TENNECO

DRIVING ADVANCEMENTS
IN GLOBAL MOBILITY

Tenneco Advance Modelling and Simulation Studies for Cold Start Challenges in EU-VII/CN-VII Architectures

ECT 2023
02/11/2023

- Yogesh Choudhary

Agenda


Where we are today (BS-VI/EU-VI/CN-VI)
Emissions Control Technologies for EU-VII, CN-VII
- NTI - Architectures
Architectural Challenges
Tenneco's Advance System Modeling and 1D Simulations for EU-VII/CN-VII EATS
Potential Architectural Trade-Offs
Summary
Q&A

Where we are today: EU6/VI regulations

Light Duty vehicles

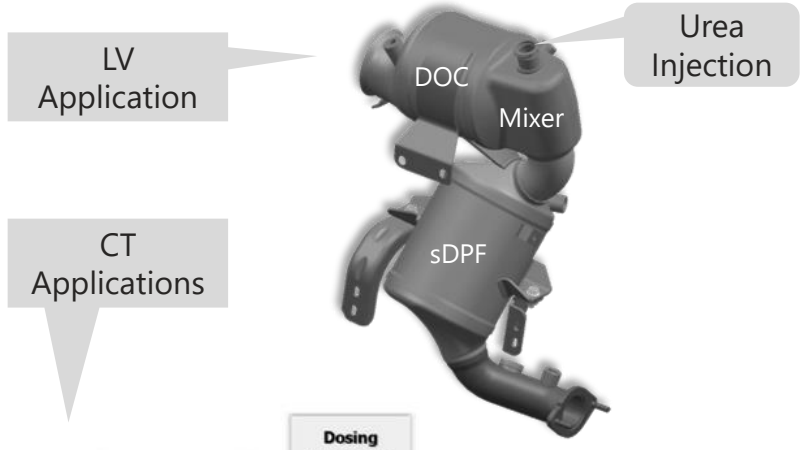
Euro 6e

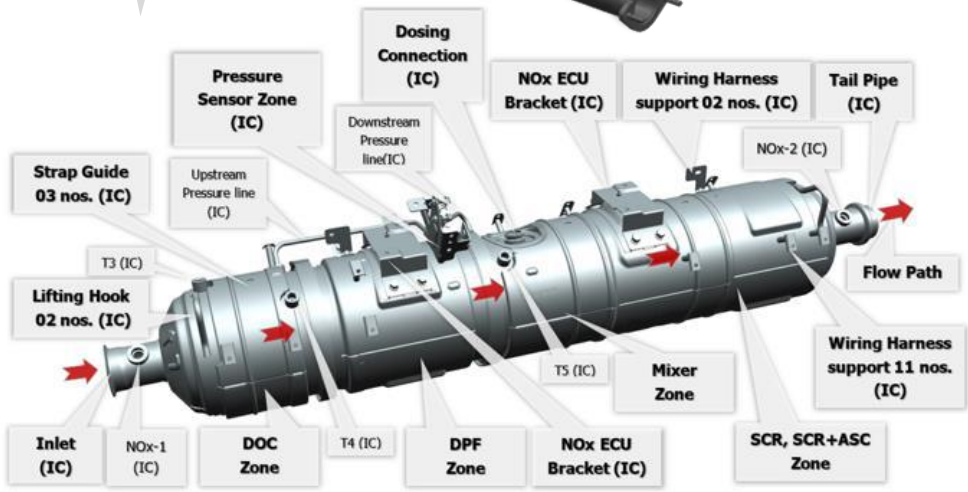
	EU6e Gasoline	EU6e Diesel
NOx [mg(km]	60	80
PM [mg(km]	4.5	4.5
PN [-]	$6*10^{11}$ >23nm	$6*10^{11}$ >23nm
CO [mg(km]	1000	500
THC [mg(km]	100	NOx+HC 170
NMHC [mg(km]	68	
NH3 [mg(km]	-	-
RDE CF	NOx 1.1/ PN 1.34	NOx 1.1/ PN 1.34
Cold start	(16km) ***	
Durability	160kkm (ISC 100kkm 5y)	
Evap	2g @ 48h diurnal test	
OBM	no	no

