



Advanced Engine Technologies for Upcoming BSVII Compliance in Heavy-Duty Diesel Engines

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Driving Mobility through Innovation since 1966

Engine Development Laboratory

The Automotive Research Association of India

22nd Oct 2026

Facilitating & Creating
SAFER, SUSTAINABLE & SMARTER MOBILITY



LOWER EMISSIONS



CLEANER AIR



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A BETTER TOMORROW



Research, Development & Testing at ARAI

Access to world-class facilities for development and validation



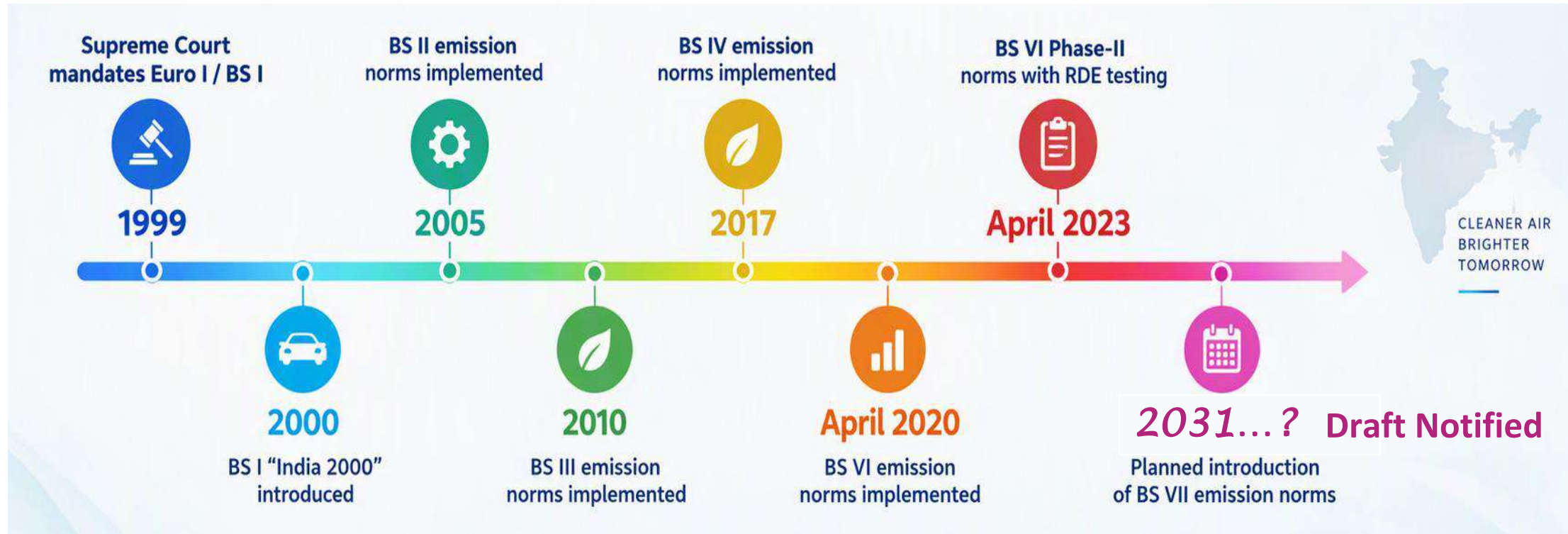
- Engine, vehicle and component testing
- Emissions and performance validation
- Environmental and durability testing





- Emission Challenges
- Engine Technological Solutions
- Experimental Studies on Advanced Combustion
- Results and Discussions
- Summary





Tighter limits. Broader coverage. Greater real-world impact.

Parameter	Euro VI			Euro 7 (WHSC / WHTC)	Change (%)	RDE (/kWh)
	Petrol (Transient)	Diesel (Steady State)	Diesel (Transient)			
NOx (mg/kWh)	460	400	460	200	↓ 50%	260
PM (mg/kWh)	10	10	10	8	↓ 20%	-
Particle Number (#/kWh)	6 × 10 ¹¹ @ 23 nm	6 × 10 ¹¹ @ 23 nm	8 × 10 ¹¹ @ 23 nm	6 × 10 ¹¹ <u>@ 10 nm</u>	Much stricter measurement	9 × 10 ¹¹ @ 10 nm
CO (mg/kWh)	4000	4000	1500	1500	No change	1950
THC (mg/kWh)	-	160	130	-	-	-
NH ₃ (mg/kWh)	10 ppm	10 ppm	10 ppm	60	Newly monitored	85
CH ₄ (mg/kWh)	500	-	-	500	Added focus	650
NMOG (mg/kWh)	-	-	Not included	80	New limit	105
N ₂ O (mg/kWh)	-	-	Not included	200	New limit	260
Formaldehyde	-	-	-	-		-

Note: "-" indicates not specified in the source table. RDE = Real Driving Emissions.

Key Takeaways

1



Significant NOx Reduction

- NOx limit reduced from 460 mg/kWh (Euro VI) to 200 mg/kWh (Euro 7)
- ~50% tighter regulation

2



Stricter Particulate Control

- PM limit reduced from 10 mg/kWh to 8 mg/kWh (~20% reduction)
- Particle Number measurement more stringent (23 nm → 10 nm)
- Enhanced control of ultrafine particles

3



Expanded Pollutant Coverage

- **New** regulatory focus on **CH₄** (500 mg/kWh)
- **NMOG** introduced (80 mg/kWh)
- **N₂O** introduced (200 mg/kWh)
- **NH₃** newly monitored (60 mg/kWh)

4



Real Driving Emissions (RDE) Compliance

- Additional RDE requirements increase real-world control
- Key RDE limits: NOx (260), NMOG (105), N₂O (260), NH₃ (85) mg/kWh
- Ensures cleaner performance beyond laboratory conditions



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Parameter	BS VI HDV	BS VII Draft HDV	Change
Emission Compliance Period	Up to 700,000 km / 7 years	Up to 875,000 km / 15 years (vehicle category dependent)	Significant increase
In-Service Conformity (ISC)	Required	Extended over full useful life	Strengthened
Real-World Emission Monitoring (OBM)	Limited	Mandatory throughout life	New requirement
OTA Data Reporting	Not required	Mandatory from 2033	New requirement
Market Surveillance	Limited	Independent on-road compliance checks	New requirement
After-treatment Durability	DOC/DPF/SCR durability demonstration	Extended life demonstration to BS VII useful life	More stringent

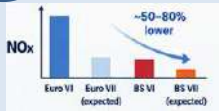
BS VII strengthens :

