Prepared for:

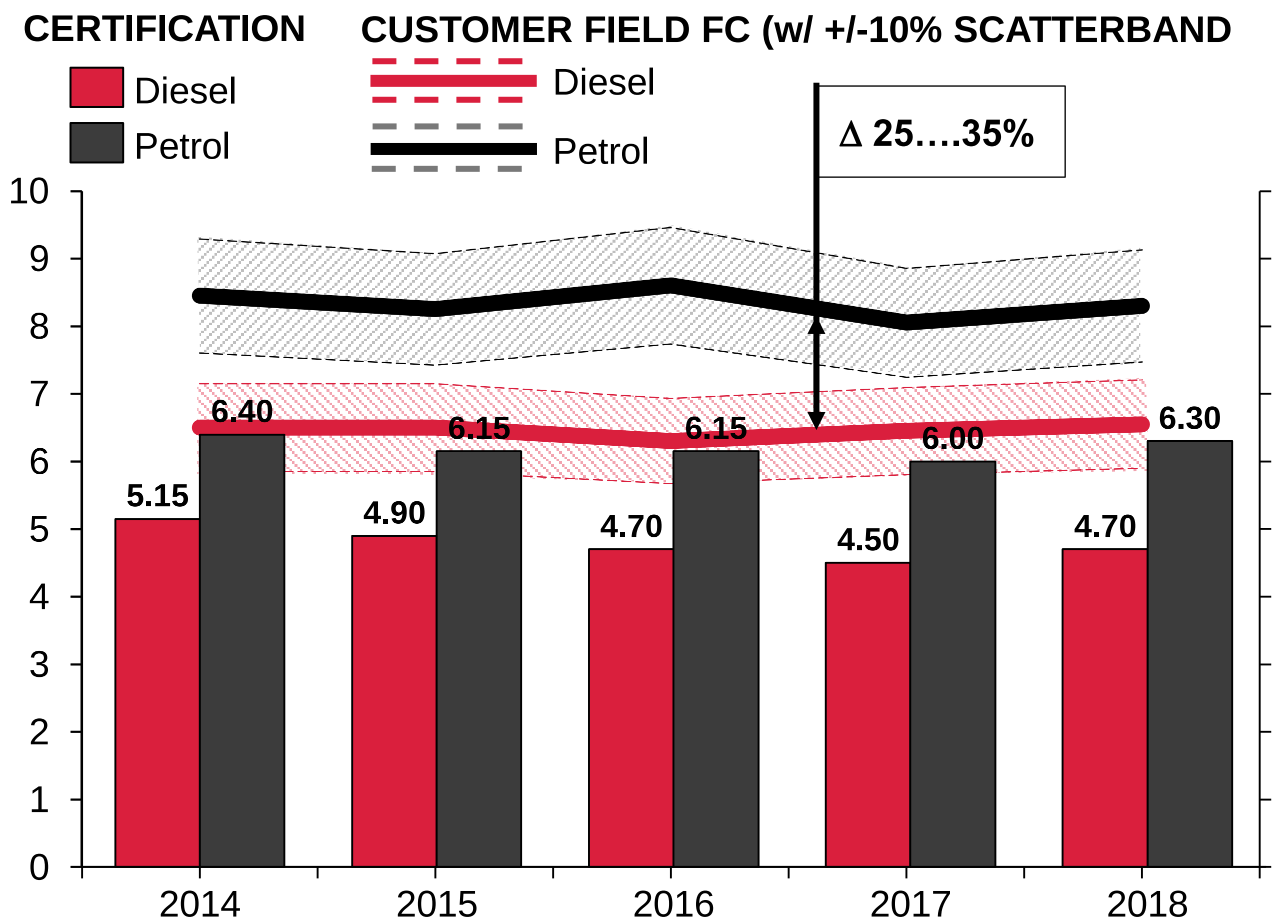
ECT 2019

FEV India, November 14th , 2019
Manoj Panda, FEV India & Thomas Körfer, FEV Group GmbH

For comprehensive GHG reduction the real world CO_2 footprint remains relevant, having substantial benefits for diesel-powered vehicles

FEV

IF REAL CO_2 EMISSIONS FROM MOBILITY REALLY COUNT ➔ DIESEL COMBUSTION PRINCIPLE IS 1ST CHOICE



- Substantial gap for both propulsion types for cert data vs. real world figures
- w/out deeper differentiation ≥25 % advantage for Diesel-powered vehicles
- Diesel powertrains play a key role in the OEM strategies to meet tighter CO_2/CAFE standards
- Modern Diesel powertrains keep the advantage despite more complex emissions controls systems
- Weight difference in typical Petrol/Diesel applications not considered here.

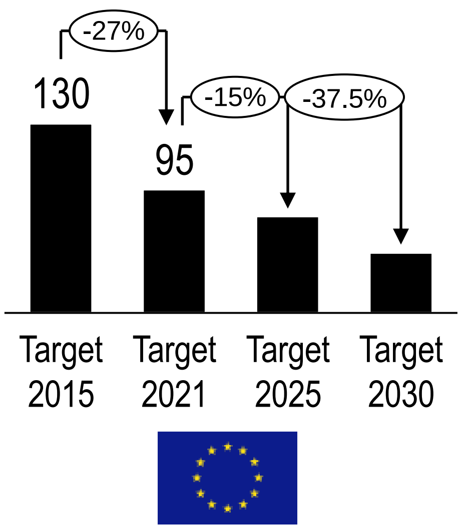
Source: EmissionAnalytics; FEV

Until 2025 fleet average CO_2 emissions will be reduced by more than 30% vs. 2015 baseline in EU, US, CN and JP…..IN to follow

FUEL ECONOMY/GHG/ CO_2 REGULATION – **PASSENGER CARS (M1 CATEGORY)**

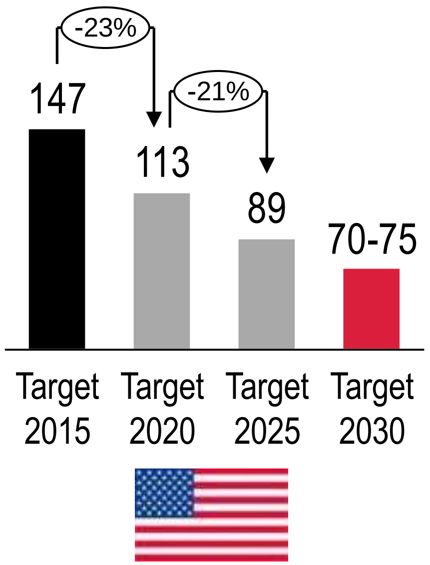
Confirmed   Proposed target (under review)   Scenario

NEDC
CO_2 emission in g/km



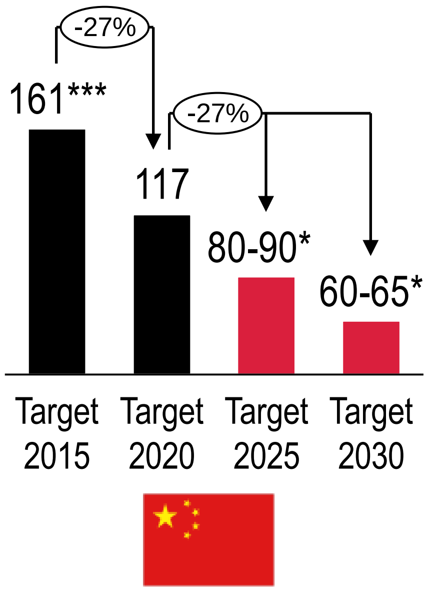
Passenger Car

EPA 2-cycle
CO_2 emission in g/km



Passenger Car

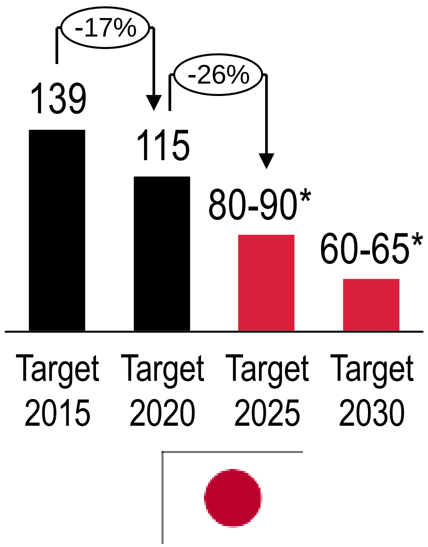
NEDC
CO_2 emission in g/km*



Passenger Car

Note: Target in 2015: 6.9*** L/100km; in 2020 5.0 l/100 km
Conversion 2340* gCO2/l used

JC08 drive cycle
CO_2 emission in g/km



Passenger Car

Note: Target in 2015: 6.9 L/100km; in 2020 5.0 l/100 km
Conversion 2340* gCO2/l used

* Scenario, China is expected to recover EU targets and Japan will show similar values; ***): No fleet target – calculated form individual targets
// values for EU and CN are based on NEDC to gain comparability, for CN & JP figures are converted from l/km; **): gasoline conversion factor: 23.2 g/l; Diesel conversion factor: 26.5 g/l)
Source: ICCT, European Commission, Bosch, ACEA, FEV

SCR integrated into DPF as well as dual dosing will increase rise in market penetration due to increasingly stringent emission legislation

TECHNOLOGY MATURITY: EMISSION CONTROL

	Technology maturity			Market penetration								
				EU			China			USA		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Advanced late post injection	Series development phase	Series development phase	Series development phase	100%	100%	100%	100%	100%	100%	100%	100%	100%
External fuel dozer	Series development phase	Series development phase	Series development phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
Electric heated catalyst	Concept phase	Series development phase	Series development phase	0%	<5%	<25%	0%	0%	<25%	0%	<5%	<25%
SCR integrated in DPF[1)]	Series development phase	Series development phase	Series development phase	<50%	<100%	100%	<25%	<75%	100%	<25%	<100%	100%
NH_3 Sensor	Concept phase	Series development phase	Series development phase	0%	<5%	<25%	0%	<5%	<25%	0%	<5%	<25%
Passive only DPF[2)]	Research phase	Research phase	Concept phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
Passive NO_x adsorber	Concept phase	Concept phase	Concept phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
PM Sensor	Concept phase	Series development phase	Series development phase	100%	100%	100%	<75%	100%	100%	100%	100%	100%
SCR Dual Dosing	Concept phase	Series development phase	Series development phase	0%	<100%	<100%	0%	<75%	<100%	0%	<100%	<100%
Through-flow DPF	Series development phase	Series development phase	Series development phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
Wall-flow DPF	Series development phase	Series development phase	Series development phase	100%	100%	100%	100%	100%	100%	100%	100%	100%

