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# Auralization of road noise CAE simulation results for interactive sound quality evaluations

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**ABSTRACT**

*Road noise is one of the dominant contributions to a vehicle interior noise when driving below highway speed. In this paper, we present the process we developed to support automotive OEMs with road noise engineering during vehicle design and development. The process allows to auralize, in a driving simulator for NVH, road noise CAE simulation results obtained from coupled multibody, structural finite-elements and acoustic models. With this process, engineers can now listen to a vehicle sound and perform interactive sound quality evaluation for road noise even before physical prototypes are available.*

## 1. INTRODUCTION

Automotive customers are constantly expecting better NVH (noise, vibration and harshness) performance for new vehicles. This trend is even accelerating with electric vehicles. Electric

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powertrains are quieter than internal combustion engines, drivers and passengers are then getting used to a quieter driving experience and this in turns, pushes the expectations for road and wind noise further down.
Road noise is the dominant contribution to a vehicle interior noise when cruising below highway speed. Road noise includes a structure-borne and an airborne contribution.

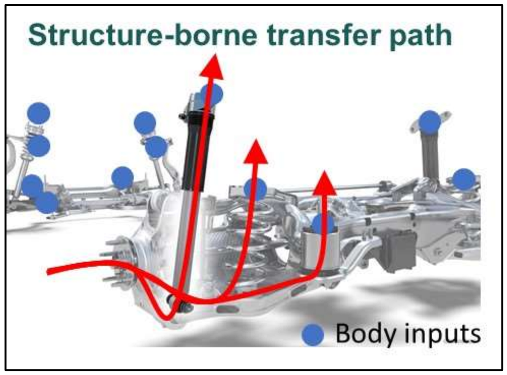

Figure 1: road noise – structure-borne path

The tire/road interaction generates vibrations that propagate through the suspension to create forces that excite the body at the suspension attachment points. These forces are then responsible for the structure-borne road noise as illustrated in Figure 1. In addition, the noise generated at the tire/road interface (i.e., the leading and trailing edge) propagates to the vehicle cabin and this corresponds to the airborne path as illustrated in Figure 2

Figure 2: road noise – airborne path

In this paper, we present the process we created to simulate and auralize the road noise of automotive vehicles. We focus on the structure-borne road noise, a process for airborne road noise has already been proposed in [1]. The objective is to apply this process as early as possible when developing new vehicles to assess the road noise performance, identify any risk of not meeting the customer expectations and define design countermeasures if necessary. The process uses as input the results from CAE simulations to calculate the body interface forces and the transfer functions between the attachment points and the driver's ear sound pressure level. These inputs are then combined to create sounds that are evaluated in a driving simulator for NVH. We used a passenger truck as application case to illustrate the process.
We describe in section 2 the truck CAE simulation models (multibody and finite-element). We introduce in Section 3 the driving simulator for NVH. The process we propose is presented in Section 4. In section 5, we share the results from the truck application case. The section 6 is reserved for the conclusions and the next steps.

## 2. CAE SIMULATION MODELS

### 2.1. Multibody Model

The transient loads to be used later in the process are calculated from a full-vehicle multibody system model developed in Adams Car (Figure 3). To get accurate loads, the model consists of flexible bodies for the frame, cab and flatbed, it has non-linear characteristics of bushings, bump stops, springs and dampers, and a detailed representation of the leaf springs. Integrator settings are tuned to get converged results and the HHT integrator is used to get the best computing performance. FTire from Cosin is used to model the tires to get good accuracy of the road input. In total the multibody system model consists of 1200 degrees of freedom. The model is driven by the driver model in Adams following the road at 6 pre-defined constant vehicle speeds: 10, 30, 50, 70, 90, 110 km/h. The road is an ISO8608 stochastic road of class C.

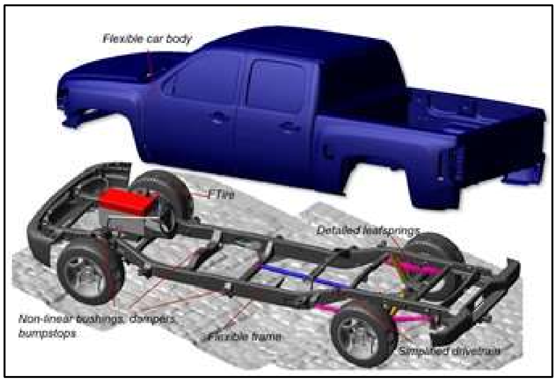


Figure 3: overview of the Adams Car model used to generate the transient loads on the car body