- Lower RDE NO_x levels
- Longer useful life requirements
- Continuous OBM and market surveillance link RDE performance with lifetime compliance.
- ISC extended over longer vehicle life
- Stronger focus on "emissions for entire vehicle life,



1

Tighter NOx Challenge



- Cold Cycle NOx Challenge
- Low Load /Low NOx across Wider Range
- Lower Engine-out NOx gives better RDE Margin

4

Increased Durability Requirements



- Combustion System remain robust under ageing conditions i.e Injector, EGR TC
- Initial Compliance alone will not be sufficient

7

Optimized Combustion System



- Improved Combustion and Lower NOx/PM reduces Load on SCR, DPF systems
- Helps reduce costly, Oversized, Complex EAT system

2

Tighter PM & PN Limits



- PM & PN Limits much Tighter
- Soot Formation increases DPF Loading Regen Frequency
- Reducing PM at Source is much better

5

Fuel Economy & CO2



- NOx /PM Reduction without penalizing fuel economy
- Higher Combustion Efficiency for better CO2 & Emissions

8

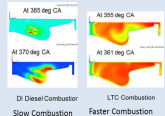
Dual SCR Aftertreatment System



- Dual SCR Architecture with Close Coupled SCR + DPF + SCR 2
- Faster Light Off
- Reduced Cold NOx

3

Real Driving Emission Compliance



- Faster Load Changes, temperature and ambient changes exposes Combustion Weakness
- Robust and stable Combustion across wider Range is needed

6

Tight OBD & Monitoring Requirements



- Combustion Variability directly impacts emission control Robustness
- More repeatable and predictable combustion improves compliance confidence

9

Electric Heater for Aftertreatment



- Electrically Heated Catalyst for Faster Warmup
- Rapid Warm-up –Cold Cycle NOx
- Improved Low Load Urban Operation



1

Optimize Air Management



- Higher Oxygen Utilization
- Higher Boost & Air Handling Efficiency
- Higher EGR Tolerance
- Improved Volumetric Efficiency

2

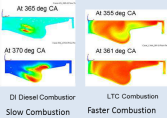
Fuel Injection System



- Higher Injection pressure
- ECU Control Strategies
- Optimized Rate Shape
- Flexible Multiple Injections

3

Advanced Combustion Strategies & VVT/VVL



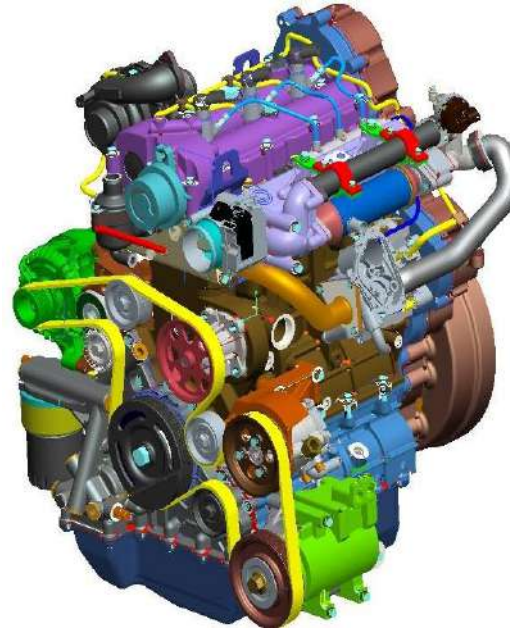
- LTC / Partially Pre Mixed Combustion
- Wider LTC Range Coverage
- EGR Assisted Low Temperature or
- Valve Timing Assisted LTC combustion

4

Optimized Spray –Bowl Interaction



- Optimized Bowl Geometry
- Improved Spray-Bowl Interaction
- Minimize Local Fuel Rich Zones
- Robust Combustion under Transient



Cleaner Combustion
Higher Efficiency
Lower Emission

5

Optimized EGR



- Higher EGR Rates
- Better EGR Distribution
- Maintain Combustion Stability with EGR

6

Cold Start & Low Load Improvement



- Improved Atomization & Vaporization
- Optimized Combustion Control
- Faster Heat-up

7

Friction Reduction, Efficiency Improvement



- Optimized Piston Ring Pack
- Improve Thermal Efficiency

8

Alternate Fuel Compatibility



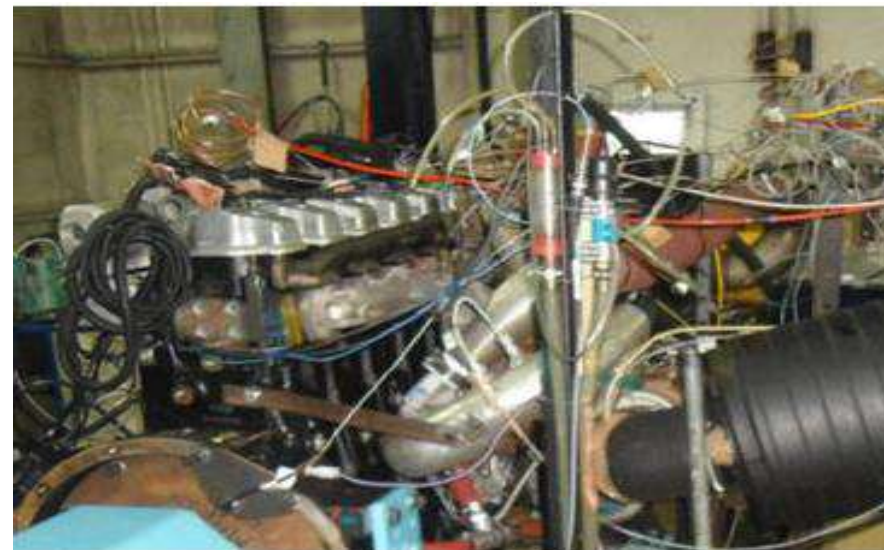
- Readiness for Renewable Diesel
- Bio-Diesel, e-fuels
- Minimal H/W Changes with Flexible Calibration



- HDV engine has been selected 6-cylinder engines with ~1 ltr/cylinder
- BMEP level of the engine is 17 - 20 bar