1) Includes systems w/ and w/o dual dosing, 2) w/o active regeneration backup
Source: FEV

Technology Maturity: Research phase, Concept phase, Series development phase
Market penetration: 0%, <5%, <25%, <50%, <75%, <100%, 100%

Variable geometry turbochargers will continue to have the highest market share; electrified solutions gain traction starting from 2025

TECHNOLOGY MATURITY: AIR MANAGEMENT

	Technology maturity			Market penetration								
				EU			China			USA		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Two stage turbocharger	Series development phase	Series development phase	Series development phase	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<25%	<25%
Advanced turbocharger[1)]	Research phase	Concept phase	Series development phase	0%	0%	<5%	0%	0%	<5%	0%	0%	<5%
Electric turbo compressor	Concept phase	Series development phase	Series development phase	0%	<25%	<25%	0%	<5%	<25%	0%	<5%	<5%
Electric assisted turbocharger	Concept phase	Concept phase	Series development phase	0%	0%	<25%	0%	0%	<25%	0%	0%	<5%
Variable turbine geometry	Series development phase	Series development phase	Series development phase	<75%	<75%	<50%	<50%	<50%	<50%	<50%	<50%	<50%
Cylinder deactivation	Research phase	Concept phase	Series development phase	0%	0%	<75%	0%	0%	<25%	0%	0%	<25%
Variable Valve Lift (VVL)	Research phase	Concept phase	Series development phase	0%	<5%	<25%	0%	0%	<5%	0%	0%	<5%
Variable Valve Timing (VVT)	Research phase	Concept phase	Series development phase	0%	<5%	<5%	0%	0%	<5%	0%	<5%	<5%

Note: 1) Advanced turbocharger for LCVs refers to advanced geometry design by additive manufacturing and roller bearings for turbochargers
Source: FEV

Technology Maturity: Research phase, Concept phase, Series development phase
Market penetration: 0%, <5%, <25%, <50%, <75%, <100%, 100%

In PC markets cooled high pressure EGR is state of the art, some systems are combined with low pressure EGR

TECHNOLOGY MATURITY: EXHAUST GAS RECIRCULATION

	Technology maturity			Market penetration								
				EU			China			USA		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Cooled high pressure EGR	Series development phase	Series development phase	Series development phase	<100%	<100%	<100%	<100%	<100%	<100%	<100%	<100%	<100%
Cooled low pressure EGR	Series development phase	Series development phase	Series development phase	<50%	<50%	<75%	<50%	<50%	<75%	<75%	<100%	<100%
No EGR concepts	Series development phase	Series development phase	Series development phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
Non-cooled high pressure EGR	Series development phase	Series development phase	Series development phase	<25%	<5%	0%	<25%	<5%	0%	<5%	<5%	0%

TECHNOLOGY MATURITY: ACTUATORS

	Technology maturity			Market penetration								
				EU			China			USA		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Variable mech. oil pump	Series development phase	Series development phase	Series development phase	100%	100%	100%	100%	100%	100%	100%	100%	100%
Electric oil pump	Concept phase	Concept phase	Concept phase	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable mech. water pump	Series development phase	Series development phase	Series development phase	<50%	<75%	<50%	<50%	<75%	<50%	<50%	<75%	<50%
Electric water pump	Series development phase	Series development phase	Series development phase	<5%	<25%	<50%	<5%	<25%	<50%	<5%	<25%	<50%

Technology Maturity: Research phase, Concept phase, Series development phase

Market penetration: 0%, <5%, <25%, <50%, <75%, <100%, 100%

Source: FEV

Control technologies will increase shares across all markets; especially advanced model based controls will have a high market penetration

TECHNOLOGY MATURITY: CONTROL SYSTEM TECHNOLOGIES

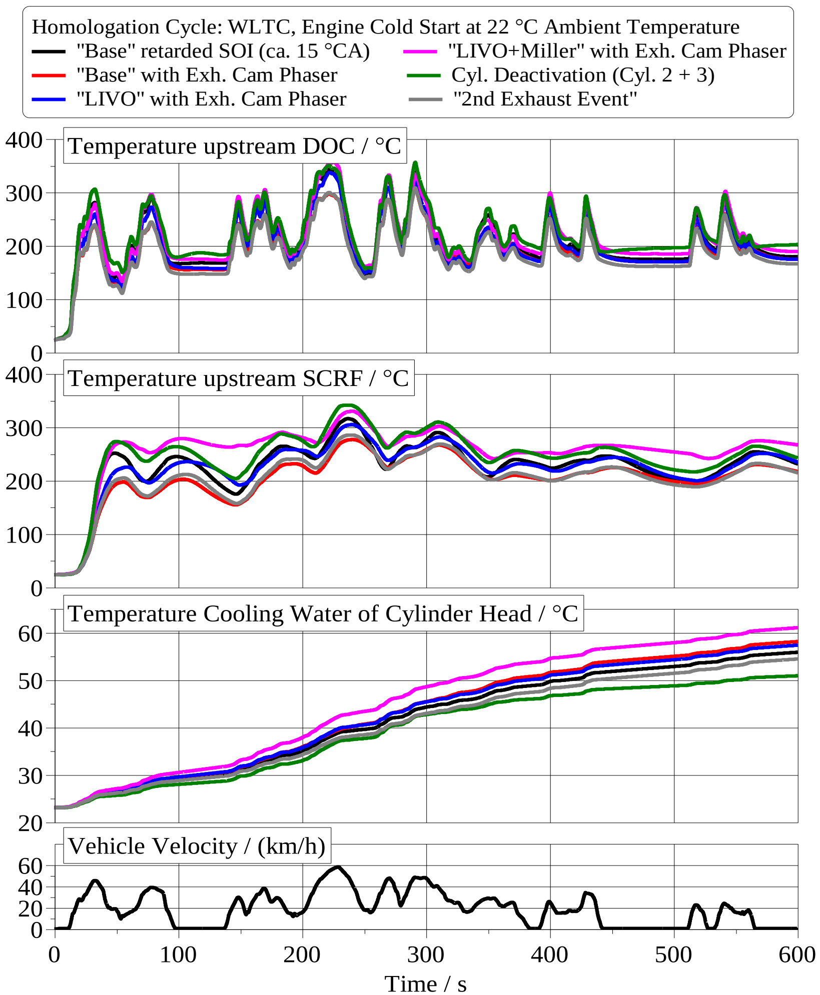
	Technology maturity			Market penetration								
				EU			China			USA		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Adaptive ECU	Series development phase	Series development phase	Series development phase	0%	<5%	<50%	0%	<5%	<50%	0%	<5%	<50%
Advanced model based controls	Series development phase	Series development phase	Series development phase	<50%	<75%	<100%	<50%	<75%	<100%	<50%	<75%	<100%
Closed loop combustion control	Concept phase	Series development phase	Series development phase	0%	<5%	<50%	0%	<5%	<50%	0%	<5%	<50%
Condition based maintenance	Concept phase	Series development phase	Series development phase	0%	<25%	<75%	0%	<25%	<50%	0%	<5%	<25%
Closed loop combustion rate shaping	Concept phase	Series development phase	Series development phase	0%	<5%	<25%	0%	<5%	<25%	0%	<5%	<25%
Open loop combustion rate shaping	Concept phase	Series development phase	Series development phase	0%	<50%	<25%	0%	<50%	<25%	0%	<50%	<25%

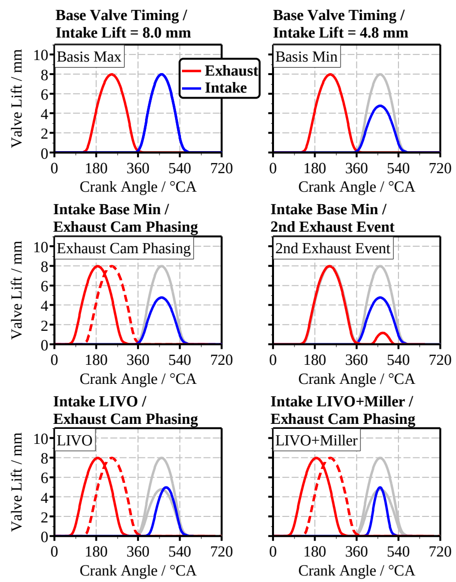
Technology Maturity: Research phase, Concept phase, Series development phase

