor approach for paths quantification and correlation.

The project was divided in the following steps:

- Paths quantification
- Sources quantification and mapping
- Receivers quantification
- Correlation and model updates.

Paths Quantification

Boundary Element Model Preparation An indoor test Pass-by noise set-up [4], according to ISO 362-3:2016, is composed of a hemi-anechoic room, two rows of microphone arrays and the vehicle in the middle of the room accelerated on a chassis dynamometer. In order to simulate paths, i.e. Frequency Response Functions between acoustic sources and receiver microphones a VA One [5] Boundary Element Model (BEM) of a car (Figures 2 and 3) was built including sensors, sources and floor.

An infinite rigid plane was used to reproduce the floor in first instance.

FIGURE 2 Example of a BE model of a vehicle including acoustic sources used for PBN prediction.

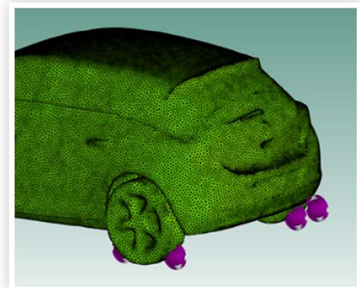
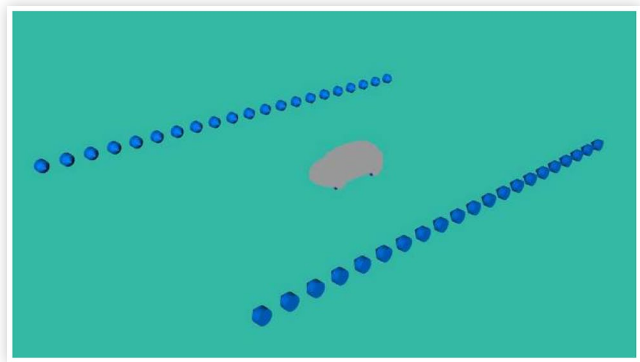


FIGURE 3 Example of a BE model of indoor Pass-by noise simulation set-up.



The frequency range of interest was up to 2,500 Hz and considering six elements per wavelength the model consists of about 97,000 wetted nodes. The mesh size is about 22 mm.

The BE model contains acoustics sources defined by monopoles that represent the power inputs of Volume Velocity Sources (Q).

The BE model was solved using a DMP solver overnight and computation cluster and 720 P/Q Frequency Response Functions (FRF) were then calculated between each monopole and each sensor.

Frequency Response Functions Measurement A test campaign was performed at General Motors proving ground measuring Frequency Response Functions to correlate and validate the BE vibroacoustic model [6]. All measurements were performed in a hemi-anechoic room (Figures 4, 5 and 6).

FRFs were measured using an inverse technique, taking advantage of the reciprocity of the FRFs. Experimental sources were placed at receiver microphones locations and microphones were placed at sources locations. A finer spacing was used for microphones in the proximity of the car to have better resolution. Low frequency and mid-high frequency Volume Velocity Sources were used in order to cover the frequency range of interest for Pass-by noise (PBN) calculation. Low frequency Volume Velocity Source was used up to 300 Hz [7]; above that value mid-high frequency Volume Velocity Source was used to obtain desired measurements up to 2,500 Hz.

It was chosen to use the sum of the FRFs to correlate and validate the BE vibroacoustic model since the total number

FIGURE 4 Example of transfer functions measurement test set-up for engine.

