CORNING

Presented at ECMA workshops at ARAI & ICAT
PART 1

Vehicle Engine Efficiency and Emissions
Review of Regulations & Technology Trends

Sept 11th – 12th, 2019

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Summary – Light Duty

Fuel economy / CO_2 emissions

- CO_2 reduction targets across the world will require a 3 – 6% improvement in fuel economy per year
- Electrification mandates being proposed: China is now including hybrids in NEVs.

Technology trends / implications

- Various advanced ICE technologies still to be deployed. Pathways to 50% BTE outlined.
- Hybrids offer a 20 – 30% reduction in CO_2 today
- Lower comb. temperatures emphasize the role of advanced after-treatment systems

Criteria Pollutant Regulations

- Particulate emissions is a key health concern : PN regulations in EU/CN/IN
- US still the tightest for gas emission standards
- With tailpipe emissions approaching near-zero, focus now on real-world and in-use compliance
- Key elements of post Euro 6 regulations are being discussed

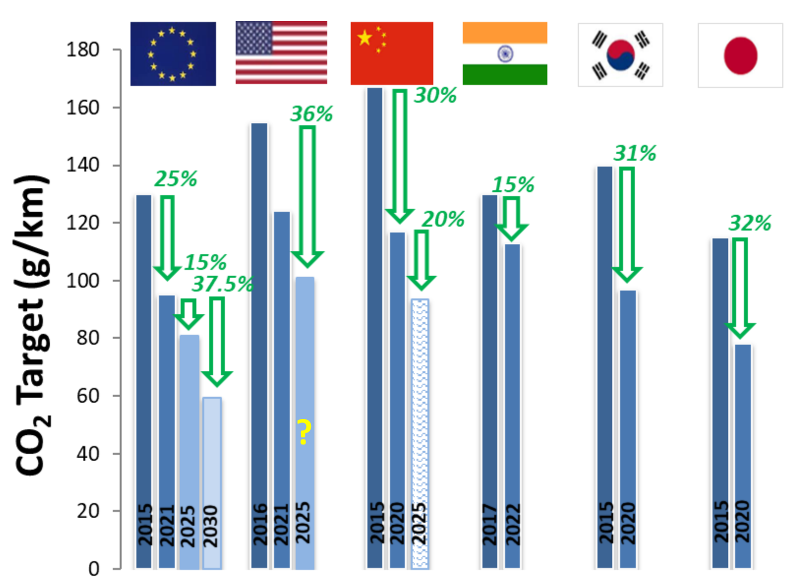
Technologies to reduce criteria pollutants

- Gasoline particulate filters (GPFs) widely being deployed in EU and China
- Reduction of cold start emissions is critical : TWC, HC-traps, SCR, DOCs are improving
- Euro 6 RDE compliant gasoline and Diesel vehicles certified and exceed the requirements
- Hybrids can have unique emission challenges which must be tackled

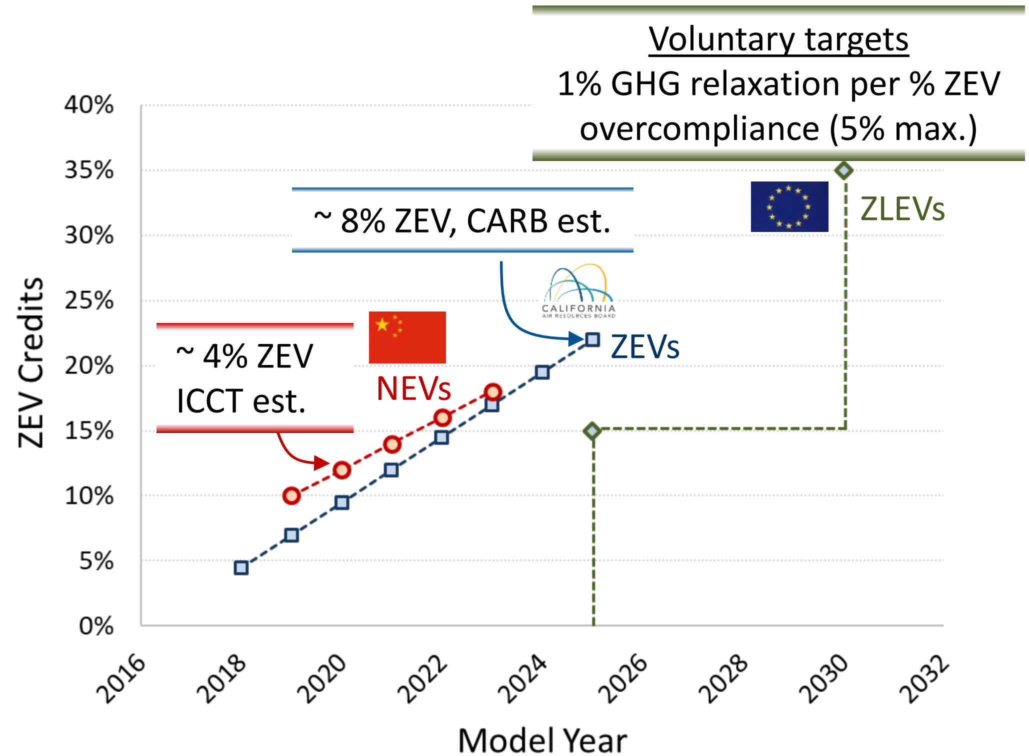
Regulations & Technologies to reduce Fuel Consumption

Light-duty regulations summary
Fuel economy / GHG / Electrification

3 – 6% reduction in fuel consumption per year



Electrification mandates (ZEV and PHEVs)

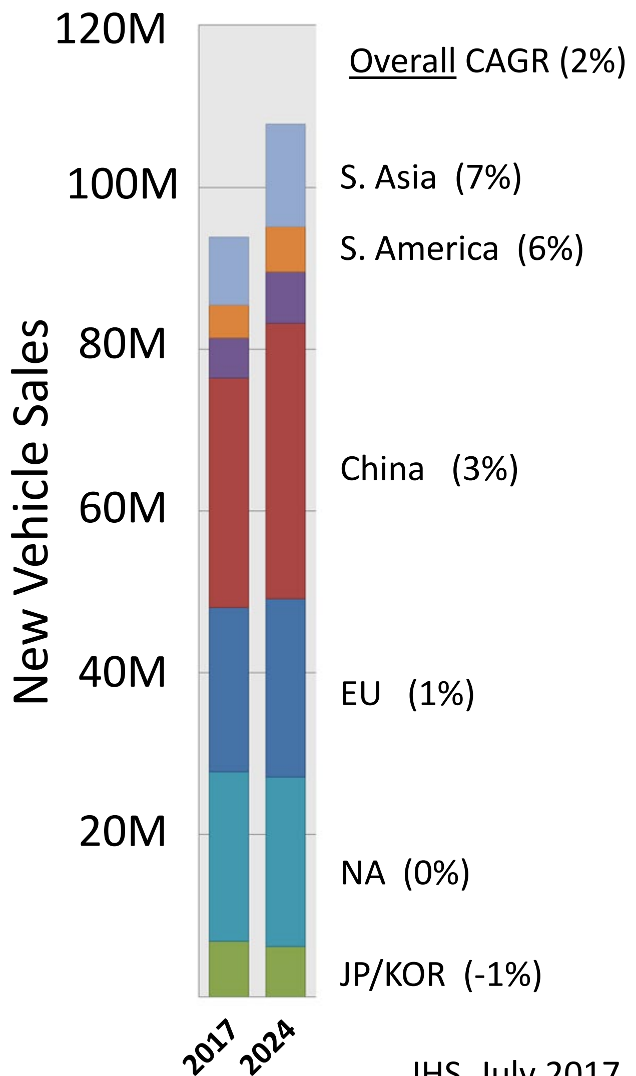


ZEVs = ZEVs with AER > 50 mi

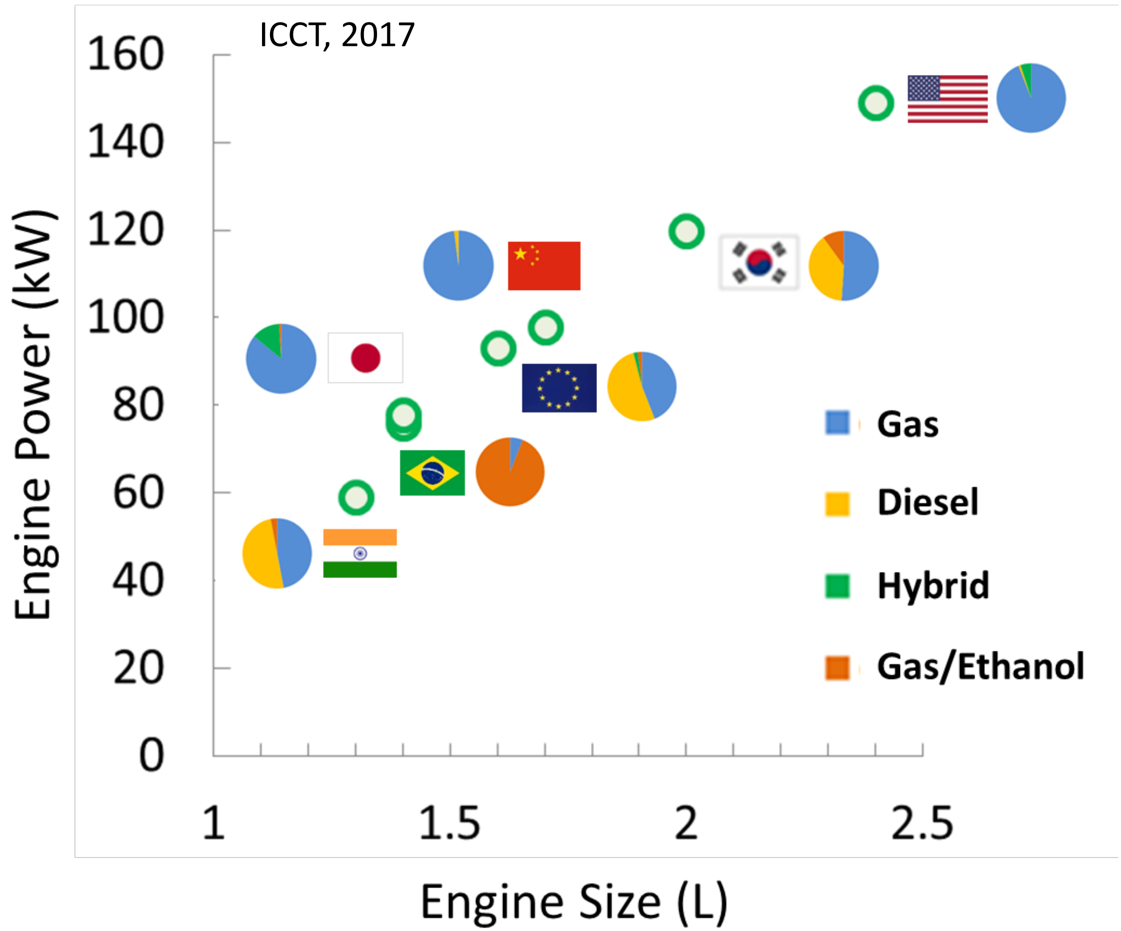
NEVs = ZEVs with AER > 100km, Sp. > 100 km/h
PHEV with AER > 50km, FCV with AER > 300 km

