Implementation and Challenges of RDE with BS-VI Norms - 2020

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Cummins Emission Solutions

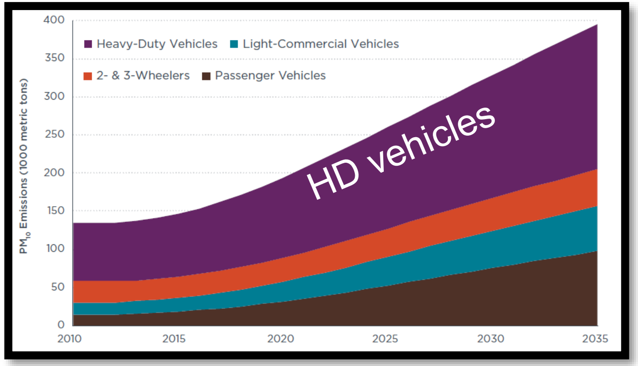
Emission Control Technology for Sustainable Growth
November 9 - 10, 2016
India Habitat Centre, Lodhi Road, New Delhi, India
Event Organised by: ECMA

Outline

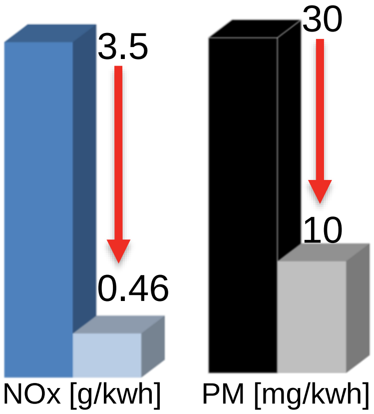
- Evolution of Regulations and CES Technologies Readiness
- BS-VI Engine System Challenges
- BS-VI Aftertreatment Technology Considerations

Why leapfrog to BS-VI?

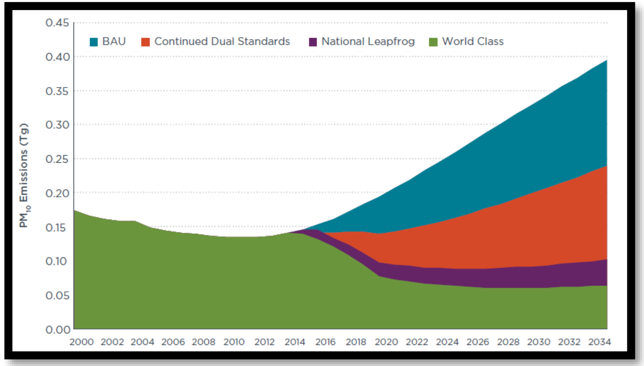
Projected total PM10 emissions in the absence of further policy action



BS-IV to BS-VI



Projected total PM10 emissions in the presence of further policy action



- India wide vehicular NOx & PM10 emission predicted to increase 260% between 2015 & 2035
  - *HD vehicles predicted to account for 50% total vehicular PM_{10} emissions & 38% NO_x emissions by 2035 and up to 40% PM_{10} & 90% NO_x emissions in certain cities come from HD vehicles.*
- Early introduction of BS-VI standards nationwide can help to reduce net emissions of NOx & PM10 by up to 86% by 2035
- Accelerated move to BS-VI ambitious compared to historic European regulatory trajectory

Evolution of regulations and CES technologies

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1980's

By-pass burner diesel particulate filter system developed

First commercial product (natural gas oxidation catalyst)

1990's

Cummins launched diesel oxidation catalysts for medium duty diesel engines

Cummins acquired Nelson Industries (acoustic muffler design capability)

2002

Fleetguard Emission Solutions Founded

Retrofit Product Introduced

2006

Fleetguard Emission Solutions became Cummins Emission Solutions

Euro IV SCR product launched

2007

EPA 2007 DPF product launched

Cummins Emission Solutions (CES) Inc. formed

2008

Expansion to Brazil and China

Euro V SCR product launched

2009

CES formed strategic alliance with Faurecia (then EMCON)

2010

EPA 2010 Product Launched

NS4 Product Introduced in China

2011

Sale of Exhaust Business to Global Tube Inc. announced

Tier 4 Interim off-highway product launched

Advanced development of UA2 Air-Assisted Urea Dosing System announced

2012

Business celebrates 10th Anniversary

Cummins acquired SCR division of Hilite International; launch of the UL2 Liquid-Only Urea Dosing System

Euro V launch in Brazil

2013

Euro VI and EPA 2013 Product Launches

2014

Urea Tanks & Lines availability announced

Grand Opening of Cummins Mineral Point East (CMPE) for High-Horsepower manufacturing

2015

Single Module introduced for EPA 2017

Evolution of regulations and CES technologies

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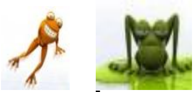
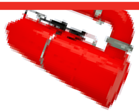
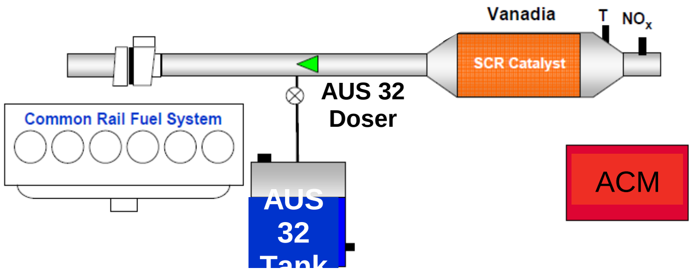
BS-IV 2017  BS-VI 2020

Short lead times but technologies and unrivalled experience exists to meet the challenges



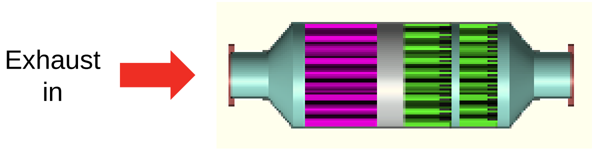
BS-VI: Proven CES aftertreatment systems for NOx and PM exist in the Indian market

Cummins Emission Solutions



For engines w/o EGR

- More than 7 years of experience in Indian duty cycle conditions
- Validated system for emerging market
- Same & Similar system being used in China for NSIV and NSV emission norms
- Sub system level and vehicle level validation completed

