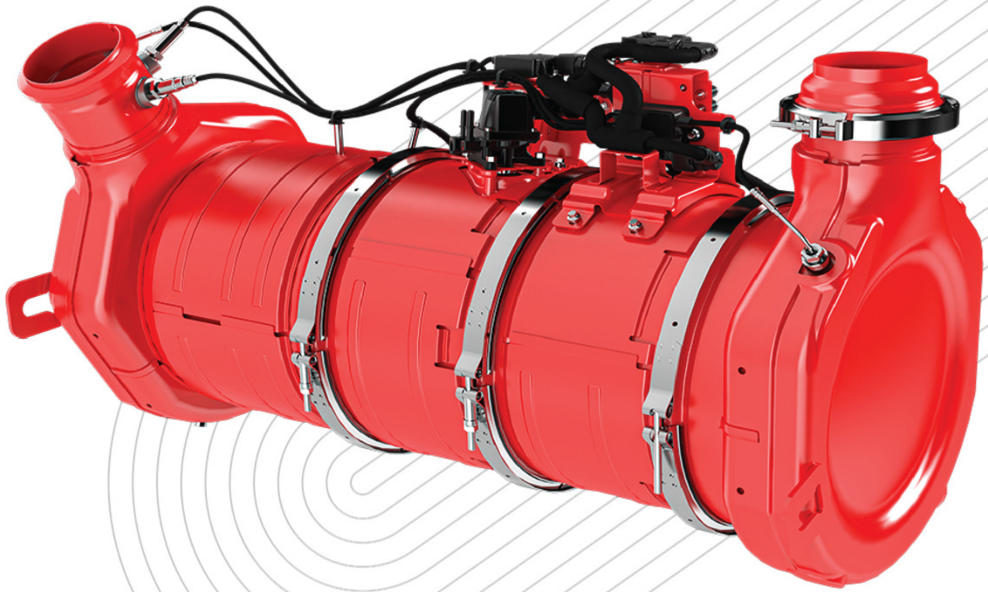
# 1D+3D Simulations Coupling to Predict System Out $NO_x$ in Aftertreatment Systems



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Oct 8, 2025

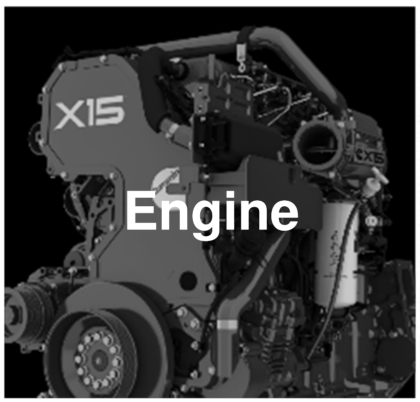
**Cummins Emission Solution, CTCI, Pune**

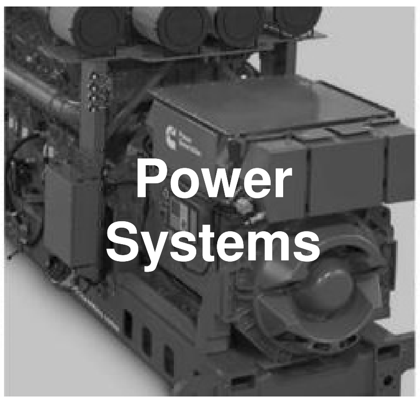
# Acronyms

- Aftertreatment System (ATS)
- Diesel Oxidation Catalyst (DOC)
- Diesel particulate Filter (DPF)
- Selective Catalytic Reduction (SCR)
- Ammonia Slip Catalyst (ASC)
- Ammonia to $NO_X$ Ratio (ANR)
- Computational Fluid Dynamics (CFD)
- Diesel Exhaust Fluid (DEF or AdBlue)

# Five operating segments

Cummins has a long track record of delivering leading power solutions.
As we look ahead, we know our industries and regions will continue to change,
and we are committed to bringing our customers the right technology at the right time.