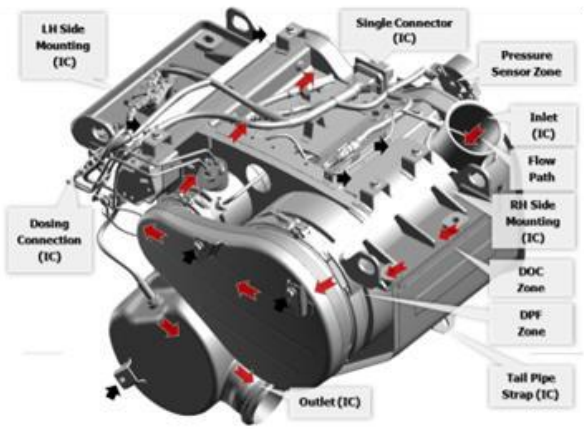
Heavy Duty vehicles

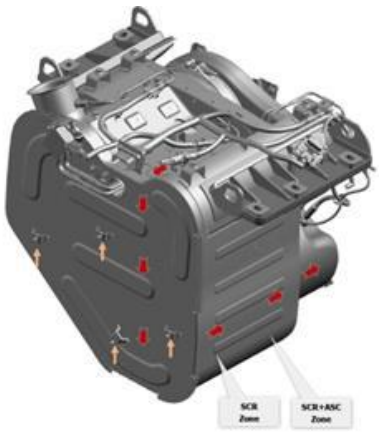
Euro VI

	EUVI
NOx [mg/kWh]	460 mg/kWh
PM [mg/kWh]	10 mg/kWh
PN [-]	$6*10^{11}$ >23nm
CO [mg/kWh]	4000 mg/kWh
NMOG [mg/kWh]	160 mg/kWh
NH3 [mg/kWh]	10 ppm
CH4 [mg/kWh]	500 mg/kWh
N2O [mg/kWh]	-
Durability	500 kkm 7y
OBM	-









Where we heading: Potential EU-VII/CN-VII regulations

Euro7 & AQD - Update on EU Regulations

Euro7-Regulation: Co-Decision Process/ Summary of latest Stakeholder Positions

EURO7/VII EMISSION LIMITS
PASSENGER CARS AND VANS

Euro 6e ← → Euro 7

	EU6e Gasoline	EU6e Diesel	EU7 COM(2022) 586	EU Council 22.09.2023		ENVI 12.10.2023 M1,N1 Class1 ****
				Gasoline	Diesel	
NOx [mg(km]	60	80	60	60	80	60
PM [mg(km]	4.5	4.5	4.5	4.5		4.5
PN [-]	$6*10^{11}$ >23nm	$6*10^{11}$ >23nm	$6*10^{11}$ >10nm	$6*10^{11}$ >23nm		$6*10^{11}$ >10nm
CO [mg(km]	1000	500	500	1000	500	500
THC [mg(km]	100	NOx+HC 170	100	100	NOx+HC 170	100
NMHC [mg(km]	68		68	68		68
NH3 [mg(km]	-	-	20	-		20
RDE CF	NOx 1.1/ PN 1.34	NOx 1.1/ PN 1.34	1.0	?		-
Cold start	(16km) ***		10km **	(16km) ***		10 km **
Durability	160kkm (ISC 100kkm 5y)		160kkm 8y 200kkm 10y *	160kkm 8y 200kkm 10y *		200kkm 10y 240kkm 12y *
Evap	2g @ 48h diurnal test		0.5g @ 48h diurnal test	2.0 g/test		0.5g @ 48h diurnal test
OBM	no	no	yes	yes		yes

* Durability multiplier of 1.2 applicable between 160kkm and 200kkm
** EU7 Cold start budget [mg] = Distance x emission limit;
***EU6 minimum trip distance of urban phase RDE
****Slightly higher values for N1 class2 and 3

ISC: In-Service Conformity

Where we heading: Potential EU-VII/CN-VII regulations

Euro7 & AQD - Update on EU Regulations

Euro7-Regulation: Co-Decision Process/ Summary of latest Stakeholder Positions

EURO7/VII EMISSION LIMITS
HEAVY DUTY VEHICLES (LORRIES AND BUSES)