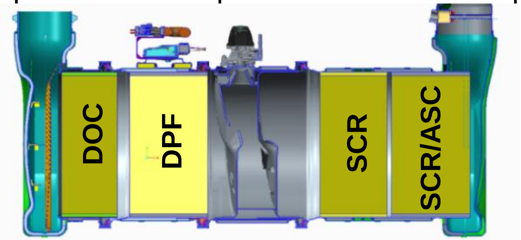


For engines w/EGR

- Specialized cell structure for filter to deliver consistent reduction in PM
- High thermal and mechanical robustness
- No transient soot release even with significant dynamic changes in vehicle operation

What makes up BS-VI legislation and how is it different from BS-IV

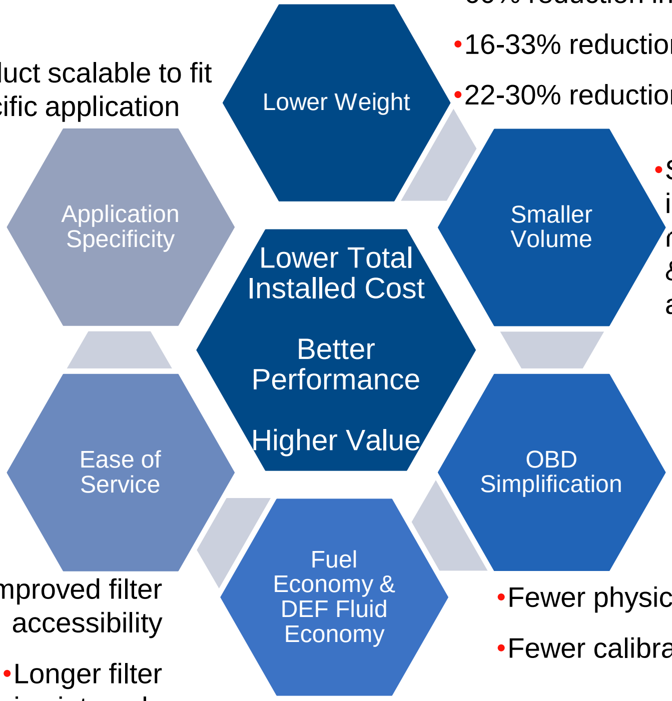
		NOx mg/kwh	**PM / PN** mg/# / kwh
Type approval	Cycles: WHTC *(14% cold + 86% hot)* WHSC	400 460	10 / 6 x 10^{11} 10 / 8 x 10^{11}
	OCE: WNTE *(3 random cells, 15 modes)*	600	16
	OBD: BS-VI-1 OBD – 2020 BS-VI-2 OBD – 2023	1500 1200	monitor 25 / -
	DF: Evaluation as per AIS 137 or	1.15	1.05 / 1.0
	NOx control		
PEMS	Demonstration at type approval		
ISC	PEMS data collection: 2020-2023		
	PEMS for RDE: 2023 *(work based window)*	1.5	-
Durability	<16T: 300 000kms/6y >16T: 600 000kms/7y		



BS-VI is similar to Euro VI regulation and natural starting point for the development emission control technologies

- Product scalable to fit specific application

- 60% reduction in space claim
- 16-33% reduction Medium Duty
- 22-30% reduction Heavy Duty

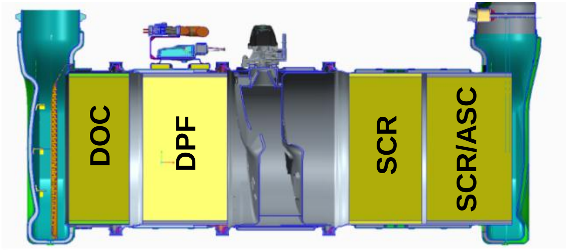


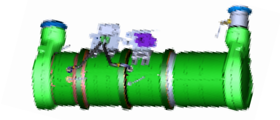
- Significant reduction in 3D footprint required on Medium & Heavy Duty applications

- Improved filter accessibility
- Longer filter service intervals

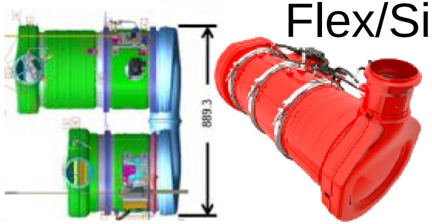
- Fewer physical sensors
- Fewer calibrations

- Weight Reduction
- Fewer regenerations
- Reduced Backpressure





Single module
LD - <5L

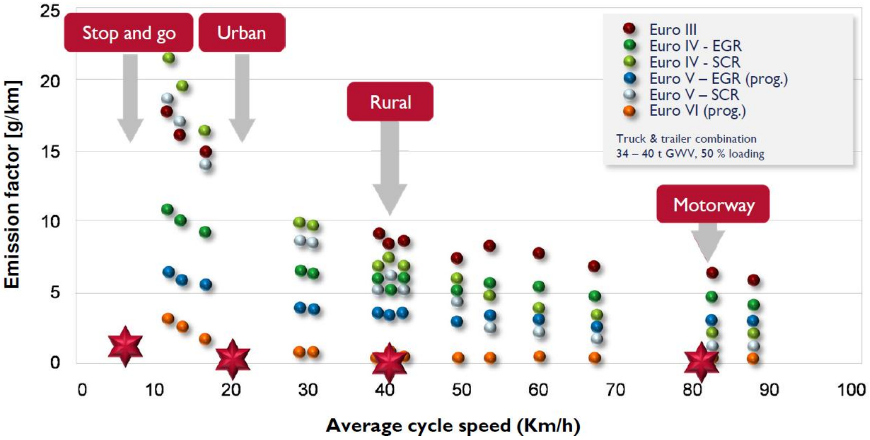


Flex/Single Module
MD - 5–9L

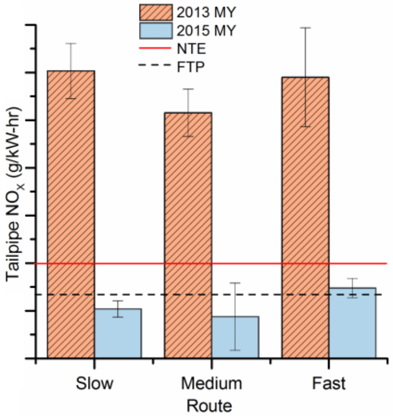
Compact Box
HD - >10L

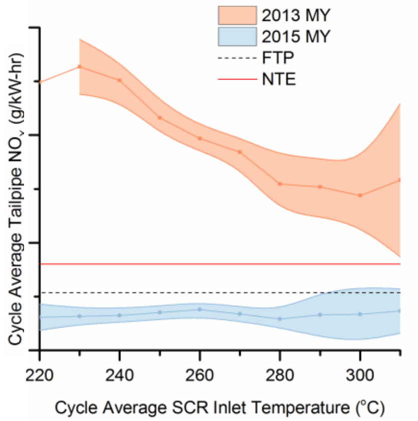
Euro VI, EPA 2010 systems are working in real world

