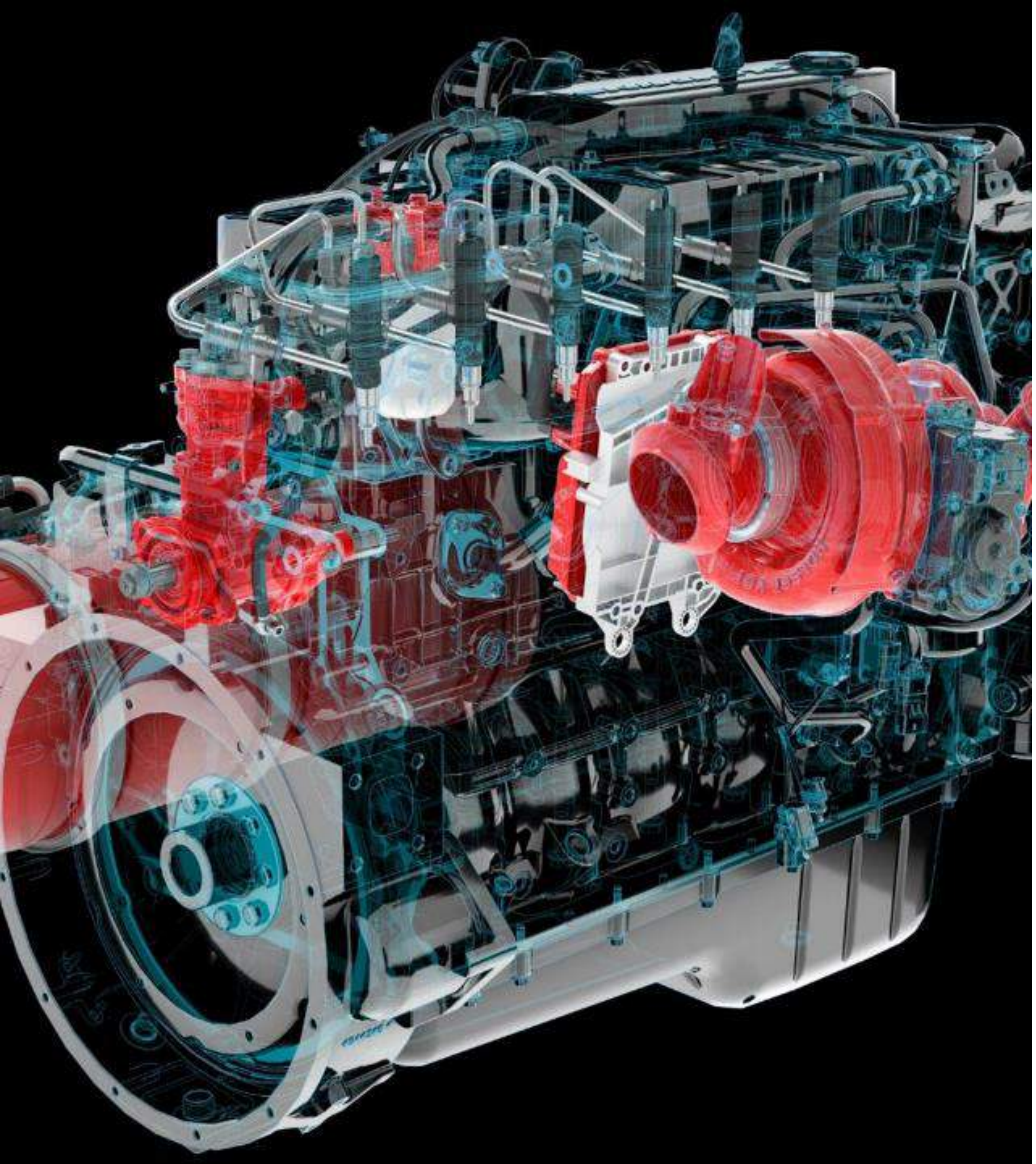

Emission Solutions

Simulation approaches to predict Transient performance of Aftertreatment systems

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Cummins Emission Solutions, CTCI, Pune

Oct 22, 2024

Acronyms

1. Aftertreatment System (ATS)
2. Diesel Oxidation Catalyst (DOC)
3. Diesel particulate Filter (DPF)
4. Selective Catalytic Reduction (SCR)
5. Ammonia Oxidation Catalyst (AMOX)
6. Ammonia to NO_X Ratio (ANR)
7. Computational Fluid Dynamics (CFD)
8. Diesel Exhaust Fluid (DEF or AdBlue)
9. Particulate Matter (PM)

Five operating segments

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As we look ahead, we know our industries and regions will continue to change,
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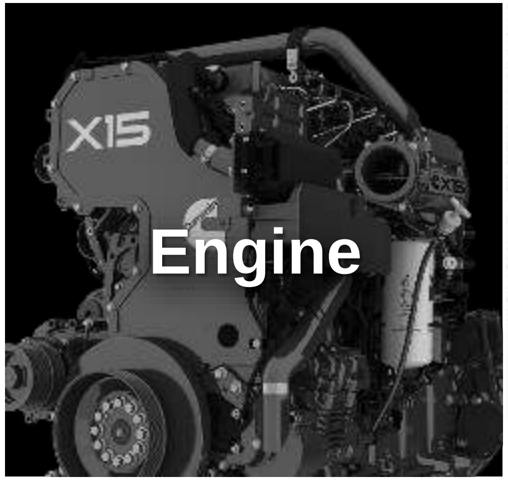