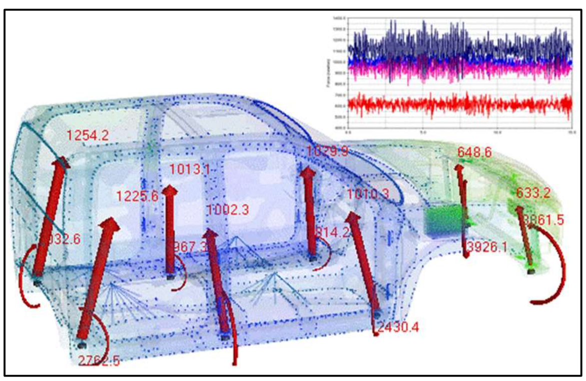


Figure 4: overview of the body interface loads

The model is simulated driving over the road at each velocity for 20 seconds and the results are output with a step size of 1ms. Each simulation takes approximately 10 minutes to run. The loads (forces and torques) at all the connection points (Figure 4) to the cab body are calculated and exported to be later used in the calculation of the sound pressure levels inside the cab.

### 2.2. Vibroacoustic model for transfer function calculation

A vibroacoustic finite element model (Figure 5) is built in MSC Nastran PEM to compute the transfer functions between the mounting points and two virtual microphones located at the driver's and front passenger's ears. The model can simulate interior noise up to 500 Hz. It consists of the car body structure, the interior cavity and a trimmed firewall panel. The model is solved with a SOL111 solution sequence, where the mode shapes are extracted as a first step, and then the vibroacoustic response is calculated using modal superposition. The trimmed firewall is coupled with the structure and the cavity using the Reduced Impedance Matrix approach as outlined in [2]. The trim is connected to the structure via a glued connection at a few elements and via a sliding connection for the rest. The cavity connection is considered impervious since the cavity is connected to the heavy layer of the firewall, which is modelled as a solid.

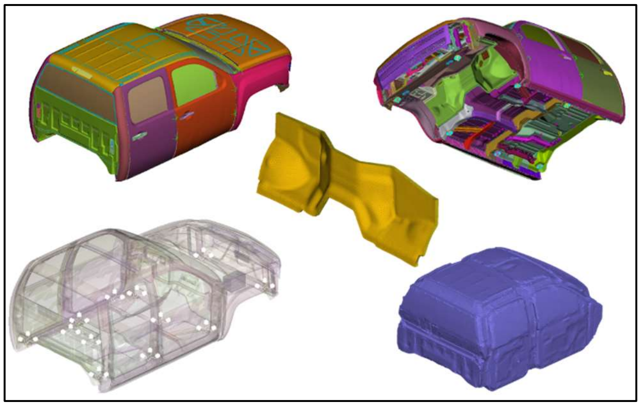

Figure 5: model geometry and mesh

The car body structure comprises approximately 450 thousand elements, which amount to about 2.7 million degrees of freedom (DOF). The modal extraction for the cavity is performed up to 750 Hz, identifying 3963 modes. The cavity consists of about 730 thousand elements, which amount to 130 thousand DOF, identifying 569 modes up to 1000 Hz. Finally, the trimmed firewall consists of 2 layers comprising a total of 30816 elements. The layers are a 30 mm porous layer of polyurethane foam and a 2 mm heavy layer.

