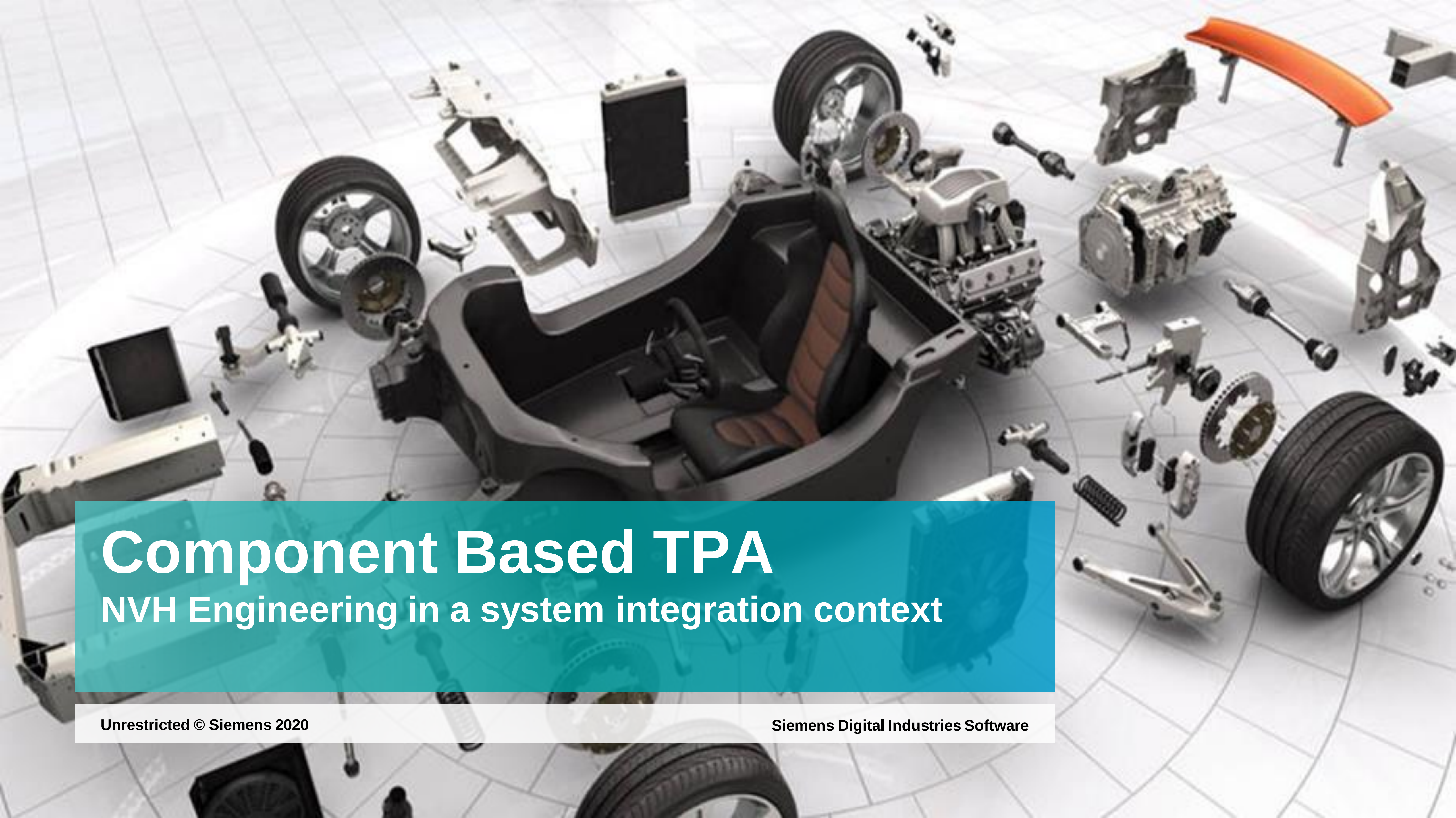

# Component Based TPA

## NVH Engineering in a system integration context

# Overview

## Outline

- TPA Introduction
- Component TPA Introduction
  - 1 Component TPA Theory
  - 2 Virtual Point Transformation Theory
- Application & Reference cases
  - 1 Road Noise Synthesis
  - 2 PBN Noise Synthesis

# Overview

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## Outline

**TPA Introduction**



# Transfer Path Analysis
# Engineering Challenge

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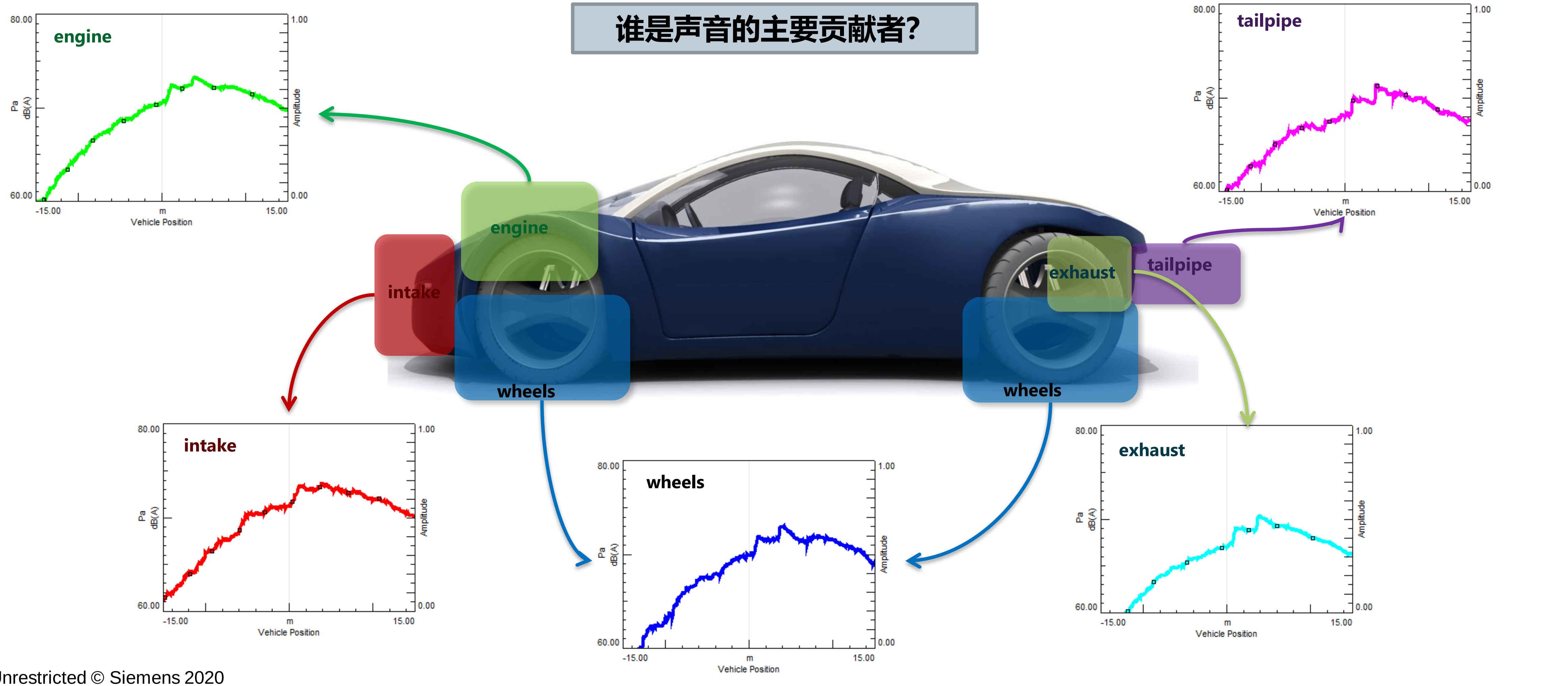
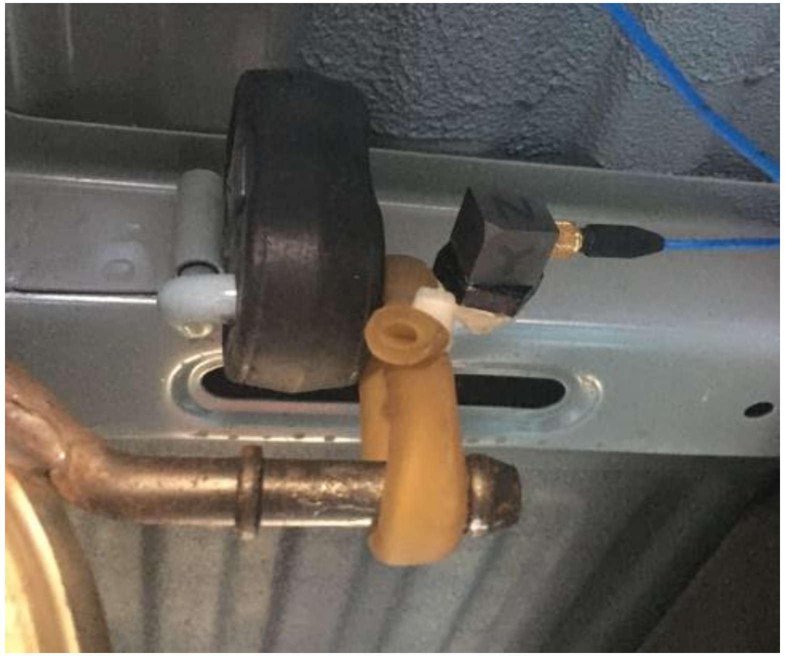


# Transfer Path Analysis
# Traditional Method

## Masking



# Transfer Path Analysis
## Source-transfer-receiver approach

Transmission

Drive line

HVAC

Exhaust

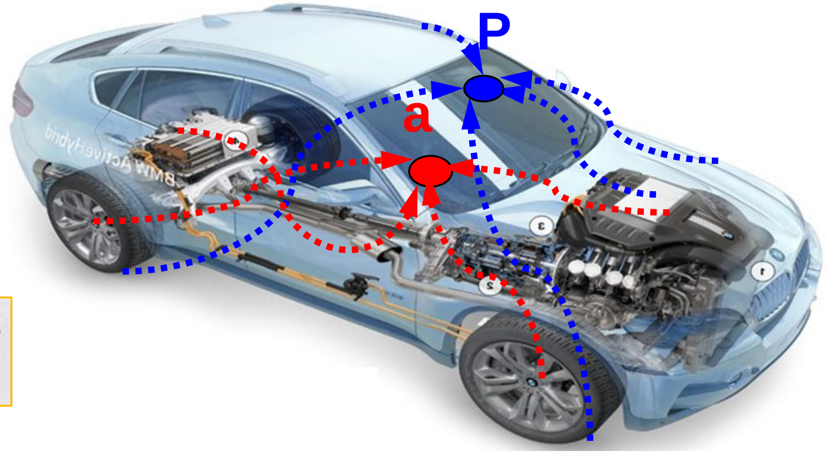
Wiper System

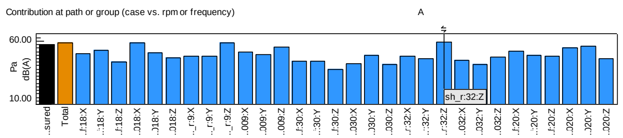
EPS

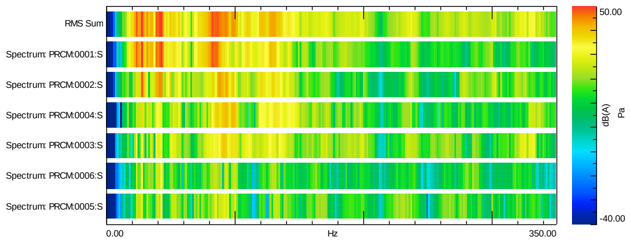
Tyres

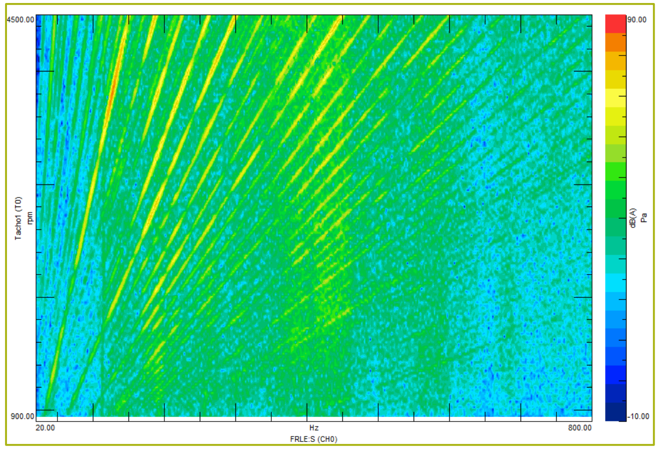
Engine

(H)EV




Source ($F_i$,$Q_j$) X Transfer (NTF) = Receiver ($y_k$)

# Transfer Path Analysis
## Step 1: Which path is contributing?

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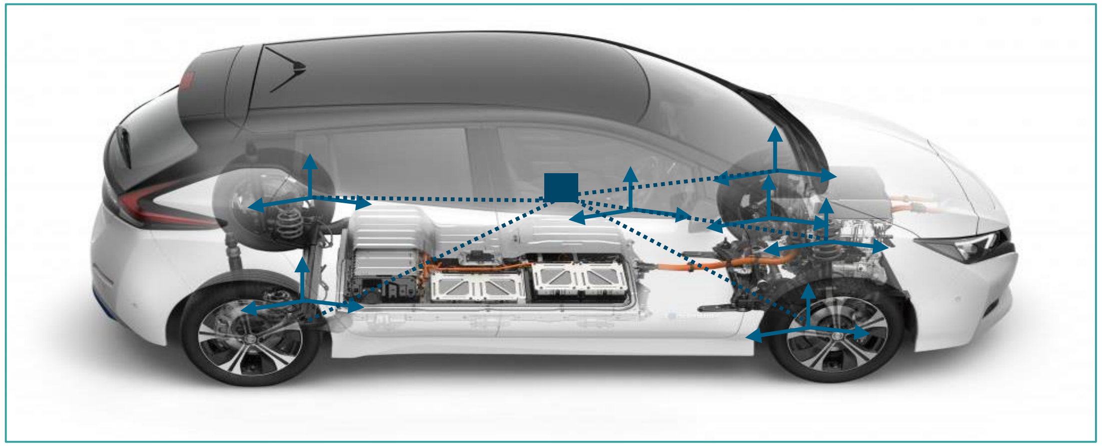
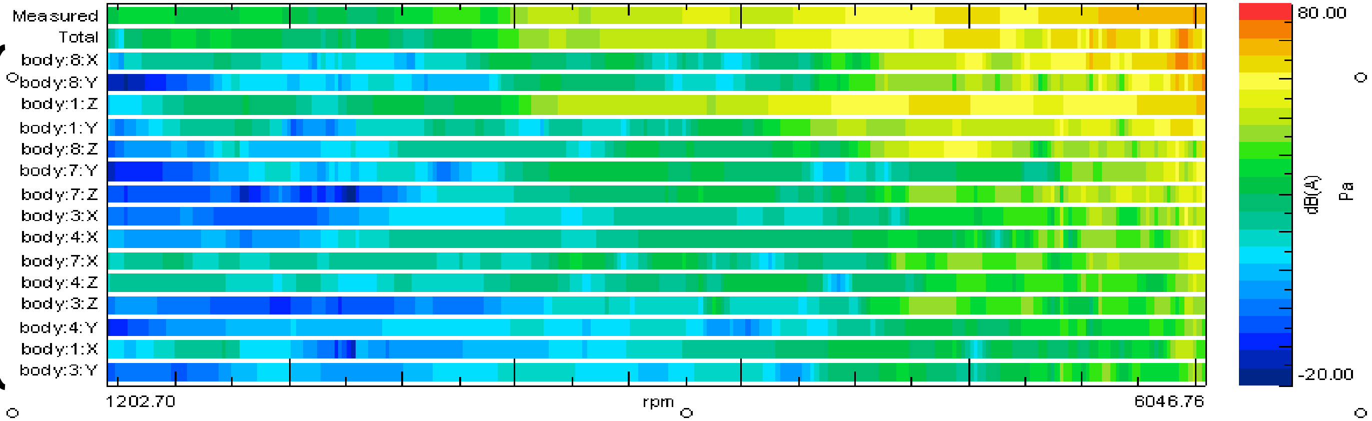


$$y_k = \sum_{i=1}^{n} y_i$$



# Transfer Path Analysis
## Step 2: Why is path contributing?

$$y_i = H_{ik} \; F_i$$

**Receiver**

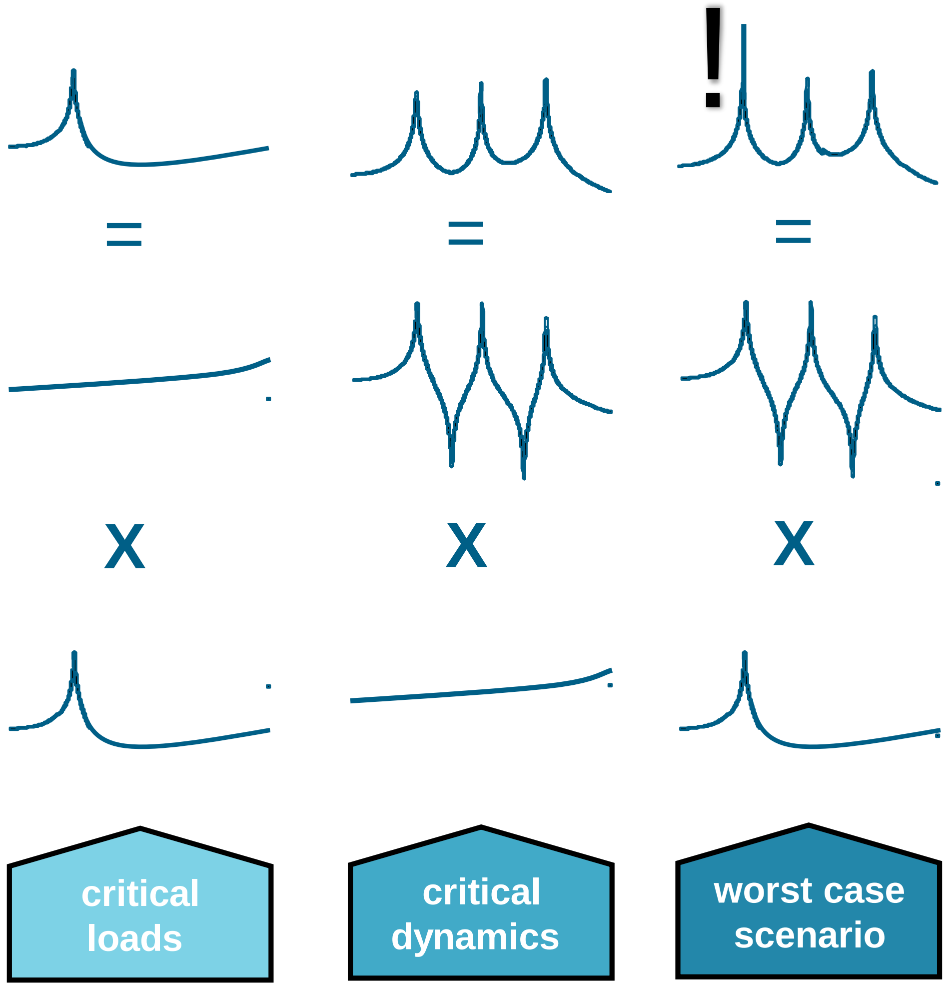
Noise & Vibration

**Transmitter**

System characteristics

**Source**

Structural / Acoustic Loads



# Transfer Path Analysis

*Throughout the vehicle development cycle*

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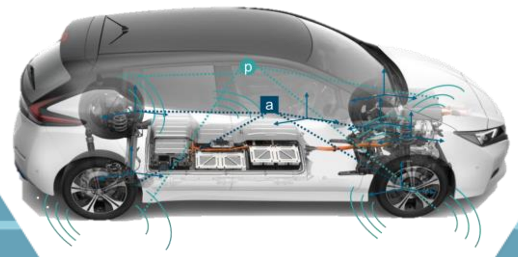
Target Setting | Concept validation | Detailed Engineering | Validation/Refinement



Bench marking & Target setting

Concept Analysis

Load Identification

CAE based contribution analysis

What-if games & optimization

Troubleshooting

Critical component & Path Identification

Auralization & Optimization

**Classical TPA** | **Test/CAE combined TPA** | **Classical TPA**

# Transfer Path Analysis
# Work Flow

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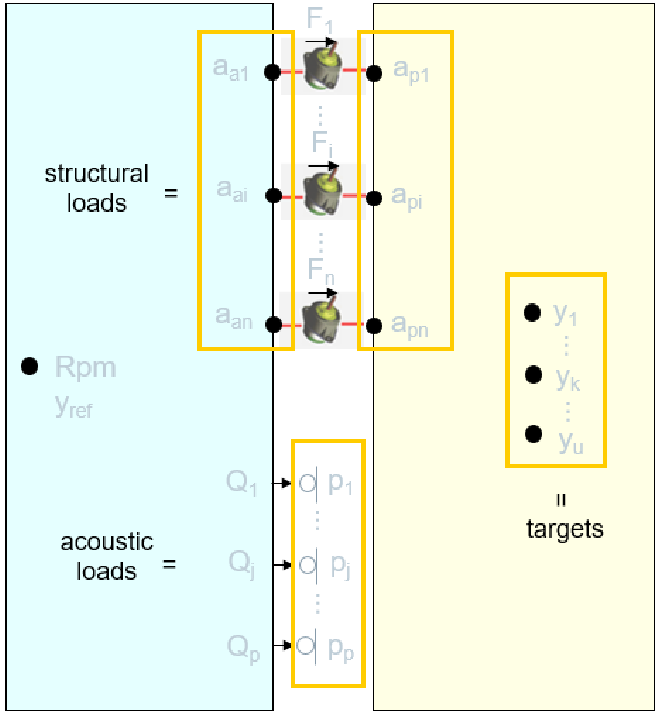
## Step 1: Operational Measurements

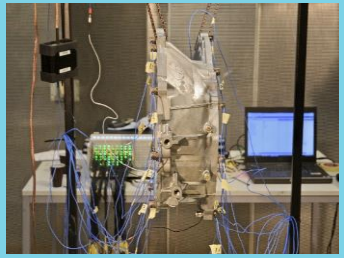
### Signature Testing

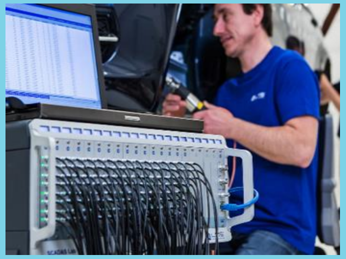



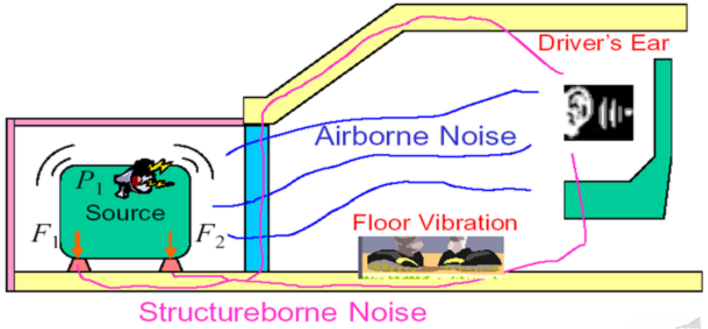
# Transfer Path Analysis
# Work Flow

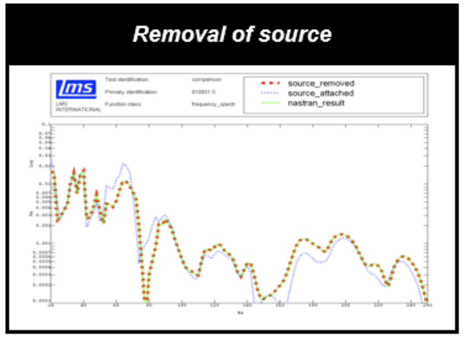
## Step 2: FRF Measurement

**Impact Testing** | **MIMO FRF Testing** | **MIMO SineTesting**








# Transfer Path Analysis
# Work Flow

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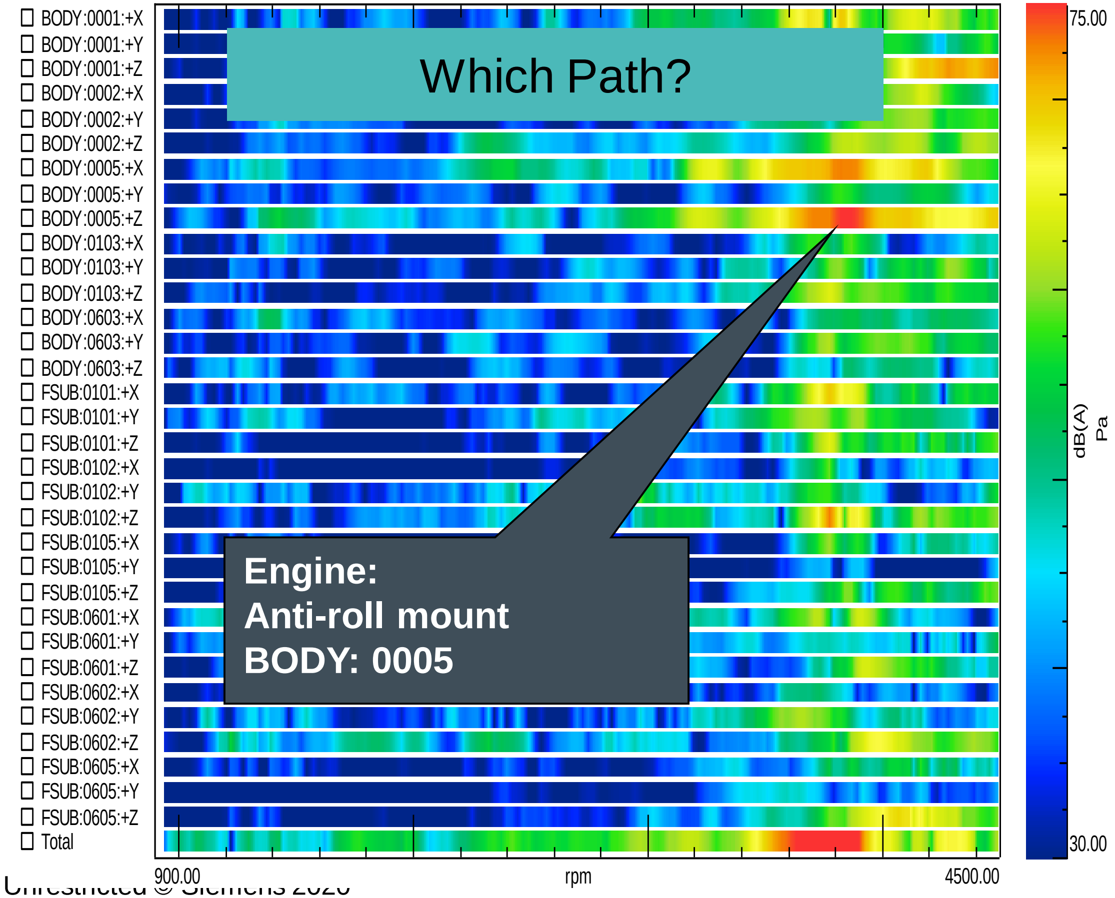
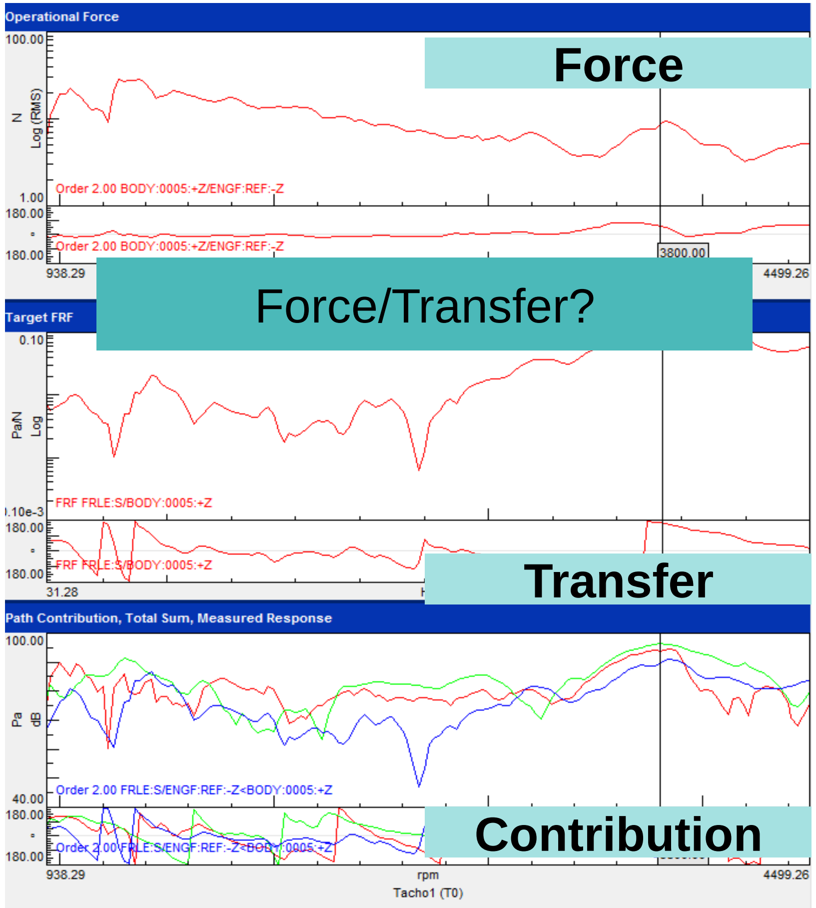
## Step 3: Contribution Analysis



# Transfer Path Analysis
## Siemens Innovation - Most complete solution

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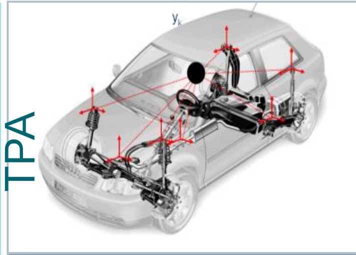
### Engine TPA

Engine TPA: Engine mounts / suspensions

- Engine contribution to interior noise, driving wheel vibration, seats vibration
  - Structural contribution through engine/exhaust mounts, suspension
  - Airborne contribution of engine and exhaust
- Frequency Domain TPA (0-500Hz)
  - Order based analysis
- Time Domain TPA
  - Auralization, Idle noise analysis

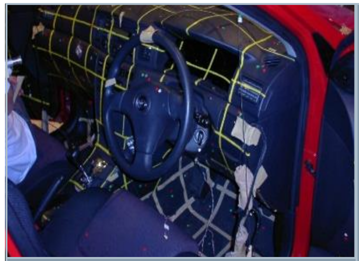
### Road Noise TPA



Road noise is generated by multiple partially correlated forces acting on the suspension

- Wheels / Suspension contribution to interior noise, driving wheel vibration, seats vibration
  - Structural contribution through suspension elements
- Frequency Domain TPA (0-500Hz)
  - Base on Virtual Referenced Spectrum (PCA)
  - Force identification per principal component
- → On road / chassis-dyno measurements (Engine off / coast down)

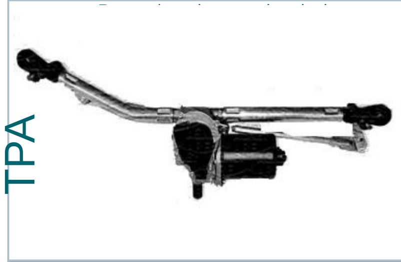
### Airborne TPA



Airborne Source Quantification: Engine noise, wind noise, panel contributions

- Panel contribution to interior noise
  - Engine, road noise contribution through body panels
  - Engine direct radiation
  - Wind noise
- Frequency Domain TPA
  - Order, spectrum or multi-reference based depending on original source
- Multi-Level TPA
  - Detailed downstream contribution analysis for critical paths resulting from engine or road noise TPA

### Component TPA



Individual component contribution: motor noise of wiper mechanism

- Motor contribution to interior noise
  - Structural contribution through mechanism mounts
  - Airborne contribution
- Frequency Domain TPA (500-2000Hz)
  - Contribution analysis
  - Force identification
  - → Spectrum or Autopower based (Energetic method)
- Time Domain TPA
  - Transient analysis
  - Auralization
  - Sound quality metrics

### PBN +TPA

In-room Pass-by Noise (I-PBN)

- Car components contribution to pass-by microphones
  - Engine
  - Tires
  - Exhaust
- Frequency Domain TPA (200-8000Hz)
  - Energetic approach based on Autopowers
- Time Domain TPA
  - Microphone mixing to E-PBN equivalent microphone
  - Overall Level in function of position

### Time Domain TPA


- **Most complete & advanced TPA portfolio**
- **One integrated solution**

# Transfer Path Analysis
## Siemens Innovation - Most complete solution

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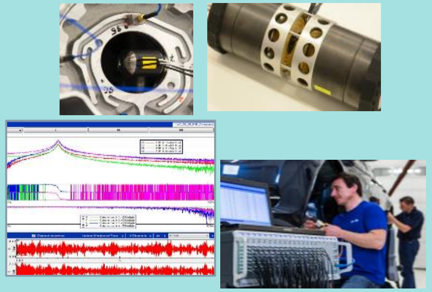
| Testing | | Analysis | | |
|---|---|---|---|---|
| **FRF measurements** | **Operational measurements** | **Load Identification** | **Contribution Analysis** | **Predictive Analysis** |

### Testing

#### FRF measurements



Accurate FRF and NTF measurements for load identification and contribution analysis

Simcenter Structures Acquistion

#### Operational measurements

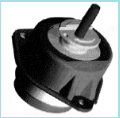

Operational measurements for operational load identification

Simcenter Signature Acquisition

### Analysis

#### Load Identification

$$E^I(\omega) = K^I(\omega) * \frac{-\omega^2}{(g^{aI}(\omega) - g^{bI}(\omega))}$$

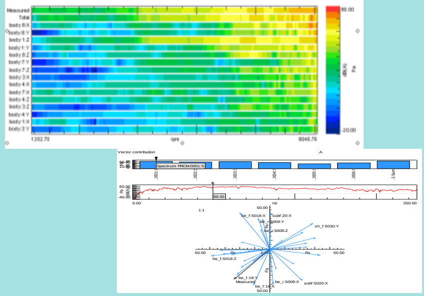


$$\begin{bmatrix} F_1(\omega) \\ F_2(\omega) \\ \vdots \\ F_n(\omega) \end{bmatrix} = \begin{bmatrix} H_{11}(\omega) & H_{21}(\omega) & \cdots & H_{n1}(\omega) \\ H_{12}(\omega) & H_{22}(\omega) & \cdots & H_{n2}(\omega) \\ \vdots & \vdots & \vdots & \vdots \\ H_{1v}(\omega) & H_{2v}(\omega) & \cdots & H_{nv}(\omega) \end{bmatrix}^{-1} \begin{bmatrix} a_1(\omega) \\ a_2(\omega) \\ \vdots \\ a_v(\omega) \end{bmatrix}$$

Load identification using the appropriate technique

Simcenter Transfer Path Analysis

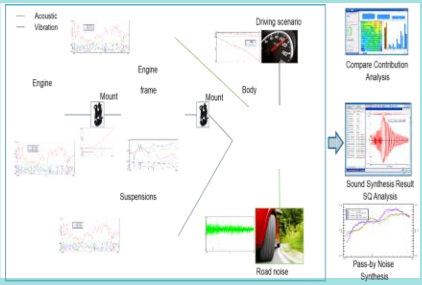
#### Contribution Analysis



Load identification and validation based on different techniques

Simcenter Transfer Path Analysis

#### Predictive Analysis




Predict full vehicle performance for each variant and load case

Simcenter Component Based TPA

**Simcenter provides a fully integrated environment for streamlined work- and data flows**

# Transfer Path Analysis
# Siemens Innovation - Most complete solution

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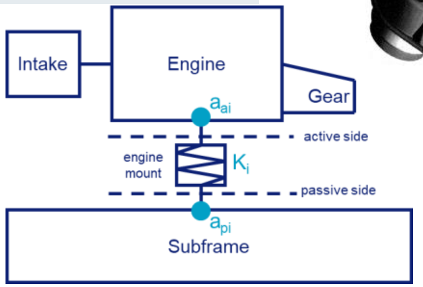
## Mount Stiffness

$$F_i(\omega) = K_i(\omega) \cdot \frac{(a_{ai}(\omega) - a_{pi}(\omega))}{-\omega^2}$$

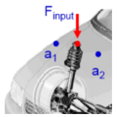



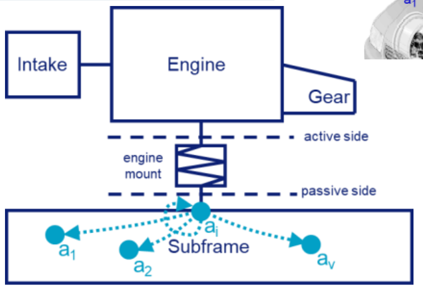

Fast and easy setup

Requires mount stiffness curves

## Matrix Inversion

$$\{F(\omega)\} = [H(\omega)]^{-1} \cdot \{a(\omega)\}$$



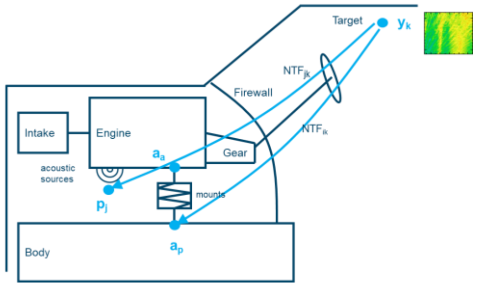



Works for all kind of connections (soft & rigid)