Euro VI ← → Euro 7

	EUVI	EUVII Cold	EUVII Hot	EU Council 22.09.2023		ENVI 12.10.2023	
				WHSC/WHTC	RDE	WHSC/WHTC	RDE
NOx [mg/kWh]	460 mg/kWh	350 mg/kWh	90 mg/kWh	230	300	200	260
PM [mg/kWh]	10 mg/kWh	12 mg/kWh	8 mg/kWh	8	-	8	10
PN [-]	$6*10^{11}$ >23nm	$5*10^{11}$ >10nm	$2*10^{11}$ >10nm	$6*10^{11}$ >23nm	$9*10^{11}$ >23nm	$6*10^{11}$ >10nm	$7.8*10^{11}$ >23nm
CO [mg/kWh]	4000 mg/kWh	3500 mg/kWh	200 mg/kWh	1500	1950	1500	1950
NMOG [mg/kWh]	160 mg/kWh	200 mg/kWh	50 mg/kWh	80	105	75	98
NH3 [mg/kWh]	10 ppm	65 mg/kWh	65 mg/kWh	65	85	60	78
CH4 [mg/kWh]	500 mg/kWh	500 mg/kWh	250 mg/kWh	500	650	500	650
N2O [mg/kWh]	-	160 mg/kWh	100 mg/kWh	200	260	160	208
Durability	500 kkm 7y	Main lifetime 700 kkm 15y Add. Lifetime: 875 kkm		N2,N3,M3* 300 kkm 8y / 375 kkm 10y N3,M3 700kkm 12y, 875 kkm 15y		N2,N3,M3* 340 kkm 10y / 400 kkm 12y N3,M3 750kkm 15y, 900 kkm 17y	
OBM	-	yes		yes		yes	

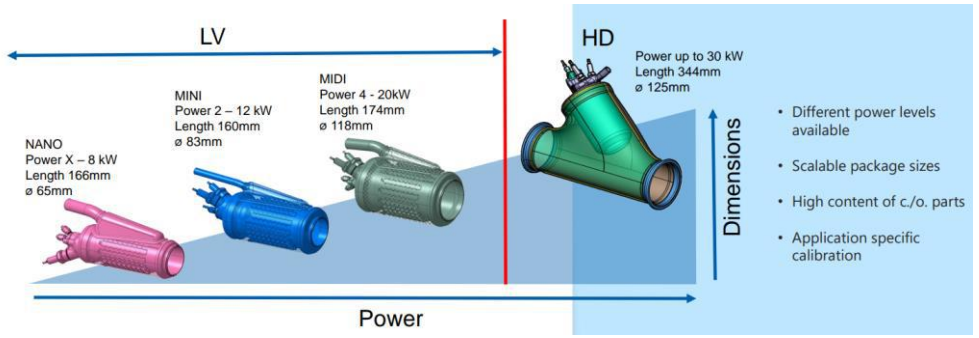
* N2, N3 < 16t, M3 <7,5t

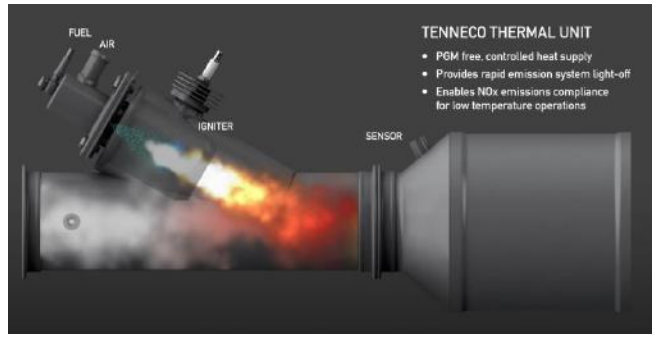
* N2, N3 < 16t, M3 <7,5t

New Technology Introduction

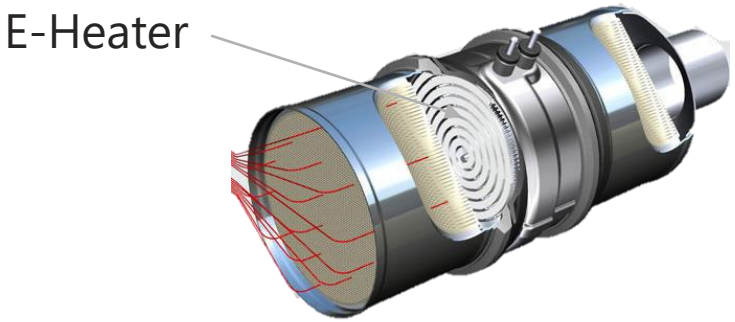
- Cold Start Thermal Unit (CSTU)
  - 2kW – 35kW
- E-Heater
  - 1 kW – 17kW
- Cylinder De-activation

