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Automotive Emissions Control: Challenges from real world performance requirements

The future of automotive technology beyond ‘Dieselgate’

3rd REMEDIO Seminar: Sustainable Urban Mobility: Confronting Air Pollution and Climate Change
22 May 2018 - City Hall of Thessaloniki

Outline

- Short personal profile
- The reasons that underpin the need for action to mitigate road transport emissions
- What has European policy done so far and what is it in the pipeline?
- What do these mean in terms of
  - Testing requirements
  - Impacts on vehicle technology
  - Simulation and modeling

Personnel

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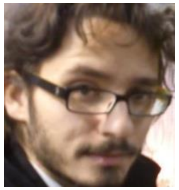
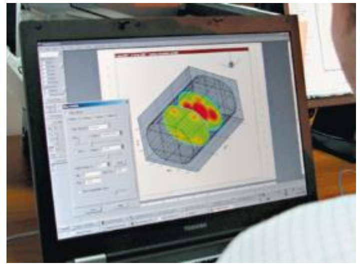


Technica l Staff

Scientific & research areas



Exhaust gas emissions & after-treatment technology

Vehicle fuel efficiency

Renewable fuels

Extensive know-how in combustion engines and emissions **measurement** technology combined with advanced CAE and **modeling** techniques

…**keeping the big picture on vehicle environmental performance!**

CERT
Quality Assurance ISO 9001
QMSCERT

Main Facilities

Chassis dyno for vehicle emissions testing

3 fully equipped engine benches for emissions testing

Fuel injector test rig

Mobile biomass gasification unit

~400+ m^2 test facilities supporting non-stop measurements

~250 m^2 office area accommodating ~ 25 researchers

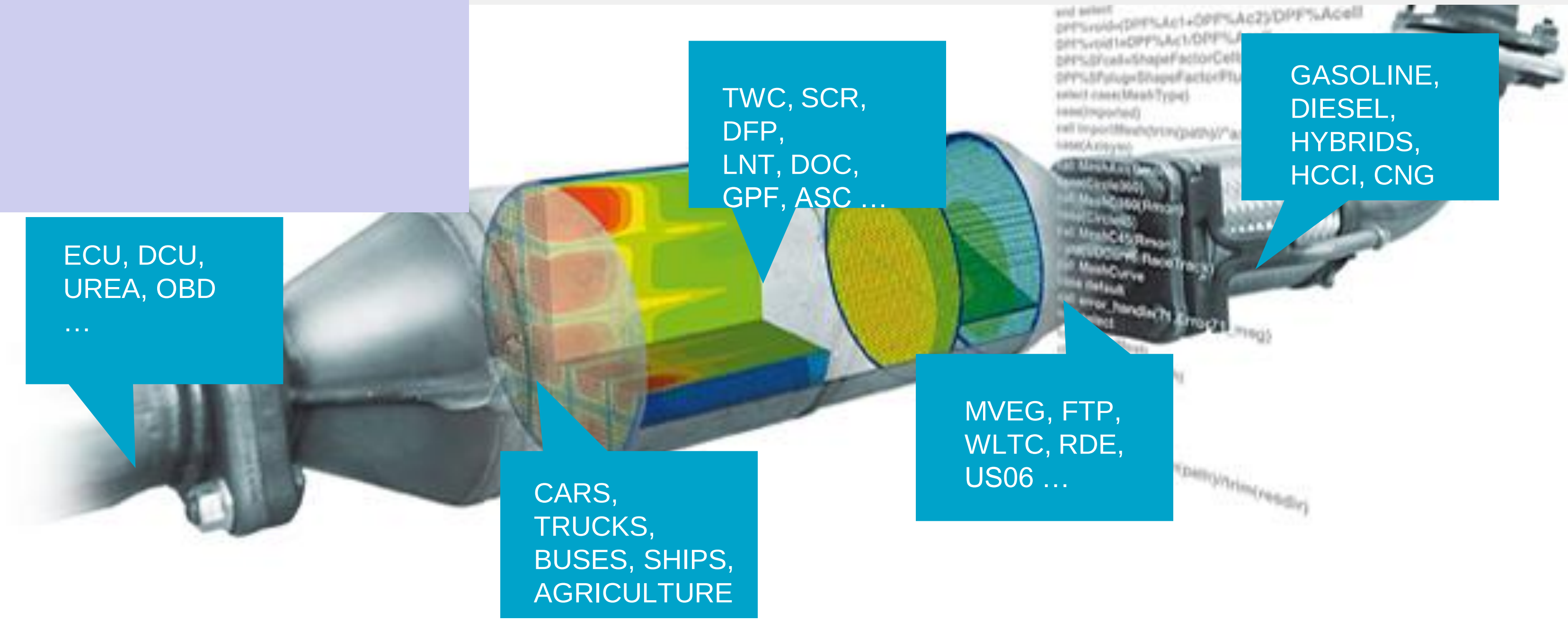
axisuite®

Exothermia
modeling efficiency

Complex problems call for expert solutions

Exhaust After-Treatment is a multi-parameter problem, exceeding the capacities of ‘conventional’ experimental methods.

Acceptable costs are only possible by employing reliable simulation across the development process.



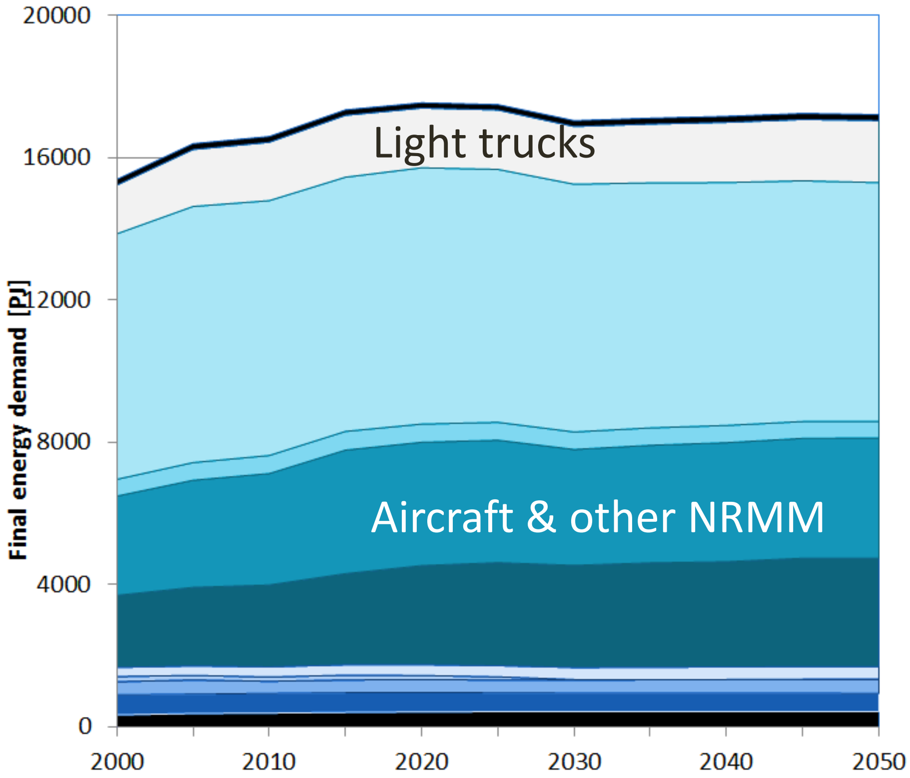
Suite of main tools

copert 4	• Estimates emissions from on-road vehicle fleets • Used by 22 out of 28 MS for official submission of road emission inventories • Developed for the European Environment Agency • Free for use
copert AUSTRALIA	• Estimates emissions from on-road vehicles in Australia • Developed in collaboration with Queensland Govt • Official method in National Pollutant Inventory (NPI) • Commercially available
Sibyl	• Includes historic and projected stock and activity data • Delivers alternative scenarios for energy and emissions • Includes advanced technologies and mobility patterns • Commercially available

ROAD TRANSPORT EMISSIONS CONTINUE TO BE IMPORTANT

Energy projection per mode

- Transport accounts for 1/3 of total energy consumption and 1/4 of total GHGs
- Road transport alone contributes to 20% of total manmade EU GHG



Baseline for EU27:

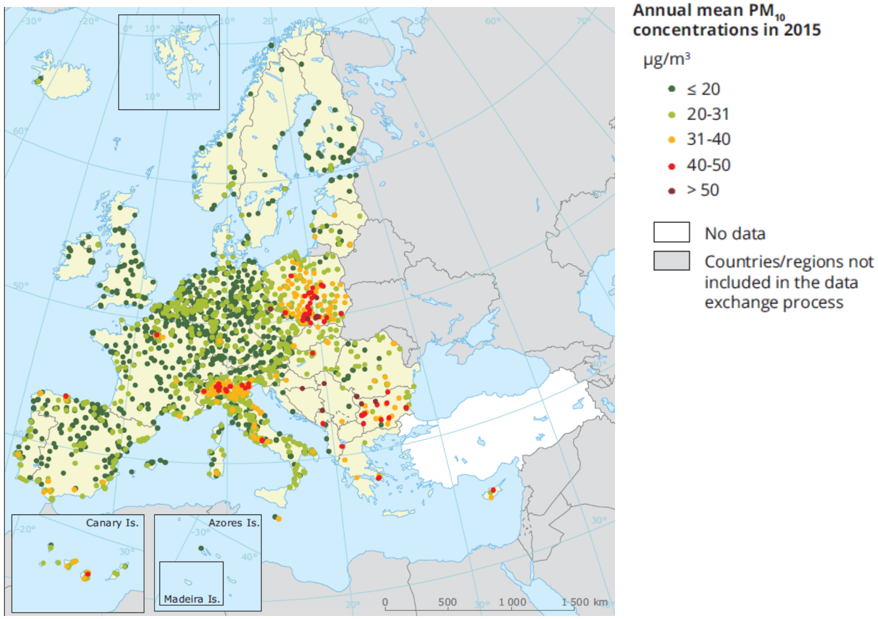
- Most important change:
  Gasoline:Diesel for cars drops from 2.0 in 2000 to 1.15 in 2030
- Non-road vehicles:
  Aircraft have biggest share in consumption – but here only LTO emissions are counted
- Mobile machines, ships, rail make up the rest

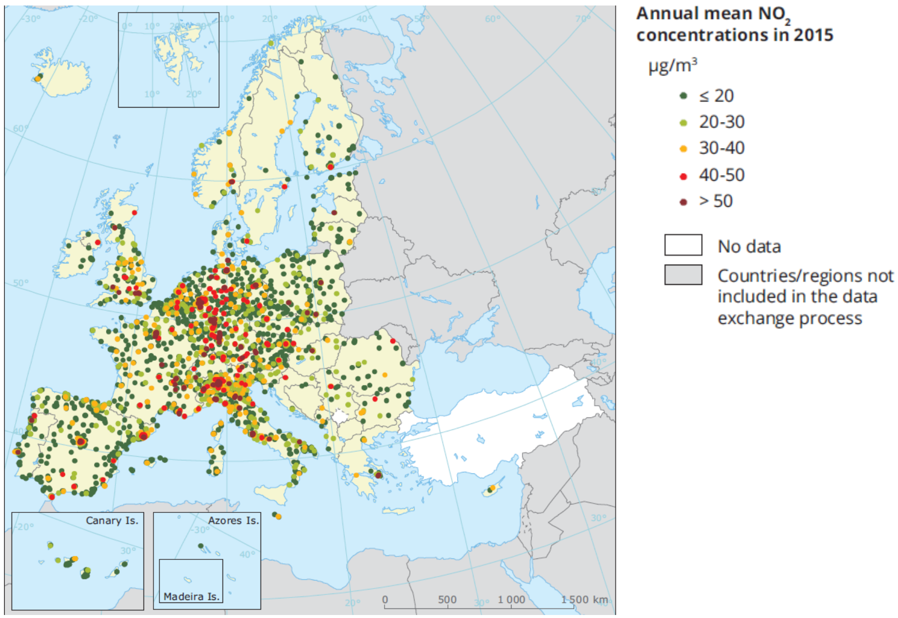
Source: Amann (ed.), 2012, Review of TSAP, IIASA

Annual Mean Air Quality in the EU (2015, PM and NO2)

PM10 conc. (red) **>40 μg/m³**
(green) **>20 μg/m³ (WHO annual limit)**

NO2 conc. (red) **>40 μg/m³**





PM10: - Exceedances of annual limit value (40 μg/m³) in only 3 % of all the reporting stations
- The stricter value of the WHO (20 μg/m³) was exceeded at 54 % of the stations and in all the reporting countries

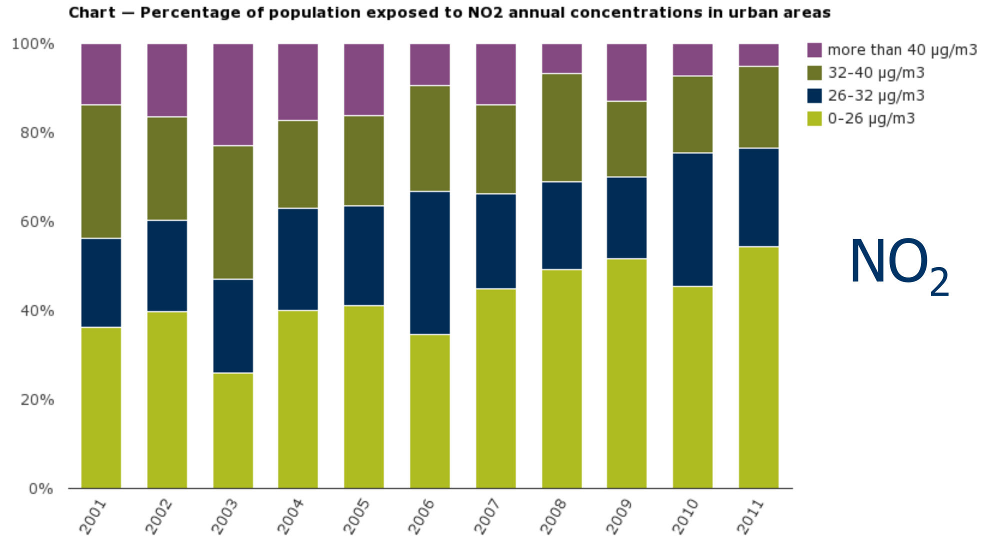
NO2: - The highest concentrations (89 % of all values above the annual limit value=40 μg/m³) at traffic stations

The average contribution of local traffic to urban PM10, PM2.5 and NO_2 is estimated at 15%, 35% and 46%, respectively

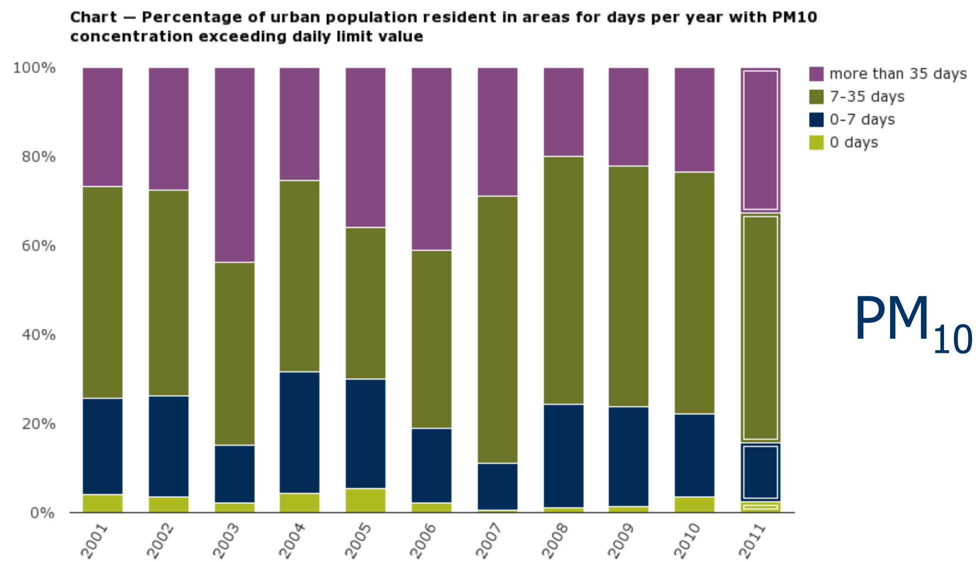
Source: EEA 2017

Population exposed to high pollution

A significant fraction of the population continues to live in areas where acceptable AQ levels are not respected