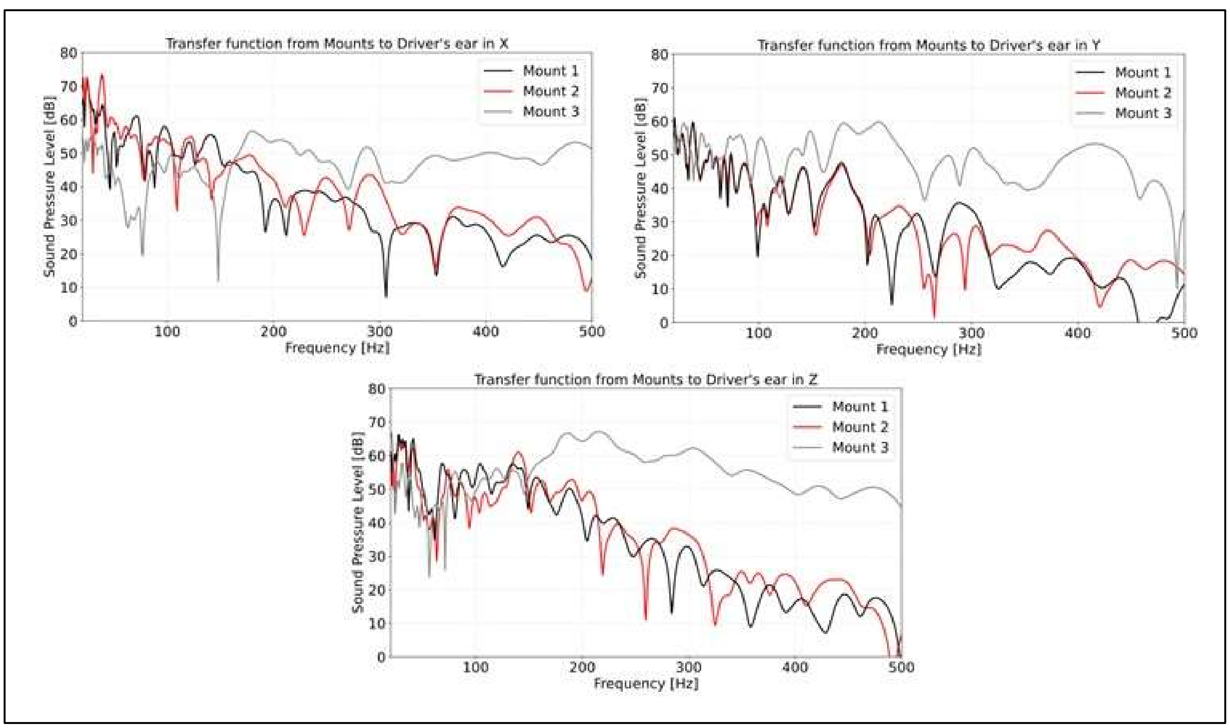


Figure 6: transfer functions (Pa/N)

For the loading, 8 mounting points are loaded in six directions (three for translation and three for rotation) to simulate road noise. The loads are unitary in order to calculate the transfer functions (Figure 6) and the actual SPL can be found by the recombination of the transfer functions with the forces exported by the previous multi-body simulation.

## 3. DRIVING SIMULATOR FOR NVH

The vehicle interior sound is evaluated in the driving simulator for NHV represented in Figure 7. The simulator uses as input the throttle pedal, gear shift and steering wheel and plays the vehicle interior sound corresponding to the instantaneous operating conditions using headphones or speakers. The sound replay is calibrated, it is at the same level as one would experience in the vehicle. The interior sound includes the contribution from the powertrain (harmonic and broadband rpm dependent background noise), road (structure-borne and airborne contribution as velocity dependent contributions) and wind noise (velocity dependent). The noise from accessories can also be included in the simulations. Each of these sounds is represented either as a total contribution at the drivers' ears or decomposed into sources and contributions. We have used the latter approach with the sources corresponding to the attachment forces at each body mount.

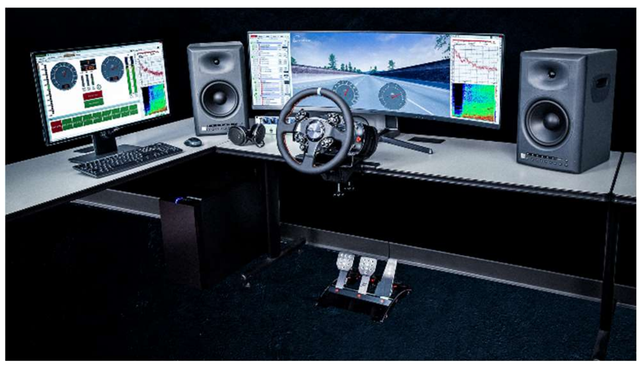

Figure 7: driving simulator for NVH

## 4. PROCESS FOR AURALIZATION

The process to auralize the structure-borne road noise uses as input the results from the CAE simulations. The body interfaces forces calculated in the time domain are combined with the transfer functions defined in the frequency domain to compute the time domain contributions to the vehicle interior noise. There is one contribution for each interface force in each direction. Both translation and rotation degrees of freedom are considered even if in practice, the contribution from the rotation degrees of freedom is expected to be negligible compared to the translation degrees of freedom. The amount of data to be processed can quickly become significant due to the number of mounts or attachment points, directions (3 translation and 3 rotations) and load cases (number of road profiles multiplied by the number of vehicle speeds). The process is made efficient thanks to the use of a data preprocessing tool. It allows to automate the definition and combination of all the input data to generate the interior sound contributions. The mount forces are exported from the multibody simulation tool, 1 data file is created for each mount with the forces in each direction organized in columns. The transfer functions are exported in a single data file.

For the work presented here, there are 8 body mounts with forces acting in 6 directions. We have simulated 6 vehicle speeds (10, 30, 50, 70, 90 and 110kph) for one road profile. We then have a total of 288 contributions. When driving the vehicle in the simulator, these contributions are interpolated to generate the interior sound at any given vehicle speed between the simulated ones.

