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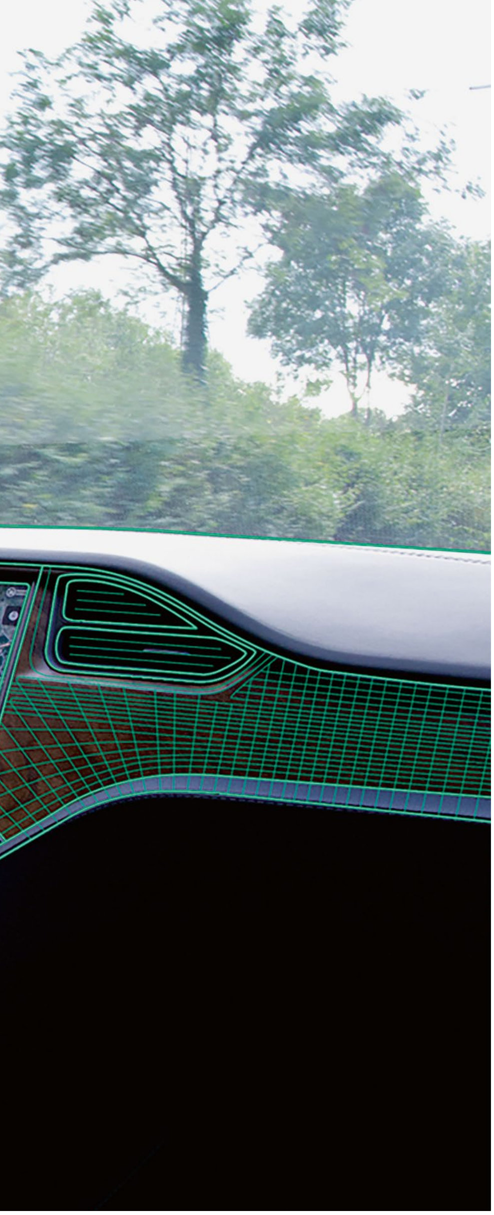
# Prediction of Road Noise Using Virtual Prototypes

While the range of models offered by car manufacturers is increasingly growing, expanded digital possibilities mean that the number of real tests is also falling sharply in NVH developments. Siemens Digital Industries Software shows how CAE and test component models can be used to make reliable predictions for the acoustic behavior of future vehicles.

The automotive industry is set to reduce its reliance on physical prototypes for testing Noise, Vibration, and Harshness (NVH) issues due to several well-known industry trends. Because of increasing vehicle diversity, test-based validation of component integration in all vehicle configurations is no longer feasible. Instead, the industry is looking to digitalize their development processes to save both development time and cost. Additionally, the drive electrification has shifted the priorities for remaining physical prototypes, favoring road and wind noise aspects over traditional sources like powertrain noise.

## FROM PHYSICAL PROTOTYPES TO SCALABLE VIRTUAL PROTOTYPES

Component-based Transfer Path Analysis (C-TPA) is a crucial technology for enabling this shift from physical to virtual prototypes. In C-TPA, each component of the vehicle is characterized



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independently using either test-based or CAE-based methods, and vehicle prototypes are then virtually assembled through mathematical coupling of the component data. This allows vehicle NVH performance to be assessed in any stage of development by combining test- and CAE-based component characterizations as needed. Additionally, the approach is scalable to any number of vehicle configurations as components can be replaced through mathematical operations, **FIGURE 1**.

However, the true value of C-TPA lies in its ability to break down traditional collaboration barriers, such as between test and CAE engineers, component departments, or even OEMs and suppliers. At the same time, this multitude of stakeholders also poses a high risk for user error in practice, as each domain expert will use their own established methods, conventions, and tools to characterize their components. A key element for success is the implementation of a streamlined and holistic virtual prototyping process shared by all stakeholders. This ensures the consistency of the predicted vehicle NVH performance at every stage of development.

## TEST-BASED COMPONENT CHARACTERIZATION

In C-TPA, a distinction is made between source components, which generate operational excitations, and receiver components, which transfer excitations on to the NVH targets, **FIGURE 2**. Source components are modeled using "invariant" loads, such as blocked forces, and impedances Frequency Response Functions (FRFs) at their output connection interfaces. Likewise, receiver components are modeled by impedance FRFs and transfer sensitivities between their input and output connection interfaces. The effects of virtually coupling the source and receiver components are then predicted from their respective impedance FRFs using Frequency-based Substructuring (FBS).