NO_2

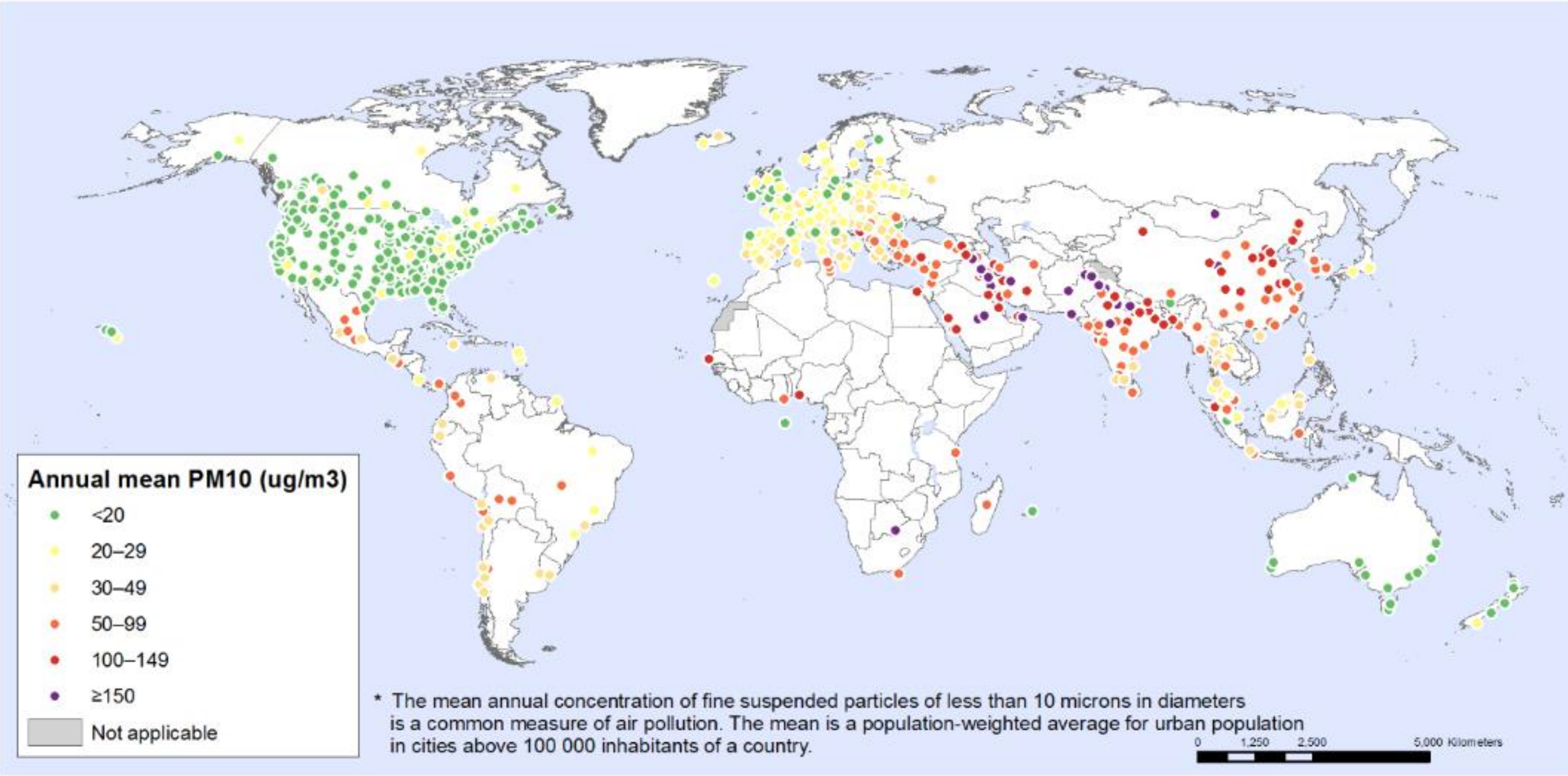


PM_{10}

Fraction of population above AQ limits

Source: European Environment Agency

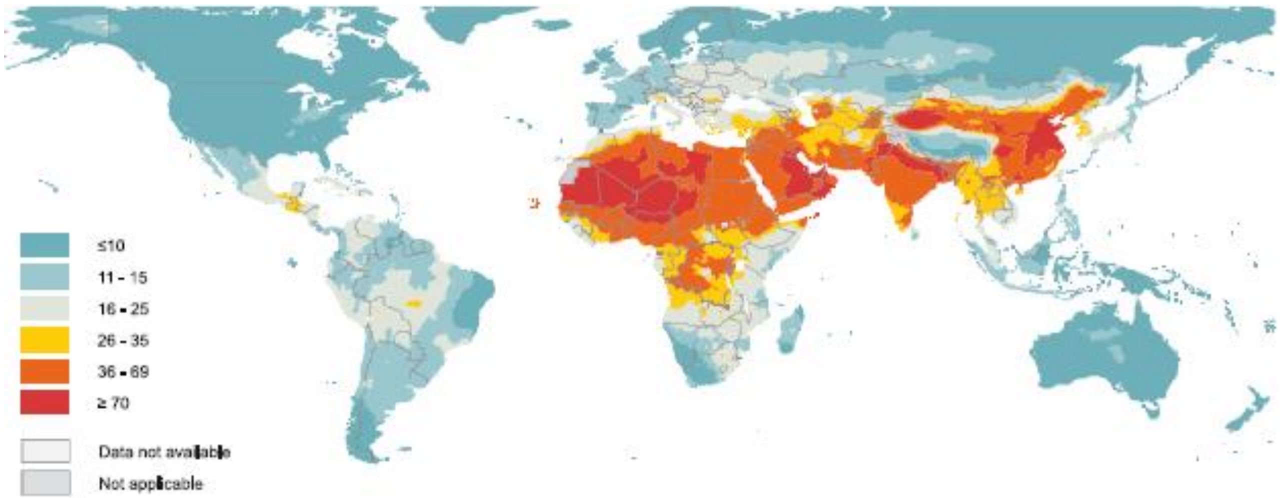
Exposure to PM_{10} in 1100 urban areas, 2003 – 2010

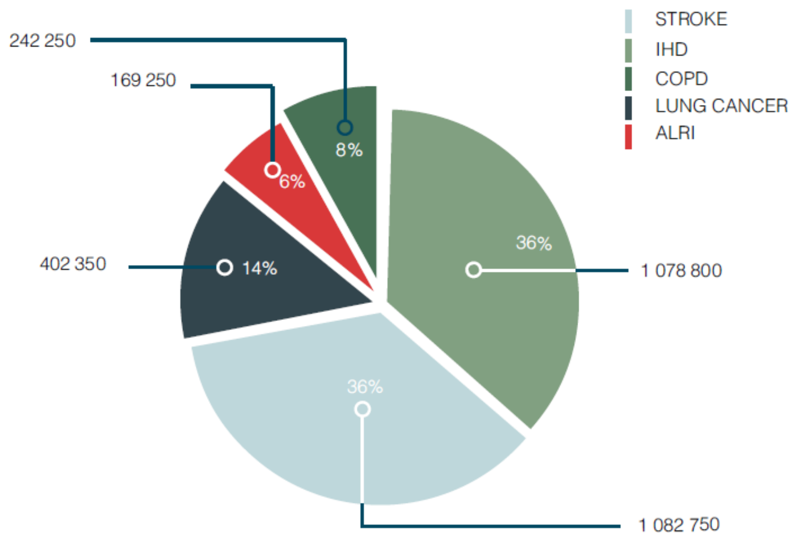


WHO Air Quality Guideline: Annual mean PM10 = 20 µg/m³

Source: WHO, 2012

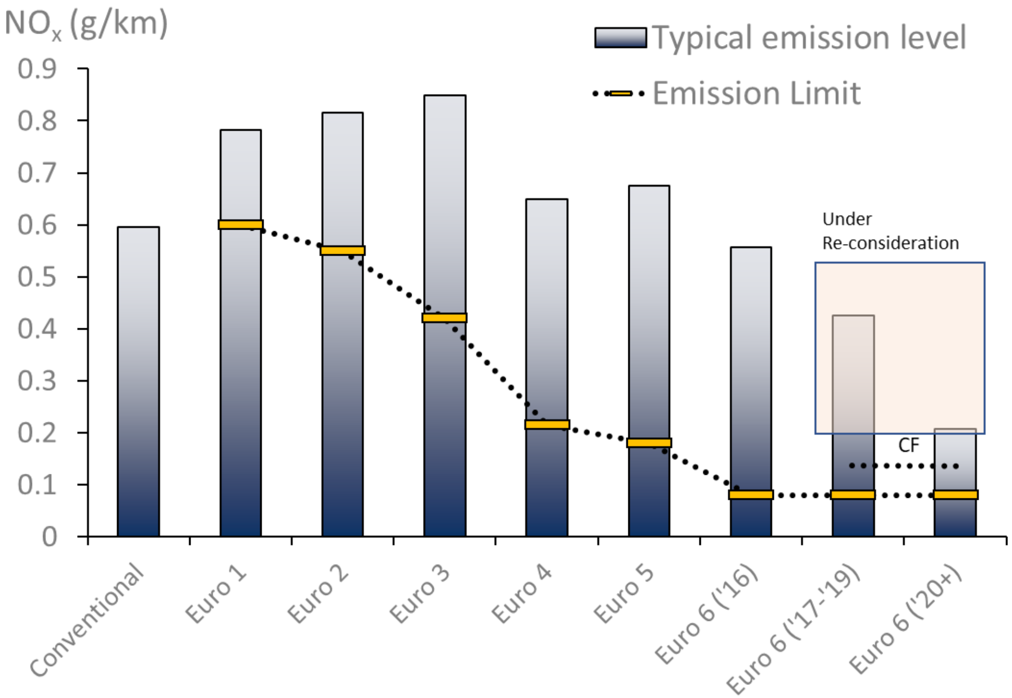
Modelled annual median concentration of PM2.5 (μg/m^3) and deaths attributed to ambient air pollution





Source: WHO, 2016

Emission levels: Light Duty Vehicles



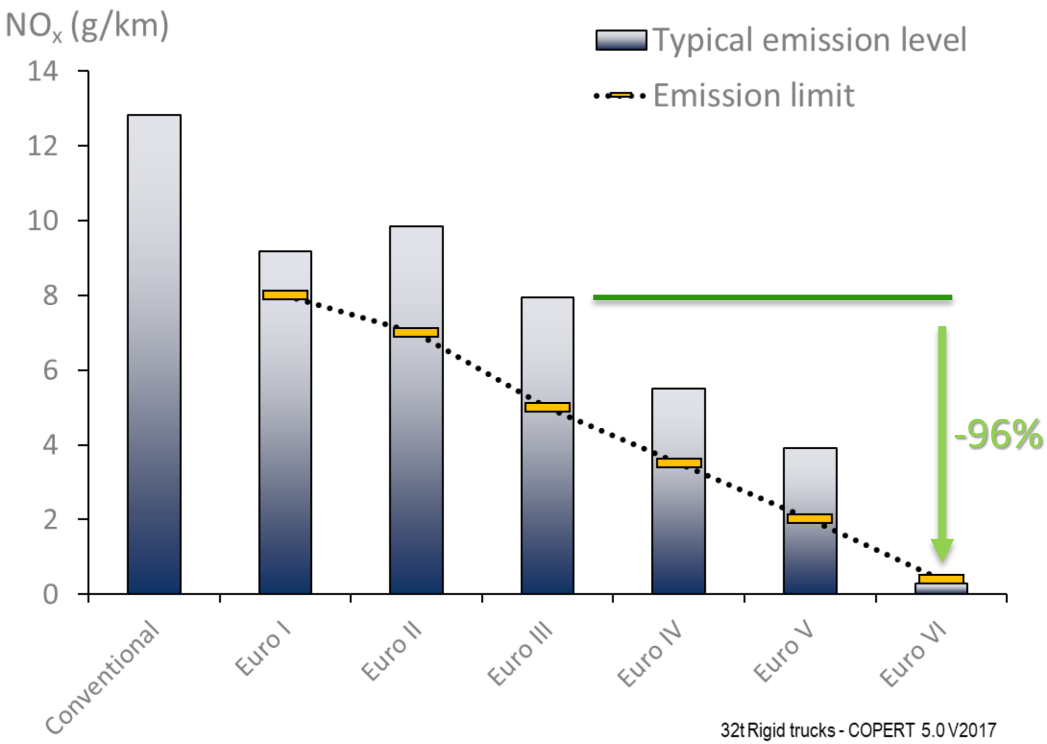
Medium diesel PCs - COPERT 5.0 V2017

Significant exceedances up to Euro 5

Expected reductions at Euro 6 step. Still limited evidence – models under revision

Light Duty Vehicles	M1 – Passenger Cars	Carriage of people and their luggage up to 8 seats	
	N1 – Light Commercial Vehicles	Carriage of goods and M_{max} ≤ 3,5 t	

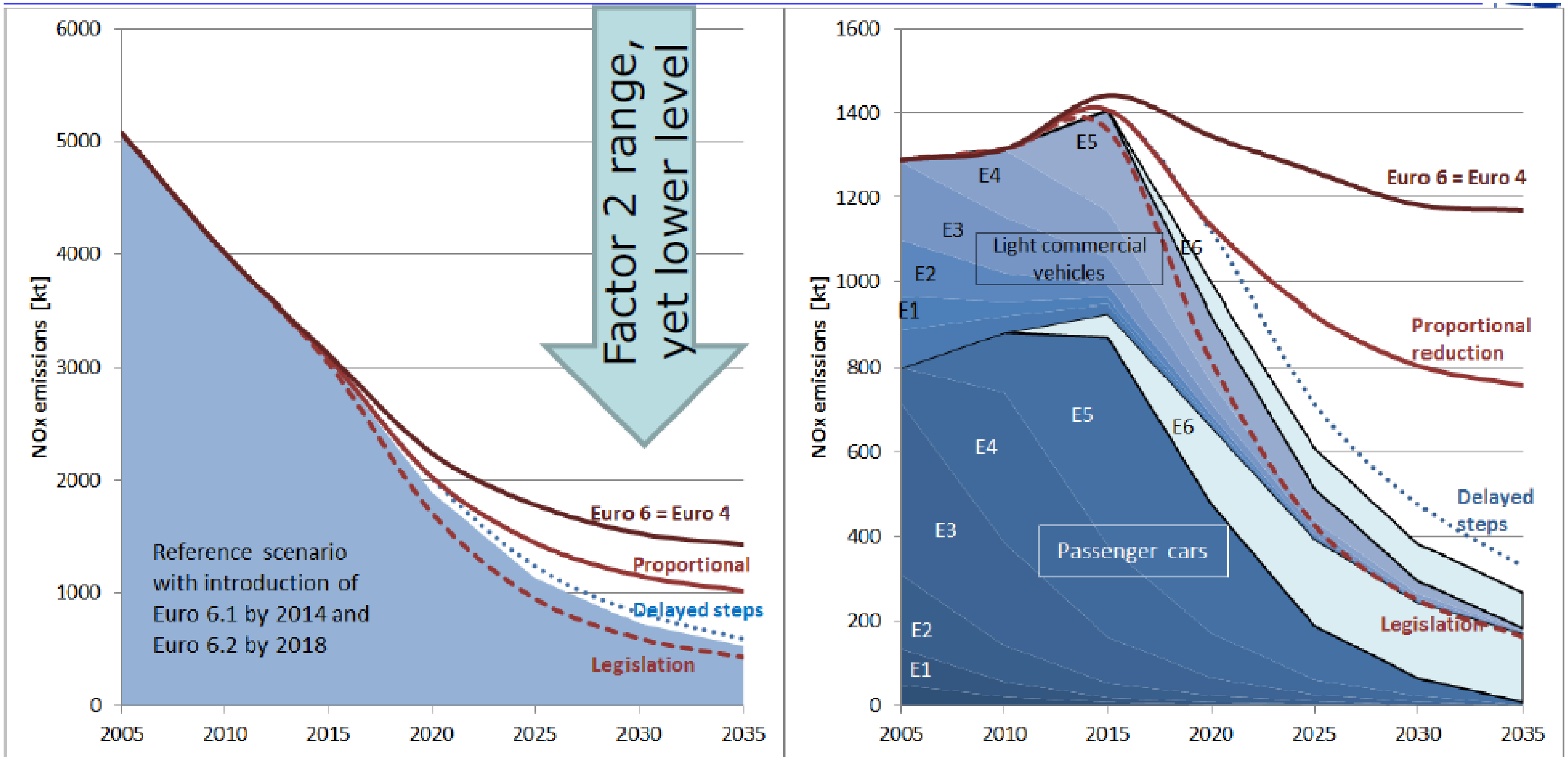
Emission levels: Heavy Duty Vehicles



Generally, consistent reductions between emission limits and emission factors

Heavy Duty Vehicles	N3 - Heavy Goods Vehicles	Carriage of goods and M_{max} > 12 t	 
	M3 - Buses	Carriage of people and their luggage, more than 8 seats and M_{max}>5 t	 
	N3S - Special purpose vehicles	Special arrangements and/or carrying equipment	 

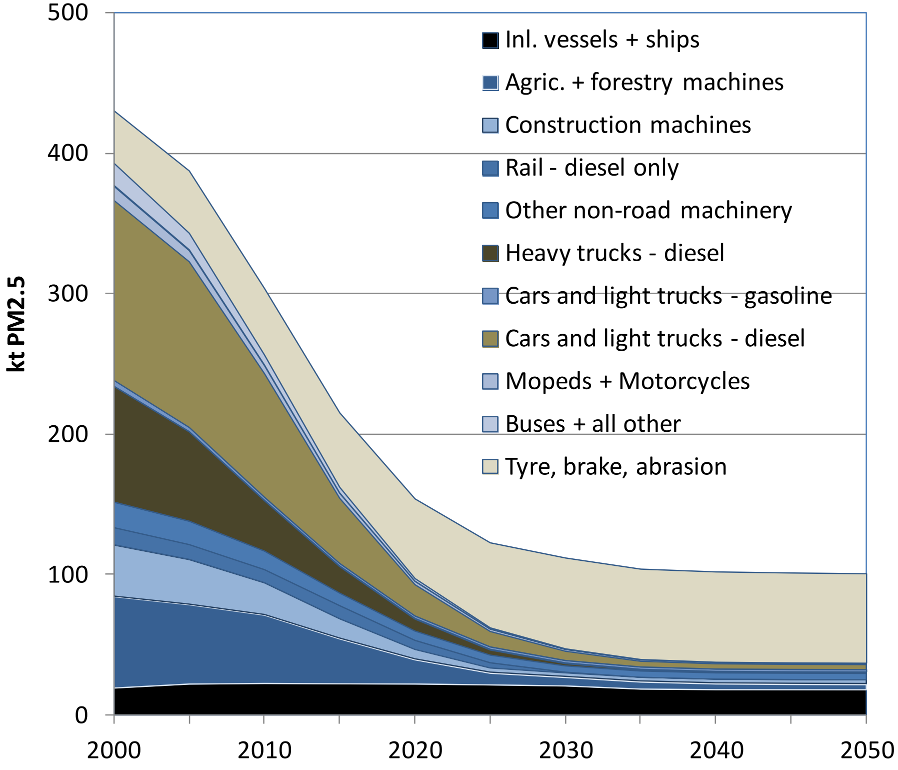
NO_x projections



"Legislation": Euro 6 = 80 mg/km from 2015. **"Delayed steps"**: As Reference, but Euro 6.2 only from 2020 onwards. "**Proportional reduction**": Euro 6 = 380 mg/km from 2015. **"Euro 6 = Euro 4"**: Euro 6 = 730 mg/km from 2015