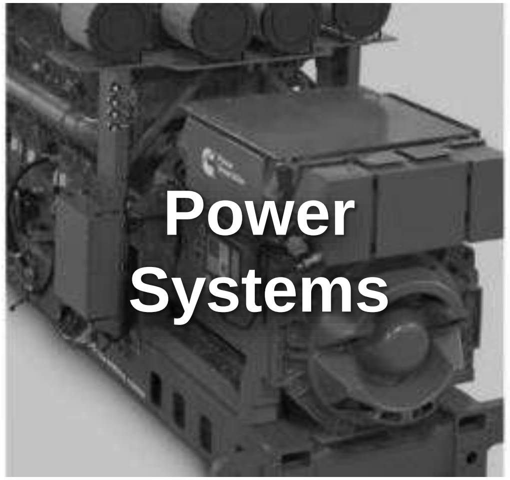

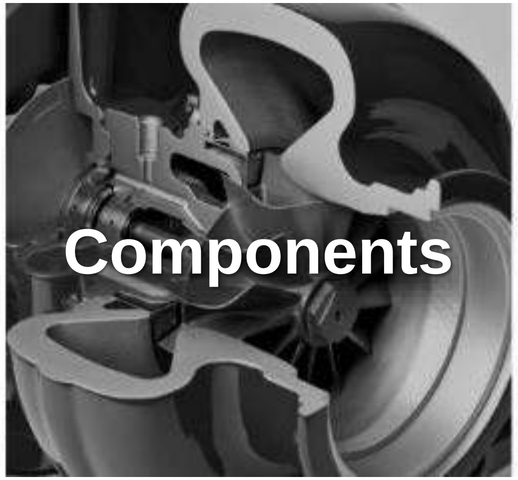

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Aftertreatment solutions

Leading
Global designer, integrator, manufacturer and distributor of exhaust aftertreatment systems and components

20+ Years of aftertreatment experience

10 Manufacturing facilities

AND

7 Technical centers around the globe

CORE TECHNOLOGIES

Diesel Oxidation Catalyst (DOC)

Diesel Particulate (DPF) Filter

Selective Catalytic Reduction (SCR) System

Doser Technology Business

Ammonia delivery system

Controls

Multiple **integration programs** with non-Cummins OEMs and engine manufacturers

Agenda

1. Introduction
2. 3D CFD+1D AVL BOOST Coupling Overview
3. 3D CFD+1D AVL BOOST Coupling Approach: PDF Method
4. Case Study : Conversion Efficiency
5. Application: Sensor Accuracy Modeling Process and Automation
6. Case Study : Sensor Accuracy
7. Application: System Level Modeling In Closed Loop
8. Case Study: System Level Modeling
9. Summary and Conclusion

Introduction

1. Aftertreatment system cleans exhaust gases.
2. DPF: collects and oxidizes the soot.
3. DOC: aids in hydrocarbon oxidation process.
4. DEF is injected into the hot exhaust stream in the Decomposition Reactor.
5. SCR: converts NO_x and urea mixture into harmless nitrogen gas (N_2) and water vapor (H_2O).