Engine Configuration

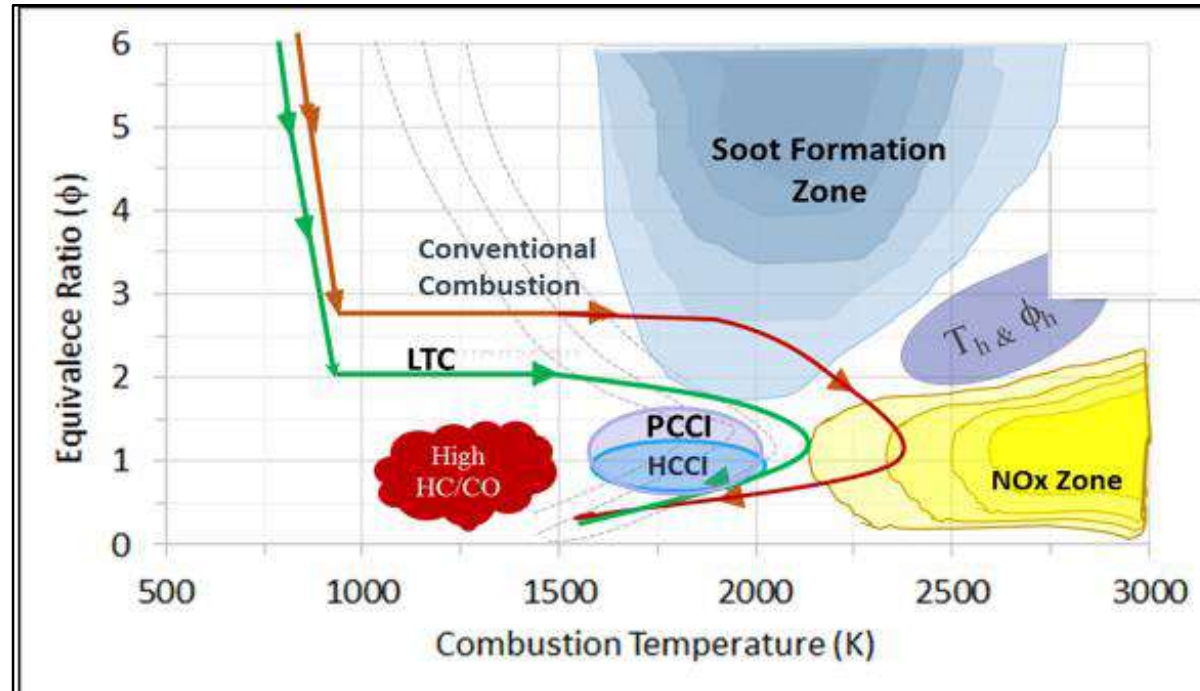
Engine type	DI-Inline, Water Cooled, Heavy duty
Rated Power, kW @ rpm	~ 200 @ 2200
Max BMEP, bar	20
Injection system	Baseline – 1600 bar New Modified - 2200 bar
EGR system	cEGR (LP + HP EGR)
Compression Ratio	lower
Swirl	reduced
Type of Aspiration options	Single VGT & 2 staged-Turbocharging
EGR system	HP EGR and EGR coolers
Spray Angle	Optimized Bowl & Spray



- New High Pressure FIS System- Upto 2200 Bar Injection Pressures
- New Turbocharging System – Higher Boost Pressures
- New EGR system – Optimized EGR rates
- ECU Control & Calibration



Advanced Combustion Concept Development

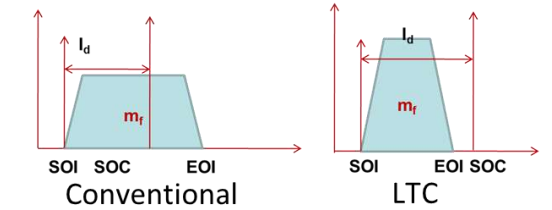
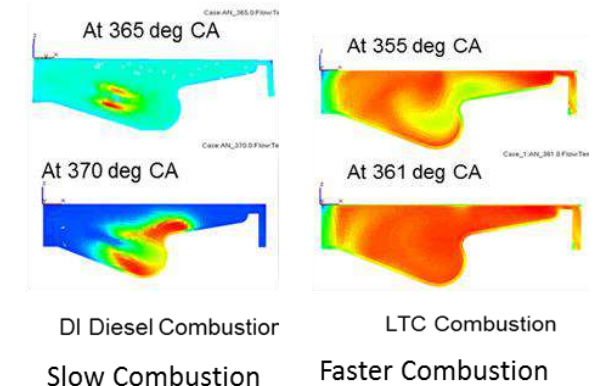
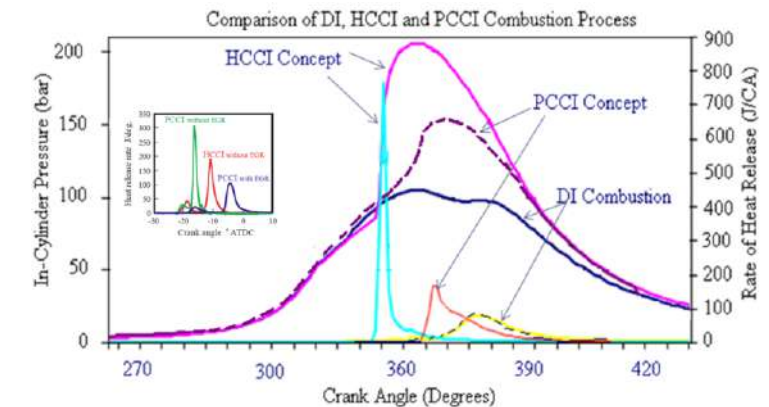