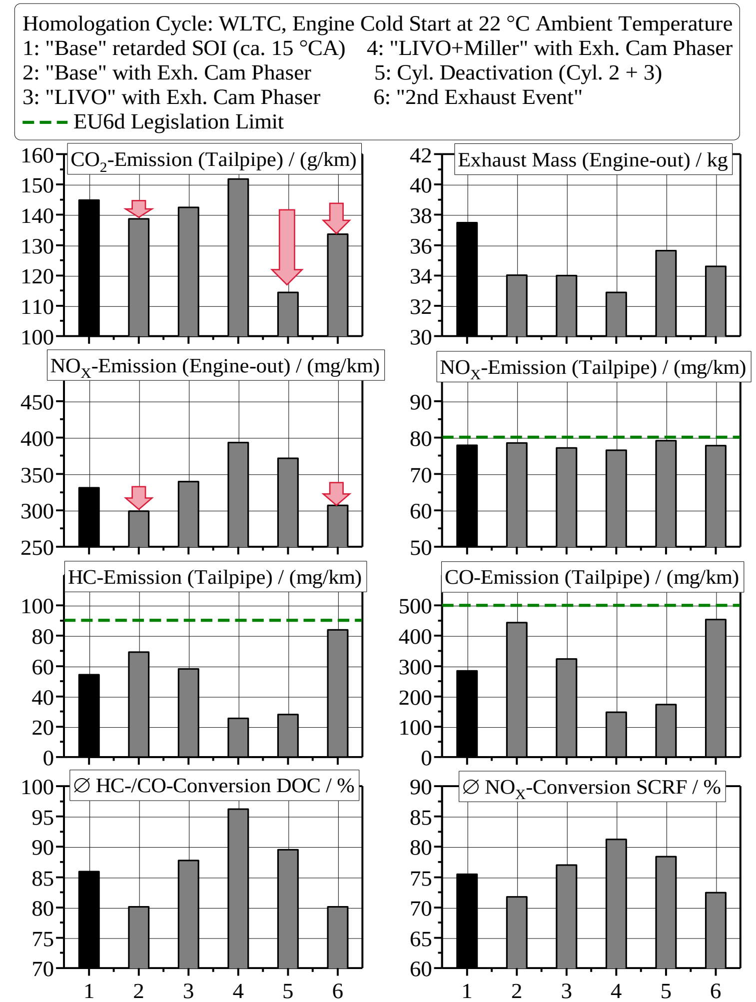
Market penetration: 0%, <5%, <25%, <50%, <75%, <100%, 100%

Source: FEV

Fuel-efficient Thermal Management of Exhaust line is strongly supported by multiple functionalities from applied VVA technologies in specific modes



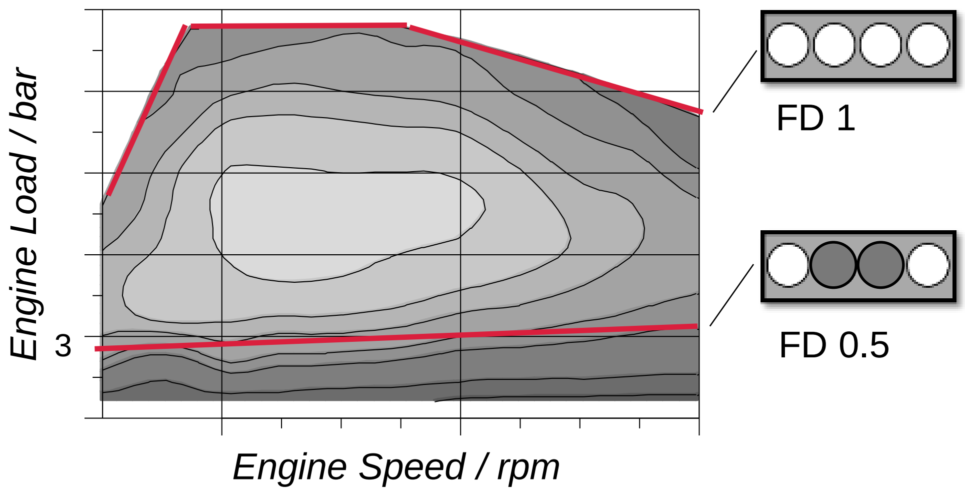




LD-Engine Efficiency Improvement
Cylinder Deactivation (CDA) and Dynamic Skip Fire (DSF)

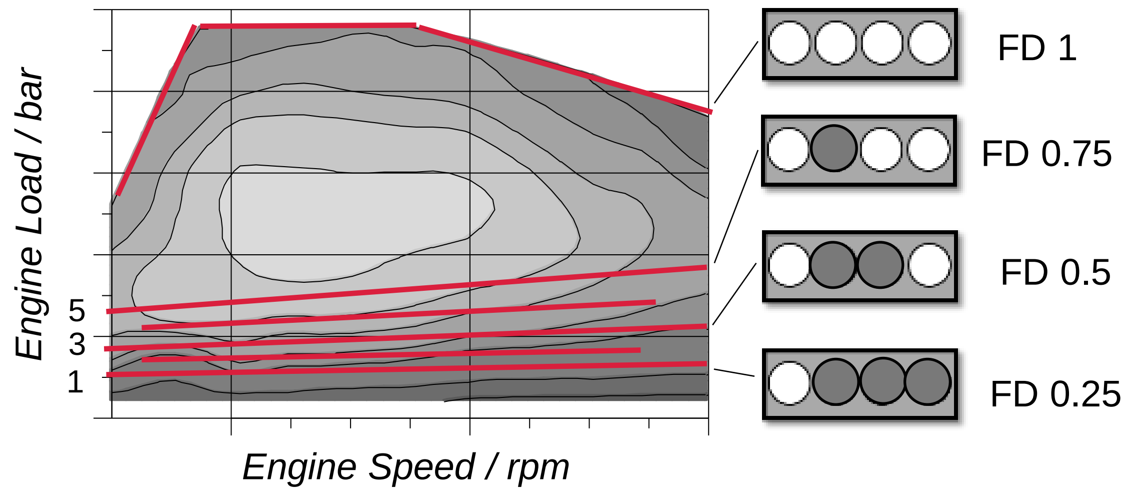
CDA

- Hard swich between 4 and 2 cylinders mode as function of engine operating point
- Firing density (FD) 1 and 0.5 only



DSF

- Continuous dynamic switch between
  - FD 1 → full engine
  - FD 0 → deceleration cylinder cut-off (DCCO)



LD-Engine Efficiency Improvement
WLTC Simulation of CDA and DSF

BASE ENGINE – CDA - DSF COMPARISON

WLTP Cycle / Min CO2 GSS			Base Eng	CDA		dDSF	
			Val	Val	Variation %	Val	Variation %
C-Seg Vehicle	CO2	g/km	135	133.9	-0.8	129.5	**-4.1**
	EO NOx	mg/km	221.5	221.7	+0.1	224.6	+1.4
	TP NOx	mg/km	45.2	44.8	-0.9	44.4	**-2.0**
	NOx eff.	%	80	80	+0.2	80	+0.9
SUV Vehicle	CO2	g/km	174.0	173.2	-0.9	170.1	**-2.2**
	EO NOx	mg/km	411.3	411.6	+0.1	413.9	+0.6
	TP NOx	mg/km	61.8	62.0	+0.3	61.9	+0.1
	NOx eff.	%	85	85	0.0	85	+0.1

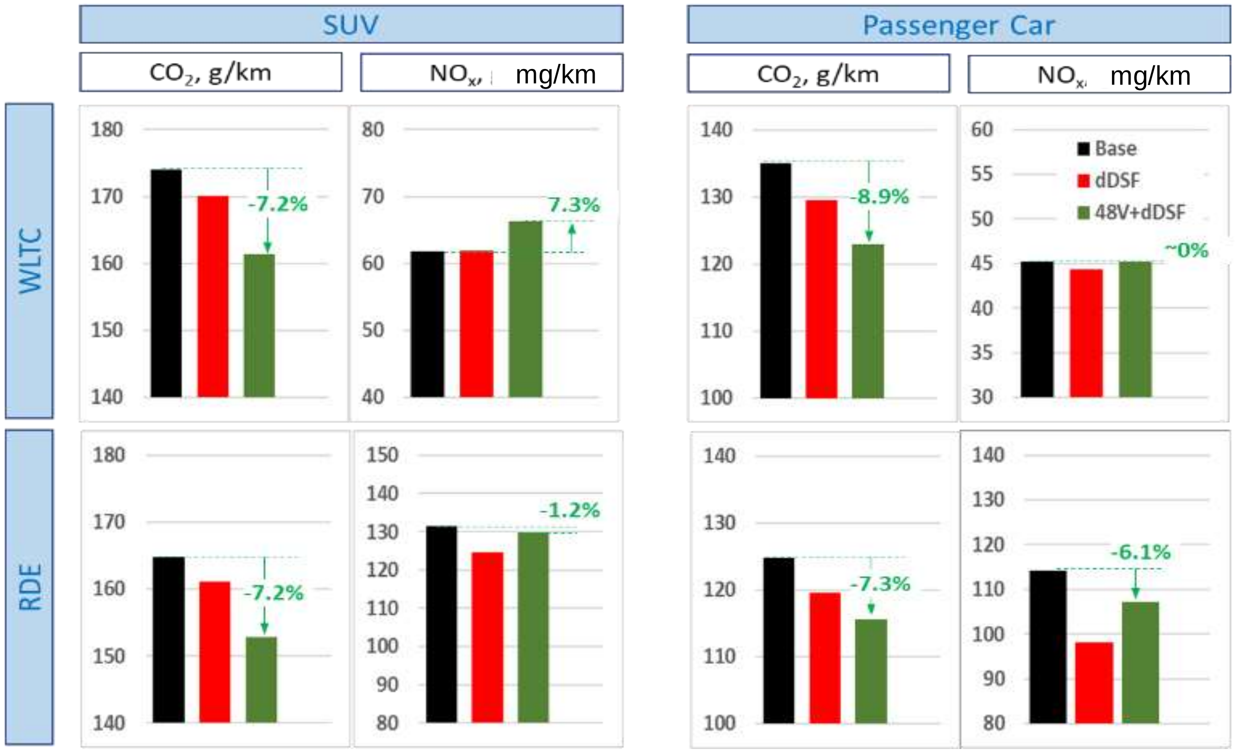
- Increased operating range with deactivated cylinders with DSF offeres significant fuel economy benefit over CDA

Intelligent combination of future technologies – mild hybridization and advanced cylinder deactivation – enlarge improvement potential