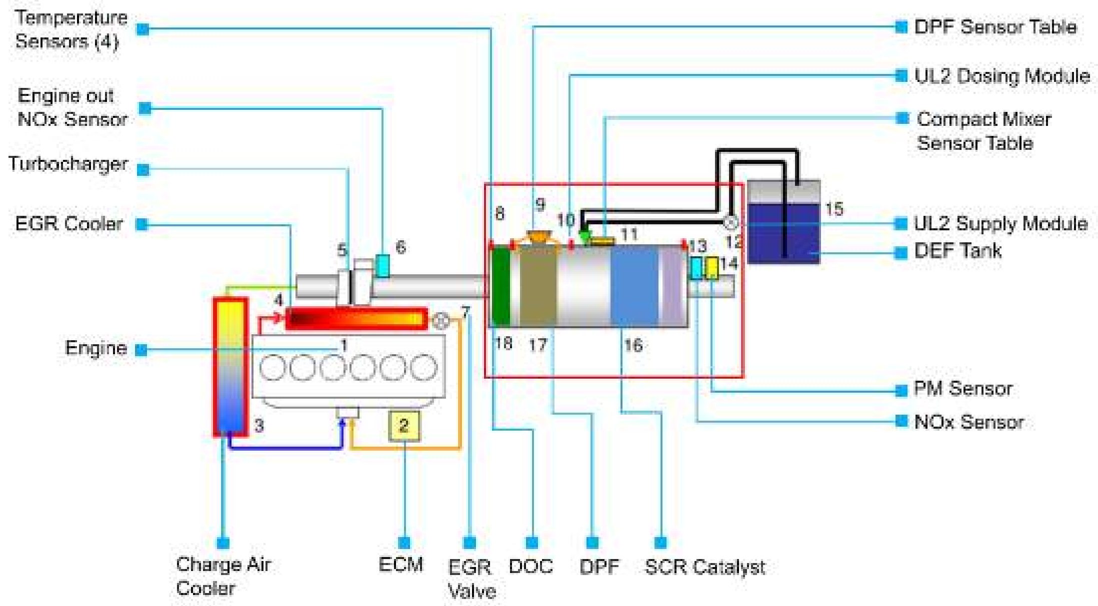


Fig: Overview of After treatment system

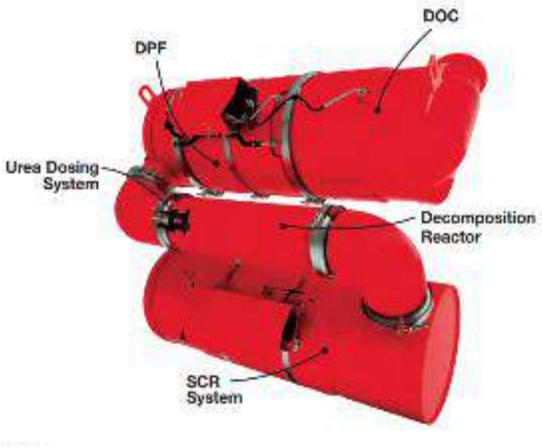


Fig: Cummins After treatment system

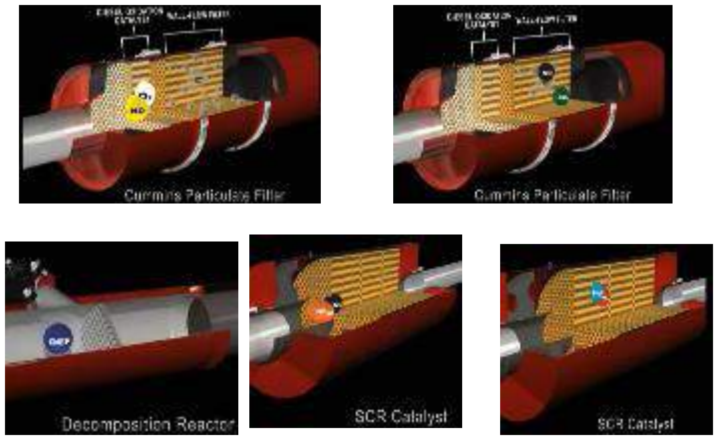


Fig: Cut section of Cummins After treatment system

https://www.youtube.com/watch?v=NvLj6e7JdUo

3D+1D coupling overview and scope of the study

1. Steady state 3D CFD:
    1. ANR special distribution prediction.
    2. Not feasible running transient cycles.
    3. Tools: ANSYS Fluent, Converge CFD
2. 1D kinetic models:
    1. Real time prediction of transient SCR performance.
    2. Can not capture the effect of non-axial non-uniformities.
    3. Tool: AVL BOOST
3. 3D+1D coupling methods:
    1. Predict transient SCR system performance, taking the effect of ANR non-uniformity into account.
    2. Non-uniform storage on the catalyst due to non-uniform ANR distribution is also considered.

Scope : Product development and modification by using 3D-1D coupling process developed in Cummins Emission Solutions (CES)

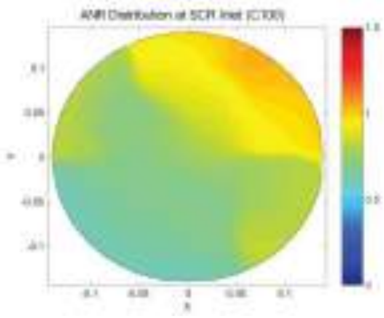


Fig: ANR contour at SCR inlet

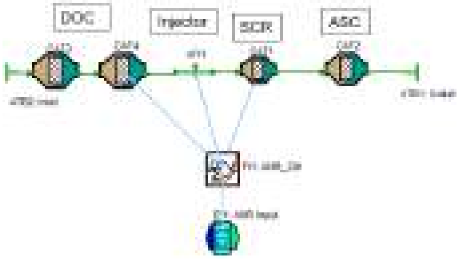


Fig: AVL BOOST case

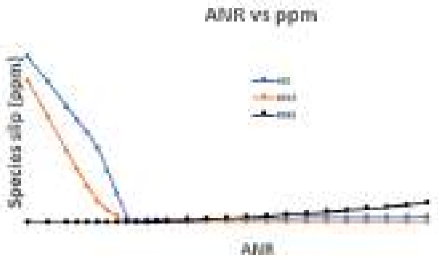


Fig: Transfer function

Ref: Kalyankar, A., Munnannur, A., and Liu, Z., "Predictive Modeling of Impact of ANR Non-Uniformity on Transient SCR System DeNOx Performance," SAE Technical Paper 2015-01-1055