Source: Kleefeld and Ntziachristos (2012) TSAP Review

$PM_{2.5}$ projections



Baseline:

- Reductions until 2030 vs. 2005
  >90%: diesel HDV&LDV, locos, NRMM
  ~70% other mobile machines

- **Road abrasion**, tyre, clutch and brake wear increase with traffic volume, >80% of emissions from road vehicles in 2030

Source: Kleefeld and Ntziachristos (2012) TSAP Review

AIR POLLUTANTS REGULATIONS

Vehicle category definition

Light Duty Vehicles	M1 – Passenger Cars	Carriage of people and their luggage up to 8 seats	
	N1 – Light Commercial Vehicles	Carriage of goods and $M_{max} \leq 3{,}5$ t	
Heavy Duty Vehicles	N3 - Heavy Goods Vehicles	Carriage of goods and $M_{max} > 12$ t	
	M3 - Buses	Carriage of people and their luggage, more than 8 seats and M_{max}>5 t	
	N3S - Special purpose vehicles	Special arrangements and/or carrying equipment	

Regulation 2007/46/EC as last amended by 758/2015

Activity in the regulatory front - LDVs

Year	Regulation	Content
2007	715/2007	Introduction of Euro 5 and Euro 6
	2007/46	New regulation on vehicle type approvals
2008	692/2008	Euro 5 & 6 implementation procedures and modalities
2009	79/2009	Extension of type approval for H_2 vehicles
	443/2009	CO_2 specific targets from passenger cars
	661/2009	Mandatory implementation of GSIs and TPMs on PCs
2010	406/2010	Certificate of conformity of H_2 vehicles
2011	510/2011	CO_2 specific targets from vans
	566/2011	IUPR and In-Service conformity testing for Euro 6
	725/2011	Certification of eco-innovations
2012	65/2012	Implementation of GSIs
	459/2012	PN number for GDIs and Euro 6 OBD limits
	630/2012	TA provisions for H2, H2NG, and hybrid electric vehicles
2013	195/2013	Introduction of eco-innovations as part of the type approvals
2016	427/2016	1^{st} Package of RDE
	646/2016	2^{nd} Package of RDE: CFs and Dynamic Range
2017	1151/2017	WLTP replaces NEDC, repeals 692/2008
	1152&3/2017	CO_2 correlation between WLTP and NEDC – LCV & PC
	1154/2017	3^{rd} Package RDE: Cold start and PN (+hybrids, regenerating devices)
2018	under voting	4th Package RDE: In-Service Conformity (ISC); third-party testing provisions for market surveillance; PEMS data evaluation methods; methods, and the RDE evaluation of Plug-in Hybrid Electric Vehicles (PHEV).

Real driving emissions control – need & approach

Euro 6 at different driving conditions - LAT

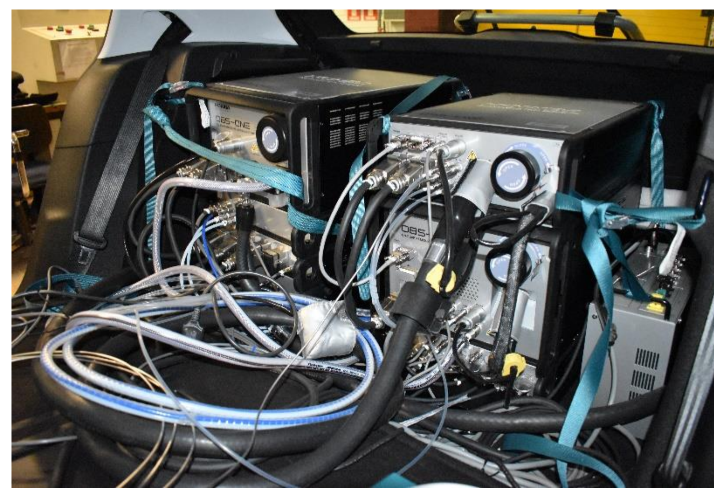
Driving	CO_2 (g/km)	CO (mg/km)	NO_x (mg/km)	CF_{NOx}
RDE	150	2.9	360	4.5
Hilly	334	10.7	3907	49

Euro 6 at different ambient temperature - TNO

Driving	NO_x (mg/km)	CF_{NOx}
CADC 23^{o}C	26	0.3
PEMS 2^{o}C	665	8.3

Portable Emission Measurement System (PEMS)

AVL Gas PEMS iS, PN PEMS iS
CO, CO_2, NO, NO_2, PN, EFM



Horiba OBS-ONE
CO, CO_2, NO, NO_x, HC, PN, EFM

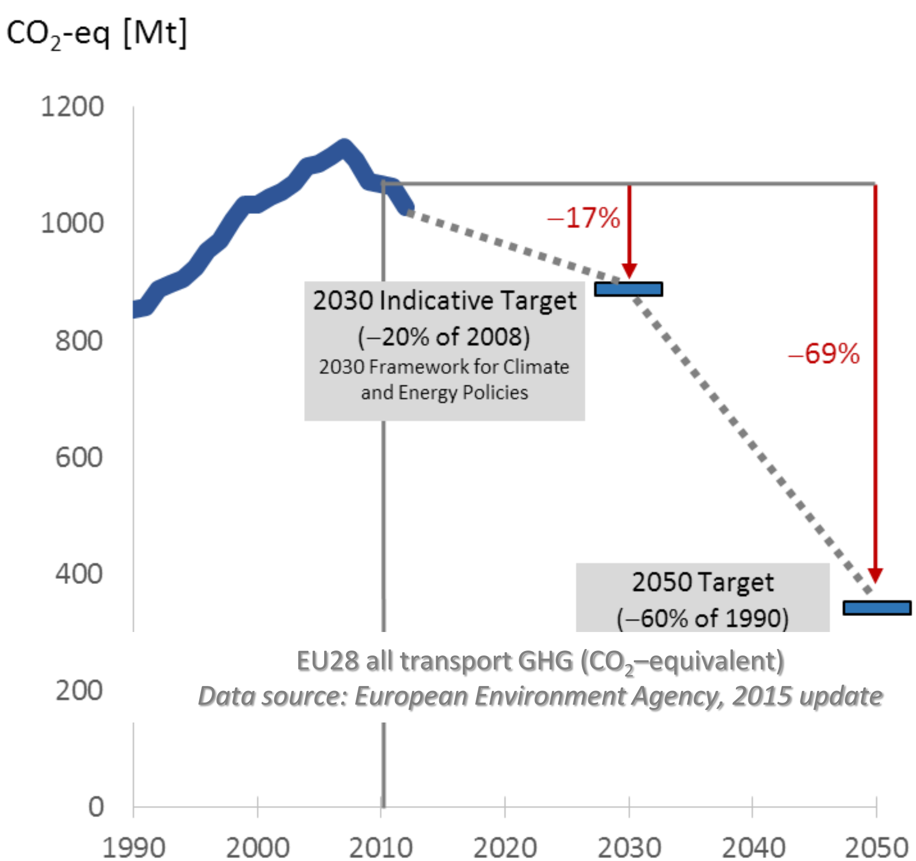
Regulations under preparation

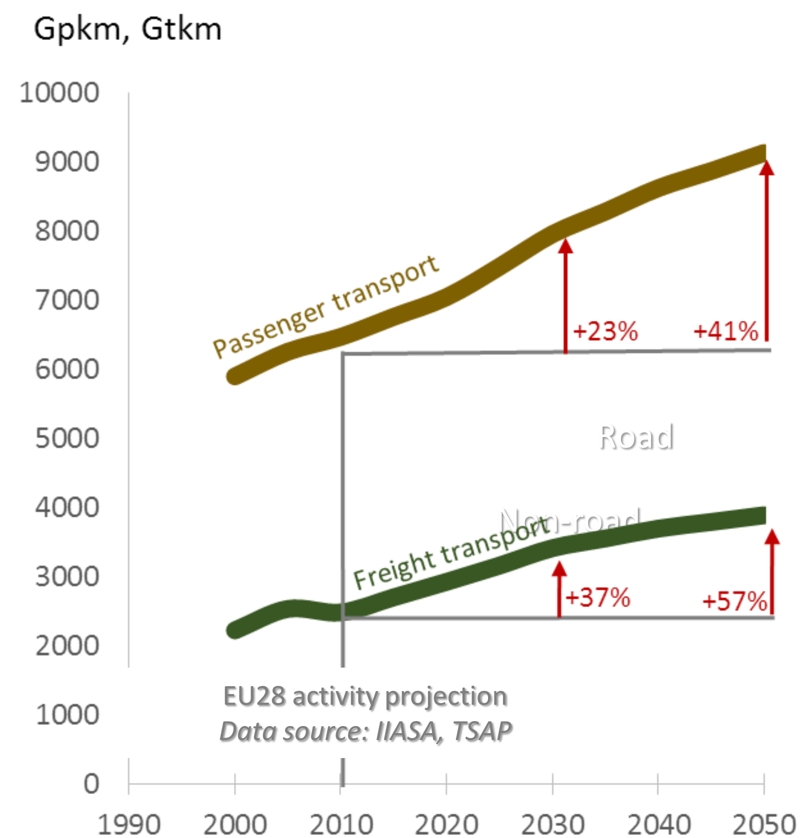
- CO_2 regulations
  - New CO_2 emissions targets for PCs and Vans
  - CO_2 labeling for HDVs
- Regulated air pollutants
  - Euro 6 and VI OBD (incl. PM/PN monitoring)
  - GDI PN PMP
  - 4th RDE Package
  - L-category vehicles (scooters, motorcycles, …)
- RDE for CO2?
- Other issues (durability, NO2, NH3, tyre and brake wear…)

CO_2 REGULATIONS

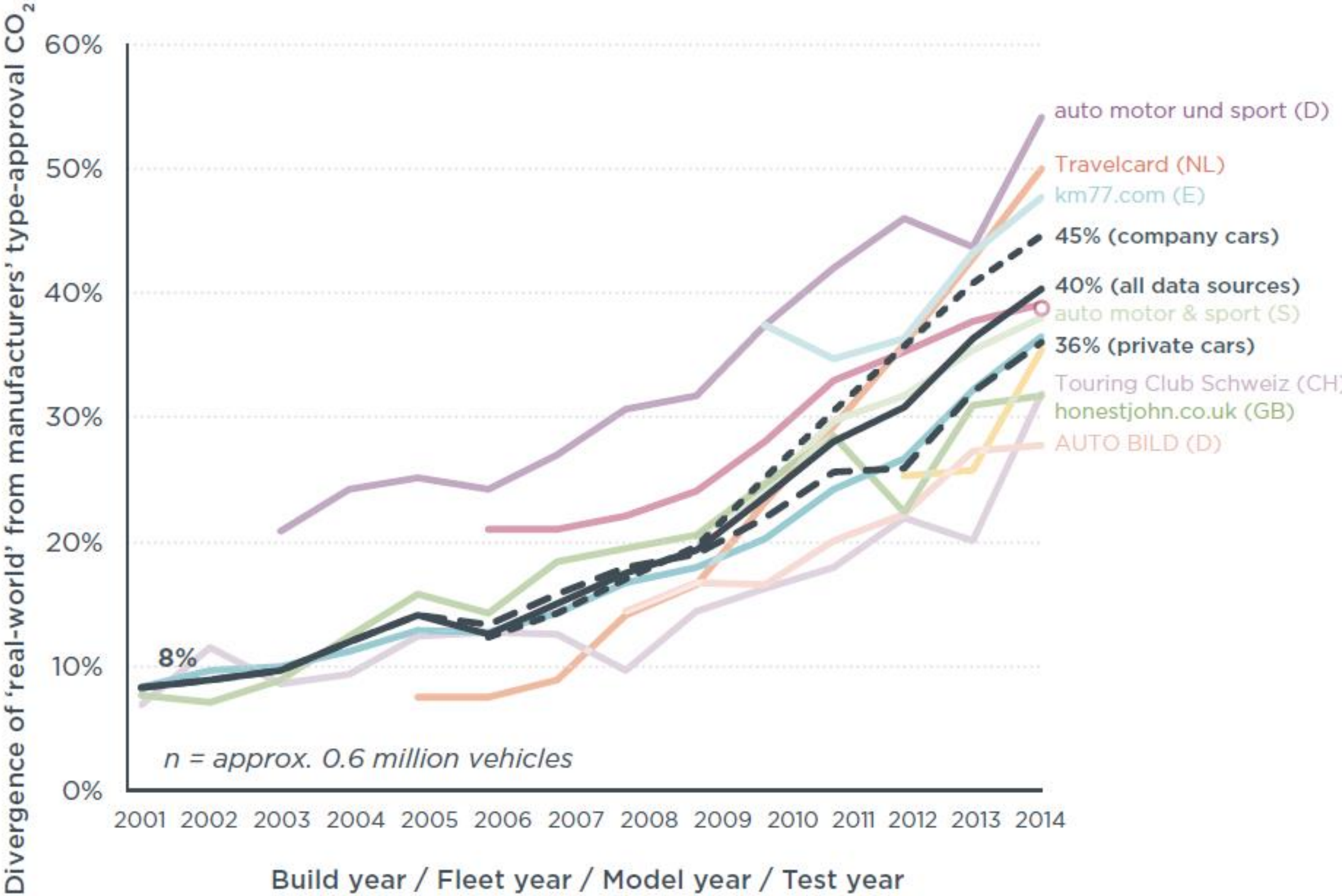
European objectives for Transport

Demanding CO_2 objectives despite projected strong activity growth





Divergence of real-world CO2 emissions from

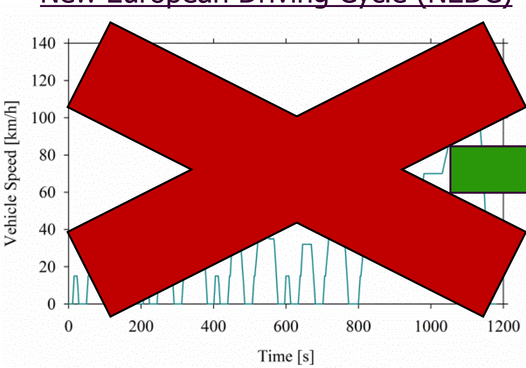


Source: ICCT. 2015

Application of WLTP measurement protocol

CO_2

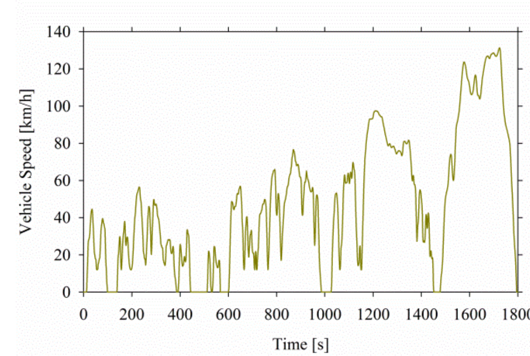
New European Driving Cycle (NEDC)



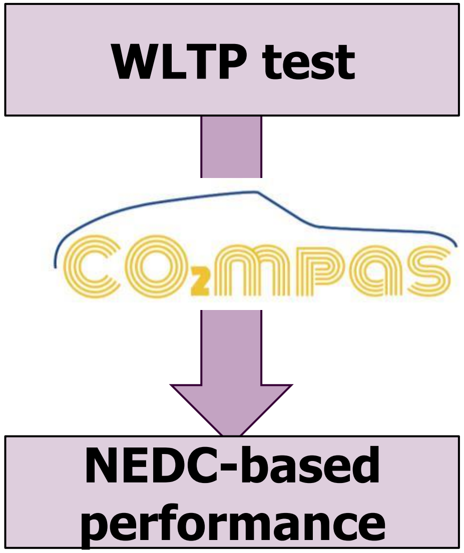
<118 g/km

95 g/km

Worldwide harmonized Test Procedure (WLTP)



- Has been used since 70s.
- Does not consider real-world driving characteristics such as extra weight, temperature range, A/C usage.
- 40% less fuel consumption compared to reality.



- ✓ The driving profile is the outcome of real world data gathered in EU, US and Japan.
- ✓ Improves aspects of the NEDC that were not sufficiently clarified.
- ✓ Targets to reflect the real-world fuel consumption benefit when the vehicle fleet composition changes.