FEV

48V TECHNOLOGY COLLABORATES PERFECTLY WITH TAILORED DSF STRATEGIES

48V BSG



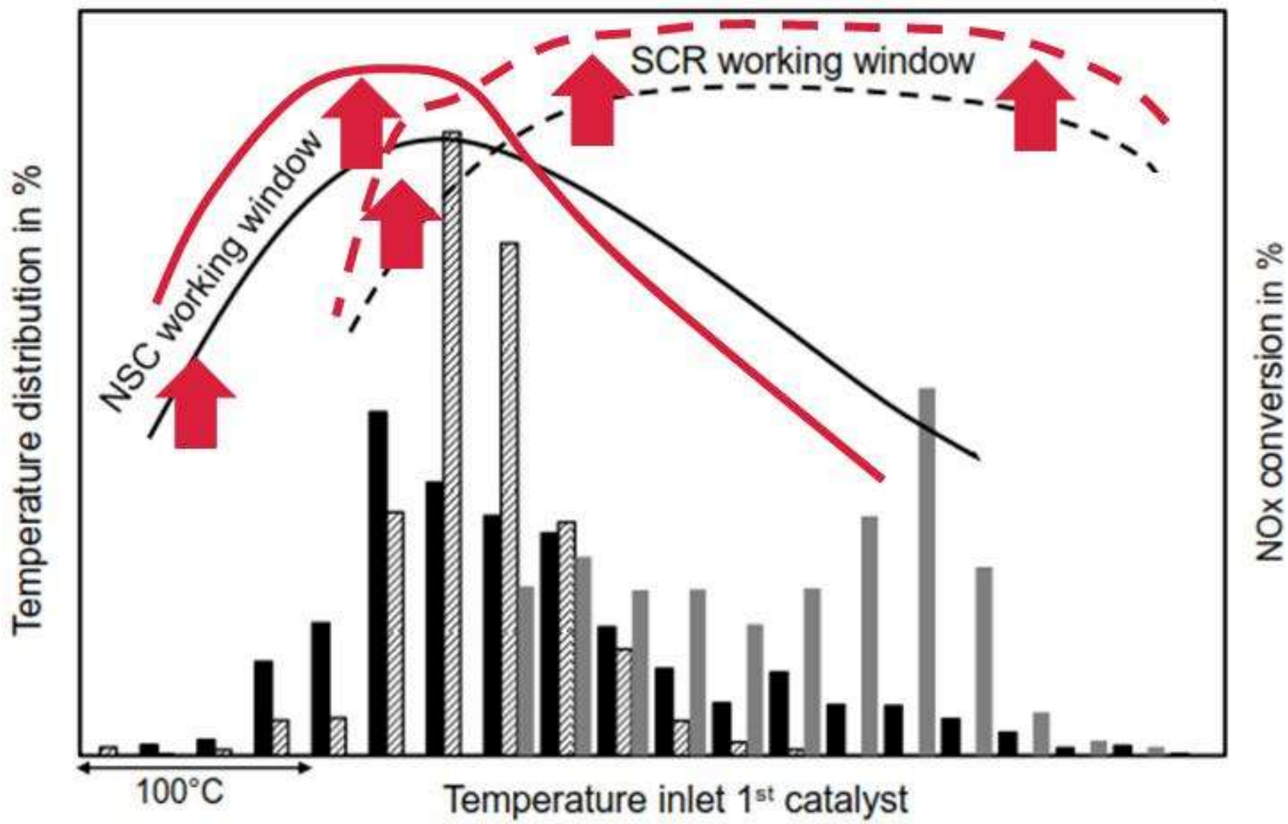
The synergy between DSF technology and 48V mild hybrid further improve CO2 emissions to as high as 8.9%

TULA

Source: FEV

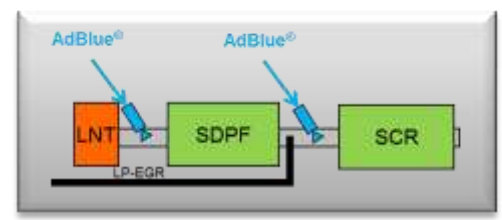
Future EATS Systems are designed to achieve the widest possible temperature window with highest conversion efficiencies

COMBINED DENOX-EFFICIENCY OF LNT AND SCR



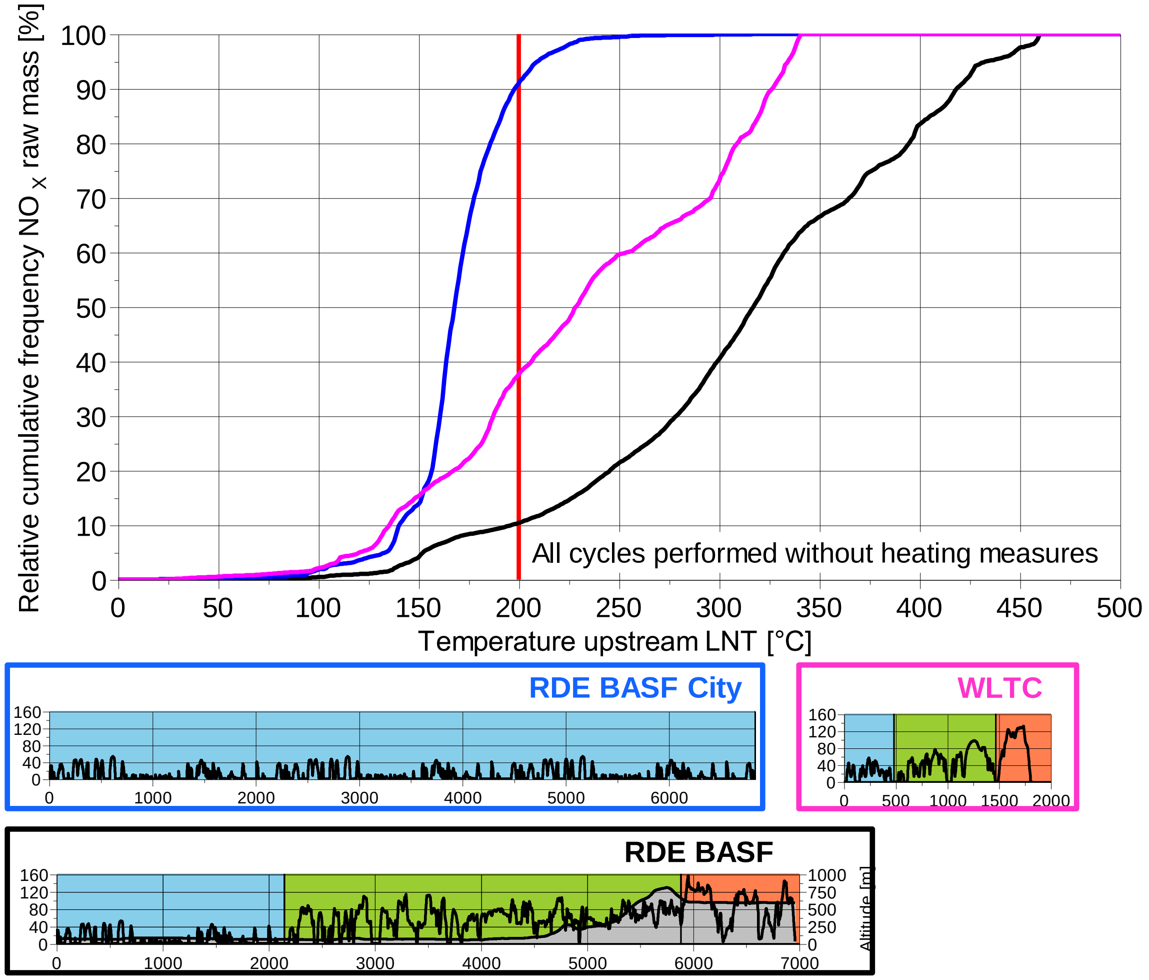
Comments

- LNT serves for low temperature NOx conversion
- SCR efficiency is focused on higher temperature regime
- Dual dosing increases total SCR efficiency in entire SCR temperature regime



Low speed city driving is the most challenging for the EATS Low Temperature NO_x conversion as major challenge

COMBINED DENOX-EFFICIENCY OF LNT AND SCR



Source: BASF, FEV. MinNox 2018

Comments

- Highly ambitious urban RDE profile:
  - NO_X engine out emissions at < 200°C
  - LNT temperature < 200°C
  - $DeNO_X$ release > ~175°C mean LNT temperature

→ **Heating strategy required**

- Mixed trip profile w/ high SCR efficiency:

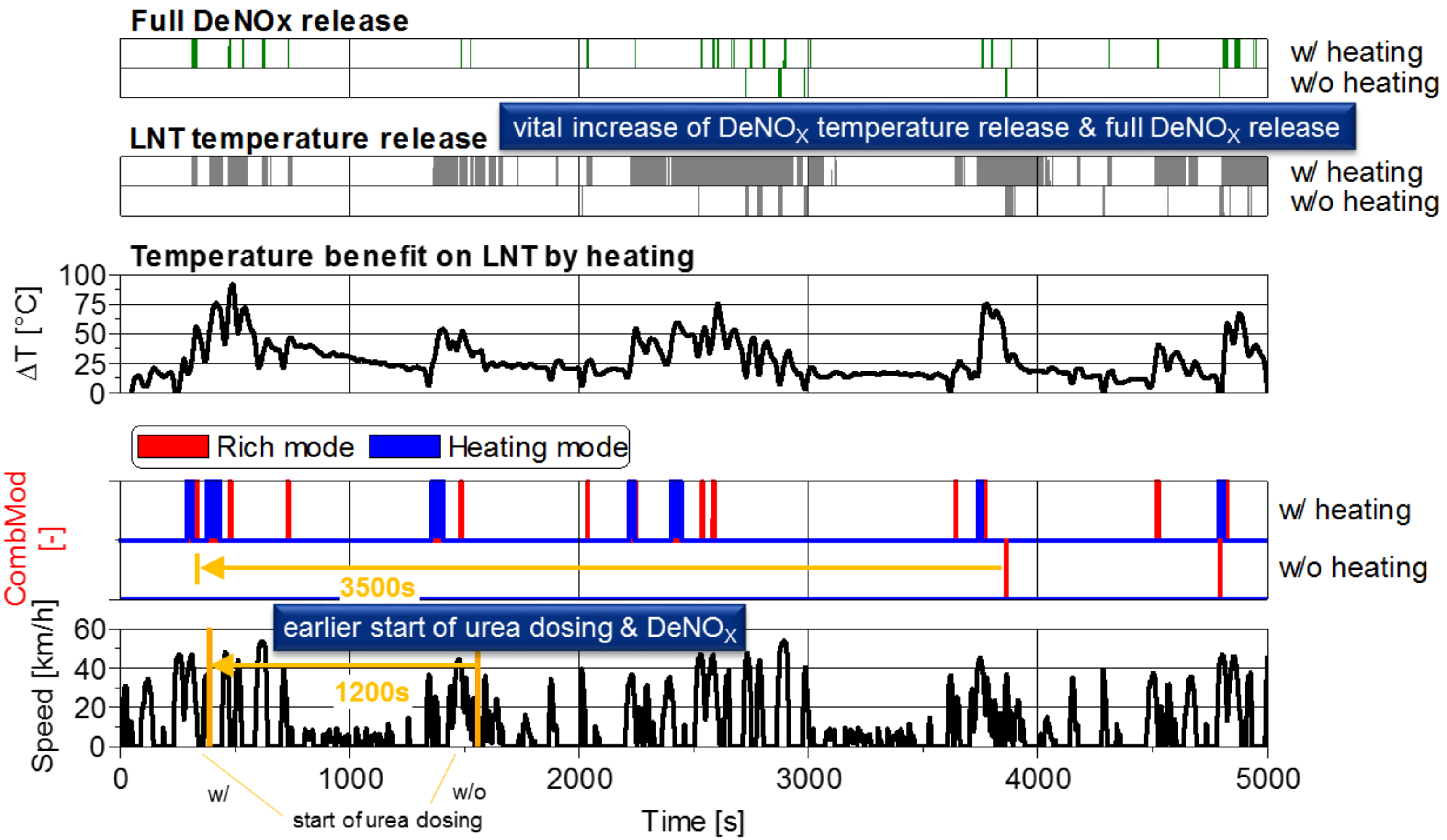
→ **Combined coordinator for LNT & SCR is mandatory**

- Furthermore: uphill driving & strong accelerations w/ high NO_X raw emissions

→ **Inclusion of AMOx for NO_X reduction is necessary**

Heating Enables Early LNT $DeNO_x$ and SCR DeNOx
Engine Heating Mode for LNT Applied

EXAMPLE FOR LOW LOAD RDE CYCLE WITH C-CLASS VEHICLE EU6D

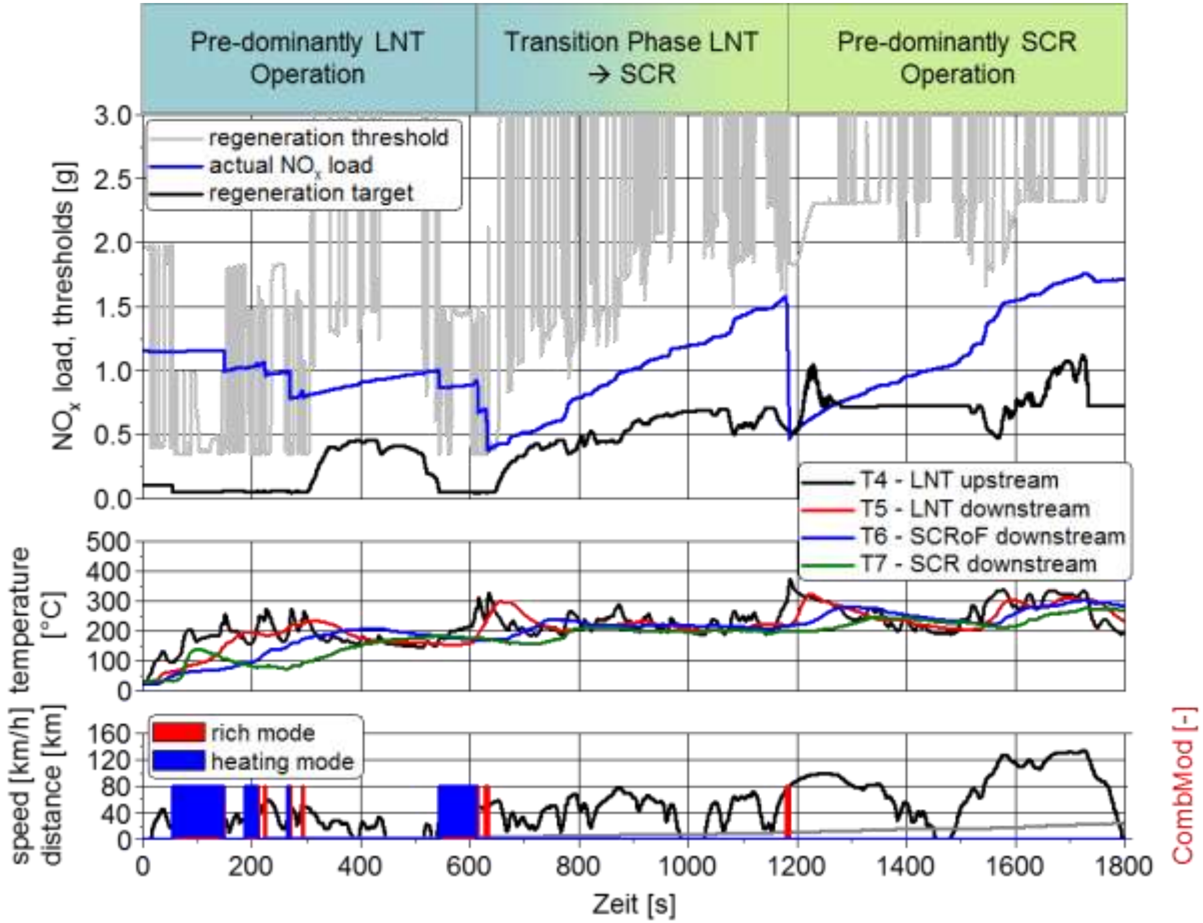


average release temperatures: DeNOx ~ 175 °C, urea dosing ~170°C

Source: BASF, FEV. MinNox 2018

Combined Coordinator for LNT & SCR Control
Separation of Operation Windows

EXAMPLE: WLTP WITH C-CLASS VEHICLE EU6D



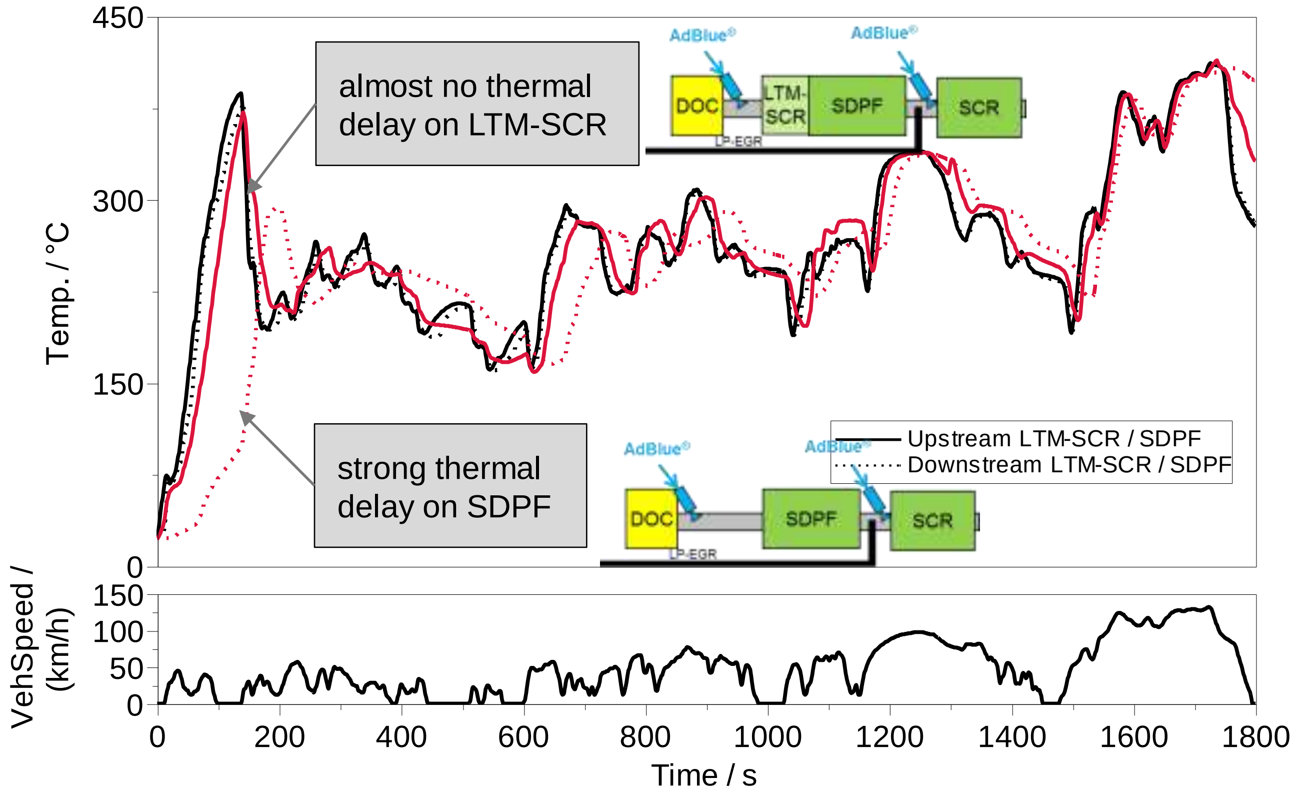
Source: BASF, FEV. MinNox 2018

Comments

- High LNT regeneration frequency during city phase
- Depending on SCR performance and system status coordinator realizes change in several functions of LNT operation strategy
- At maximum SCR performance no complete LNT deactivation to avoid high NOX loadings at end of vehicle operation

Clustered and tailored DeNOx compounds deliver extended functional windows and provide the requested reserves for robust tailpipe emissions