Test-based characterization can be used for components where physical prototypes are available, or which are difficult to simulate. A typical example in road noise applications is the tire-wheel assembly, a source component with highly complex internal excitation mechanisms which are too difficult to measure or simulate directly. Instead, the tire-wheel excitations will be modeled using an equivalent set of blocked forces at the connection interface to the wheel hub. These are the theoretical forces the tire-wheel would exert on an infinitely rigid receiver.

On the receiver side, the vehicle can either be modeled as a monolithic

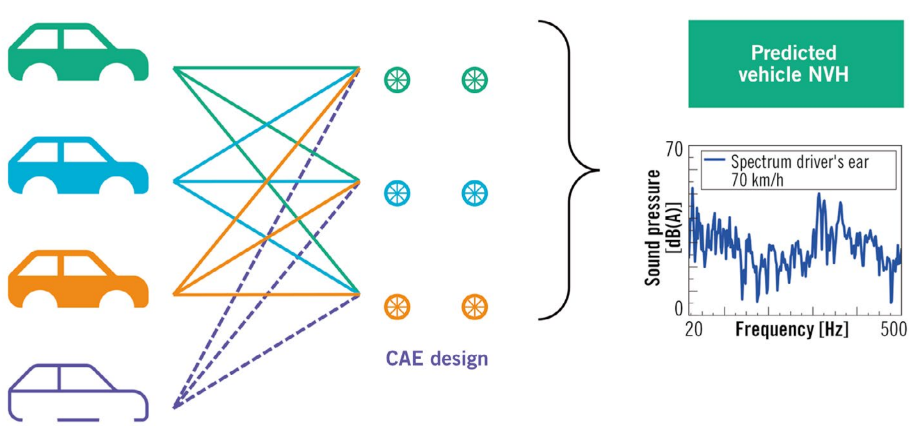


**FIGURE 1** Virtual prototyping offers a scalable method for evaluating vehicle NVH performance across a wide range of configurations (© Siemens Digital Industries Software)


**FIGURE 2** C-TPA decomposes the vehicle into independent models for source and receiver components (© Siemens Digital Industries Software)

component, or using separate suspension, strut mount, subframe and body models, depending on the desired level of complexity in the virtual prototype. In principle, any target location is valid for evaluating predicted NVH performance, such as cabin noise microphones or seat rail accelerometers.

## OVERCOMING PRACTICAL LIMITATIONS OF PHYSICAL TESTING

In general, the transmission of road surface excitations through the vehicle's structure tends to dominate road noise up to about 500 Hz [1]. Directly measuring blocked forces up to this frequency range is challenging in practice however, as even purposefully built stiff test benches will suffer from dynamic flexibilities that affect measurement accuracy.

A better alternative is to estimate the blocked forces using "in-situ TPA," a method where forces are estimated from operational response data and transfer sensitivities are measured at indicators instrumented on any receiver [2]. This method provides reliable blocked forces well above the frequency range required for road noise and can be applied on any available test bench or vehicle, even if the test bench is not rigid.

When applying in-situ TPA, it is important to consider the physical connection interface between the wheel and wheel hub. These are typically connected using four or five wheel bolts, each providing excitations in three translational and three rotational Degrees of Freedom (DOFs). Attempting to estimate such a dense set of blocked forces in such a small physical area can lead to significant numerical stability issues in practice.

The numerical stability of the force estimation problem can be significantly improved using Virtual Point Transformation (VPT), which transforms the overly complex physical connection interface into a single virtual point with six DOFs [3]. The basis for this transformation is the assumption that the structure behaves locally rigid, which allows the behavior of the virtual point to be derived from nearby measurements. Not only does this significantly simplify the force estimation problem, it also provides easy access to rotational DOFs, which are otherwise challenging to measure directly.

However, a notorious problem when applying VPT is the flexibility to excite all translational and rotational DOFs of the virtual point. This cannot always reliably be achieved with traditional hammers and shakers, which can only excite perpendicularly to the local geometry. A solution to this problem is the use of in-plane excitation adapters, which enable both normal and in-plane excitation DOFs to be applied at any attachment point when using Simcenter Qsources shakers [4]. Simcenter Qsources is a comprehensive suite of innovative sound and vibration excitation hardware for measuring driving points and structural and vibro-acoustic frequency response functions.