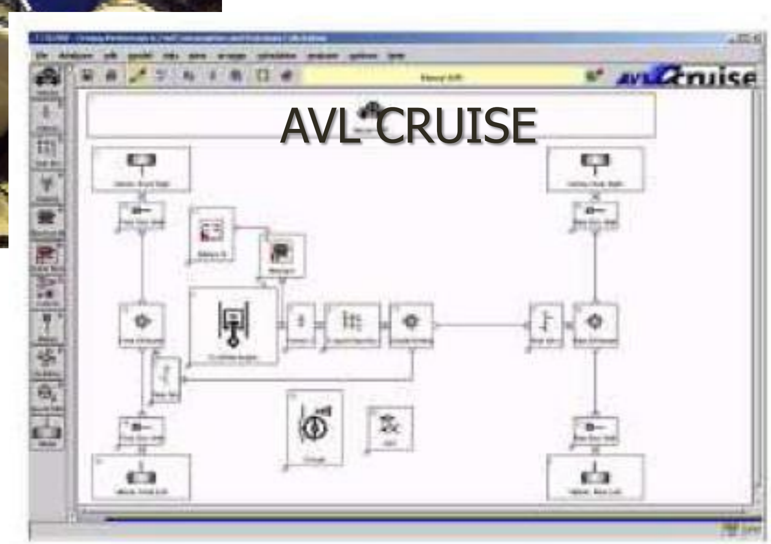
Testing at NEDC	Testing at WLTP, translating at NEDC	Testing at WLTP

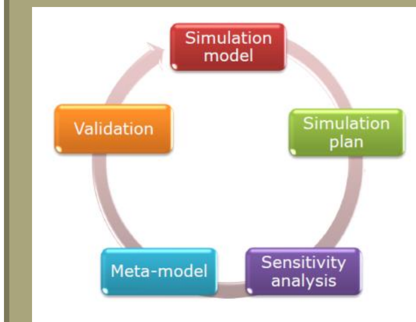
2017 2021

CO_2 WLTP-NEDC correlation exercise

Chassis dyno tests
(~30 vehs)

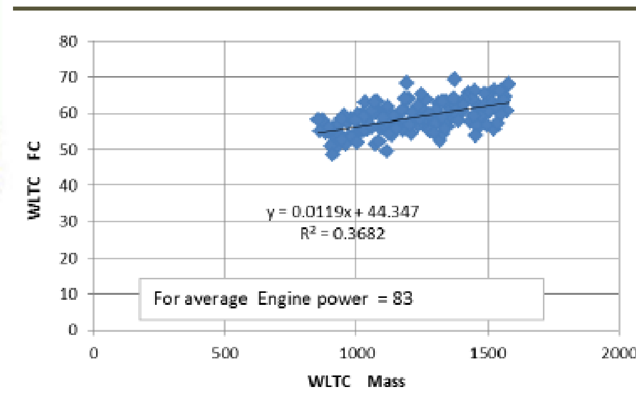
Vehicle level Technology
Simulations (~15000 sims)





Overall approach

Segment-level simulations:
Meta-model (Physical or
statistical approach)

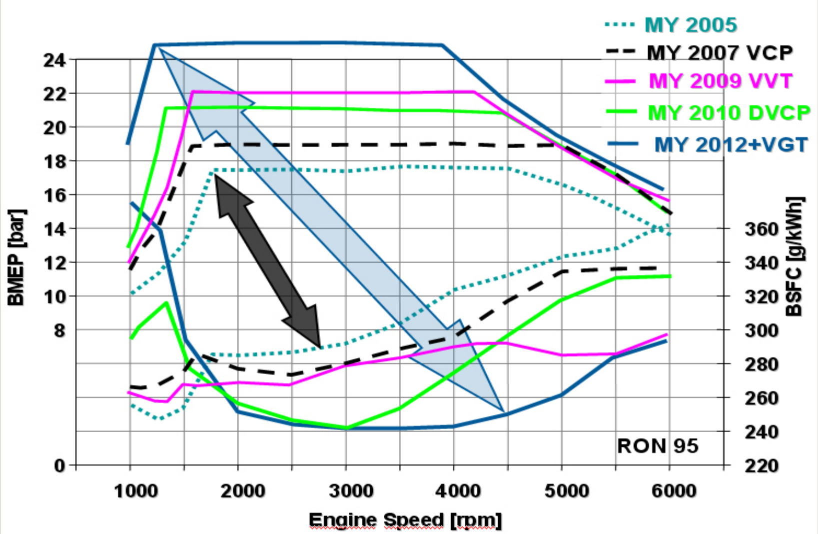


Technologies examined in WLTP-NEDC translation

Technology

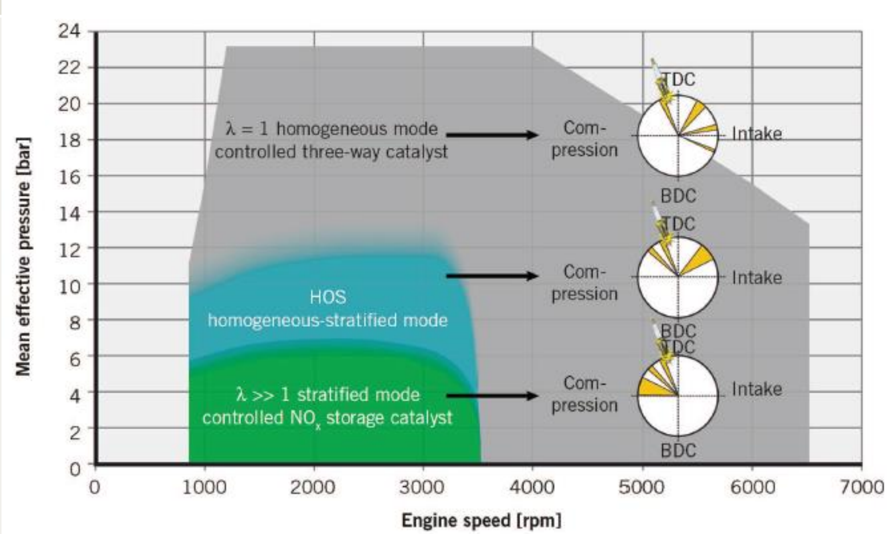
Downspeeding, Downsizing

Source: AVL



Lean burn

Source: MTZ 5/2013 Vol. 74



Technologies examined in WLTP-NEDC translation

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<tr><th>Technology</th><th></th></tr>
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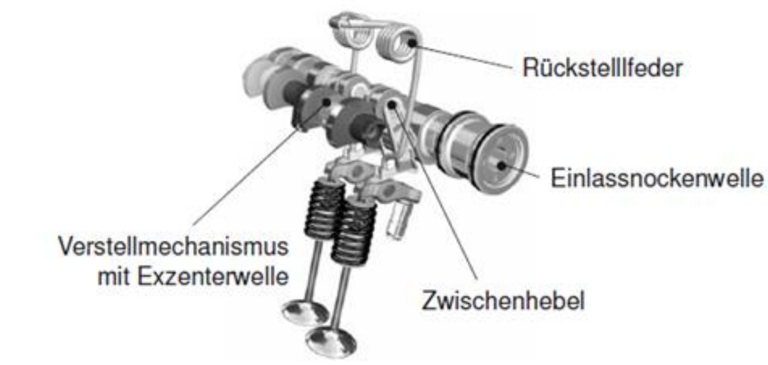
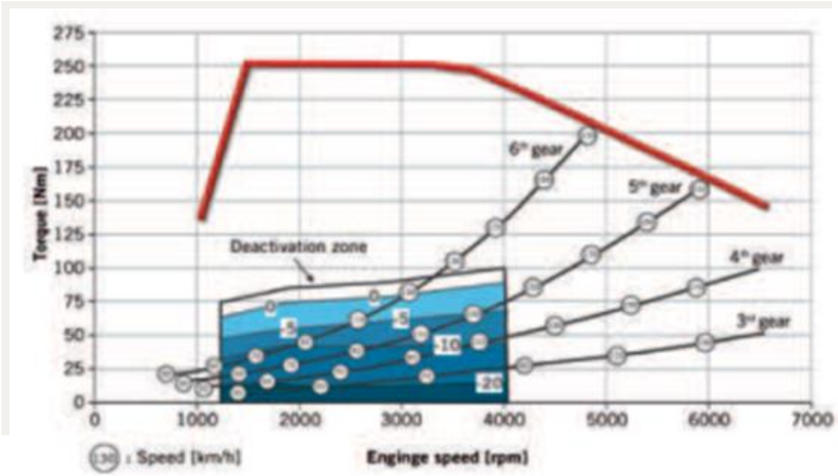
(e.g. Vanos, Valvetronic)</td><td>

Abb. 12-18: Vollvariable kontinuierliche Ventilsteuerung BMW Valvetronic [Bildquelle: BMW Group]</td></tr>
<tr><td>Cylinder deactivation</td><td>
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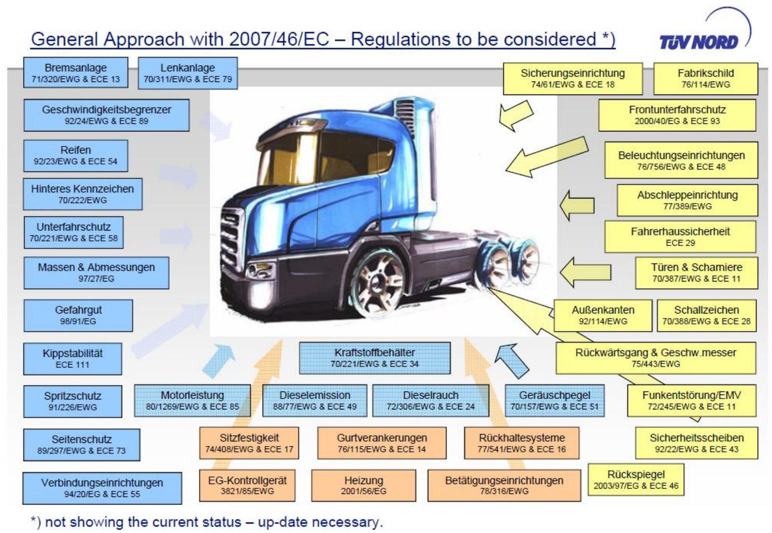
</table>

Source: MTZ 03/2012 vol. 73

CO_2 from HDVs

- CO_2 emissions from HDV have not been addressed yet
  - Vehicle type approval complexity
  - Articulated vehicles carry different semi-trailers



- Energy efficiency in trucks has always been in the forefront of vehicle / engine development
  - Fuel cost is the most significant criterion in choosing a truck
  - Energy efficiency improvements have already shifted CO_2 emissions downwards and have advanced relevant technologies

Monitoring CO_2 emissions from HDV

- Selected option: Vehicle Simulation
  - Simulation for whole vehicle supported by component testing
  - Joint Commission – ACEA effort
- VECTO Simulation tool (Version 1) launched by the JRC in 10/2012

VECTO
Vehicle Energy Consumption Calculation Tool

- 2012-2014: campaign towards final regulation
  - ACEA – JRC –Consultants experimental campaign ("Proof of Concept")
  - Completion of simulation tool
  - Finalize regulation / harmonize with other activities (eg Heavy Duty Hybrid powertrains)

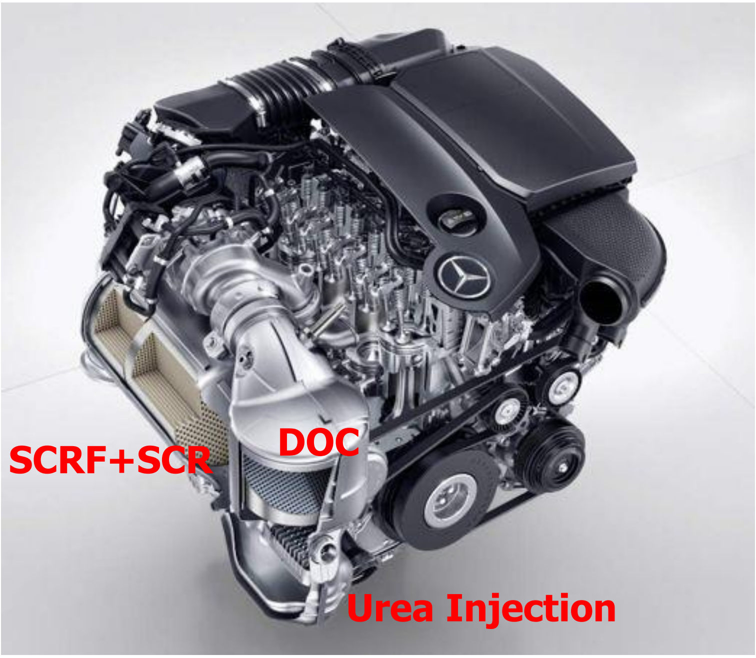
Source: Fontaras (2012) JRC Presentation

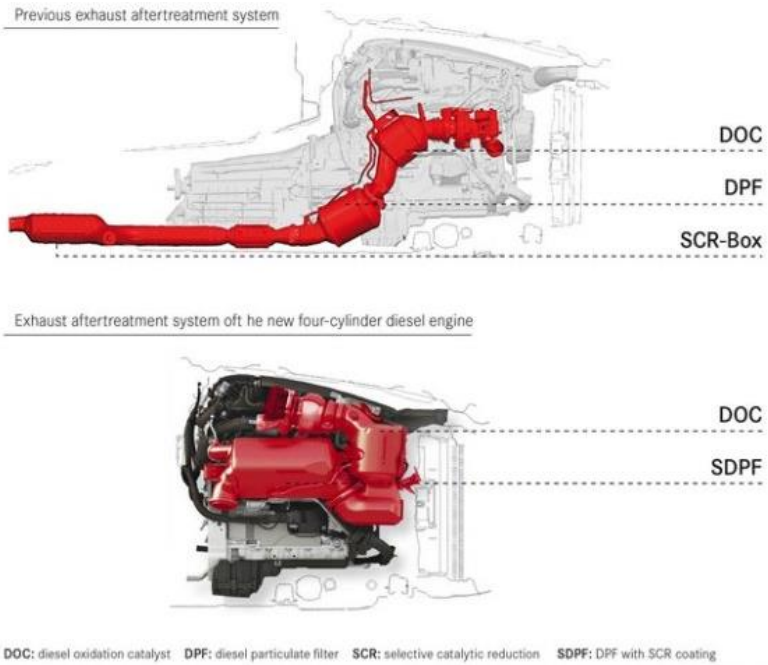
DIESEL EMISSION CONTROL TECHNOLOGY

Some history on diesel vehicle technologies

Emission Standard	Intro Year	Engine measures	Exhaust aftertreatment
Euro 1	1992	Combustion chamber and intake system improvements	None
Euro 2	1996	Direct Injection, fuel pressure improvement	Oxidation catalyst
Euro 3	2000	Exhaust Gas Recirculation, Common Rail Injection	Pre-catalyst and main catalyst First diesel particle filters
Euro 4	2005	Multiple injections, increase of injection pressure	Pre-catalyst and main catalyst More extensive use of DPFs
Euro 5	2010	High pressure cooled EGR and Combustion optimization	Pre-catalyst and main catalyst or catalyzed DPF mandatory
Euro 6	2014	HP and LP Cooled EGR and Combustion optimization	DPF + Close coupled DOC + Lean NOx trap (LNT) or Selective Catalytic Reduction (SCR) system

Latest Euro 6(d) diesel emission control (RDE Compliant)



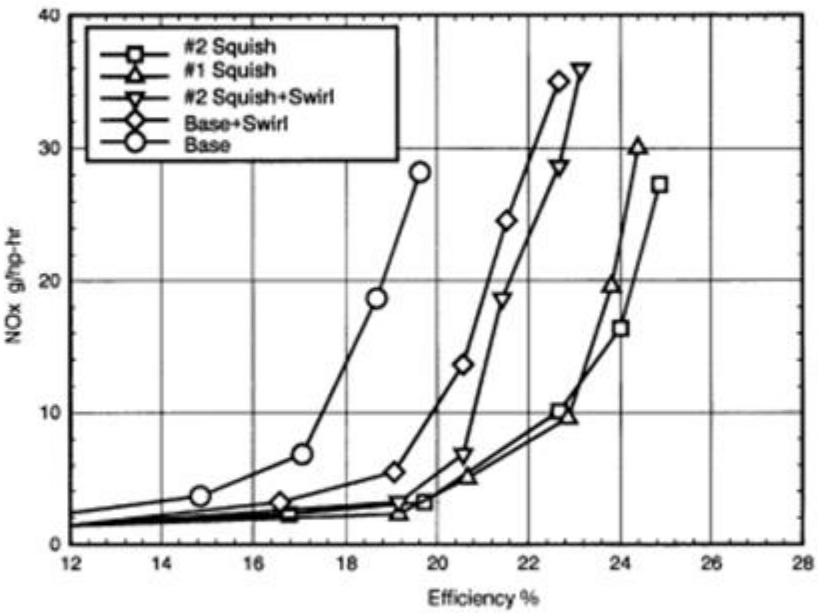


Main elements of first diesel Euro 6d LDV (RDE Compliant):

- Turbo-charged, common rail, high pressure injection
- Close-coupled oxidation catalyst
- Selective catalytic reduction (SCR) coated DPF
- Additional SCR
- Hybrid HP (low load) and LP (high load) EGR for NOx control

Source: Mercedes - Benz

Why these have not been effective?