ZLEVs = Vehicles with CO_2 emissions < 50 g/km

Mobility choices are “local” – and demand diverse technology approaches

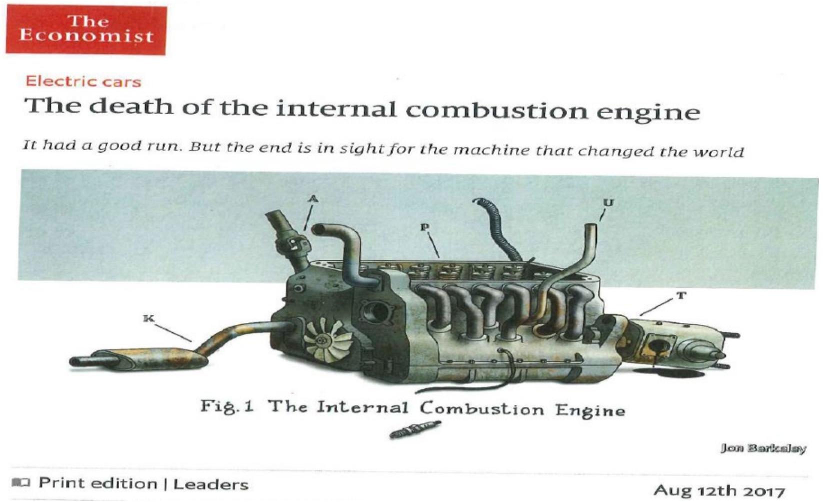


IHS, July 2017



ICEs are not going away anytime soon

Mild hybrids expected to gain share. Pure EVs driven by mandates.
Rapid improvements in battery costs and infrastructure happening


The Economist

Electric cars

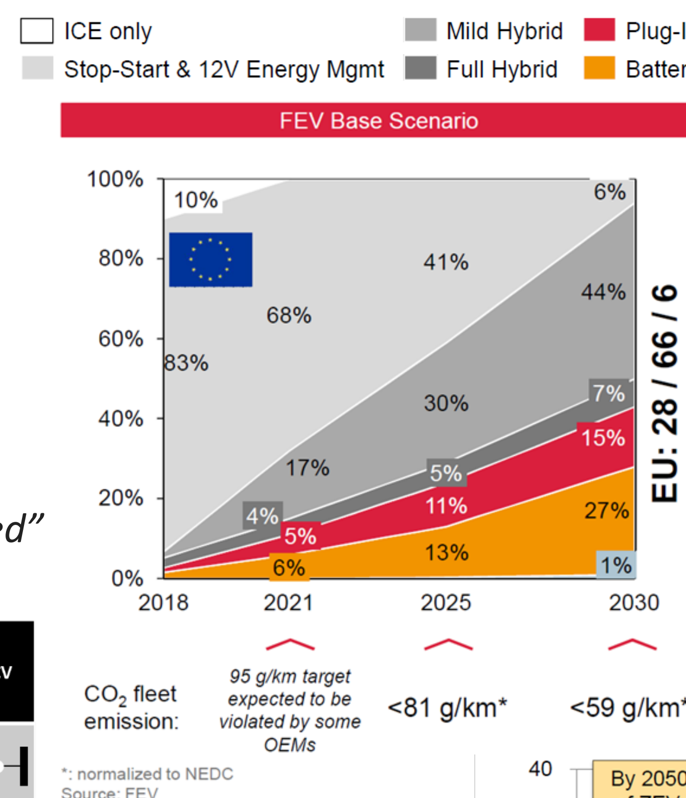
The death of the internal combustion engine

It had a good run. But the end is in sight for the machine that changed the world

Print edition | Leaders

Aug 12th 2017

"The reports of my death are greatly exaggerated" – Mark Twain



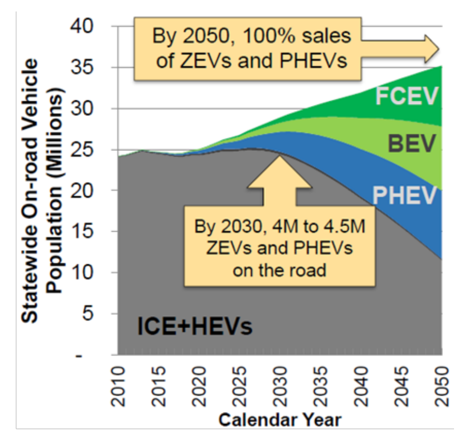
*: normalized to NEDC
Source: FEV

In 2030:
72% vehicles with ICE in EU
Similar in China,
90% in US

Propulsion Design	ICE	ICE S/S	Mild Hybrid	Full Hybrid: Conventional Full Hybrid	Full Hybrid: PHEV (Plug-in Hybrid)	(B)EV	FCV
System Design	E	E M B	E M B	E M B	E M B	M B	M FC
System Definition: Engine	✓	✓	✓	✓	✓		
System Definition: Motor		✓	✓	✓	✓	✓	✓
System Definition: Stop/Start		✓	✓	✓	✓		
System Definition: Propel Vehicle	Engine	Engine	Engine	Engine and/or Motor	Engine and/or Motor	Motor	Motor
System Definition: External Charging					✓	✓	✓
Technology / features		Stop/start	48V, BAS, IMA	Series/parallel Atkinson cycle	Charge depleting mode Larger batteries		

In 2030: 90% vehicles with ICE in California

SAE Govt. Industry Mtg. 2018



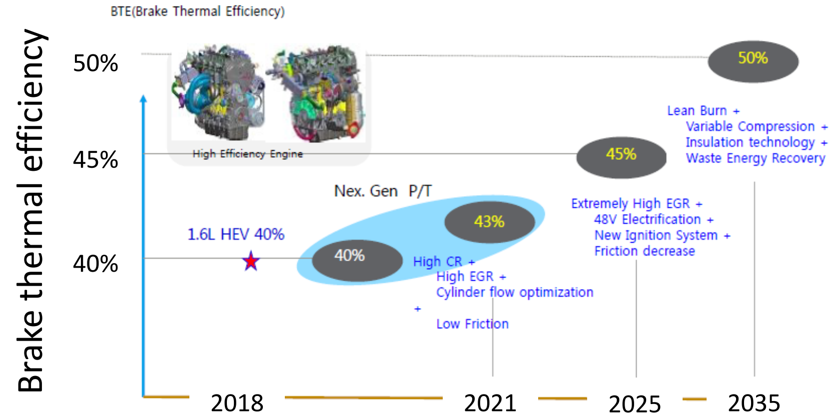
Advanced combustion technologies coupled with electrification are being adopted to reduce fuel consumption

Technology	Fuel Consumption / CO_2 Reduction
Direct Injection	1.5%
c-EGR	2 – 5%
High CR (Atkinson cycle, c-EGR, DI, VVT)	10 – 14%
Miller cycle (Turbocharged Atk., c-EGR)	12 – 20%
Variable CR	10 – 15%
Dyn. cylinder deactivation (+ VVL)	6 – 8%
Adv. turbocharging, e-boost	5%
2-stroke opp. piston (Diesel, GCI)	30 – 50%
Dedicated-EGR	10%
Water Injection	5 – 7%
On-board separation of high RON fuel	10 – 15%
Lean-burn gasoline	10 – 15%
HCCI w/ spark assist	20 – 30%
Low T Comb. (GDCI, RCCI)	> 35%

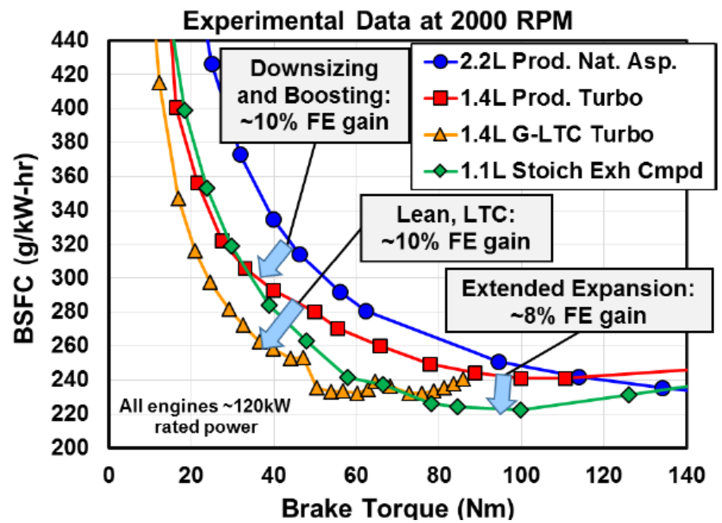
+3% synergy with mild hybridization (Dyn. cylinder deactivation)

SAE High Eff. ICE Conference, 2018

HMC : High CR, 48V, Low friction, VCR, WHR



GM : Downsizing, lean-burn, turbo-compounding



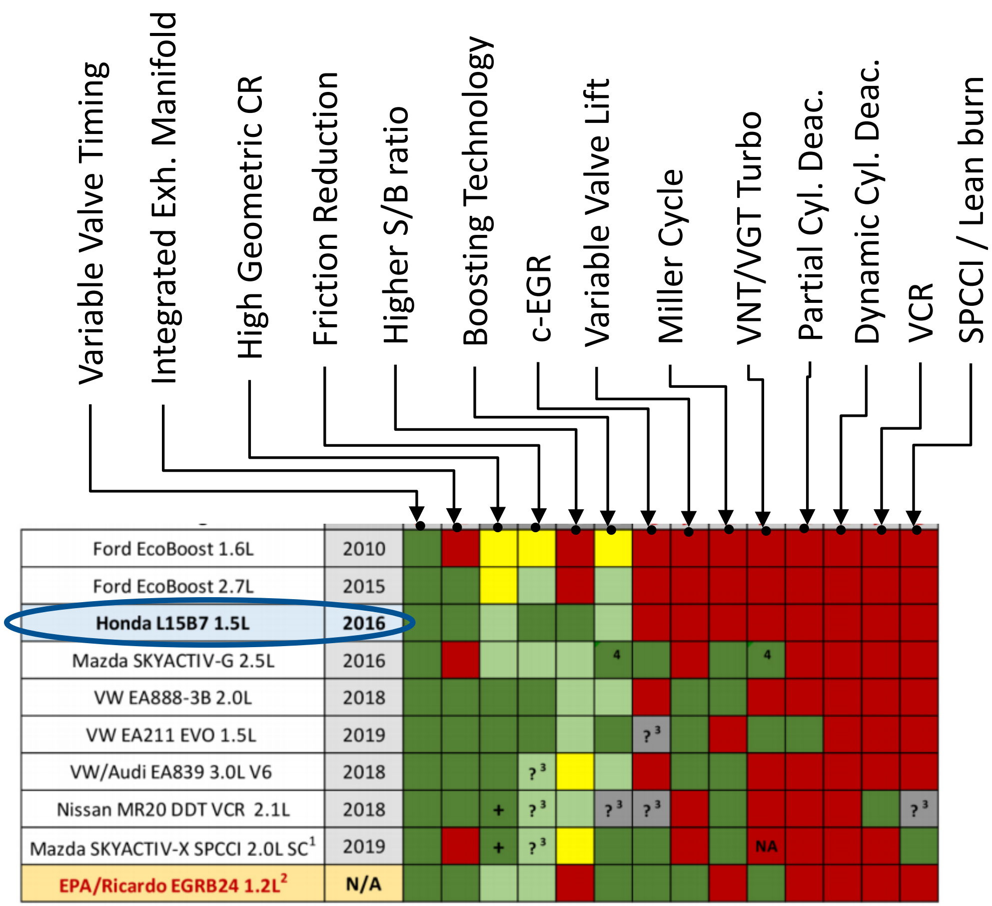
There is still significant untapped potential of advanced ICE technologies