FIGURE 5 Example of transfer functions measurement test set-up for tailpipe

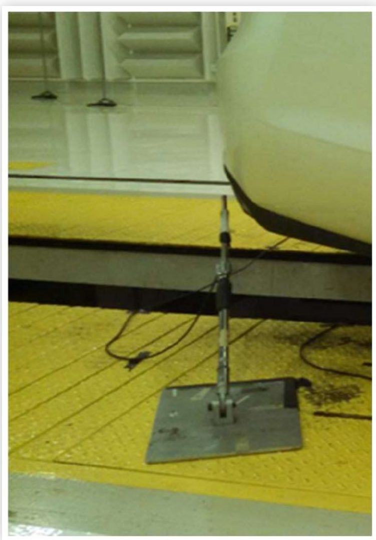


FIGURE 6 Example of transfer functions measurement test set-up for tires

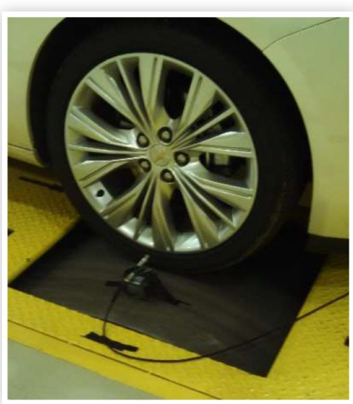


FIGURE 7 Transfer functions grouping for tires and tailpipes

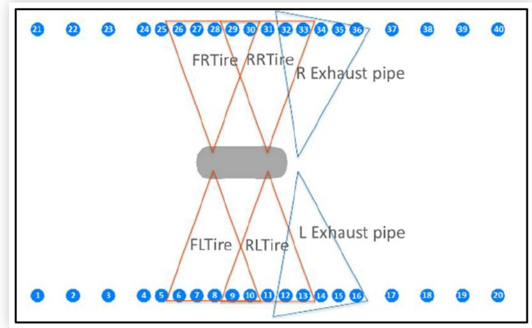


FIGURE 8 Transfer functions grouping for powertrain

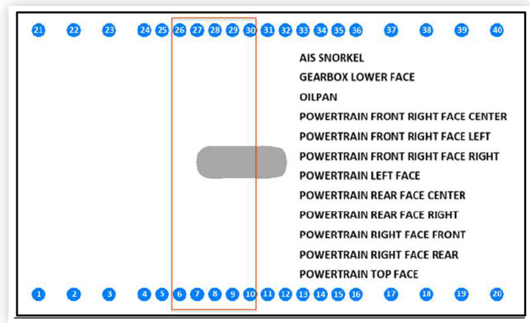
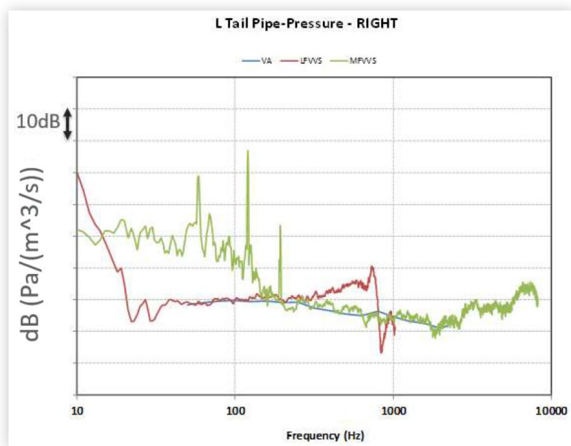


FIGURE 9 FRF sum comparison for exterior source



of FRFs was very large. It was then decided to group microphones according to the closest location of the source.

Eight different grouping were made: four for tires, two for tailpipes and two for powertrain as shown in Figures 7 and 8.

For external sources, where absorption does not play a big role especially if the ground is reflective, correlation was very good (Figure 9). In Figure 9 the red curve represents the sum of the FRFs for the low frequency Volume Velocity Source and should be considered for correlation valid up to 300 Hz; the green curve, representing the sum of FRFs for mid-high frequency Volume Velocity source must be considered from 300 Hz up to 2,500 Hz.

The blue curve represents the sum of FRFs obtained from BE simulation showing same trend and level of test data. For internal sources, located around the powertrain, without using any specific impedance results were not fully satisfactory (Figure 10).

FIGURE 10 FRF sum comparison for interior source no trim applied

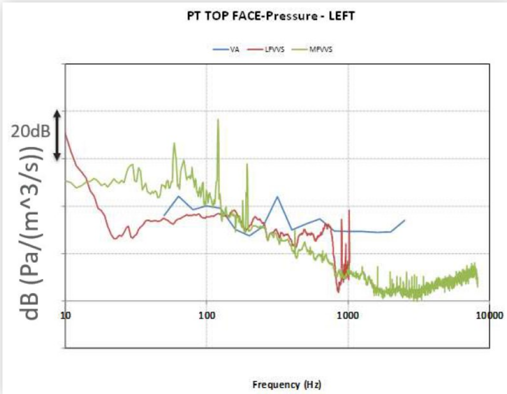


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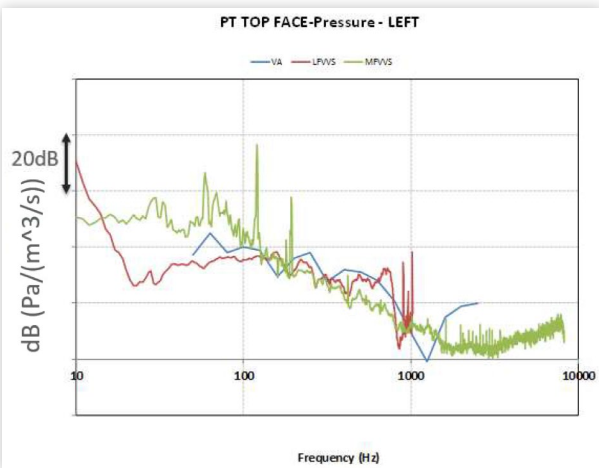
FIGURE 11 FRF sum comparison for interior source after BE model modification



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Then it was decided to add impedance values to the BE model for the hoodliner and the engine cover to represent noise control treatments.