EXAMPLE: SDPF VS. LT-SCR/SDPF IN WLTC CYCLE



Results

- SDPF downstream temperature shows a strong delay in temperature increase due to
  - high thermal mass of SDPF substrate
  - evaporation of condensed water in the porous substrate
- LTM-SCR shows very fast temperature rise downstream brick
  - very low thermal mass
  - only neglegible amount of trapped condensed water

→ light-off advantage for LTM-SCR

Source: FEV

Mainstream EATS topologies for ultra-low Post EU-6d / CN-6b emission standards without electrification - Improved Cascaded DeNOx-Systems

<table>
<tr><th>Layout</th><th>Remarks</th></tr>
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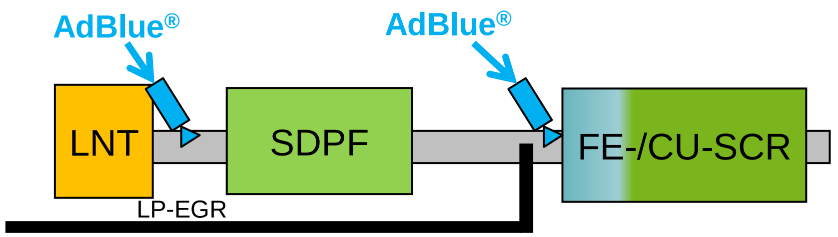

</td><td>
LNT focused / experienced OEMs LNT
+ combines all advantages of LNT and twin dosing
+ fits even for very challenging applications
+ FE-/CU-Zeolith in UF for extra-high temperatures SCR
- very complex control (LNT and 2 x active SCR)
- high system costs
- high application effort
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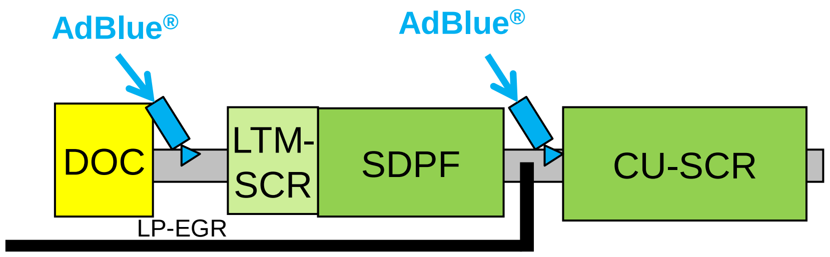
Mainstream for heavier/LCV Applications



LTM-SCR: low thermal mass SCR (e.g. on metal substrate)
</td><td>
SCR focused and non LNT experienced OEMs
+ LT-SCR serves for low temperature NO_x conversion due earlier light off LT-SCR
+ Increased robustness of high SCR-conversion rates
+ Reduced control complexity (only SCR)
- Challenging towards installation space → possibly reduction of SDPF volume
- reduced passive regeneration
</td></tr>
</table>

Source: FEV

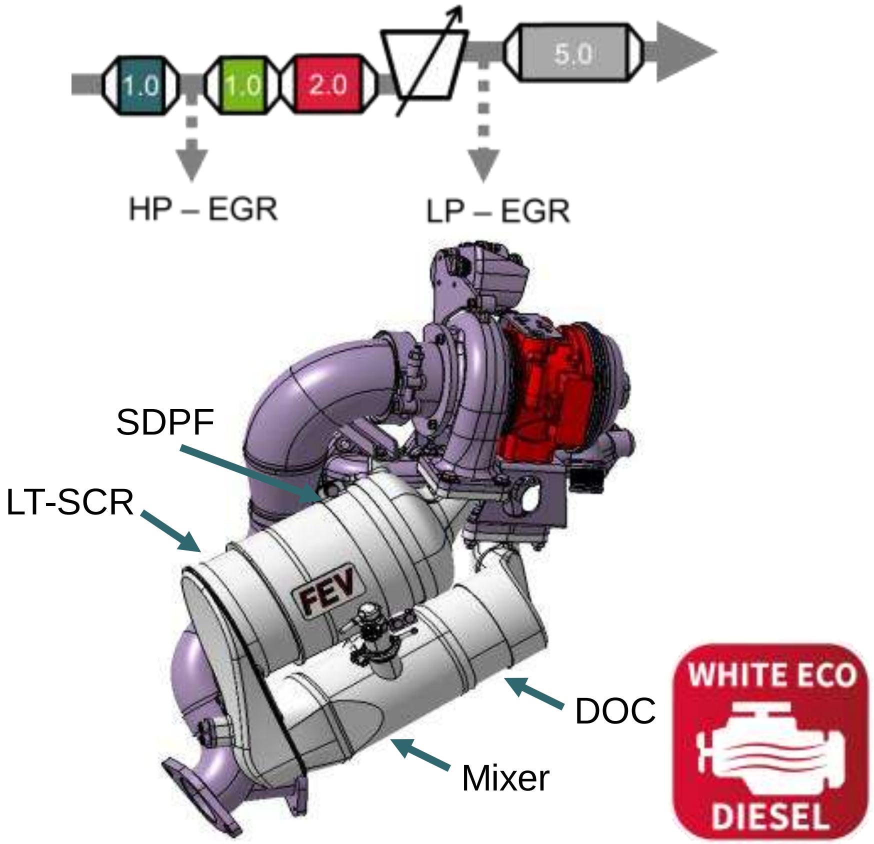
FEV White Eco Diesel
Summary

MAJOR ACHIEVEMENTS AND RESULTS → COMPETITIVE DIESEL POWERTRAIN BY 48V FULL USE

Results

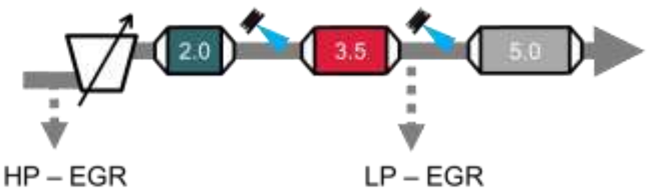
- Specification of 48-Volt MHD platform including:
  - 11kW electric turbocharger with VGT
  - optimized & resized pre-turbine EATS layout
  - adjusted EGR concept
  - mild-hybrid operation strategy incl. controls for electric turbocharger
- The White Eco Concept shows:
  - A potential to comply with low NOx emission @ 35mg/km even in low load driving cycles
  - A significant CO_2 saving potential from reduced exhaust heating in low load driving cycles
- Next steps:
  - Final vehicle calibration and testing (hybrid system, air-path, e-TC, dual dosing SCR, …)

Final Pre-Turbine EATS Design



FEV White Eco Diesel
Benchmark of Final System Layout

FUEL PENALTY WHEN ENGINE HEATING MEASURES ARE USED TO ACHIEVE MAX. 35MG/KM NOX EMISSION

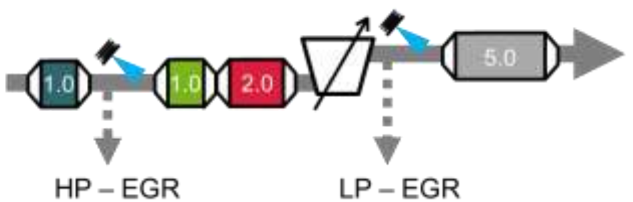


Reference System (12 V):

- 12 V w/ alternator

Reference System (48 V):

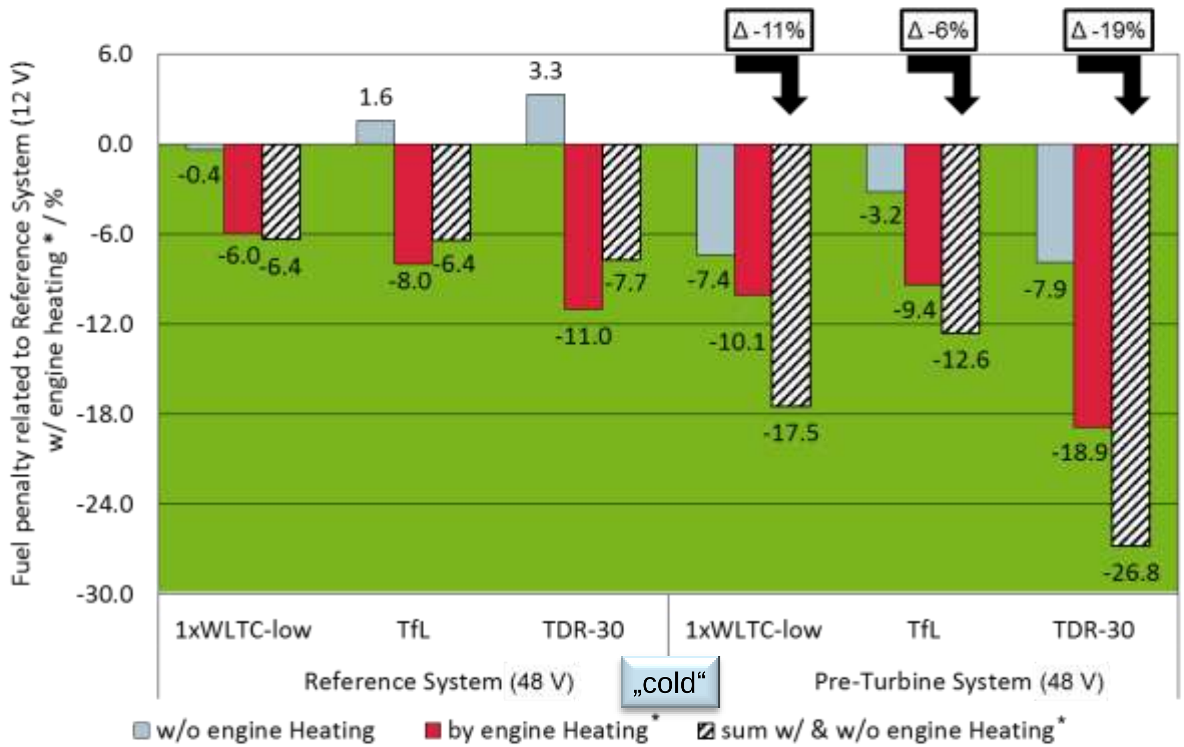
- 48 V w/ BSG
- 48 V e-DOC
- Bidirectional DC/DC converter



final Pre-Turbine System (No. 6, 48 V):