Source: TU Graz



Publication in preparation by Andrew Kotz, William Northrop and David Kittelson from University of Minnesota, in collaboration with IREE, MetroTransit, and Cummins





- Real world emissions very low, even at low vehicle speeds.
- Much closer alignment between real world and engine dyno certification limits than previous legislation

- Cummins pro-actively bridged the gap between regulatory cycle requirements and low-load real-world operation
  — *Example: University of Minnesota study of 2013 urban buses in Minneapolis showed regulatory compliance but pointed at limitations of real-world performance. The 2015 product showed consistently effective NOx control on all bus routes.*

Euro VI, EPA 2010 systems are working in real world

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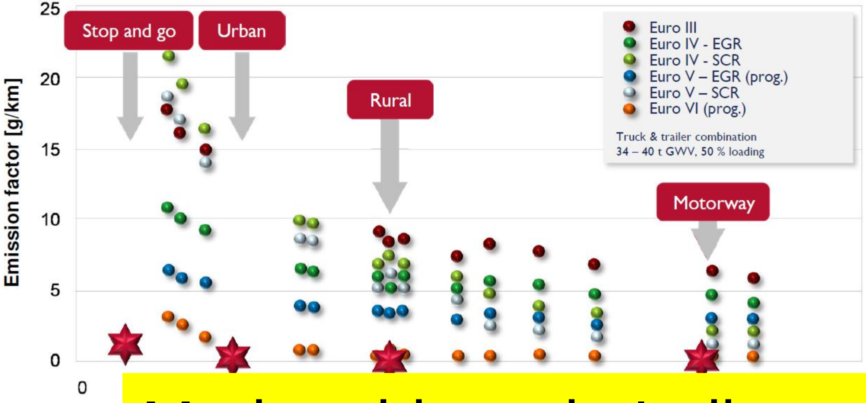

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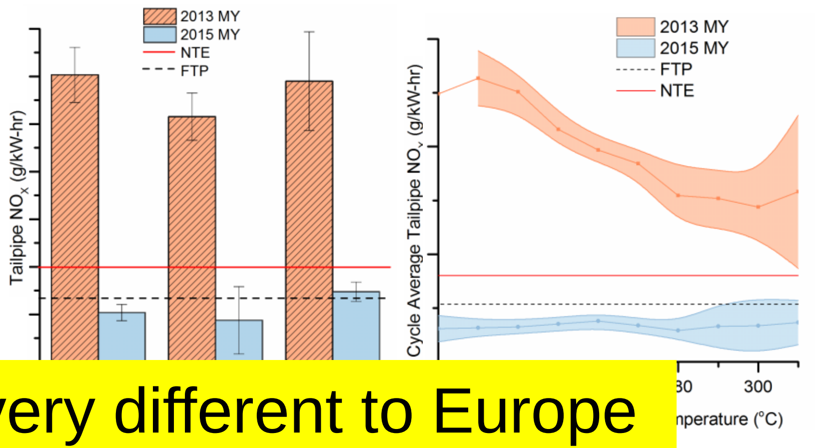

Market drivers in India are very different to Europe and require a significantly different approach to system design in order to deliver a product truly optimized for the market

- Re… p ev… ts and
- Mu… real world and engine dyno certification limits than previous legislation

Example: University of Minnesota study of 2013 urban buses in Minneapolis showed regulatory compliance but pointed at limitations of real-world performance. The 2015 product showed consistently effective NOx control on all bus routes.

BS-VI Engine System Challenges

India operating at significantly lower power to weight ratios compared to the rest of the Euro emissionized world