DIVERSE MARKETS

# WE WORK WITH CUSTOMERS IN ALMOST EVERY INDUSTRY IMAGINABLE

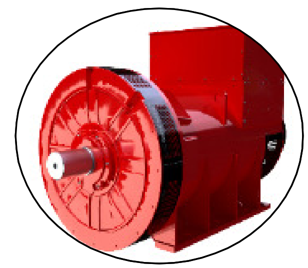

MINING


MARINE


OIL & GAS


RAIL


DEFENSE


CUMMINS GENERATOR TECHNOLOGIES


MOBILE POWER


INDUSTRIAL POWER


MISSION CRITICAL POWER


DATA CENTERS


ENERGY MANAGEMENT SOLUTIONS

# 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

### Introduction

- ATS components functions
- Simulation parameters

### 1D Boost Model for ATS

- Brief outline of the Boost model
- Coupling with 3D CFD

### Case Study

- Comparison of system out $NO_x$ on different mixer designs
- Comparison of NOx conversion for design selection

### Summary

- Conclusion and future scope

# Introduction

- Aftertreatment system cleans exhaust gases
- DPF: collects and oxidizes the soot
- DOC: aids in oxidation process
- DEF is injected into the hot exhaust stream in the Decomposition Reactor
- SCR: converts the toxic $NO_x$ and urea mixture into harmless nitrogen gas ($N_2$) and water vapor ($H_2O$)