Benefits

- Low NOx and Soot
- Better Fuel Efficiency
- EAT - Cost Effective

Applications

- Compatible all type of fuels
- Passenger cars/Tractor/CEV/HCV/LCV/Gensets



Simulation Approach for selection of hardware

➤ Air Handling/Gas Exchange

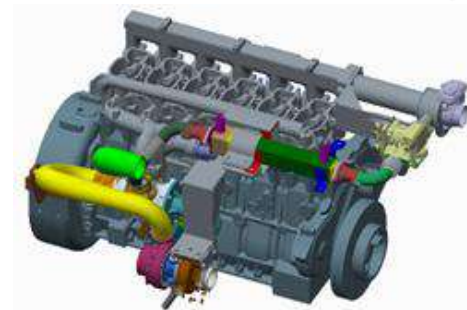
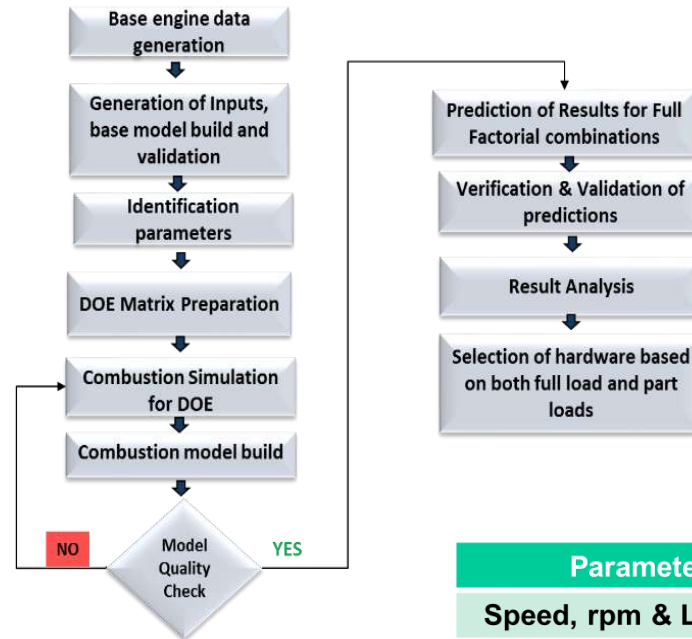
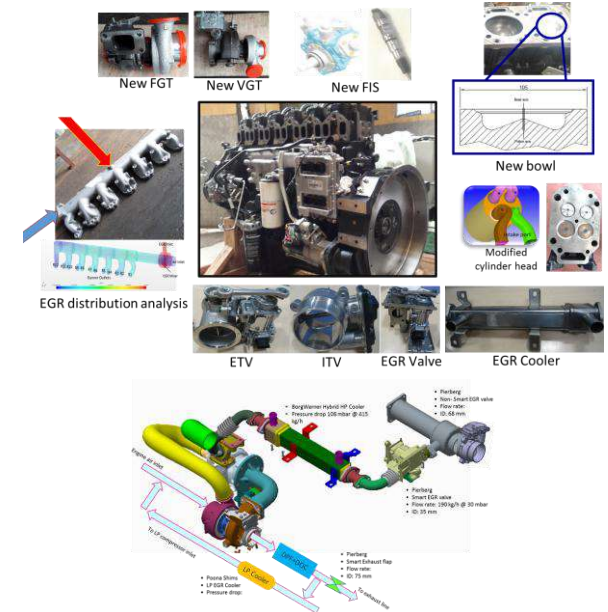
- Turbocharger – High Boost
- Intake & Exhaust Manifold
- Gas Exchange

➤ EGR System - Valve, Cooling, Mixer

- HP EGR

➤ Engine Simulation

- Engine Performance
- Emission Trends
- Heat Balance



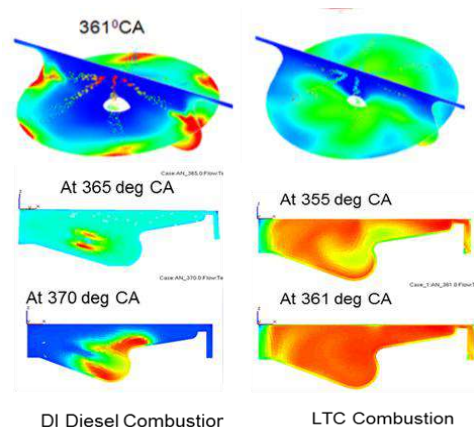
Parameters	1	2
Speed, rpm & Load, Nm	1400 & 25%	1400 & 50%
Rail Pressure	1000, 1200, 1400	1200, 1400, 1600
EGR %	30 and 40	30 and 40
Split Ratio	10%-90% 20%-80% 30%-70%	10%-90% 20%-80% 30%-70%
Main Timing	5, 10, 15	5, 10, 15
Spray Cone Angle	120°, 130° and 140°	120°, 130° and 140°
Swirl Ratio	1.2, 1.4 and 1.8	1.2, 1.4 and 1.8



LTC Strategy

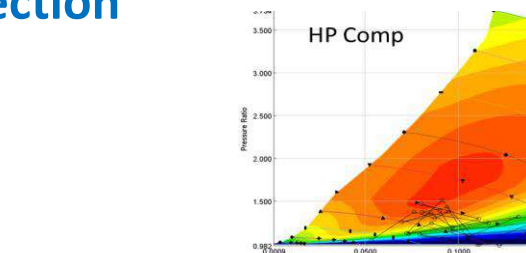
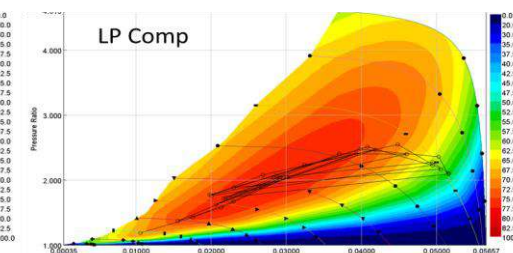
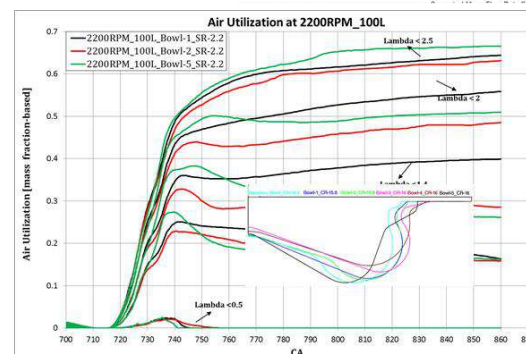
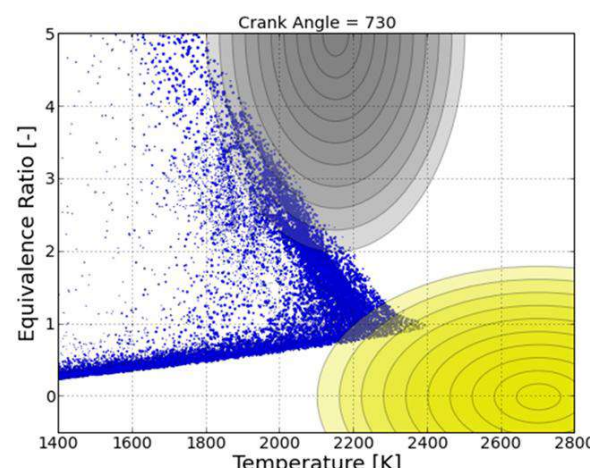
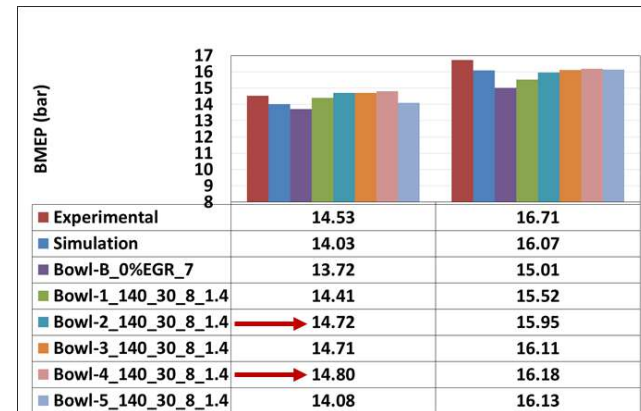
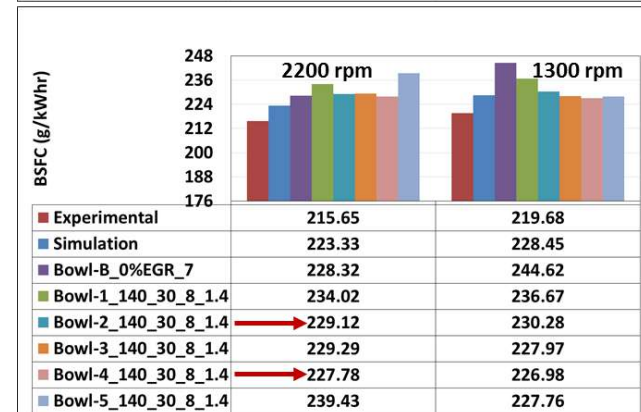
- Increasing Boost & EGR
- Multiple Injection (Early)
- Highly premixed charge
- Bowl geometry
- Injection Pressure
- Spray bowl Interaction
- Compression Ratio
- Number of Nozzle Holes
- Nozzle Tip Protrusion
- Injection Timing
- Injection Duration
- Boost Pressure
- Swirl
- EGR Ratio