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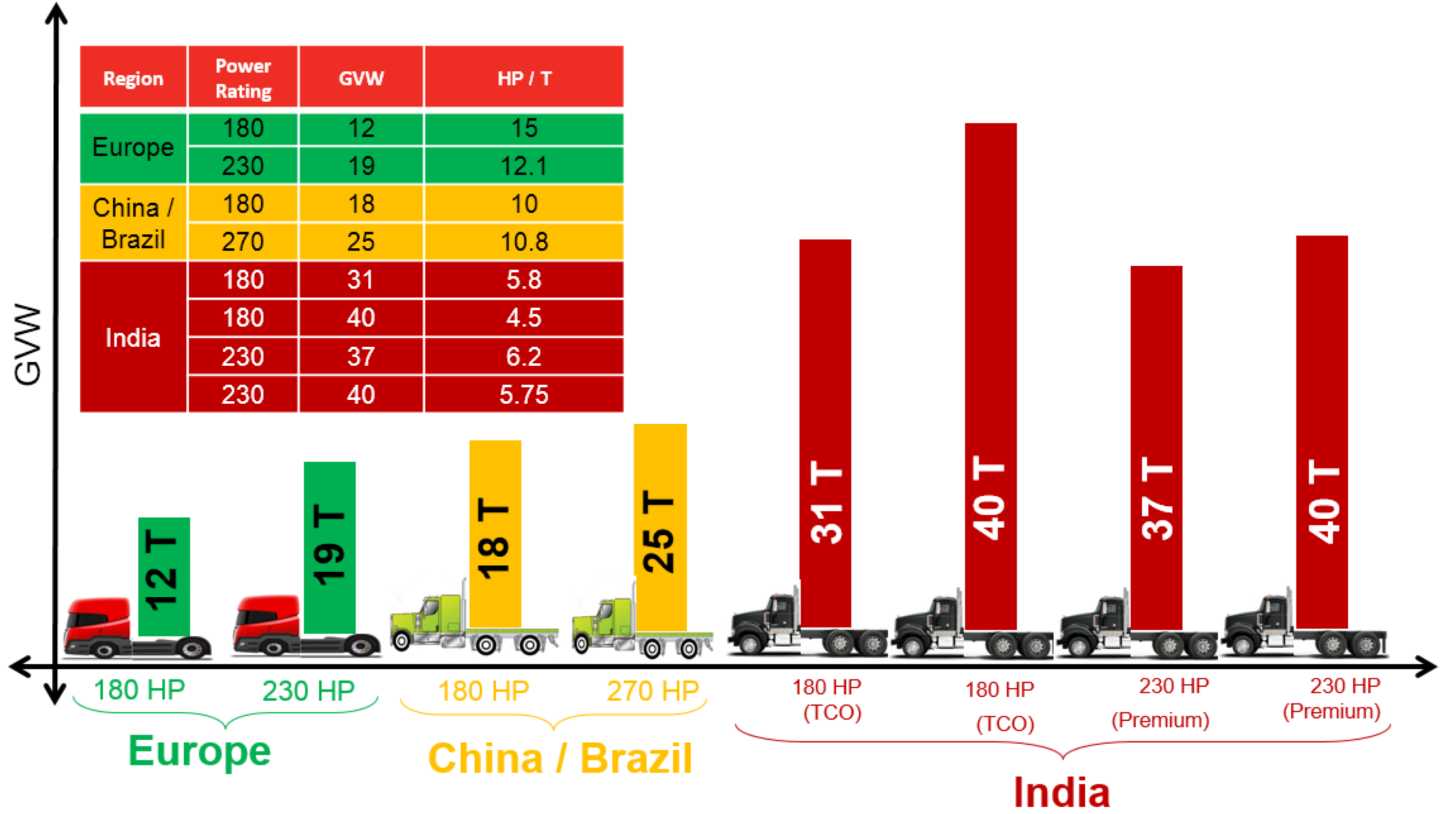
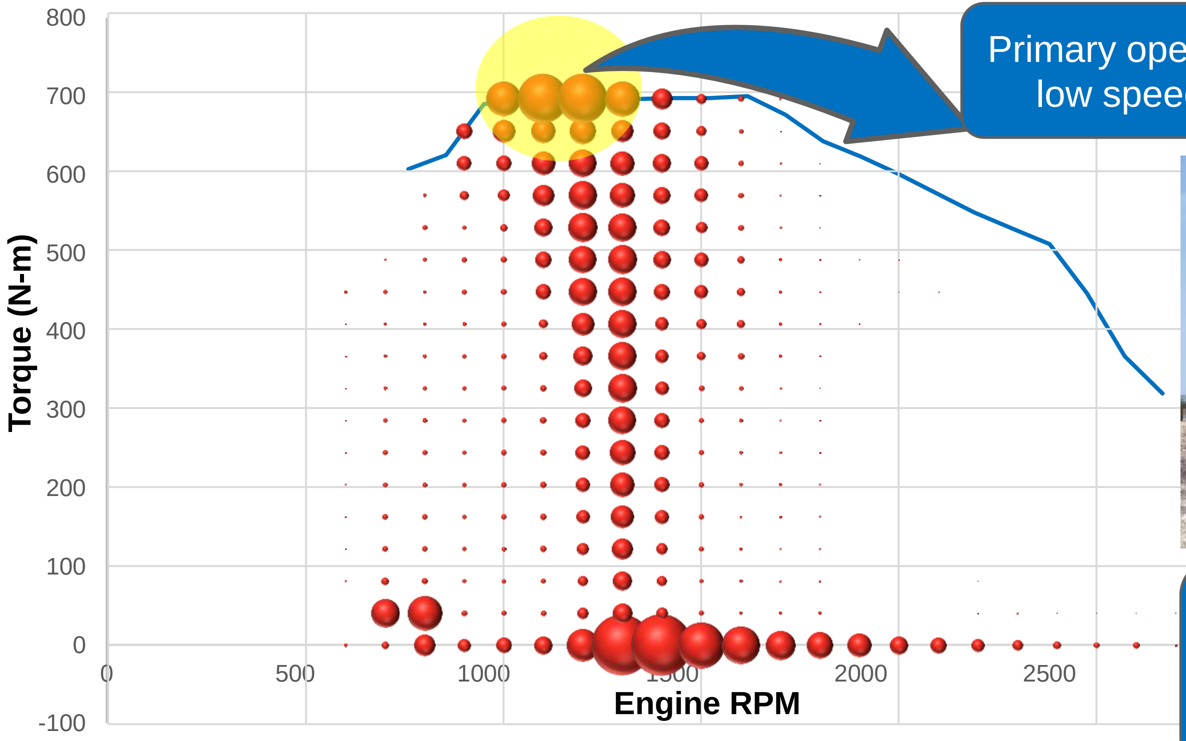
Region	Power Rating	GVW	HP / T
Europe	180	12	15
	230	19	12.1
China / Brazil	180	18	10
	270	25	10.8
India	180	31	5.8
	180	40	4.5
	230	37	6.2
	230	40	5.75