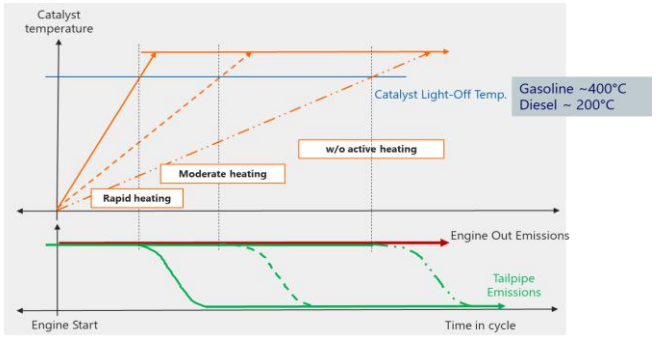
CSTU – A Tenneco Proprietary Product





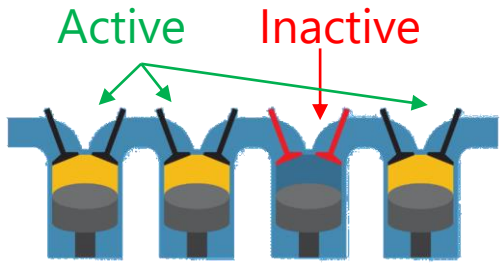
E-Heater – Various Suppliers





→ Heat up strategy has direct impact to tailpipe emission reduction

CDA – Various Suppliers



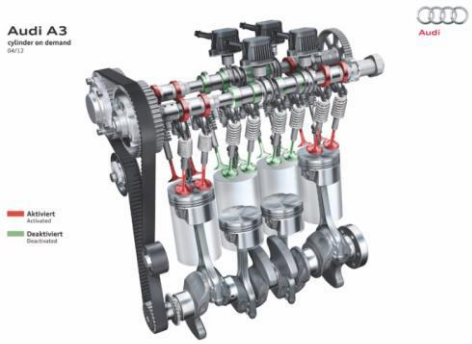


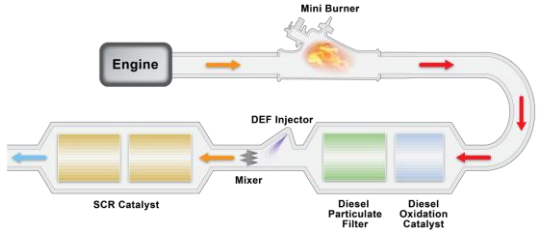
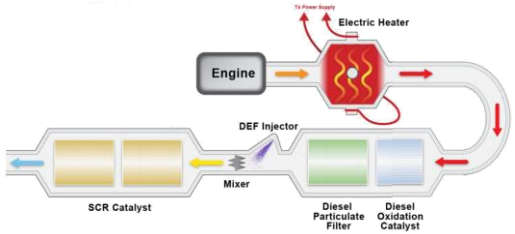
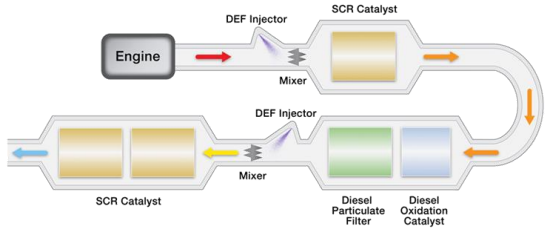
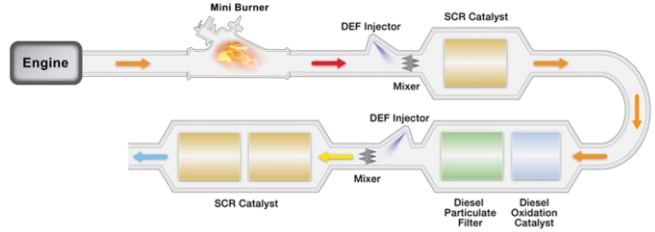
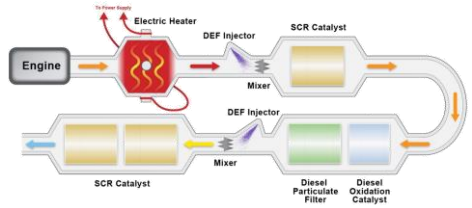
Photo Courtesy: Audi

Strategies to meet EU-VII / CN-VII / EPA 2027 emissions norms

Potential Engine Add-ons (Optional):
- EGR (Exhaust Gas Recirculation)
- CDA (Cylinder De-Activation)

Add-on Heat Source to ATS:
- CSTU: Cold Start Thermal Unit or Pre-Burner
- E-Heater