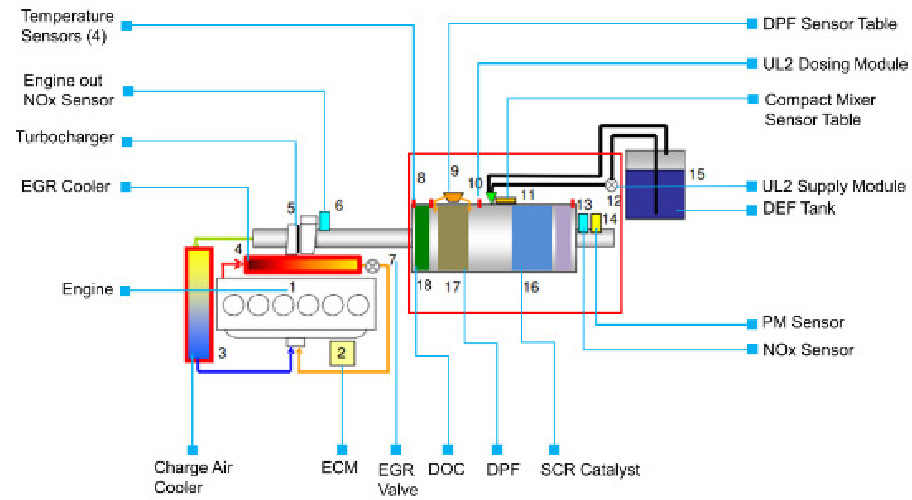



Fig 1: Overview of After treatment system

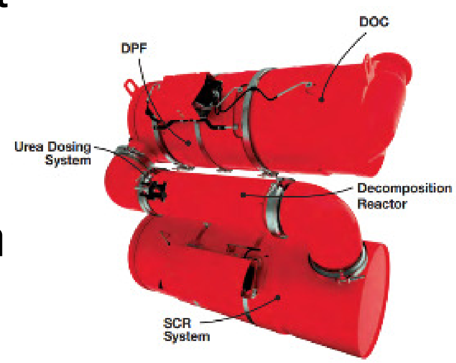



Fig 2: Cummins After treatment system

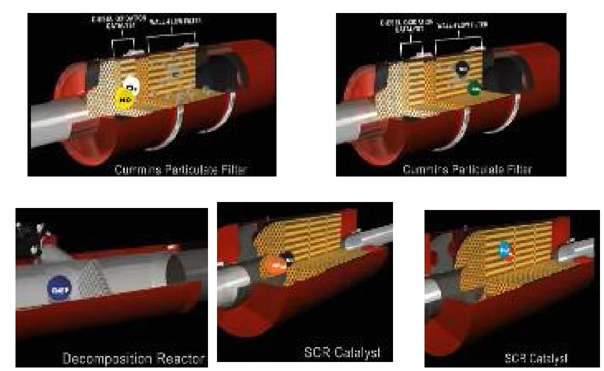