Combustion Package Selection



Spray Bowl Interaction

Parameters	Base Engine	Test Engine
Engine	6 cylinder	
Valves	4 Valves	
Displacement	~7 ltr	
Compression Ratio	Higher	Lower
FIS	Common rail ~1600 bar	Common rail ~2200 bar
Nozzle	wider SCA	Narrower SCA (~120° x 8 holes)
TC	Single stage FGT	VG/2 Stage
EGR	NO	Cooled HP Loop
Bowl	Deep Bowl	Shallow Bowl





Virtual Test Bed

- DSPACE SCALEXIO HIL
- 20 AI, 30 AO, 30 DI, 28 DO
- Control Desk, Configuration Desk
- PUMA, IGEM, ISAC
- CruiseM, MOBEO
- CAMEO, MATLAB
- CONCERTO

ECU Pre-Calibration

- System concept evaluation
- Initial ECU dataset check
- Calibration & Mapping
- Multiple Injection Strategies
- Sensors and Actuators functionality
- Control Strategy
- Pre-calibration tasks

Calibration

- Engine Calibration for Steady state
- Transient Calibration
- Off cycle & RDE emissions

Robustness & Validations

- Altitude & ambient trials (non-standard conditions)
- Sensitivity analysis
- Component protection
- Aging related trials



Engine Performance & Emission Calibration

Synchronization, First firing, Base mapping

Hardware screening – Nozzle, Bowl, Swirl etc

Full load performance Mapping

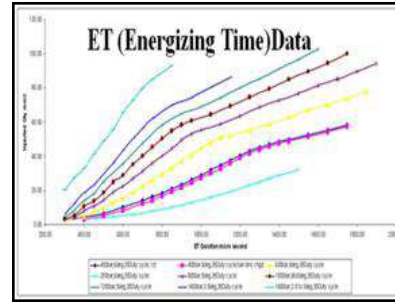
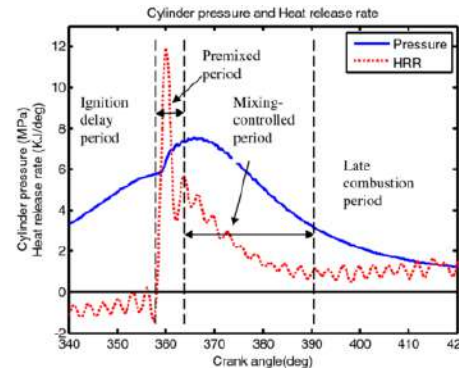
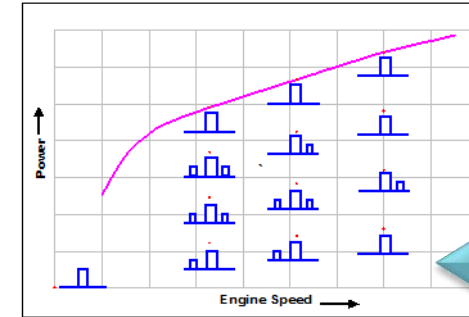
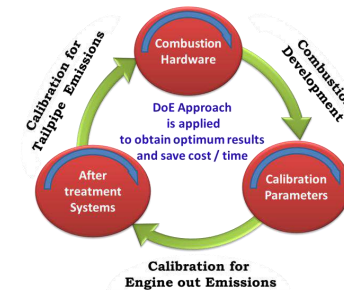
EGR & Boost pressure Optimization

Multiple injection Strategies

Steady state cycle emission calibration

Transient cycle emission calibration

Off cycle emission calibration



Injection Pressure

Main Injection

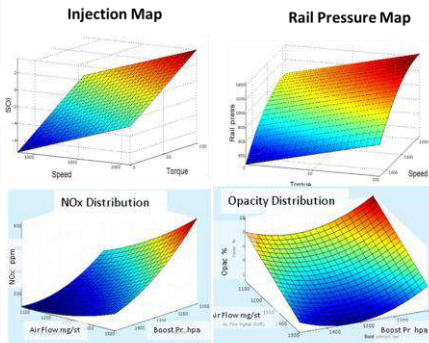
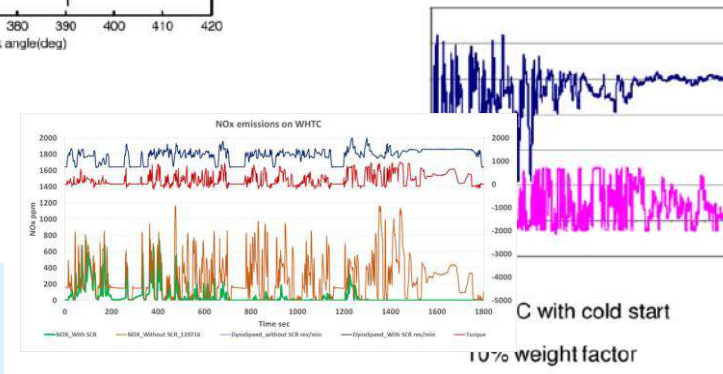
- Quantity
- Separation