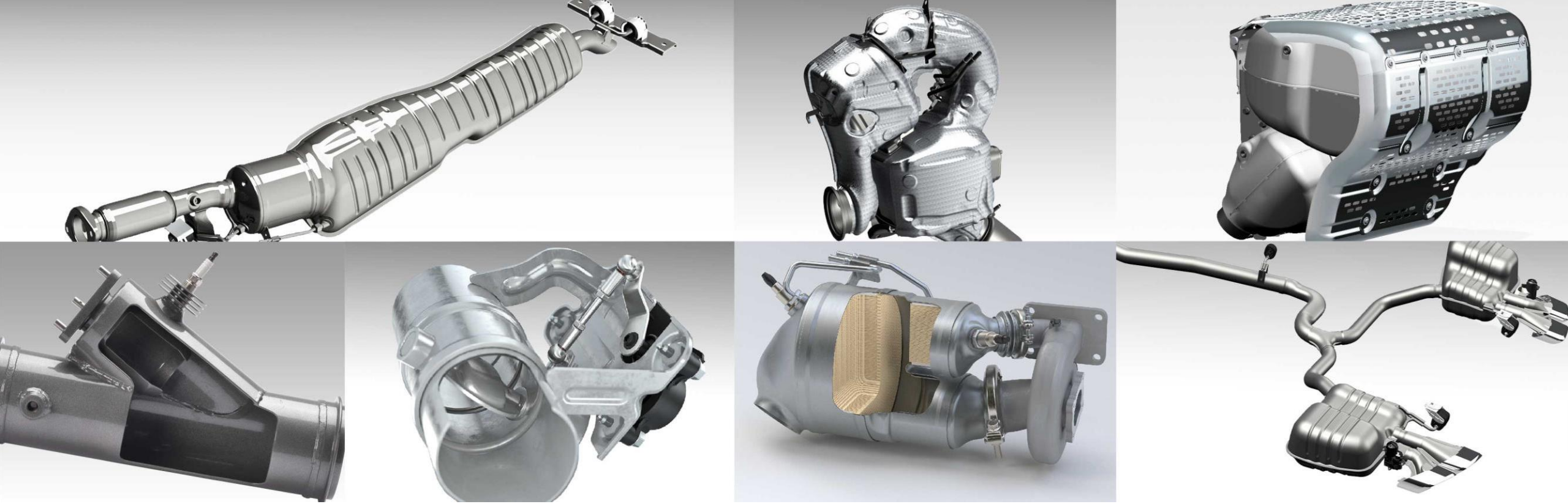
E-Heater options:
- 24V
- 48V

Architecture combinations	Illustration
EU-VI EATS + CSTU	
EU-VI EATS + E-Heater	
EU-VI EATS + Dual Dosing	
EU-VI EATS + Dual Dosing + CSTU	
EU-VI EATS + Dual Dosing + E-Heater	

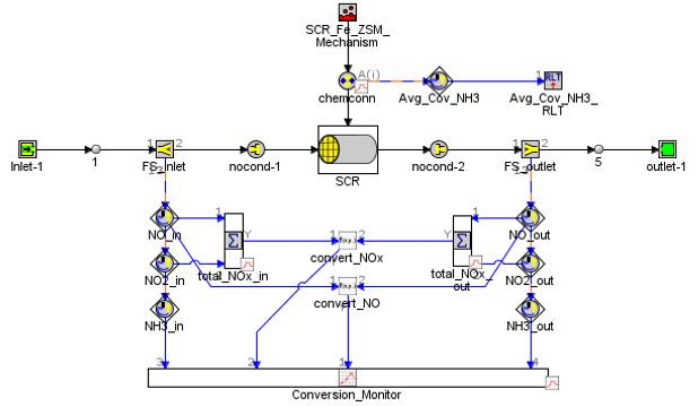
EU-VII / CN-VII Architectural Potential Challenges

Architecture combinations	Can meet EU-VII limits?	Challenges
EU-VI EATS + CSTU	Yes	• **Less/no margin with regulatory limits** • Large catalyst volume • System packaging • CSTU / E-Heater response time w.r.t. Cold start assist (controller required) • Air supply to CSTU or 48V battery for E-Heater • New calibration strategies • Early catalyst aging
EU-VI EATS + E-Heater	Yes	
EU-VI EATS + Dual Dosing	Yes	• **Less/no margin with regulatory limits** • **Complex calibration strategies** • System packaging
EU-VI EATS + Dual Dosing + CSTU ✓	Yes	• **Complex calibration strategies** • System packaging • CSTU / E-Heater response time w.r.t. Cold start assist • Air supply to CSTU or 48V battery for E-Heater • Early catalyst aging
EU-VI EATS + Dual Dosing + E-Heater ✓		

✓ Tenneco is partnering with OEMs and catalyst suppliers to jointly investigate these architectures and develop EATS controls through System modelling and 1D simulations using GT-Suite software