Danaiah et al. (2012), doi: 10.5923/j.scit.20120201.09

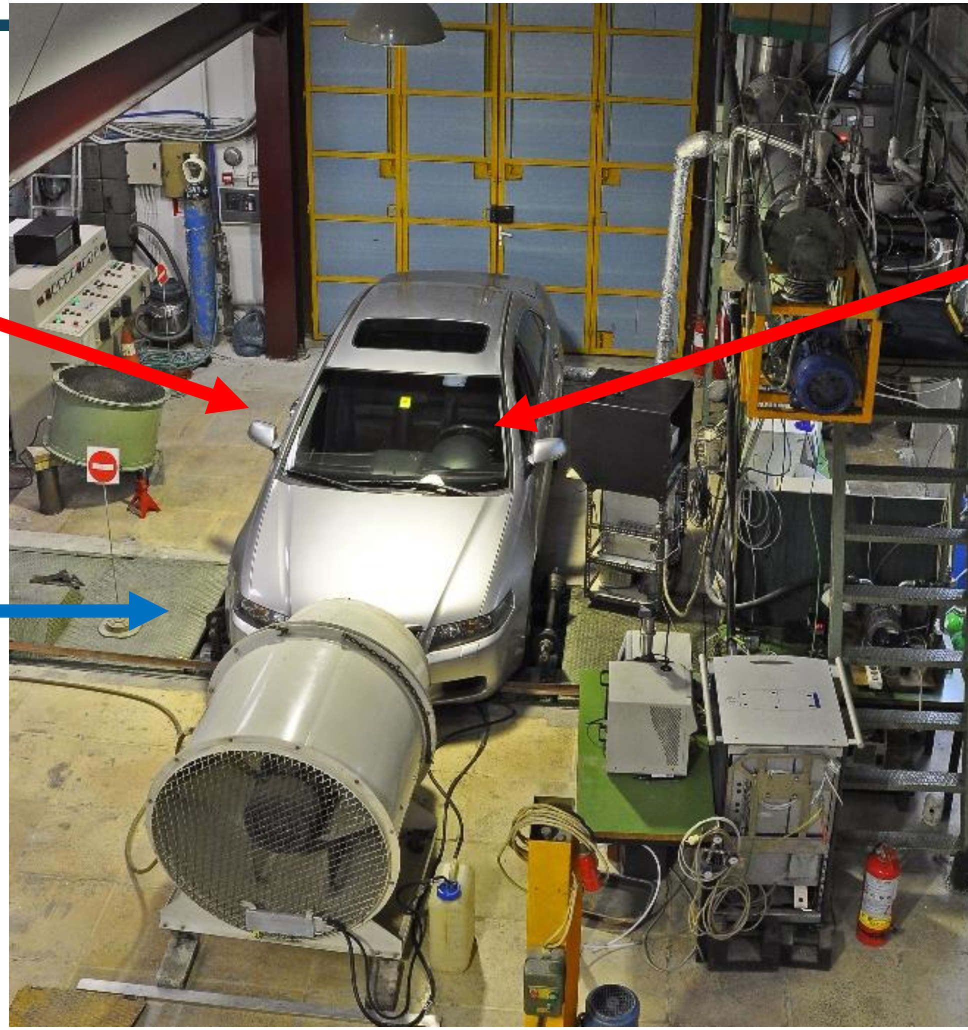
There is a **fundamental trade-off** between fuel consumption and NOx emissions (all engines - not only diesel)

- Also because less frequent use of emission control
  - Increased the lifetime of the system
  - Decreased additive consumption

What is now the ‘new’ problem?

Non powered axle is stationary

Rollers used to simulate actual road load



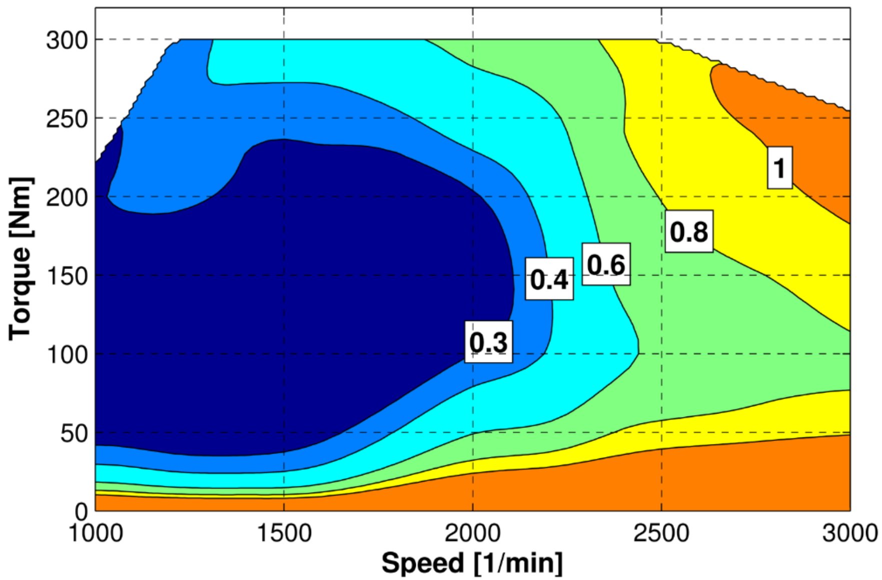
No steering

1. Temperature is set to up to 22-28^{o}C
2. Vehicle is pre-conditioned with given profiles and soaked to start with a cold-start

➢ The vehicle has many ‘hints’ to realise it is being tested

If the car recognizes it is being tested…

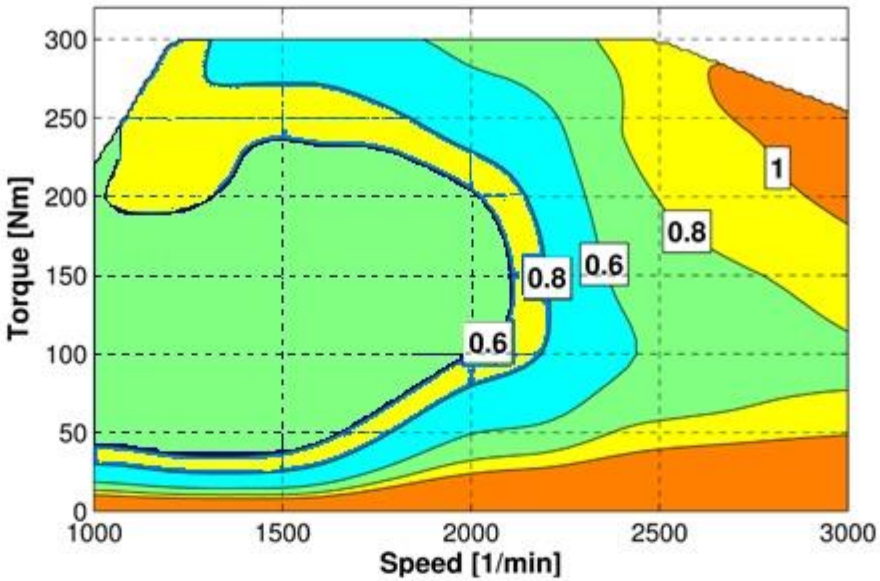
Regulated – In the lab



Typical NOx engine map [Regulated]

Source: Nuesch et al., Energies 2014, 7(5), 3148-3178

Defeat- On the road

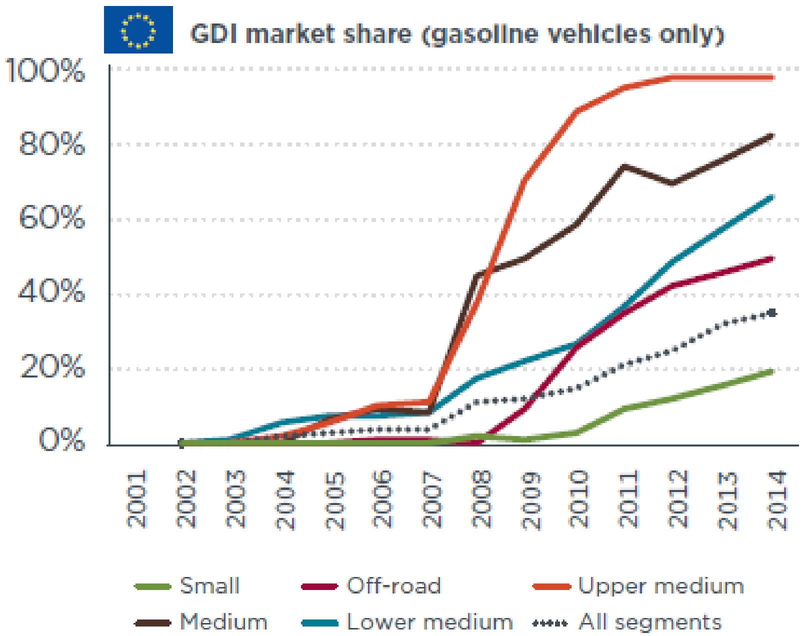


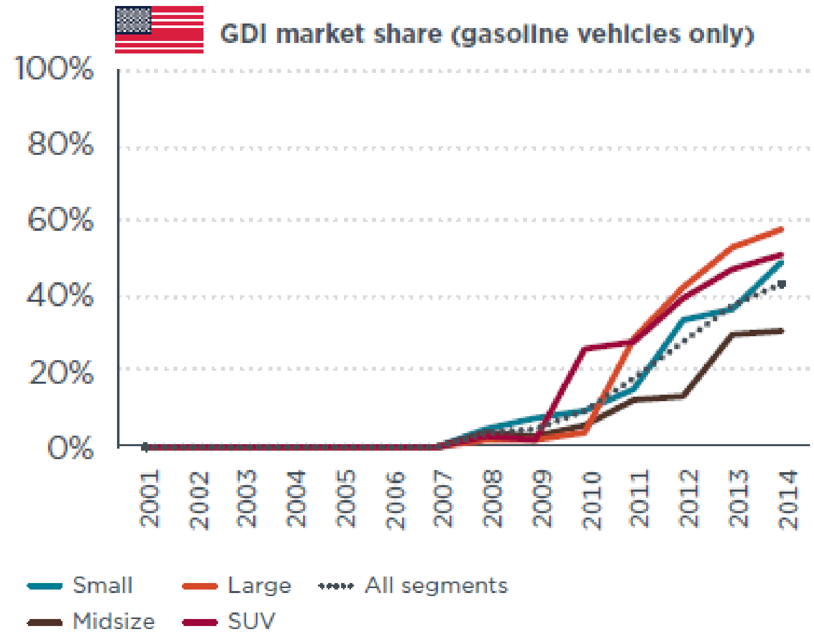
Assumed NOx engine map

So, is diesel fundamentally dirty?

- Diesel NOx issues have taken advantage of loopholes in regulations
  - e.g. similar to CO_2 from ALL vehicle types
- Robust deNOx technology is currently available; can efficiently reduce NO_x within required limits
  - 10 years ago we had the same discussion for diesel PM that was satisfactorily addressed because of the PN limit
- Real-drive (RDE) NOx emissions control implemented
- Diesel NOx+PM control is expensive hence petrol engines will gradually replace diesel in the medium and small vehicle sectors

Gasoline Direct Injection (GDI) passenger cars in the EU and the US



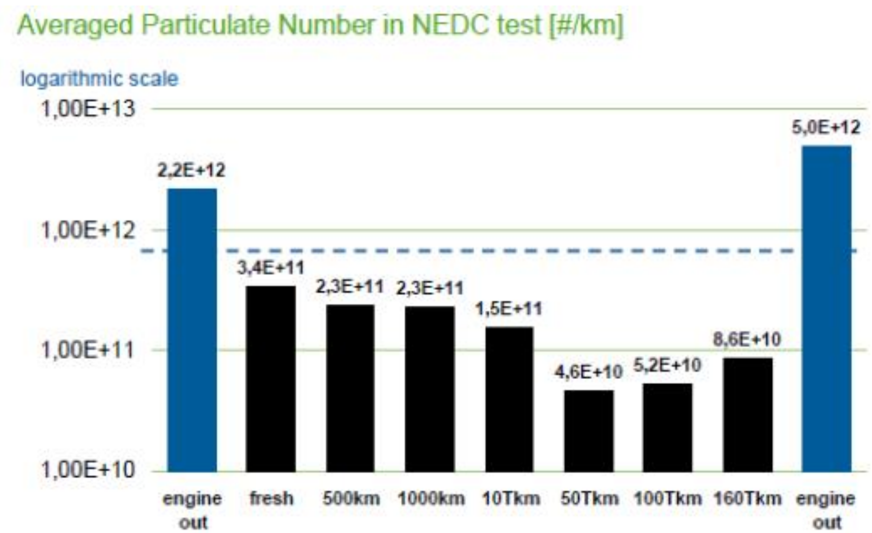


- In 2015 the market share of GDIs represented 40 % of new gasoline car registrations in both the EU and the US.
- In 2005, GDI appeared on a mere 3% of cars sold in the EU (zero in the US).
- These vehicles comlied with a temporary EURO6 PN emission limit of $6*10^{12}$ particles/km

Source: ICCT. 2016

The need for Gasoline Particle Filter

Stage	Date (New Types / All Models)	PN Limit
Euro 6b	2014.09/2015.09	6×10^{12} km^{-1}
Euro 6c	2017.09/2018.09	6×10^{11} km^{-1}

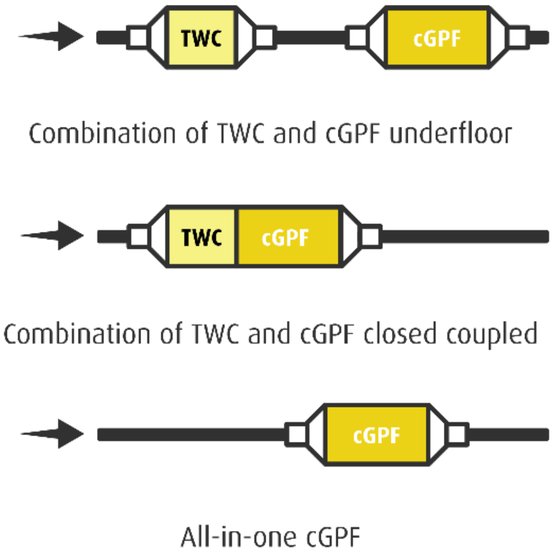


Source: Umicore (2012) CAPoC Conference

- PMP PN regulations built around diesel emission control
- Non zero number of sub-23 nm particles from GDI vehicles

Latest petrol Euro 6 engine and emissions control configuration (RDE compliant)

GPF, **Source**: AECC



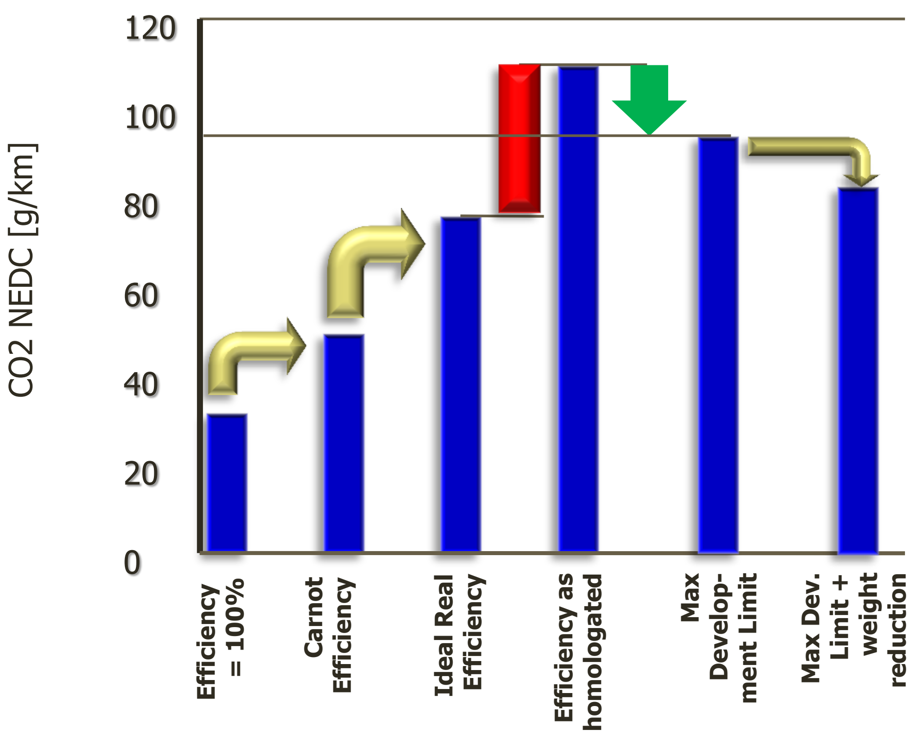
Possible Aftertreatment Configurations
Source: Umicore

Main elements of a typical RDE-compliant petrol Euro 6 aftertreatment:

- Close-coupled TWC, similar to Euro 5 vehicles
- Catalysed Gasoline Particulate Filter (GPF), close-coupled or underfloor
- Possible secondary air injection for fast production of exotherm in catalyst

WILL THE COMBUSTION ENGINE DRIVE THE LOW CARBON VEHICLE?