Pilot Injection

- Injections
- Quantity
- Separation

Post Injection

- Injections
- Quantity
- Separation



Boost Pressure

Airflow

Variable Swirl

Total EGR

HP/LP EGR Split

Intake Throttle



LOWER EMISSIONS



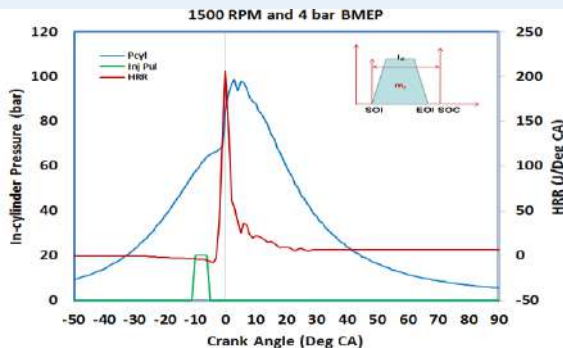
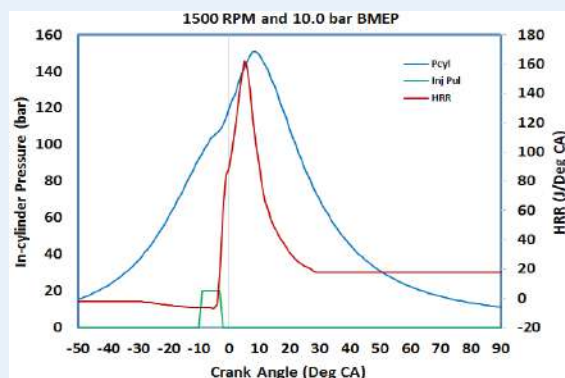
CLEANER AIR



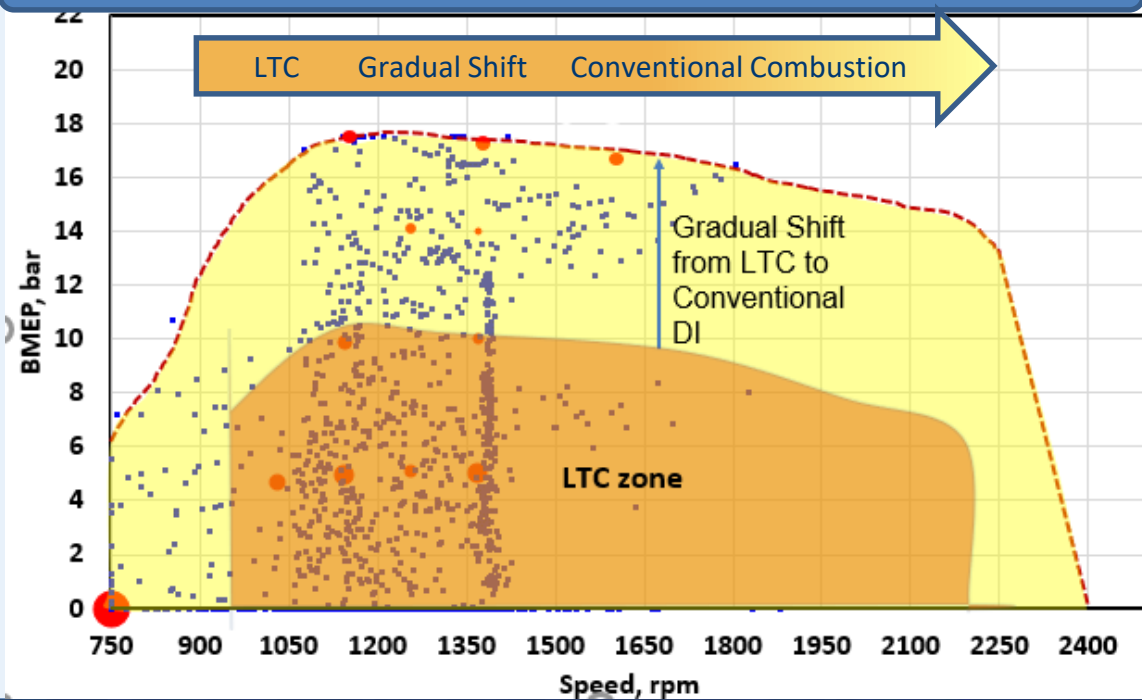
SUSTAINABLE MOBILITY



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Engine Operating Map – Low Temperature Zone



- As the loads increases, ignition delay decreases and combustion process shifting from LTC to conventional diffusion mode
- Engine calibration performed for both LTC and conventional combustion to achieve targets

Challenges in the Transition Region (40–70% Load)

- High pressure rise rate (combustion noise)
- Misfire due to excessive dilution
- Increased HC and CO in PPC mode
- Soot spike during mode switching
- Turbocharger matching issues

Use a blended combustion zone with gradual changes in control parameters.

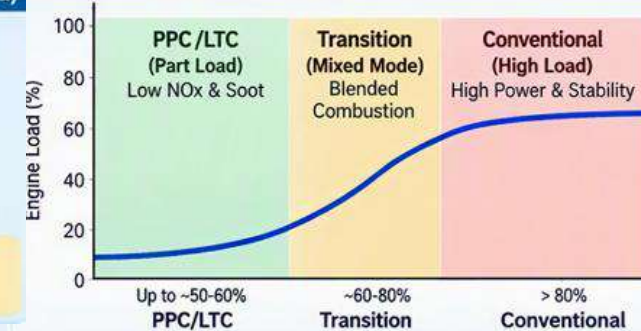
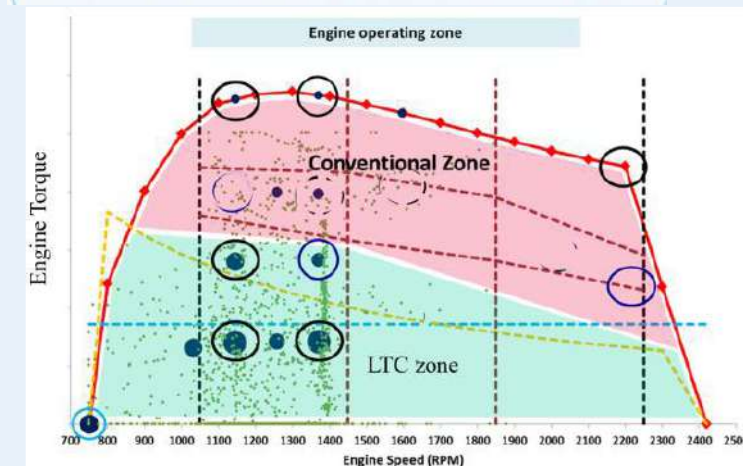
1 Variable EGR Strategy