Typical 6L 180hp India inter city truck duty cycle

Emission Solutions



Primary operation zone is low speed peak torque

High GVW: up to 40T

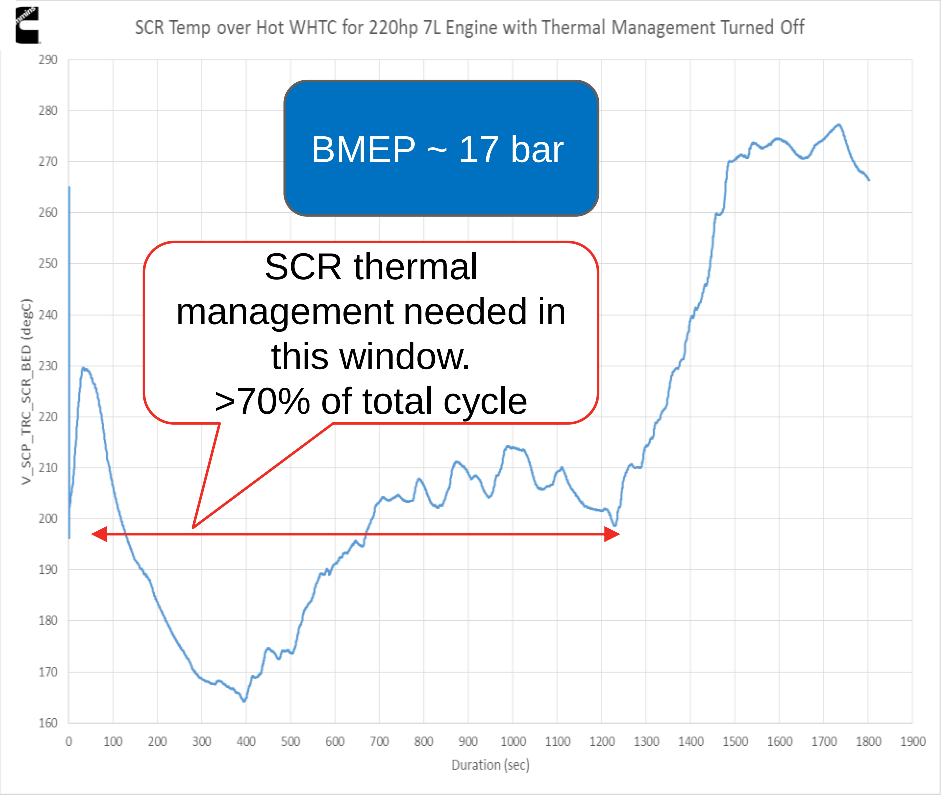
Low speed: 35-55km/h on-hwy

Market perception of high durability & low TCO (15bar BMEP)

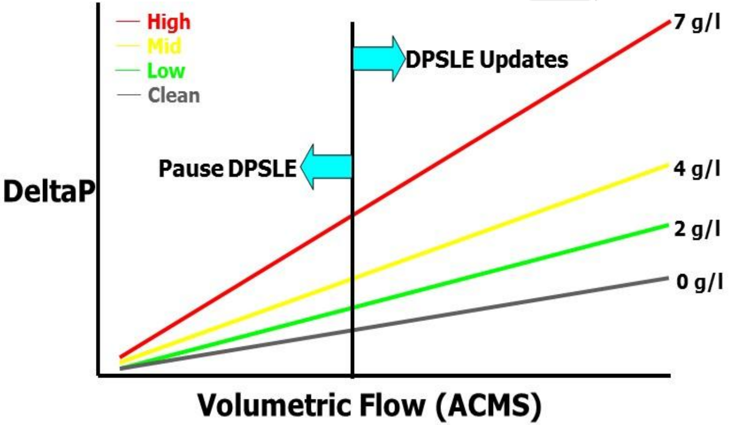
What is the implication of BS-VI to very low power density engines?

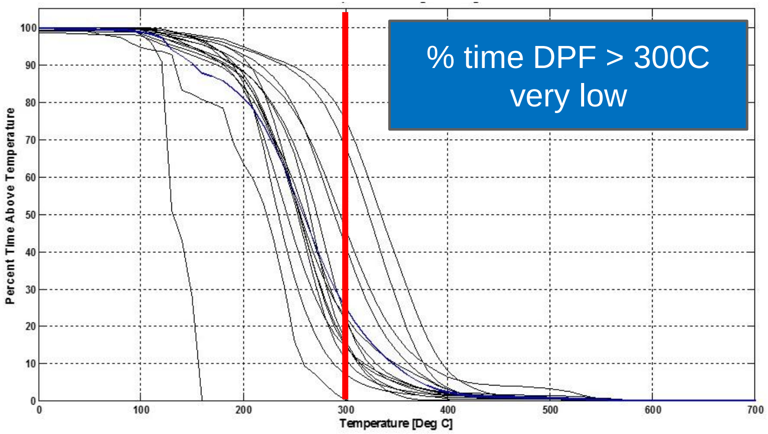
Low BMEP engines may struggle to make and maintain SCR temperature in WHTC

- For BS-VI, the WHTC & In Service Compliance emission cycles impose new challenges (e.g. thermal management of after-treatment) requiring new engine system considerations – a “low BMEP” engine may be undesirable from a fuel economy perspective.
  - *Euro VI experience suggests ~ 17bar BMEP as a lower threshold to pass the WHTC emissions cycle with acceptable fuel consumption.*
  - *A 6L 180hp engine would drop below 15 bar.*
- Could this create a shift in the market dynamics to optimize BMEP?
  - *Increases in engine power? Engine downsizing?*



Typical inner city truck duty cycle





- Very challenging conditions for passive DPF regeneration.
- Direct DPF soot load measurement very challenging combined with propensity for transient smoke.
- Drivers for active regen capability and model based soot load estimation.

India market demographics

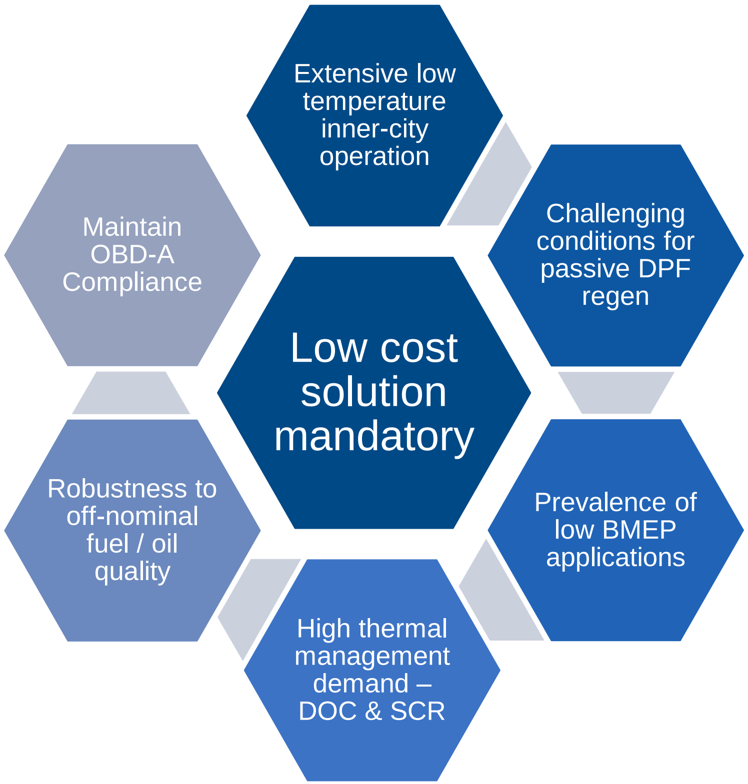
Emission Solutions






- Road and infrastructure conditions challenging
- Maintenance / service practices still fairly basic
- Challenging environmental conditions: *Vibration, Cleanliness, Fuel / Lube / AdBlue quality*