No stiffness curves required

## OPAX

$$F_i(\omega) = f(\text{parameters}, a_{ai}(\omega), a_{pi}(\omega))$$

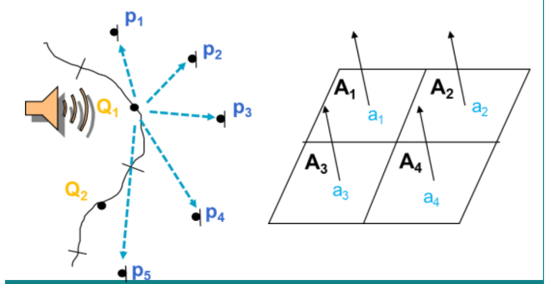



Reduced number of required measurements

Fast troubleshooting method

## ASQ/Panel Contribution

$$\{Q\} = [H^{PQ}]^{-1} * \{P\} \qquad Q_i = A_i * a_i$$




Quantify airborne contributions of nozzles, panels or component housings

**Load identification techniques for fast troubleshooting to detailed structural & airborne load determination**

# Transfer Path Analysis
## Siemens Innovation - Most complete solution
### Strain based load identification

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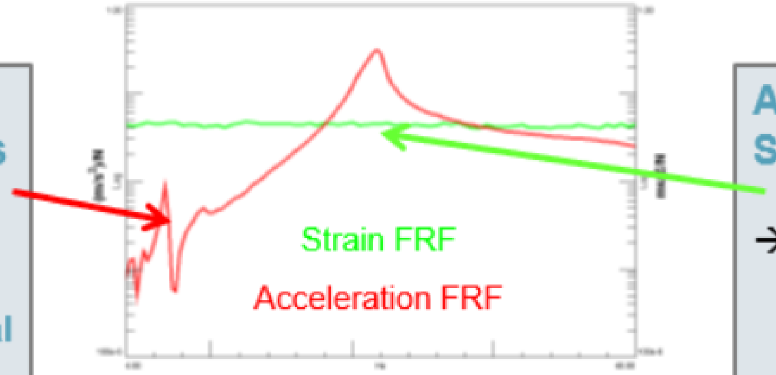
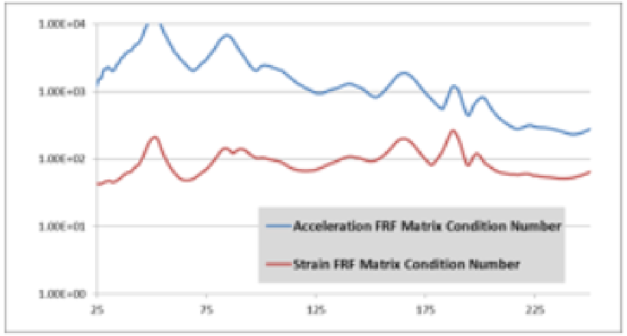
**Classic approach: Acceleration Indicators**

→ Acceleration responses are dominated by a **limited** amount of **global** structural body modes
→ Potential limitation for force estimation possibilities



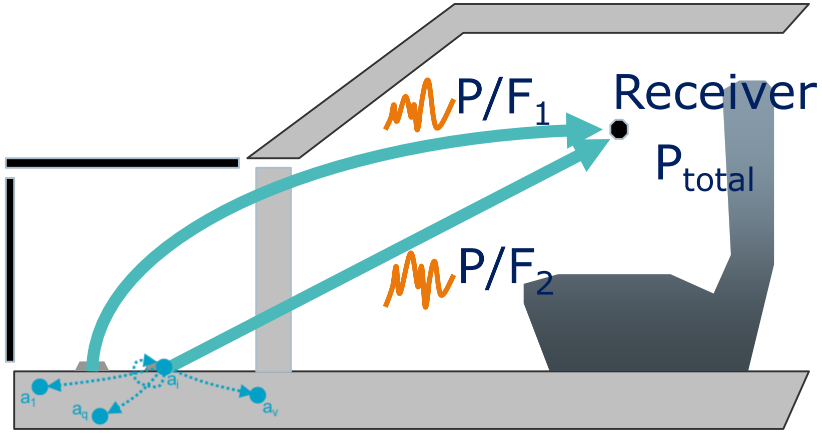

**Advanced approach: Strain Indicators**

→ Strain responses are dominated by a **high** amount of **local** structural body modes
→ Extended possibilities for load separation / identification

**Separating nearby paths**

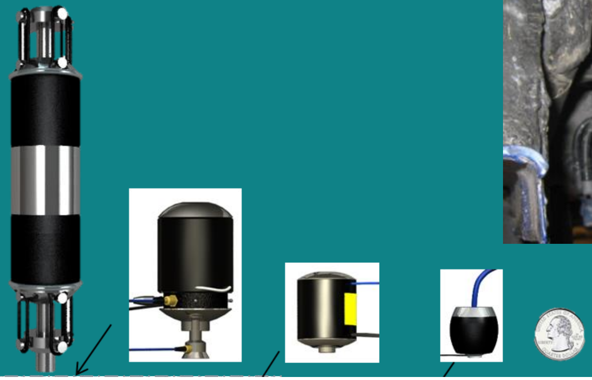

**Simcenter provides a state-of-art load identification techniques**

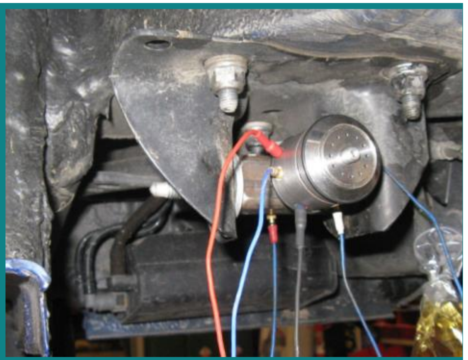
# Transfer Path Analysis
## Siemens Innovation - More productivity and insight
### Efficient & Accurate FRF Acquisition

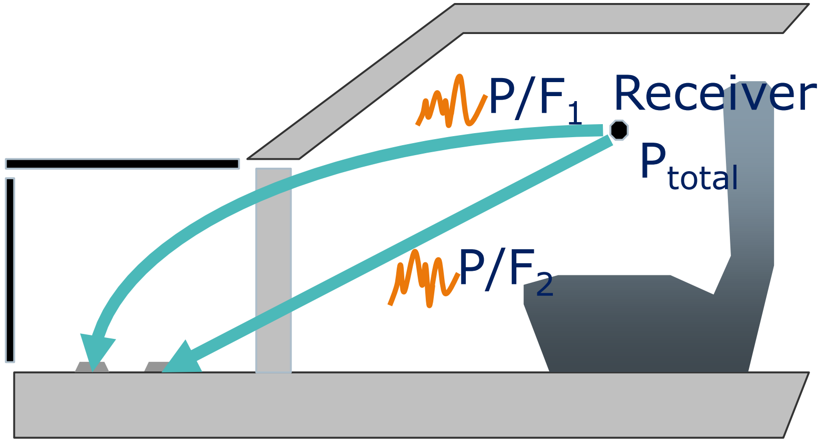



**Direct FRF Measurements**

- Modal Hammer
  - ✓ Common.limited quality and repeatability
- Shaker
  - ✓ shakers overcome hammer issues, if small and applicable

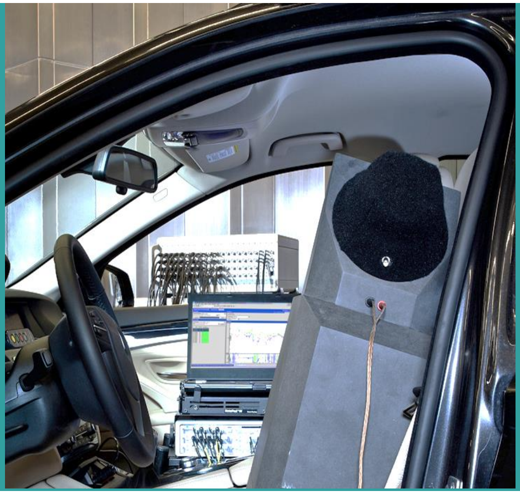







**Reciprocal FRF measurement**

- Measurement of multiple/all NTF (noise transfer functions) at once, faster than roving hammer or shakers



# Transfer Path Analysis

## Siemens Innovation - More productivity and insight

Verify data quality and gain insight – the Heatmap Heatmap

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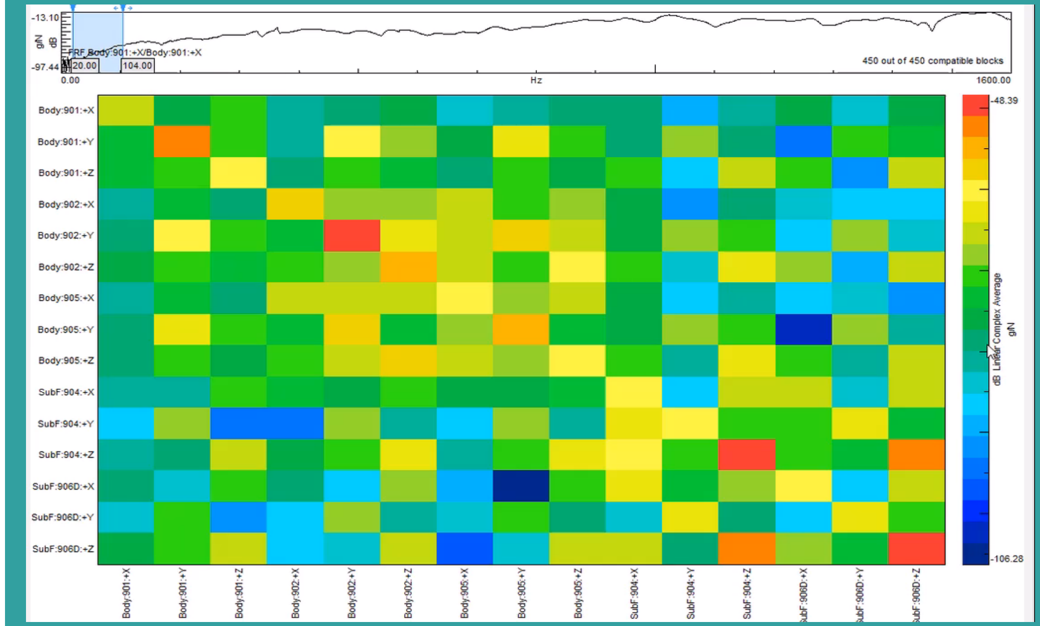
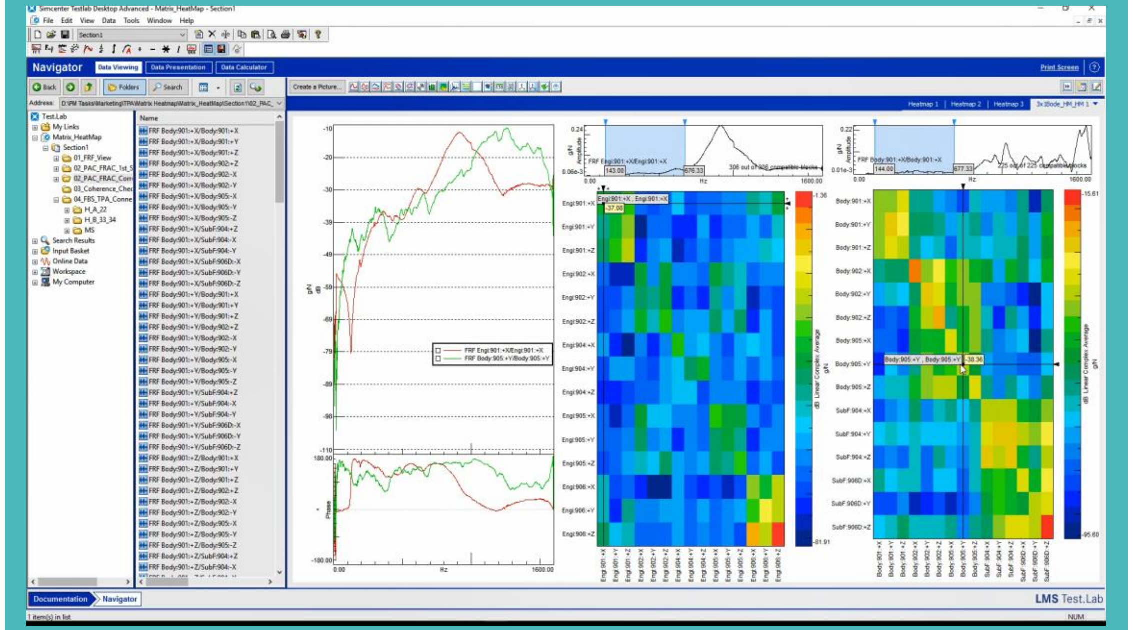


**Instant verification of FRF consistency by checking reciprocity, linearity and directions errors**



**Gain insight in the system dynamics**

**1000+ FRFs in one view**

# Transfer Path Analysis
## Siemens Innovation - More productivity and insight

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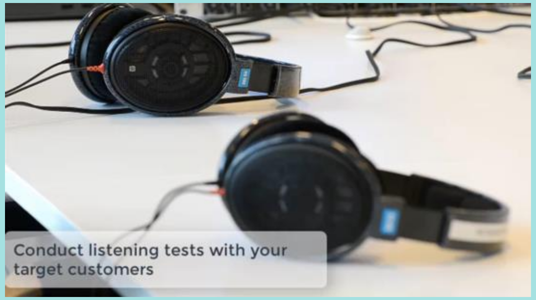
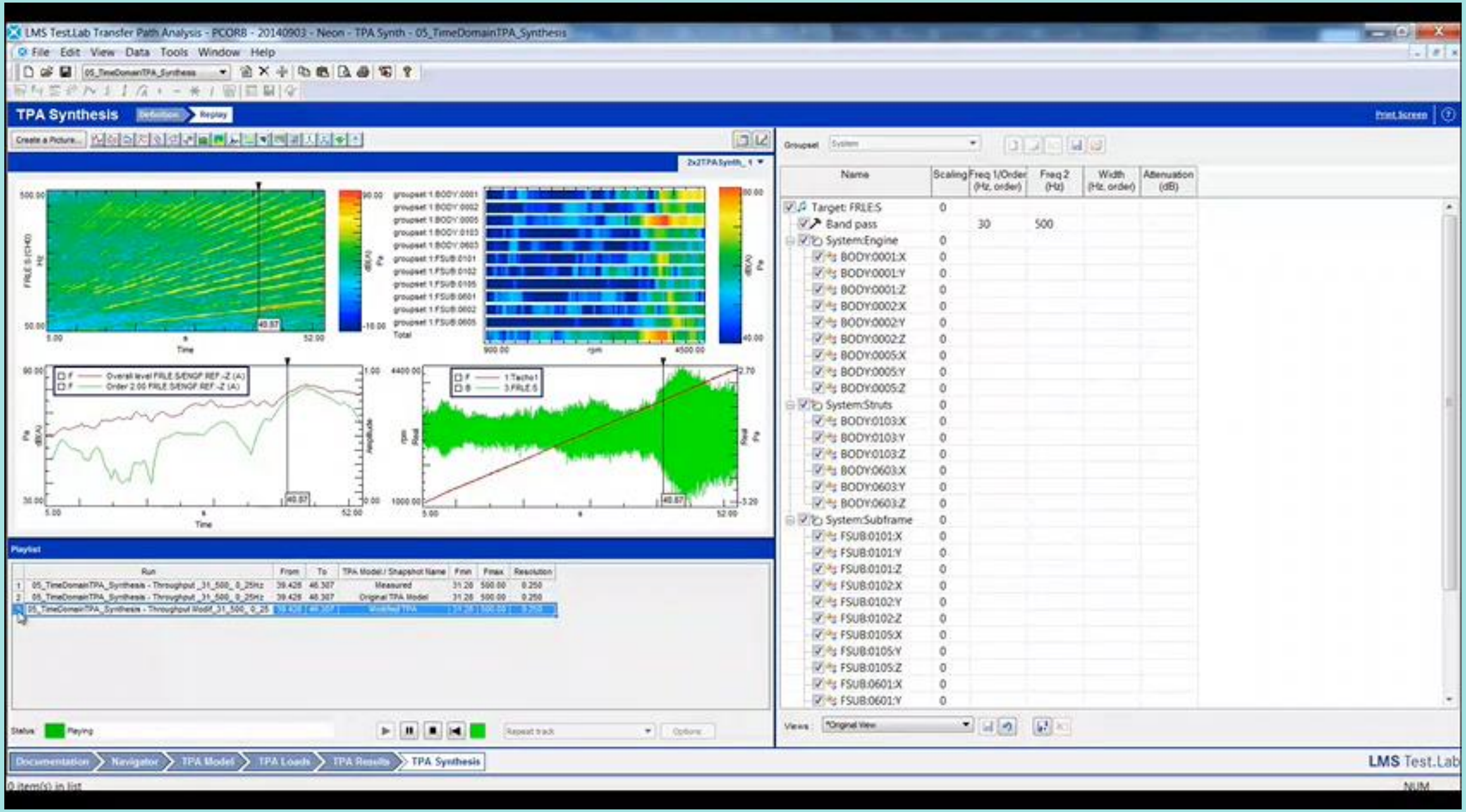
Immediate assessment of design modifications. real-time filtering and auralization of partial contributions for subjective sound qualification and A/B comparisons



# Transfer Path Analysis
## Siemens Innovation – 40 years Engineering Experience

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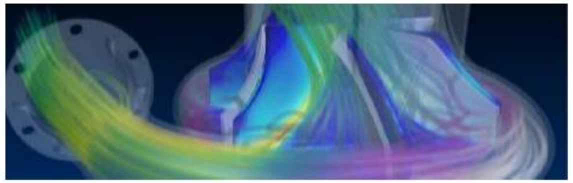
**Rely on 40 years of engineering insight in NVH testing**

Troubleshooting

Co-development

Technology transfer

Engineering process transformation



**Performance Engineering**

Noise & Vibration

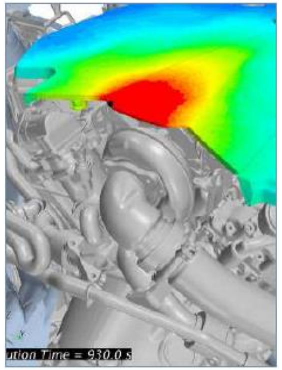
Durability

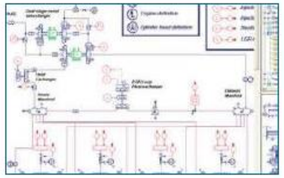
Fuel consumption

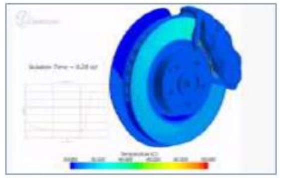
Mechatronics development

CFD

Combustion







Co-develop a dedicated TPA Process
TPA Technology transfer, TPA Troubleshooting

# Transfer Path Analysis
## Siemens Innovation - 40 years Engineering Experience

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**Rely on 40 years of engineering insight in NVH testing**

### Full vehicle experience of local team

| | |
|---|---|
| Changfeng | cP2 Full vehicle development, NVH, dur, etc |
| Geely | EC7 Full vehicle NVH improvement |
| FCC | B90 Full vehicle NVH development |
| FCC | X80 SUV Full vehicle NVH development |
| FCC | B70 Full vehicle NVH development |
| Haima | S7 SUV Full vehicle NVH development |
| Chery | New SUV Full vehicle NVH control |
| Chery | Sendan Full vehicle NVH control |
| Haima | BA01 Full vehicle NVH development |
| GAC Fiat | Feixiang Full vehicle NVH improvement |
| Geely | B-class sedan Full vehicle NVH develop |
| Geely | New SUV Full vehicle NVH developmen |
| SEM | New SUV Full vehicle NVH developmen |
| BYD | Qing Hybrid Full vehicle NVH refinemen |
| BYD | Hybrid SUV Full vehicle NVH developm |

# Overview

## Outline

TPA Introduction

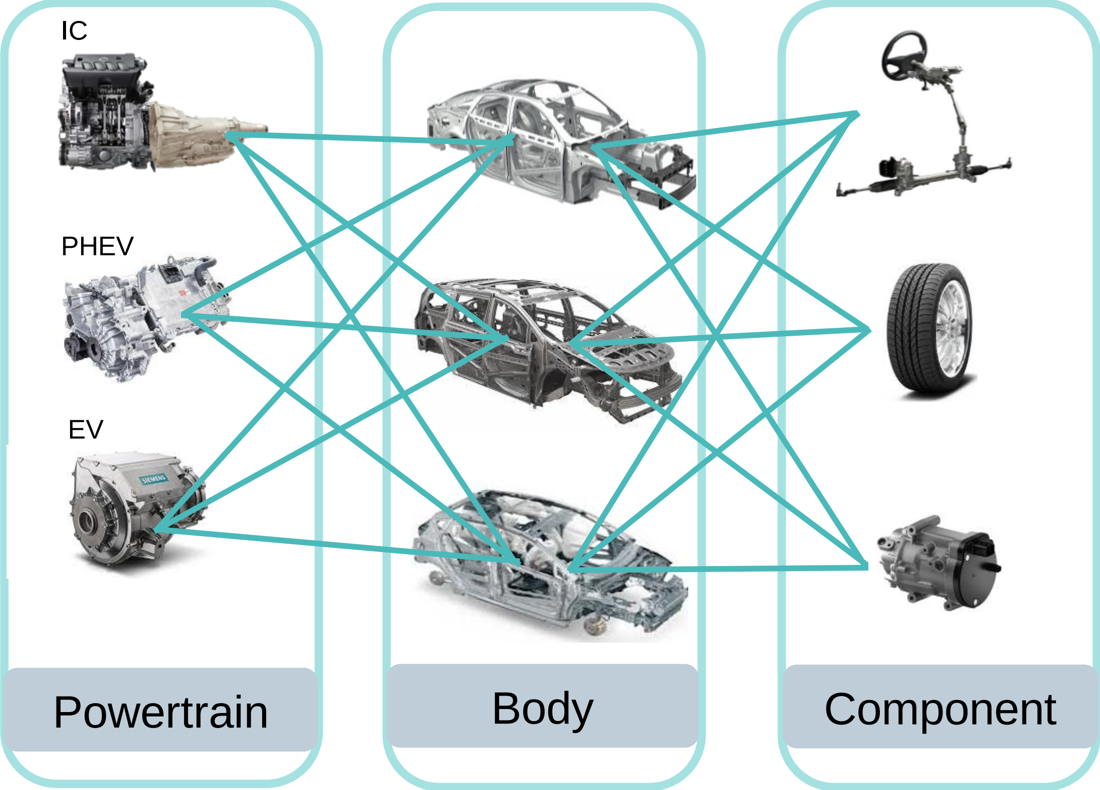
**Component TPA Introduction**

- 1 Component TPA Theory
- 2 Virtual Point Transformation Theory

Application & Reference cases

- 1 Road Noise Synthesis
- 2 PBN Noise Synthesis

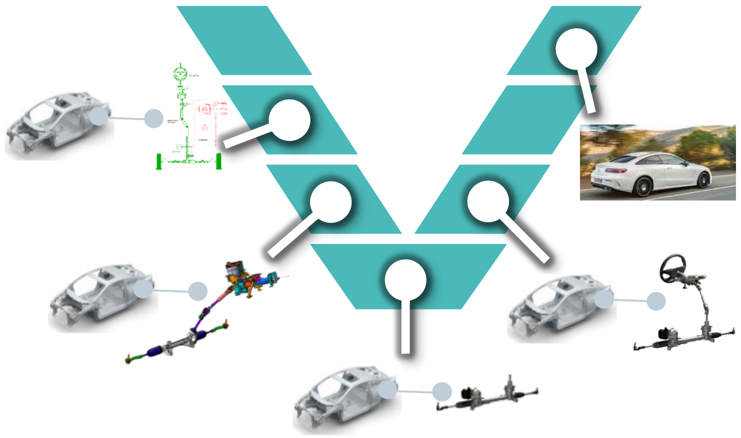
# Automotive OEMs have to reduce full vehicle testing to handle wide variety of vehicles




**# of vehicle variants**

- Increasing testing effort
- Prototype availability?
- Impact of modification?
- …

**Frontloading**



Front-loading vehicle level component NVH testing

How to ensure NVH performance while keeping development time and cost under control?

# Increasing complexity continuously challenges automotive OEM's and Suppliers

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Typical OEM-Supplier cooperation

No correct excitation data

AOEM

No detailed NVH design targets

Supplier

Implications

more vehicle variants / platform complexity / complex powertrains / shorter design cycles / reduced prototype availability / more complex load cases / …

Increasing risk of integration issues of components

Impact on time-to-market and possible expensive modifications

Control NVH Performance

Improved OEM-Supplier cooperation

Invariant load description

AOEM

Realistic NVH design targets

Supplier

# Component based TPA for component design evaluations
# Enable realistic test bench based NVH target verification

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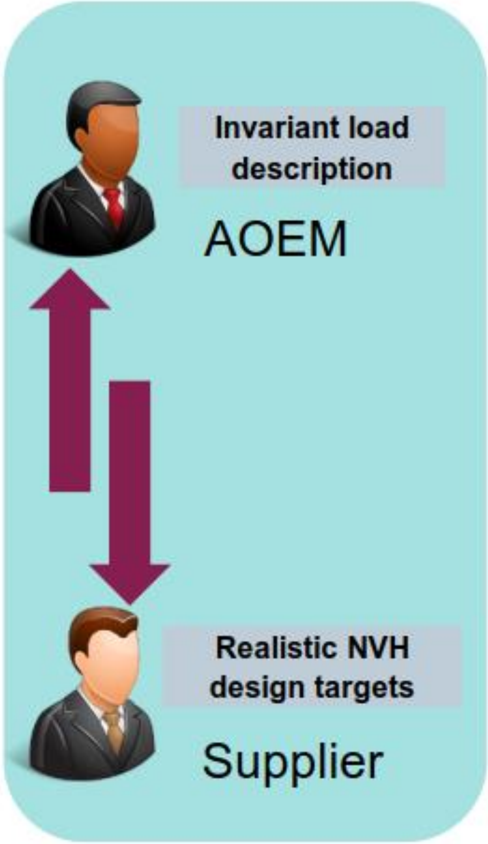
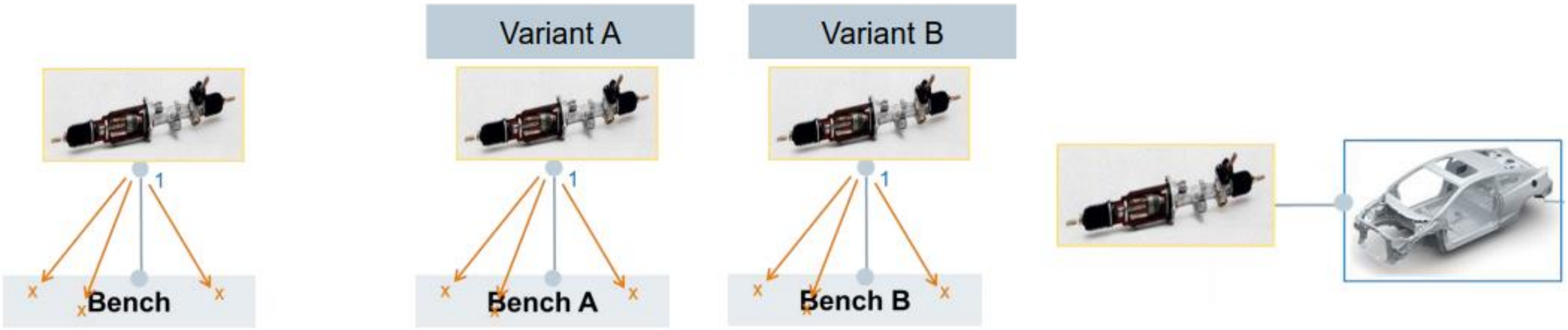



Validate performance against test bench independent targets

Validate objectively impact of design modifications or compare variants irrespective of test bench

Predict assembly NVH performance to optimize system integration

## How to keep control of the NVH Performance at any stage of the development cycle?

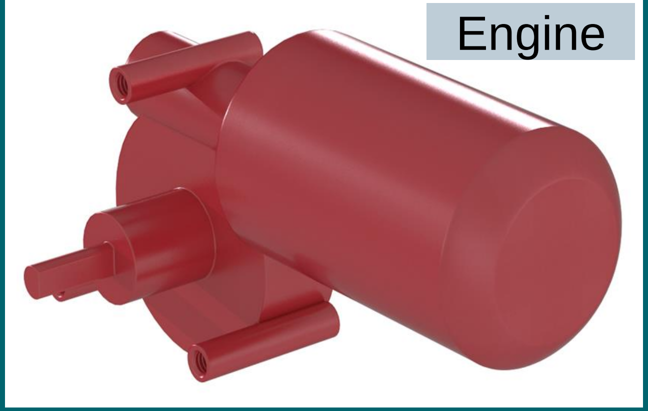
**Can we provide a method that addresses all these challenges?**

YES, WE CAN!

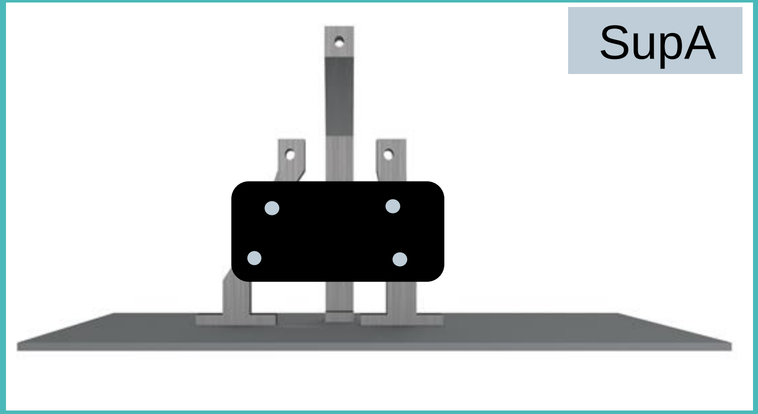
Component Based TPA

# Component Based TPA

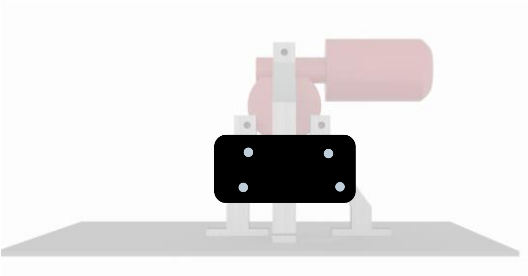
## Source Tested Separately

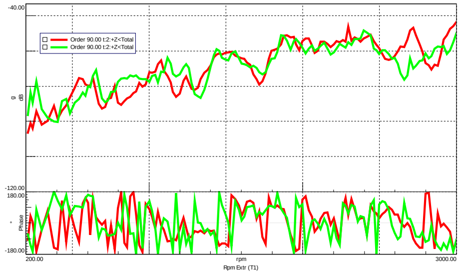



## Receiver Tested Separately




## Virtual Assembly and Prediction





# Component Based TPA process

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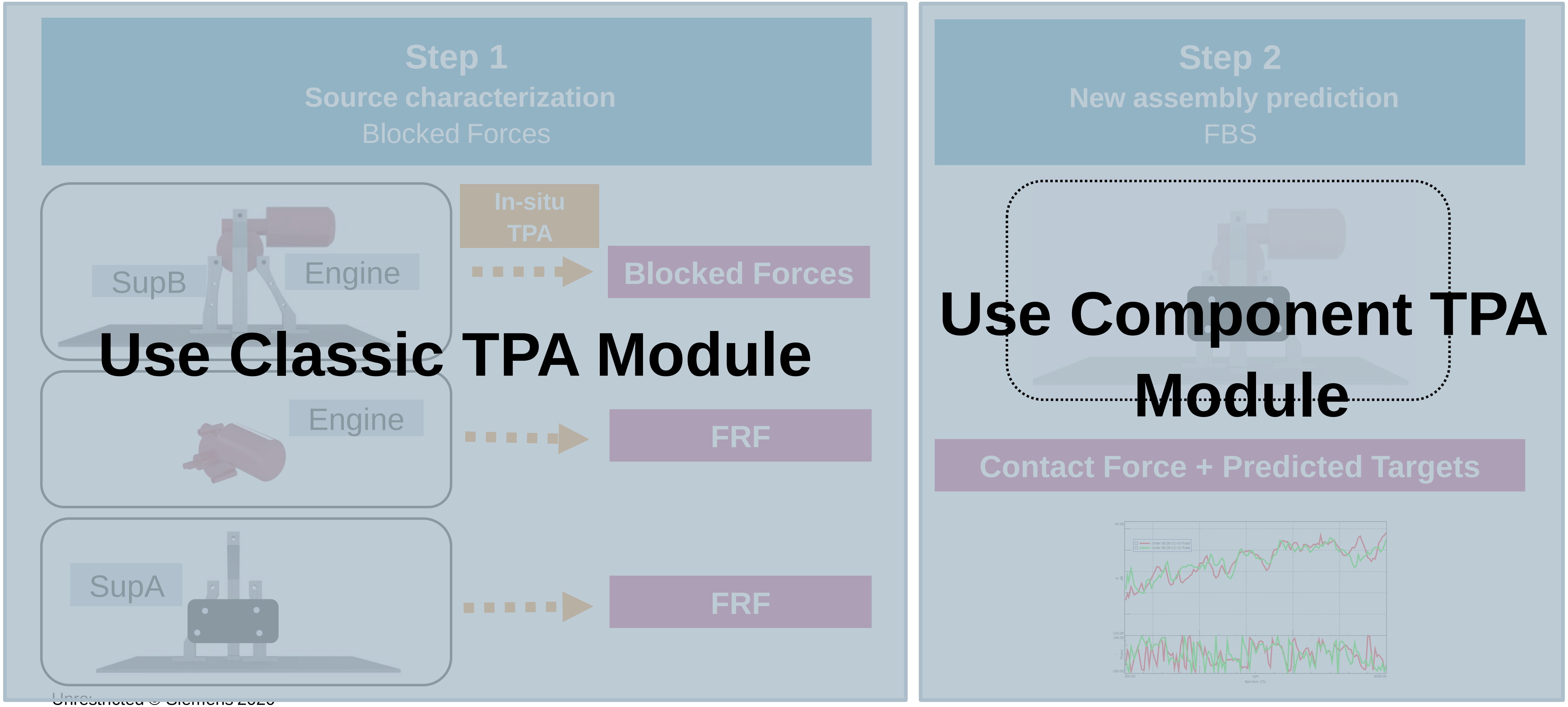

# Simcenter Testlab 2019.1

*Component Based TPA: Assembly & Prediction*

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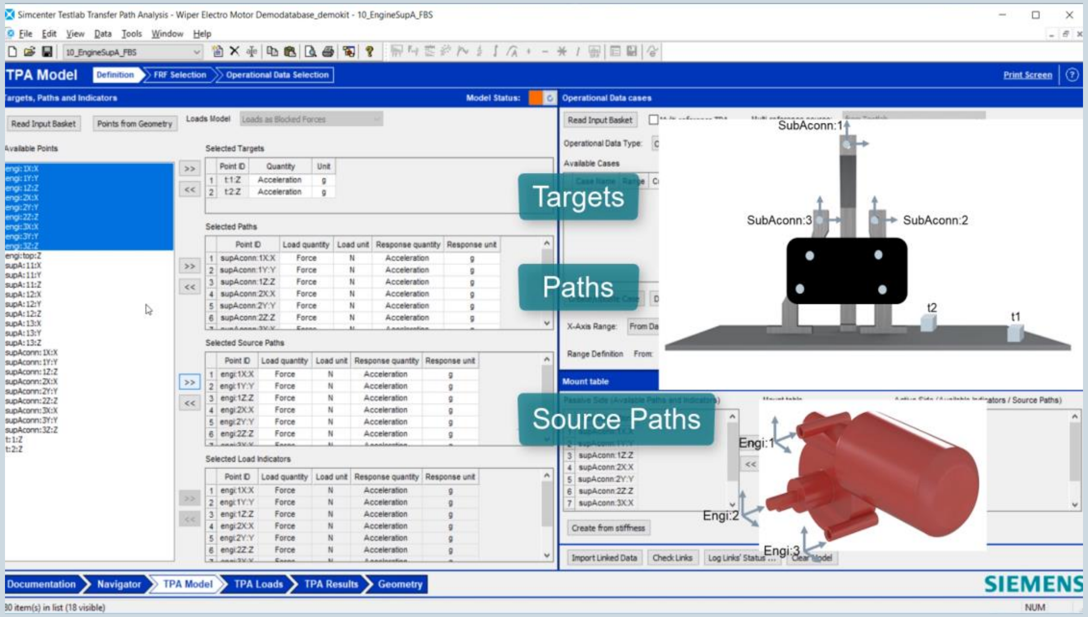
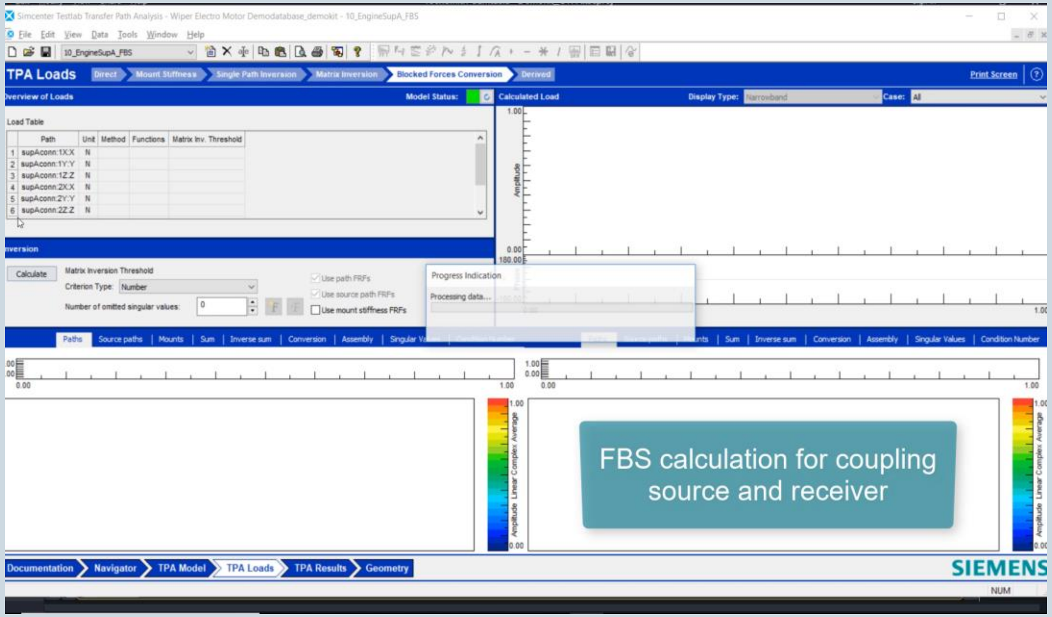
## 1. Assembly Definition