EPA, SAE 2018-01-0319 & High Eff. ICE Conference 2018

Benchmarking of Honda 1.5L engine

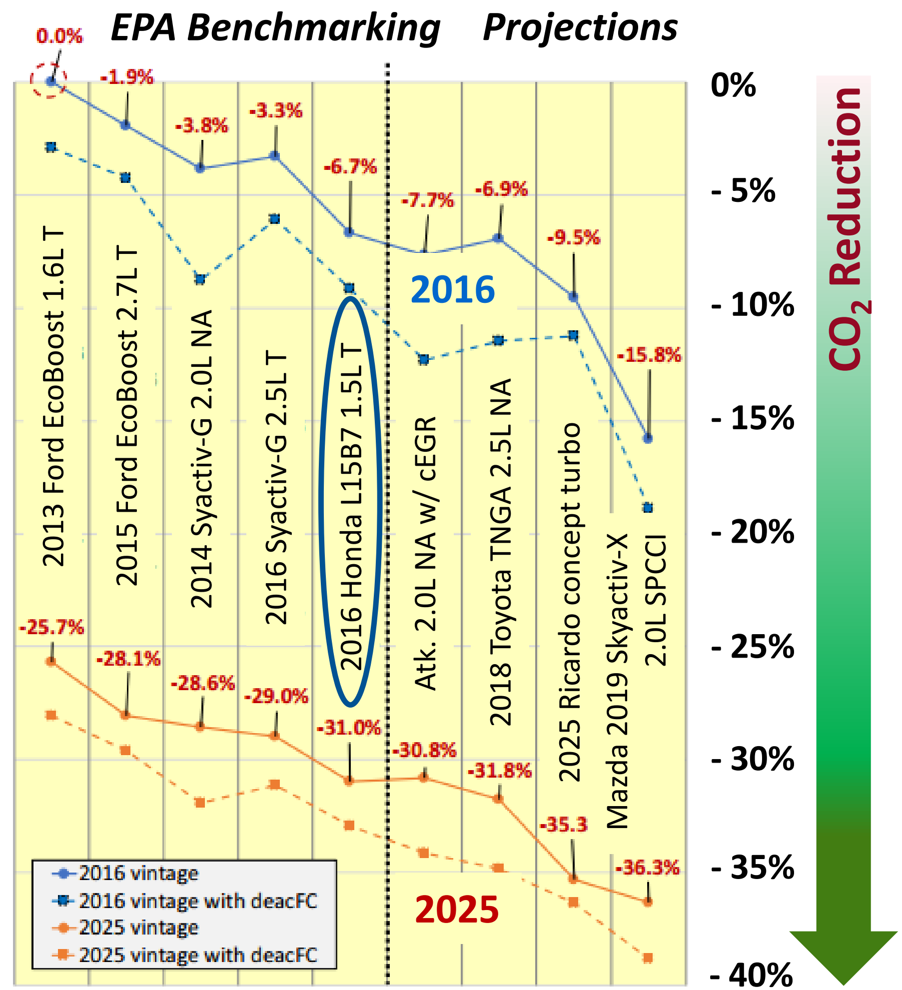
6.7% improvement over MY 2013 1.6L T (VVT, CVT, ..)

Early implementation | Nearing maturity | Not implemented



2016 → 2025 (Mid-sized cars)

- 10% lower aero & rolling resistance
- Start/stop
- Higher eff. accessories
- Weight reduction (7%)



Technologies being explored to reduce exhaust T & enable λ = 1 operation without power loss

Fuel enrichment increases fuel consumption and high CO emissions

High CR for fuel efficiency

↓

High temp. at high loads

↓

Engine knock, thermal stress for downstream components

Solutions

Variable compression ratio (VCR)

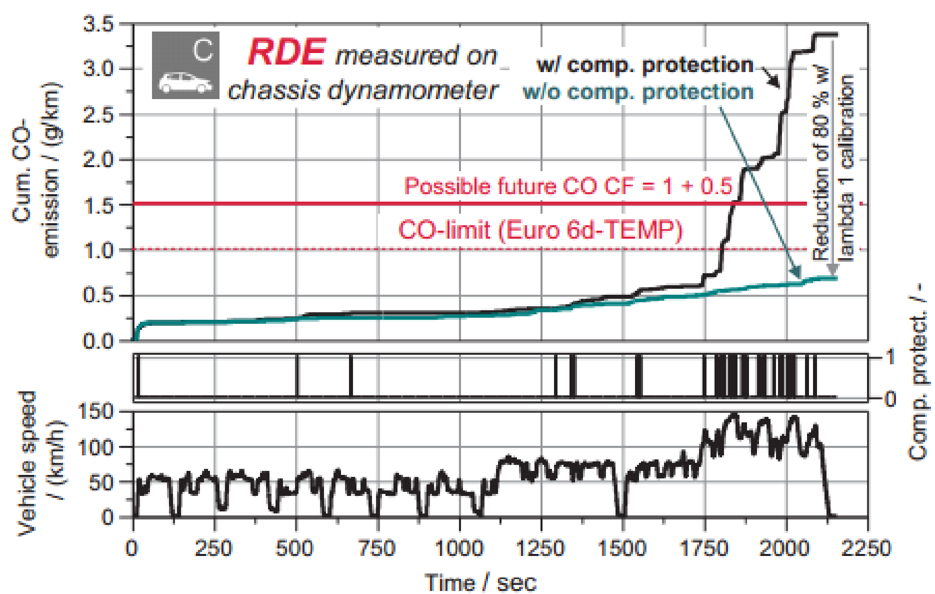
Improved turbines & catalysts

Water injection (WI)

Octane on demand (OOD)

Fuel enrichment leads to high CO emissions

FEV, Aachen Univ. 30th Int. AVL Conf. “Engine & Environment”, 2018

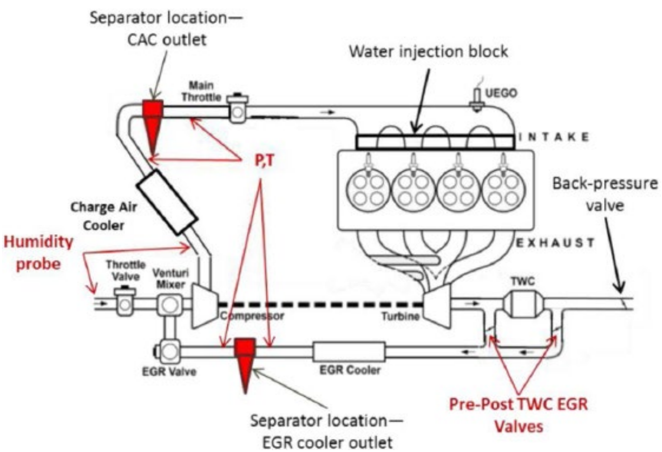


Water recovery from exhaust explored for water injection

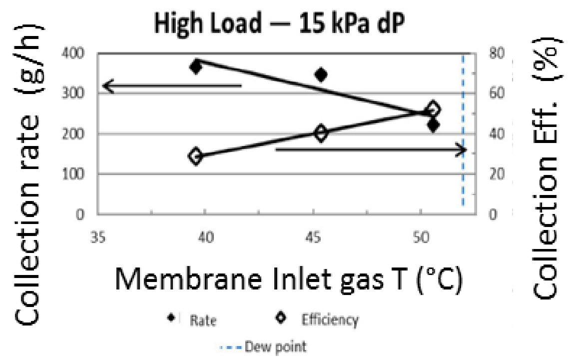
Tenneco, SAE 2018-01-0369

Engine: 2.0L GDI, CR 9.5 : 1, LP-EGR Water : port injected

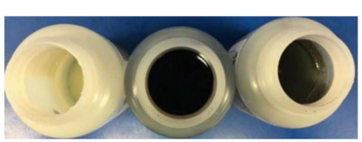
Two locations for water separation : (1) Post EGR cooler (2) Post charge air cooler



Condensate collection rate & efficiency is sensitive to inlet gas T



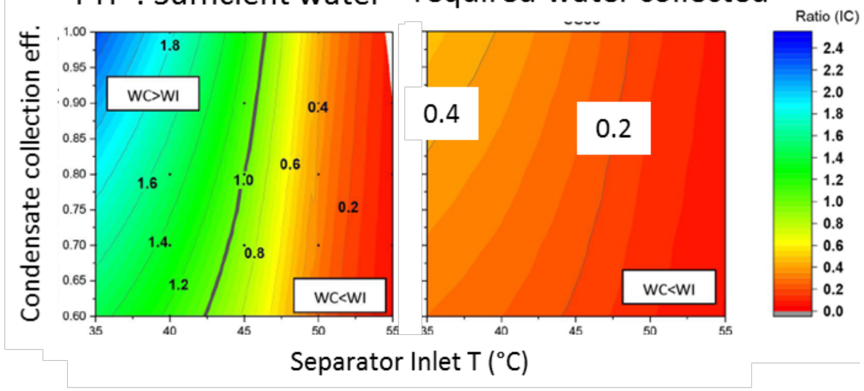
Water quality best for membrane separator



MEM Active Cyclone

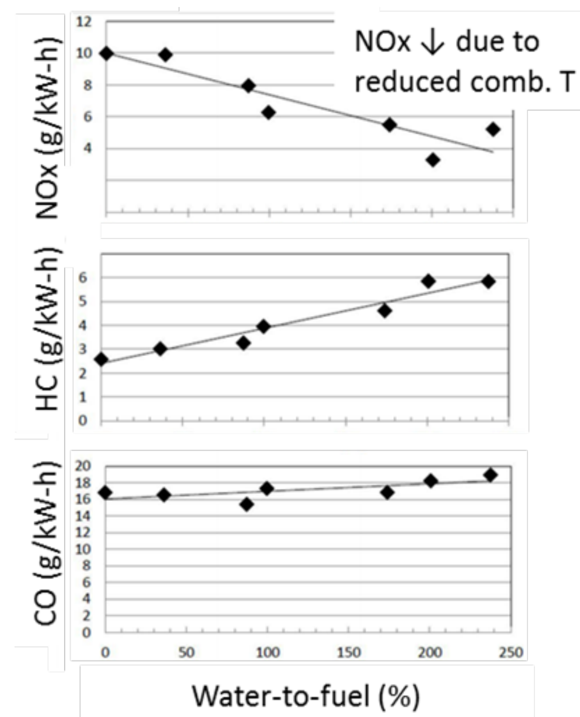
Simulations US06: 40 – 70% of required water collected

FTP : Sufficient water



High load

3000 rpm, 14bar BMEP, 10% EGR

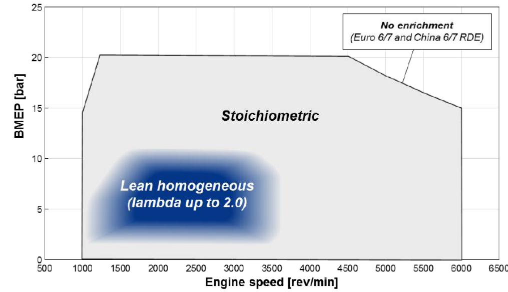


Full load fuel economy improved by 13%

Lean homogenous combustion system is promising to deliver 10% reduction in CO_2 while meeting post-Euro 6 RDE emissions