Even if we only focus on the structure-borne road noise performance, it is very important to include the total vehicle sound in the evaluations. This is to ensure that the evaluations are performed with the proper context to avoid overlooking or overemphasizing on specific issues. In previous work, we have shown that CAE simulation can be used generate the powertrain, airborne road noise and wind noise creating a full virtual prototype. Alternatively, the simulated structure-borne road noise can also be complemented with powertrain, road airborne and wind noise characterized from measurement data to create a hybrid prototype. This approach may be more efficient if the focus is only on the structure-borne road noise. In that case, measurement data acquired on a prototype, predecessor or even a benchmark vehicle is suitable to create the proper context. In this project, we have used measurement data acquired on an electric vehicle to characterize the powertrain, airborne road noise and wind noise. The powertrain noise is defined as a load dependent harmonic noise, the airborne road noise and wind noise are extracted from a principal component analysis (or multiple coherence output power) as a velocity dependent interior noise [3]. For this analysis, we have used past measurement results on a production vehicle where the wheel center vibration, and the tire leading and trailing edge microphones were defined as the structure-borne and airborne references in the principal component analysis. The wind noise is assumed to correspond to the remaining uncorrelated noise.

## 5. RESULTS

We followed the process described above to create a virtual prototype of the passenger truck for structure-borne road noise evaluation in the driving simulator. The model also included powertrain, airborne road noise and wind noise defined from measurement data.

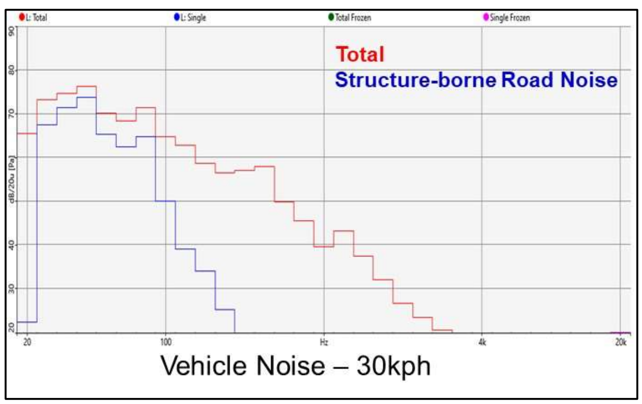


Figure 8: interior sound at 30kph

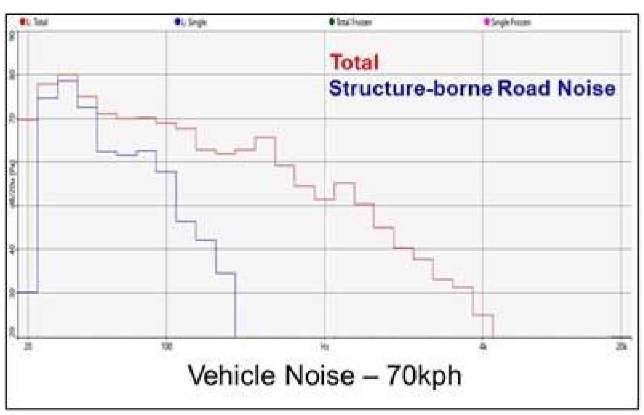


Figure 9: interior sound at 70kph

Example of results are presented in Figure 8 for a steady driving condition at 30kph and in Figure 9 for 70kph. The figures show the structure-borne road noise and total interior sound third-octave spectra. The sounds can also be subjectively evaluated in the driving simulator. The results show that the level beyond 200Hz is lower than what is normally expected as the tire model does not include the contribution for the cavity mode. But even with this, the structure-borne road noise is clearly a dominant contribution at low frequency. With this model, we can now compare the results against target curves and subjectively evaluate the vehicle interior sound. To get to this point, we did not need to have access to a physical prototype and this is where lies the value of the proposed process. These results can be generated from the very early stages of a vehicle development program when design decisions are still being made. This helps identify the risks of NVH issues and support the definition and evaluation of design countermeasures if necessary. Being able to listen and experience makes the decision process even easier. Our experience shows that it is easier to justify the need for design countermeasures when stakeholders and decision makers can experience how the interior sound will be affected. Being able to translate a quantitative difference in the sound pressure results into a change in perceptions always prove to be very valuable.

## 6. CONCLUSIONS

We have presented the process we developed to evaluate a vehicle structure-borne road noise performance using forces derived from multibody simulation and transfer functions calculated using a finite-element model. The results are evaluated in a driving simulator for NVH that replaces the use of physical prototypes. This process is available from the very early stages of a vehicle development program and is effective at minimizing the risks of late NVH issues. In future work, we will switch to a different tire model that captures the effect of the tire cavity mode. This will further increase the frequency range of our predictions. We will also work to improve the data flow to streamline the interfacing between the different solutions. We also plan on extending the process to include vibration targets to be evaluated in a driving simulator for sound and vibration.

## 7. REFERENCES


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