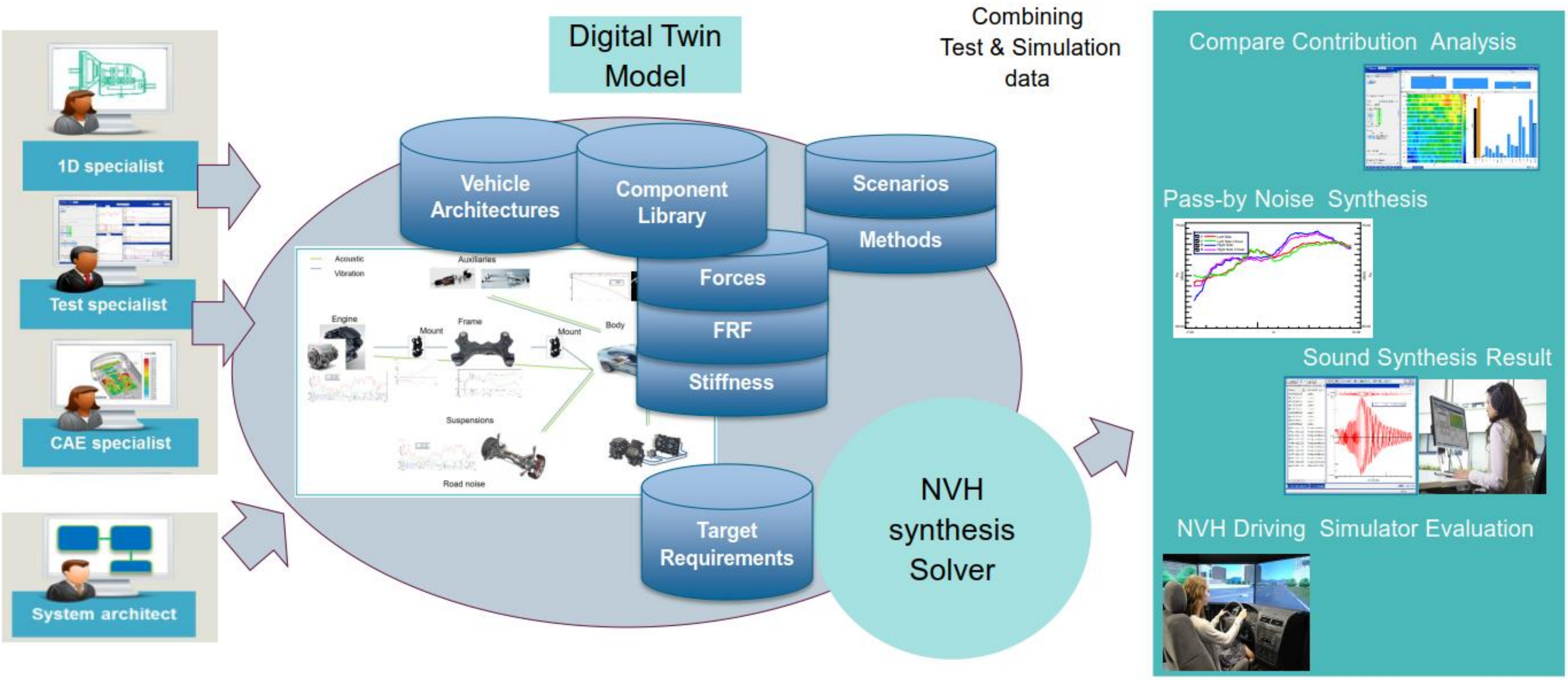



## 2. Load & Contribution Prediction




**The complete Component Based TPA process fully integrated in Simcenter Testlab**

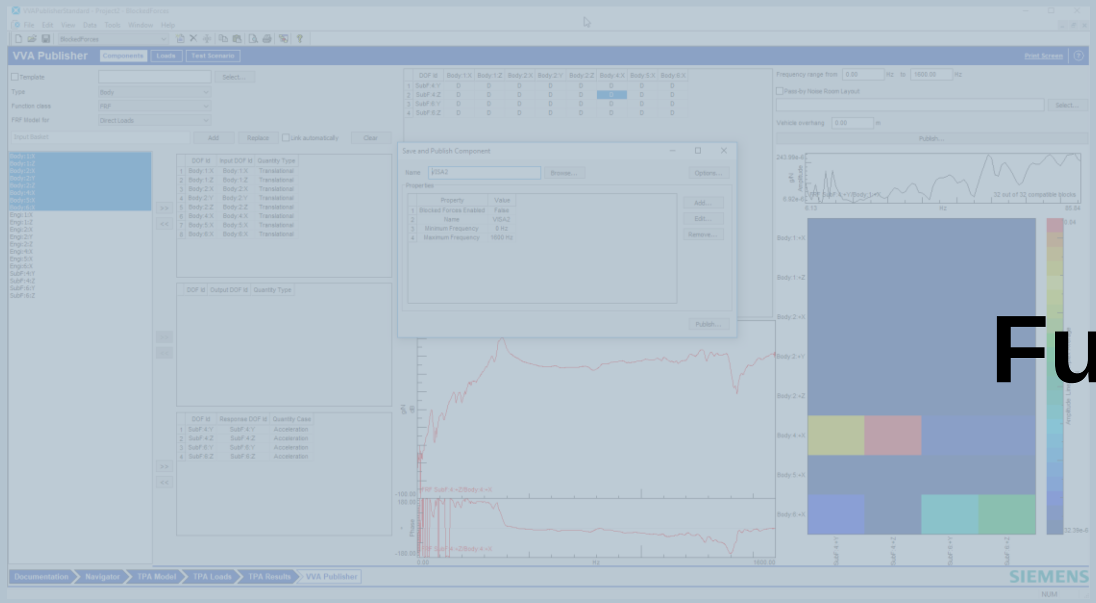
# Component based TPA for full vehicle NVH Assessment Concept



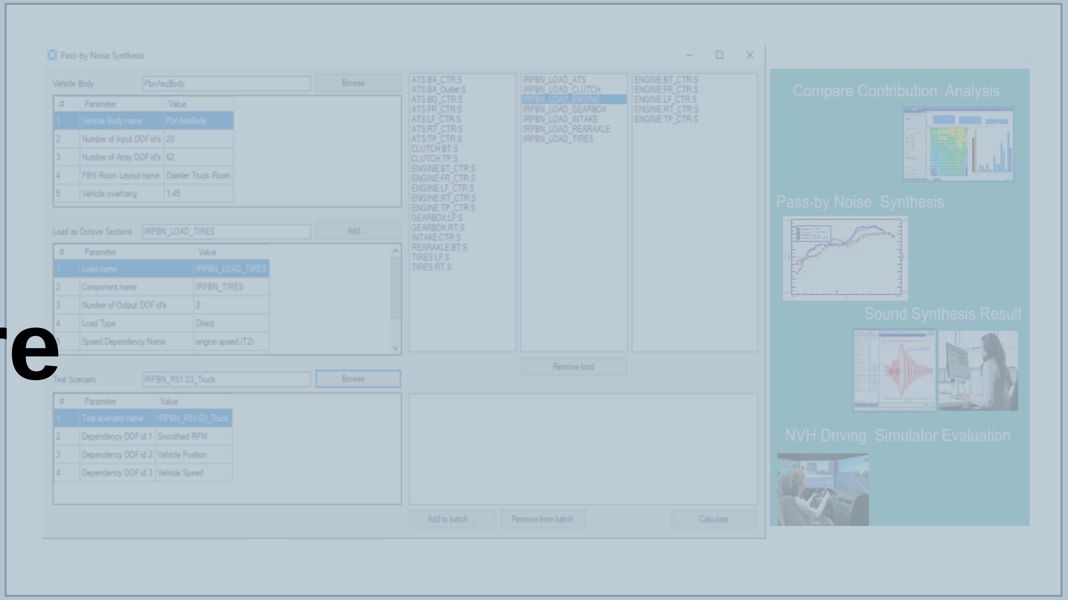
# Simcenter Testlab NVH Synthesis

*Model Based Development for NVH*

## 1. NVH Component Definition




## 2. NVH Synthesis Applications




**Future**

***Enable NVH what-if analysis from concept to final troubleshooting***

# Overview

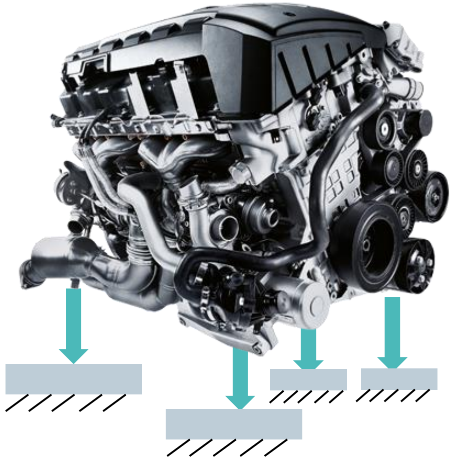
## Outline



# Component-based TPA
## Step 1: Source characterization - Invariant load

**Structure-borne:**

Blocked Forces



**Airborne:**

Volume Velocities

**Invariant load characterization**

Receiver independent, allowing:

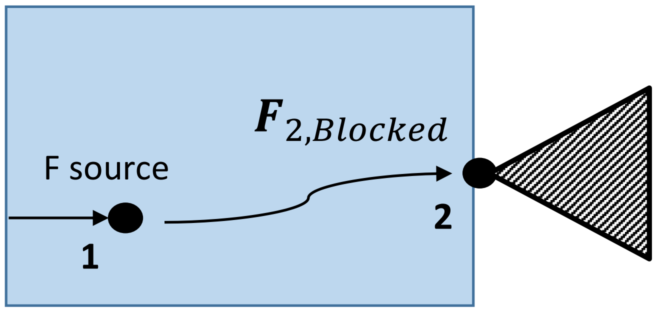
- Validating sources against receiver independent targets
- Benchmarking or validating modifications
- Predicting NVH performance in arbitrary source-receiver assemblies

# Component-based TPA
## Step 1: Source characterization - Structure Borne

**Three possible methodologies to obtain independent source description**

### 1. Blocked Force

**Source A**

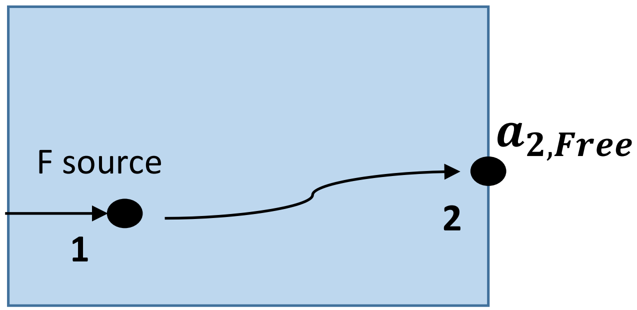



**Rigid test rig → Most times not possible**

Source: Mondot, Petersson, Characterization of structure-borne sound sources: The source descriptor and the coupling function 1987

### 2. Free Velocity

**Source A**

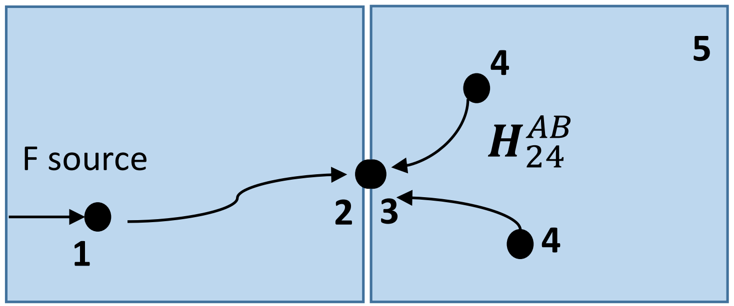



$$[H_{22}^{A}]^{-1} a_{2,Free} = F_{2,Blocked}$$

**Source in free free conditions ISO 9611**

### 3. In-Situ TPA

**Source A** **Receiver B**




$$F_{2,Blocked} = [H_{24}^{AB}]^{+} a_4$$

**Any receiver is valid ISO 20270 FDIS**

Source:Elliott, Moorhouse, Characterization of the structure borne sound sources from measurements in-situ, 2008

# Component-based TPA
## Step 1: Source characterization - Different local FRF

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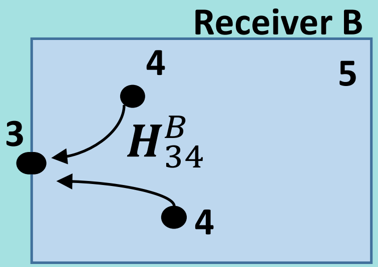
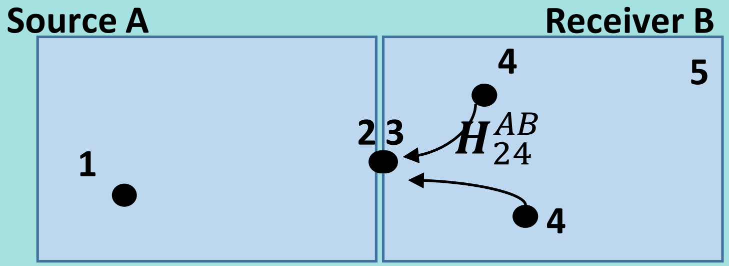
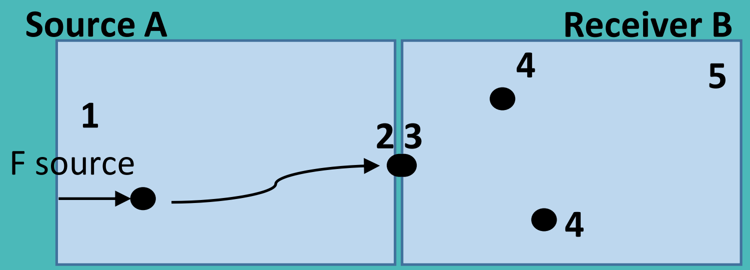
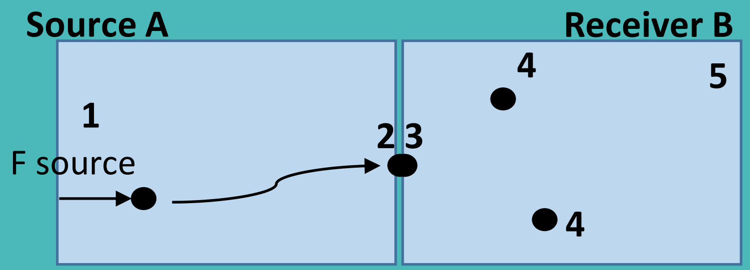
| | Classic TPA<br>Determination **contact forces** | | Component Based TPA<br>Determination **blocked forces** |
|---|---|---|---|
| **1. Local FRF for load identification** | (see figure 1 below) | $\neq$ | (see figure 2 below) |
| **2. Operational measurements** | (see figure 3 below) | $=$ | (see figure 4 below) |
| **3. Force Identification** | $F_{3,Contact} = [H^{B}_{34}]^{+} a_4$ | $\neq$ | $F_{2,Blocked} = [H^{AB}_{24}]^{+} a_4$ |



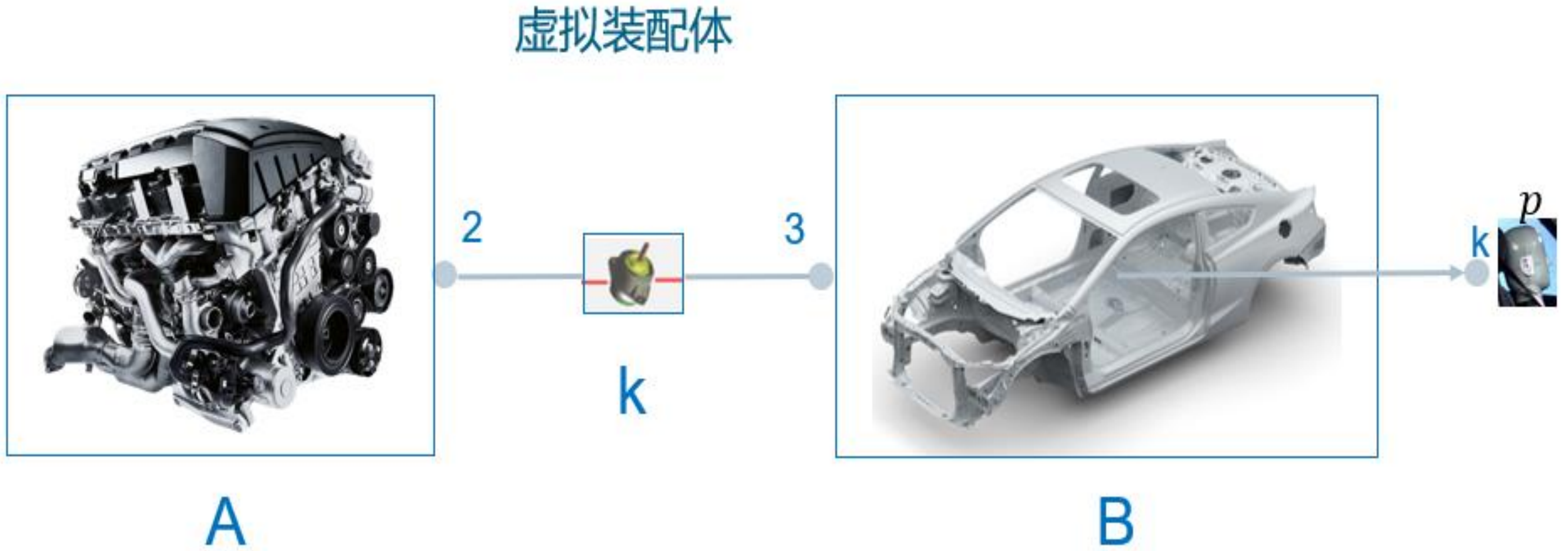



# Component-based TPA
## Step 2: Target assembly prediction

How to go from Blocked Force to *Contact* Force ?

**Use the Frequency-based Substructuring (FBS)**



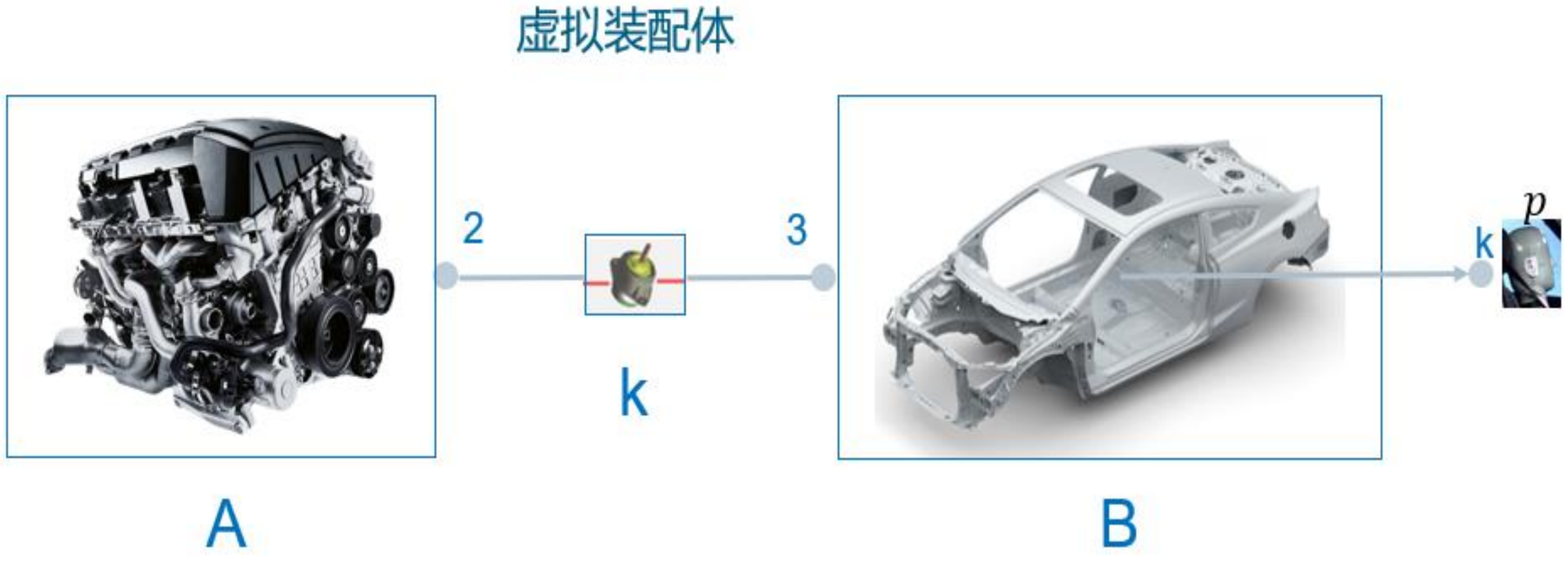

$$\{F_{contact}\} = FBS\ Conversion\ Matrix * \{F_{blocked}\}$$

$$FBS\ Conversion\ Matrix = \left[H_{22}^{A} + H_{33}^{B} + K^{-1}\right]^{-1} * \left[H_{22}^{A}\right]$$

# Component-based TPA
## Step 2: Target assembly prediction

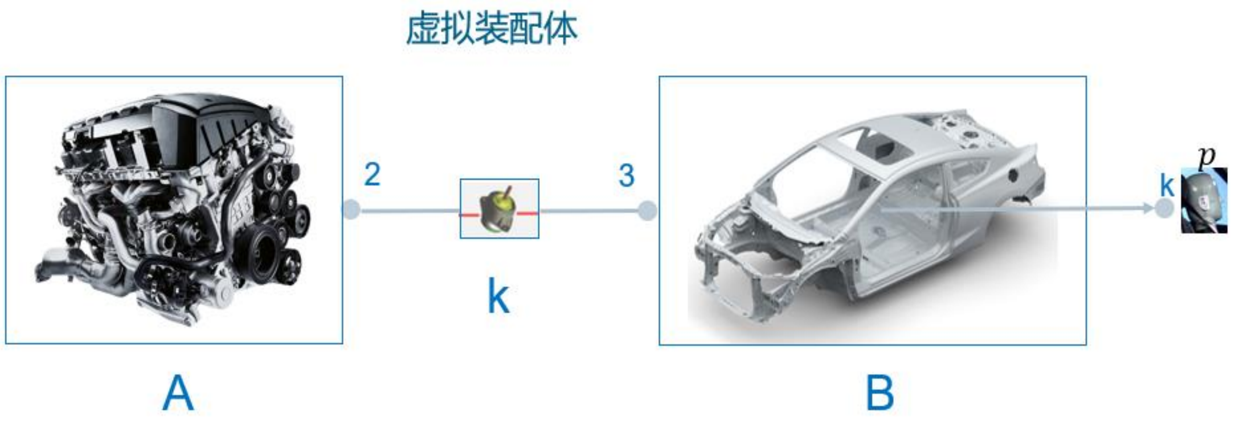
How to go from Contact Force to Target Prediction ?

### General classical TPA formulation

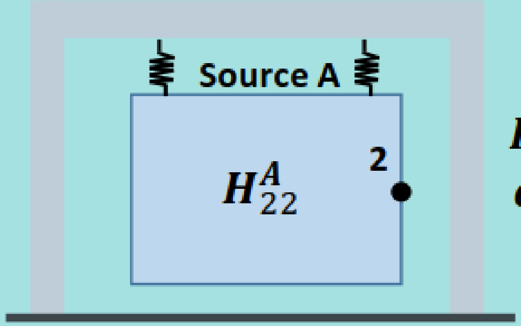



$$\{p\} = \left[H_{3k}^{B}\right] * \{F_{contact}\}$$

# Component-based TPA
## Step 2: Target assembly prediction - FB

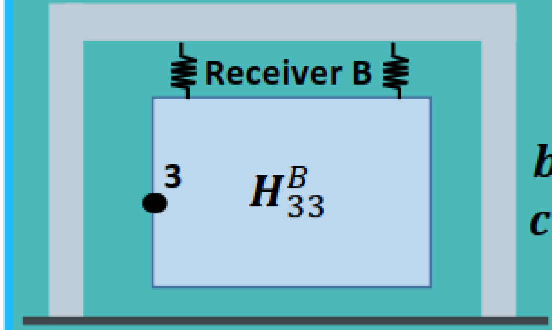



$H_{22}^{A}$ → FRF matrix of source only



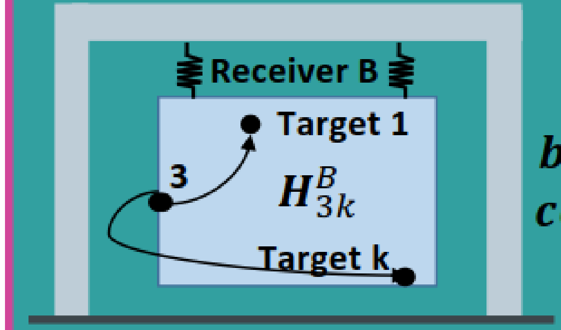

***Free free condition***

$H_{33}^{A}$ → FRF matrix of receiver only




***Real boundary conditions***

$H_{3k}^{B}$ → NTF matrix of receiver to target only




***Real boundary conditions***

# Component-based TPA
# Procedure Step1 + Step 2

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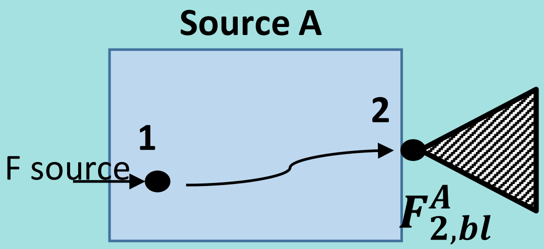
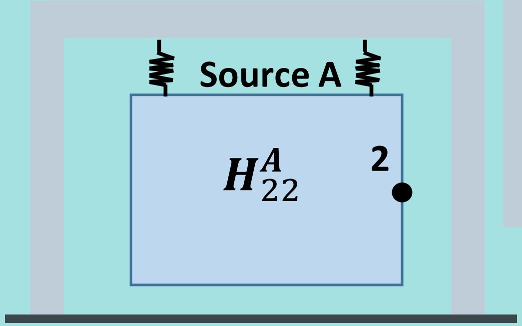
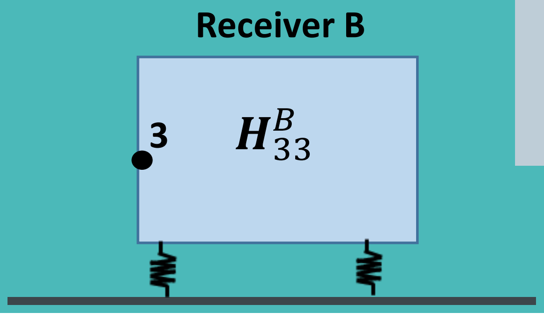
1. **Source A:**
   a. Blocked Force $\boldsymbol{F}^{A}_{2,bl}$
   b. Inertance matrix $\boldsymbol{H}^{A}_{22}$




Free-Free or pre-load condition

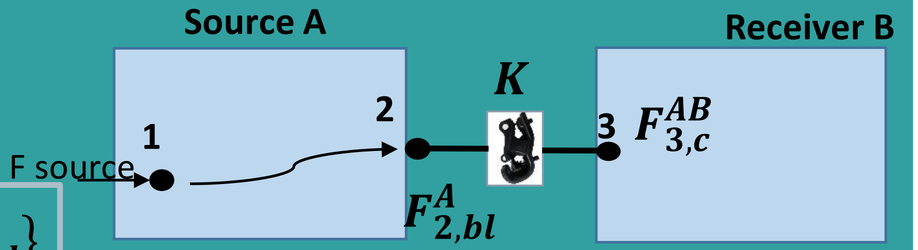
2. **Receiver B:**
   a. Inertance matrix $\boldsymbol{H}^{B}_{33}$




Realistic boundary condition

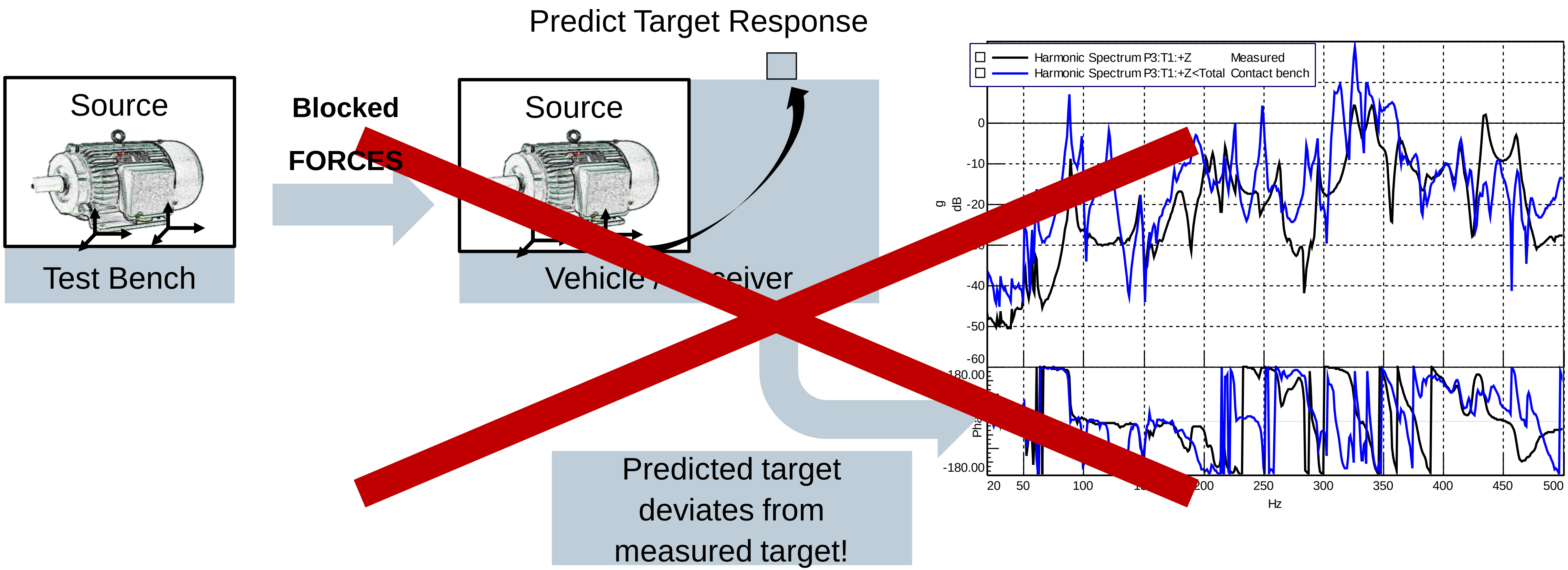
3. **Convert Blocked Force $\boldsymbol{F}^{A}_{2,bl}$ into Contact Force $\boldsymbol{F}^{AB}_{3,c}$**
   a. Mount stiffness $\boldsymbol{K}$ (not needed for rigid connections)
   b. FBS

$$\left\{\boldsymbol{F}^{AB}_{3,c}\right\} = \left[\boldsymbol{H}^{A}_{22} + \boldsymbol{H}^{B}_{33} + \boldsymbol{K}^{-1}\right]^{-1} * \left[\boldsymbol{H}^{A}_{22}\right] * \left\{\boldsymbol{F}^{A}_{2,bl}\right\}$$



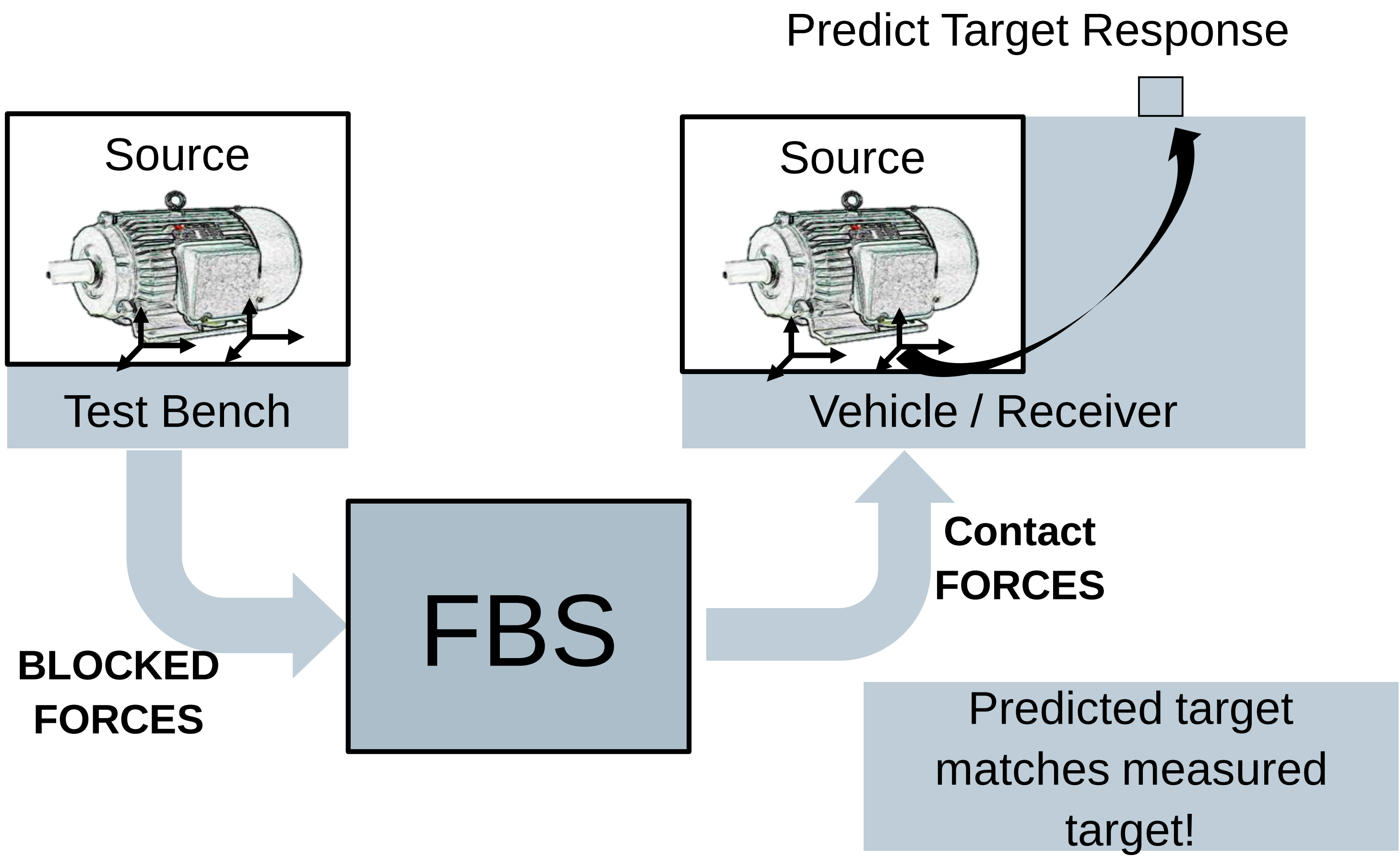
# Component-based TPA

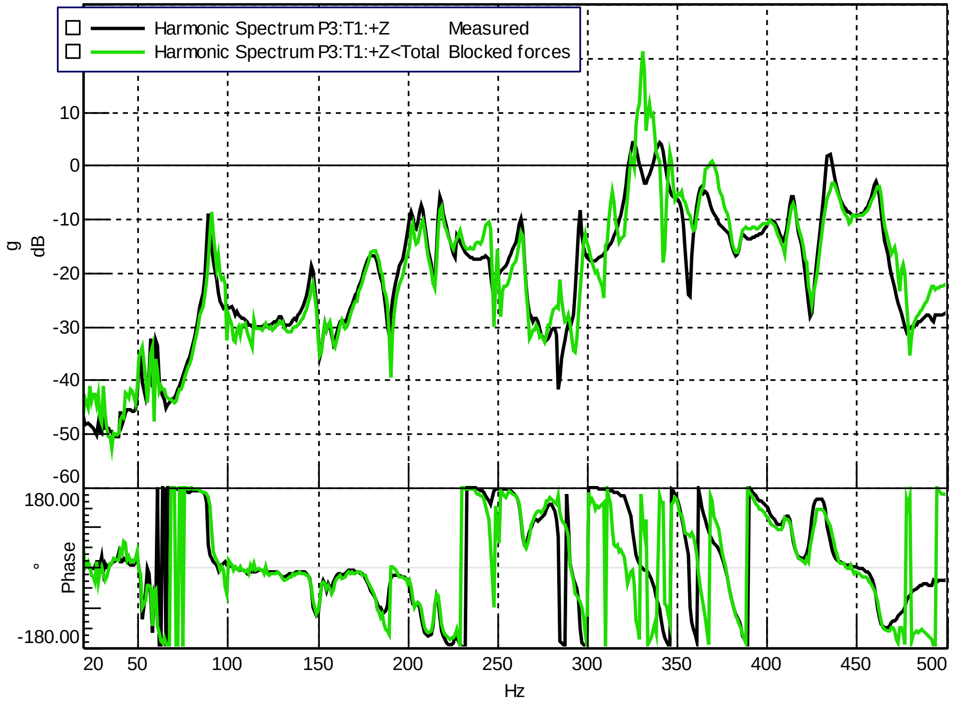
*No FBS Technology*



# Component-based TPA

*FBS Technology*



# Overview

# Outline

TPA Introduction

Component TPA Introduction

1 Component TPA Theory

2 Virtual Point Transformation Theory

Application & Reference cases

1 Road Noise Synthesis

2 PBN Noise Synthesis

# Virtual Point Transformation (VPT)

*Accurate FRFs at interface connection points*

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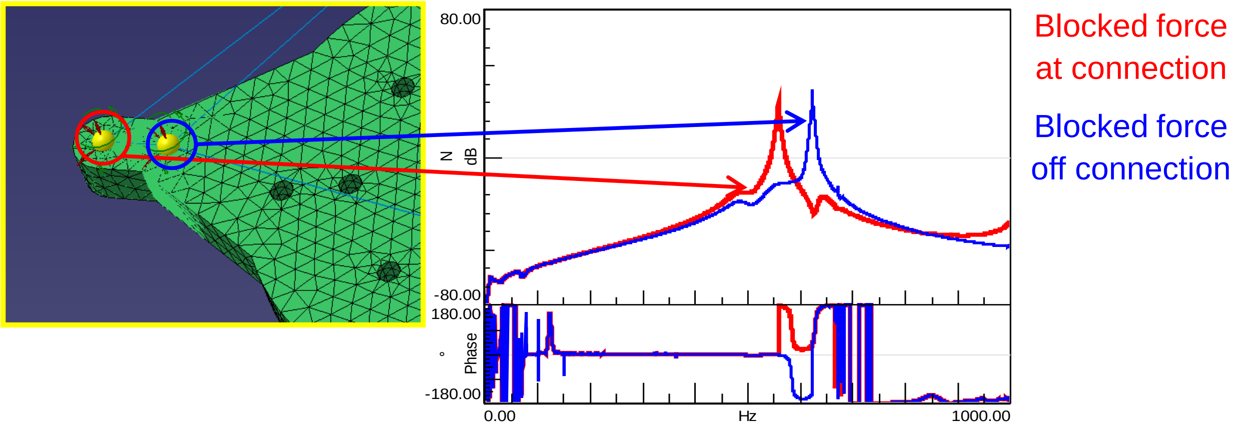
**Challenge:**