Ricardo, JLR, JM, U. Brighton   Int. Vienna Motor Symposium, 2019

Base vehicle: JLR 4cyl, 2L, GDI CR = 11:1



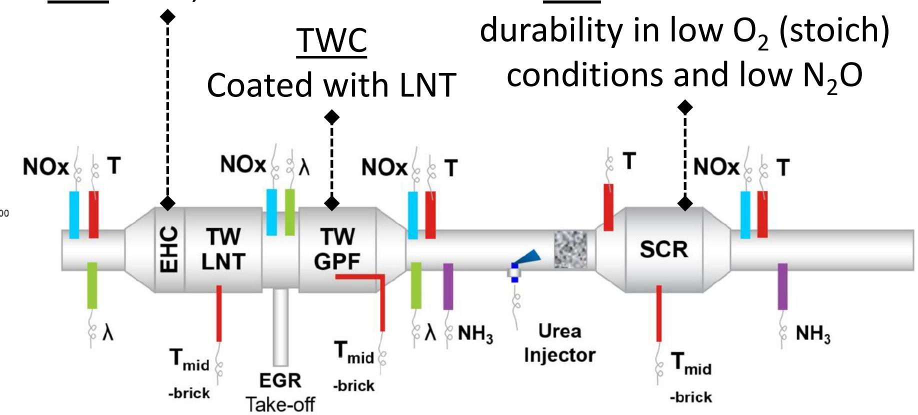
Modifications:

- Increased CR
- Inj. P = 350 bar
- Miller cycle via variable valve timing & lift
  - combination of LIVC and EIVC
- High energy (up to 500 mJ) ignition system
- Variable nozzle turbine (VNT) + 48V e-compressor
- Adv. after-treatment for RDE w/ sub-23 nm particles
- Adv. engine control system

EHC : 48V, 3 kW

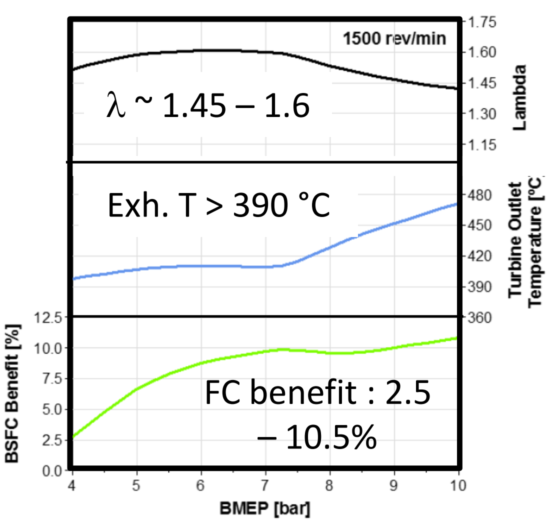
TWC
Coated with LNT

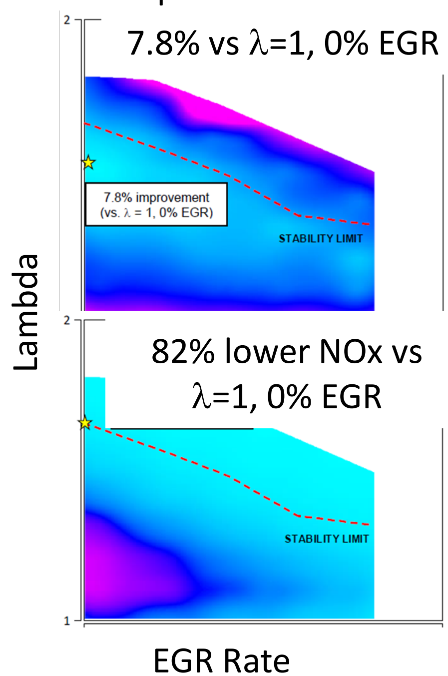
SCR : Fe-zeolite for durability in low O_2 (stoich) conditions and low N_2O



LP-EGR : Replaces water cooled exh. manifold to reduce risk of light-out

Multi-cylinder results (rpm = 1500)

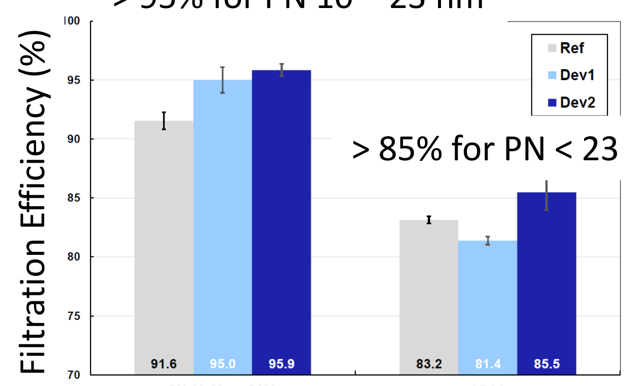




Coated GPF – WLTC Results

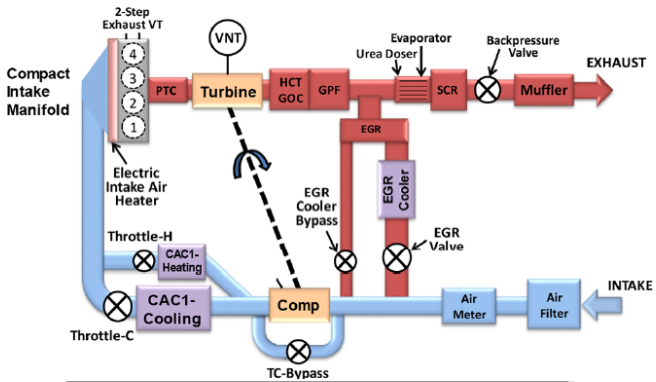
- Effective at capturing sub-23nm particles
- Catalyst promotes NO → NO_2 (for SCR)

> 95% for PN 10 – 23 nm



2.2L Gen 3X GDCI (Gasoline Direct Injection Compression Ignition): 43% BTE + Tier3Bin30 demonstrated, & path to 50% BTE

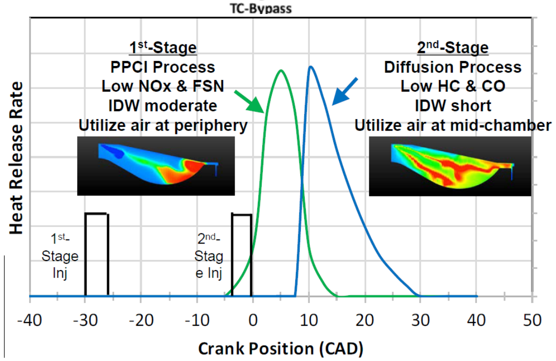
SAE 2019-01-1154 & SAE High Eff ICE 2019   Delphi Technologies



- New Two-Stage Combustion for High Load
- Variable VIC VNT Turbocharger (no SC)
- High-pressure Fuel System 1800 bar
- PPCI but no premixing – no int. stroke injections
- Fast Intake Air Temp Control (air blend) with electric air heater for Cold Start
- Higher CR 17

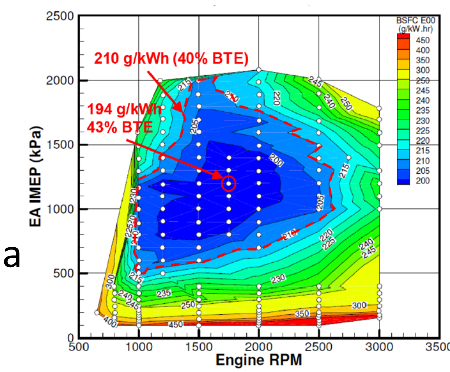
Post-turbo cat T mostly > 250 °C

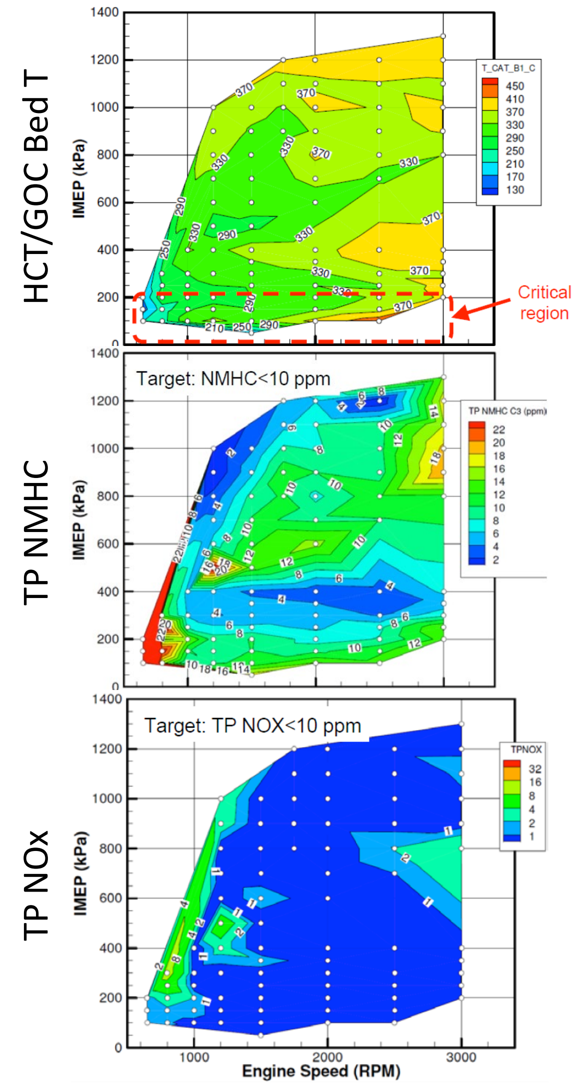
Tailpipe NMHC & NOx < 10 ppm

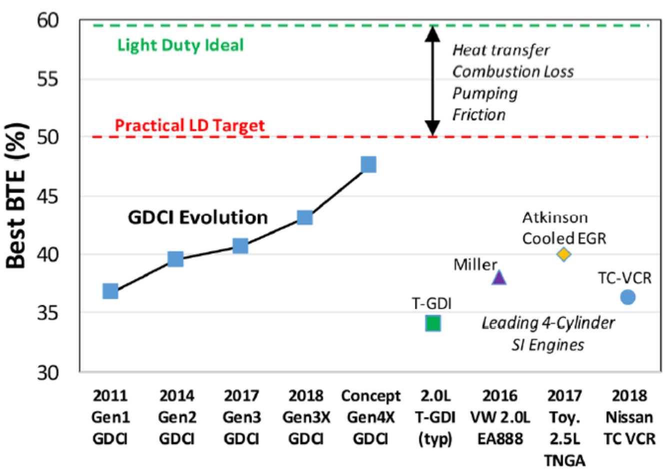


Min. BSFC
194 g/kWh
(43.5% BTE)