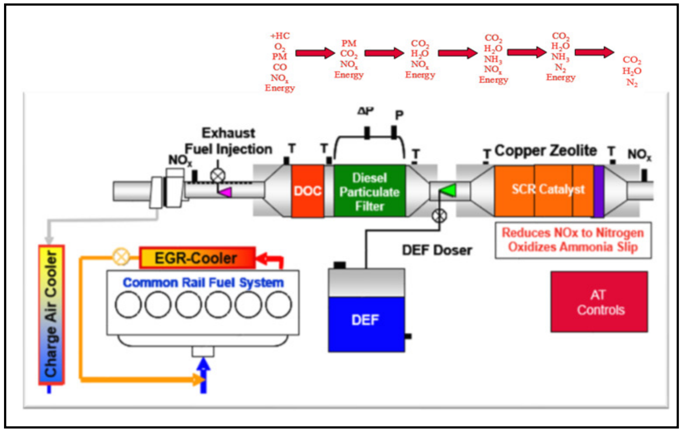



Fig 3: Cut section of Cummins After treatment system

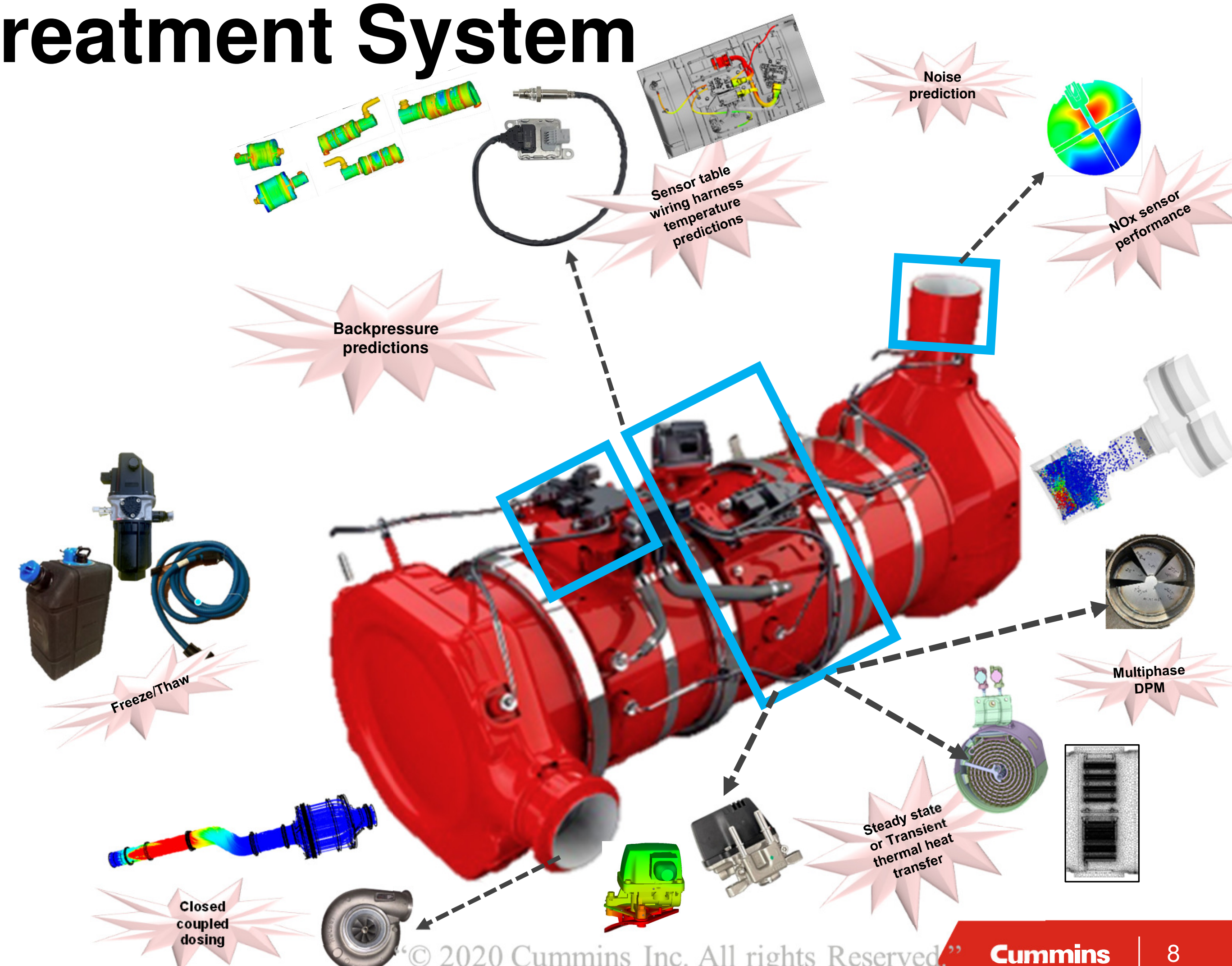
https://www.youtube.com/watch?v=NvLj6e7JdUo