- High quality transfer functions at precise locations.
- Transfer functions at difficult to access positions
- Translational and rotational transfer functions (DOFs)

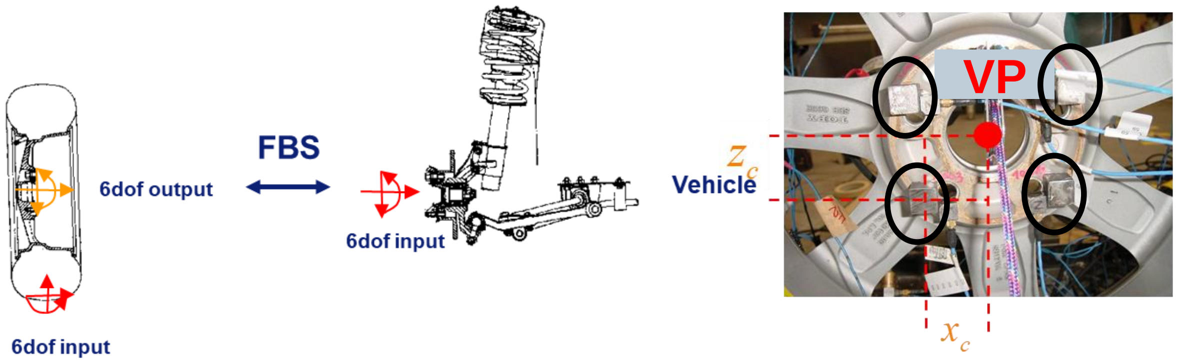
**Solution:**

- Geometrical Reduction / Virtual Point Transformation
- Assumption: local rigidity in the connection
- Input: Geometry Information and FRFs

## VPT for correct blocked force estimation



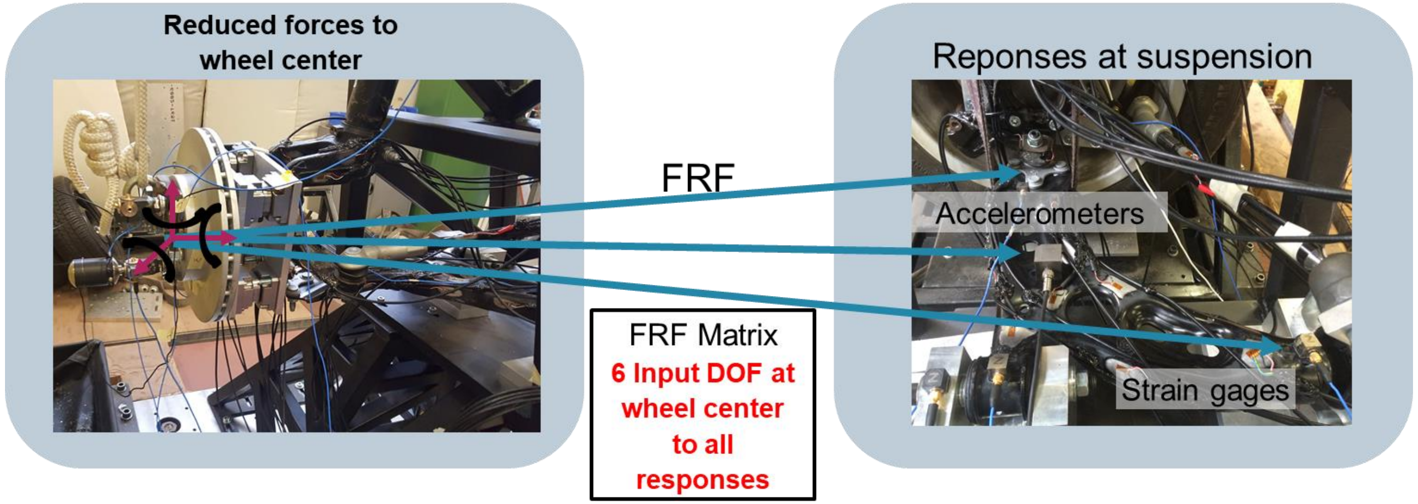

## VPT for correct assembly using FBS



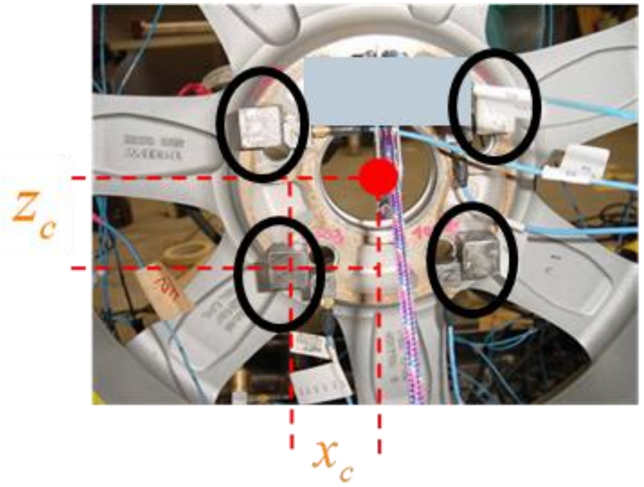
# Virtual Point Transformation (VPT) Workflow

The reduced FRF (forces and accelerations) at the wheel center will be determined in 2 steps:

- **Step1:** Force reduction




- **Step2:** Acceleration reduction




**FRF Matrix**
**6 input DOF at wheel center to 6 response DOF at wheel center**

# Virtual Point Transformation (VPT)
## Step 1: Force Matrix Reduction

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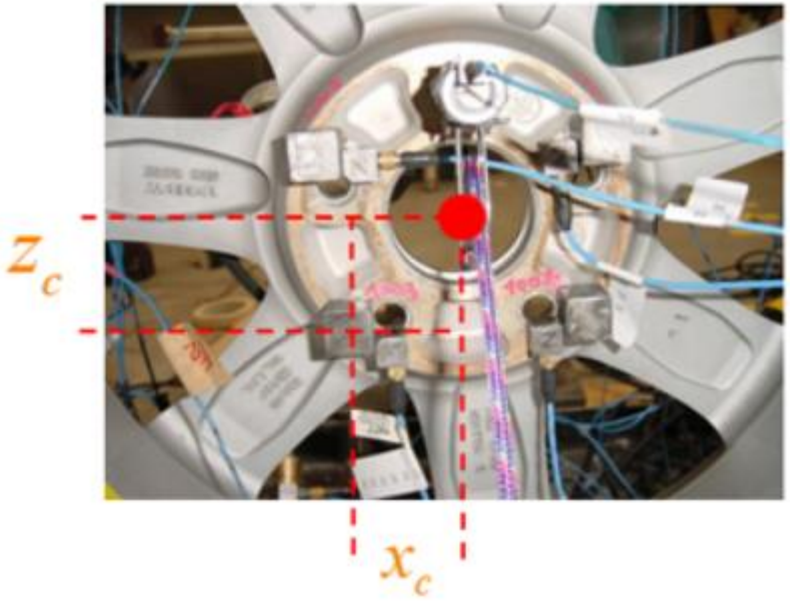
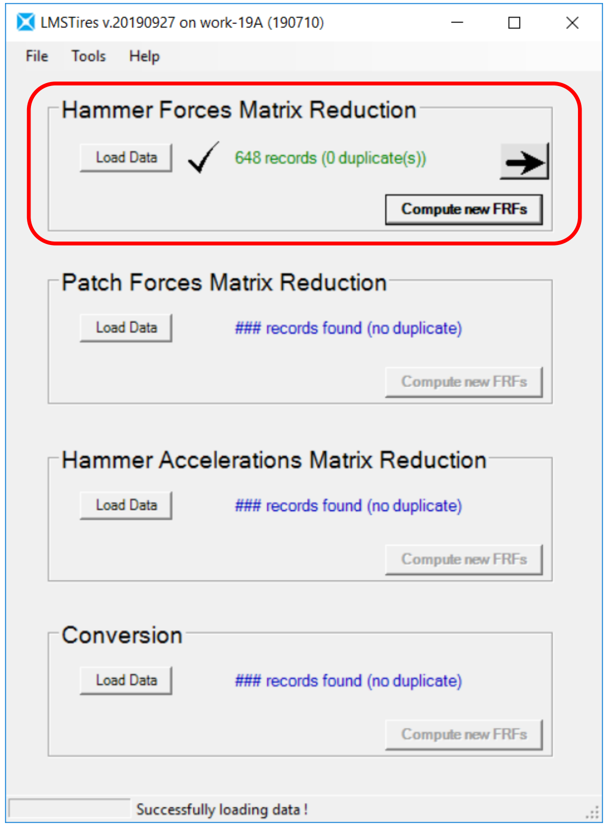
A geometric transformation is used to calculate FRFs with rim center force and moment input out of measured FRFs with hammer input on 4 cubes.

Applied forces @ cubes

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{xx} \\ M_{yy} \\ M_{zz} \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -z_{c_k} & y_{c_k} \\ z_{c_k} & 0 & -x_{c_k} \\ y_{c_k} & x_{c_k} & 0 \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}_k$$

Forces at rim center




A geometric relationship exists between the forces applied on the cubes and the equivalent forces at the rim center

# Virtual Point Transformation (VPT)
## Step 2: Acceleration Matrix Reduction

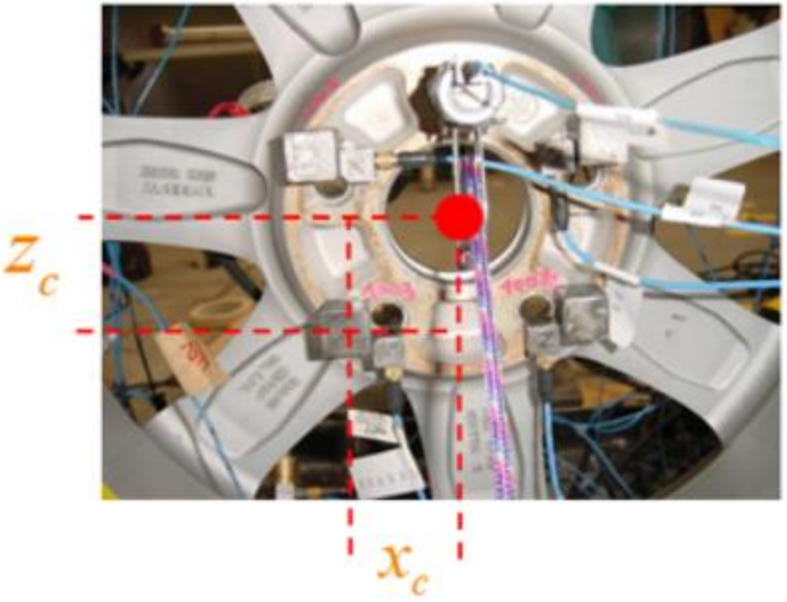
A geometric transformation is used to calculate FRFs with 6 dof response at the rim center out of measured FRFs with response on 4 cubes.

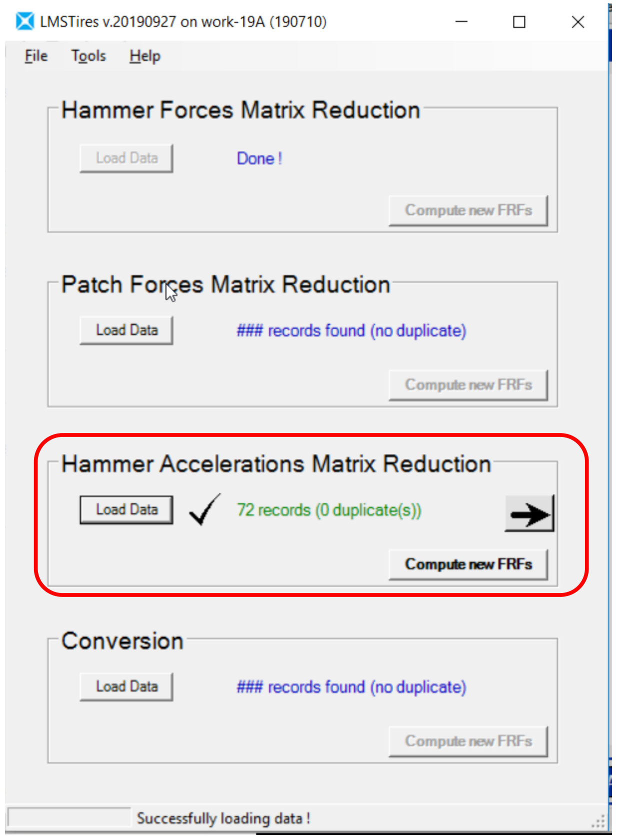
$$\begin{bmatrix} a_x \\ a_y \\ a_z \\ R_{xx} \\ R_{yy} \\ R_{zz} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{ck} & -y_{ck} \\ 0 & 1 & 0 & -z_{ck} & 0 & x_{ck} \\ 0 & 0 & 1 & y_{ck} & -x_{ck} & 0 \end{bmatrix}^{-1} \begin{Bmatrix} a_x \\ a_y \\ a_z \end{Bmatrix}$$

Accelerations at rim center

Measured accelerations on cubes

A geometric relationship exists between the accelerations on the cubes and the equivalent accelerations at the rim center



# Overview

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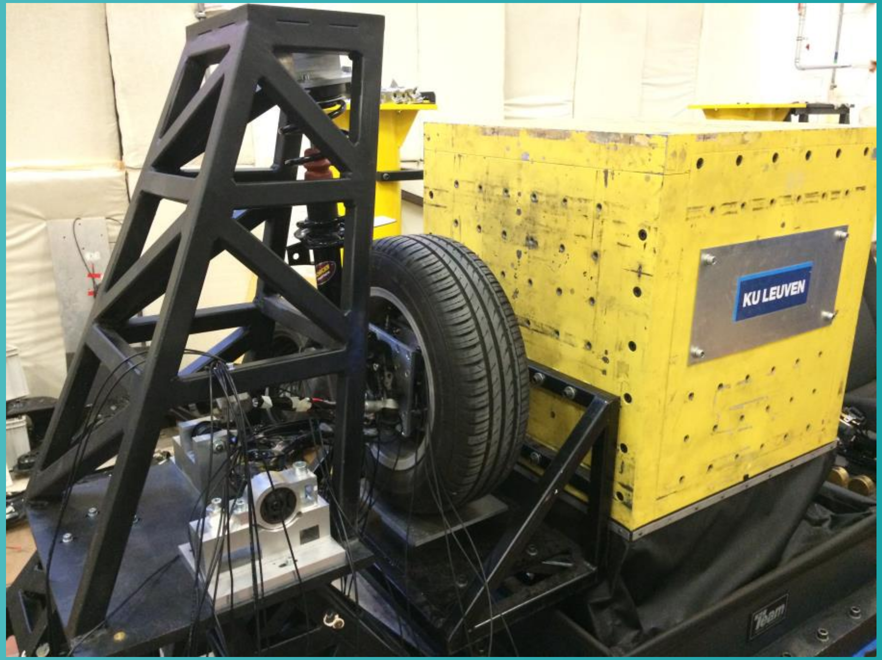
# Outline

- TPA Introduction
- Component TPA Introduction
  - 1 Component TPA Theory
  - 2 Virtual Point Transformation Theory
- Application & Reference cases
  - **1 Road Noise Synthesis**
  - 2 PBN Noise Synthesis

# Road Noise assessment project




1. **Introduction**

2. Controlled Validation: McPherson Test Rig
   - ➢ Step 1: Classical TPA – Contact Forces
   - ➢ Step 2: Component based TPA

3. Conclusions

## Shifting focus in NVH development effort

From powertrain towards road noise and aero-acoustic noise reduction

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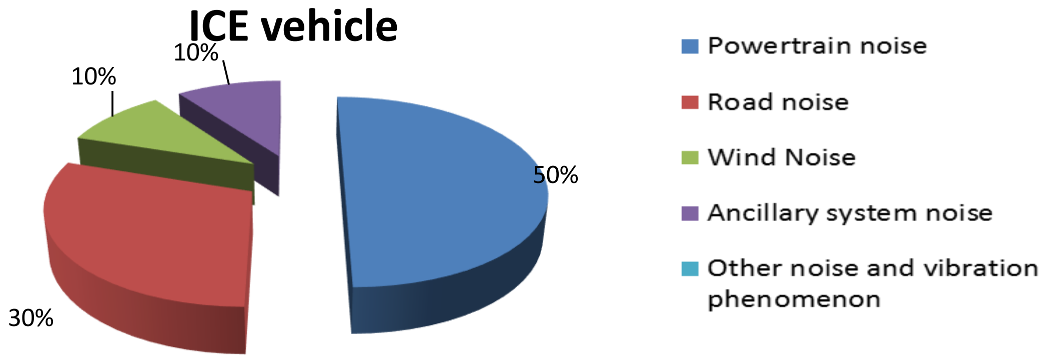
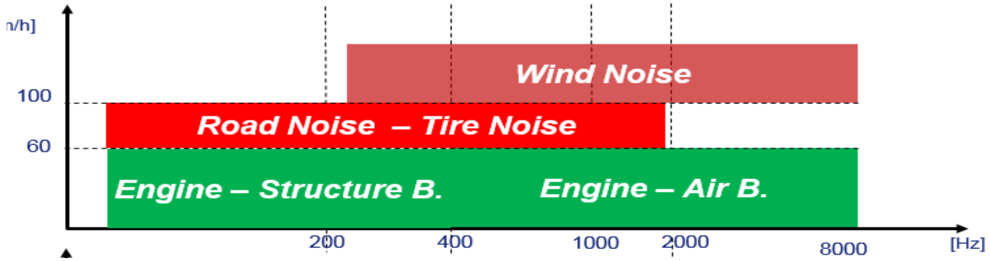
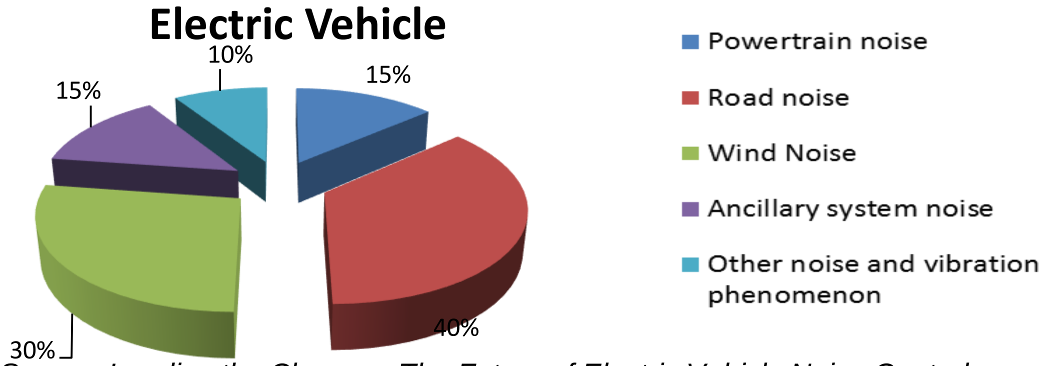
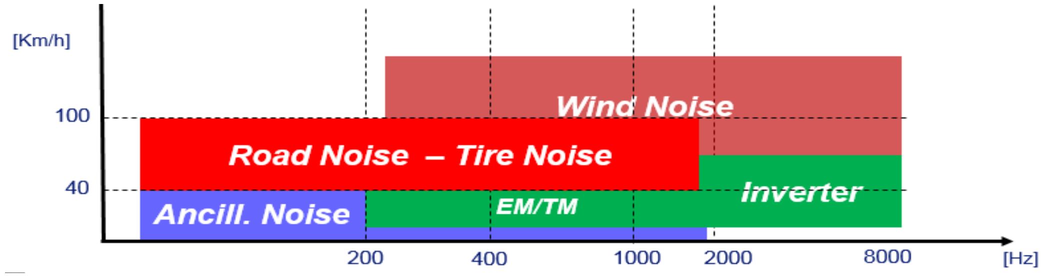



*Source: Leading the Charge – The Future of Electric Vehicle Noise Control Greg Goetchius, Sound & Vibration, April 2011*




*Source: Leading the Charge – The Future of Electric Vehicle Noise Control Greg Goetchius, Sound & Vibration, April 2011*




# Increased importance Road Noise

# Road and Tire noise
## Types of noise resulting in interior noise

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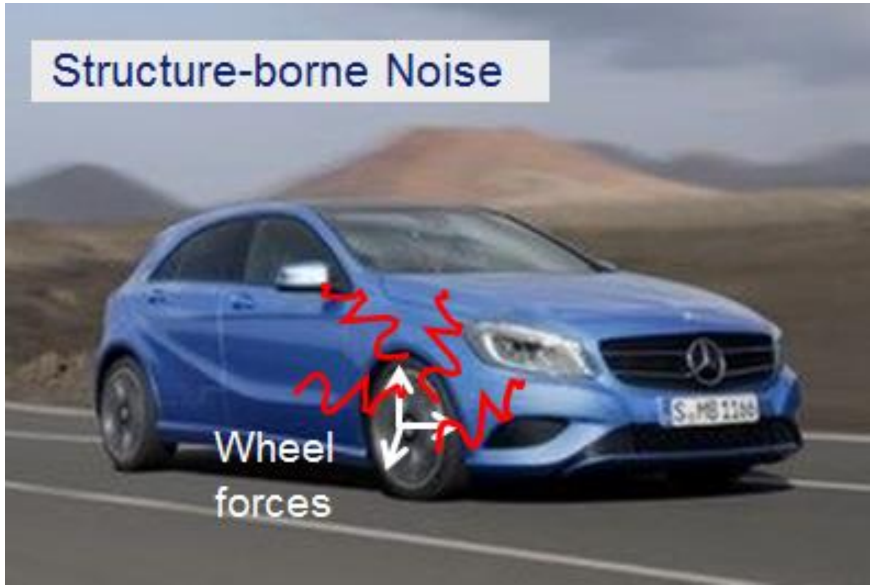
**ROAD NOISE** = structure borne

Originates from tire patch forces
→ wheel hub → car body → **occupants ears/passenger compartment**




**TIRE NOISE** = airborne

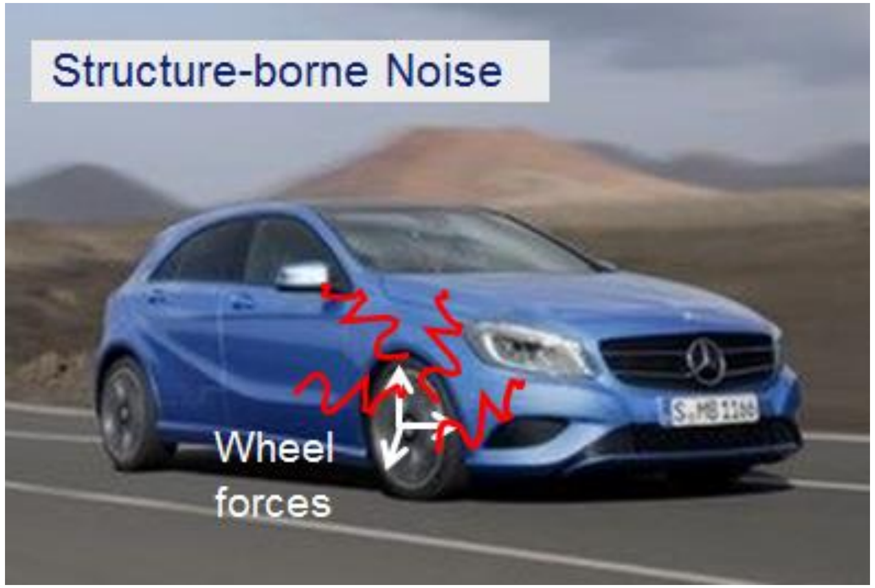
Originates from tire surface vibrations and aeroacoustic events

# Road and Tire noise

## Types of noise resulting in interior noise

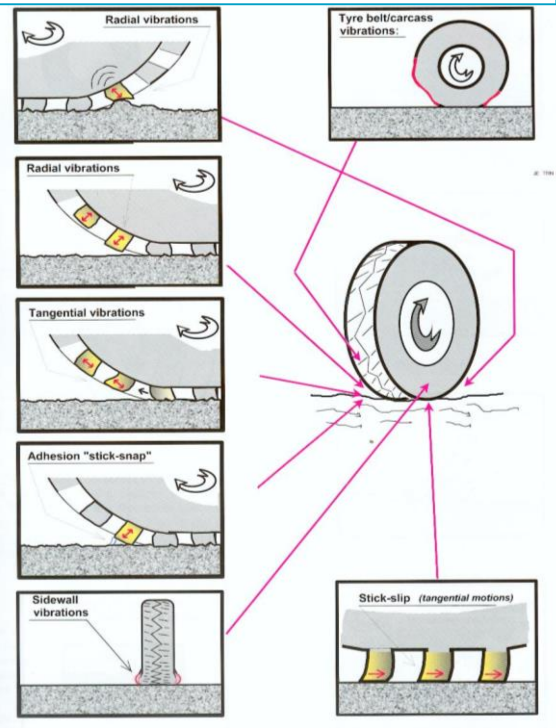
**ROAD NOISE** = structure borne

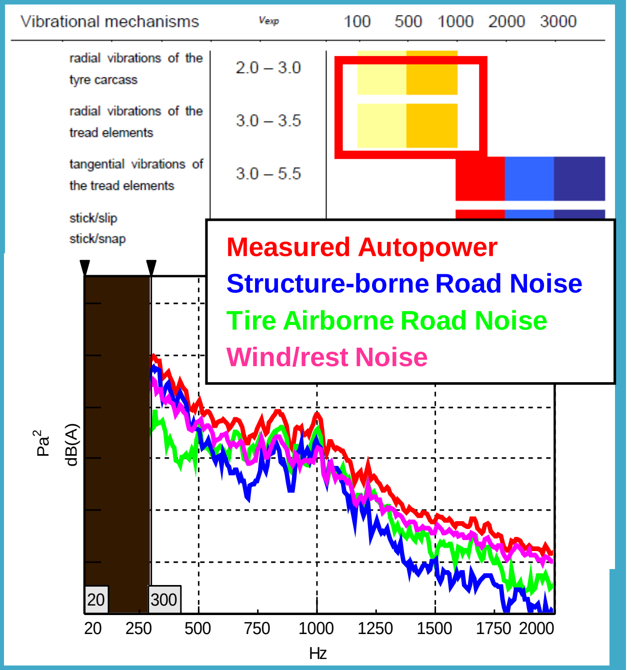
Originates from tire patch forces
→ wheel hub → car body → **occupants ears/passenger compartment**




**Frequency Range**
**Structure Borne Noise**

**VIBRATION-RELATED**
**Include mostly non-linear effects**




xx Km/h – Rough Rd

# NVH in a system integration context:
# Road Noise: Exchanging “Contact Forces”

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Tire Test Rig

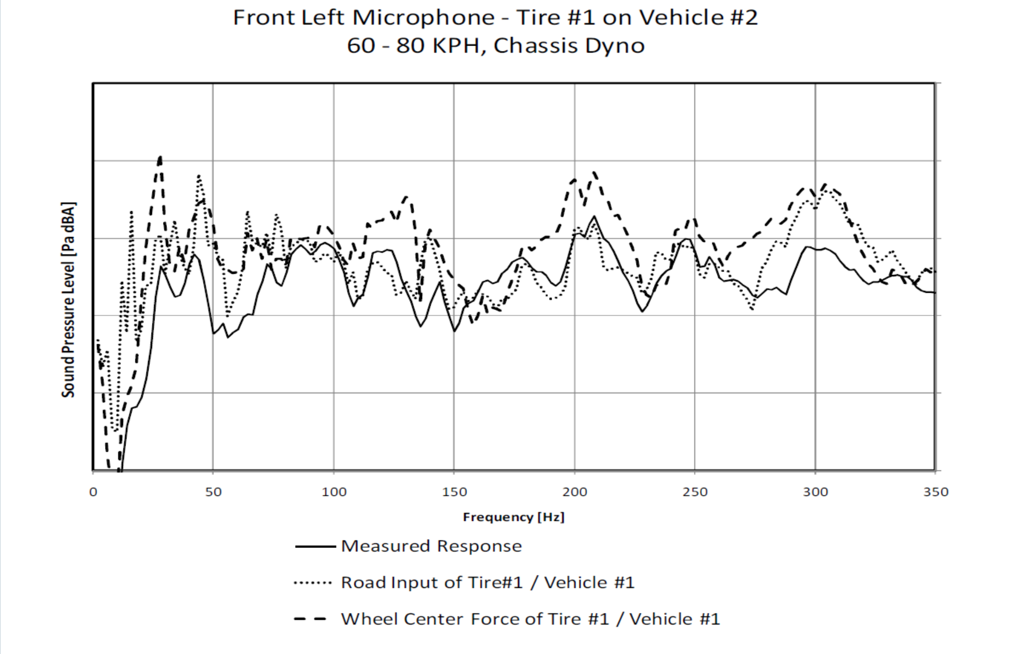
Vehicle A

Vehicle B

~~Contact Forces~~ ~~Contact Forces~~

Predictive Engineering: **Strong Coupling**
Exchange Test Source Load Model

Driver Ear: Total Contribution vs. Measured




Source: Charles Gagliano, Matt Tondra, Bruce Fouts, Theo Geluk, “Development of an Experimentally Derived Tire and Road Surface Model for Vehicle Interior Noise Prediction”, SAE World 2009

# NVH in a system integration context:
# Road Noise: Exchanging Road Displacement (incl. Tire)

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Tire Test Rig

Vehicle A

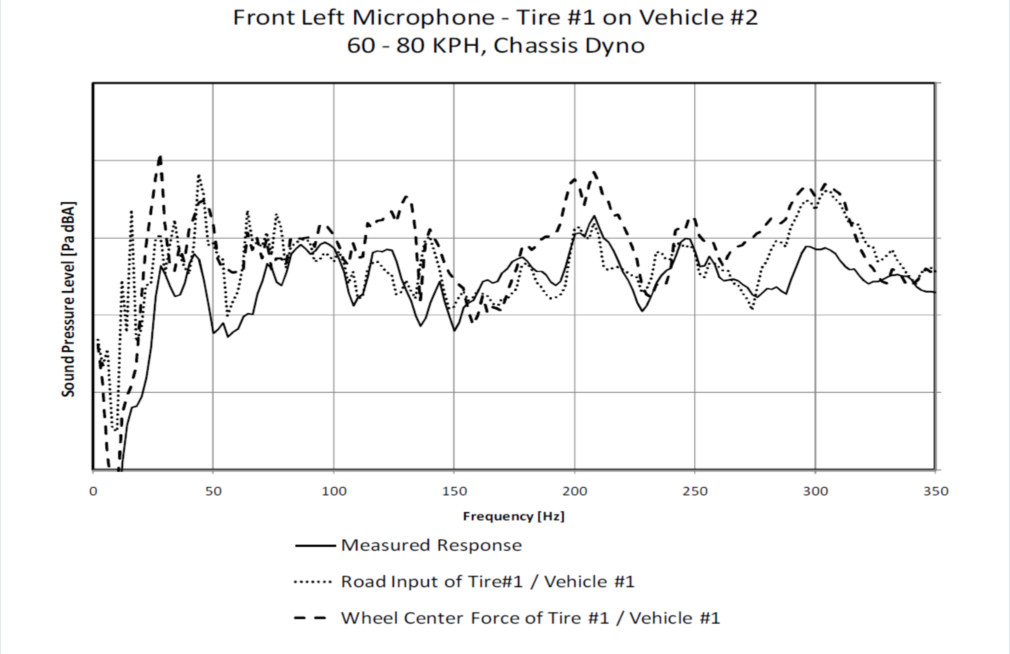
Vehicle B

**Tire Patch Displacement**

**Tire Patch Displacement**

Predictive Engineering: **Strong Coupling**
Exchange Test Source Load Model

Driver Ear: Total Contribution vs. Measured




Source: Charles Gagliano, Matt Tondra, Bruce Fouts, Theo Geluk, “Development of an Experimentally Derived Tire and Road Surface Model for Vehicle Interior Noise Prediction”, SAE World 2009

# Road Noise
# Exchanging Blocked Force (incl. Tire)

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Tire Test Rig

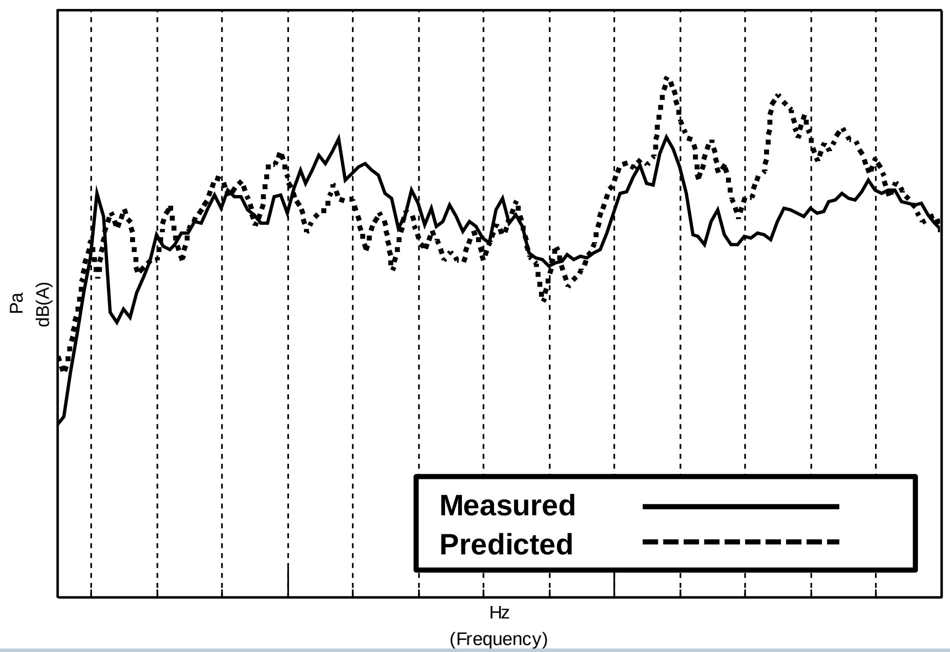

Vehicle A


Vehicle B


**Blocked Forces** **Blocked Forces**

Predictive Engineering: **Strong Coupling**
Exchange Test Source Load Model

Driver Ear: Total Contribution vs. Measured



# Project Objective: Road Noise Synthesis using Component based TPA / experimental Substructuring

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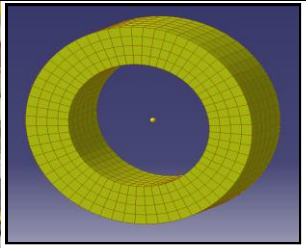
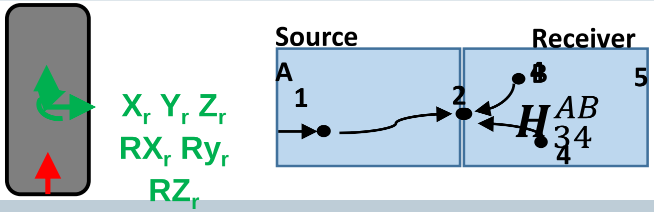
## Step 1: Source Model