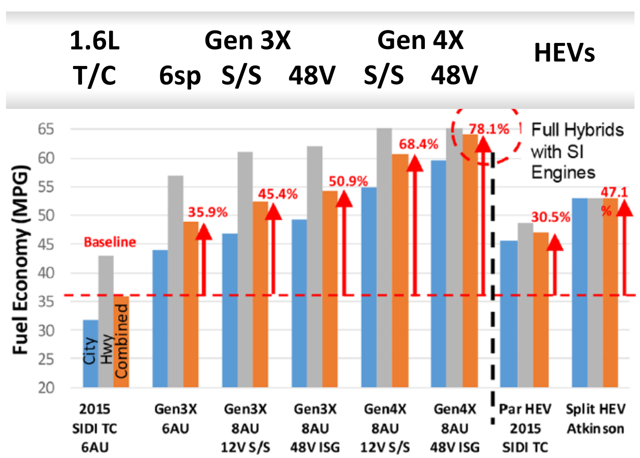
Significant area
> 40% BTE







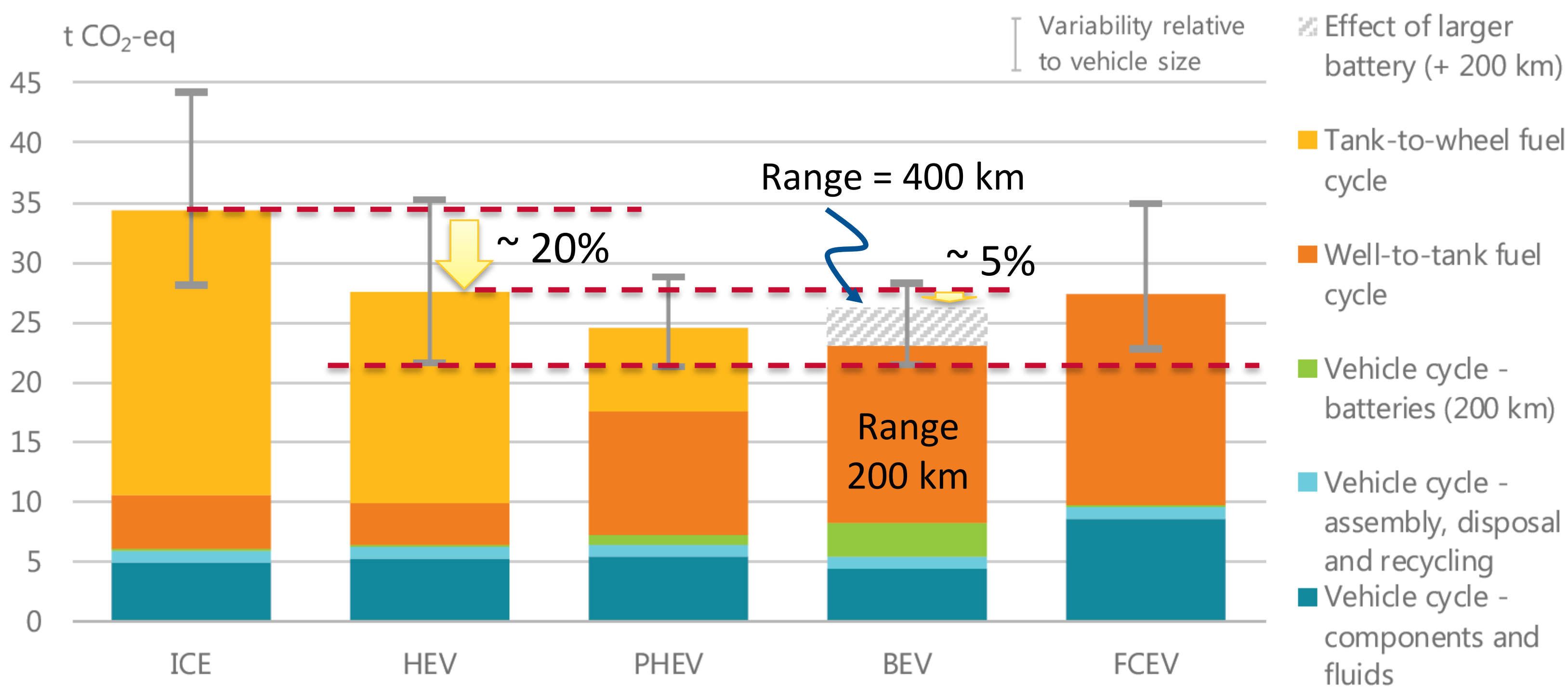
Mid-size vehicle simulations



Hybrids offer a pragmatic pathway for reducing CO_2 emissions

Global EV Outlook 2019 IEA, Electric Vehicles Initiative

- Hybrids offer ~ 20% lower CO_2 compared to ICE
- BEVs with 400 km range deliver only ~ 5 – 6% further reduction compared to hybrids
- BEVs with 200 km range deliver ~ 18% further reduction compared to hybrids → urban, short range driving is a good application for full electrification
- The best hybrids emit the *same* CO_2 as the best BEVs



Regulations - Criteria Pollutants

Global Light Duty Regulations

US Regs Drive Advanced Substrates, EU & CN Enforce Filters

		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	EPA	Tier 3 (phase in)										Tier 4 + 1 mg/mi?			
	CARB	LEV III Phase in start 3mg/mi				all 3mg/mi				LEV III + PM 1 mg/mi start 1mg/mi		all		LEV IV ?	
EU		WLTC	EU6d TEMP GDI PN 6e11 #/km CF NOx 2.1/PN 1.5		EU6d Final CF ≤1.5		EU7? CF=1, PN >10nm, NO2/NH3/HCHO/N2O/others?								
JP		JP 09 (JC08)	New PNLT (WLTC - Phase 1-3)				Diesel RDE (CF=2.0) Gasoline RDE								
Korea	Diesel	WLTC	EU6d TEMP		EU6d Final		EU7?								
	Gasoline	K-LEV III (phase in)										LEV IV + 1 mg/mi?			
China	Nation	Diesel Gasoline	China 5 (~EU5)		CN6a RDE Monitor		CN6b RDE CF TBD						CN 7?		
	Beijing	BJ 6	CN6b w/o RDE												
India	Nation	BS III	BS IV		BS VI (~EU6b) RDE Monitor		RDE CF=?							BS VII ?	
	12 Cities	BS IV (~EU4)													
Australia		EU5									EU6				
Thailand		EU4					EU5						EU6		
Brazil		PROCONVE L6					PROCONVE L7 (~ Tier 3 Bin 125)			PROCONVE L8 NMHC+NOx = 50		40		30 + PM 3mg/mi	
Russia		EU5						EU6							
S. African nations		~ EU2					EU4							EU5 ?	

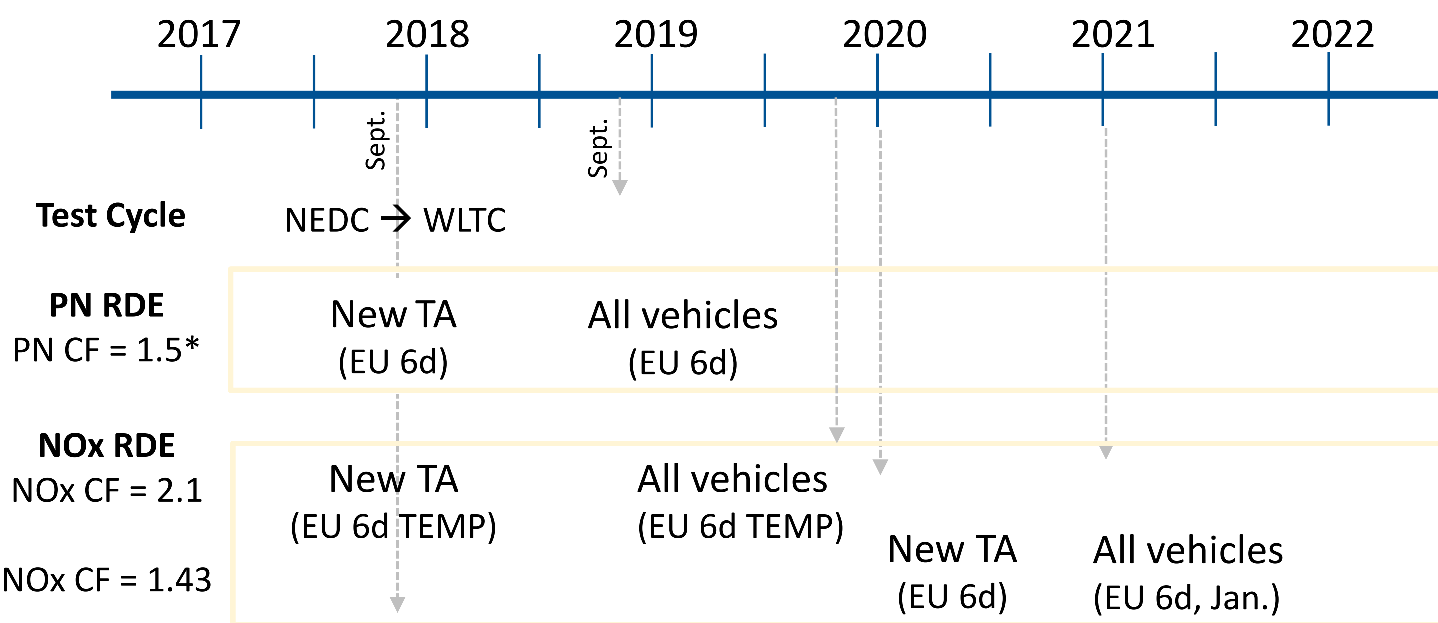
Emission test methodologies and tailpipe limits across major markets

Diverse approaches, but emphasis on reducing in-use, urban emissions

	USA	EU	China	India	Japan
Lab test cycle	FTP 75 US 06	WLTP	WLTP	NEDC (WLTP being considered)	WLTP
PEMS-based RDE	No formal "RDE" test	Yes	Yes Monitoring in 2020	Yes Start in 2023	Yes Diesel only
PM	3 mg/mi (~ 1.9 mg/km) CA states : 1 mg/mi	4.5 mg/km	6a : 4.5 mg/km 6b : 3 mg/km	4.5 mg/km	5 mg/km
PN	No	Yes, CF = 1.5 Diesel, GDI only	Yes, CF = 2.1 All engines	Yes, CF = ? Diesel, GDI only	No PN
NOx	Tightest gas std. NMHC+NOx = 30 mg/mi	Diesel : 80 mg/km Gasoline : 60 mg/km PEMS CF = 1.43	Fuel neutral 6a : 60 mg/km 6b : 35 mg/km PEMS CF = 2.1	Diesel : 80 mg/km Gasoline : 60 mg/km PEMS CF = ?	CF = 2.0
Cold start	Yes	Yes	No	Yes	Yes Correction by 1/1.6
Urban / Rural / Motorway speeds	N/A	< 60 km/h 60-90 km/h 90-145 km/h	< 60 km/h 60-90 km/h 90-145 km/h	< 40 km/h 40-60 km/h 60-80 km/h	< 40 km/h 40-60 km/h > 60 km/h

EU light-duty regulations
Gasoline

Gasoline	CO mg/km	THC mg/km	NMHC mg/km	NOx mg/km	N_2O mg/km	PM mg/km	PN #/km	Engines	RDE	CF	Durability km
EU 6d Temp	1000	100	68	60	-	4.5	6.0×10^{11}	GDI	TA IUC	NOx = 2.1, PN = 1.5	160K
EU 6d Final										NOx = 1.5, PN = 1.5	