# CFD in After-treatment System




## Role of Analysis in Emissions Control

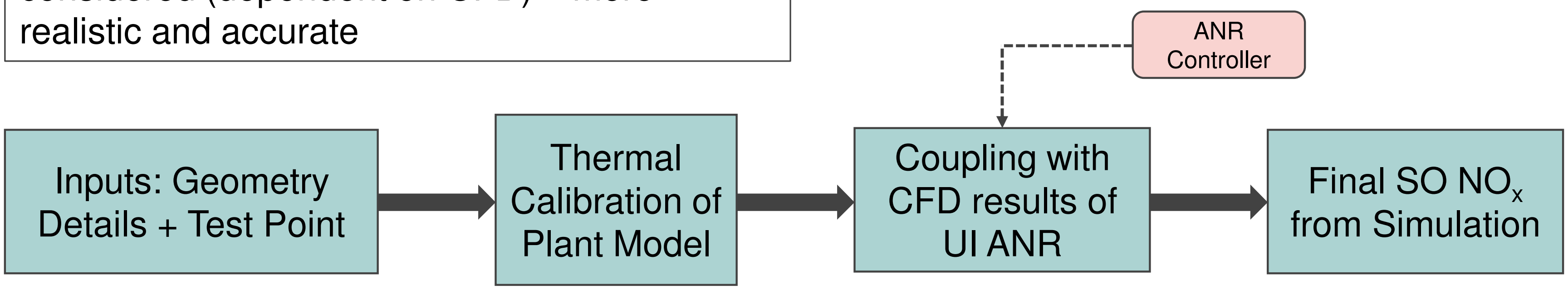
- Flow and Temperature Modeling
- Multiphase simulation
- Wall film deposit prediction
- Freeze/Thaw robustness



# 1D Boost Plant Model for ATS

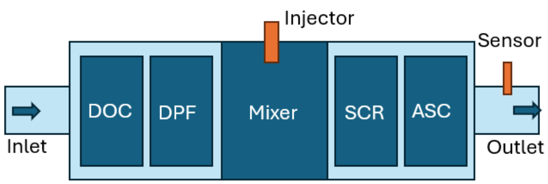
**Single Channel**: Uniform ANR is considered (independent of CFD) – less accurate