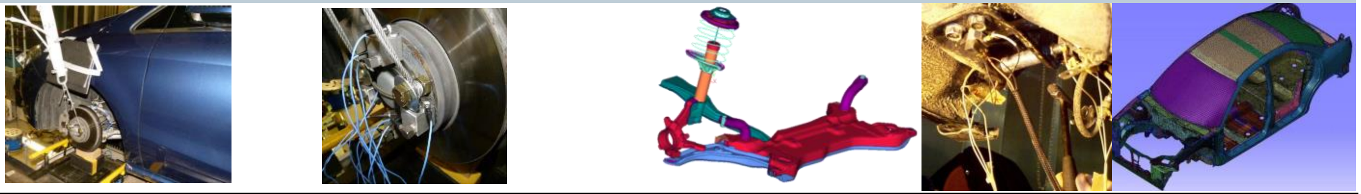
Experimental or FEM Tire Model

### In-Situ TPA



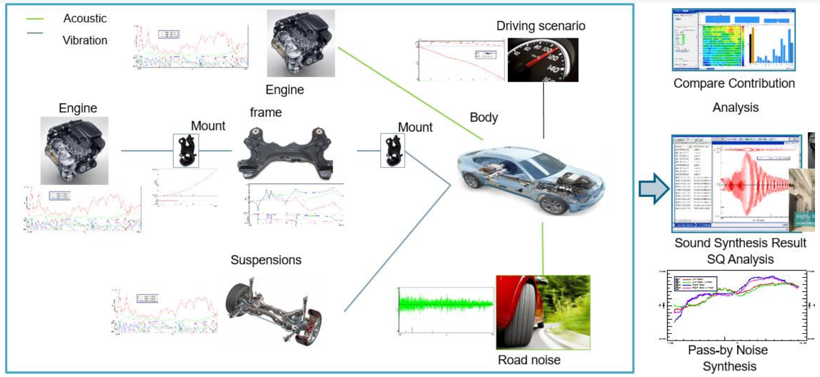

Operational Loads: Blocked Forces

### Test or FEM



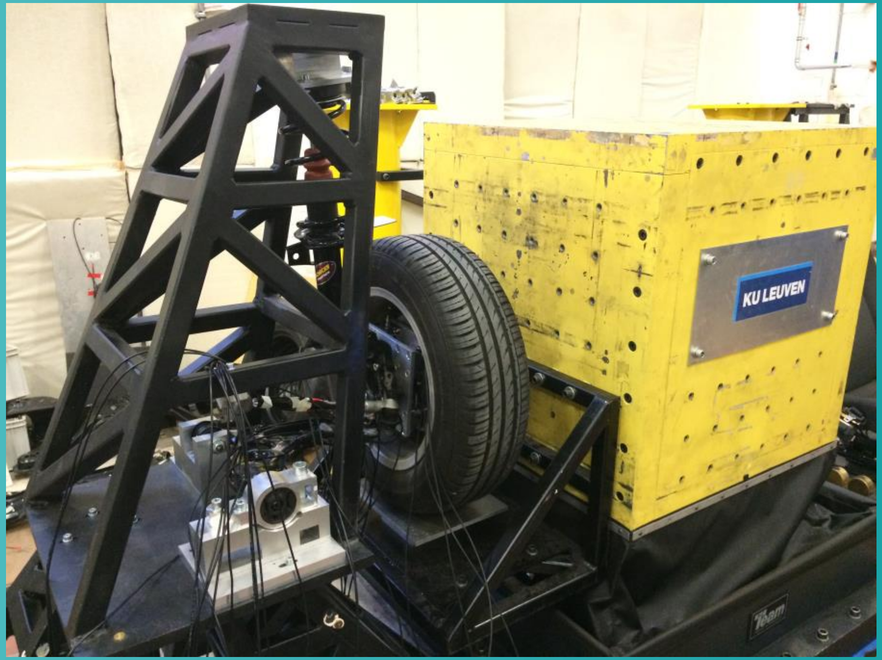
## Step 2: Receiver (Suspension + Body) Model

## Step 3
### Road Noise Synthesis




Virtual Vehicle Assembly

# Road Noise Synthesis
# Component Based TPA

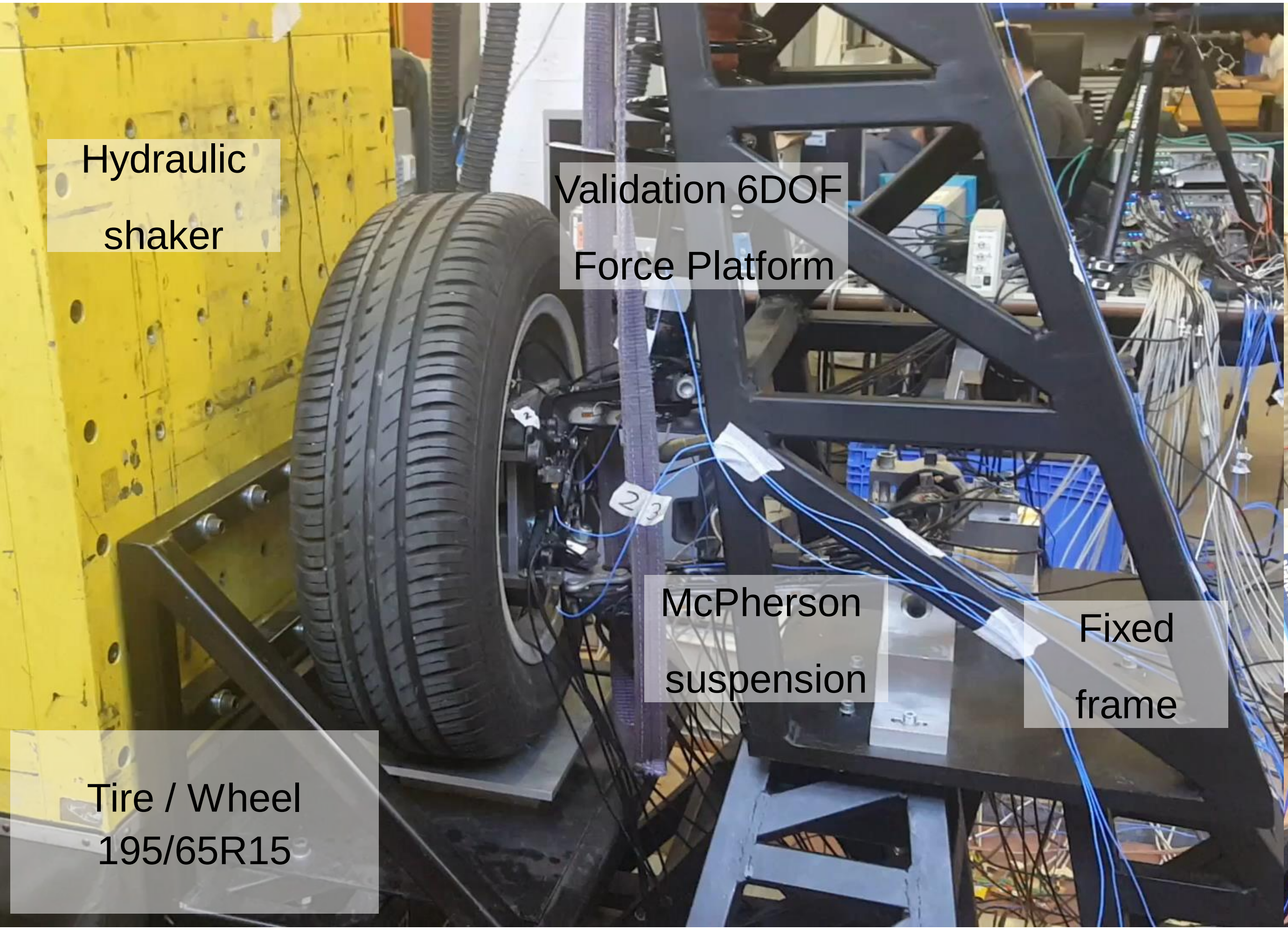


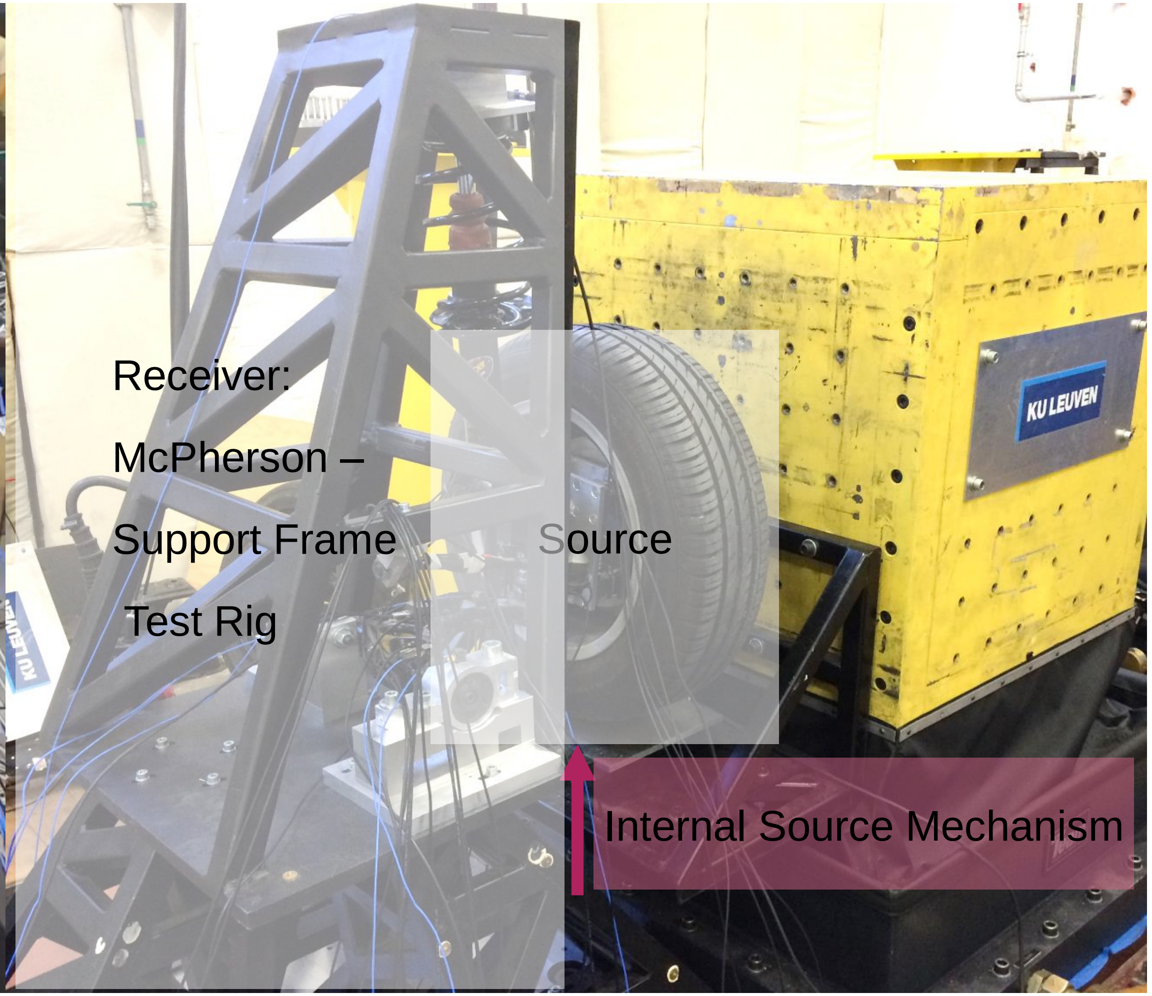

1. Introduction

2. **Controlled Validation: McPherson Test Rig**
   - ➢ **Step 1: Classical TPA**
   - ➢ Step 2: Component based TPA

4. Conclusions

# KU Leuven: McPherson Test Rig
## Test setup

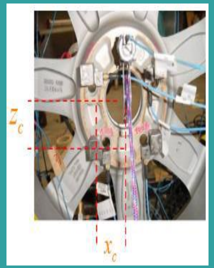


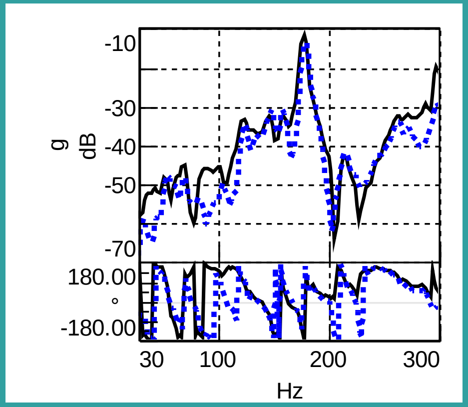
# 1. Classical Transfer Path Analysis
# Wheel Center Contact Force Estimation

Operational Measurements on the Receiver

FRF Measurements from Wheel Hub Reference

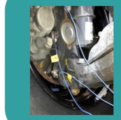


FRF Geometric Reduction - 6 DOF Wheel Spindle

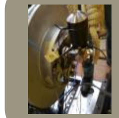



Matrix Inversion
6 DOF Load Estimation
& Contribution

# 1. Classical Transfer Path Analysis
# Operational Measurements



Operational Measurements on the Receiver



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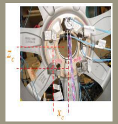

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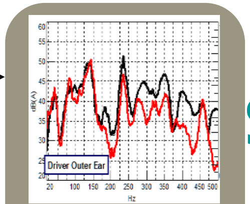


Matrix Inversion 6 DOF Load Estimation & Contribution

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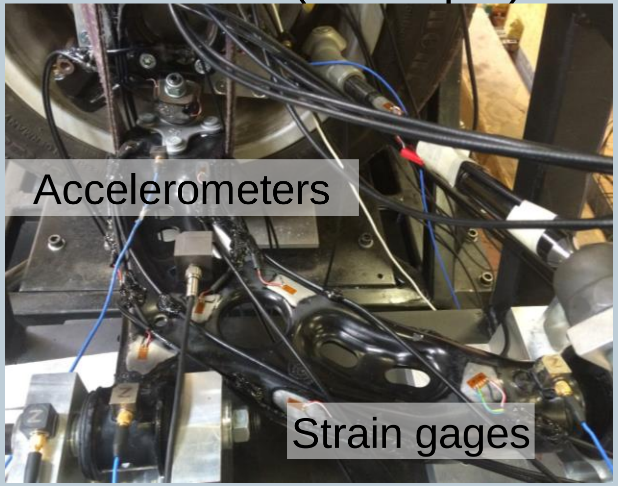
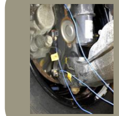
Controlled
Z-Axis Excitation

Indicators ( Example)

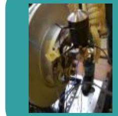



Indicator Sensor: Typical 3…5 x
3D Accelerometer on knuckle

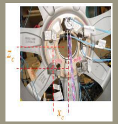
# 1. Classical Transfer Path Analysis Operational Measurements



Operational Measurements on the Receiver



FRF Measurements from Wheel Hub Reference



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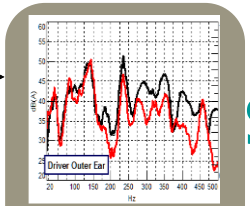


Matrix Inversion 6 DOF Load Estimation & Contribution

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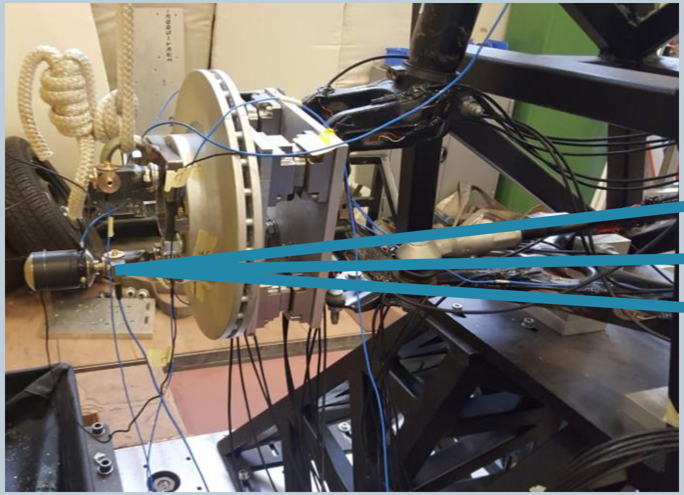


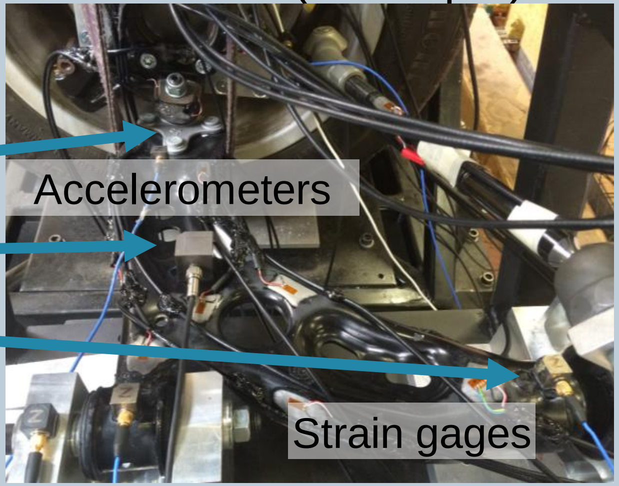
LMS Qsource Integral Shaker Receiver FRF Measurements

FRF

FRF Matrix

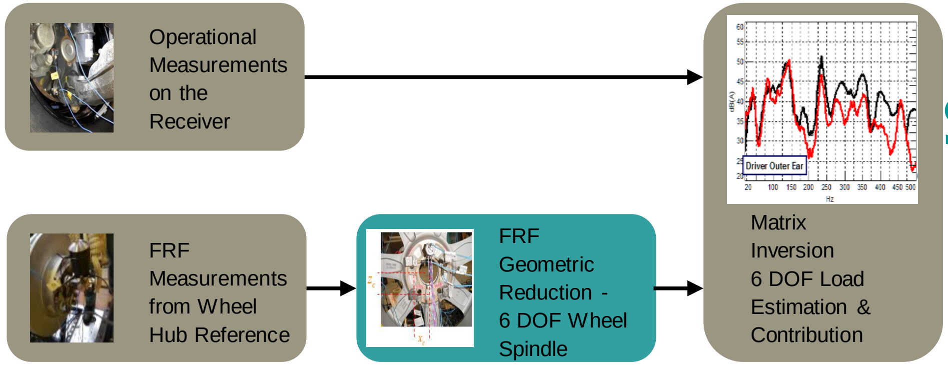
12 Input DOF
x
15 Indicator DOF

Indicators ( Example)




Indicator Sensor: Typical 3…5 x 3D Accelerometer on knuckle

# 1. Classical Transfer Path Analysis Geometrical Reduction / Virtual Point Transformation

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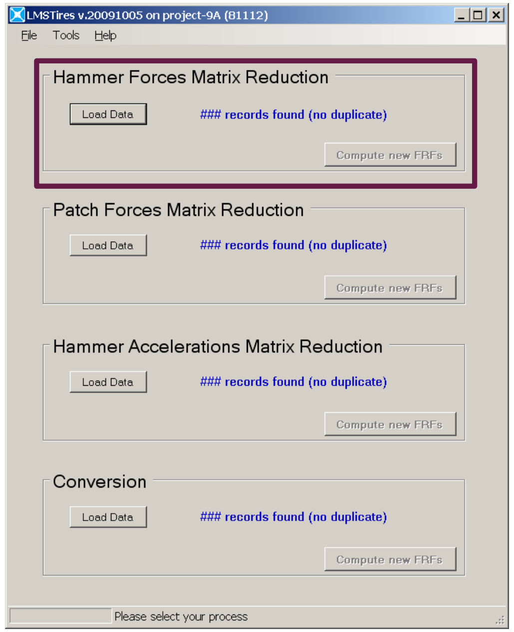
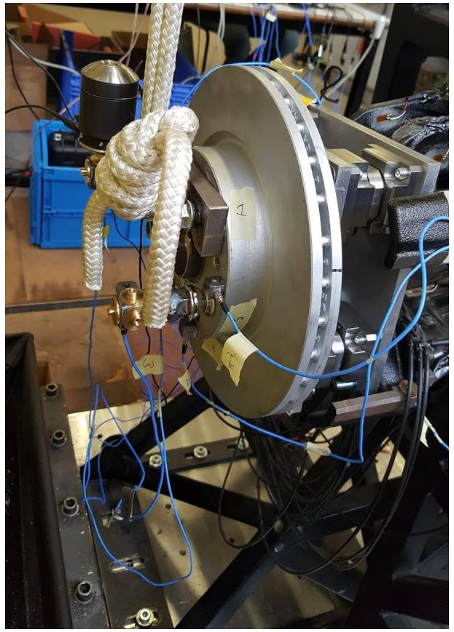


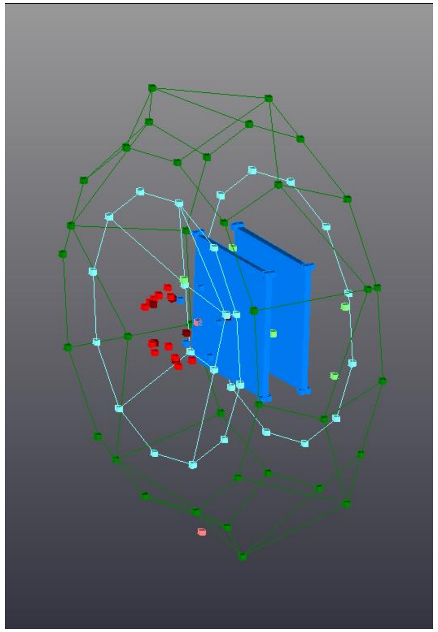

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{xx} \\ M_{yy} \\ M_{zz} \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -z_{c_k} & y_{c_k} \\ z_{c_k} & 0 & -x_{c_k} \\ y_{c_k} & x_{c_k} & 0 \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}_k$$

Forces at wheel center

R

Applied forces @ wheel hub

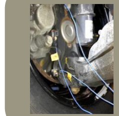


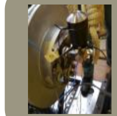


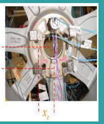
Sources:

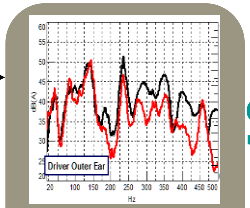
- Stefaan Helderweirt, Herman Van der Auweraer, Peter Mas, Luigi Bregant, Daniele Casagrande, APPLICATION OF ACCELEROMETER-BASED ROTATIONAL DEGREE OF FREEDOM MEASUREMENTS FOR ENGINE SUBFRAME MODELLING, IMAC 2001
- Maarten van der Seijs, van den Bosch, Daniel J. Rixen, Dennis de Klerk, An improved methodology for the virtual point transformation of measured frequency response functions in dynamic substructuring , CompDyn 2013

# 1. Classical Transfer Path Analysis Geometrical Reduction / Virtual Point Transformation


Operational Measurements on the Receiver


FRF Measurements from Wheel Hub Reference


FRF Geometric Reduction - 6 DOF Wheel Spindle



Matrix Inversion 6 DOF Load Estimation & Contribution

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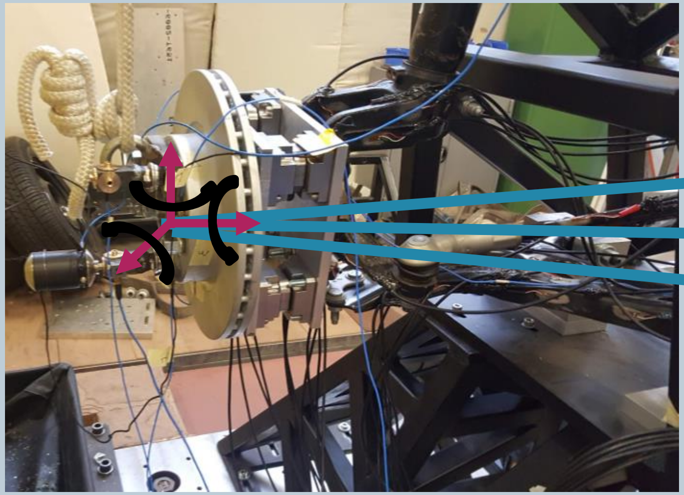


LMS Qsource Integral Shaker Receiver FRF Measurements

FRF

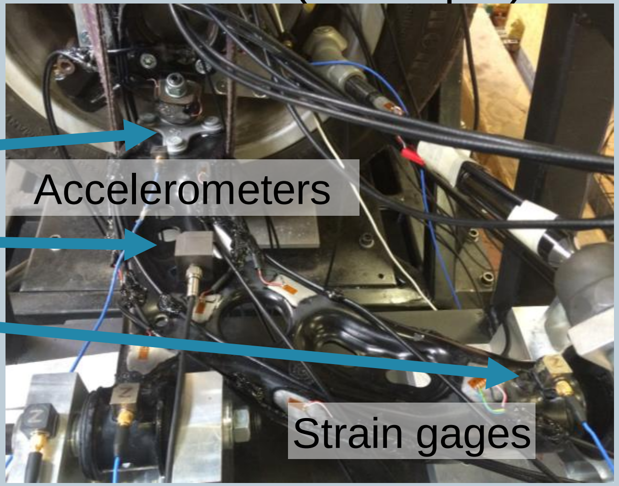
FRF Matrix

**6 Input DOF**

x

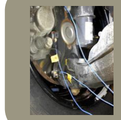
15 Indicator DOF

Indicators ( Example)

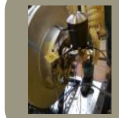



Indicator Sensor: Typical 3…5 x 3D Accelerometer on knuckle

# 1. Classical Transfer Path Analysis Results



Operational Measurements on the Receiver



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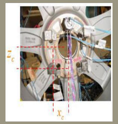
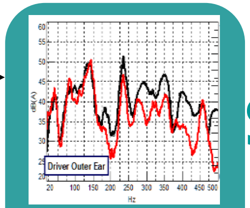


FRF Geometric Reduction - 6 DOF Wheel Spindle



Matrix Inversion 6 DOF Load Estimation & Contribution

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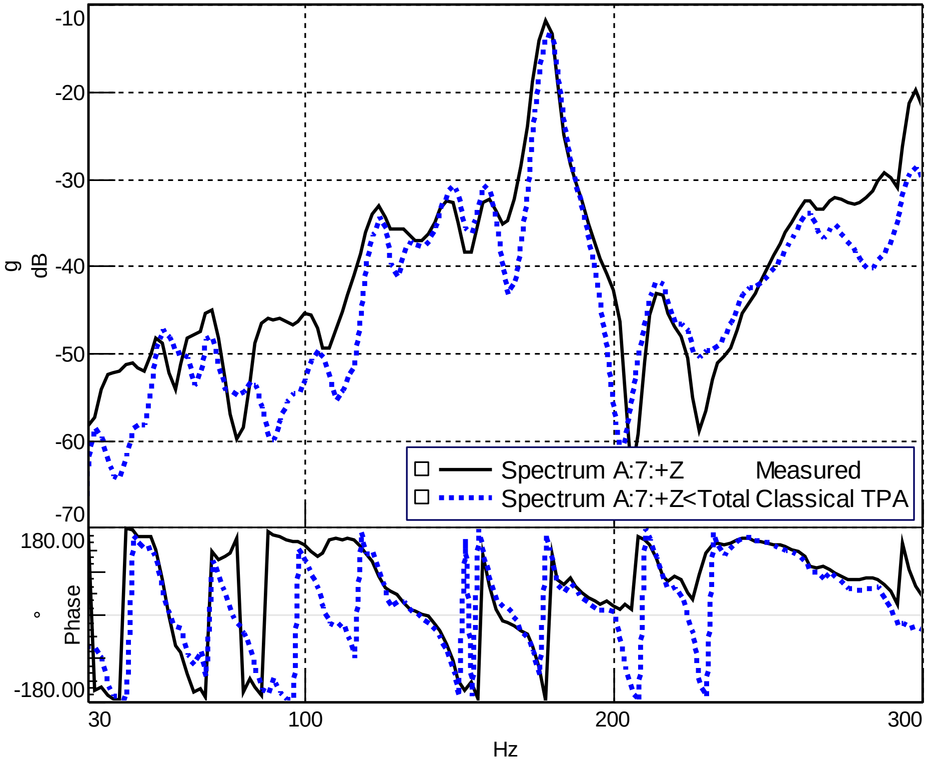
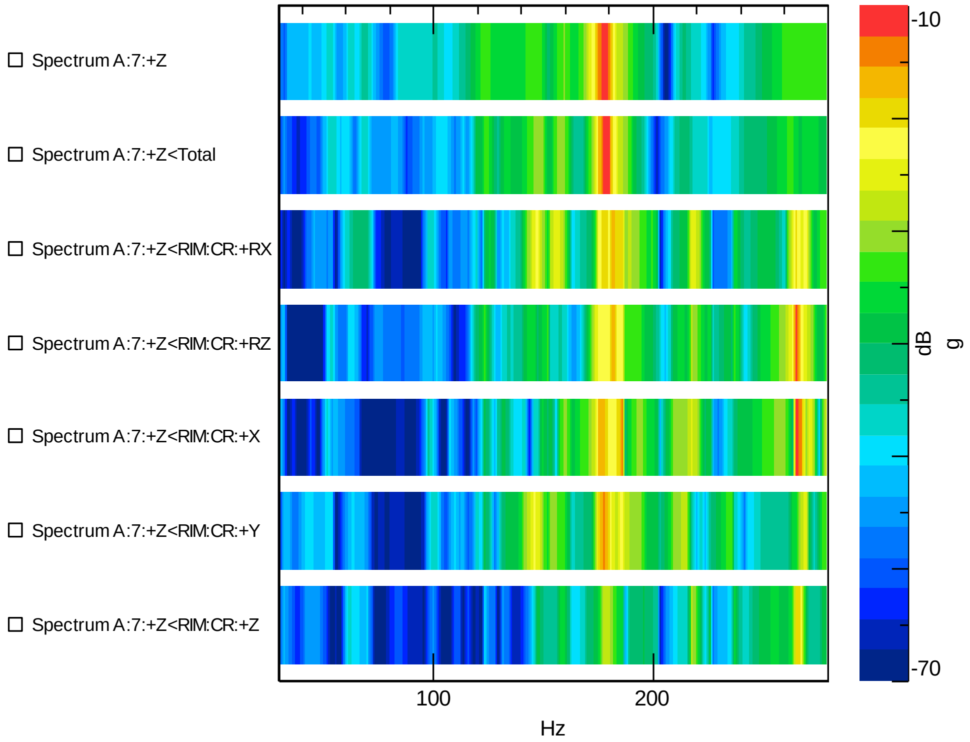
$$u_j = \sum_i H_{ji}^{B} F_{r\,i}$$



# Road Noise Synthesis
# Component Based TPA

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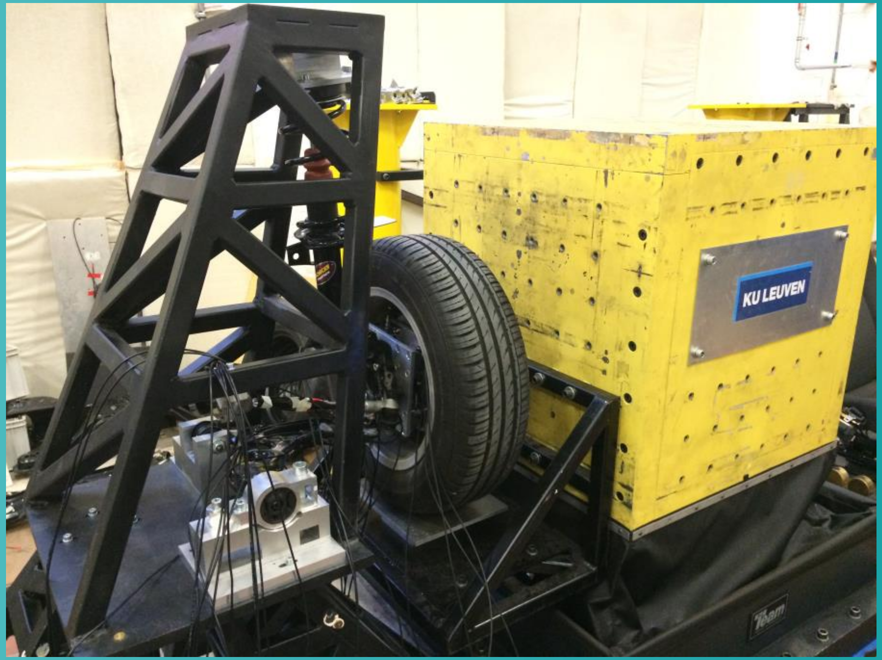


1. Introduction

2. **Controlled Validation: McPherson Test Rig**
   - Step 1: Classical TPA – Contact Forces
   - **Step 2: Component based TPA**

3. Conclusions

# Component Based TPA – Substructuring

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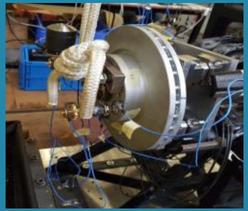
## Virtual Full System NTF Validation

$$[H_{42}^{AB}] = [H_{43}^{B}][H_{22}^{A} + H_{33}^{B}]^{-1} * [H_{22}^{A}]$$

**Source**
FRF Model

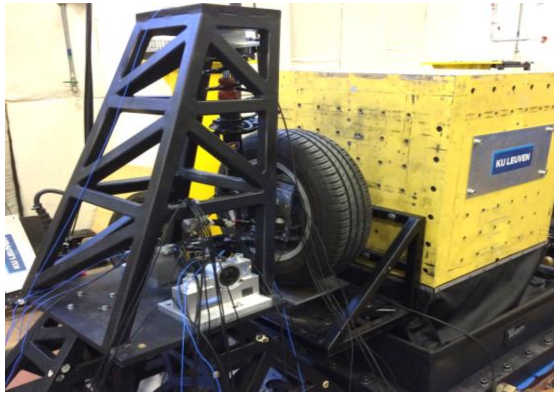
$H_{22}^{A}$

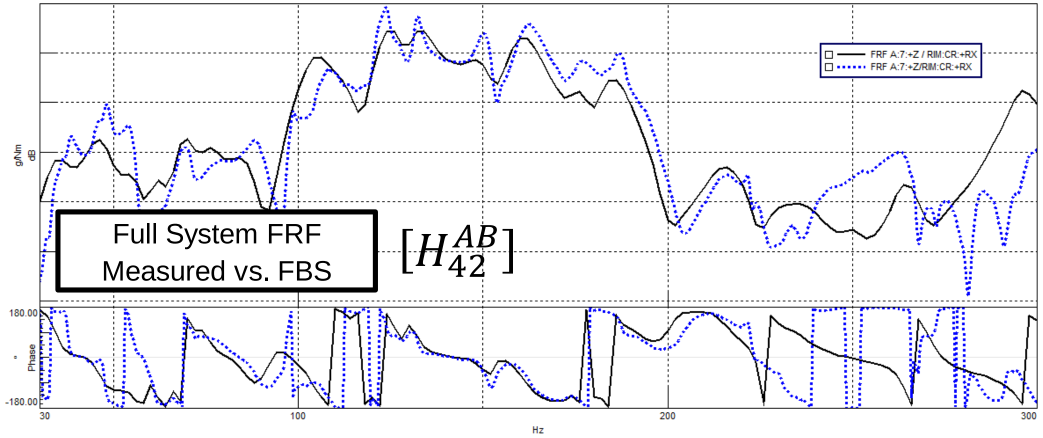


**Receiver**
FRF Model

$H_{33}^{B}$

$H_{43}^{B}$






Full System FRF
Measured vs. FBS

$[H_{42}^{AB}]$

# Component Based TPA – Substructuring
# Frequency Based Substructuring – LM FBS

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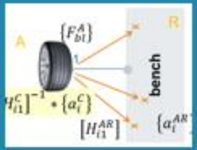
## Virtual Full System Target Validation