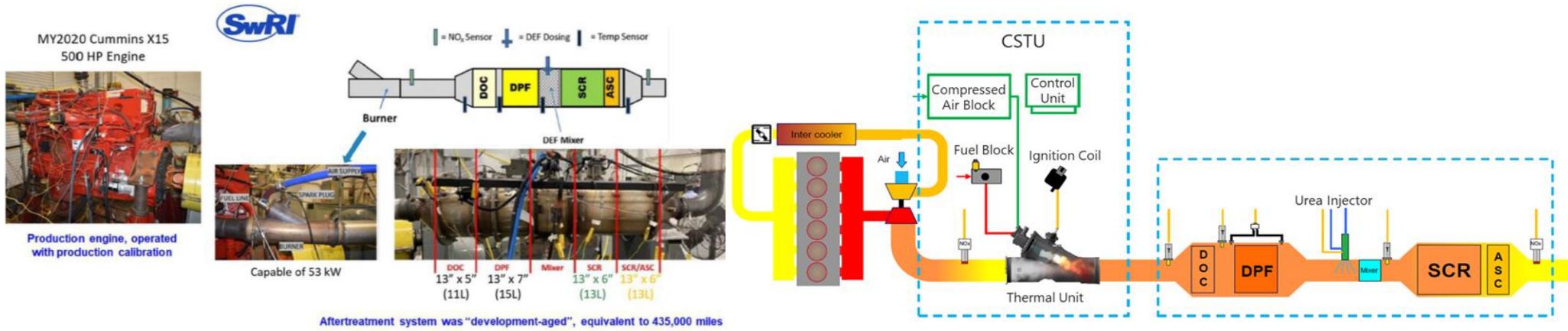
Tenneco's Advance System Modeling and 1D Simulations for EU-VII/CN-VII EATS



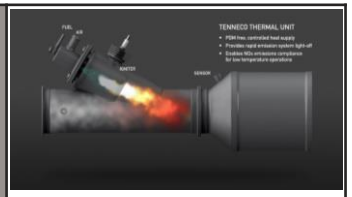
PARTNERING WITH RESEARCH INSTITUTES, OEMS, CATALYST COATERS AND OTHER TIER-I SUPPLIER FOR JOINT INVESTIGATION

Tenneco Global Development : Solution and Testing

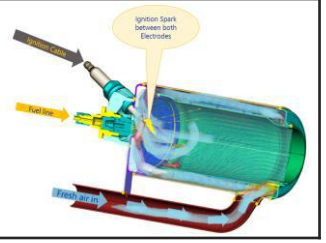
SwRI Testing With CT Engine and CSTU



Inline CSTU



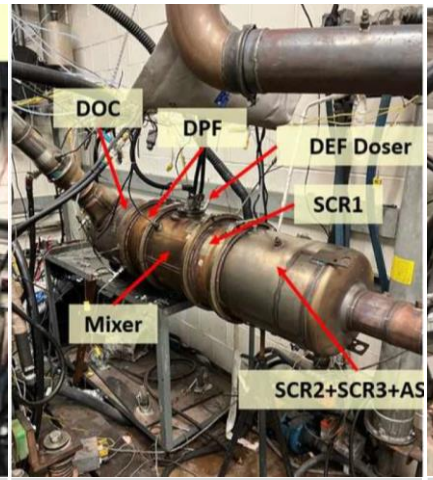
Stand Alone CSTU



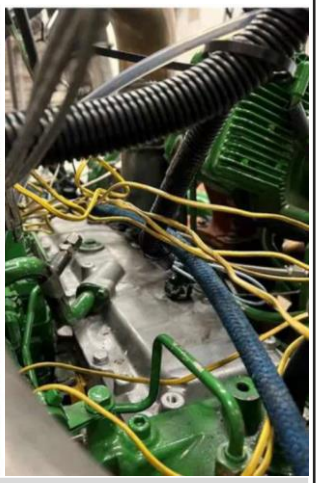
SwRI (Southwest Research Institute) Testing With OH Engine

OEM-1 Tier 4f engine (~7L)

Aftertreatment System Prototype Switchback



Aftertreatment System Prototype Inline



Closed Crankcase emission

Testing with E-Heater

- Canning/Integration status
  - Robust & durable design against high temperatures, high mechanical loads & vibration
  - High Eigenfrequency → robust against engine excitation

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Tenneco EU-VII / CN-VII EATS Model library:

Generic Models ready for:

1. Baseline EU-VI/BS-VI ATS (Base-ATS)
2. Base-ATS + CSTU
3. Base-ATS + E-Heater
4. Base-ATS + DD
5. Base-ATS + DD + CSTU
6. Base-ATS + DD + E-Heater