Aftertreatment challenge for BS-VI



- A low cost solution is a market pre-requisite – significant price reductions over Euro VI expected.
- Requirements are significantly more challenging
  - *Durability (300 to 700 kms)*
  - *OBD-1 (2020?) and OBD-2 (2023?)*
  - *in-service conformity (2020) and monitoring (?)*
- Significant advances in engine and AT thermal management capabilities are expected

Delivering a robust, fit-for-market solution is a significant challenge!

BS-VI Aftertreatment Technology Considerations

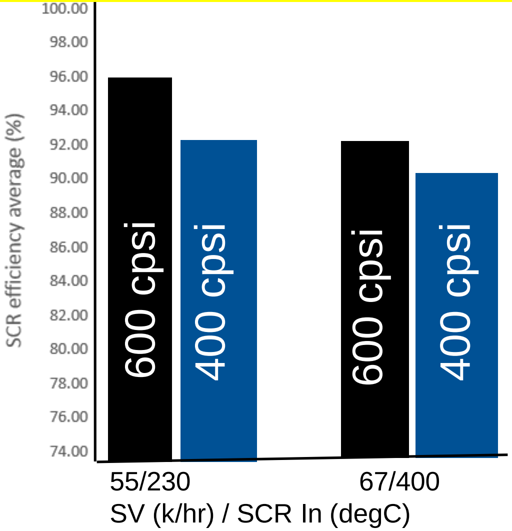
Mitigating NOx and PM aftertreatment cost: Reduce catalyst volume

- Direct Benefits
  - *Reduce substrate & washcoat costs.*
  - *Improved cold cycle warm up.*
- Indirect Benefits
  - *Less catalyst mounting mat required.*
  - *Less steel required for catalyst sleeves.*
  - *Less steel required for canning.*
  - *Less surface area for heat rejection hence less insulation required.*
  - *Less heat loss through system so potential to reduce number of temperature sensors.*

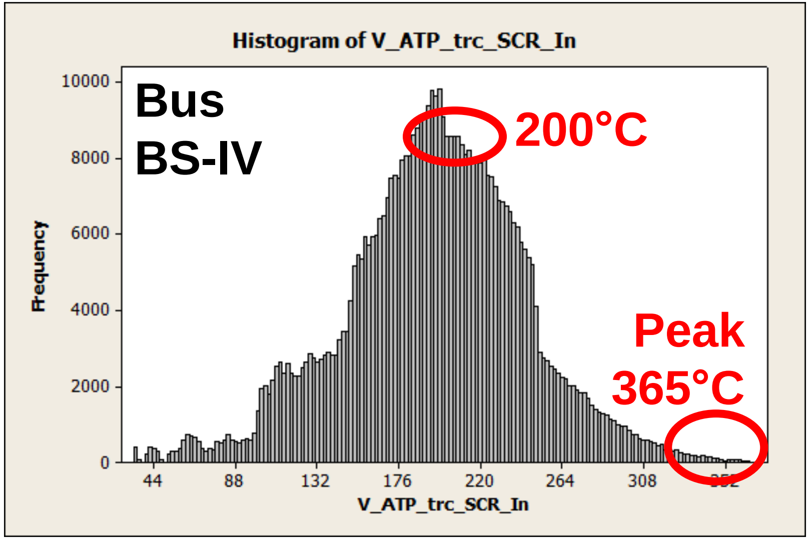
Switchback

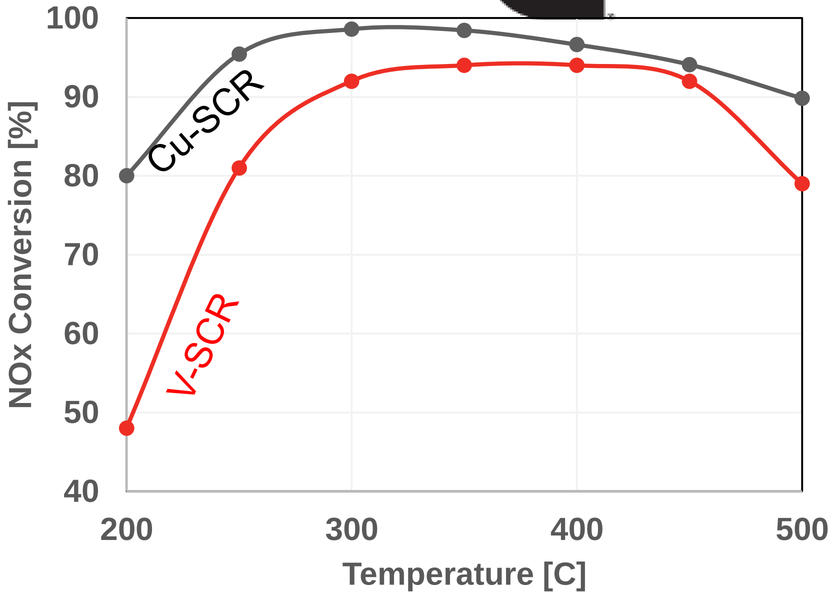
Single Module

ATS size reduction is enabled by the development of advanced catalyst and canning design



Cu-SCR and V-SCR technologies for NOx control





- Advanced aftertreatment systems are challenged by low-T duty cycle
- Cu-SCR, first introduced by CES in to HD market, shows higher NOx conversion at low temperatures
  - *Additional NO2 in the feed gas increases NOx conversion over V-SCR but still inferior to Cu-SCR*