3D CFD+1D AVL BOOST coupling overview

3D analysis

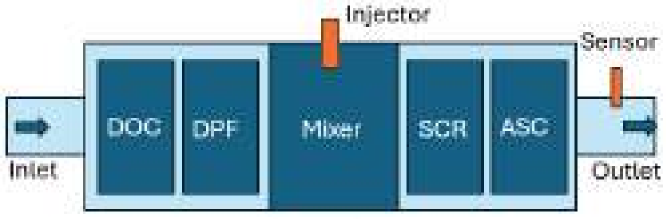


Fig: ATF architecture

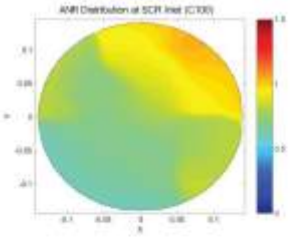


Fig: ANR contour at SCR inlet

Fig: Particle tracks colored by particle diameter

1. Pressure drop
2. DEF decomposition Uniformity Index

1D analysis

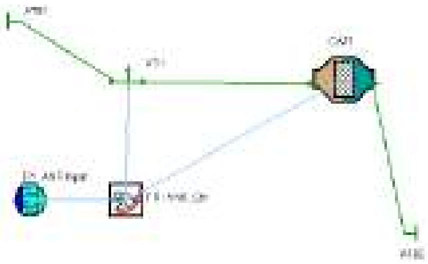


Fig: Schematic of 1D kinetic model

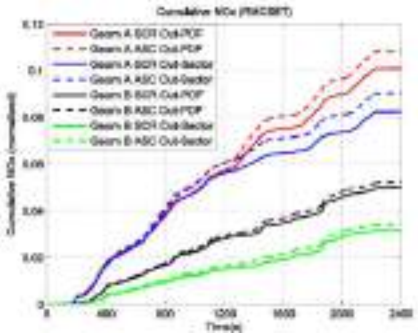


Fig: SCR out results

1. NOx conversion efficiency
2. NH_3 slip

3D+1D coupling

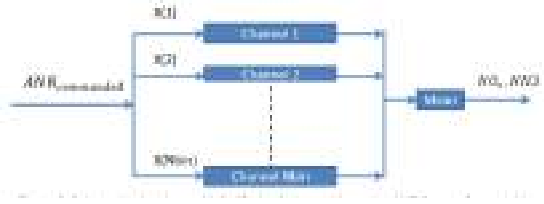


Fig: 1D simulation with varying ANR factors

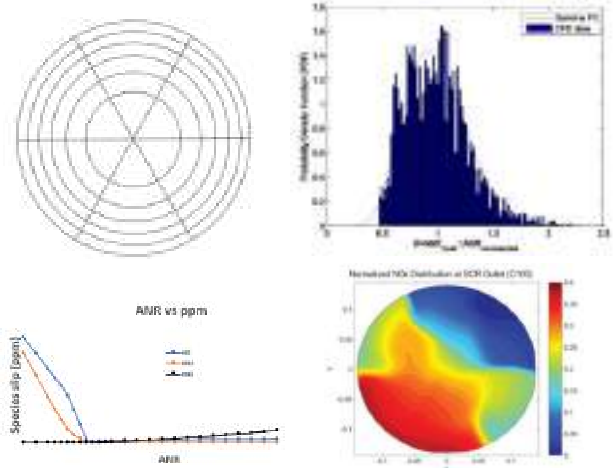


Fig: Different ways to translate data

1. Probability density function (PDF) based approach
2. Geometrical sector-based approach
3. Interpolation

3D+1D coupling application

1. Steady state and Transient NO_X conversion efficiency
2. NH_3 slip
3. Sensor accuracy
4. Design modification to meet emission performance
5. Catalyst size modification to meet emission performance

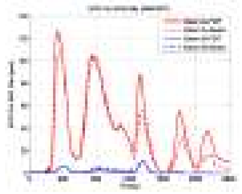


Fig: NH3 slip

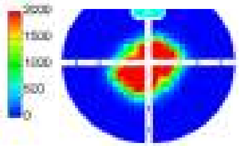
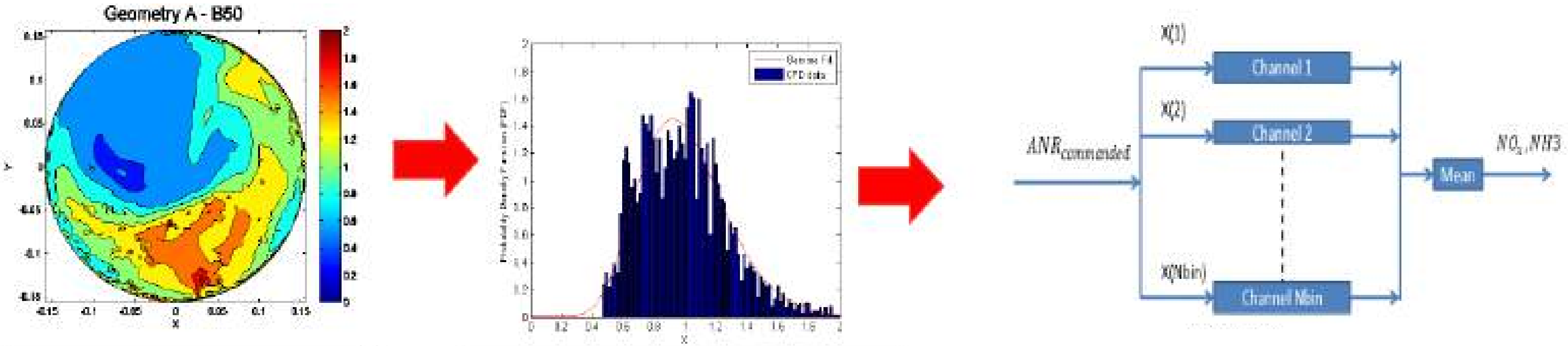


Fig: Outlet species distribution

3D+1D Coupling approach: PDF Method

1. Empirical PDF was used to fit the ANR data and then discretized into bins. Average ANR for each bin calculated and fed into BOOST for parallel simulations.
2. Can be used for both steady-state and transient simulations.
3. Data fitting and averaging results in a loss of fidelity.



ANR/Velocity distribution at catalyst inlet obtained from 3D CFD analysis

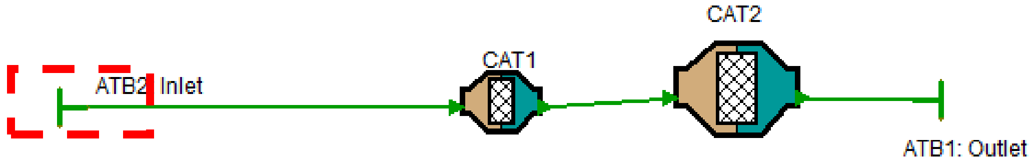
Gamma PDF used to fit the data and then discretized into bins. Average ANR/velocity for each bin calculated and fed into BOOST for parallel simulations

Multiple 1-D simulations run in AVL BOOST. Outputs averaged

Ref: Kalyankar, A., Munnannur, A., and Liu, Z., “Predictive Modeling of Impact of ANR Non-Uniformity on Transient SCR System DeNOx Performance,” SAE Technical Paper 2015-01-1055