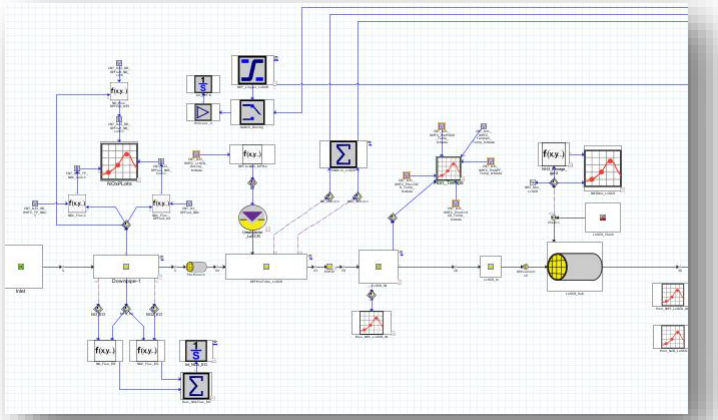


Fig: Base EATS + DD model

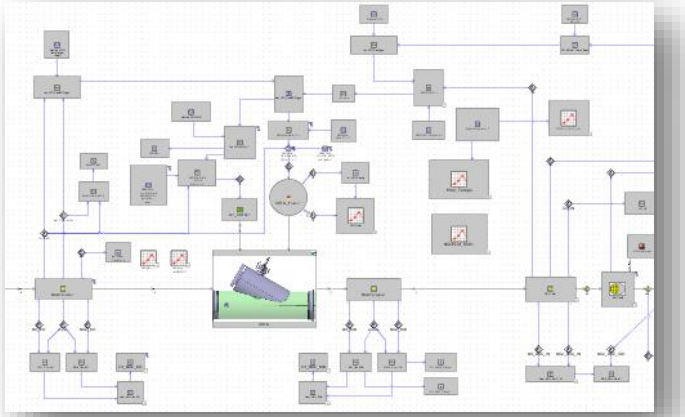


Fig: Base EATS + DD + CSTU Model

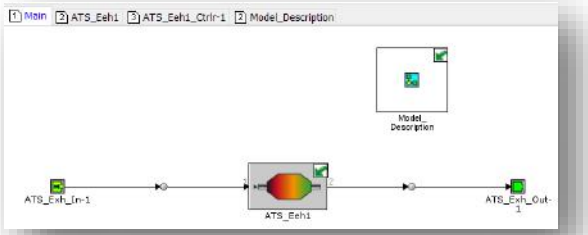


Fig: E-Heater Model
(Different model for different E-Heater)

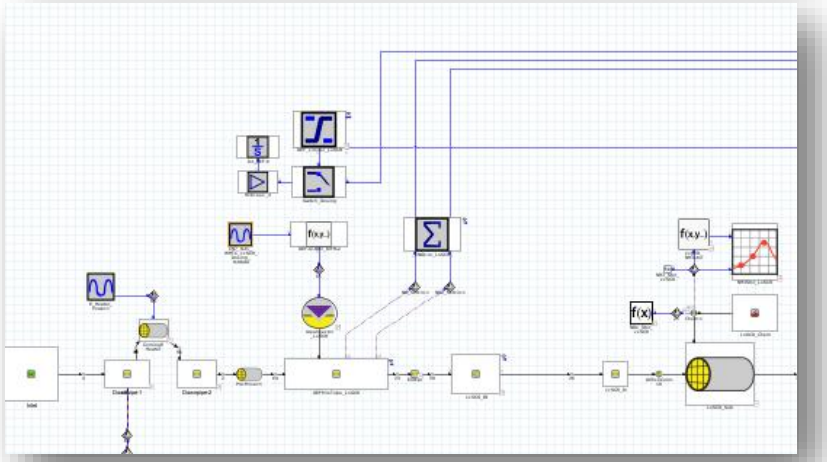


Fig: Base EATS + DD + E-Heater (Customer Specific)