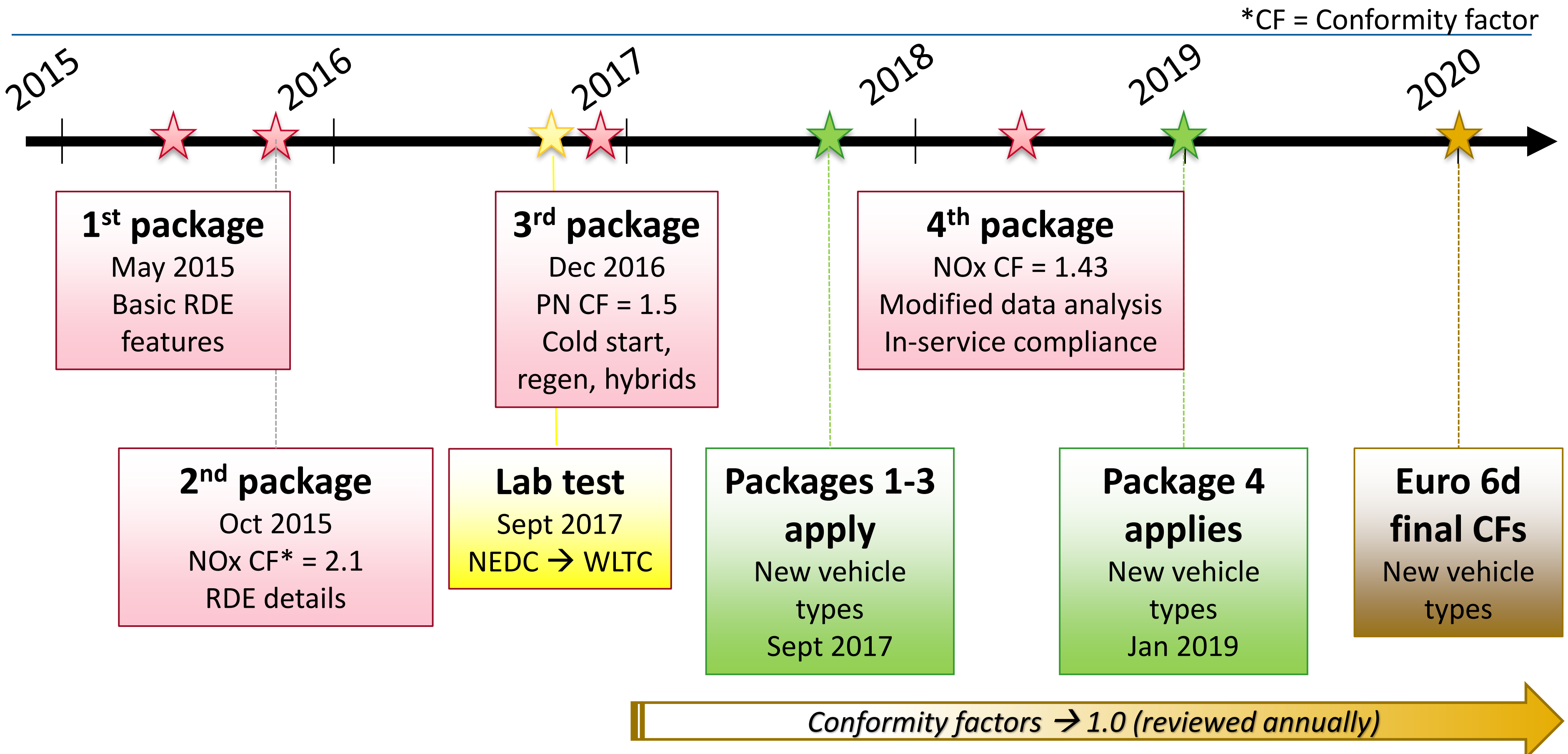


CF = Conformity factor
TA: Type approval
IUC: In-use compliance

* PN CF = 1 + “error margin = 0.5” with error margin reflecting measurement uncertainty and subject to annual review

<u>Other</u>: CO_2 emissions also to be measured on WLTP, with correction to NEDC done via CO_2MPAS correlation tool

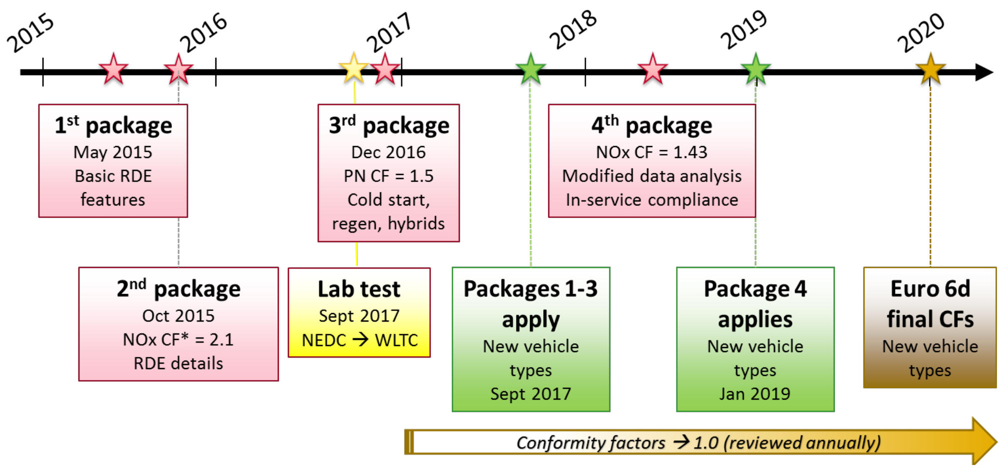
RDE test procedure progressively defined through 4 packages



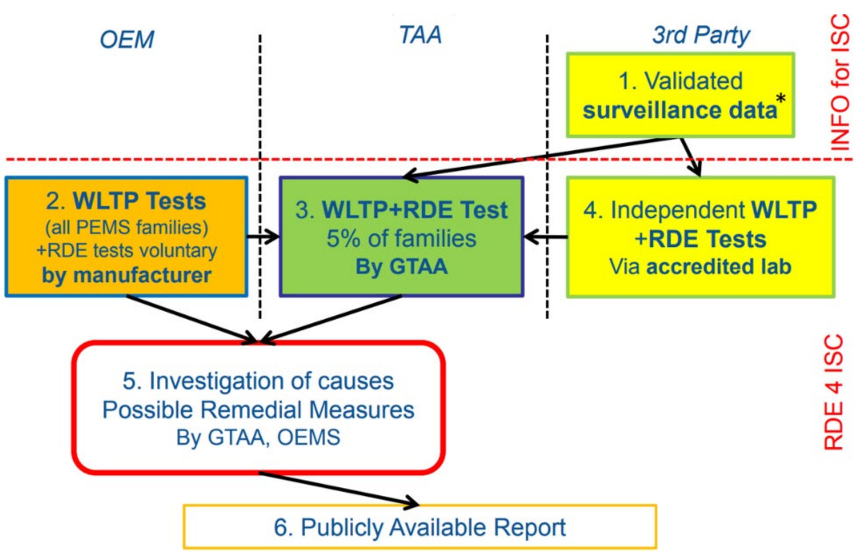
Drivers for increasing FE

- Real-world driving tests are more stringent than lab tests
- WLTC covers broader engine map than NEDC
- CFs reviewed annually, will eventually reduce to 1.0
- Emissions pinned to CO_2, includes more dynamic driving and "raw" RDE
- In-service testing via WLTP & RDE Tougher thresholds for passing
- €30K/vehicle fines for non-compliance

4th Real World Driving (RDE) package implemented in Jan 2019

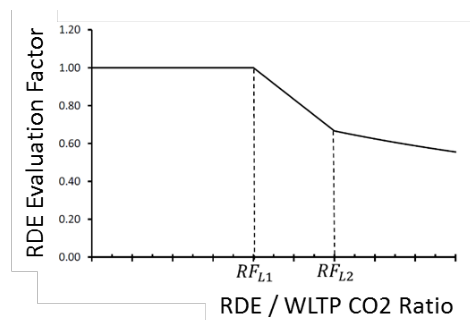


In service conformity (ISC) : Up to 100,000 km or 5 yrs.



Key changes through 4th RDE package

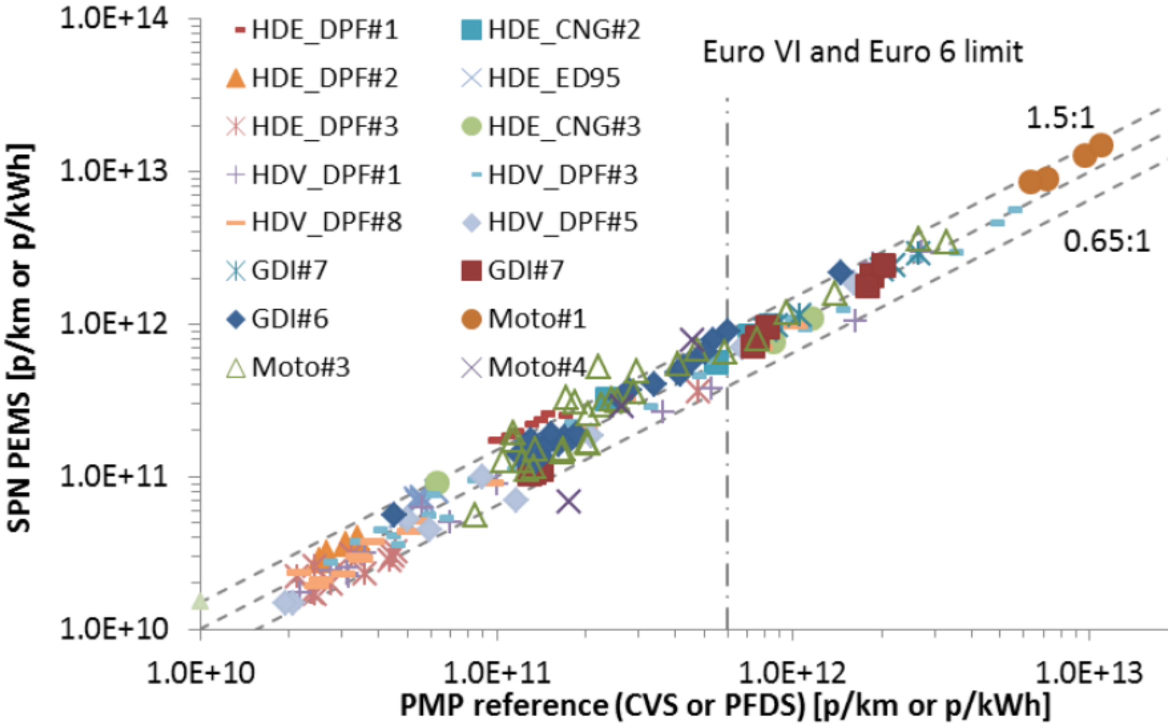
- Data analysis using moving average window method
  - Power binning (CLEAR) discontinued
- Margin error for NOx lowered from 0.5 to 0.43 (CF = 1.43) starting Jan 2020
- RDE evaluation factors defined



- Type VI (low T) optional
- Data will be made public

PEMS equipment and associated conformity factors are being reviewed every year in Europe