**Source**
Blocked
Forces

$\{F^{A}_{bl,2}\}$

**Source**
FRF Model

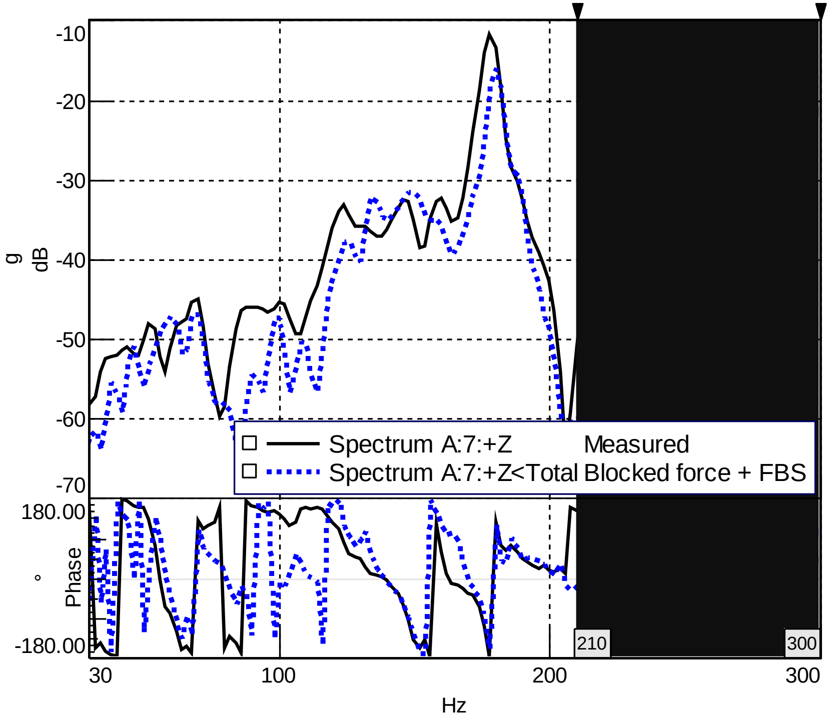
$H^{A}_{22}$

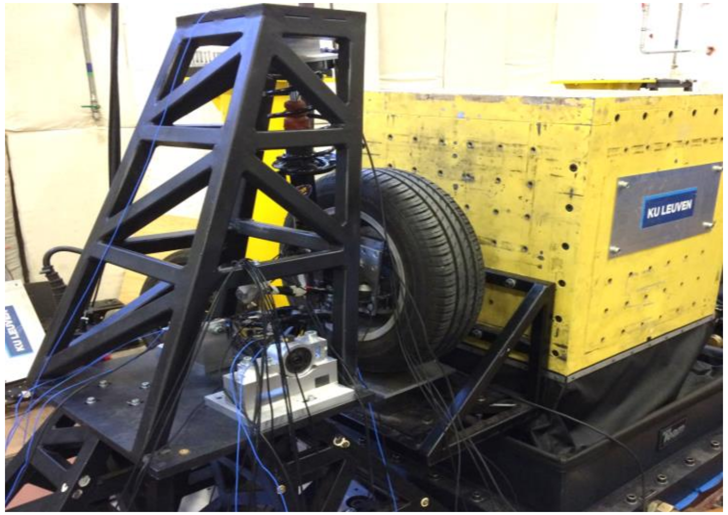
**Receiver**
FRF Model

$H^{B}_{33}$

$H^{B}_{43}$

$$p = [H^{B}_{43}] * \{F^{AB}_{3,r}\} = [H^{AB}_{42}] * \{F^{A}_{bl,2}\}$$



# Component Based TPA – Substructuring
# Frequency Based Substructuring – LM FBS

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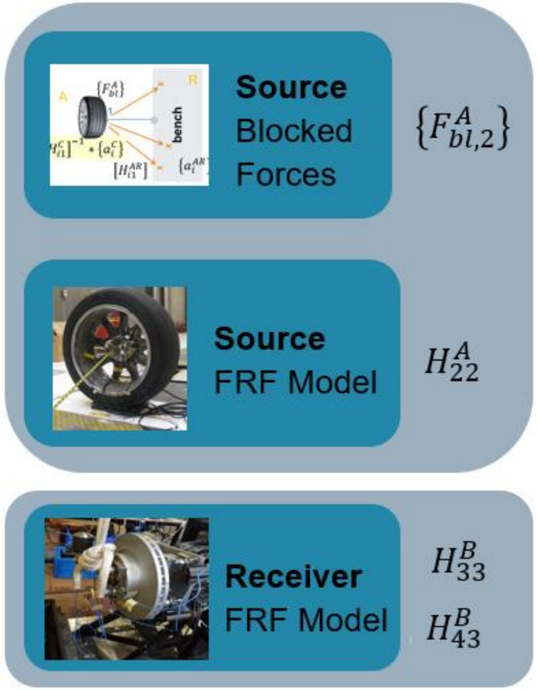
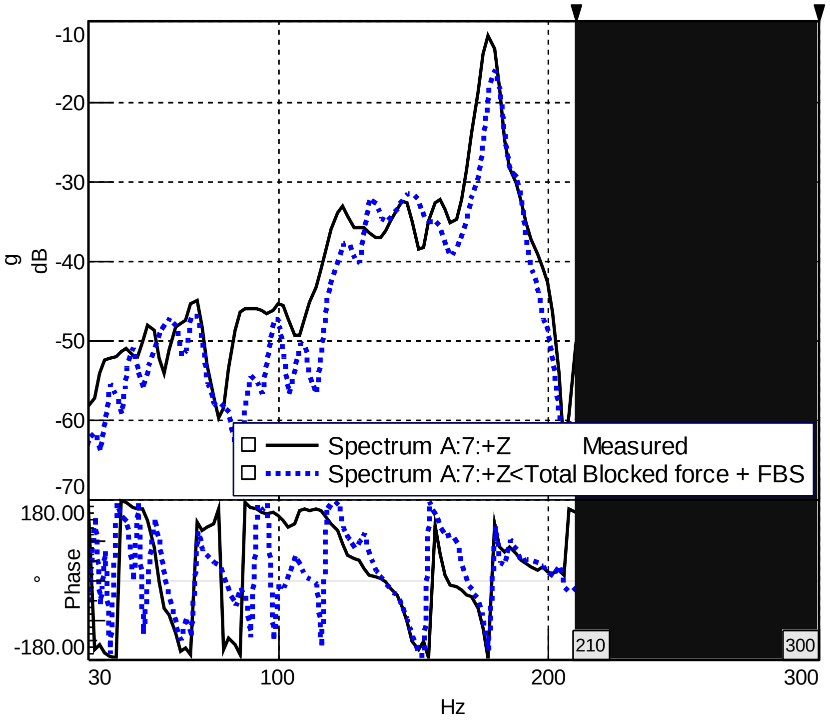
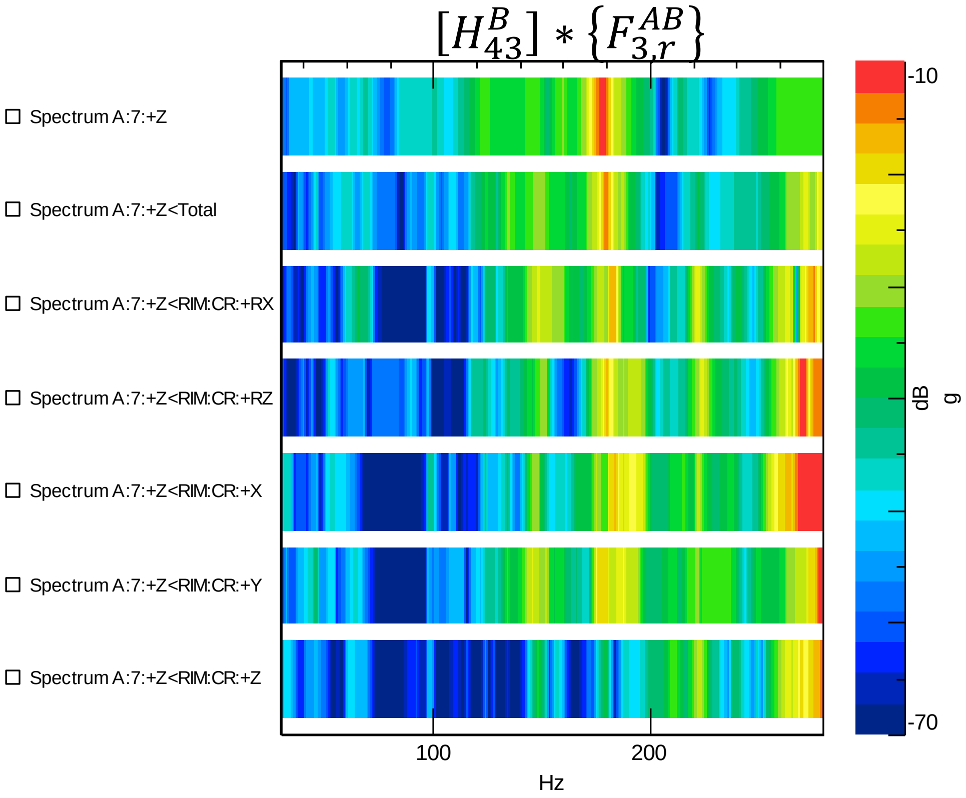
## Component Based TPA – Contributions

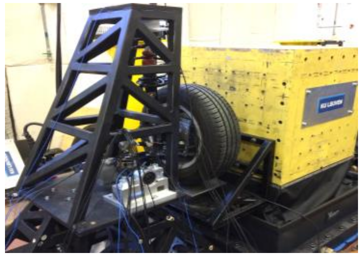


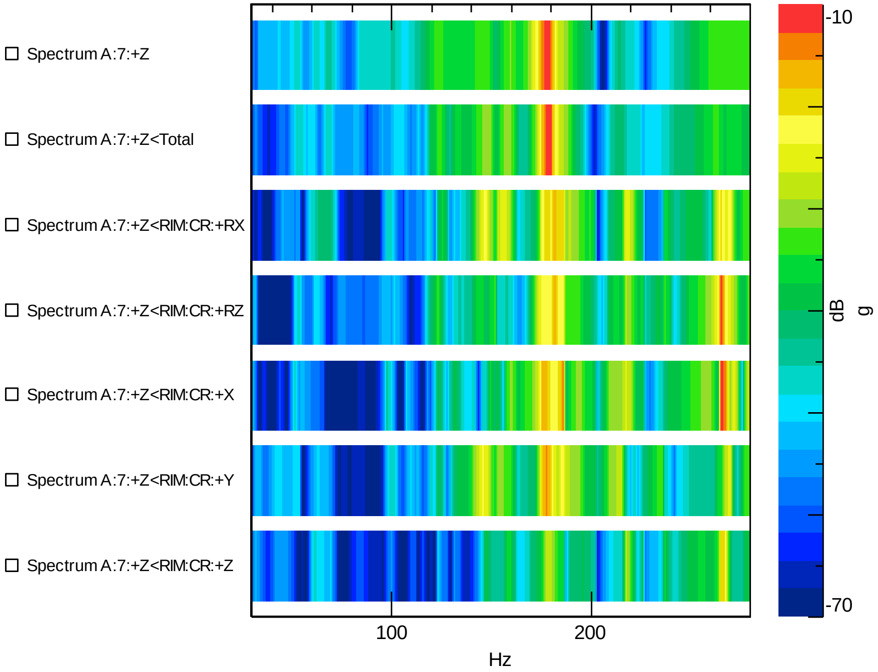



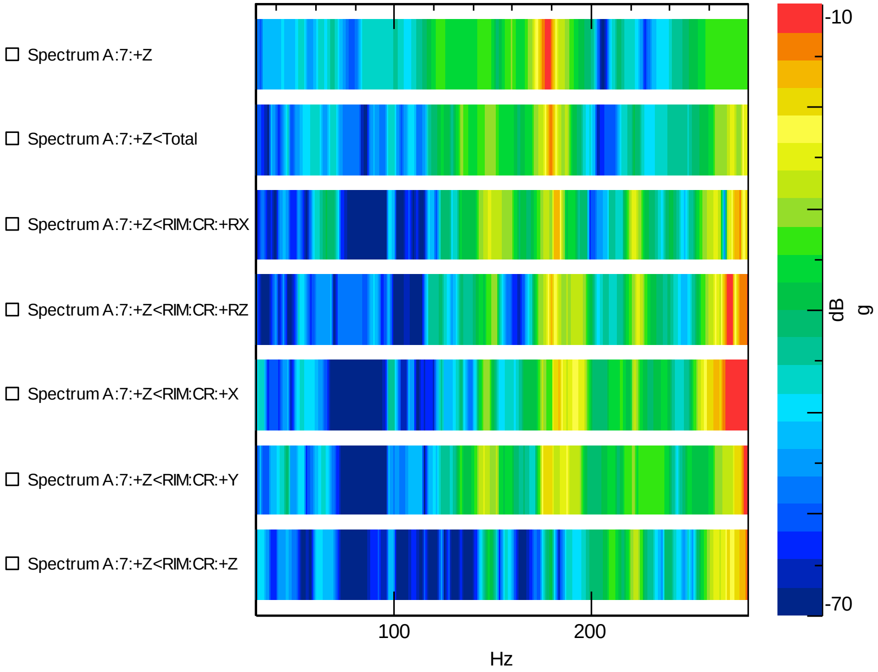



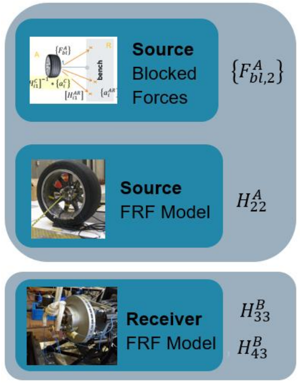
# Component Based TPA – Substructuring
# Frequency Based Substructuring – LM FBS

Classical TPA vs. Component based TPA





# Road Noise Synthesis
# Component Based TPA

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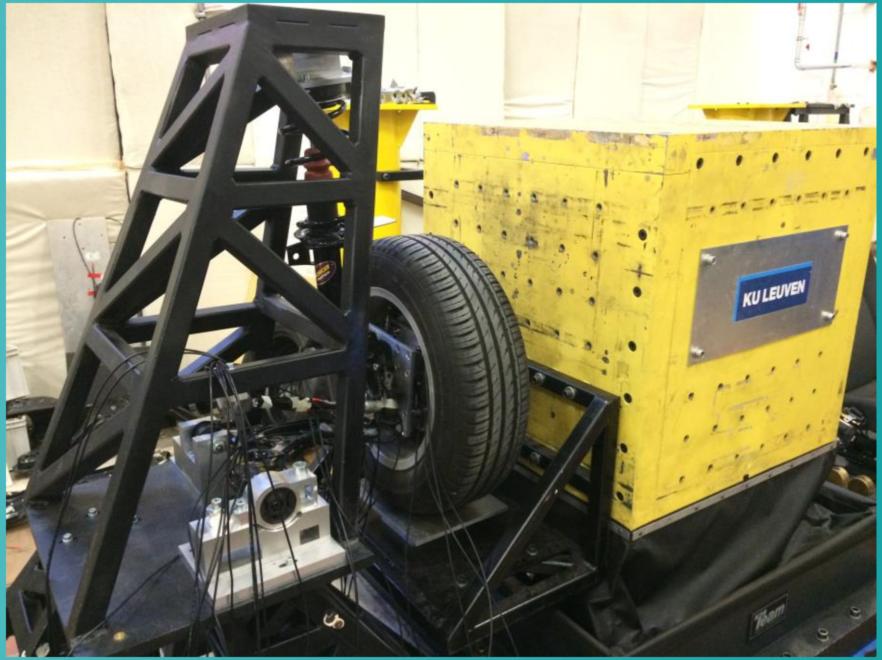


1. Introduction

2. Controlled Validation: McPherson Test Rig
   - Step 1: Classical TPA – Contact Forces
   - Step 2: Component based TPA

3. **Conclusions**

# Component based TPA for full vehicle NVH assessment

*Value proposition*

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**Integrated process to predict full vehicle levels in any arbitrary vehicle assembly**

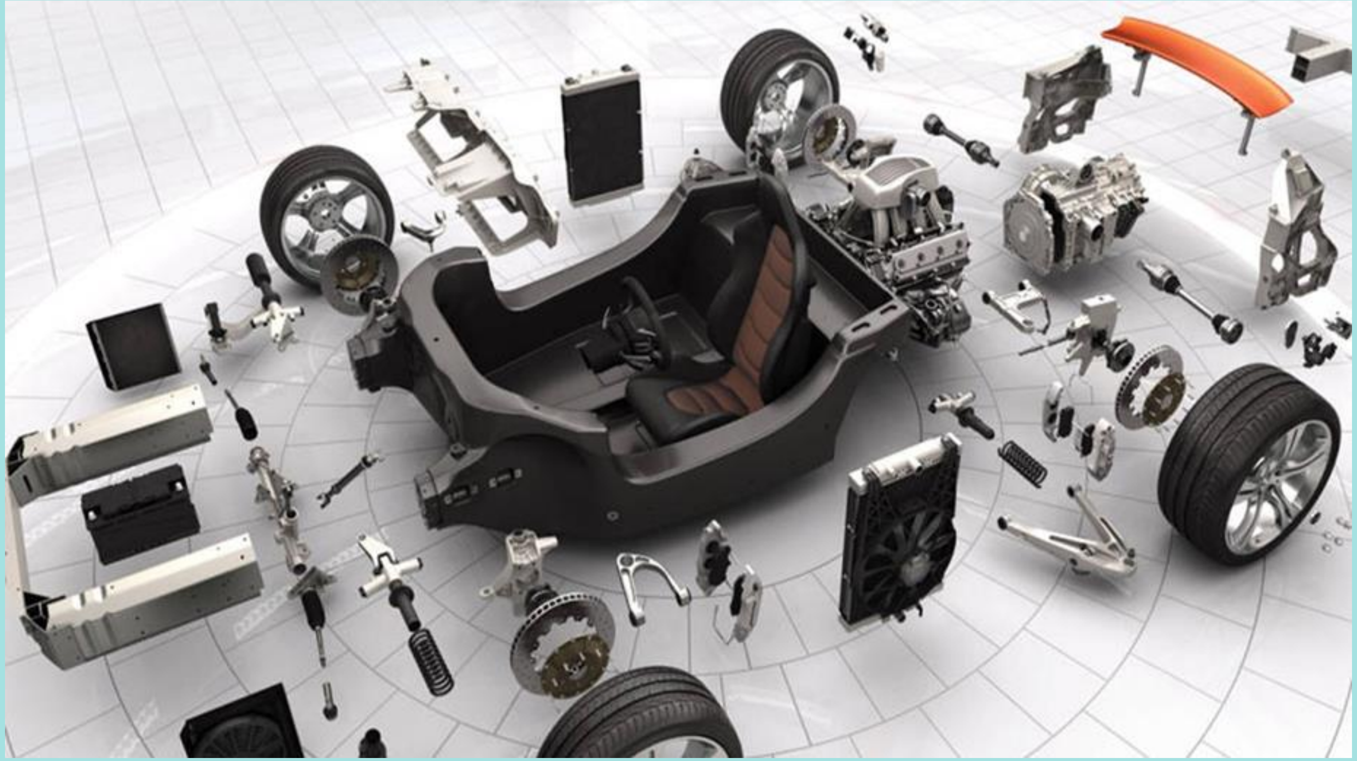
**Realistic component target setting and downcascading**

**Deliver insights by frontloading the development process**

**Provide visibility on performance to broader enterprise**

**Reduced development timeline &costs**

## Virtual Vehicle Assembly Process



# Outline



# Overview

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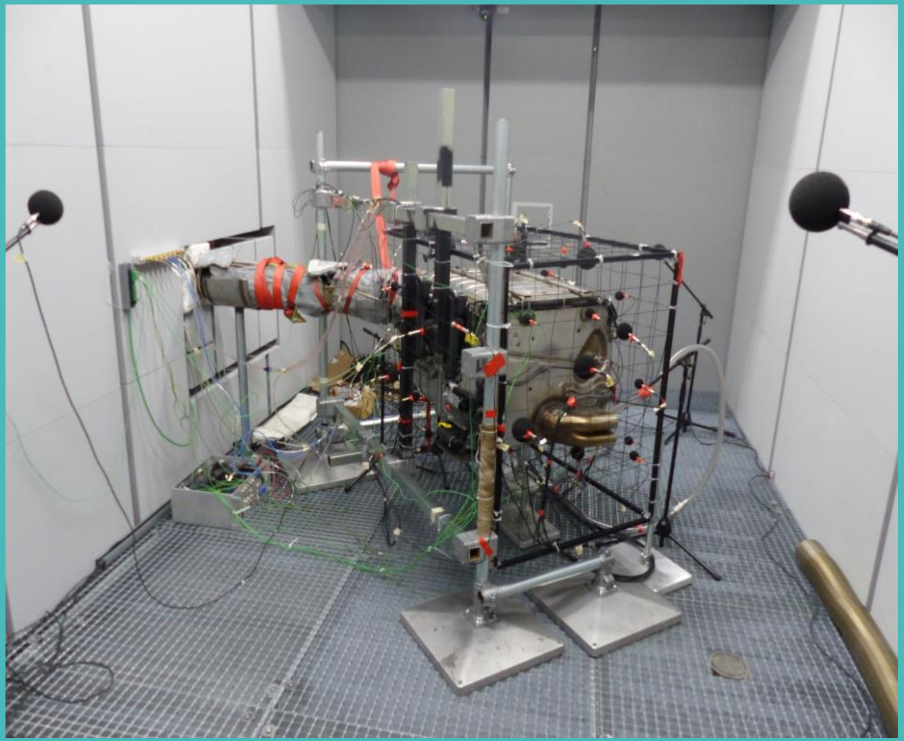


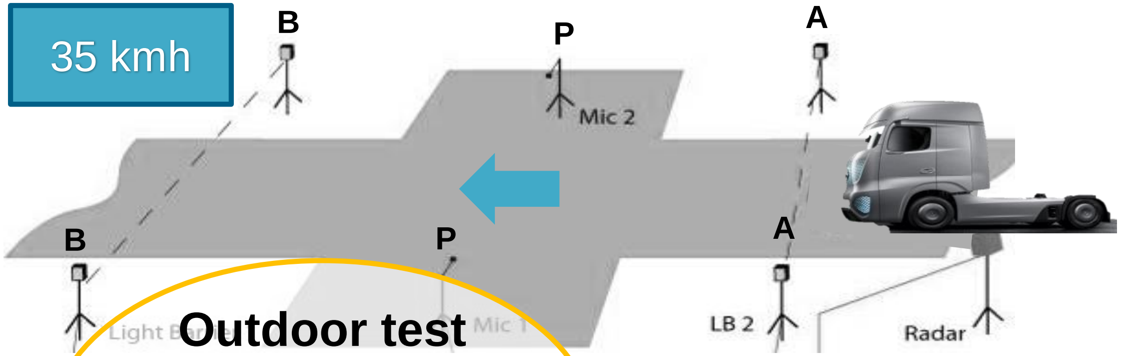
1. **Introduction**

2. PBN Synthesis: Process Validation
   - Step 1: Full Vehicle PBN ASQ
   - Step 2: Component ASQ
   - Step 3: Pass-By Noise Synthesis

3. Conclusions

# Motivation

*Testing effort and vehicle availability*




**Outdoor test track**

~7…8h testing time

ECE-R51.3 demands

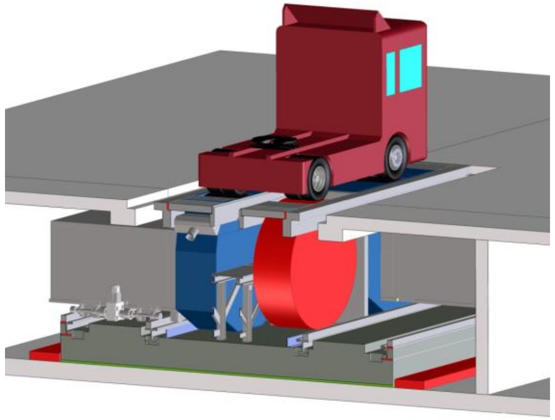
**indoor PBN facility**

~4…6h testing time

**Cost & capacities**

**Vehicle availability**

**Platform complexity**



**Improvement of accuracy & reproducibility**

# Motivation

*Development complexity*

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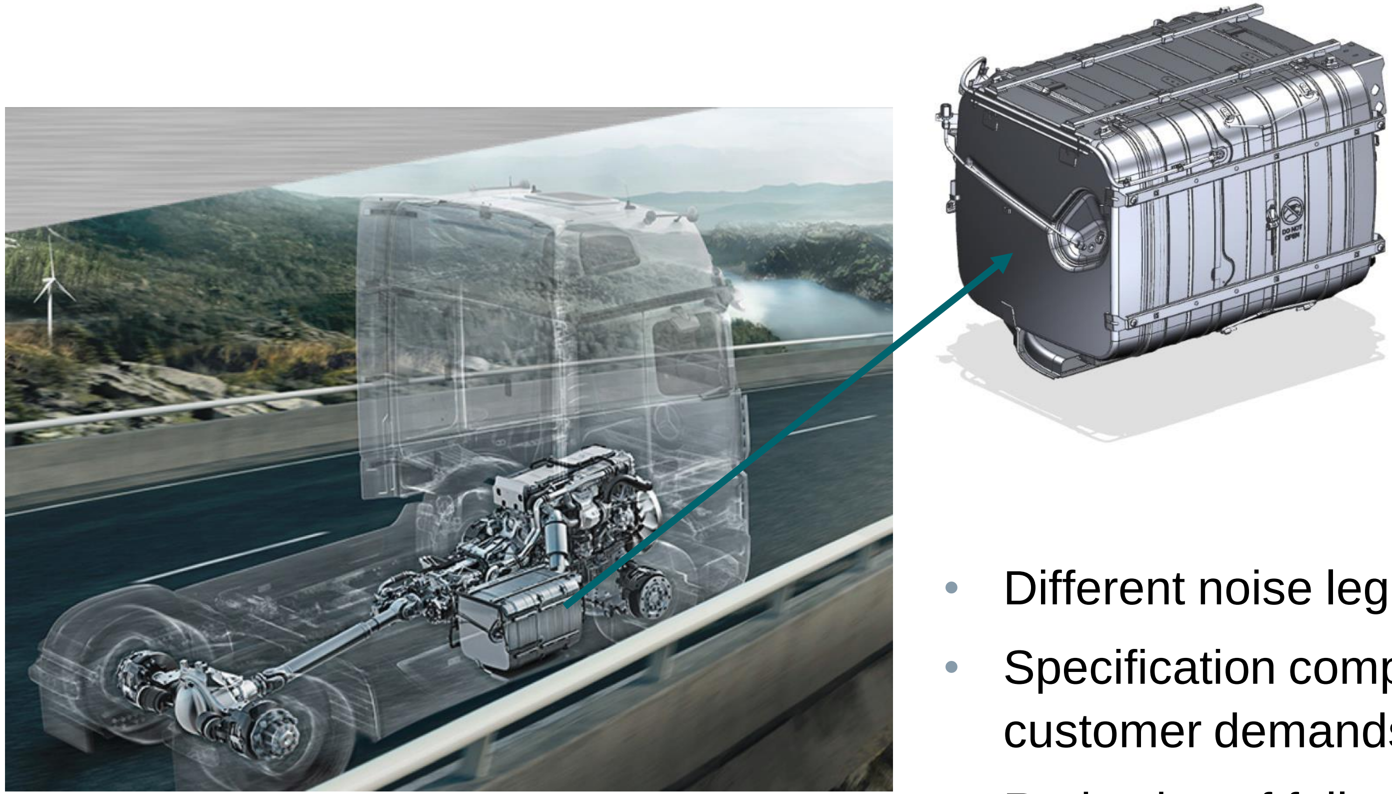
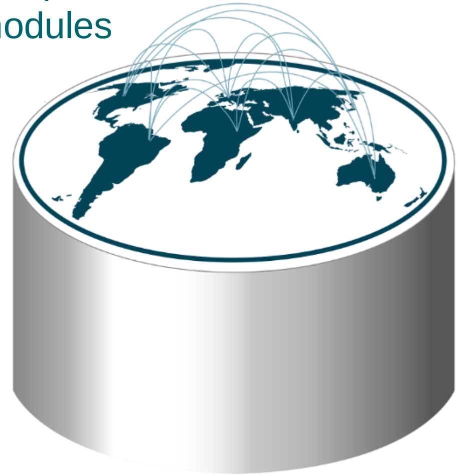
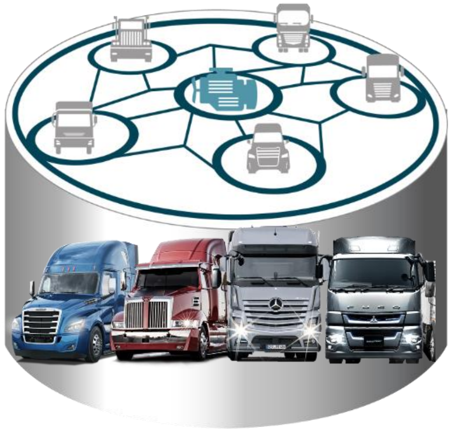


Global use of components and modules



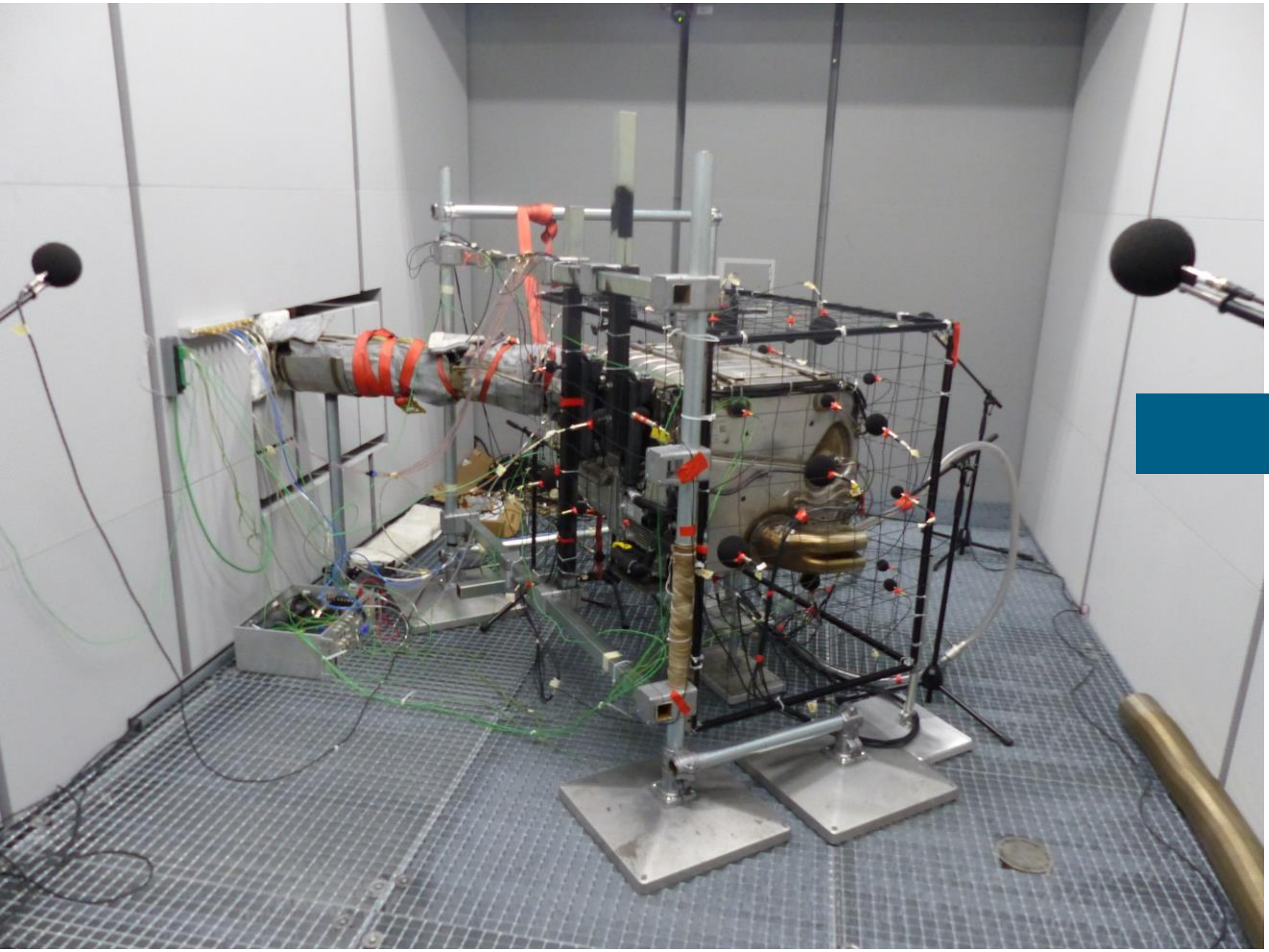
Platform strategy

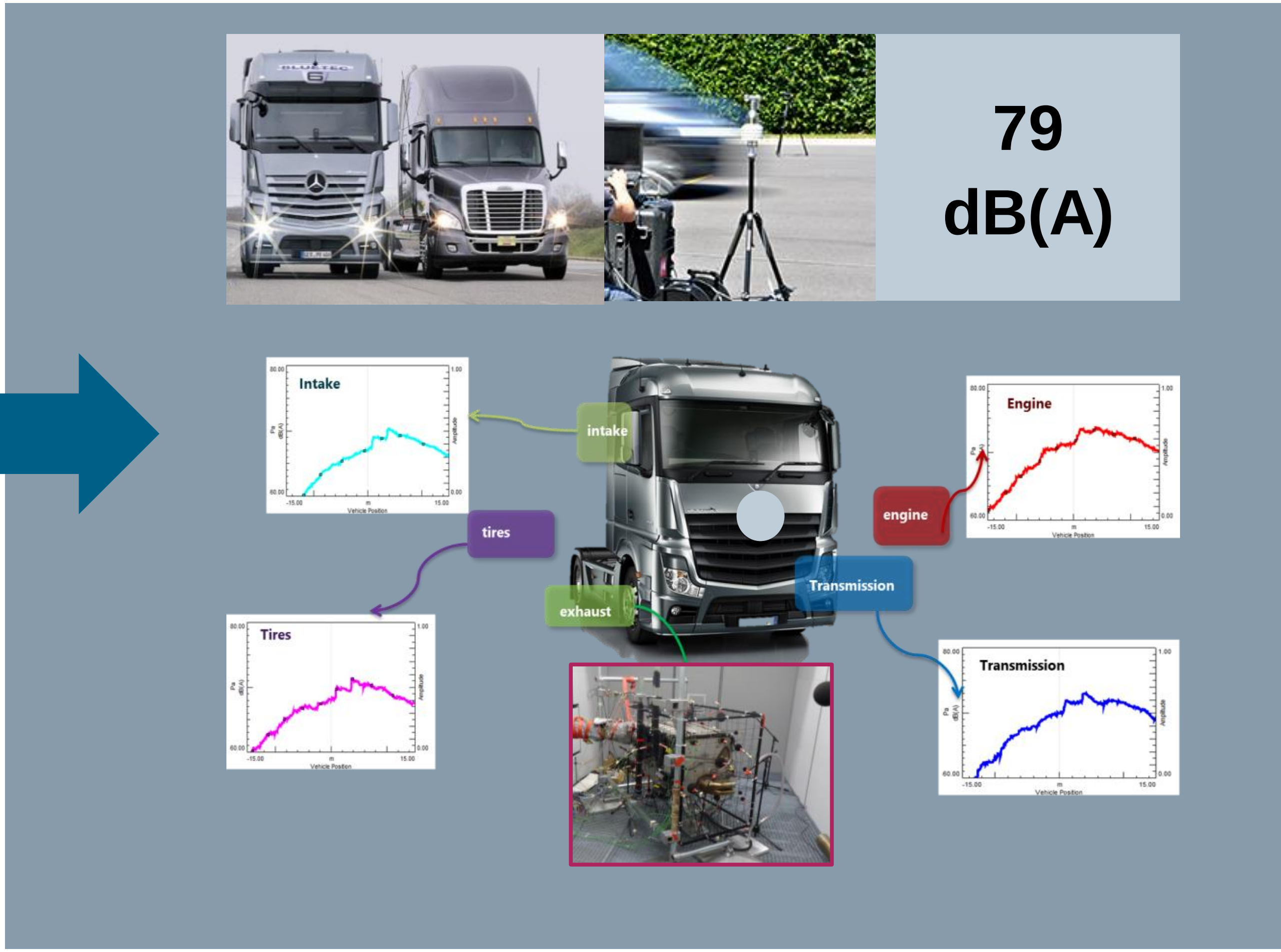


- Different noise legislations to be considered.
- Specification complexity by globalization of components and increasing customer demands.
- Reduction of full vehicle test required to handle wide variety of vehicles
- Improved accuracy of tests required to apply further optimization of design and costs.

# Research Objectives

*Contribution Prediction*



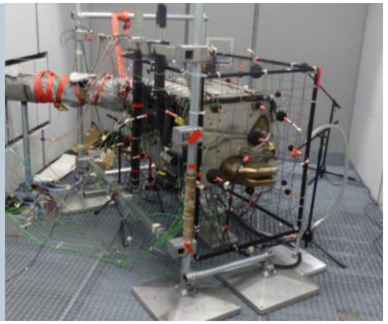


# Research Objectives
## *PBN Performance Prediction*

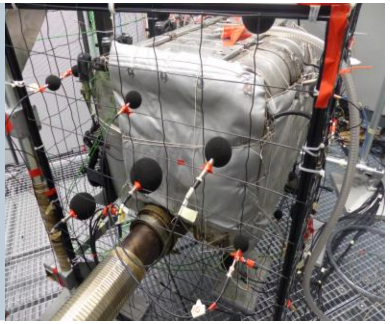
**SOURCE**

**Invariant description of sources**

**VARIANT A**



**VARIANT B**



...