Potential Architectural Trade-Offs

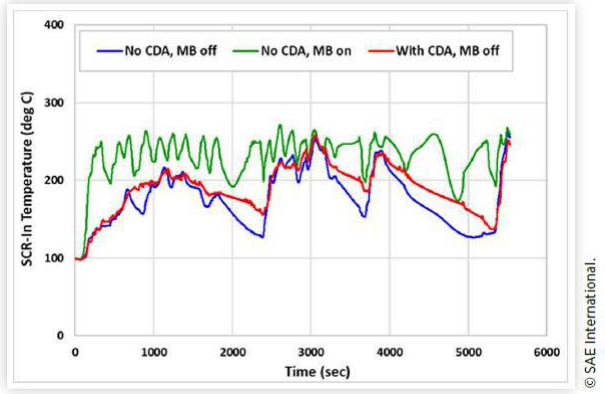
Architectures	Trade-offs
Base EATS + Heating source (CSTU/E-Heater)	• Tailpipe NOx **Vs** Energy consumed by the heating source (fuel or electric) • Tailpipe NOx **Vs** Heating source temperature **w.r.t.** DOC inlet temp limitation **Vs** SCR inlet temperature • Heating source operations Continuous **Vs** Intermittent **Vs** initial 10/20 Kms only • Etc.
Base EATS + DD	• ccSCR volume **Vs** mSCR volume • Urea dosing to ccSCR **Vs** mSCR • NOx conversion at ccSCR **Vs** DPF passive regeneration • ccSCR operations (Continuous **Vs** Intermittent **Vs** initial 10/20 Kms only) • Etc.
Base EATS + DD + Heating source (CSTU/E-Heater)	• Tailpipe NOx **Vs** Energy consumed by the heating source (fuel or electric) • NOx conversion at ccSCR **Vs** DPF passive regeneration • Urea dosing to ccSCR **Vs** ccSCR NH3 Storage **Vs** NH3 Slip from ccSCR • Etc.

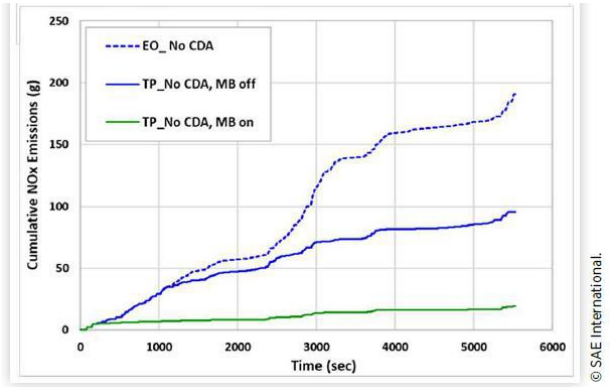
Summary

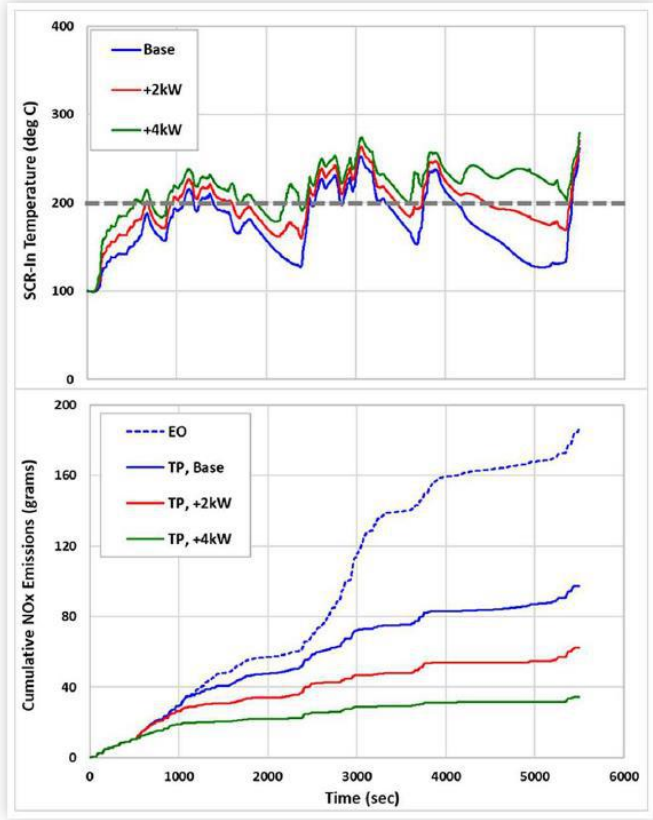
- Given the multitude of potential architectural solutions and their associated trade-offs, the testing permutations and combinations become substantial

- Hence, Tenneco is utilizing system modeling with precise input boundary conditions and conducting 1D simulations, enables us to assess all the potential EU-VII architectures along with their respective trade-offs, resulting in substantial time, cost, and effort savings.

- Below graphs are representation of assessing the CSTU and E-Heater testing, respective system modelling & 1D simulation correlation. Demonstrating LLC cycle define by CARB for Low-NOx emissions requirements; Source SAE Paper 2020-01-0359 “Simulation of Aftertreatment Thermal Management - Strategies for Low-Load Operation”





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