EU Commission, PTNSS 2019

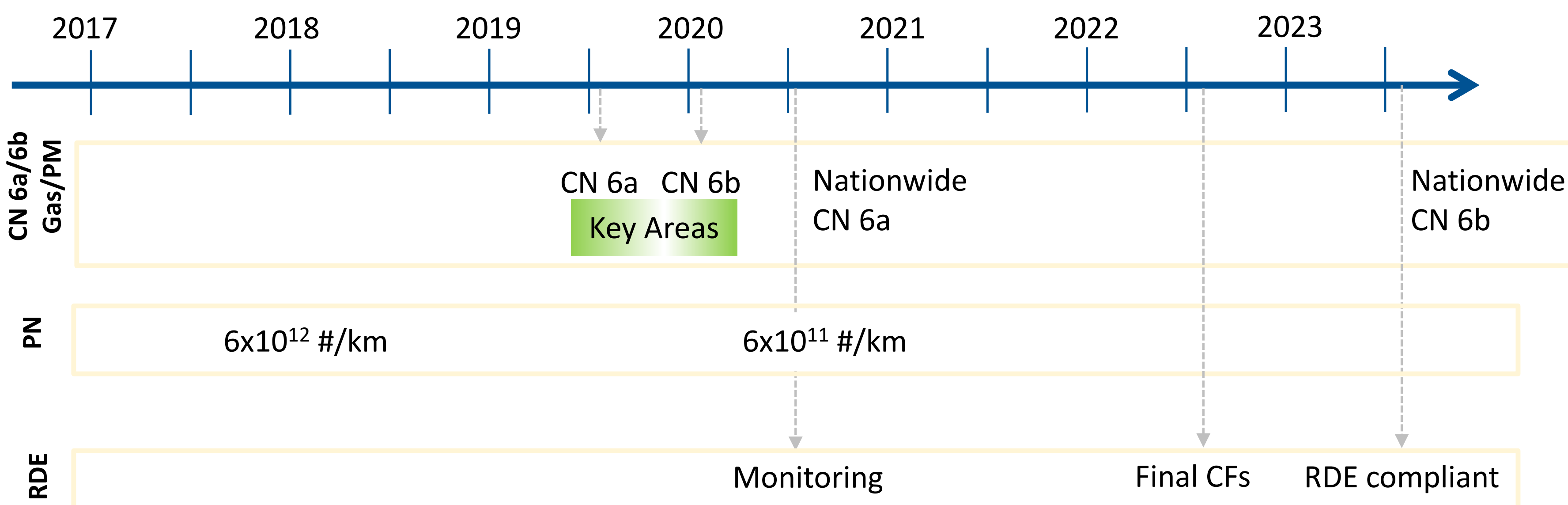


- Uncertainty of SPN PEMS is 40 – 65%. Today:
  - At the higher end for HDV
  - In the middle for LDV
  - At the lower end for CPC based systems
- Robust for most conditions (regeneration, ambient temperatures, volatiles, fuels) however until recently still some issues observed

China 6 : Tighter gas standards than Europe, PN limit applied to all vehicles (PFI as well)

Gasoline	CO mg/km	THC mg/km	NMHC mg/km	NOx mg/km	N_2O mg/km	PM mg/km	PN #/km	Engines	RDE	CF	Durability km
CN 6a	700	100	68	60	20	4.5	Before 2020/7: $6.0x10^{12}$ After 2020/7: $6.0x10^{11}$	All	TT COP IUC[1]	2020/7: Monitor 2023/7: 2.1, to be adjusted[2] in 2022	160K
CN 6b	500	50	35	35	20	3.0		All			200K

TT: type test; COP: conformity of production; IUC: in-use compliance
(1) OEMs need to run RDE at TT & IUC. Regulator can check RDE for COP & IUC. (2) Likely adjusted to a value that only system with GPF can pass. CF for PN & NOx only. Necessary to measure & record CO during RDE test.



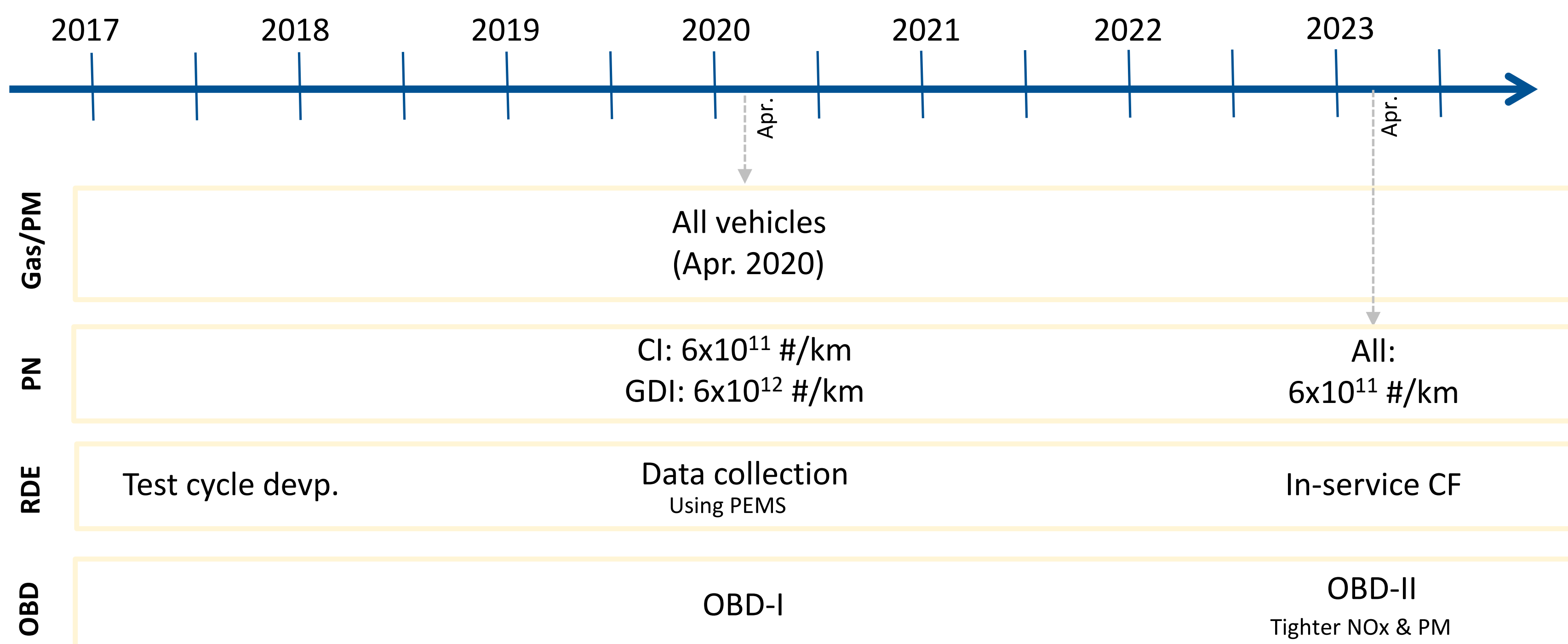
Extended RDE boundary conditions broader than Europe: Temp -7° to 38°, Altitude 0 – 2400 m

Bharat Stage (BS) VI Regulations

Nationwide implementation of BS VI regulations, Final notification released on Sept. 16th, 2016

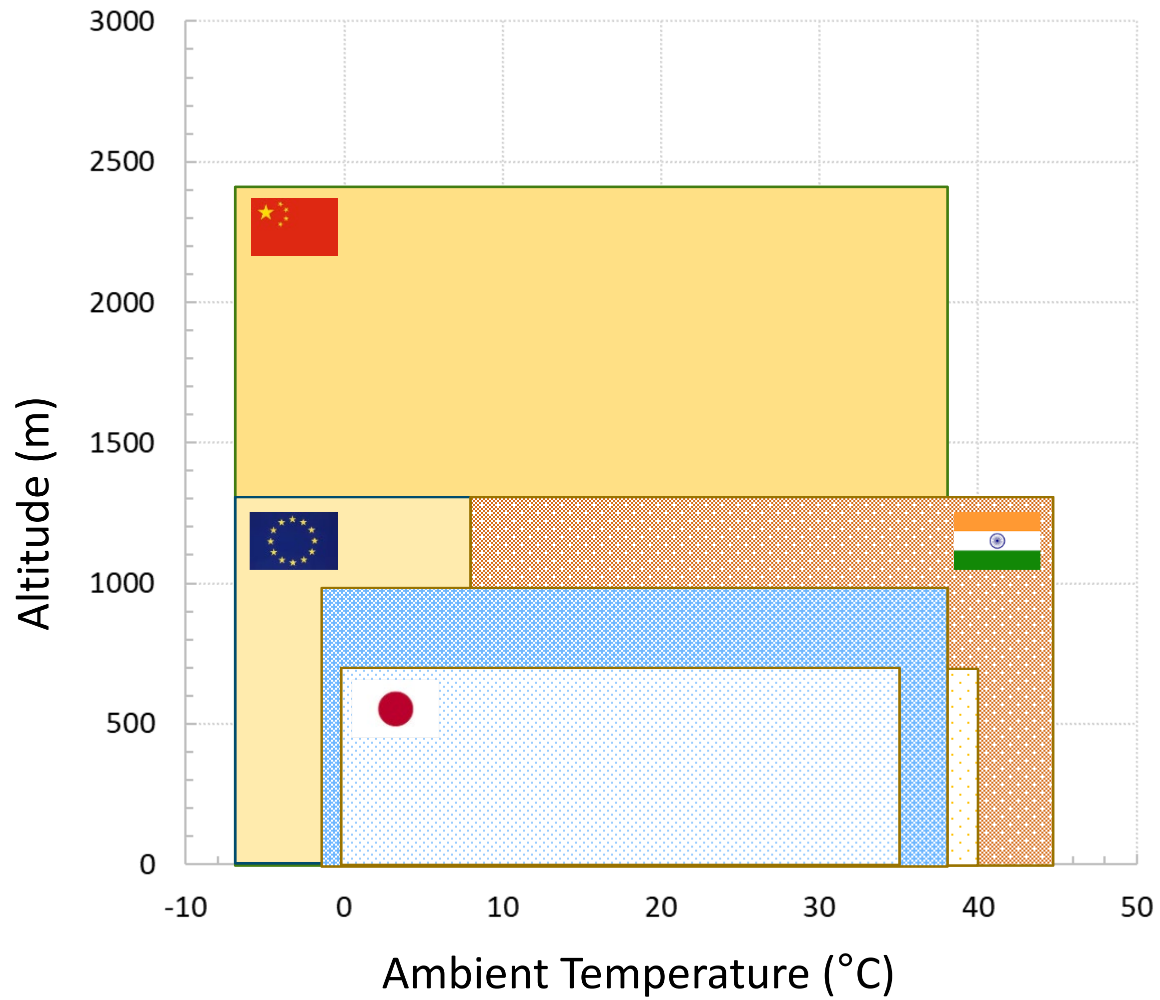
BS VI	4 Wheeler M Category	CO mg/km	THC mg/km	NMHC mg/km	NOx mg/km	THC + NOx mg/km	PM mg/km	PN #/km	RDE
	Positive Ignition (PI)	1000	100	68	60	-	4.5	$6.0x10^{11}$	Test cycle under development
	Compression Ignition (CI)	500	-	-	80	170	4.5	$6.0x10^{11}$	

NEDC, V_{max} = 90 km/h (WLTC adoption not specified yet)



RDE boundary conditions are region specific

Compared to EU: Higher altitudes in China, warmer in India



Finalized draft for real-world driving testing for BS-VI

M1 & N1 category vehicles < 3500 kg

RDE Test for type-approval and Conformity of Production

Duration: 90-120min, conduct on working days

Driving profile: Urban → Rural → Motorway, > 16 km each

Cold start emissions (gas and PN) : Included in evaluation

Altitude: Start & end elevation < 100 m, Cum. Alt. < 1200 m/100 km

Break-in : 3000 kms

Fuel: Either reference fuel or commercial fuel at choice of OEM

Boundary Conditions	Moderate (Ref. EU)	Extended* (Ref. EU)
Altitude (m)	0 – 700 (0 – 700)	700 – 1300 (700 – 1300)
Temp. (°C)	10 – 40 (0 – 30)	8 – 10; 40 – 45 (-7 – 0; 30 – 35)