New results, considering acoustic treatments, showed significant improvement for sources around the power-train (Figure 11).

Sources Quantification and Mapping

A similar technique used for the measurement of the FRFs was used to back calculate the strength of the sources (sound power or Volume Velocity Source) to be implemented in the BE model.

For the engine sources it was decided to place 18 microphones around the engine compartment where Volume Velocity sources could be located. FRFs were measured between each Volume Velocity source and each microphone related to engine sources.

Sound pressure level was then recorded during operating conditions in the 18 microphones.

The well-known Transfer Path Analysis (TPA) is the chosen method to obtain the Volume Velocity sources. Volume velocity sources are obtained with the following formula:

$$\{Q_i\} = \left[T_{ij}\right]^{-1}\{p_j\}^2 \tag{7}$$

with $[T_{ij}]$ the matrix of the transfer functions, $\{Q_i\}$ the vector the volume velocity sources and $\{p_j\}$ the pressure at the field microphones. A similar process was used to evaluate the exhaust sound power.

All measurements were performed in a hemi-anechoic room while tire measurements were performed directly on a General Motors tire test bench. All postprocessed sources in this work were considered uncorrelated but their correlation, if exists, can be considered. This is especially helpful when multiple exhausts are present in the car to take into account possible acoustic cancellation effects.

The indoor test simulates the outdoor test, where the vehicle is moving through a track, potentially varying its speed and engine RPM. Since the Volume Velocity of a source is generally dependent on either RPM or vehicle velocity, it is important that the correct set of source excitation data is used at each position on the track. For instance, tire sources are generally dependent on the vehicle velocity, while engine sources are dependent on RPM. To fully determine the sound power characteristics of a source at a given position on the track, therefore, it is necessary to know how vehicle velocity and engine RPM varies as the vehicle moves through the track.

In the present work time histories of RPMs vs position and velocity vs position were used as shown in Figures 12 and 13.

Receiver Quantification and Validation

Using back calculated sources mapped to the right position on the track and simulated Frequency Response Functions it was possible to calculate sound pressure levels for all receiver microphones and evaluate Pass-by noise performance (Figure 14). The process of obtaining the SPL at a given position x_i on the track, for a given source s_j, followed the steps below [3]:

- Obtain the velocity or RPM of the source at x_i, for a velocity- or rpm-dependent source, respectively. Call this information $m_{vel/rpm,i}$. If x_i is not available on the data,

FIGURE 12 Velocity in function of position

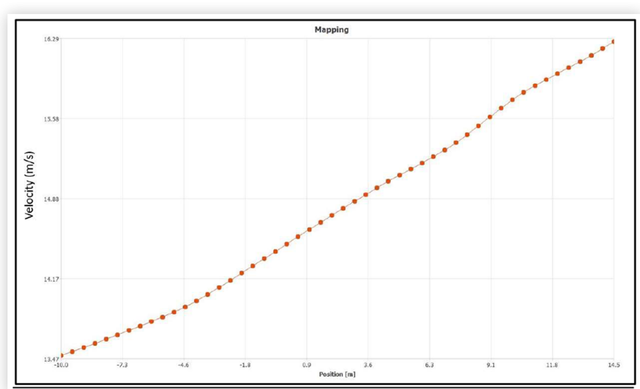

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FIGURE 13 RPMs in function of position

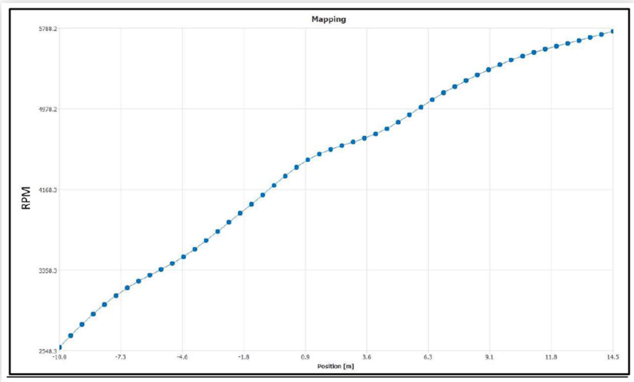
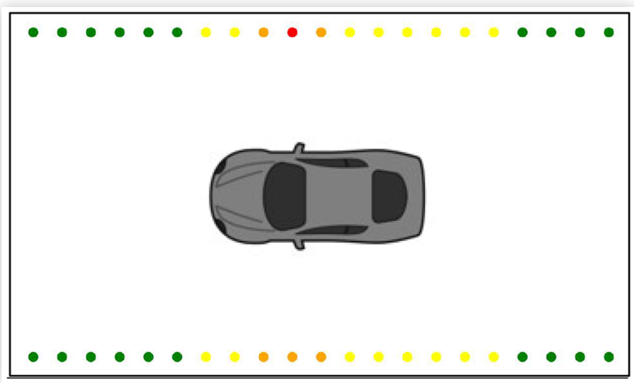


FIGURE 14 Example of a Road View for Pass-by assessment



compute $m_{vel/rpm,i}$ by interpolating from the closest available positions, x_{i-1} and x_{i+1}.