**Multi-Channel**: Spatial variation of ANR is considered (dependent on CFD) – more realistic and accurate



# 3D CFD+1D AVL BOOST Coupling Overview

## 3D analysis



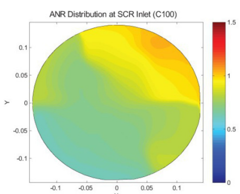




Fig5: ANR contour at SCR inlet

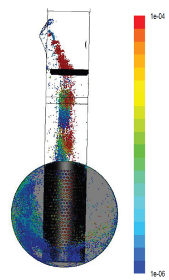


Fig6: Particle tracks colored by particle diameter

- Pressure drop
- DEF decomposition Uniformity Index

## 1D analysis

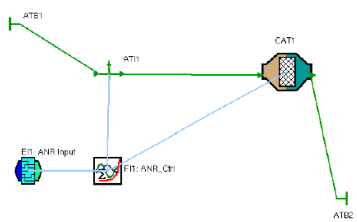



Fig7: Schematic of BOOST model

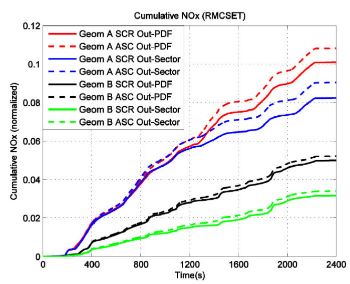



Fig8: SCR out results

- $NO_x$ conversion efficiency
- $NH_3$ slip

## 1D+3D coupling

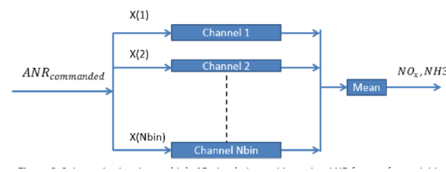



Fig9: 1D simulation with varying ANR factors

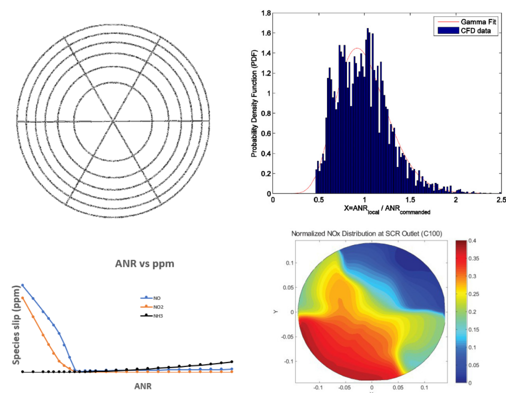
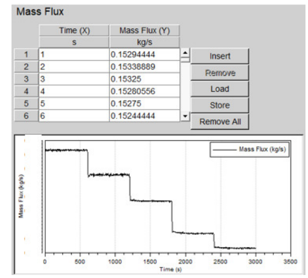



Fig10: Different ways to translate data

- Probability density function (PDF) based approach
- Geometrical sector-based approach
- Interpolation

## Coupling application

- Define ANR factors for different boundary conditions
- Divide transient cycle in bins at which factors are calculated




- Run transient cycle to predict $NO_x$, $NH_3$ slip

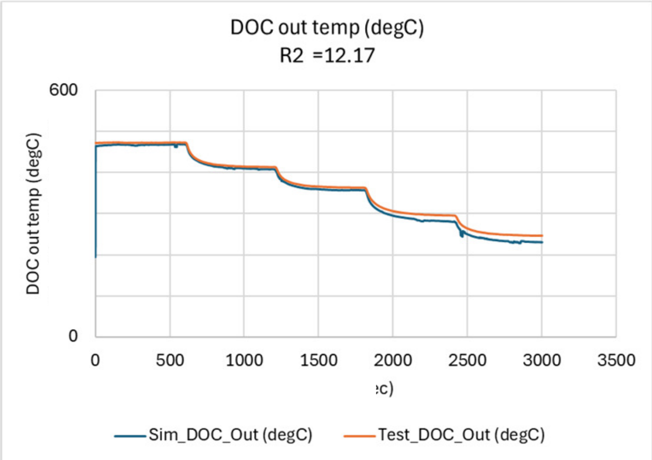
Ref: Kalyankar, A., Munnannur, A., and Liu, Z., "Predictive Modeling of Impact of ANR Non-Uniformity on Transient SCR System DeNOx Performance," SAE Technical Paper 2015-01-1055

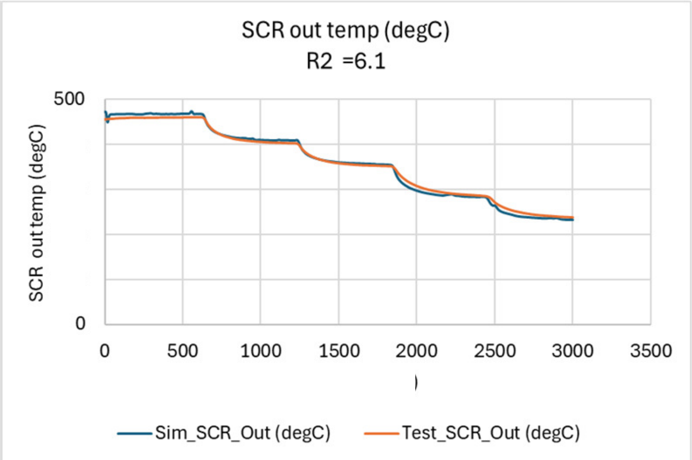
# Case Study 1: Comparison of ATS Designs

## Thermal Calibration Results

- ❑ Calibration of temperature and pressure drop is performed for baseline model.