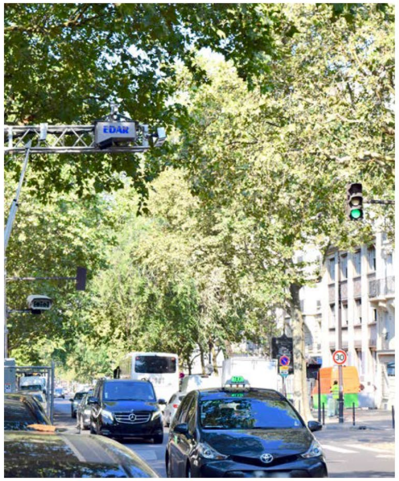
*Data in extended range divided by 1.6

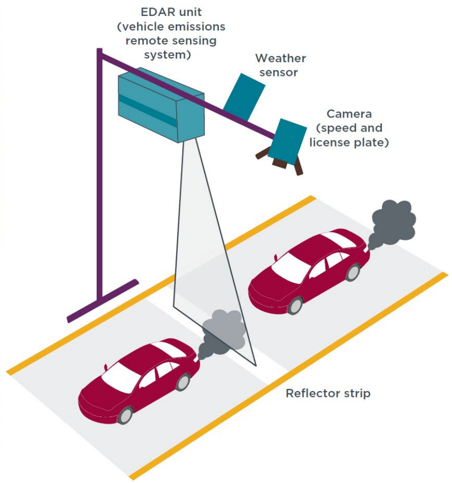
Route (share)	M1 Category	N1 category	Ref. EU
Urban Phase 1 (24 - 44%)	V < 45 km/h V_{avg} = 15 – 30 km/h Stops : 6 – 30% of duration Each stop < 5 min	V < 40 km/h V_{avg} = 15 – 30 km/h Stops : 6 – 30% of duration Each stop < 5 min	V < 60 km/h V_{avg} = 15 – 40 km/h Stops : 6 – 30% of duration Each stop < 5 min
Rural Phase 2 (23 - 43%)	V = 45 – 65 km/h	V = 40 – 60 km/h	V = 60-90km/h
Motorway Phase 3 (23 - 43%)	V ≥ 65 km/h V > 75km/h for > 5min V can be > 100 km/h for < 3% of duration	V ≥ 60 km/h V > 70km/h for > 5min V_{max} = 80 km/h	V > 90 km/h V > 100 km/h for > 5min V < 145km/h

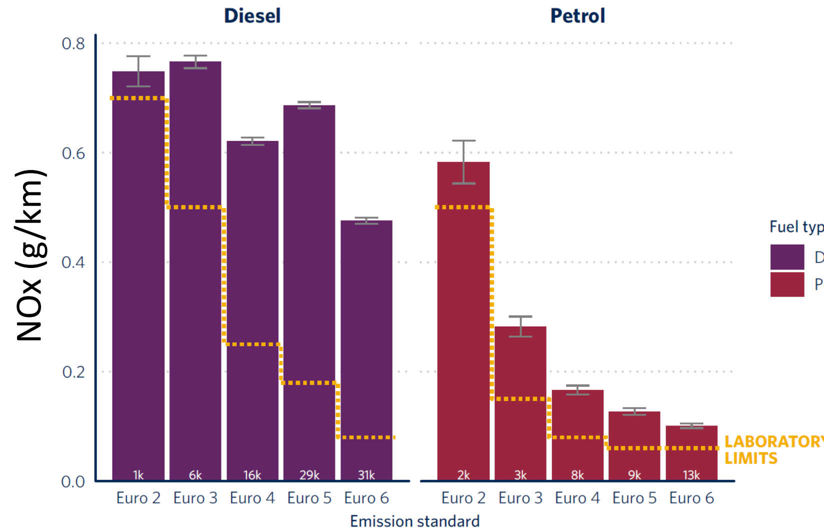
PEMS test data to be made available on publicly accessible website

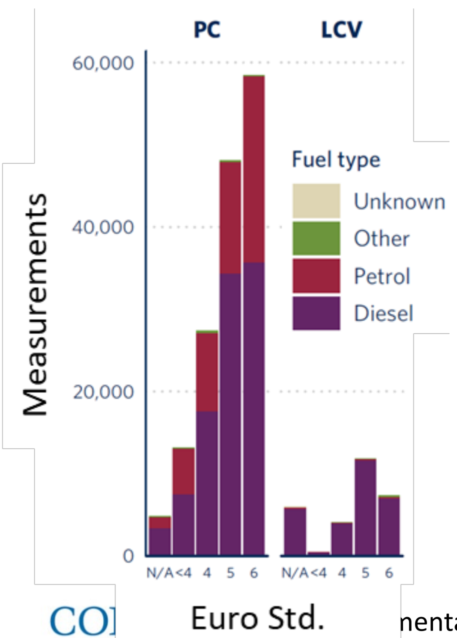
Remote sensing data shows adverse impact of warmer temperatures on Diesel emissions

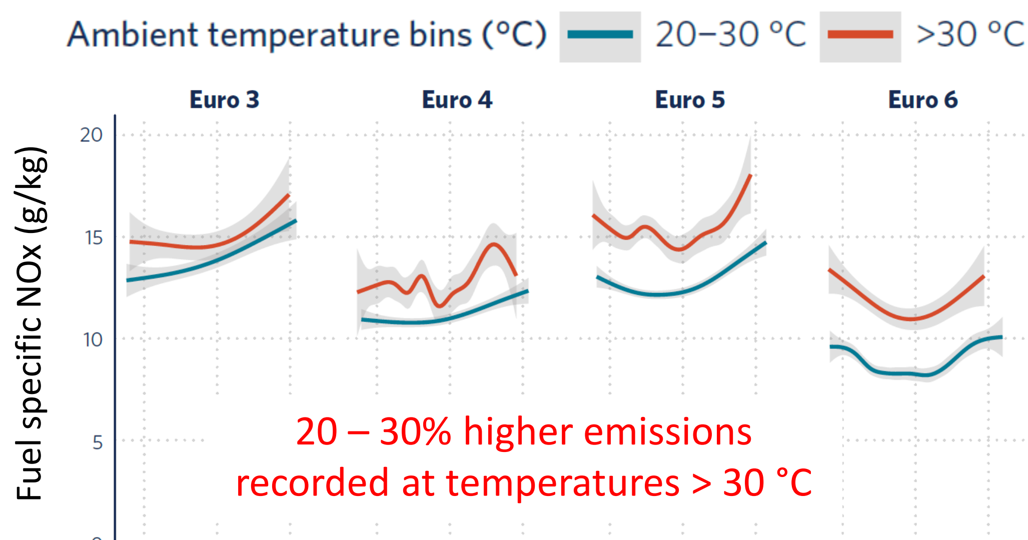
ICCT White Paper, 2019











20 – 30% higher emissions recorded at temperatures > 30 °C

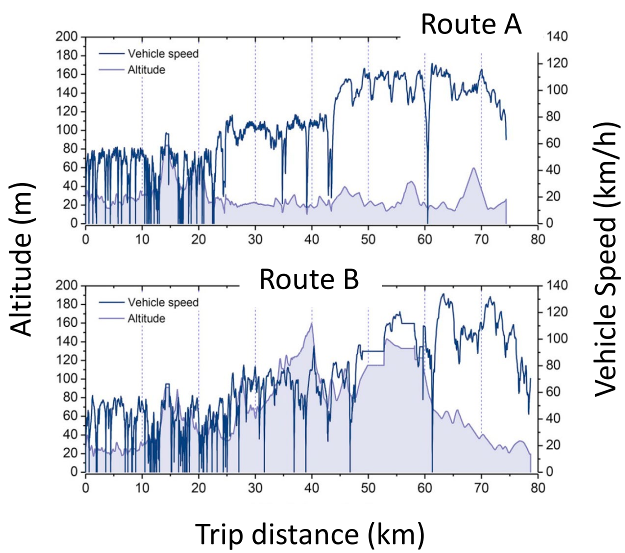
SCR offers robust performance to meet the ambient temperature variations within RDE

Korea Natl. Univ. of Transportation, Atm. Env. 196, 2019, 133 – 142.

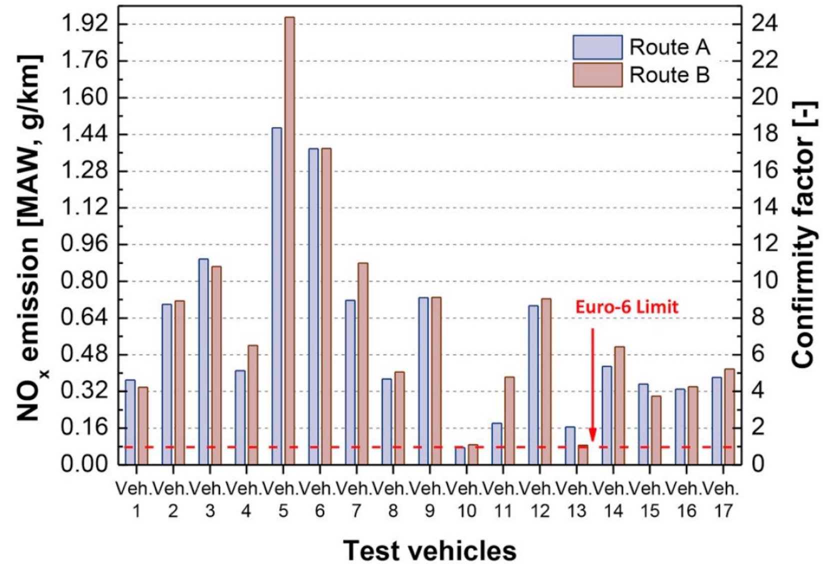
17 MY 2015 – 2016 Euro 6 vehicles

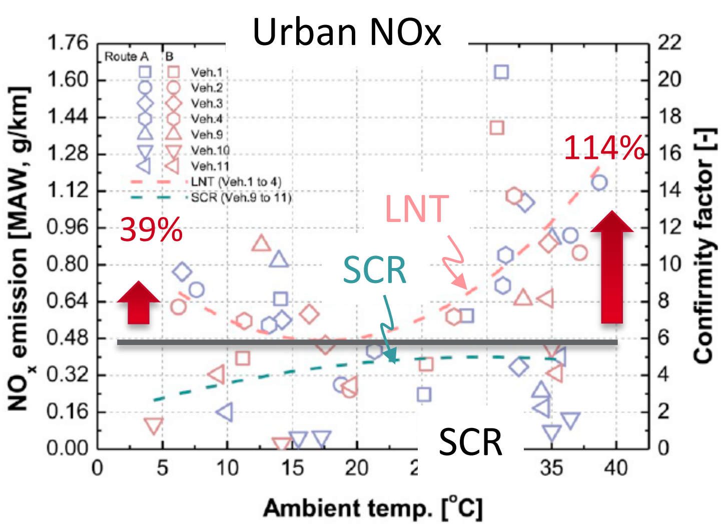
Testing done on two RDE routes

Rte. B has higher altitude variations



SCR ~ twice as effective as LNT in reducing NOx





	← LNT →	← SCR →
Engine size	1.5 – 2.0L	1.6 – 3.0L
Avg. TP NOx	9.8 – 11X Limit	4.6 – 5X Limit

Emissions increase with ambient T at either end.
Robust performance demonstrated through use of SCR

What next: Emerging possibilities for Euro 7

Tightening of criteria pollutant limits & inclusion of previously unregulated species

(1) Fuel neutral standards: Diesel = Gasoline

(2) Further reduction of limits. Example: NOx = 40 mg/km (note: China6b limit is 35 mg/km)

(3) Inclusion of PN < 23 nm (down to 10 nm)

(4) Tightening of conformity factors (CF = 1.0 or “margin error = 0” for RDE/PEMS

(5) Limits on previously unregulated species – NO_2, N_2O, NH_3, HNCO, HCHO, PAHs

(6) Replace NMHC with THC and account for CH_4 with CO_2 equivalence

(7) Low temperature test (- 7 °C) for type approval (type VI test)

(8) Limit on CO, limit on fuel enrichment

Continuous on-board monitoring : OBD → OBM