- Part load (PPC): High EGR (30–60%) → more premixing, lower temperature
- High load (Conventional): Reduce EGR (<15–20%)
- Simple and widely demonstrated

2 Multiple Injection Strategy

- Part load (PPC): Early pilot and main injection (e.g. –40° CA pilot, –15° CA main)
- High load (Conventional): Shift injections later (e.g. –10° CA pilot, +2° CA main)
- Increases premixing at low load and enables diffusion combustion at high load

Combustion Mode vs. Engine Load



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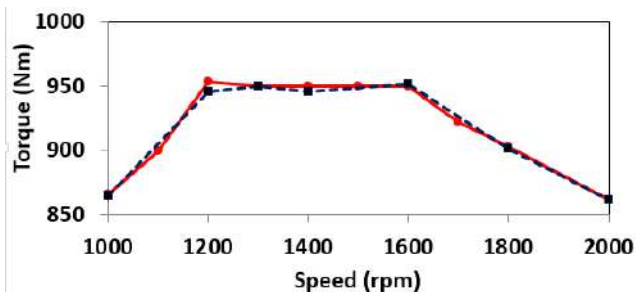
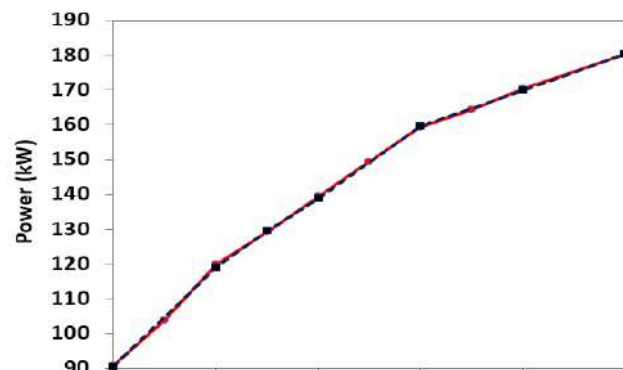
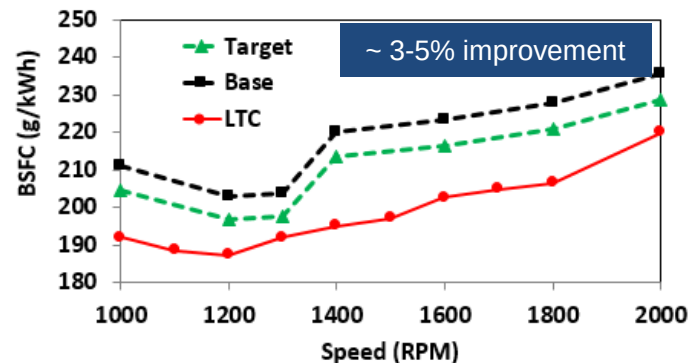


SUSTAINABLE MOBILITY

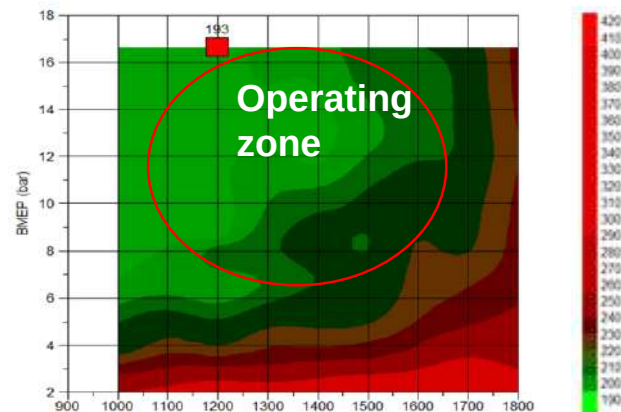
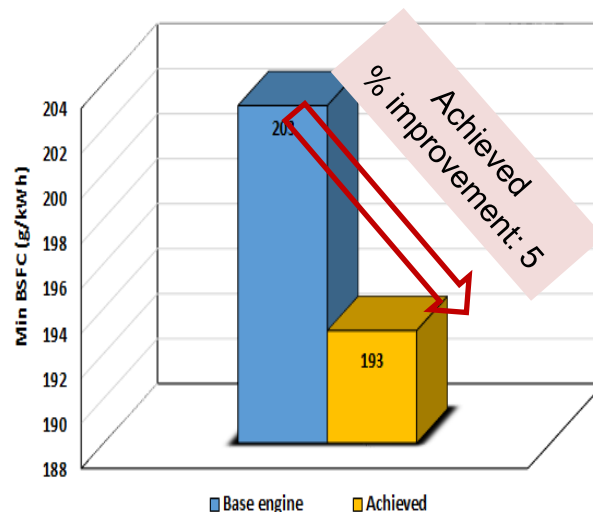


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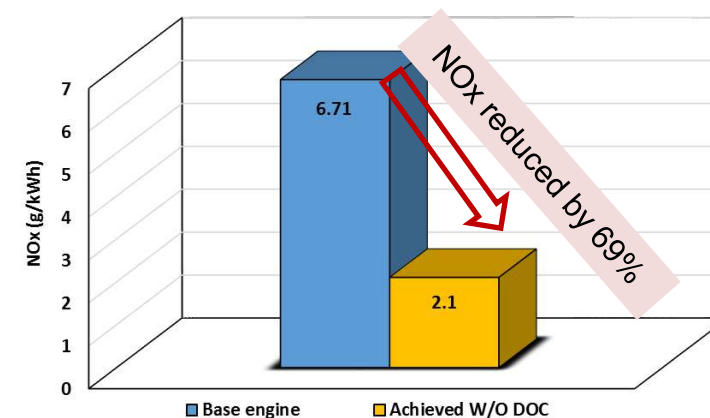
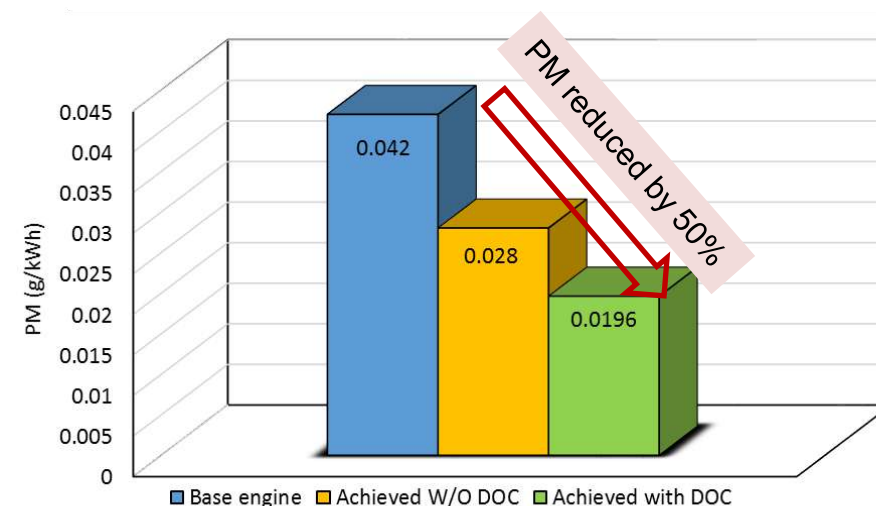
Performance Results