- Obtain the SWL spectrum at $m_{vel/rpm,i}$. If the SWL of s_j is not available at $m_{vel/rpm,i}$, compute the SWL spectrum by interpolating from the SWL at the RPMs/velocities closest to $m_{vel/rpm}$.
- Obtain the FRF between x_i and s_j, again interpolating from the closest positions if x_i is not available.
- Compute SPL using equation (2).

Since multiple sources were available, the process above was repeated for each source s_j and the results were added to obtain the total SPL.

A contribution analysis was performed showing the contribution of each source to the sound pressure level in function of position of the car on the track (Figure 15).

As expected and shown by results in function of position powertrain contribution plays a very important role. For each position was also possible to perform a contribution analysis in the frequency domain showing again the predominant role of powertrain sources (Figure 16). It is interesting to underline that also tire noise is significant, as showed by contribution analysis in function of position, especially at low speed, when the vehicle is entering the track. Tire noise will be crucial to Pass-by noise performance with recent regulations when also constant speed tests are required.

FIGURE 15 Pass-by noise results and contribution analysis in the position domain

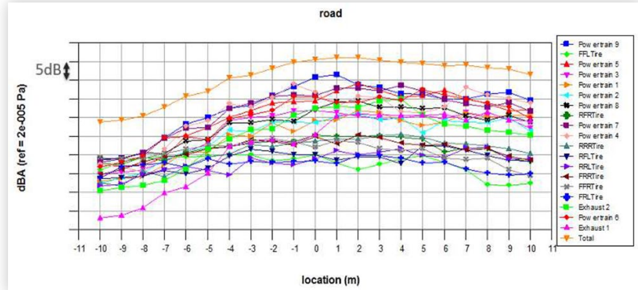
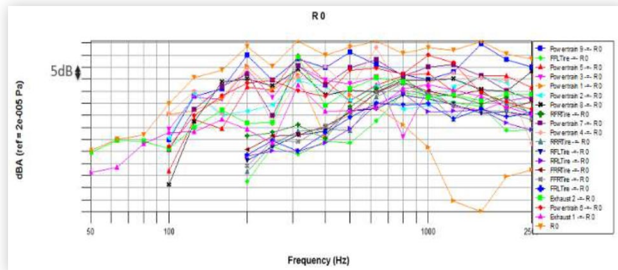


FIGURE 16 Pass-by noise results and contribution analysis in the frequency domain



An outdoor Pass-by Noise test campaign was performed at General Motors proving grounds by measuring only total sound pressure level vs position.

Correlation and Model Updates

A correlation of total sound pressure levels was made showing that first results were higher than test measurement.

One reason for this is the fact that the FRFs used for Pass-by noise prediction, useful for BE model validation in indoor conditions, did not consider road absorption.

Road absorption was added to the BE model and acoustic treatments were applied to engine cavity and wheel wells.

Different configurations were studied to obtain a better correlation for Pass-by noise level as shown in Figure 17. Finally test results were matched. However, many iterations had to be simulated due to the lack of availability of an accurate description of the sound package information.

FIGURE 17 Some of the configurations run to obtain overall level correlation.

	Run 1	Run 2	Run 3	Run 4
Engine Room Absorption	780 gsm	2x780 gsm	780 gsm	780 gsm
Wheel House (Arch) Absorption	Table	Table	2xTable	Table
Road Surface Absorption	Yes	Yes	Yes	2xYes

Conclusions

This case study has shown that it is possible to predict Pass-by noise performance of a vehicle using the "source-path-receiver approach"[1] with combination of test and simulation data.

The approach can be already used for relative comparisons and contribution analyses with good validation vs. measured transfer functions.

Contribution analysis, in position and frequency domain, is very helpful for engineers to better understand source ranking, to prioritize countermeasures and for subsystem target setting in view of the new exterior noise requirements. Absolute prediction of the Pass-by Noise fail/pass concept can be considered still premature if all acoustic treatment properties are not available and remain a future objective for the simulation.

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Contact Information

Massimiliano Calloni
ESI Group, Viale Angelo Masini, 36, 40126
Bologna, Italy
massimiliano.calloni@esi-group.com

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Definitions/Abbreviations

BE - Boundary Element

BEM - Boundary Element Model.

DMP - Distributed Memory Parallel

FRF - Frequency Response Function

NVH - Noise Vibration & Harshness

PBN - Pass-By Noise

RPM - Revolutions Per Minute

SPL - Sound Pressure Level

SWL - Sound Power Level

RPM - Revolutions Per Minute

TPA - Transfer Path Analysis

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