20+ Design Variants

**Recombine with selected components to synthesize SYSTEMS**

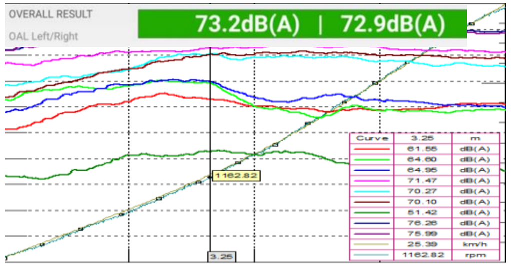
**VEHICLE 1**

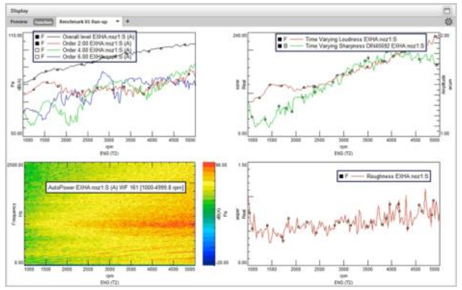
**VEHICLE VARIANTS**

...

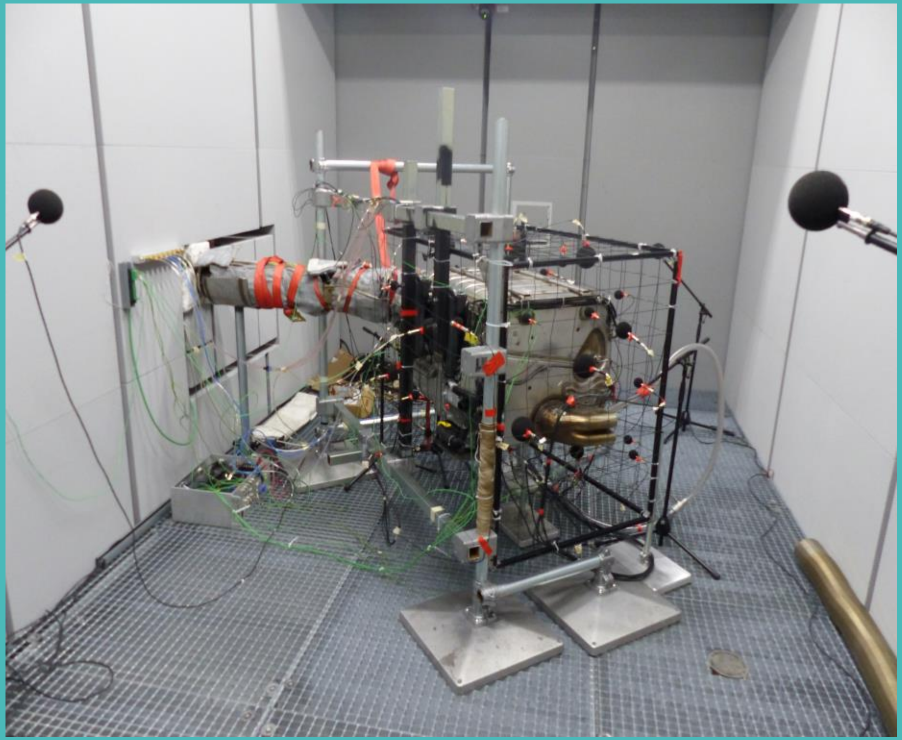
Vehicle Variants

**Predict NVH performance**



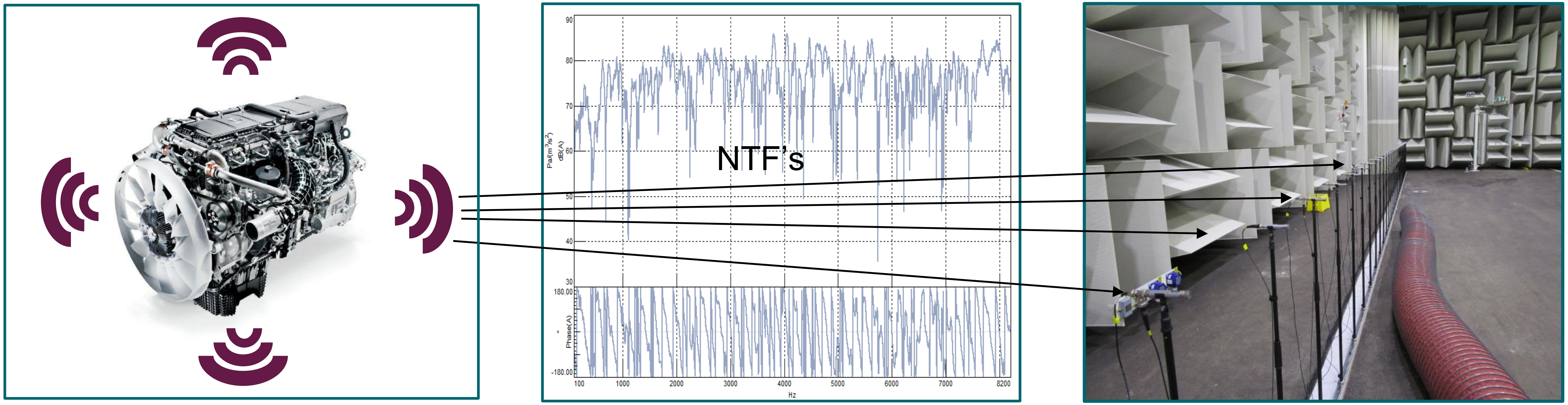



# Overview



1. Introduction
2. **PBN Synthesis: Process Validation**
   - **Step 1: Full Vehicle PBN ASQ**
   - Step 2: Component ASQ
   - Step 3: Pass-By Noise Synthesis
3. Conclusions

# Airborne: replace by set volume velocities for each source




Volume Velocities x Noise Transfer Function NTF = Contributions to each Target

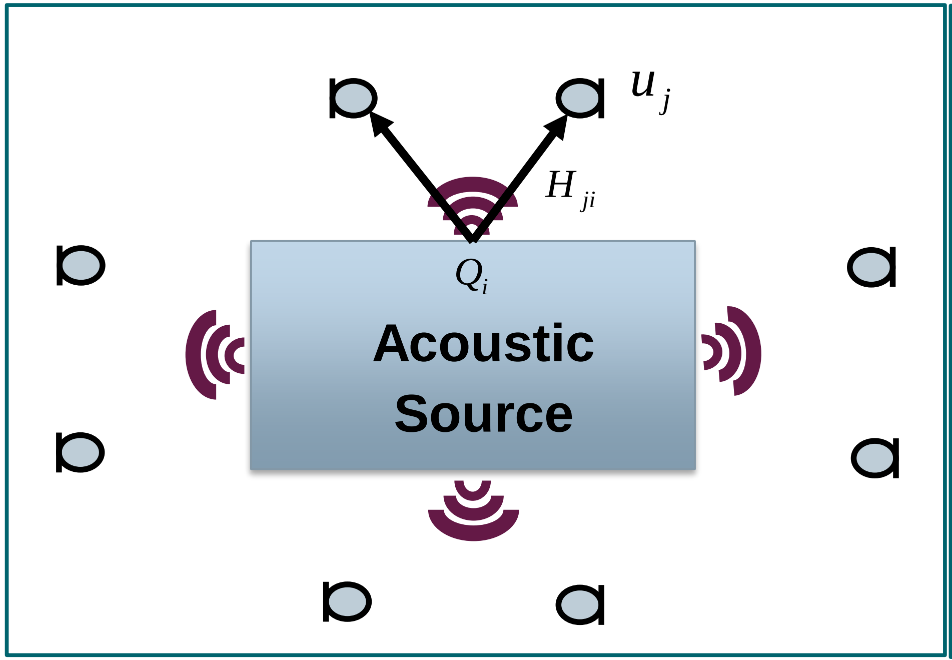
# Transfer Path Analysis

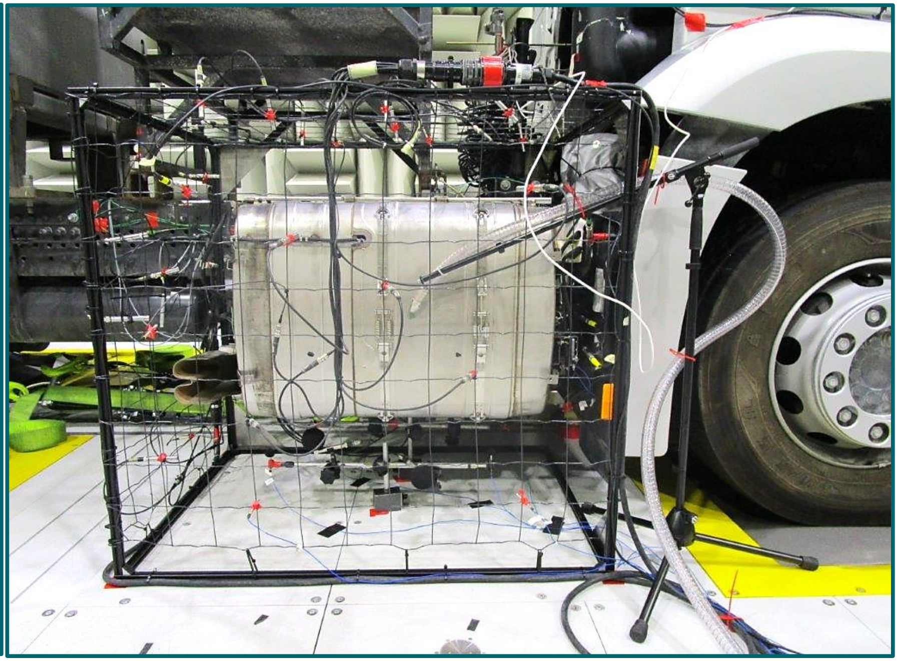
*Load identification: matrix inversion method*

$Q_i$ **Volume Velocity i**

$u_j$ **Indicator mic. j**

$H_{ji}$ **FRF between i&j**



$$\{Q_i^2(\omega)\} = [\overline{H_{ji}^2(\omega)}]^{-1} * \{u_j^2(\omega)\}$$

# Pass-by Noise Engineering – Energetic ASQ

*Time domain source contribution analysis*

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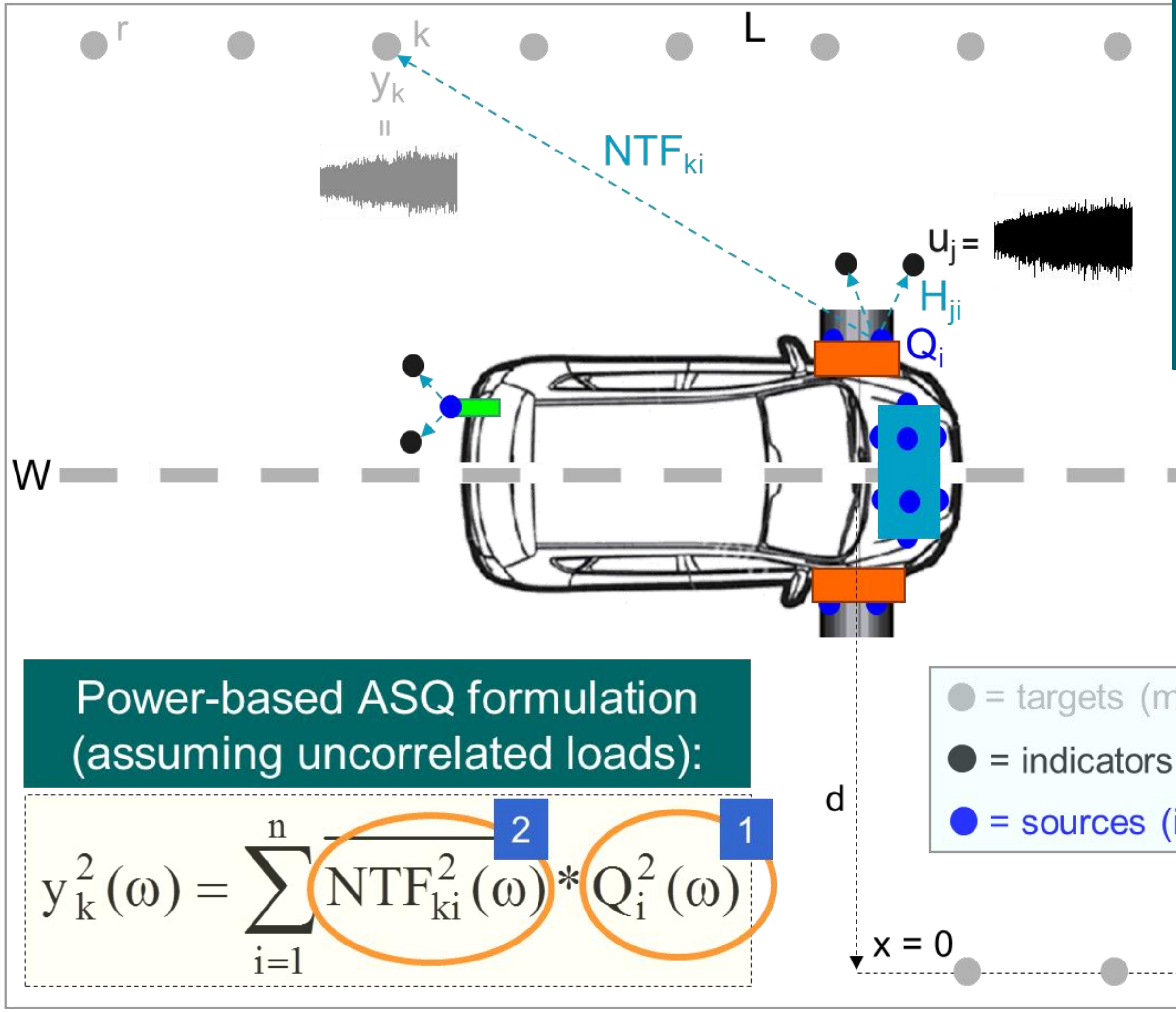
**Frequency Range**

**Subsampled**

**Transient**

**Indoor or Exterior**




Power-based ASQ formulation (assuming uncorrelated loads):

$$y_k^2(\omega) = \sum_{i=1}^{n} \overline{NTF_{ki}^2(\omega)} * Q_i^2(\omega)$$

# Instrumentation and Operational Testing

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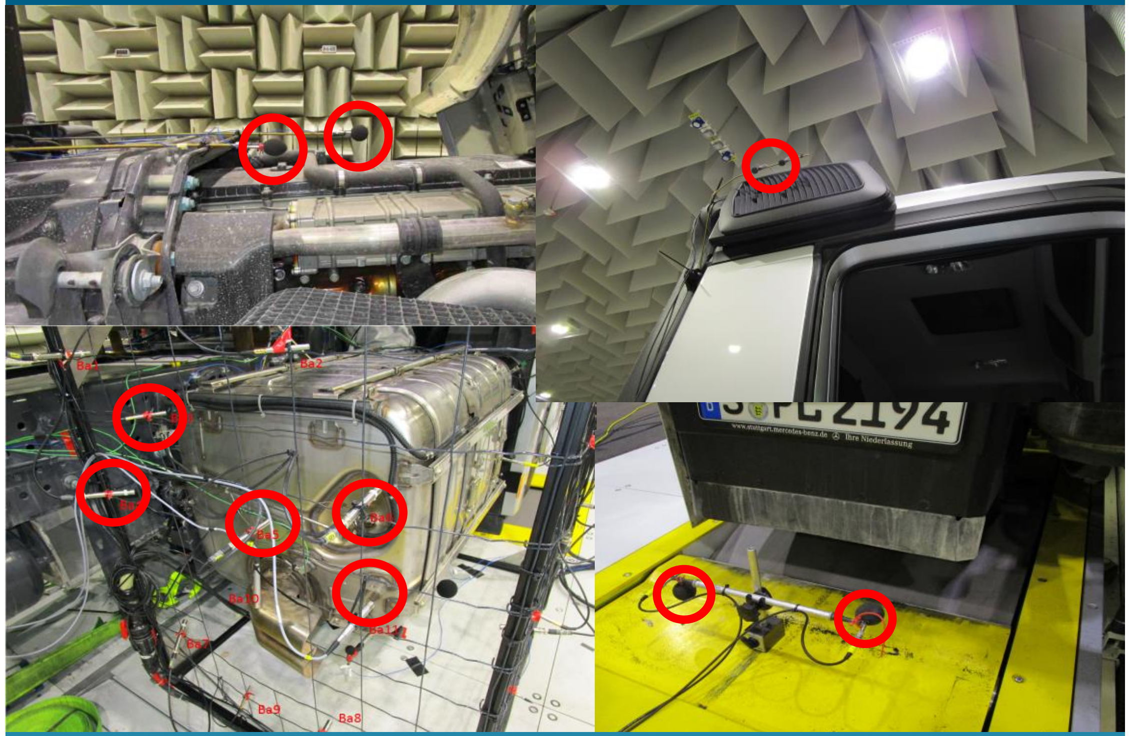
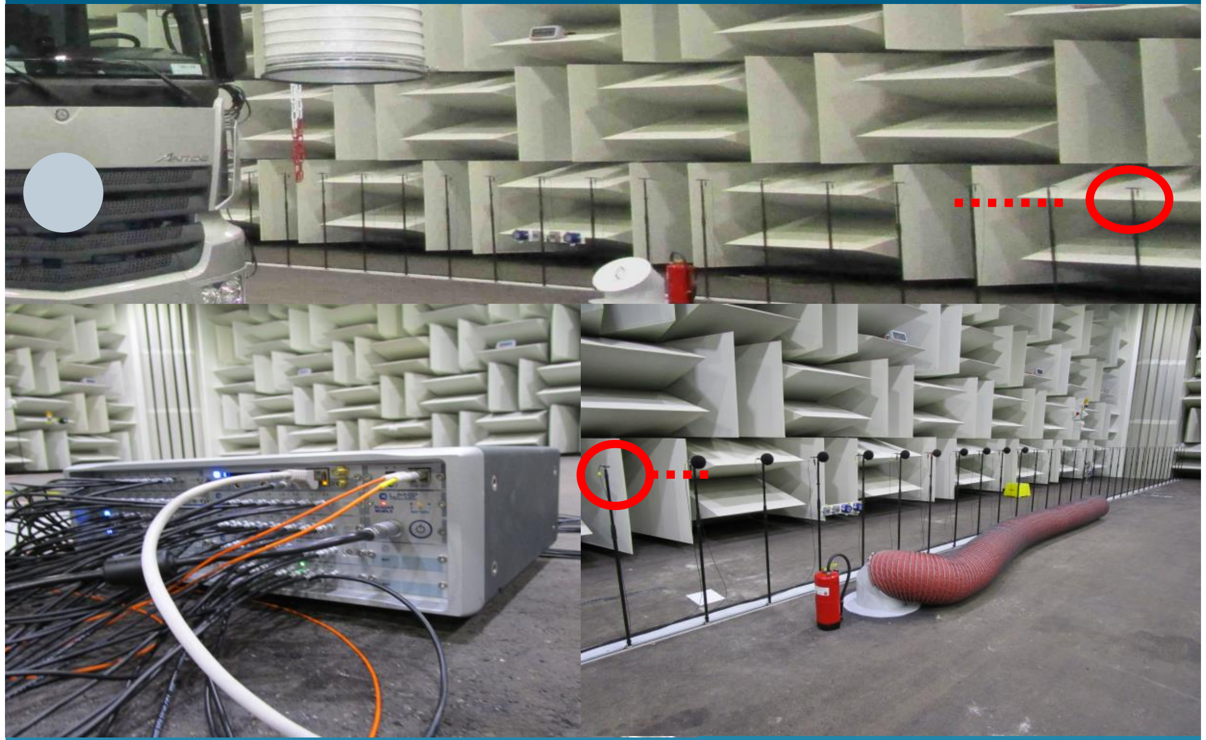
## Indicator Microphones



Exhaust ATS – Engine – Intake – Tires – Clutch – Transmission – Rear Axle

## Target Microphones



Left & Right Microphone Arrays

# Instrumentation and FRF Testing

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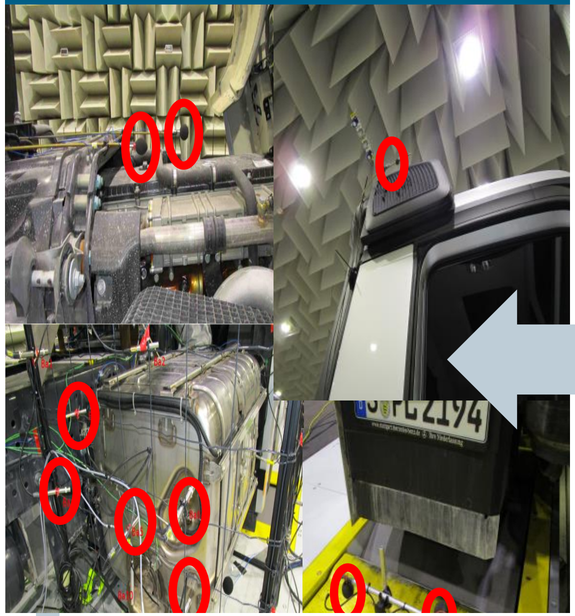
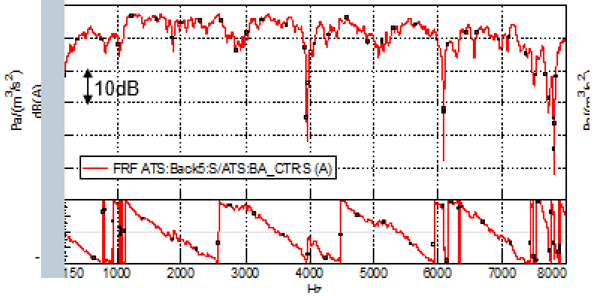
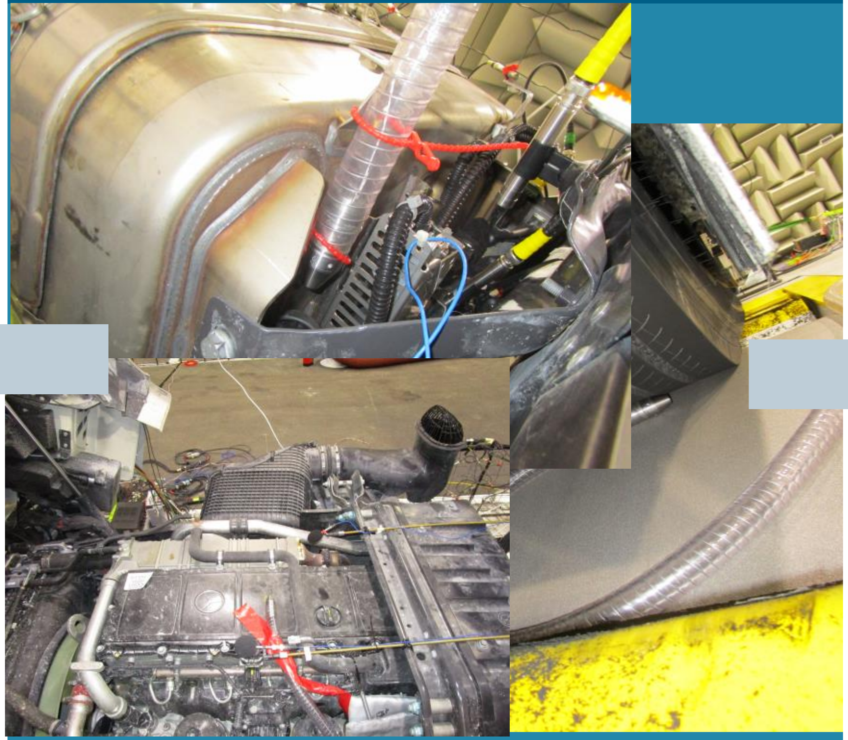
## Indicator Microphones






FRFs

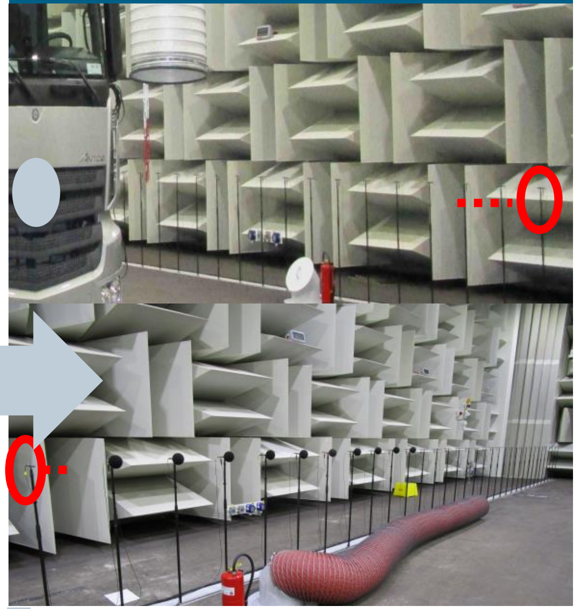
## Source Locations

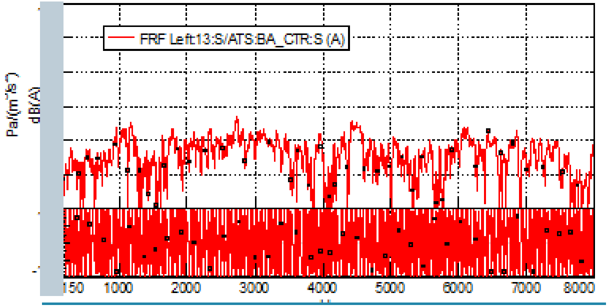


Simcenter QSource:
Volume Velocity Source

FRFs

## Target Microphones





# Interior PBN ASQ Results

*Grouped Contributions*

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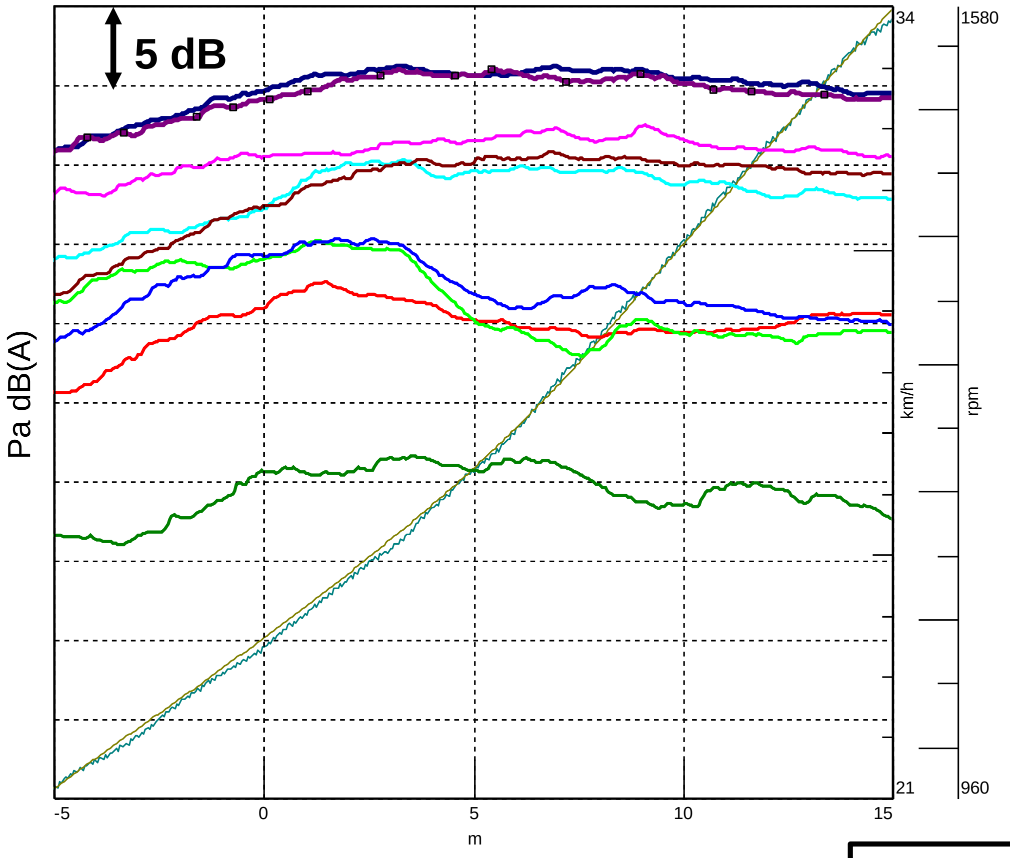
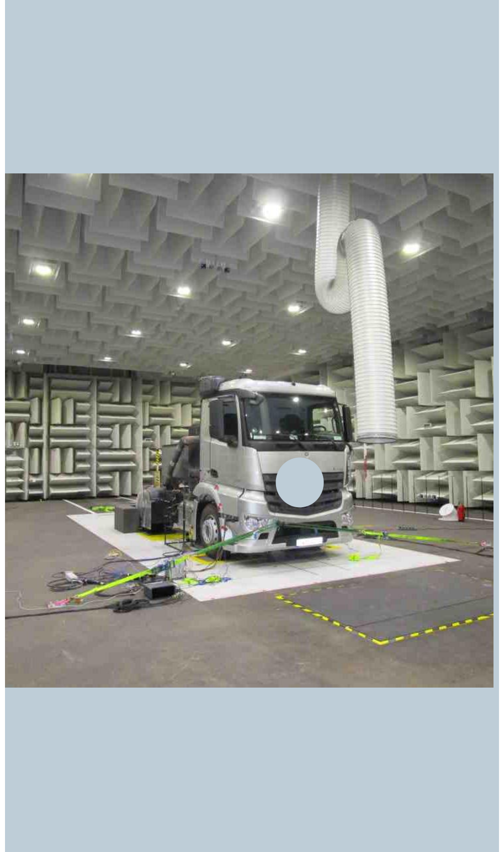
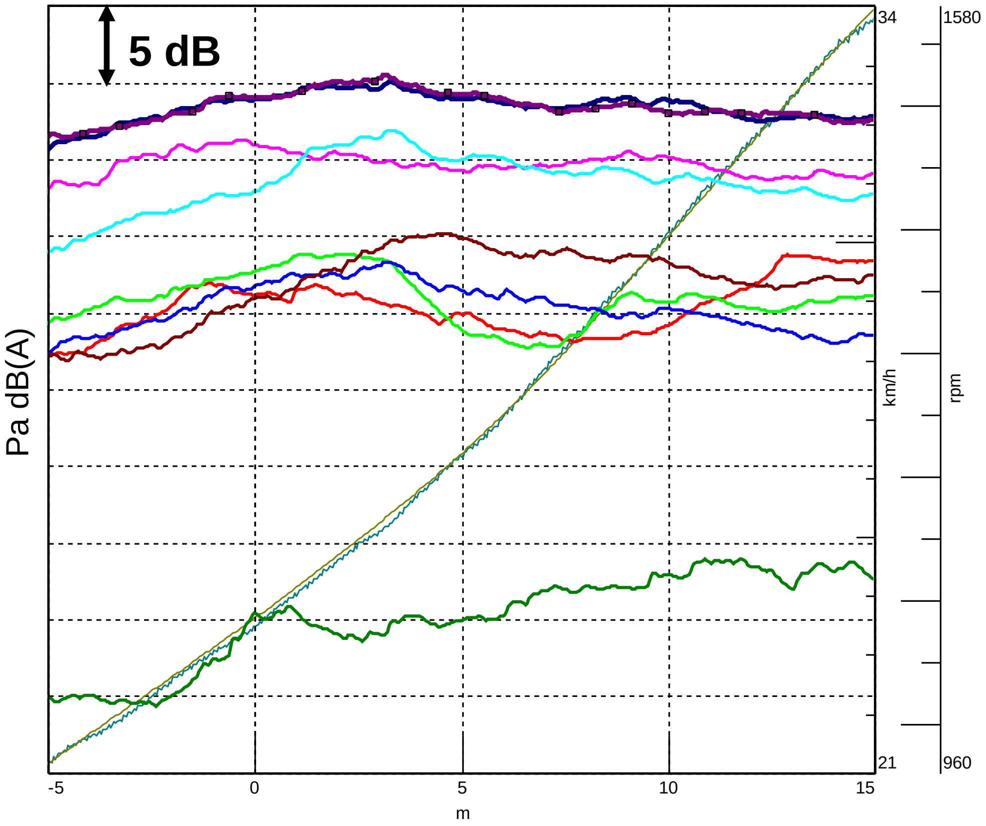
**RIGHT PBN MIC**



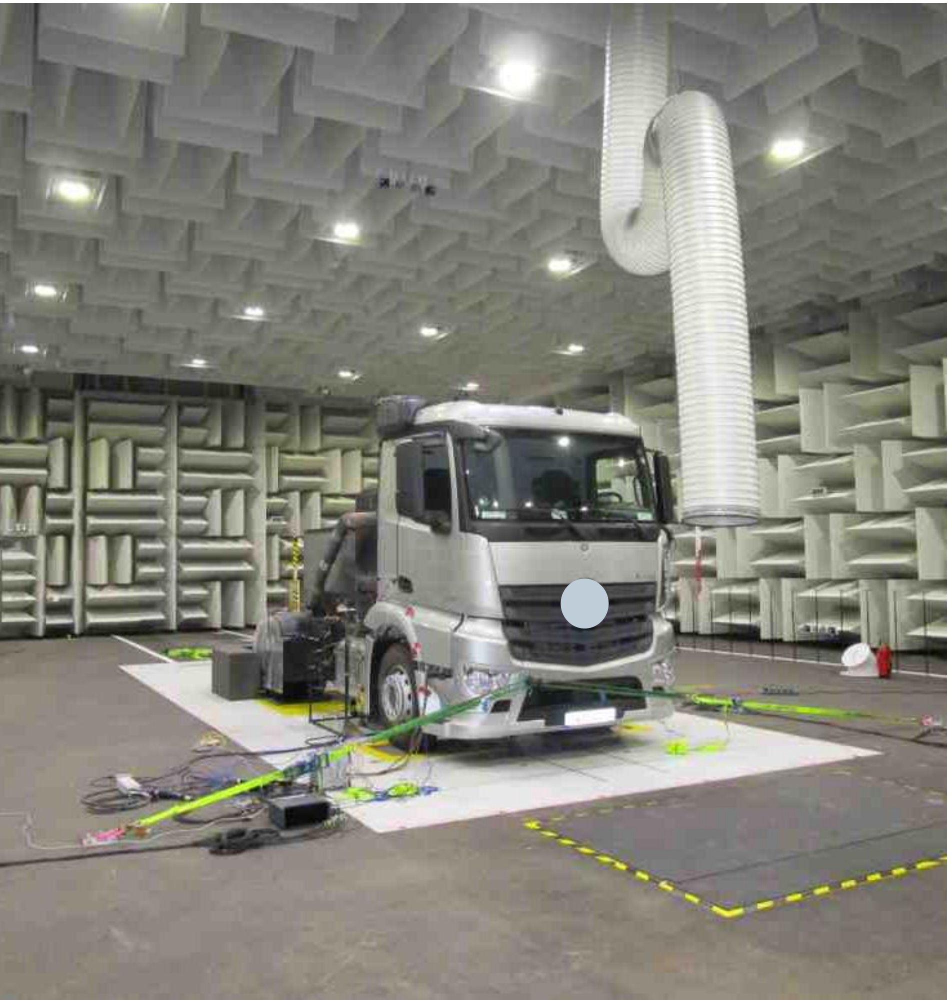
**LEFT PBN MIC**



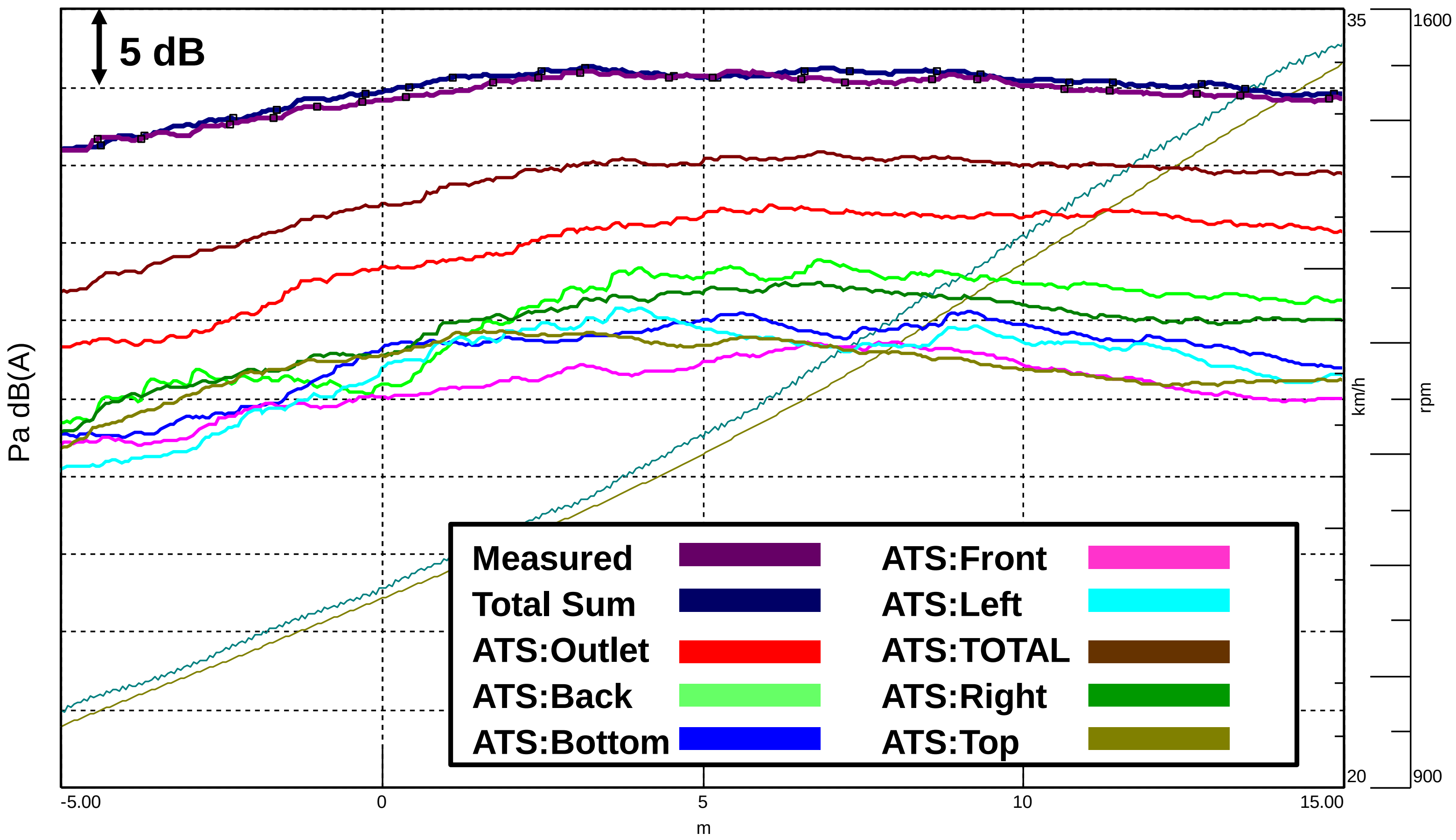

| | | | |
|---|---|---|---|
| Measured | | Engine | |
| Total Sum | | Clutch | |
| Tires | | ATS | |
| Rear Axle | | Intake | |
| Gearbox | | | |

