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# Exhaust Noise Development Based on System Models

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## Abstract

With the electrification trend in the automotive industry, a virtual and efficient development for exhaust noise performance of ICE (Internal Combustion Engine) vehicle has been demanding. To cope with this challenges, the test-data-driven MBSE (model based system engineering) has been emphasized from its credible correlation with phenomena in vehicle state. In this study, the prediction process for the exhaust noise in vehicle state with the engine and exhaust system models in system state was presented. The system models were built guaranteeing modularity, inherence and description in its operational boundary conditions such as temperature and valve openness of exhaust system. The adequate parameters describing engine source and exhaust system's acoustic transmissibility were defined and measured experimentally. The analytical equation for coupling system models was derived to predict the exhaust noise at target point and the overall process was implemented with in-house program (ENEP) for building system models and predicting exhaust noise. The credibility of the proposed method was validated in terms of predicted result and system models with measured data and empirical knowledge. The predicted exhaust noise was compared and verified with the measured data in a main combustion order level with 6 cases. It was also verified that the engine source level was proportional to engine' power and the exhaust system's transmissibility corresponded with the empirical relation with design parameters such as resonator's volume and pipe diameter, etc. The NVH developer can assemble engine and exhaust system virtually to predict exhaust noise of the vehicle to be developed at an early stage. From this virtual assembly, the system targets can be set for suppliers and the best system match can be drawn. From this study, the test-data-driven MBSE could be used for a double validation tool with vehicle based development to secure the target quality at an early stage in an efficient way.


## Introduction

The traditional development process in the company consisted of target cascading from the vehicle to system level and part design using optimization technic as shown in Figure 1. However, the overall process was mainly based on vehicle based measurement. To perform a virtual development in an early stage, a prediction method of exhaust noise by using system's inherent models such as engine sound source and exhaust system's transfer function has been developed. (blue arrow) Challenges in this process were to build independent system models without vehicle and to apply the realistic operational boundary conditions to system models for credibility of prediction results.

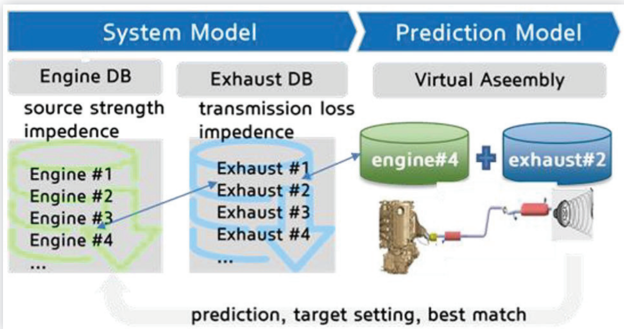
In vehicle NVH, the exhaust system is attenuating engine's exhaust noise as shown in Figure 2. The exhaust system related noise consists of many sources such as engine combustion from gas pulsation, radiation of resonator from vibration and gas flow noise, which influence on in-vehicle comfort and pass-by regulation. In this study, engine combustion induced exhaust noise was targeted as a first step for virtual development of exhaust noise.

## System Model Implementation

### Engine System Model

Engine system model was defined as exhaust noise source strength($P_s$) which expressed source's magnitude and frequency information and acoustic impedance($Z_s$) which was used for calculating the coupled system. Engine model was built at the coupling point which was set as the point after catalytic converter. To measure engine system models experimentally as shown in Figure 3, the engine was connected with the pipe installed with 2 dynamic pressure probes, which required cooling system for measurement high temperature up to 1000K. And, thermocouple was installed for measurement temperature for compensating exhaust system models which was built in a room temperature. The engine can be test in a bench or in a vehicle. In this study, the data was measured at the accelerating driving condition in a vehicle with 6 different load sets by connecting additional pipes.

**FIGURE 17** Virtual assembly with system models for prediction.




engine with larger volume than others, which resulted in larger level of engine source strength. The exhaust system of vehicle #4 had smaller volume of resonator and larger diameter of pipe than others, which resulted in smallest transmission loss out of 6 systems. In result, the predicted exhaust noise level of vehicle #4 was higher than others, which is natural result with worst system models. From the validations based on predicted level and consistency of system models, the test data driven model based prediction method could be considered to be credible.

## Application of Prediction Model

Based on the proposed method, the NVH developer can assemble engine and exhaust system virtually to predict exhaust noise of the vehicle to be developed in an early stage. From this virtual assembly, the system targets can be set for suppliers and the best system match can be drawn as shown in Figure 17.

# Summary/Conclusions

There have been many researches on system based development on exhaust noise. This study focused on developing system models guaranteeing modularity, inherence and description in its realistic operational boundary conditions such as temperature and valve openness. The analytical equation for coupling system models was derived to predict the exhaust noise at target point and the overall process was implemented with in-house program (ENEP) for building system models and predicting exhaust noise. The credibility of the proposed method was validated in terms of predicted result and system models with measured data and empirical knowledge. From this study, the test-data-driven MBSE could be used as double validation tool with vehicle based development to secure the target quality at an early stage in an efficient way.

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## Definitions/Abbreviations

**Ps** - Exhaust noise source strength

$\mathbf{P_{s+}}$ - Exhaust noise outgoing source strength

$\mathbf{R_s}$ - Engine Reflective Coefficient at coupling point

**Zs** - Engine impedance at coupling point

$\mathbf{R_l}$ - Exhaust reflective coefficient at coupling point

$\mathbf{Z_L}$ - Exhaust impedance at coupling point

$\mathbf{P^+}$ - Incident wave pressure

$\mathbf{P^-}$ - Reflective wave pressure



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