From the Ideal to Reality



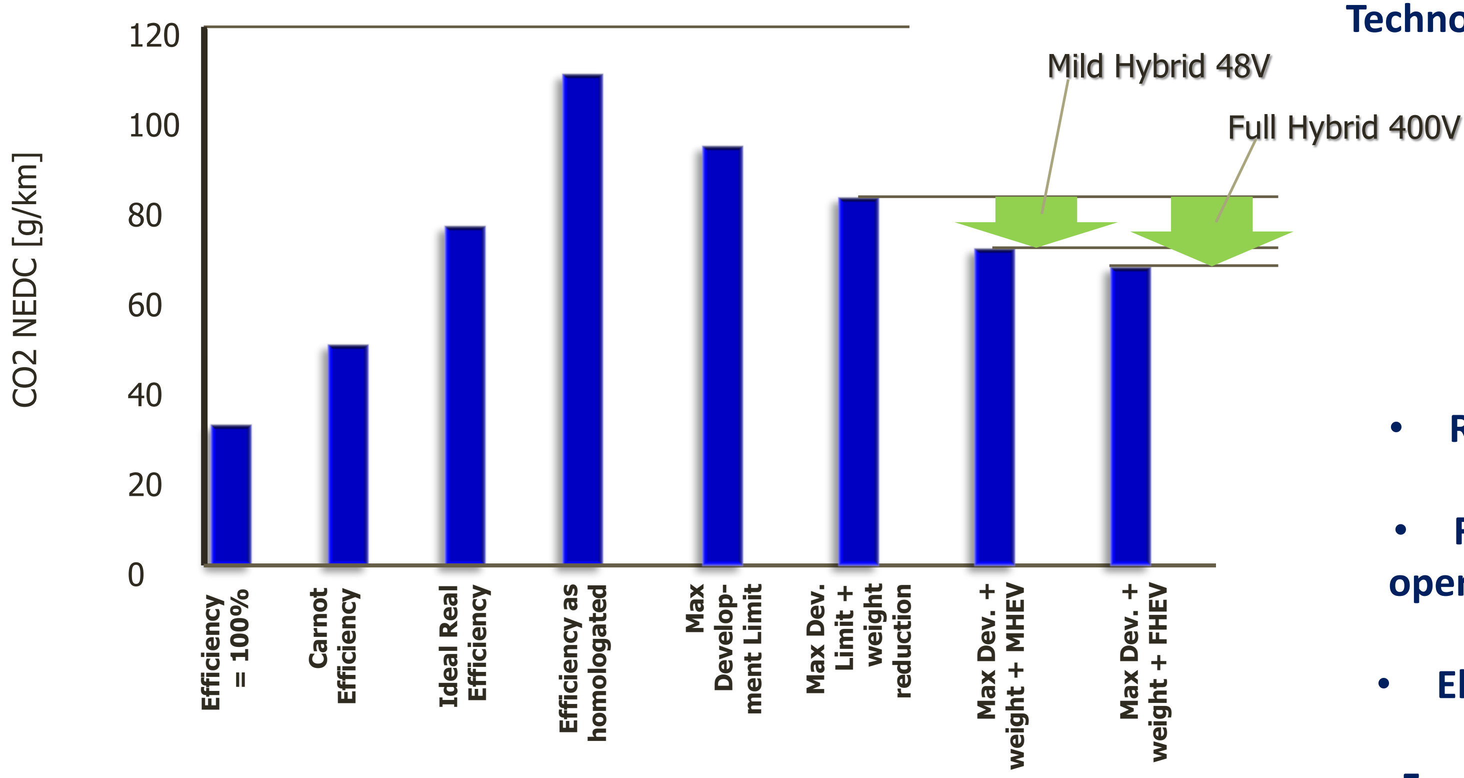
Further technology deployment to achieve 50% of the gap vs. the ideal real engine :

93-95 g/km can be reached without further vehicle actions like weight reduction / aero / rolling resistance

Realistic weight reduction can account for about 10% CO2 reduction

Source: ERTRAC - A. Schamel, Ford, 2015

A Way Forward for the IC Engine



Introduce Hybrid Technology (48-400V)

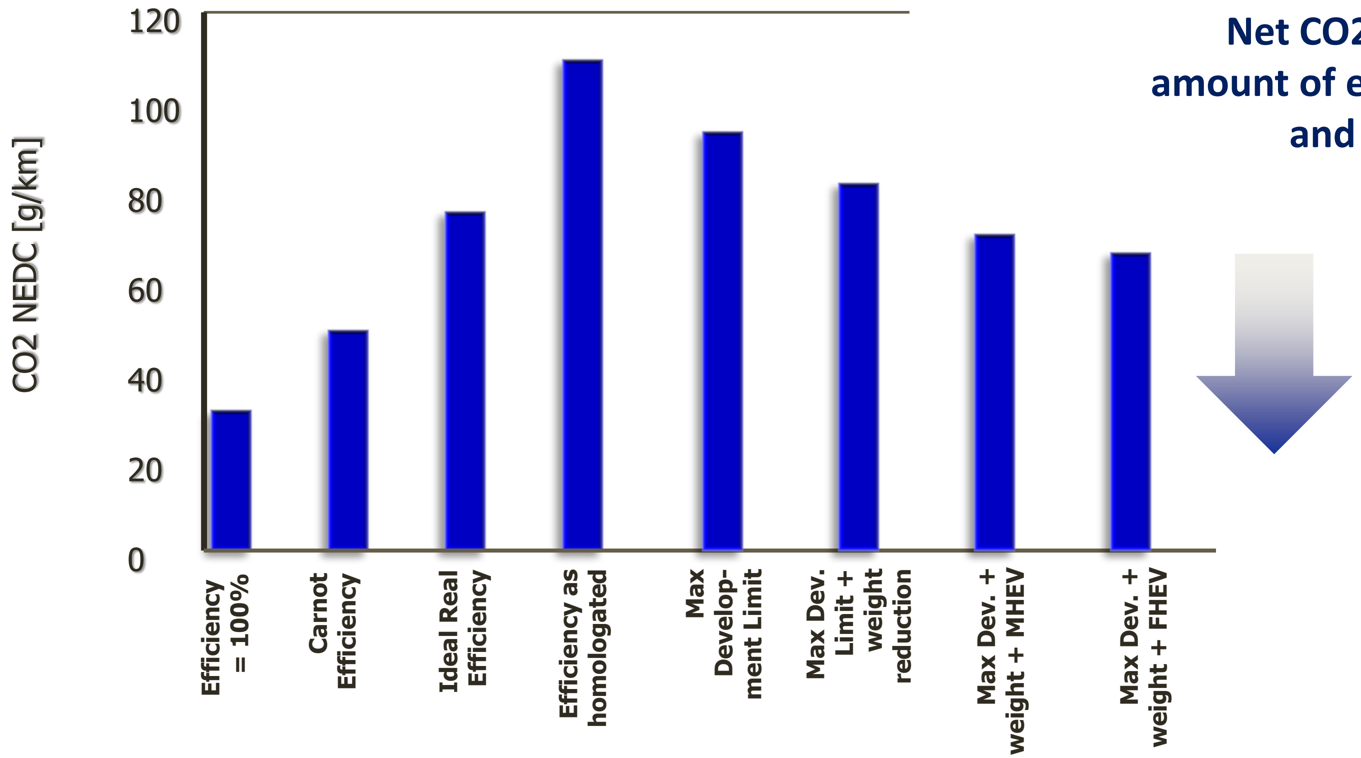
- **Recuperation**
- **FE optimized operational strategy**
- **Electric driving**
- **Free shift schedule (NEDC)**

Source: ERTRAC - A. Schamel, Ford, 2015

A Way Forward into a sustainable future

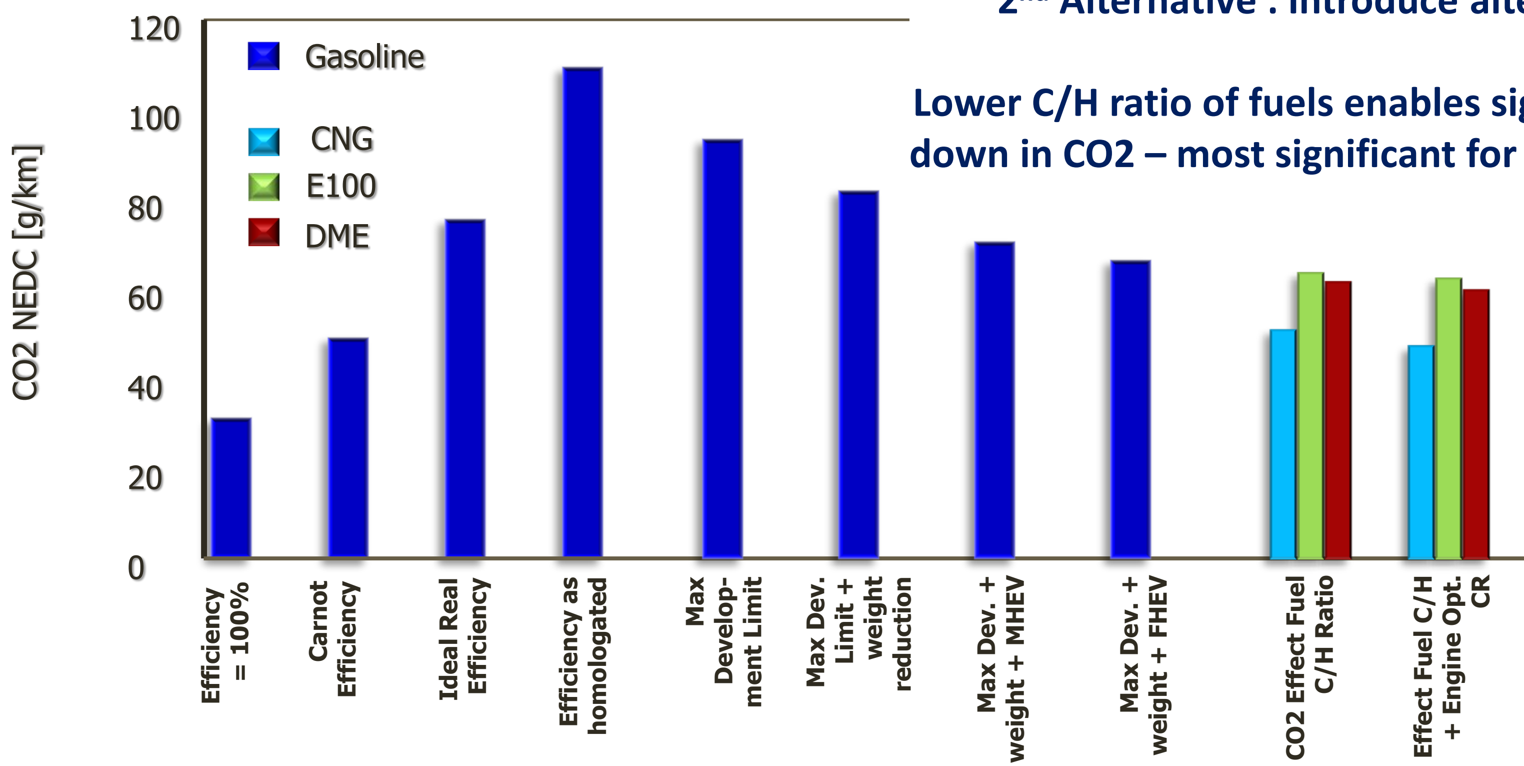
1st Alternative : Extend FHEV to PHEV

Net CO2 emission depends on amount of electric energy charged and power generation mix



Source: ERTRAC - A. Schamel, Ford, 2015

A Way Forward for the IC Engine



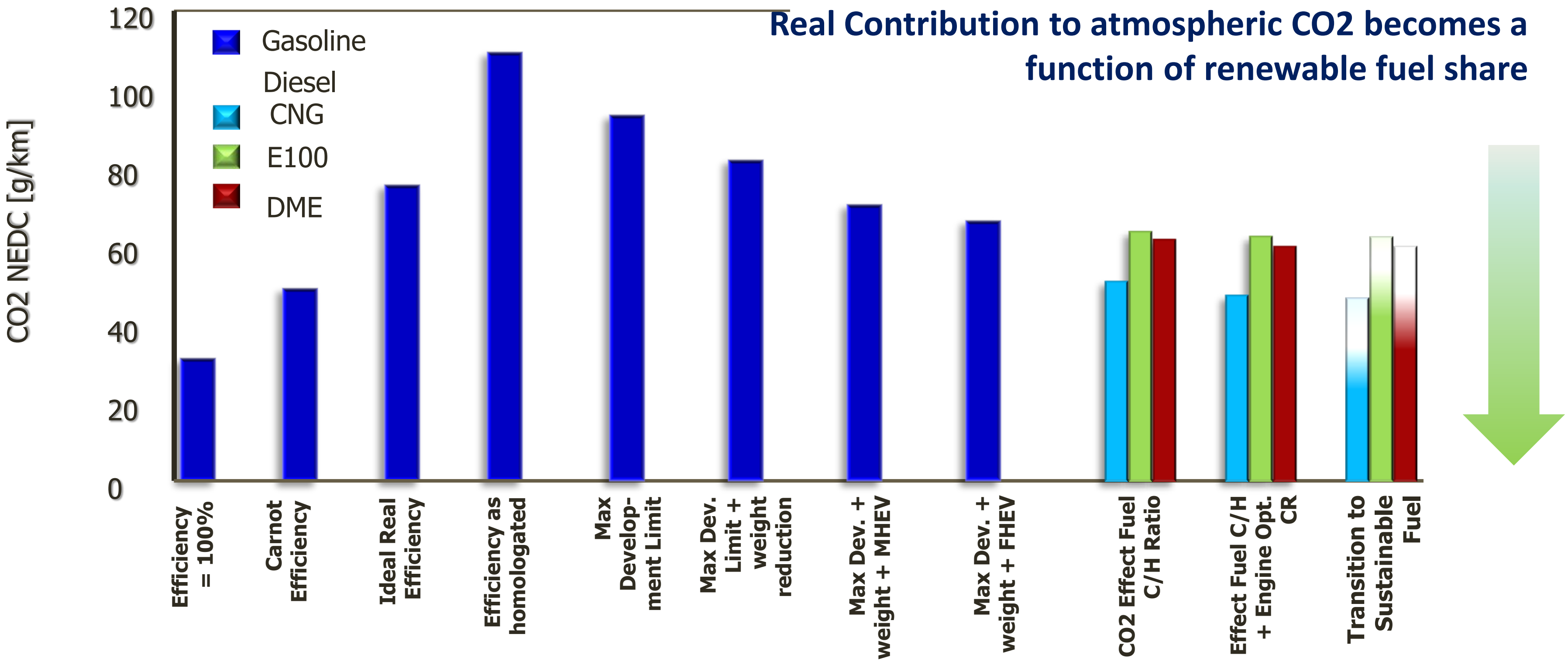
2nd Alternative : Introduce alternative fuels

Lower C/H ratio of fuels enables significant step down in CO2 – most significant for the SI engine using CNG

Source: ERTRAC - A. Schamel, Ford, 2015

A Way Forward for the IC Engine

Alternative fuels from renewable process:
Real Contribution to atmospheric CO2 becomes a function of renewable fuel share



Source: ERTRAC - A. Schamel, Ford, 2015

Alternative fuels

- Biofuels (biodiesel, bioethanol) sustainability questioned
  - Feedstock availability
  - Real CO_2 benefits obtained
  - Not positive air-quality impacts
- Renewable diesel (catalytic hydrogenation/de-oxidation of plant oils) - BTL
  - Well-controlled specifications
  - Paraffinic fuel
- Natural gas (CNG/LNG)
  - Target is a 20% reduction to CO_2 emissions
  - Adapted engine and vehicles to be studied in Horizon2020

Electric Vehicles: Not necessarily a panacea

Region	Carbon Intensity gCO_2/kWh	BMW i3 EV gCO_2/km	BMW 114d Diesel gCO_2/km	Improvement (%)
Austria	203	26	95	72
Greece	486	64	95	33
Bosnia & Herzegovina	745	98	95	-3

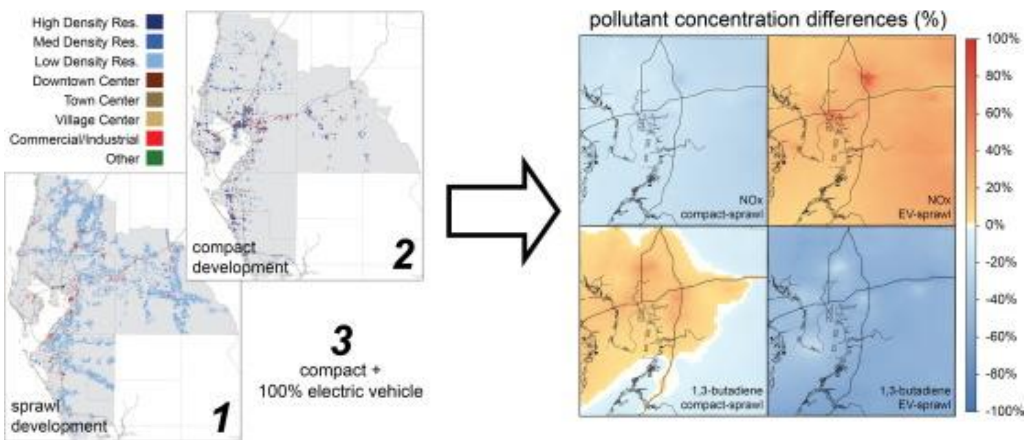
Carbon intensity data: www.electricitymap.org

BMW i3, energy consumption: 13.1 kWh/km

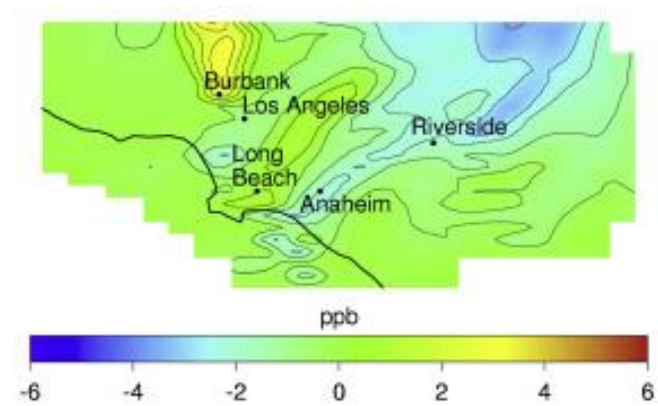
Electric vehicles may generally offer CO_2 benefits, but:

- These may not always be impressive
- Can even be negative in the region

Impact of EVs on air quality when considering upstream emissions



Source: Yu, H.; Stuart, A. L. *Sci. Total Environ.* 2017, *576*, 148



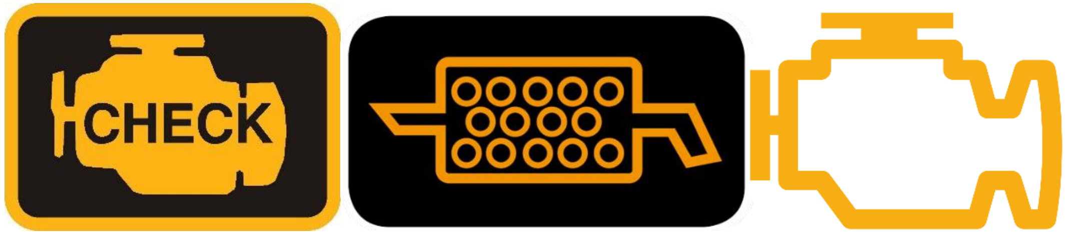
Source: Razeghi et al. *Atmos. Environ.* 2017, *137*, 90

Replacement of conventional vehicles with BEVs leads to 30-81% increase in NOx, due to upstream emissions

Relative difference in O3 concentrations over baseline replacing 40% of conventional vehicles with BEVs

ON-BOARD DIAGNOSIS AND MEASUREMENT

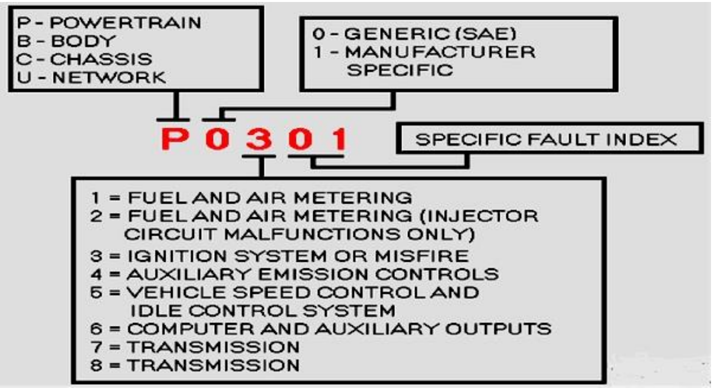
What is OBD?



‘OBD system’ = system for emission control which has the capability of identifying the likely area of malfunction by means of fault codes stored in a computer memory

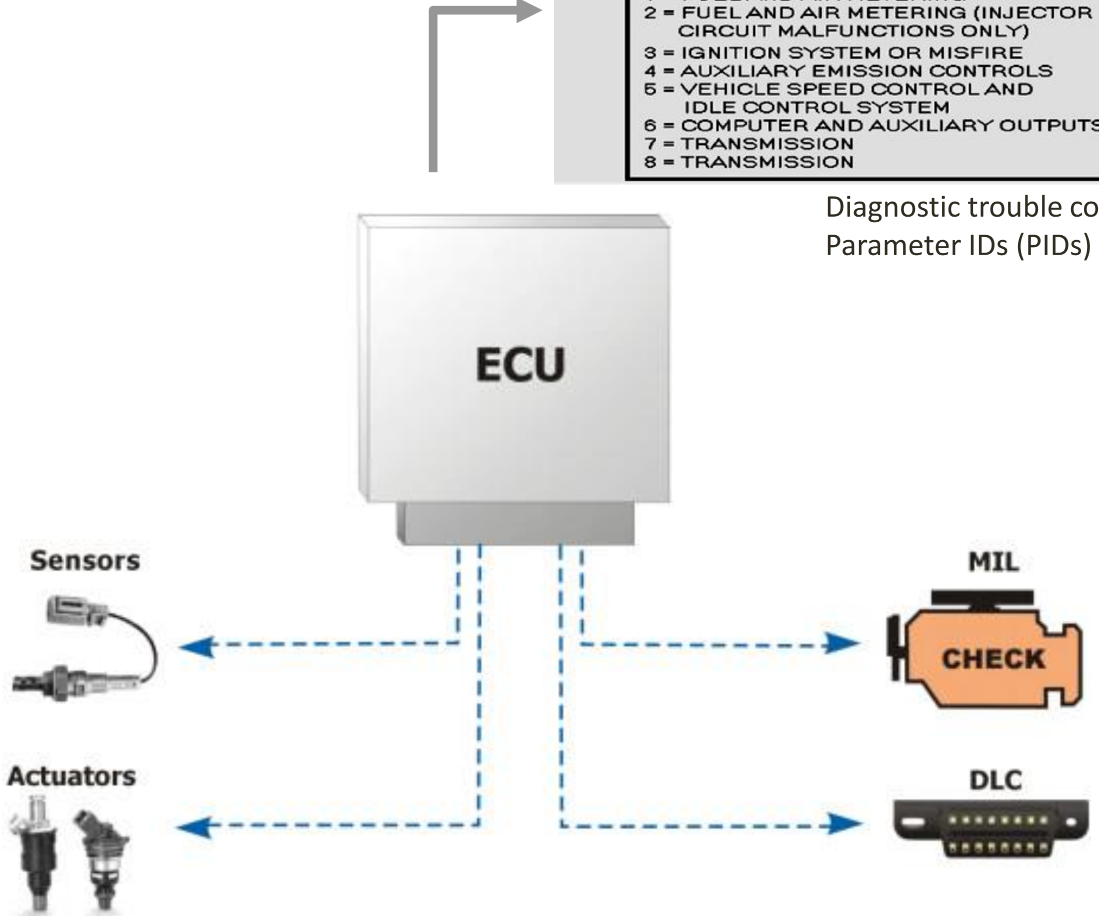
- Rationale:
  - Malfunction identification → early repair → less emissions
  - Incentive to design more robust emission control systems
  - Potential use at periodic inspections
  - Universal design for third-party diagnostic and repair equipment

OBD System Concept



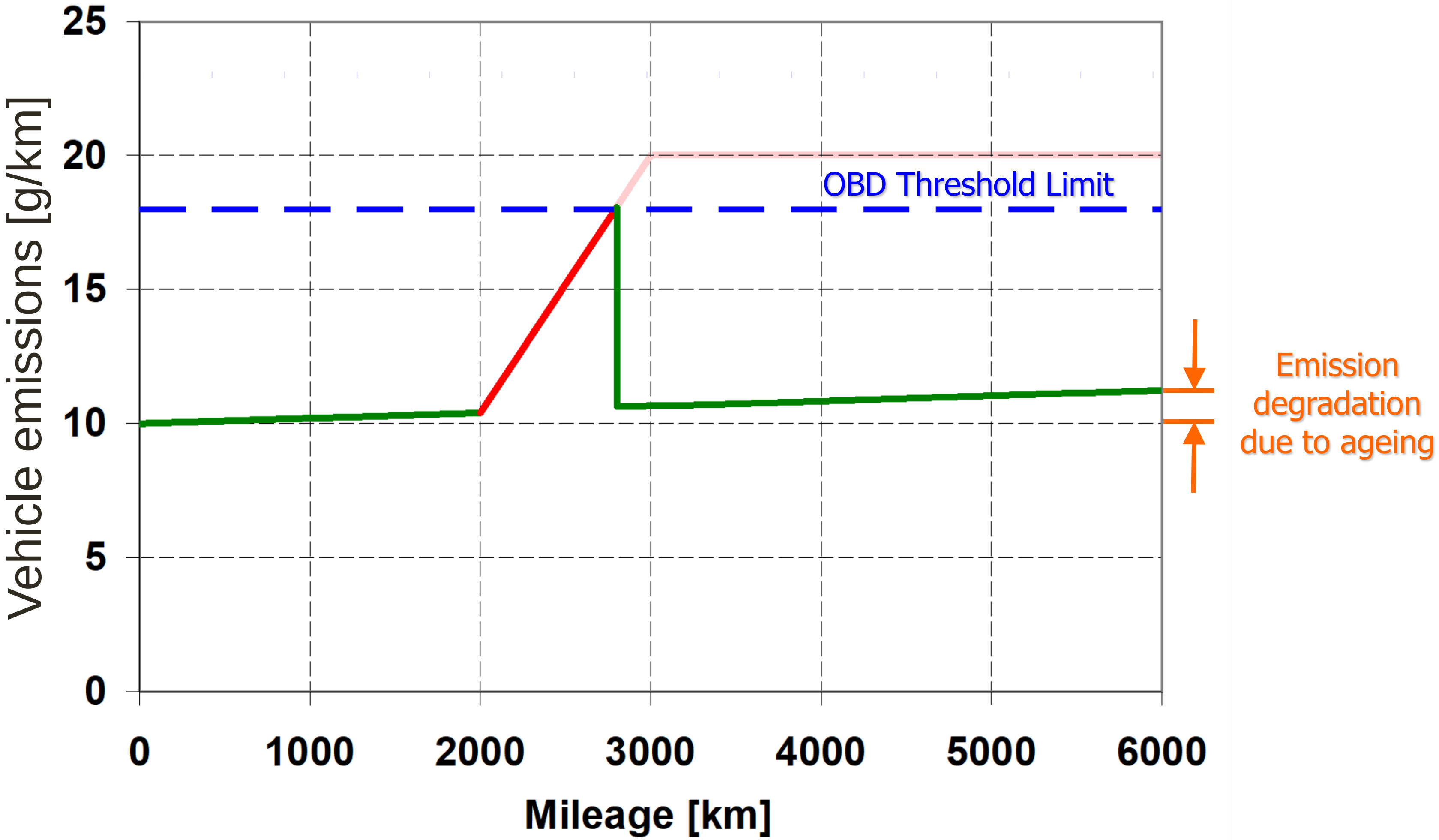
Diagnostic trouble codes (DTC) or Parameter IDs (PIDs) – P-codes

Generic scan tool

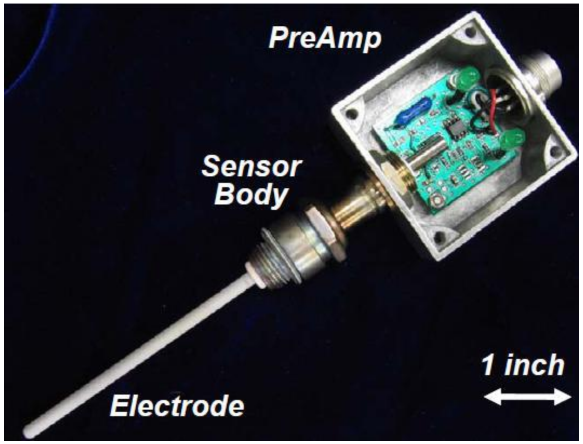


Source: www.obdsol.com

Definition of OBD Threshold Limit (OTL)



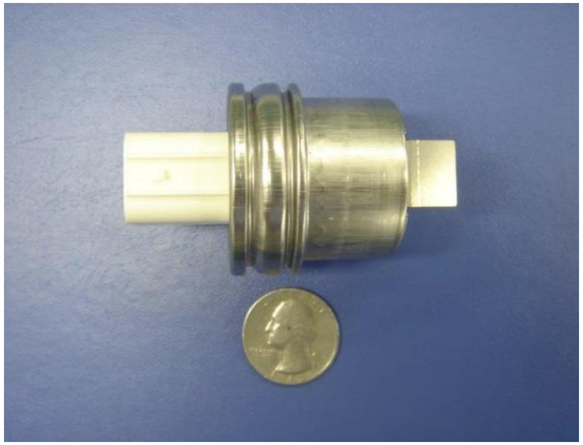
Diesel OBD sensors



Soot Sensor

Combined O_2/NOx Sensor

Ammonia Sensor



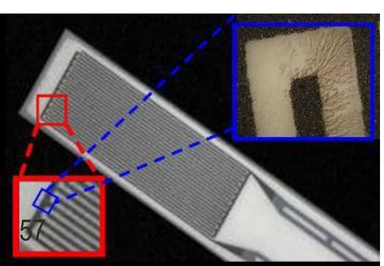
Urea Quality Sensor

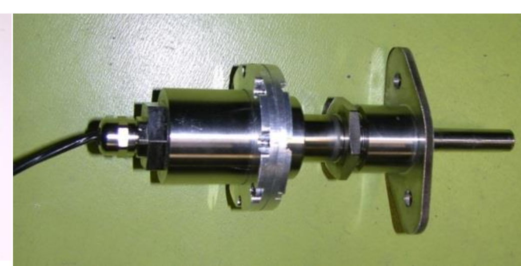
Source: MECA

Soot sensing technologies

The need for particle sensors to comply with Light and Heavy duty OBD requirements is currently being approached by the sensor developers in different ways:

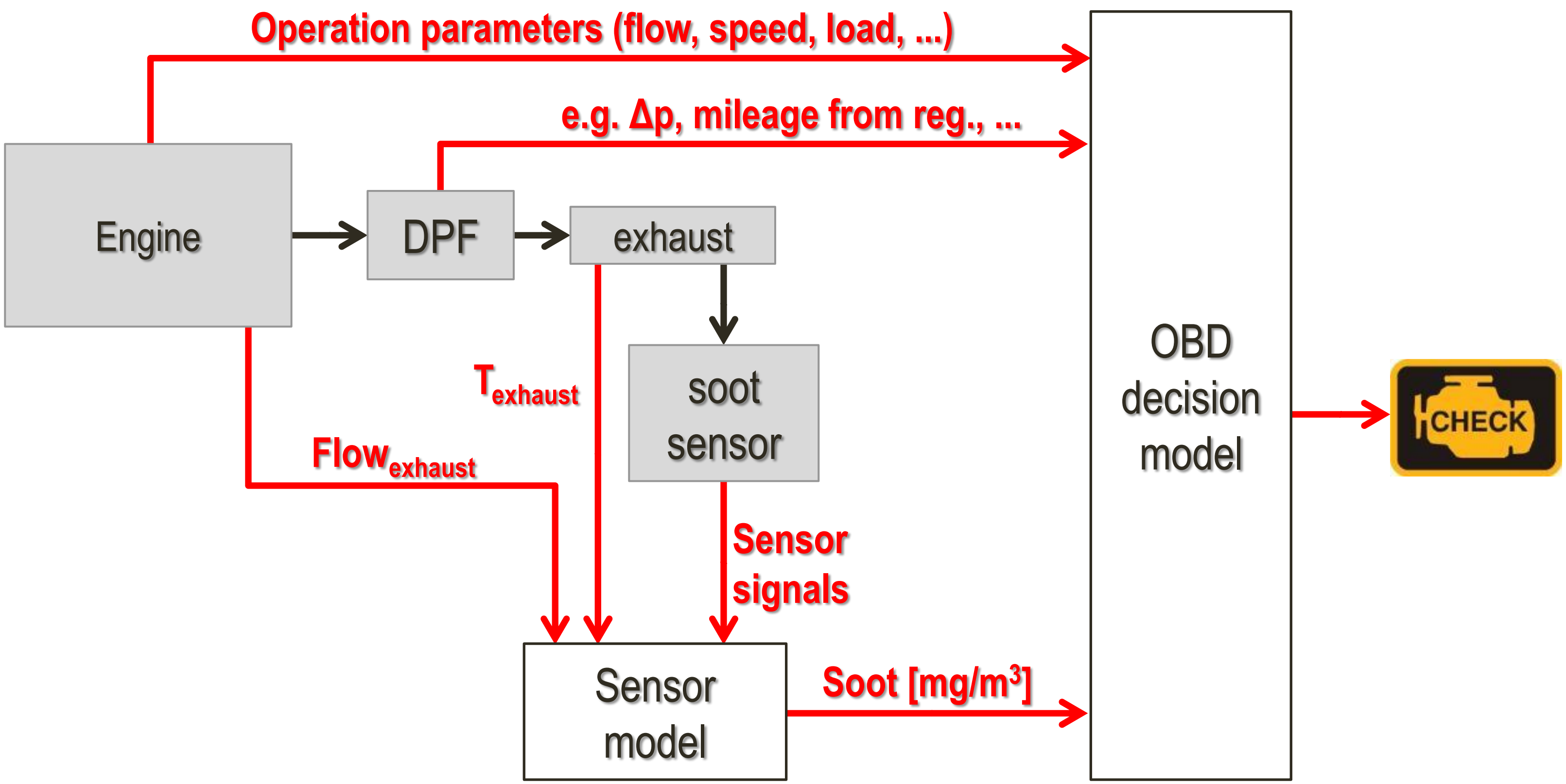
- Resistive: Bosch, Continental, Delphi, Electricfil, Stoneridge, *Sensata/Sensor-NITE*
- Particle charge: NTK-NGK, *Pegasor*, *Emisense/Watlow*
- Secondary filter: *Innexsys*
- Radio frequency: *General Electric Accusolve*





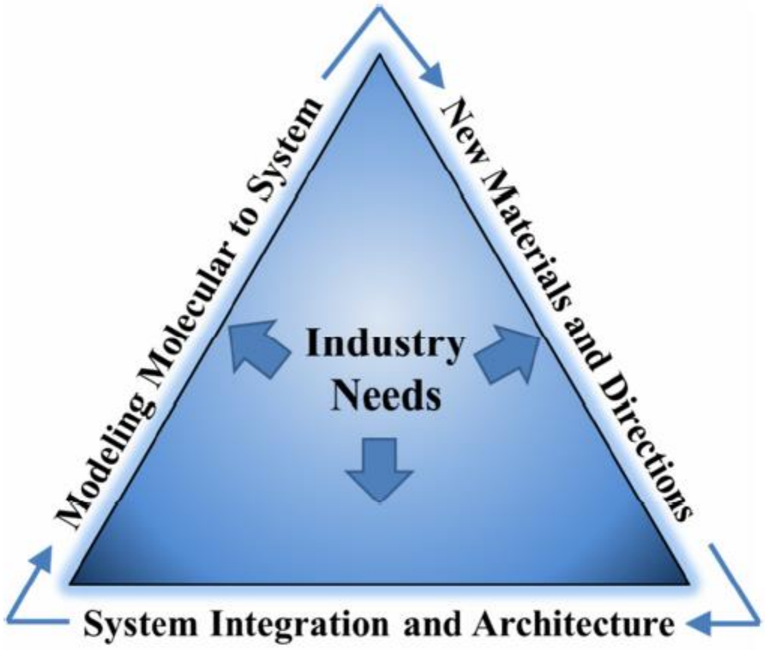
Models need to be developed to detect OTLs

Integrated OBD modeling



THE IMPORTANCE OF MODELING

Example Exhaust Aftertreatment



- Efforts to uncover new materials and processes are time consuming and resource intensive
- In today's competitive landscape, the luxury of time is no longer available
- Modeling at all levels (from atomistic to vehicle scales) is necessary to systemize our knowledge of aftertreatment
- Accurate simulations can play in the setting of effective emissions standards and the optimization emission control technologies.