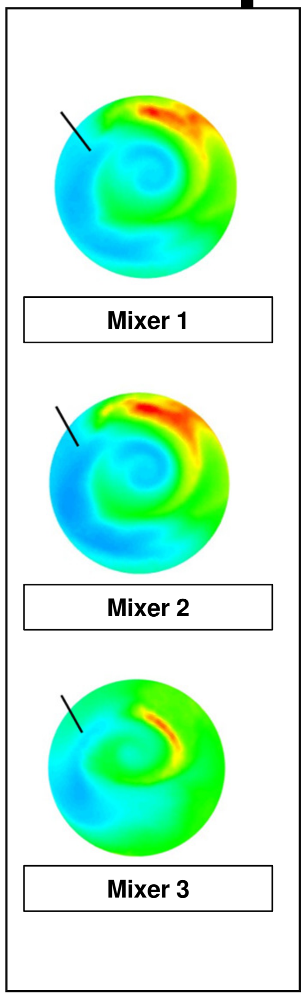
- ❑ For the test conditions, temperature at different sections are matched with the test data.

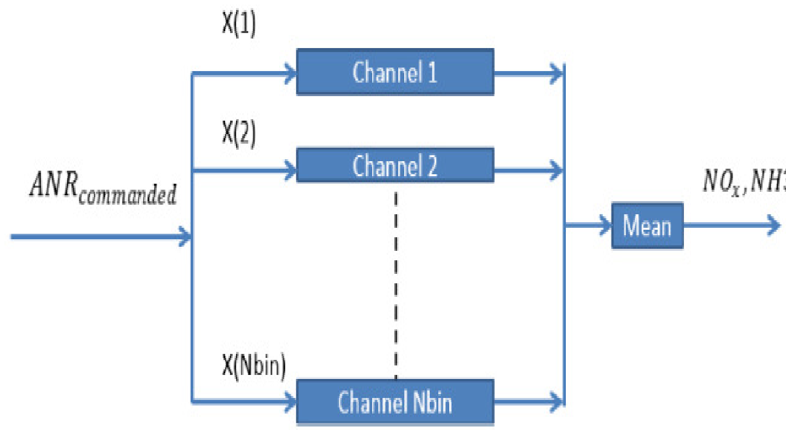


# Case Study 1: Comparison of ATS Designs

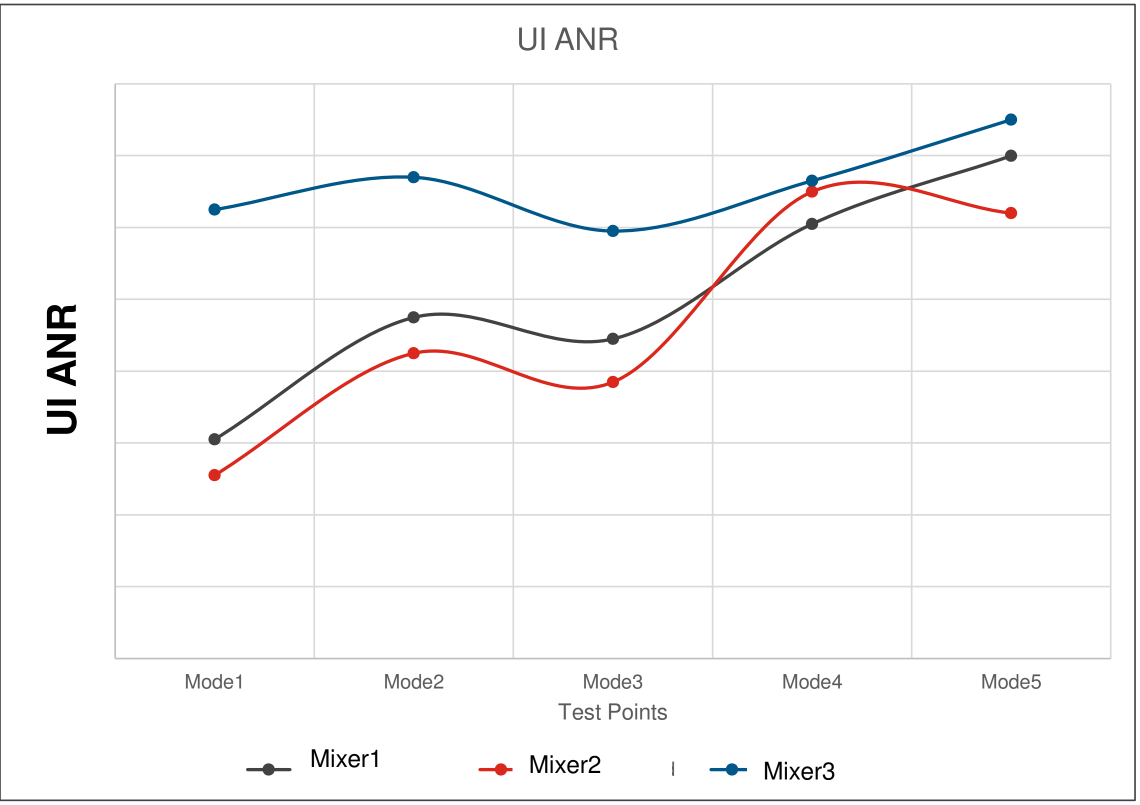
Thermally calibrated 1D Boost model

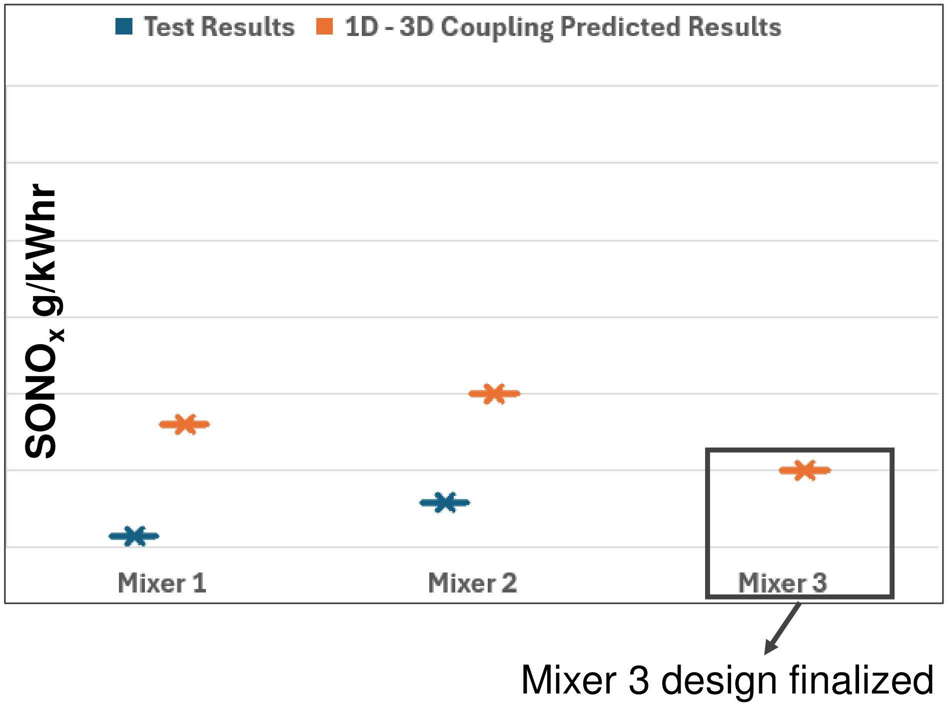



Multiple 1D simulations are run in AVL Boost and averaged out to get the final SO NOx value.