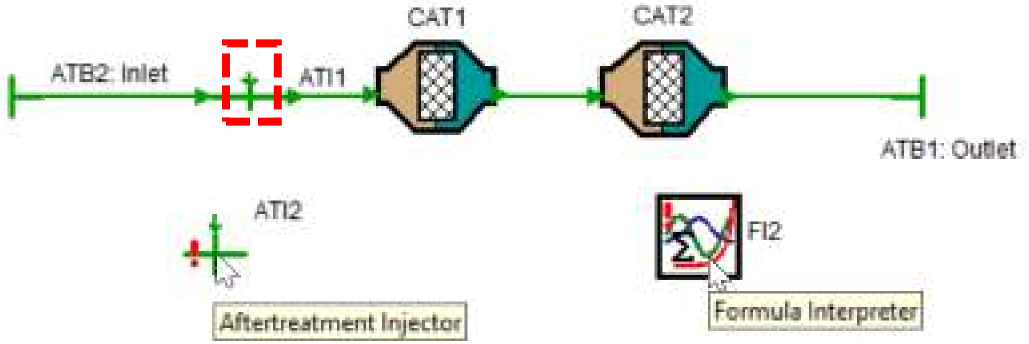
Case study: Conversion efficiency

Method 1

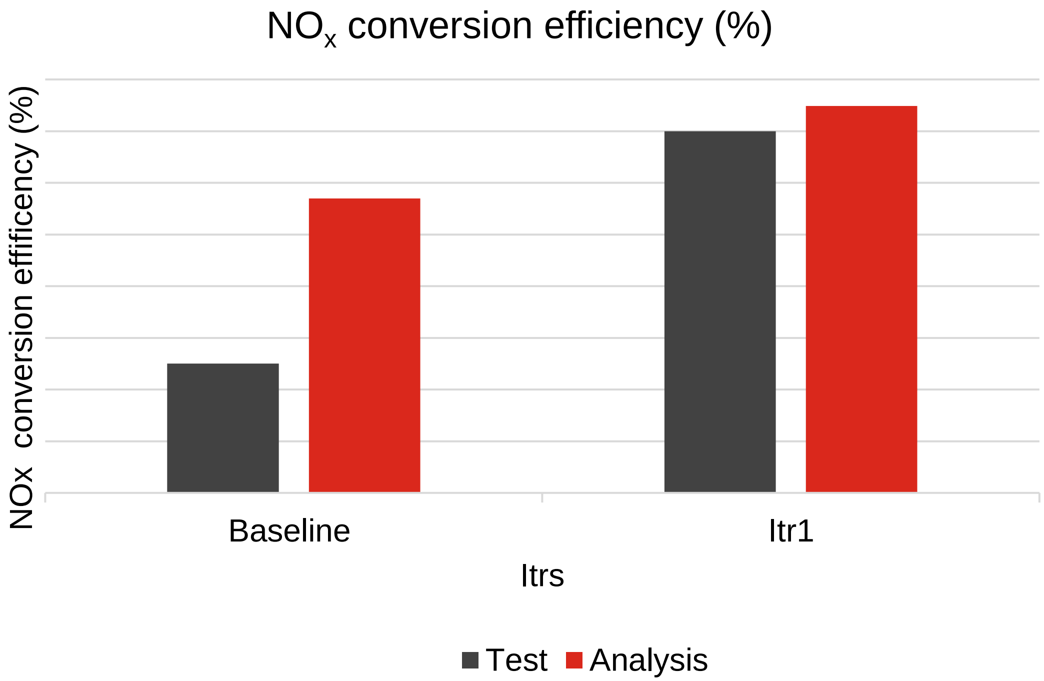


1. Mass flux and temp at inlet boundary defined as a global parameter and this input is provided through explorer.
2. NH3 ppm is calculated using ANR factors and provided as input.

Method 2

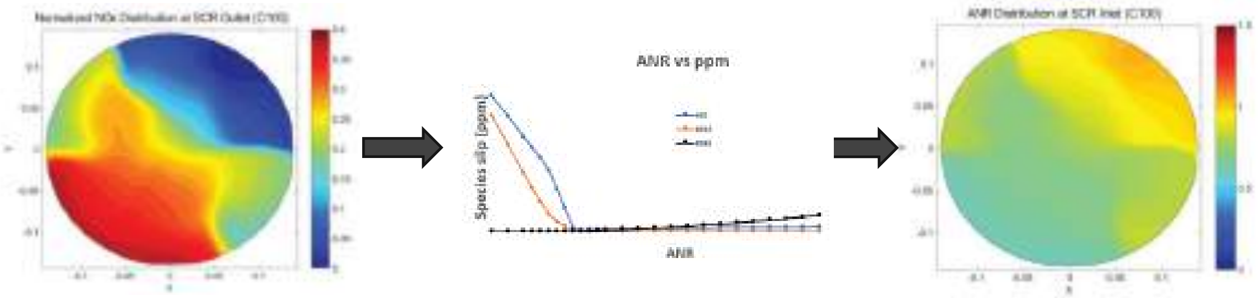


1. Mass flux and temp at inlet boundary provided as constant input.
2. DEF dosing is calculated using ANR controller, formula is provided in the calculator.

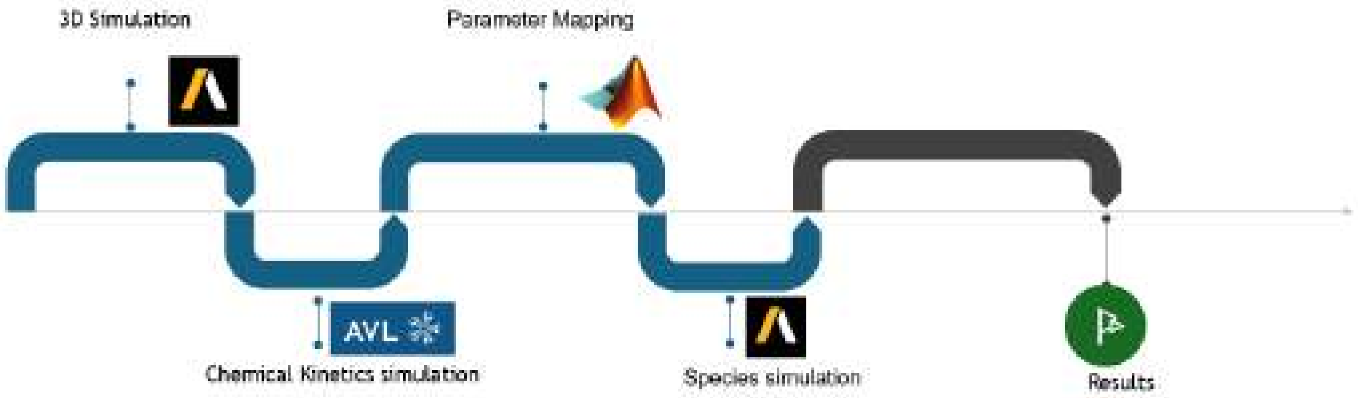


1. Based on the availability of data, the user can select the method of modeling ATS.
2. With both methods, results accuracy is good.
3. The above shown results are with the method 2 and there is a good correlation found with test data. (less than 10%)

Sensor accuracy modeling process



ANR profile | Transfer function | Species profile



AVL supports modeling catalyst reactions.
The entire analysis process is automated by using state of the art tools.