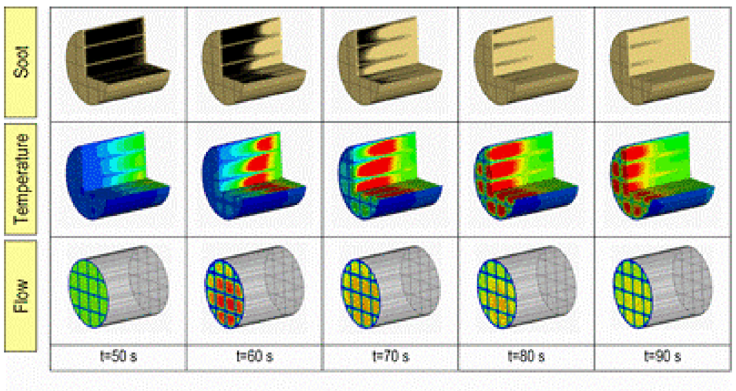
Strengths in the current state of the art include:

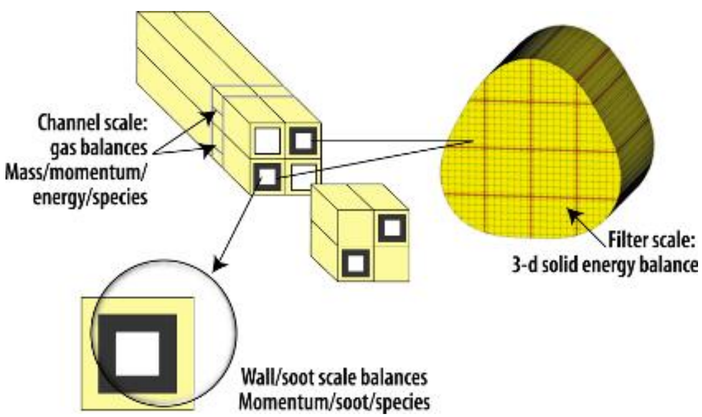
- Widely published heterogeneous catalysis reaction mechanisms
- Advanced experimental capabilities to measure local and global reaction rates and intermediate species
- Powerful software and algorithms for computational simulations of dynamic device and vehicle systems performance

Source: US DRIVE, 2012

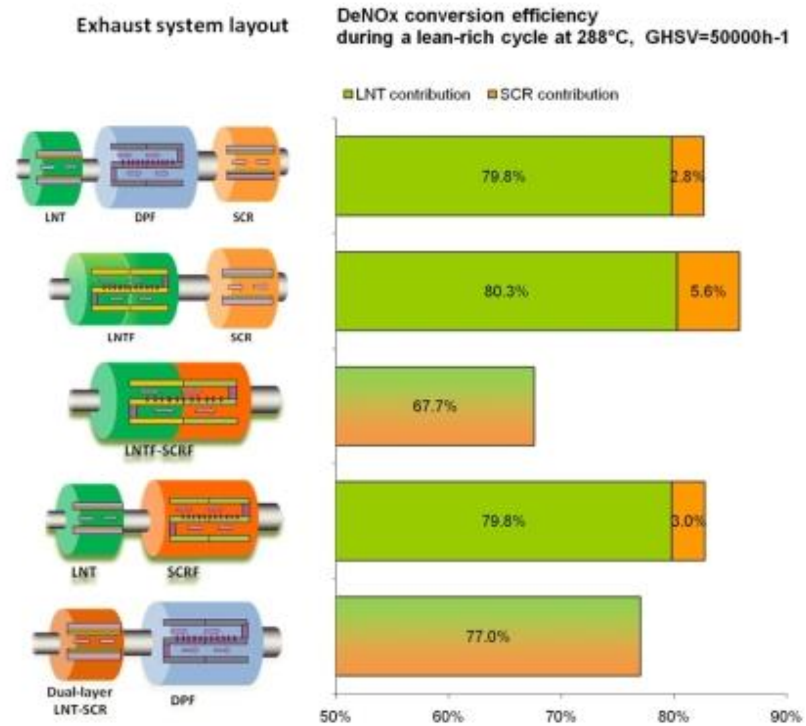
Examples of Aftertreatment Simulations (1)

Catalyzed PDF





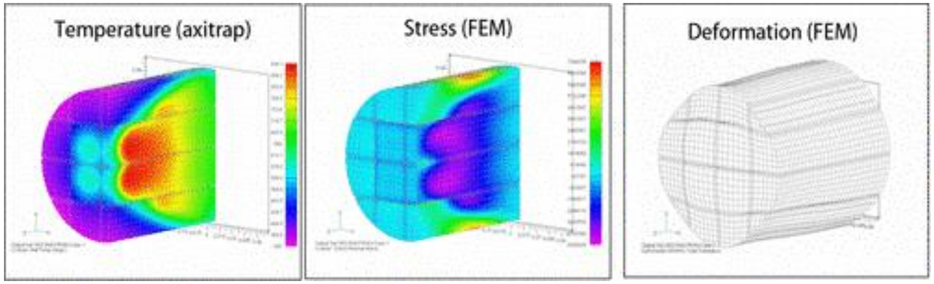
Model-based comparison of DeNOx systems



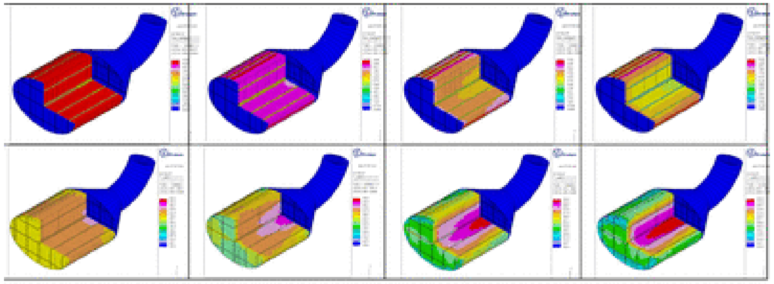
Source: Exothermia SA, 2017

Examples of Aftertreatment Simulations (2)

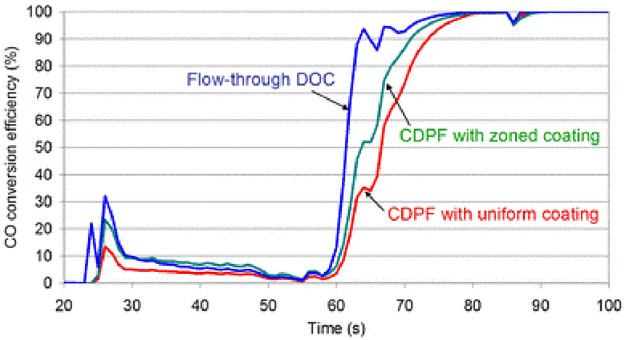
Stress analysis



Optimizing flow in substrates



Zone-coating optimization

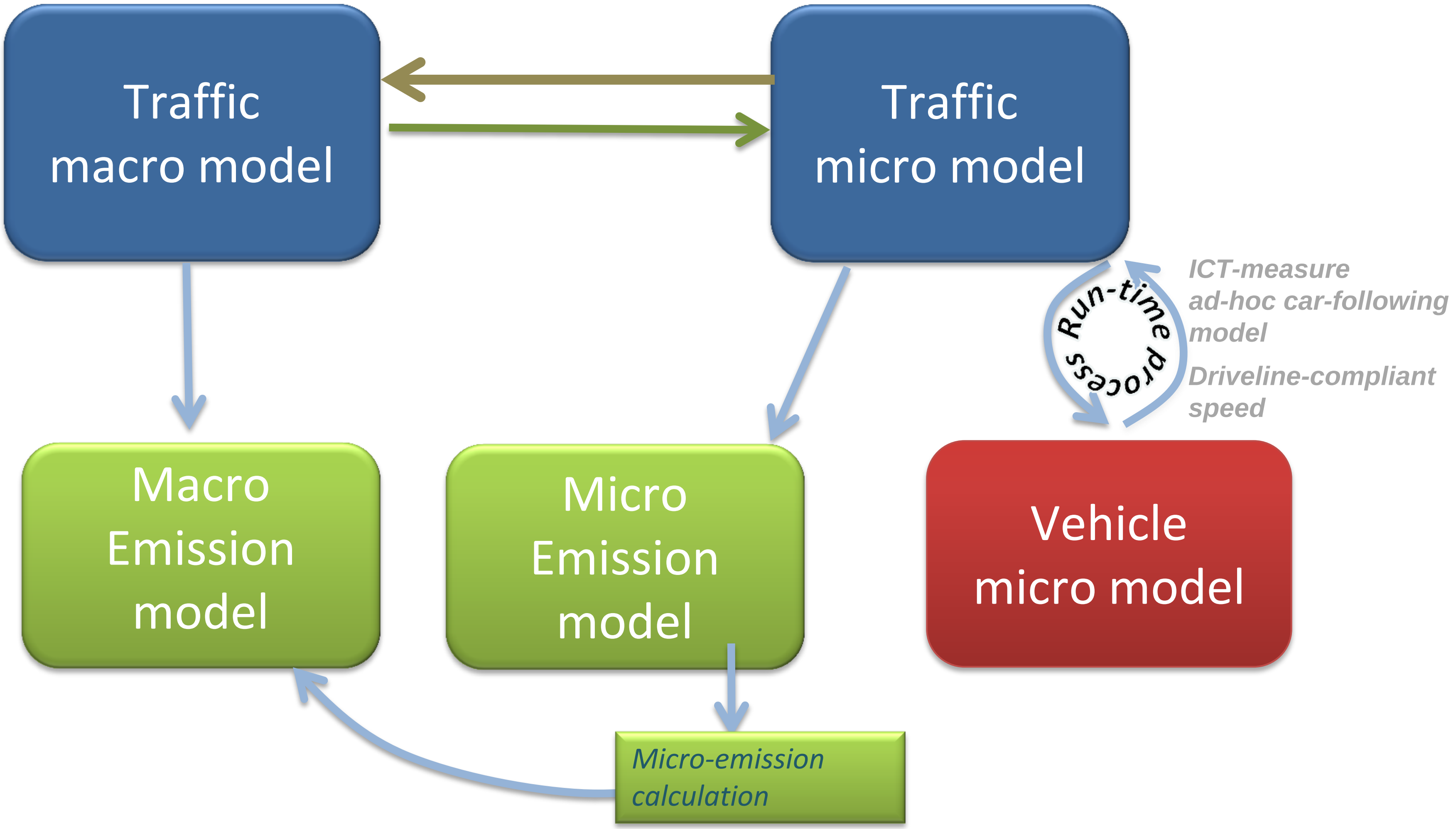


Source: Exothermia SA, 2017

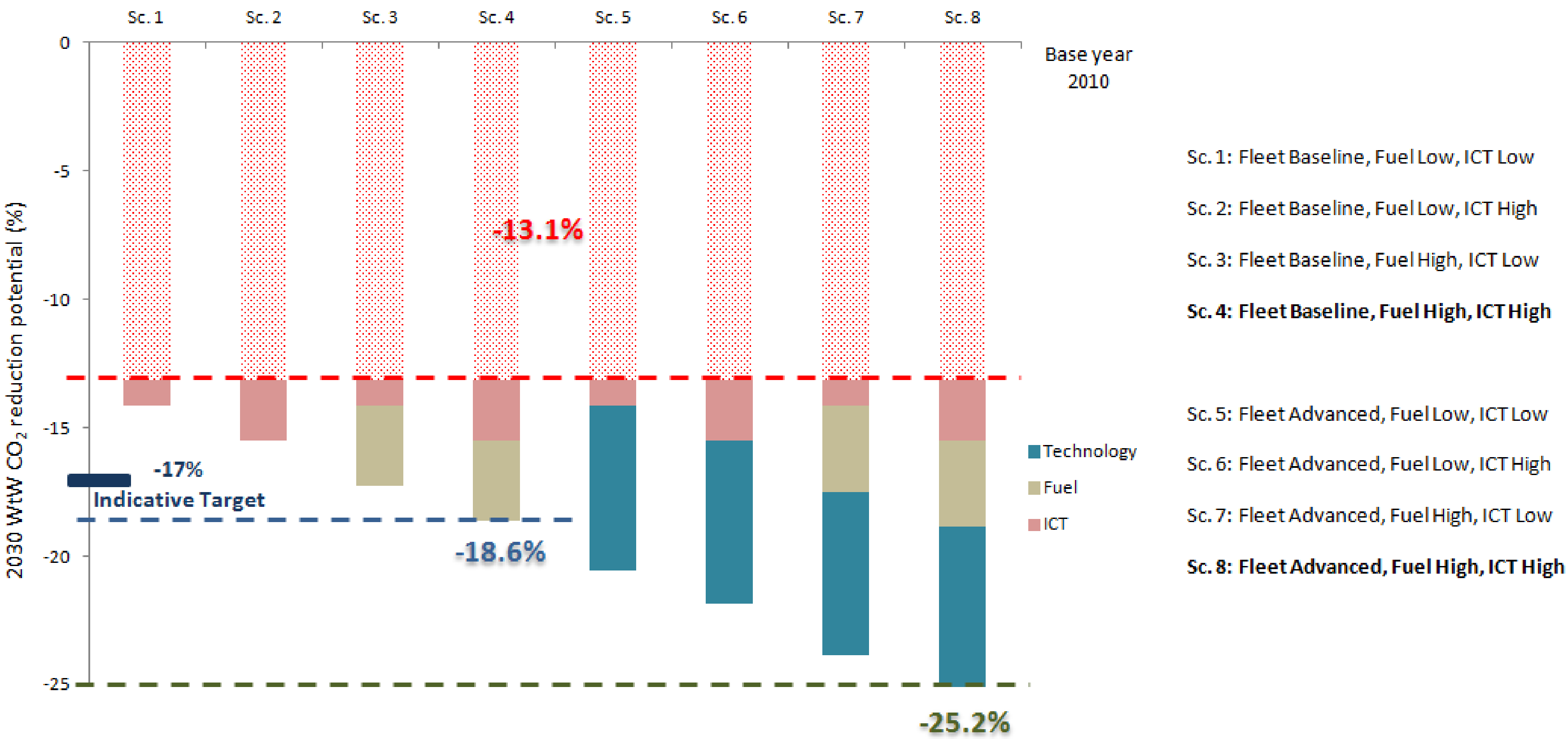
Example: Simulation of ITS effects on CO2 from Road Transport

Measure	Description and CO_2 savings
Green Navigation (GN)  	✓On-board, real-time routing recommendations taking into account traffic conditions. ✓Fuel consumption benefits.
Adaptive Cruise Ctrl (ACC)  	✓Automatic velocity adjustment subject to distance of vehicle in front. ✓Avoidance of unnecessary speed variations.
Variable Speed Limits (VSL)  	✓Speed limit management systems to avoid bottleneck effects. ✓Avoidance of stop-and-go conditions.
Urban Traffic Ctrl (UTC) 	✓Adjustment of traffic lights green cycle according to queue lengths in intersections. ✓Improvement of traffic flow conditions in saturated sections.

Model architecture



Estimate of ITS contribution to road CO_2 2030 reductions



- The 2030 indicative target could be met only with high efforts in fuels and ICT
- Max 2030 reductions (-25.2%) over 2010 can be achieved with advanced vehicle technology, high efforts in fuels and ICT measures

Outlook

- GHG control will continue to be in the forefront of EU policy and related technological advances
  - Variable degrees of hybridization
  - Gradual shift to natural gas vehicles
  - Technology and infrastructure based efficiency improvements

- ICEs will continue to be the powertrains of option for the foreseeable future. Main technology challenges:
  - Diesel (LD) NOx
  - OBD
  - NRMM
  - Power two/three and four wheelers

Thank you for your attention

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