A last point of attention is the geometric sensitivity of VPT. Since the transformation relies on geometric relationships such as relative positions and orientations between the measured DOFs and virtual point, the accuracy of the sensor positioning directly impacts the accuracy of the transformation. Manually obtaining the positions and orientations of the instrumented sensors is an imprecise and time-consuming approach. Instead, an effective strategy is to replicate the physical instrumentation setup on a virtual geometry, either from the CAD system or a geometry scanner, to automatically extract precise sensor coordinates and orientations with minimal time investment, **FIGURE 3**.

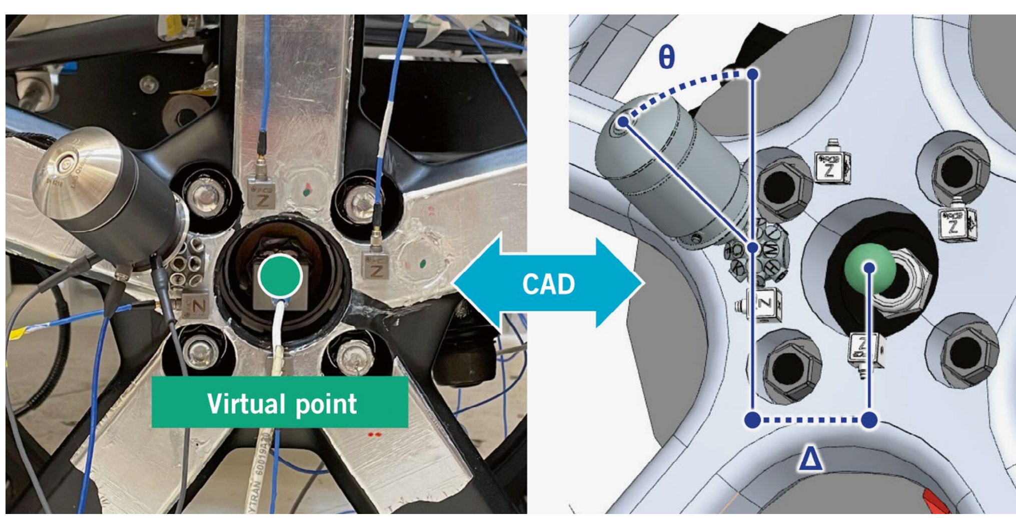


**FIGURE 3** An example instrumentation setup for tire-wheel characterization: the representation is showing the use of in-plane excitation adapters and CAD-based instrumentation for obtaining the sensor positions and orientations for VPT (© Siemens Digital Industries Software)

## TEST AND SIMULATION-BASED COMPONENT DATA

Virtual prototypes can be assembled from both test-based and simulation-based C-TPA component data. The true potential of C-TPA lies in facilitating the exchange of characterizations among various stakeholders, including test and CAE engineers, component departments, OEMs, and suppliers, to incorporate NVH prediction using virtual prototypes into the broader NVH development process. The aim is the implementation of a streamlined and holistic process, where collaboration is fostered among these diverse stakeholders.

| Type | Input | Output | Cross | Example |
|---|---|---|---|---|
| Source | | (Invariant) loads (Impedance FRFs) | | Tire/wheel |
| Passive | Impedance FRFs | Impedance FRFs | Transfer FRFs | Suspension |
| Mount | | | Mount stiffnesses | Strut mount |
| Receiver | (Impedance FRFs) | Target FRFs | | Trimmed body |
| Scenario | | Operational profiles | | 10 to 70 km/h |

**TABLE 1** Component model categories that can be used for virtual prototyping; quantities between parentheses are optional depending on the source load type (director invariant) (© Siemens Digital Industries Software)

## COLLABORATING BETWEEN STAKEHOLDERS

In context of C-TPA, any component can be reduced to a simple but comprehensive model using only characteristic data at its input and/or output connection interfaces. **TABLE 1** summarizes the various categories of component models that can be used for virtual prototyping.

Despite their simplicity, collaborating using component models can be complicated in practice as there is no unique way to define a component model for a given component. For example, engineers may disagree on what the input and output interfaces are, such as including or excluding a mount, or they may use different conventions for point naming, coordinate systems and unit systems.

A key element for success is therefore the adoption of standardized component templates to facilitate the exchange of component models. These templates ensure consistency in input and output interfaces, naming conventions, coordinate systems and operational dependencies of the component models, no matter the origin of the component data itself. The aim is to ensure a smooth and error-free virtual prototyping process that is scalable to a wide user group of various domain experts.