Applications:

1. Accuracy of sensor reading
2. Best position to place sensor
3. Geometrical changes required to meet sensor accuracy
4. Design changes for cost reduction

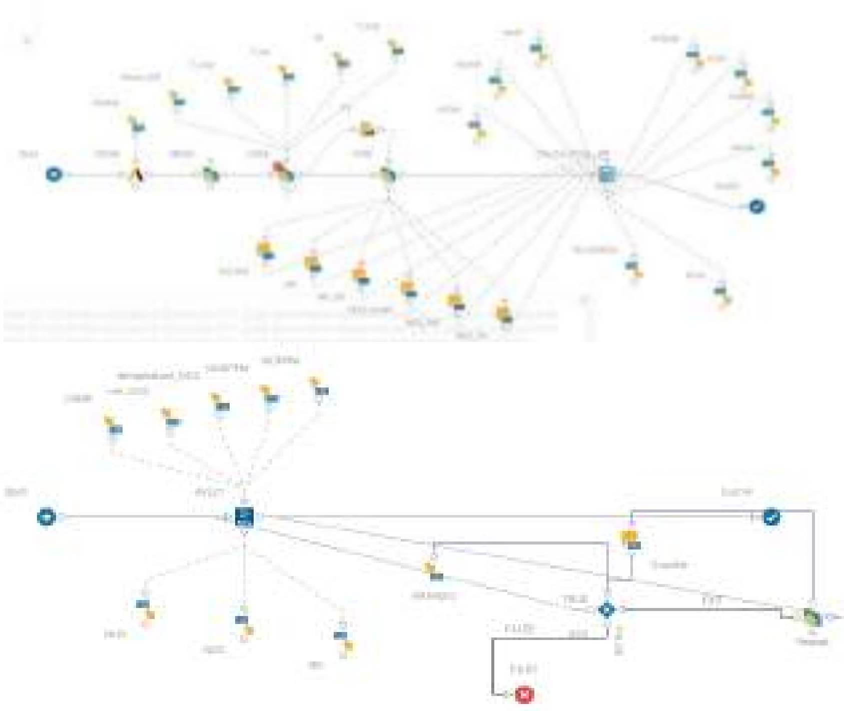


Fig: automated workflow

Case Study: Sensor accuracy

Problem statement/ Objective:
1. Reposition sensor to accurately predict the species in the exhaust gas.
2. Provide a cost-reduced solution that meets the requirement.

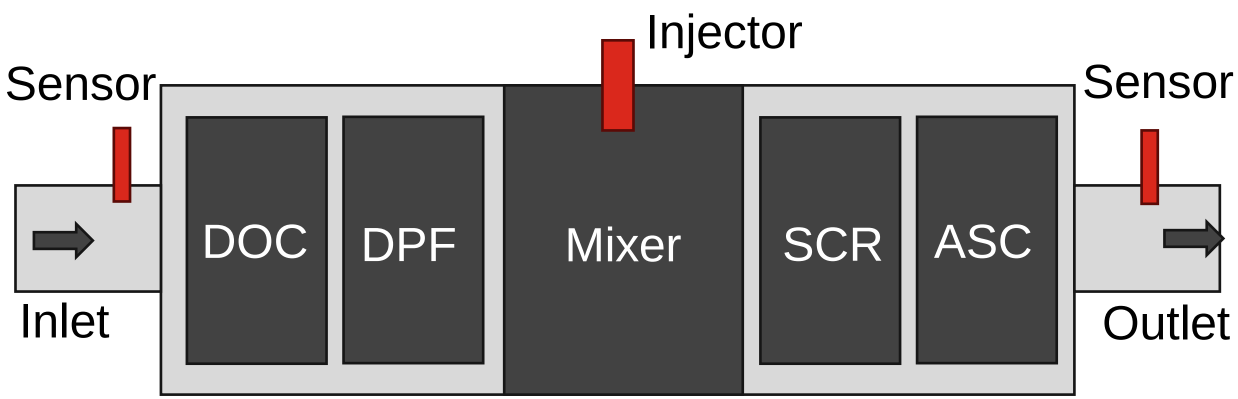


Fig: ATS architecture

$$Accuracy\ Error(\%) = 100x = \frac{(NOx_{sensor} - NOx_{Ref})}{NOx_{Ref}}$$

Test results replication

Concept	Sensor location	Sensor accuracy error (normalized)	
		Analysis	Test
Baseline	A	1.1	1.05
Concept1	B	0.19	0.16
	A	0.70	0.81
	C	1.05	1.11

Optimized concept1 which works for all clocking of sensor

Clocking	Concept	Analysis Sensor accuracy error (normalized)		
		Test Point 1	Test Point 2	Test Point 3
B	Concept1	-1.26	-0.08	1.43
	Concept1 Optimised	-1.42	0.52	5.67
A	Concept1	0.10	-0.36	-4.20
	Concept1 Optimised	0.07	-0.15	-3.01
C	Concept1	1.88	0.08	-6.82
	Concept1 Optimised	0.79	0.35	-2.10

Ref: Kalyankar, A., Munnannur, A., and Liu, Z., "CFD Modeling of Tailpipe NOx Sensor Accuracy" SAE Technical Paper 2018, doi:10.4271/03-11-04-0029