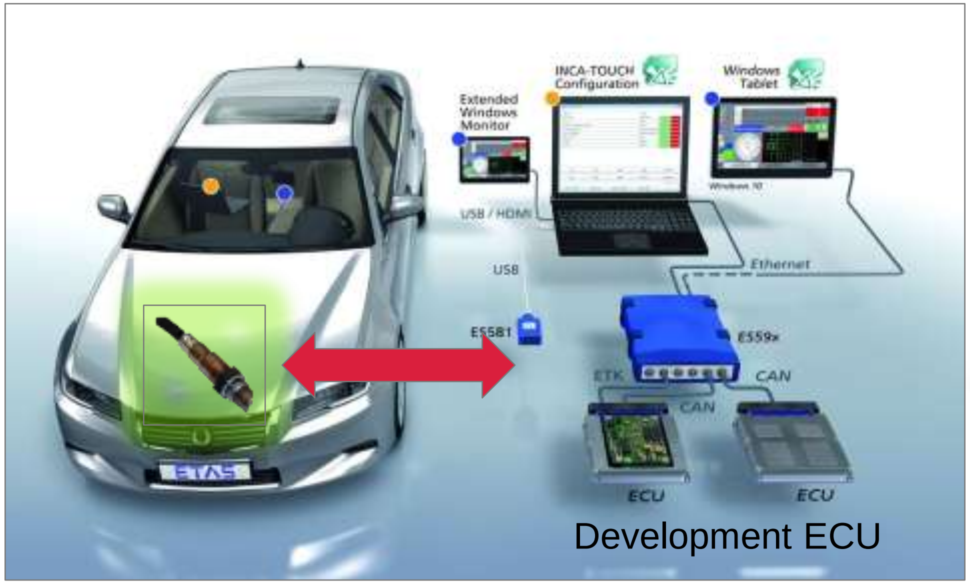
- 48 V w/ BSG
- 48 V e-Turbocharger
- Bidirectional DC/DC converter

* Volumes in l **(DOC LT-SCR SDPF UB-SCR)**



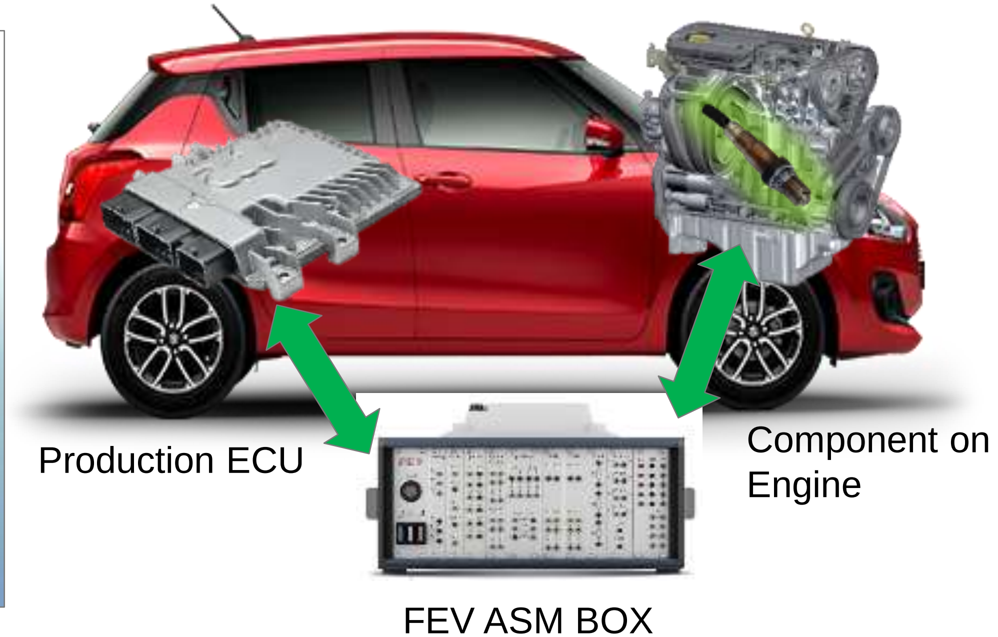
Functional Fault Simulation for OBD Type approval Demonstration Traditional Vs FEV ASM BOX approach

Traditional Approach - Functional Fault Demonstration



- Traditional Approach uses Development ECU Environment and Development Tools i.e.INCA to enable demonstration
- Development Environment for OBD Demonstration Test is NOT PREFERRED by Certification Agencies
- Proto sensor / actuator needed to simulate the OBD Failure – more efforts, time and cost

ASM BOX APPROACH



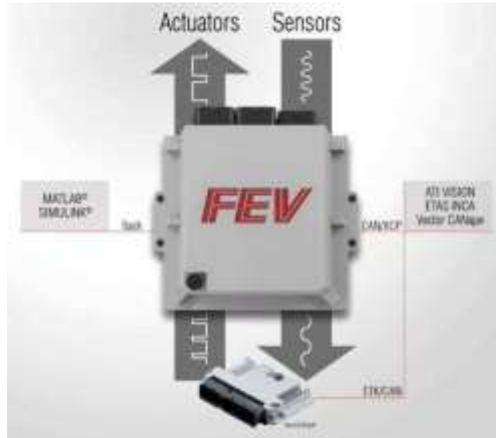
- FEV's ASM BOX Approach uses Production ECU Environment and Model Based simulation to enable demonstration
- Production ECU Environment & ASM BOX Simulation approach is approved by CARB for OBD Demonstration Test & Most Preferred by Certification Agencies worldwide

FEV' Unique Approach for OBD Fault Simulation – ASM BOX General Working principle

APPLICATION POSSIBILITIES

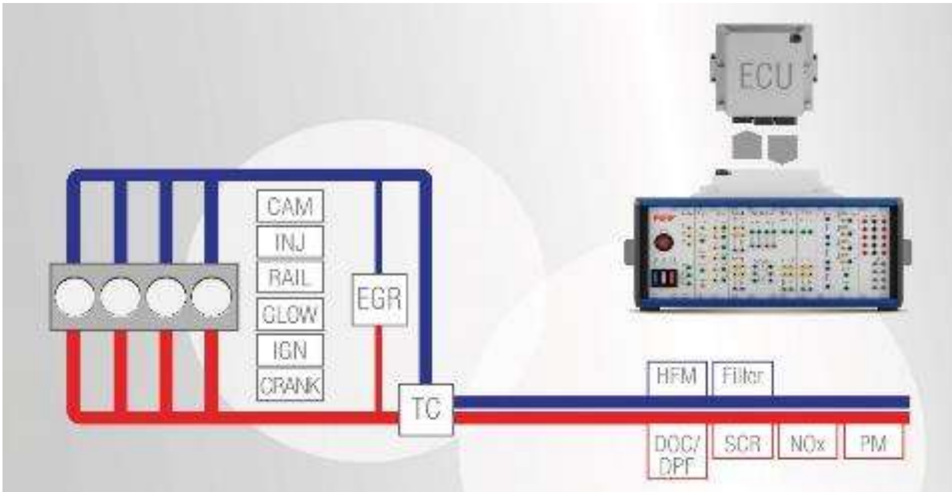
Traditional Approach

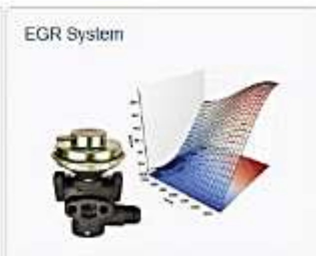
FEV ASM BOX Approach

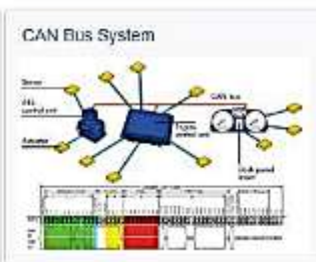


- ASM Box serves for simulation of OBD relevant failure pattern by modulation of electrical signals which are exchanged between the ECU and emission-related actuators and sensors
- No faulty hardware required for failure generation
- Based on powerful RCP system with MPC5674F processor and FPGA
- Ruggedized electronics and housing for in-vehicle use
- Time synchronous sampling of ECU data and ASM box data by XCP connection
- Available in many stages of expansion

FEV' Unique Approach for OBD Fault Simulation – ASM BOX
OBD Demonstration for Type Approval, COP, Robustness Evaluation