## PREDICTING THE NVH BEHAVIOR OF THE VEHICLE

Virtual prototypes are created by connecting component models from the component library in a block diagram representing the vehicle configuration. **FIGURE 4** shows an example virtual prototype for road noise prediction. By applying FBS to each level of the virtual assembly, the overall NVH behavior of the vehi-

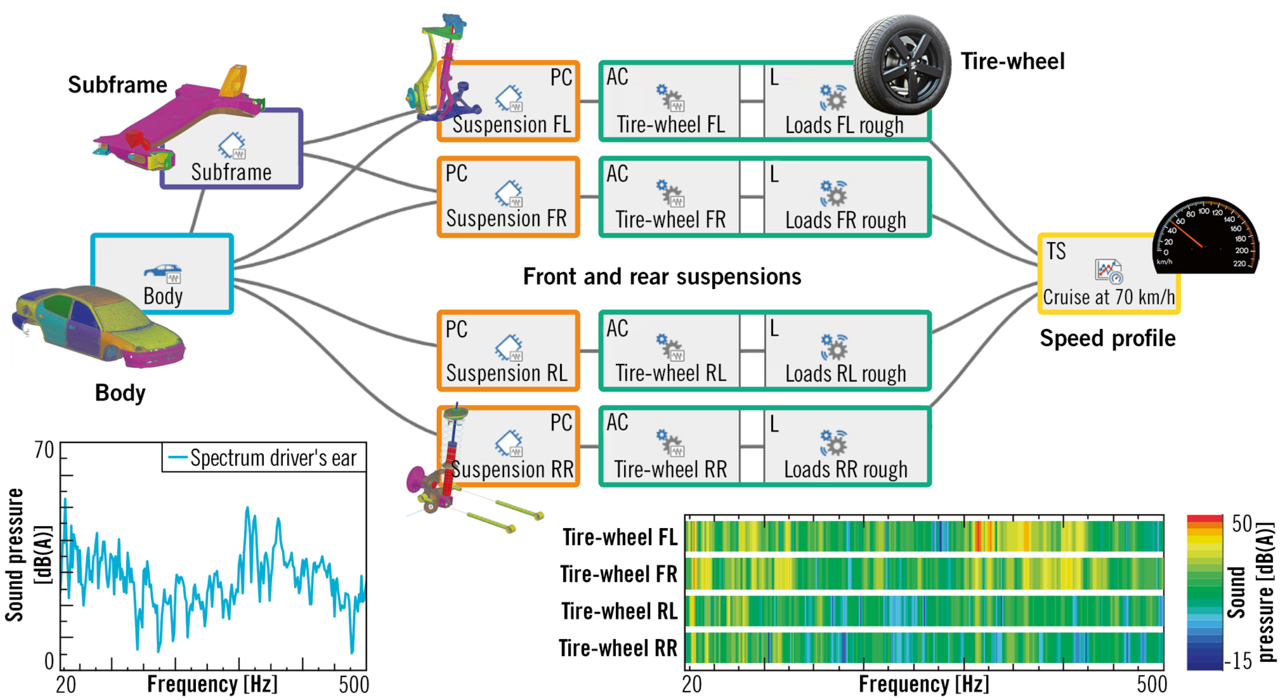


**FIGURE 4** Virtual prototype example assembled from test-based tire-wheel models and CAE-based suspension, subframe and body models; the overall road noise performance can be evaluated at any given speed and further decomposed into partial contributions from any component or connection interface (PC: passive component, AC: active component, L: load, TS: test scenario, FL: front left, FR: front right, RL: rear left, RR: rear right) (© Siemens Digital Industries Software)

cle is predicted at all available operating conditions. These target responses can then be decomposed into partial contributions per component at any level of the assembly, for example per tire-wheel, to identify dominant components. Next, the partial contributions per component can be further decomposed into partial contributions per path, for example per wheel center DOF, to identify dominant paths. Both the direct path contributions as well as cross-coupling through the assembly are quantified. Finally, path contributions can be separated into assembly contact forces and transfer FRFs to identify root-cause issues.


## SUMMARY

The automotive industry is transitioning away from heavy reliance on physical prototypes for NVH testing, driven by industry changes such as increasing vehicle diversity and electrification. Introducing virtual prototypes using test and CAE in the development processes has the potential to save an enormous amount of development time and cost. Component-based Transfer Path Analysis (C-TPA) is emerging as a pivotal technology to facilitate this shift towards virtual prototypes. By decomposing the vehicle into independent component models and simulating their interactions, C-TPA enables scalable evaluation of vehicle NVH performance for any configuration and at any design stage. However, the implementation of a streamlined and holistic process is imperative to ensure effective collaboration between the multitude of stakeholders involved.



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