System level modeling in closed loop

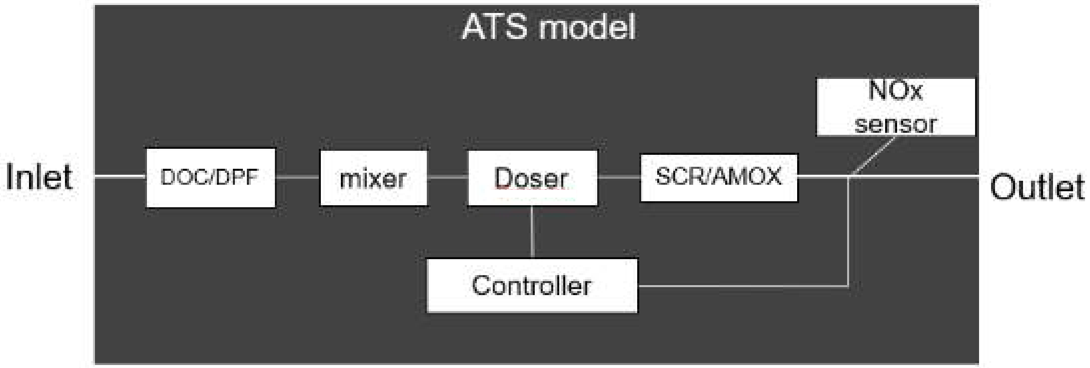


Fig: Schematic of system model

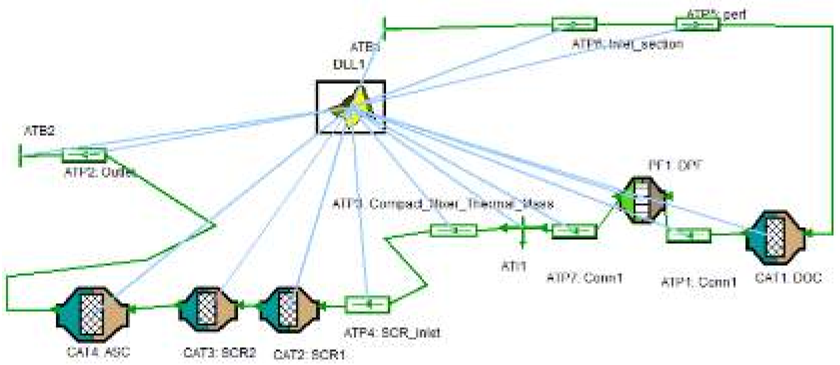
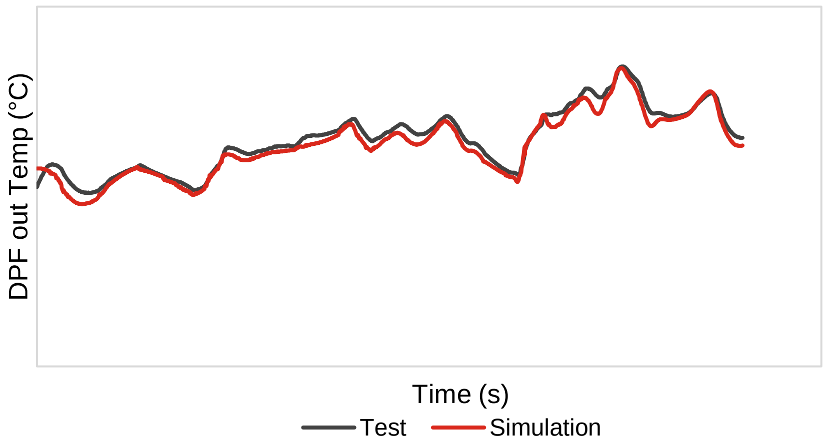


Fig: 1D kinetic model setup

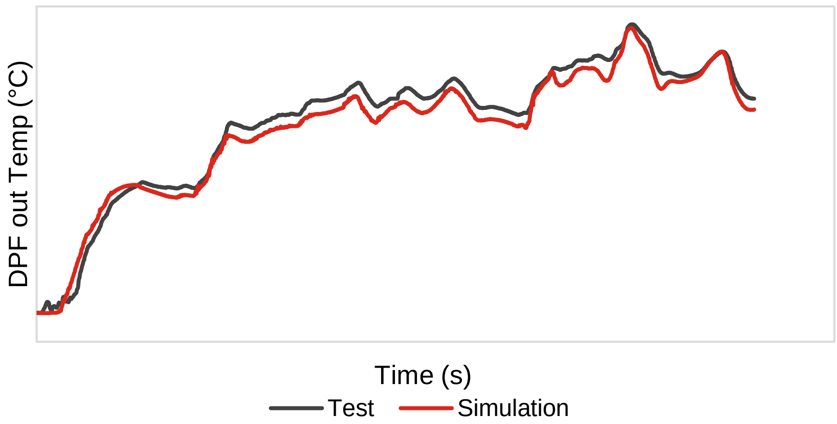
1. 1D kinetic model is created as per ATS architecture and calibrated for temperature and pressure drop.
2. Controller, sensors, and other components like doser are modeled in a closed loop architecture.
3. Application:
    1. Virtual rigs for programs to validate system
    2. Cycle emissions (NOx)
    3. Thermal management interaction
    4. Fuel economy
    5. Failed part analysis
    6. System robustness