Cu-SCR and V-SCR technologies for NOx control

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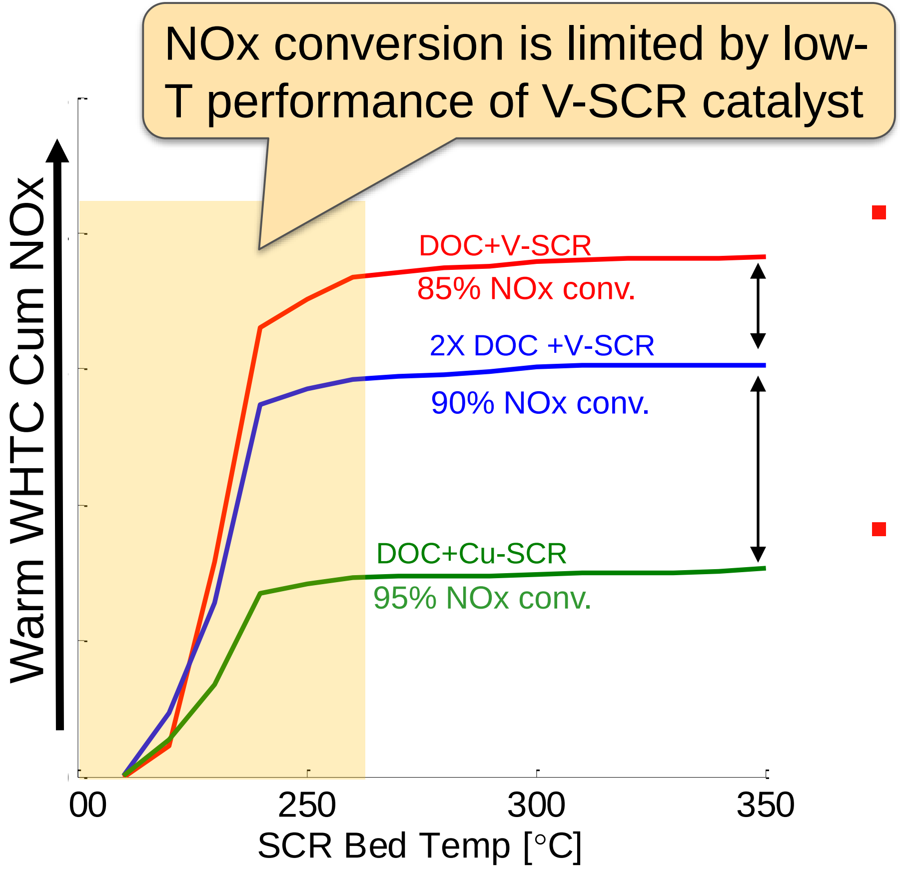

- Other levers to Improve V-SCR Performance
  - *SCR thermal management (fuel penalty)*
  - *About 30% V-SCR size increase*
  - *Upstream DOC PGM and Pt/Pd ratio increase*
- 33% Downsized Cu-SCR shows better NOx conversion than than V-SCR

BS-VI fuel quality is a primary consideration for aftertreatment architecture definition

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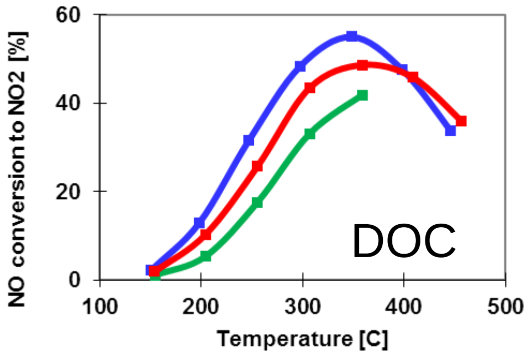
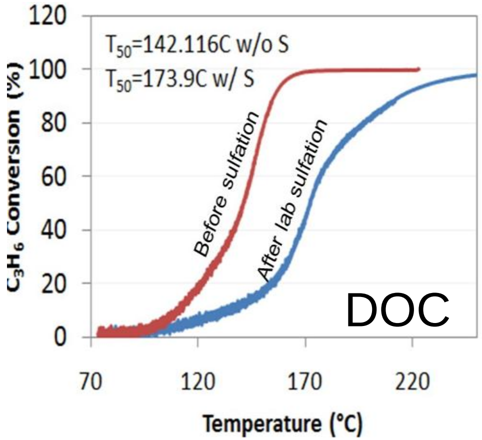
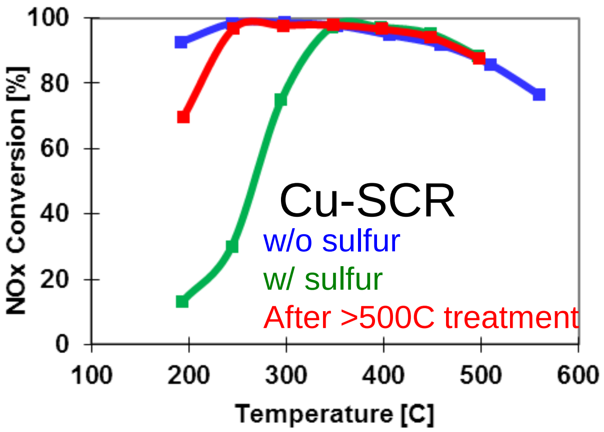




- DOC: Designed for low-T light-off and high S fuel will impact its performance leading to DPF and SCR performance loss



- Cu-SCR are sensitive to sulfur and need deSOx
  - *Typical DeSOx T >500C*
  - *High sulfur fuel increases the rate of deactivation and increases frequency of the desulfation event, resulting in a high fuel consumption penalty and catalyst aging*
- V-SCR has higher robustness to sulfur, but drives a significant increase in catalyst volume