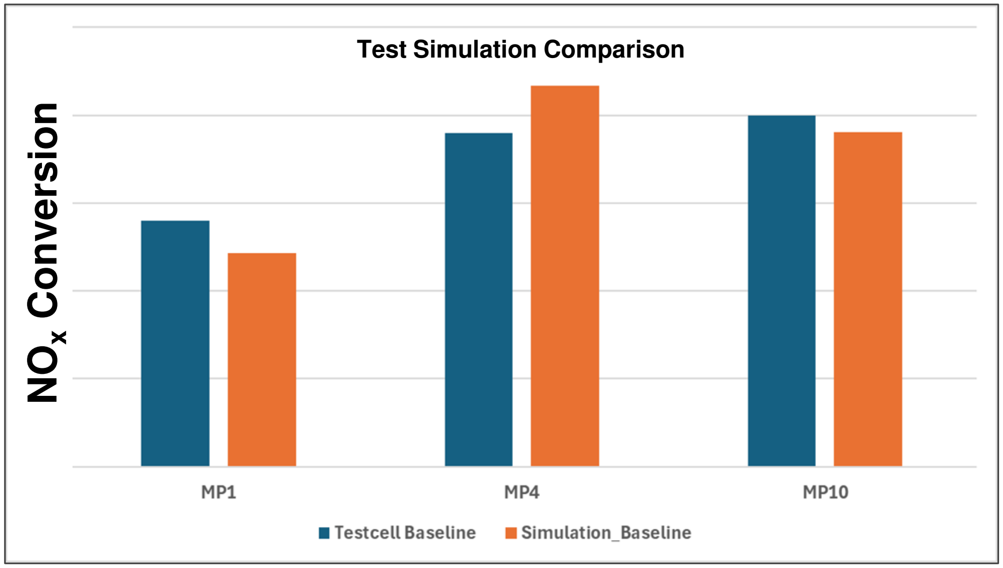
# Case Study 1: SO $NO_x$ Results

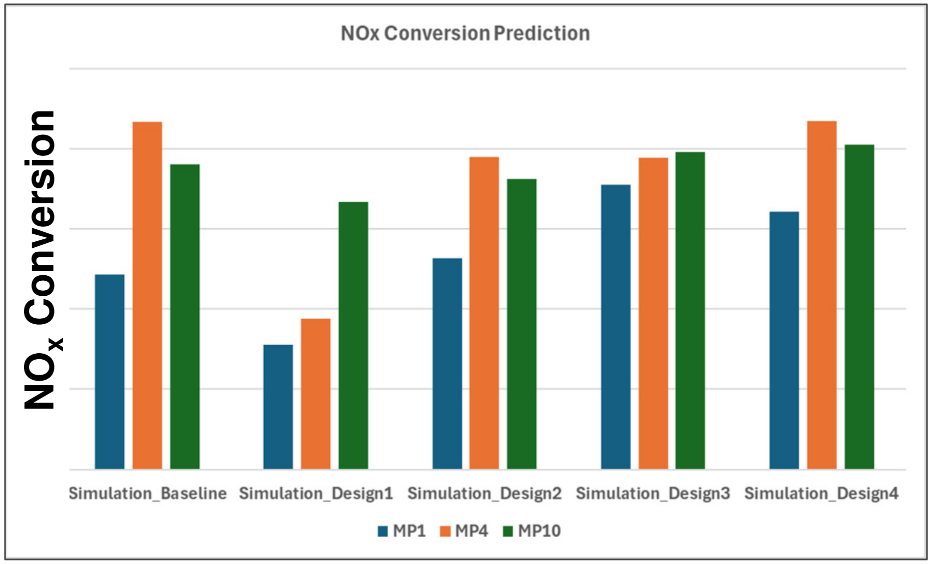



UI is lowest for Mixer2, similar trend observed in SO NOx conversion.

# Case Study 2: $NO_x$ Conversion Results




- Steady state conditions validated with actual test
- Design 4 showing better performance than baseline
- Watchout wall film impact is difficult to capture with this approach

# Summary

**Current modeling approach observations:**

- AVL BOOST™ is adopted to perform 1D simulations in ATS emission performance analysis.
- 1D Boost model is coupled with 3D simulations to capture the effect from varying designs
- SO $NO_x$ trend is matching with the test outcomes for varying designs.

**Future Scope:**

- Identify levers which can help reducing gap between analysis prediction and test.
- Validations of closed loop model with controls.

# Thank You

# Q + A