Thermal calibration of model

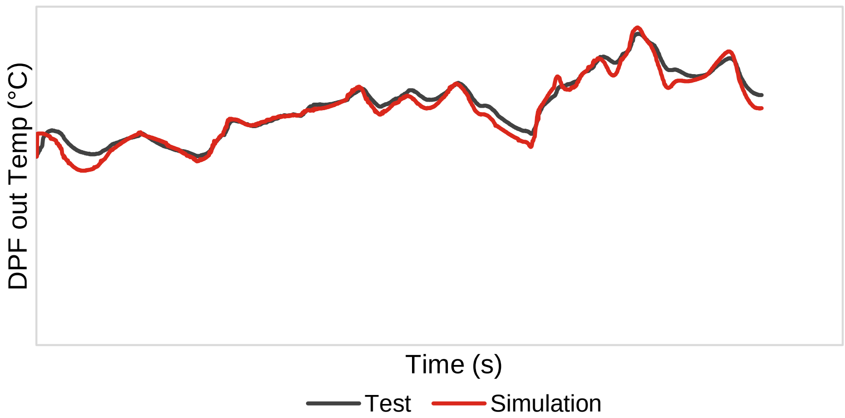
HOT DPF Out



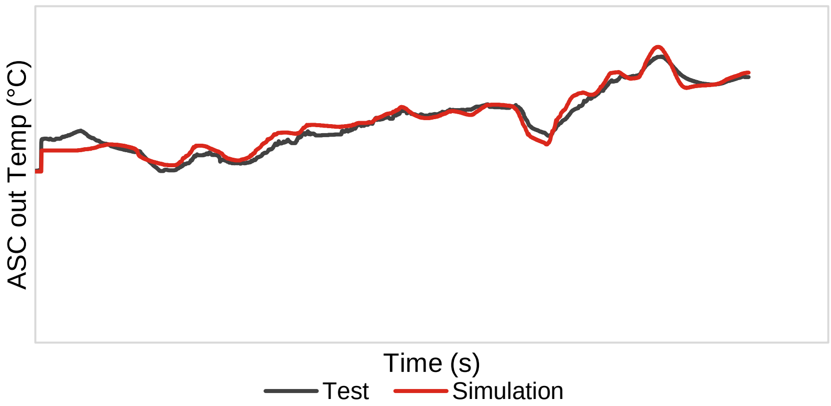
COLD DPF Out



HOT SCR Inlet



HOT ASC Out



DOC out, DPF out, and SCR in all temperatures are following test trends and the difference is very minimal.

Case study: System level modeling

Objective: The goal is to replicate emission performance test virtually for ATS

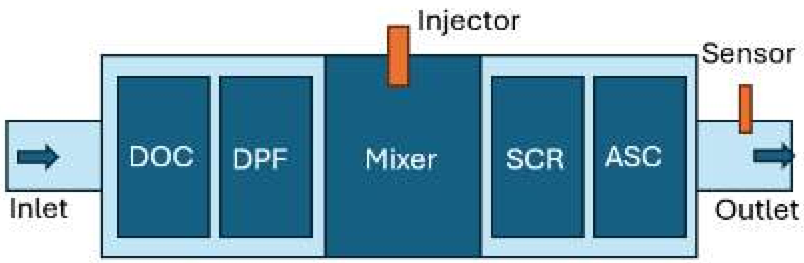
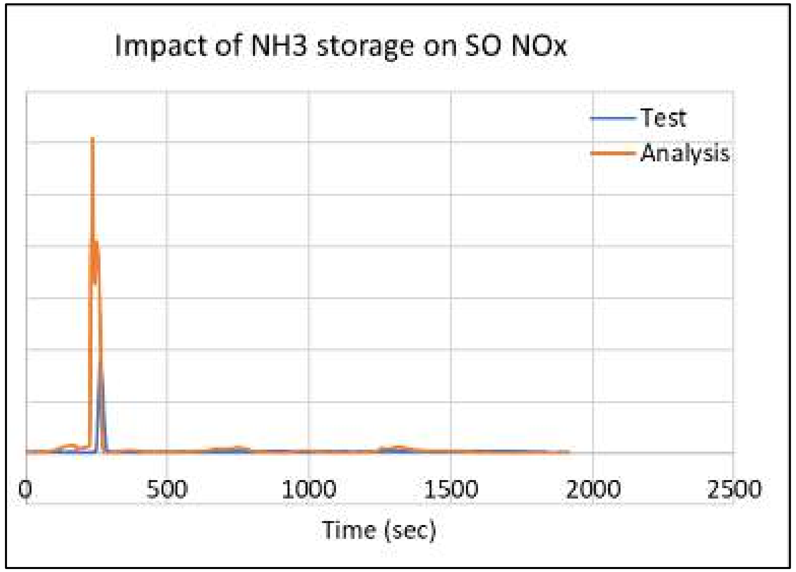


Fig: ATS architecture



1. The results shown here are without considering the 3D+1D coupling approach.
2. Implementing the 3D+1D approach to system level model is complex, the approach is ready but needs some tuning.
3. We have seen a good correlation with test results with scope for further improvement.

Summary and Conclusion

1. Lack of integrated framework resulted in lot of testing iterations at system & subsystem level.
2. The system modeling framework is developed including interactions of subsystems like doser, mixer, SCR & NOx sensor in the Aftertreatment system (ATS).The developed framework predicts the mixer effectiveness, optimized tailpipe NOx sensor location & ATS system out emissions predictions across 100 steady state data points (95 % accuracy in comparison with Test cell data)
3. System modeling is used in many ways in the ATS modeling like:
    1. Catalyst selection
    2. Emission performance analysis
    3. Design changes
    4. Cost reduction
    5. Digital Twin

References

1. Kalyankar, A., Munnannur, A., and Liu, Z., “Predictive Modeling of Impact of ANR Non-Uniformity on Transient SCR System DeNOx Performance,” SAE Technical Paper 2015-01-1055
2. Liu, Y., Chen, W., Henrichsen,M., Harinath, A. et al., “Analysis of Packaging Impact on Emission Catalyst Design,” SAE Technical Paper 2014-01-1560.
3. McKinley, T., Alleyne, A., and Lee, C., “Mixture Non-Uniformity in SCR Systems: Modeling and Uniformity Index Requirements for Steady-State and Transient Operation,” SAE Int. J. Fuels Lubr. 3(1):486-499, 2010, doi:10.4271/2010-01-0883
4. Liu, Z., Munnannur, A., Osburn, A., Srinivas, S. et al., “Exhaust Gas Sensor Module”, U.S. Patent 8756913, 2014.
5. Kalyankar, A., Munnannur, A., and Liu, Z., “CFD Modeling of Tailpipe NOx Sensor Accuracy” SAE Technical Paper 2018, doi:10.4271/03-11-04-0029

Q+A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