# Interior PBN ASQ Results: ATS Contributions

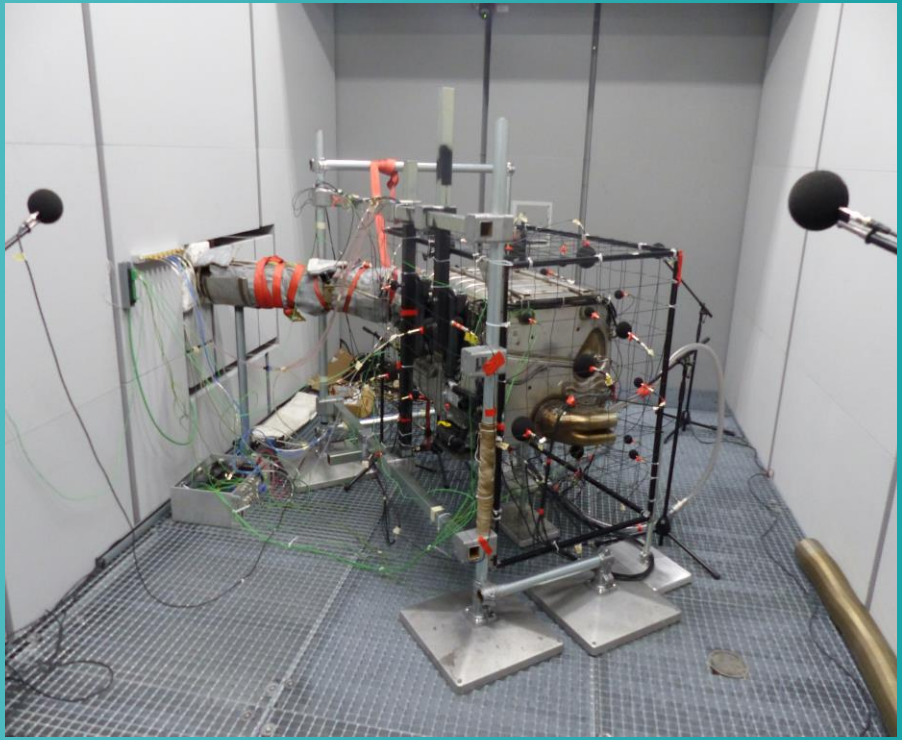
*Base configuration*



RIGHT PBN MIC



## Overview



1. Introduction

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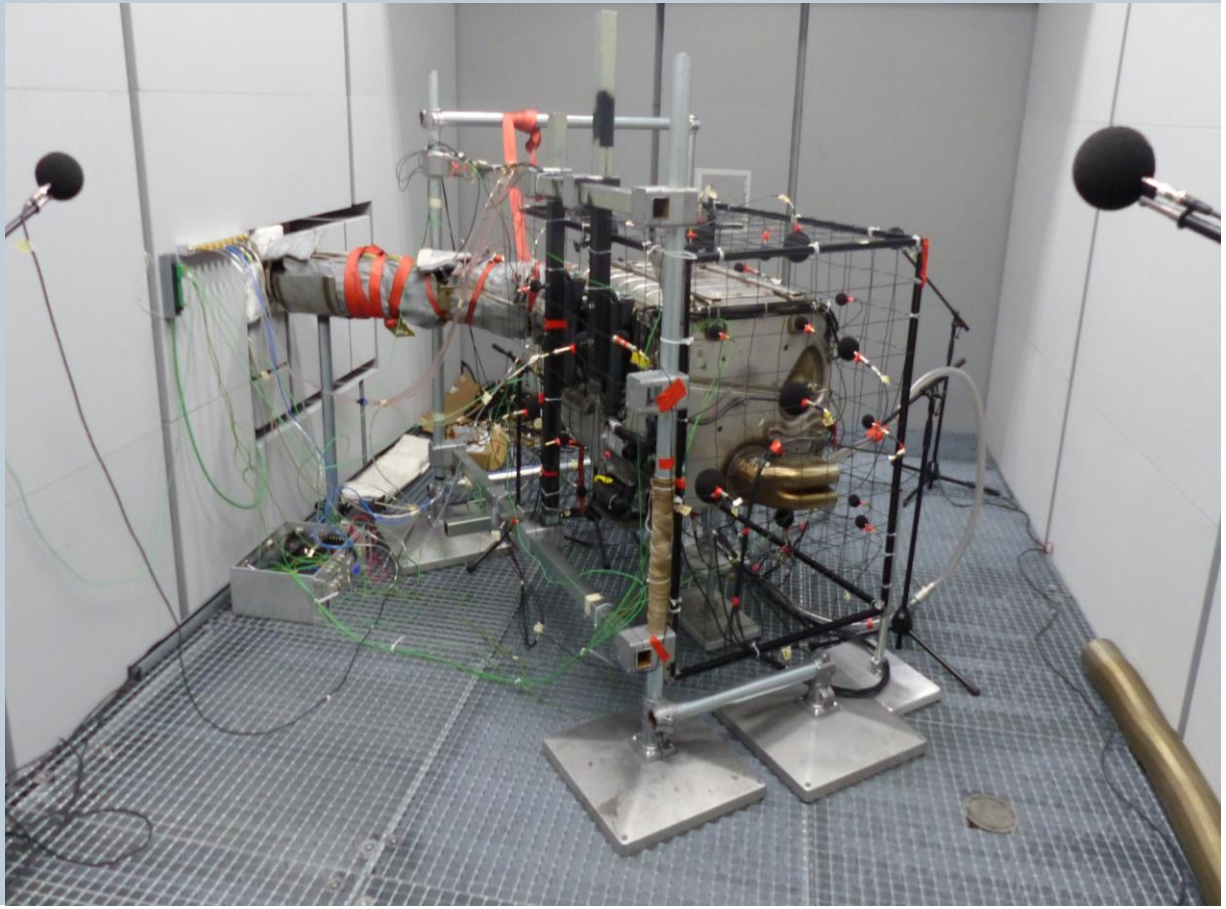
   - Step 1: Full Vehicle PBN ASQ
   - **Step 2: Component ASQ**
   - Step 3: Pass-By Noise Synthesis

3. Conclusions

# Component test rig facility

| Engine | Exhaust ATS |
| --- | --- |
|  |  |

# Instrumentation and Operational Testing

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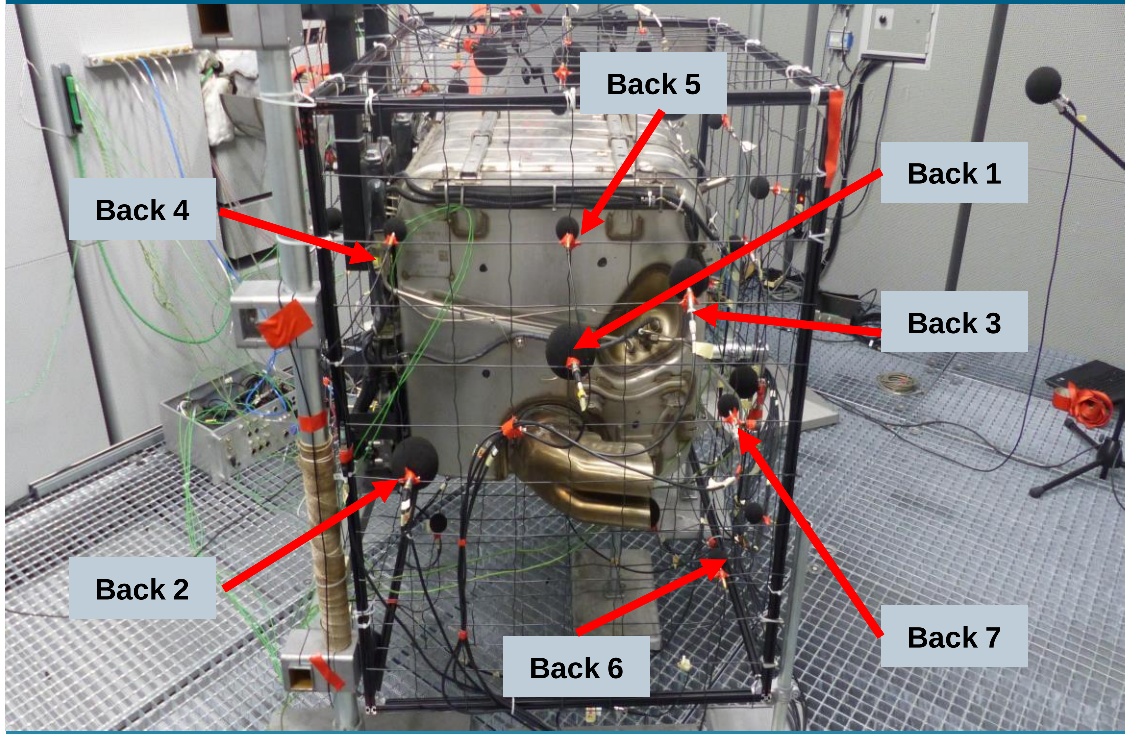
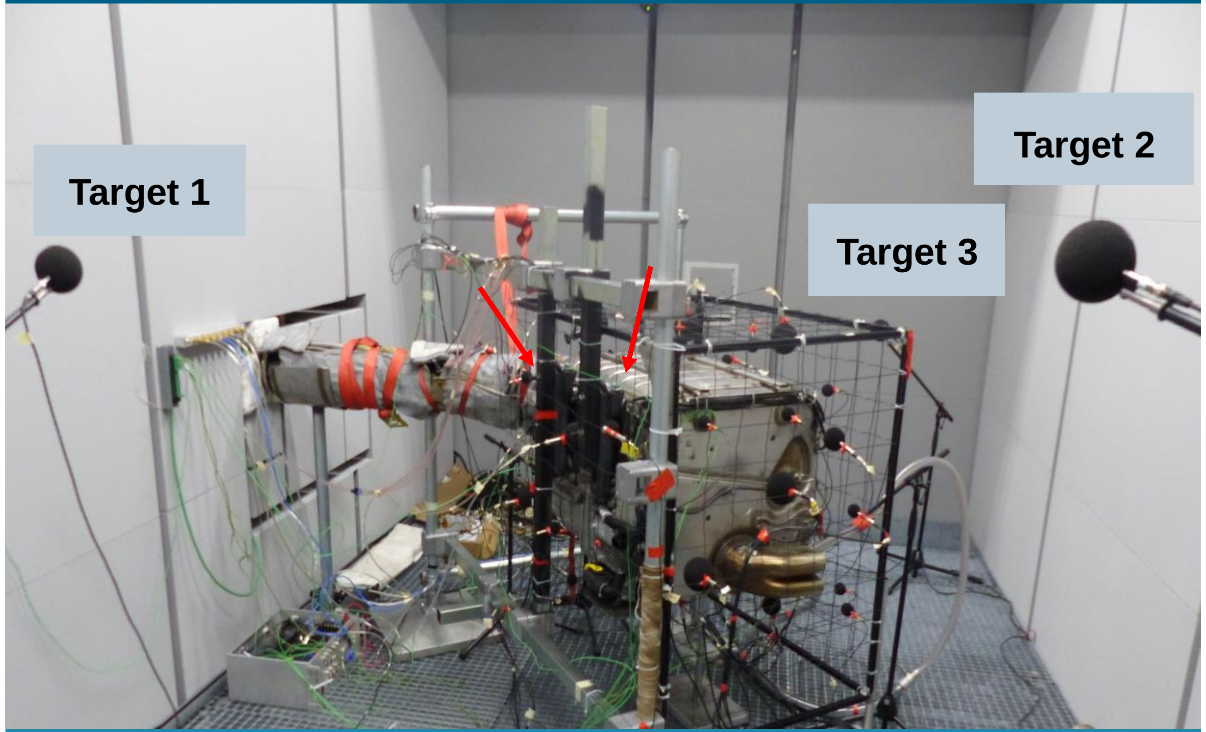
## Indicator Microphones




Exhaust ATS

## Target Microphones




Validation Target Microphones

# Instrumentation and FRF Testing

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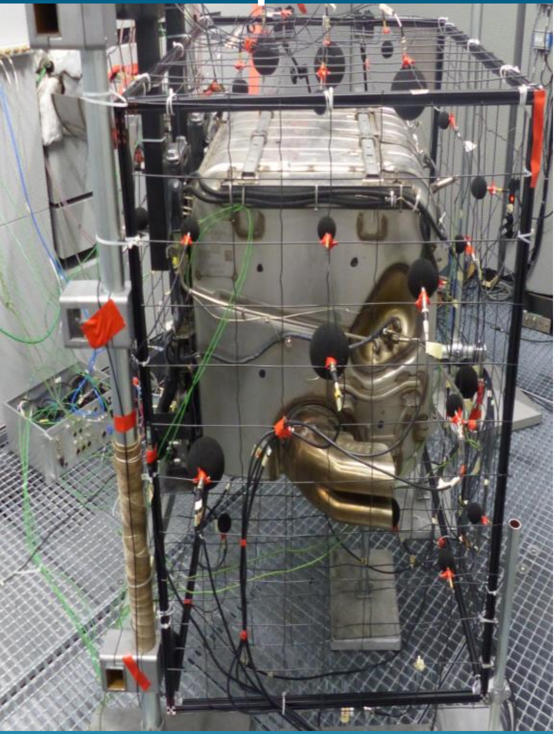
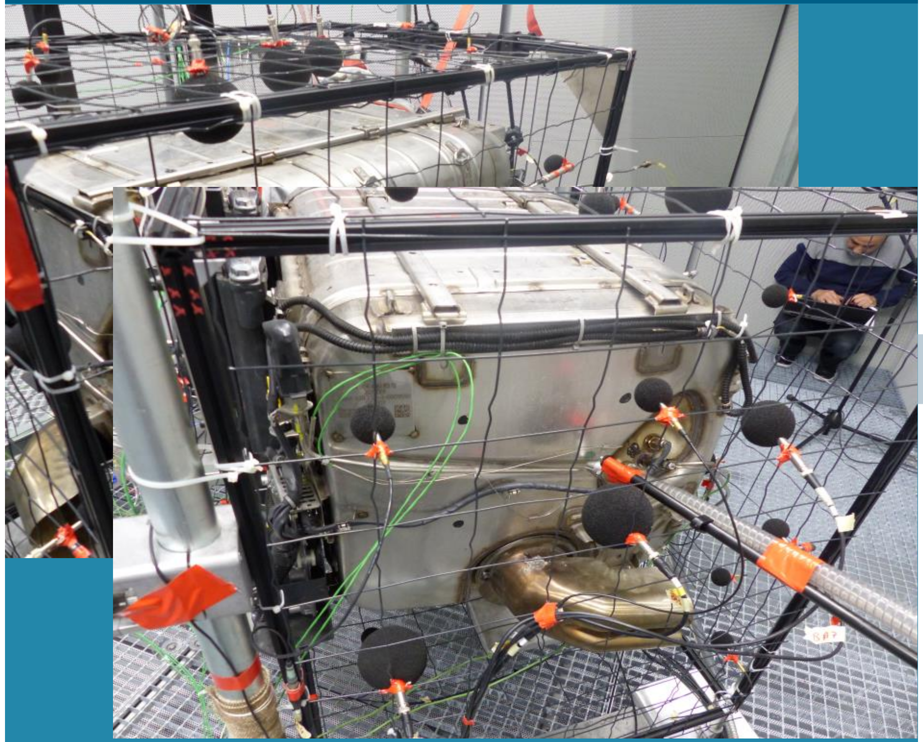
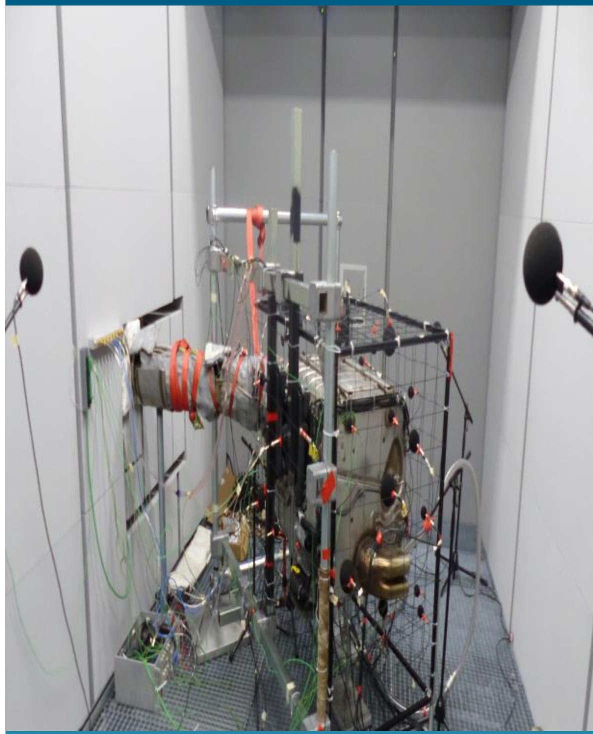
| Indicator Microphones | | Source Locations | | Target Microphones |
|---|---|---|---|---|
|  | ← FRFs |  | FRFs → |  |
| Exhaust ATS | | Simcenter QSource: Volume Velocity Source | | Validation Target Microphones |

# Configurations ATS system

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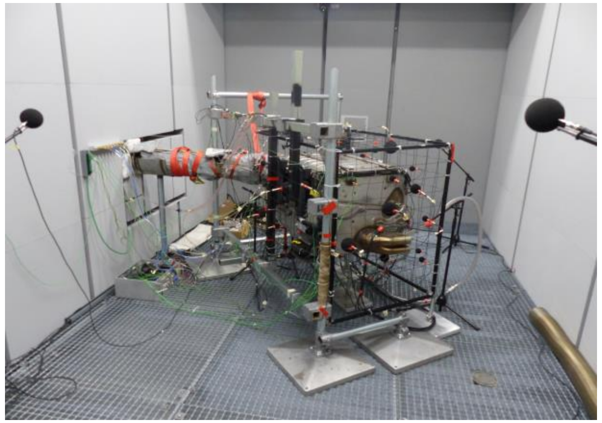
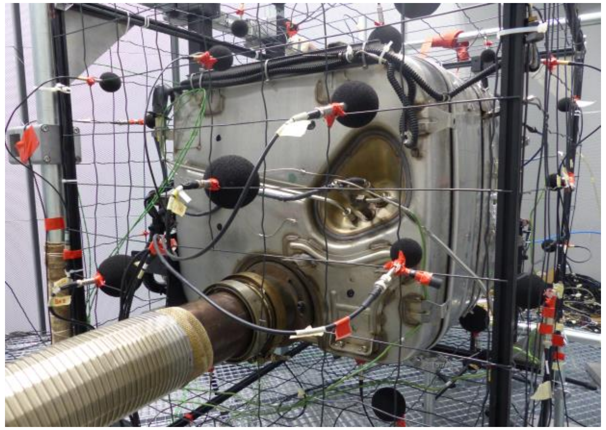
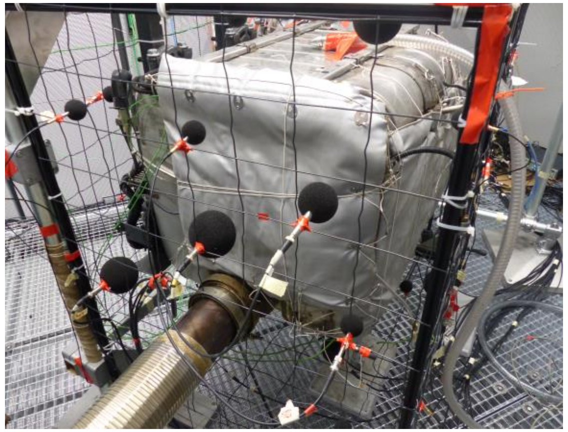
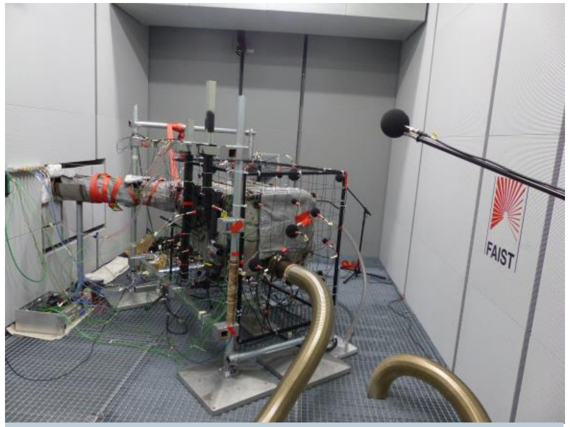



**Base**

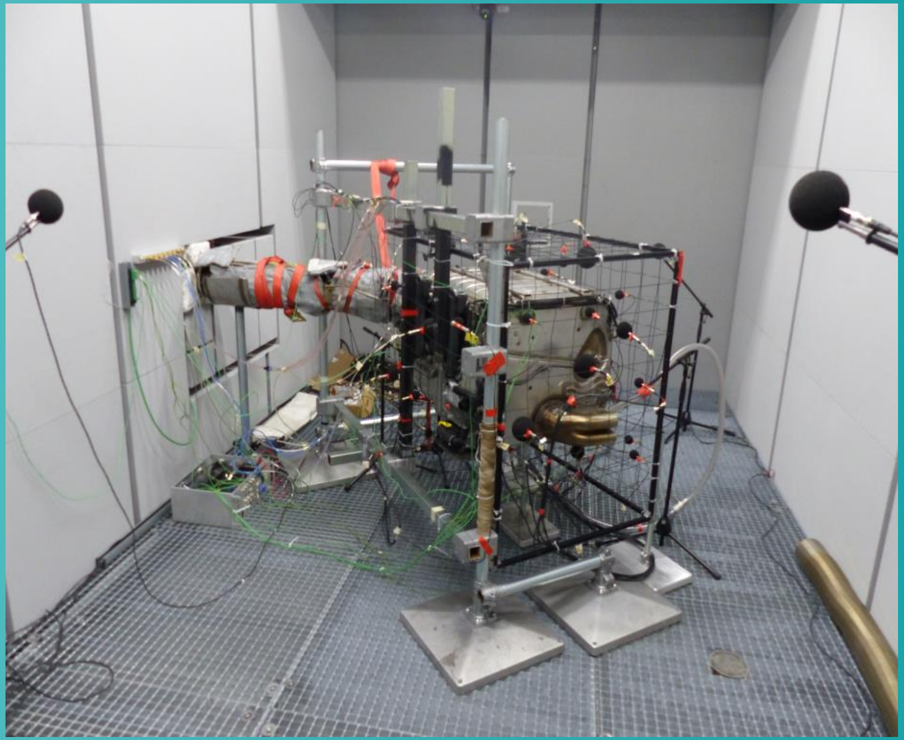



**Variant A:** Exhaust take off connected


**Variant B:** Exhaust take off connected Back/Right Covered

# Overview



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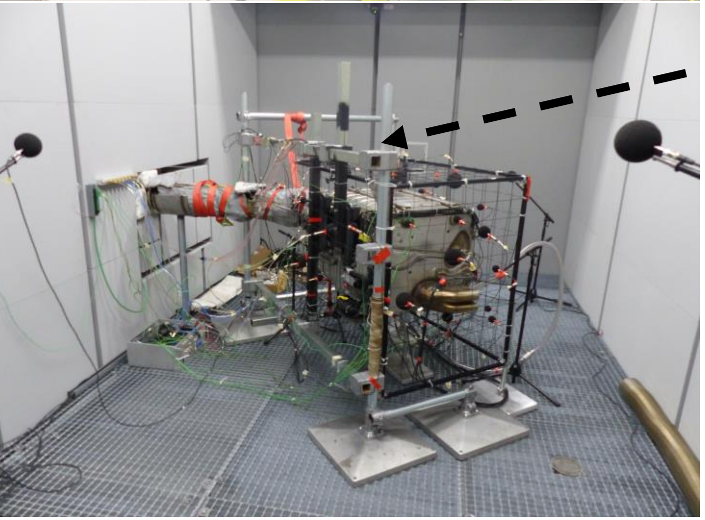
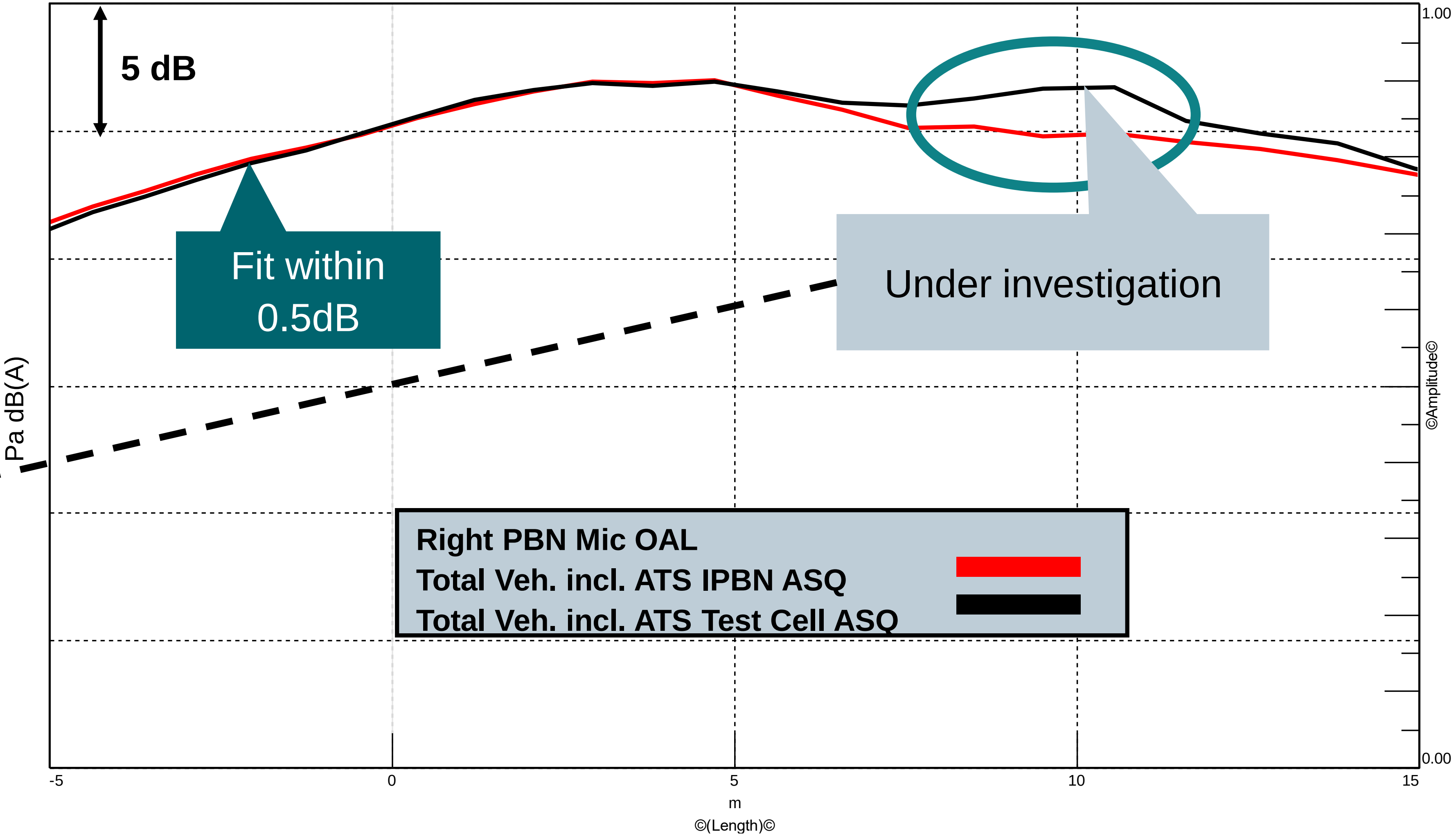
3. Conclusions

# Validation *Full Vehicle ASQ model*

## *ATS Full Vehicle or ATS Test Rig*

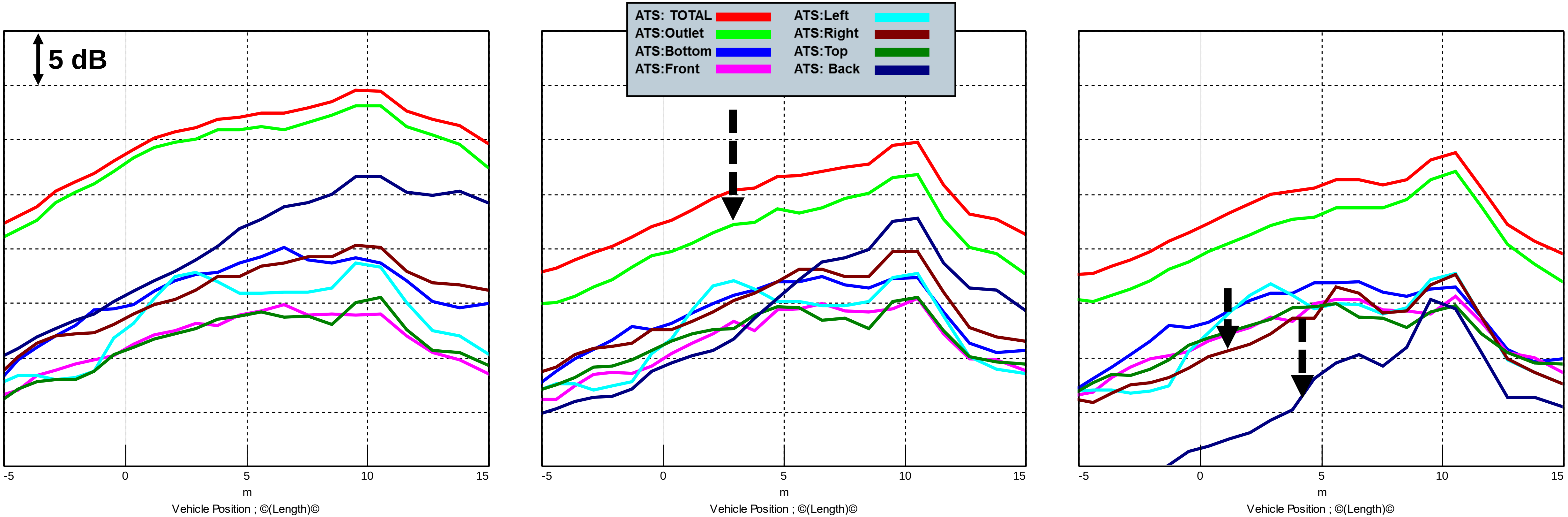


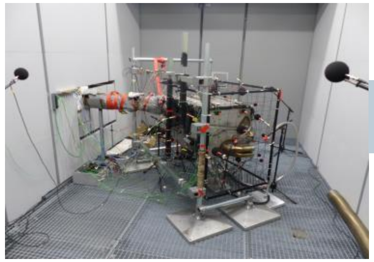


# Efficiency ATS modifications

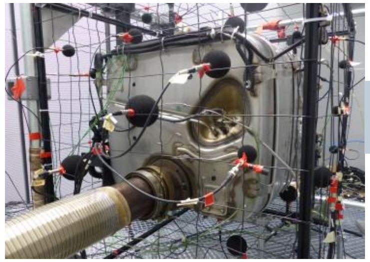
*Contribution to right Pass-by Noise microphone*



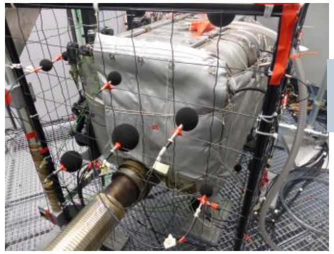


Base

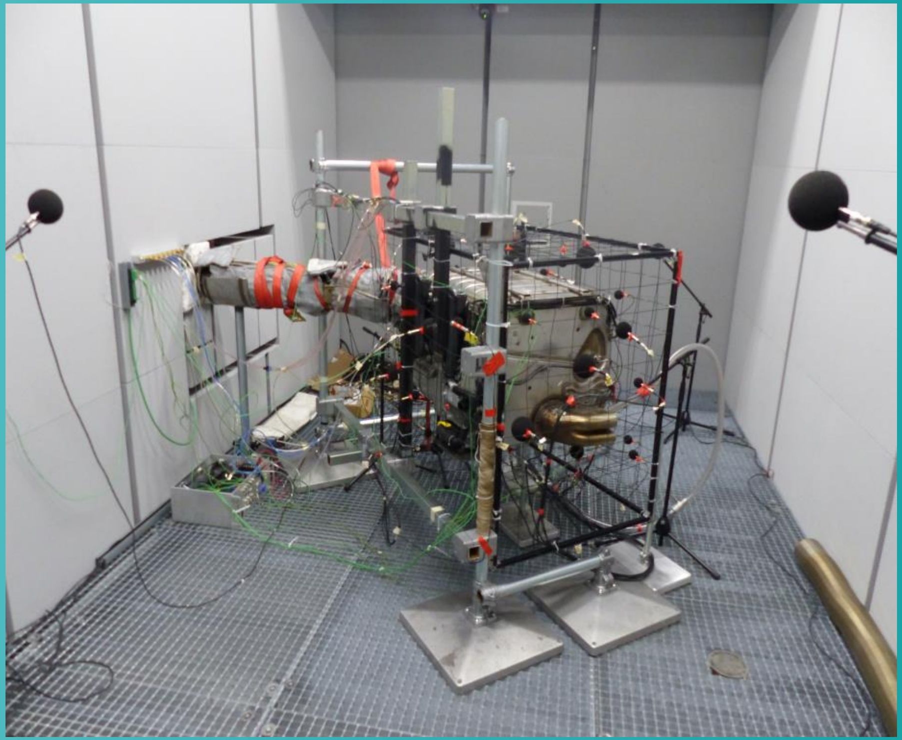


Variant A



Variant B

# Overview



1. Introduction
2. PBN Synthesis: Process Validation
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3. **Conclusions**

# *Predict pass-by noise levels of vehicle with exhaust as measured on a test bench*

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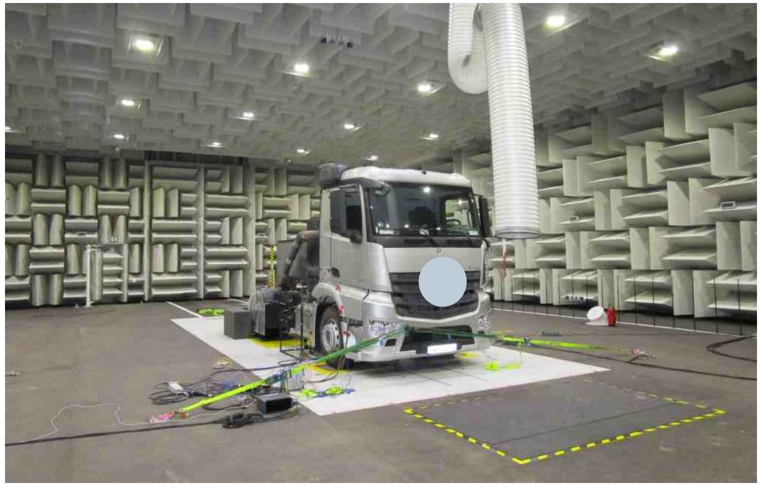
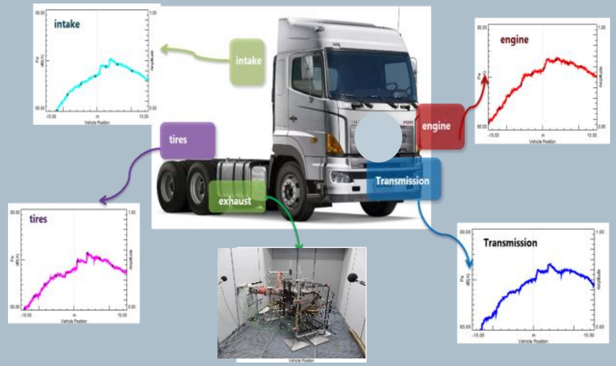


- **State of the art in-room Pass-by noise software**
- **Quantification of subsystem contribution**
- **Calculate contribution of exhaust system, as measured on a test bench**

## Towards virtual vehicle assembly




**Use virtual vehicle assembly to reduce testing time**

- Perform component tests on test bench at supplier site
- OEM assembles and evaluates different configurations based on supplier data

**The process of front loading full vehicle performance testing will lead to reduced development cost because of less physical prototypes, reduced testing time  and no expensive modifications in the late integration phase.**

# Thank you.