ASMBOX for OBD Type Approval & COP

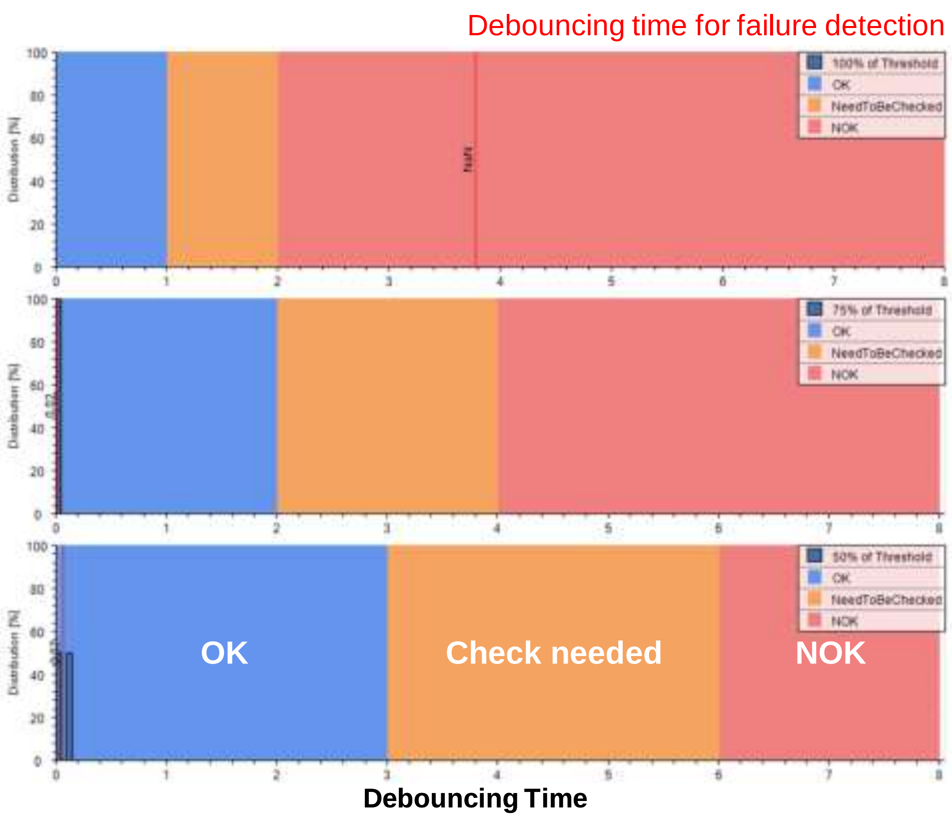
- Easy realization of complex fuel system failure pattern:
  - Injection cut-off
  - Changing start of injection and injection duration
  - Applicable for each partial injection
- Ignition turn-off
- Convenient handling by versatile break-out box
- Full flexibility by failure pattern development in MATLAB/Simulink®
- Includes a base set of failure models
- XCP access for comfortable parametrization of failure models
- Oxygen sensor signal simulation
- Control system modulation e.g. SENT, LIN and CAN

OBD Robustness – Need of the BS-VI Step2 & IUPR
Reduction in FD/ND cases is vital for all system

MS H

Robustness Requirement | Initial Calibration | Quality Assessment | Definition of WPA / BPU | Calibration Optimization | Tolerance Investigation | On-road testing | Evaluation & Confirmed

Evaluation Method – Debouncing Time

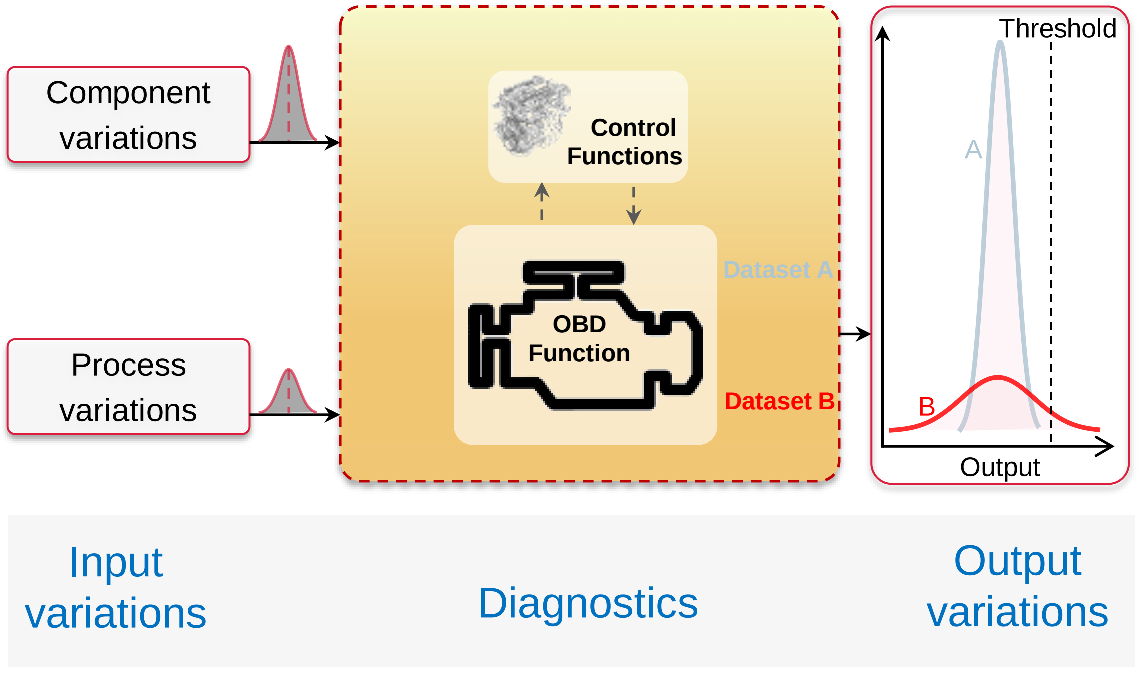


Task Description

- Internal threshold
  - 100% / 75% / 50% of actual threshold
- Different debouncing time limit based on internal threshold
  - 20% / 40% / 60% / 80% of maximum debouncing time
  - Blue area
    - Robust
  - Orange
    - Need to be checked
  - Red
    - Calibration update needed

Sensor , Actuator & System software Tolerances……….. Major deviators for a robust OBD computer

Definition of Robustness

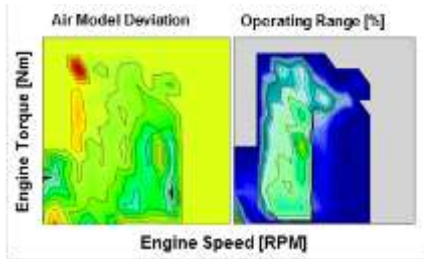


Variations

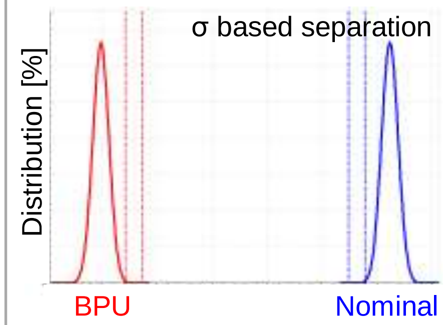
- Robustness refers to the ability of tolerating perturbations that might affect the system.
- Robust OBD is independent of input variations.
- Component variations.
  - Sensor tolerances.
  - Sensor drift
  - Sensitivity to concentration
  - Model tolerances.
  - Component tolerance.
- Process variations.
  - Drivers
  - Atmospheric
  - Critical driving conditions
  - Driving Maneuver
  - Aging of component

FEV's OBD Robustness Approach…Statistical Robustness Evaluation
To ensure every OBD system meets the IUPR norms

1. Robustness Requirement

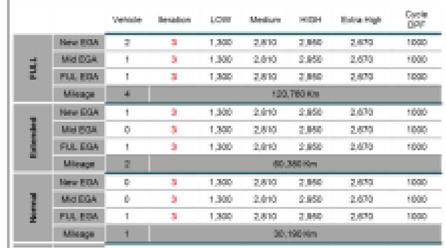


3. Quality Assessment



5. Calibration Optimization

- Test plan
- Tolerance test / simulation

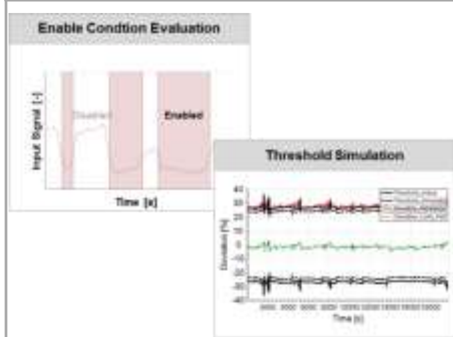


		Vehicle	Iteration	LOW	Medium	HIGH	Extra High	Cycle DPF
FULL	New EGA	2	3	1,300	2,810	2,890	2,670	1000
	Mid EGA	1	3	1,300	2,810	2,850	2,670	1000
	FUL EGA	1	3	1,300	2,810	2,890	2,670	1000
	Mileage	4	120,760 Km					
Extended	New EGA	1	3	1,300	2,810	2,850	2,670	1000
	Mid EGA	0	3	1,300	2,810	2,890	2,670	1000
	FUL EGA	1	3	1,300	2,810	2,850	2,670	1000
	Mileage	2	60,380 Km					
Normal	New EGA	0	3	1,300	2,810	2,890	2,670	1000
	Mid EGA	0	3	1,300	2,810	2,850	2,670	1000
	FUL EGA	1	3	1,300	2,810	2,890	2,670	1000
	Mileage	1	30,190 Km					

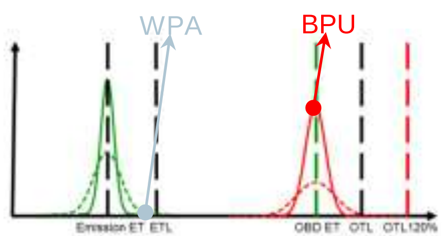
7. On-road testing

Maturity Level of Robustness Evaluation

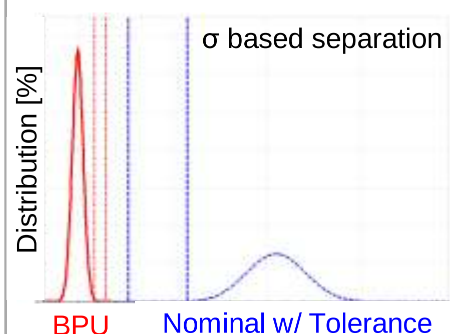
2. Initial Calibration



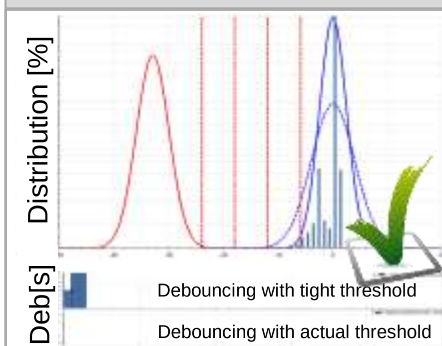
4. Definition of WPA / BPU



6. Tolerance Investigation



8. Evaluation & Confirmed



Our Values………..


CUSTOMER FOCUS
PROFESSIONALISM
COMMITMENT
OPEN-MINDEDNESS
RESPECT