BSFC Results



Emissions Results



LTC

(Low Temperature Combustion)

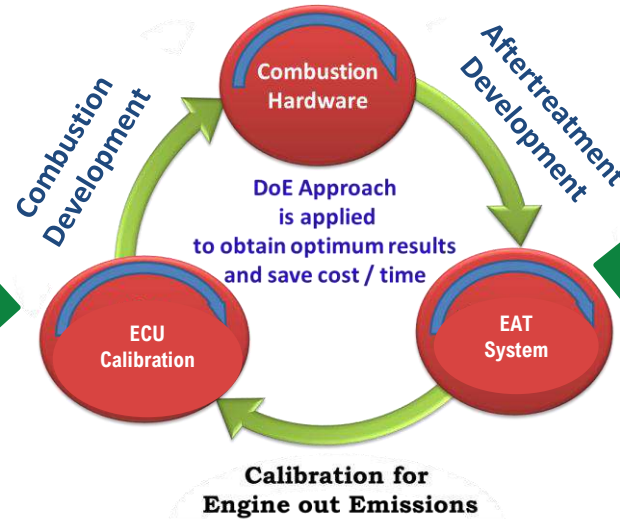


- Lower peak combustion temperatures
- Suppresses thermal NO_x formation
- Simultaneous reduction of NO_x and soot

NO_x ↓↓
PM ↓↓

COOLER COMBUSTION. CLEANER EMISSIONS.

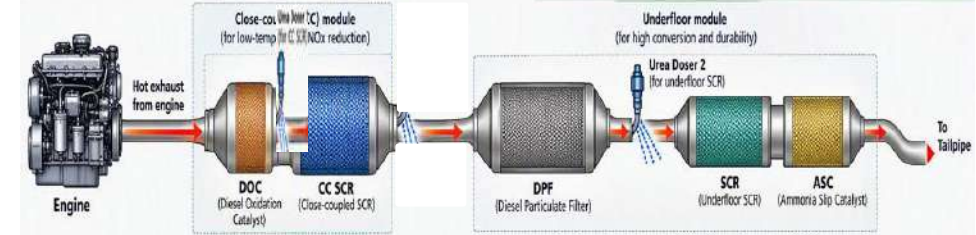
ADVANCED
COMBUSTION
FOR A CLEANER
TOMORROW



Calibrated PPC/LTC in selected low-load regions
+
Conventional combustion at medium/high loads
+
Dedicated Thermal Management.

Option 1: Close-coupled DOC + CC SCR and DPF + SCR + ASC

Dual SCR architecture with close-coupled DOC + SCR for fast light-off and high overall NO_x conversion

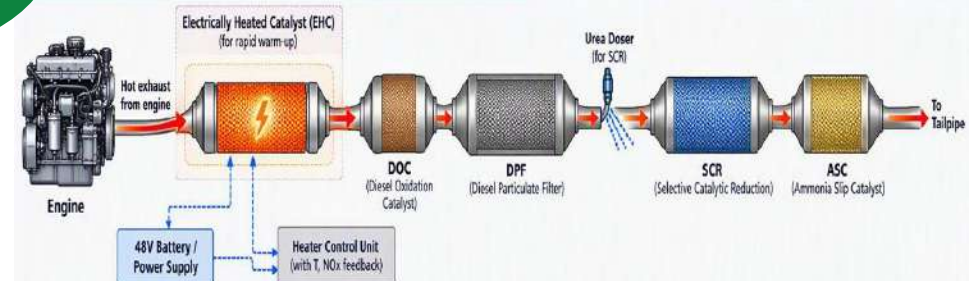


Key Benefits

- Improved low-temperature NO_x conversion (fast light-off)
- High overall NO_x reduction efficiency
- Optimized packaging (close-coupled + underfloor)
- Reduced cold-start emissions
- Enables robust BS VII compliance

Option 2: Electric Heater Assisted Aftertreatment Layout

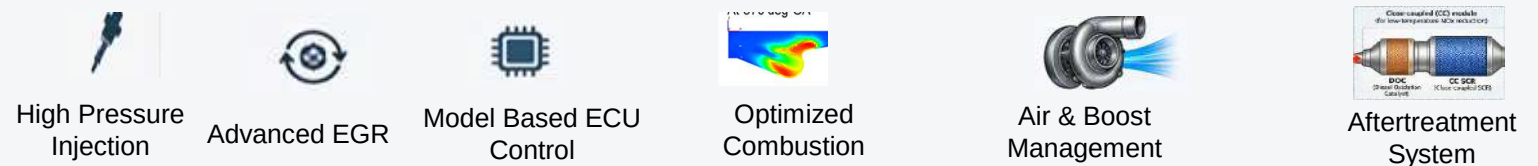
Electric heater for thermal management at cold cycle to enable early NO_x reduction



Key Benefits

- Rapid catalyst warm-up
- Effective cold-cycle NO_x reduction
- Thermal management for BS VII
- Improved low-load urban operation
- Maintains high NO_x conversion even at low ambient temperatures

Key Enabling Technologies



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Key Takeaways

- ✓ Integrated In Cylinder Engine + Aftertreatment optimization is the most practical BS-VII pathway
- ✓ Engine-out Emission (NOx) reduction becomes essential
- ✓ PPC/LTC offers major potential at part load
- ✓ Injection + boost + EGR coordination is critical
- ✓ Thermal management will become key enablers



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