Low-T SCR operation and high EO NOx poses challenges to RDE

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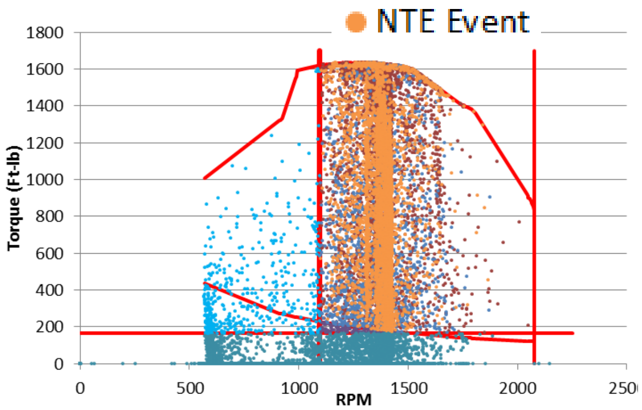
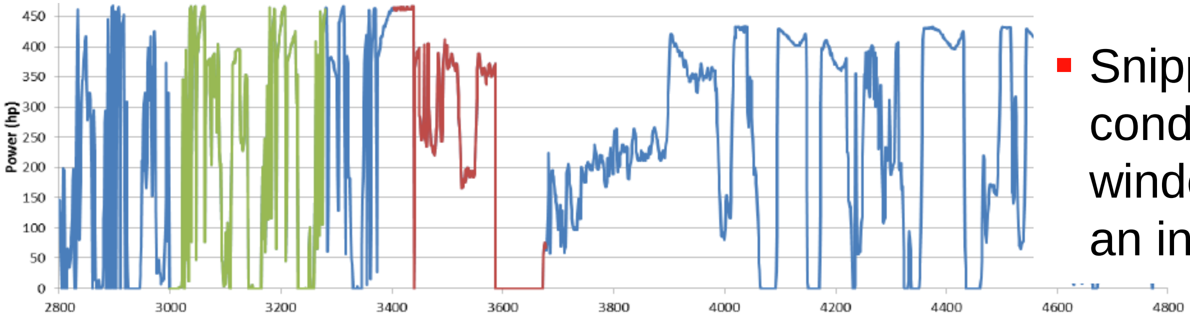
Low NOx workshop, November 3, 2016:
https://www.arb.ca.gov/msprog/hdlownox/downloads.htm

Parameter	Threshold
Torque	10%
Power	10%
Aftertreatment Temp.	No Exclusion
Time	10 seconds

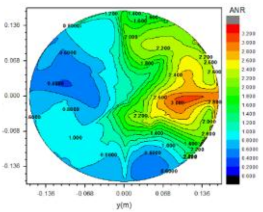


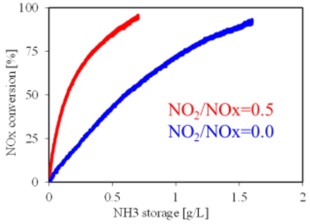
- Potential lower time, torque, power, temperature thresholds in combination with high EO NOx and low SCR temperature will be challenging to OBD, NTE and ISC

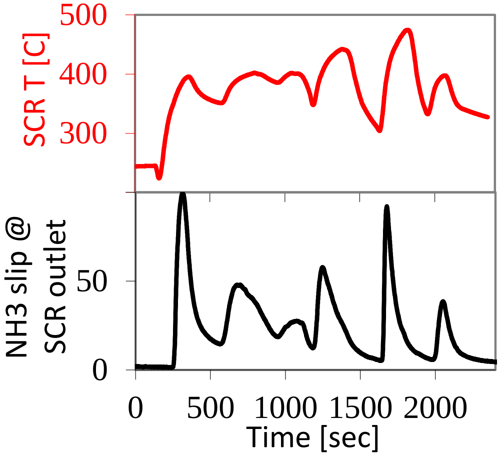


- Snippet of data from a test conducted on PEMS: A valid window is shown in green and an invalid one in red

NH3 storage and release events have to be controlled







- DEF over dosing
  - To compensate for parasitic NH3 oxidation, ANR non-uniformity, DOC and SCR catalyst aging
  - Could occur due to exhaust flow uncertainty, urea dosing variability
  - Needed for NH3 storage to achieve low-T NOx conversion
- Low to high T transients
  - Duty cycle, regen events
  - Amount of NH3 slip depends on SCR formulation, NO2/NOx, target NOx conversion among others
- Urea deposits decomposition
  - Infrequent event

NH3 slip must be minimized

- Regulations
  - Limit: 10ppm average on WHSC / WHTC
- TP sensor measures NH3 as NOx
  - Leads to false positive for high NOx emissions and impacts DEF dosing
- Odor threshold (sociability)
  - People can smell between 5-50 ppm
- OSHA / NIOSH (health and safety)
  - PEL - 50ppm
  - REL - 25 ppm TWA
  - STEL - 35ppm
  - IDLH - 300 ppm

Other factors of importance that could impact RDE

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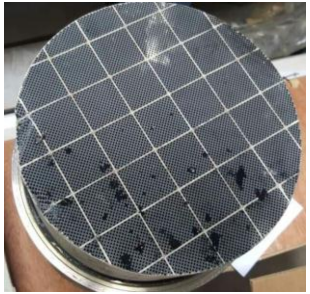
- NH3 storage and release, critical function for NOx conversion on SCR catalyst
  - *Changes in this function could lead to NH3 slip (limit to 10 ppm, NOx sensor cross sensitivity)*
- EUL aging of the catalysts
  - *Due to DPF regen (active vs passive)*
  - *Fuel / oil "S", Ash in lube*
  - *DEF contaminants*
- Sustained low temperature operation poses short and long term challenges to aftertreatment system performance
  - *DOC and DPF face plugging and associated issues*
  - *DPF maintenance (frequency is function of oil ash content) practices*
  - *DEF deposits*
  - *HC storage/release and light-off on ASC*

Field-returned systems



Low power duty cycle operation

Summary

- The similarity between the proposed BS-VI regulation and the European Euro VI regulation gives a natural starting point for the development BS-VI emission control technologies
- However, the market drivers in India are very different to Europe and require a significantly different approach to system design in order to deliver a product truly optimized for the market
- Reducing catalyst volume is a key enabler for material cost reduction throughout the aftertreatment system
- Fuel Sulphur level is a critical consideration when designing aftertreatment systems optimized for the India BS-VI market
- All of the above must be achieved in a very compressed timeline: BS-VI introduced nationwide by April 2020!