Labs of Heat Transfer & Applied Thermodynamics
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SCHOOL OF ENGINEERING
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Transport Sector Contribution to Ambient Air Pollution

2019 Transport Task Group Meeting, Tokyo, 30.10.2019

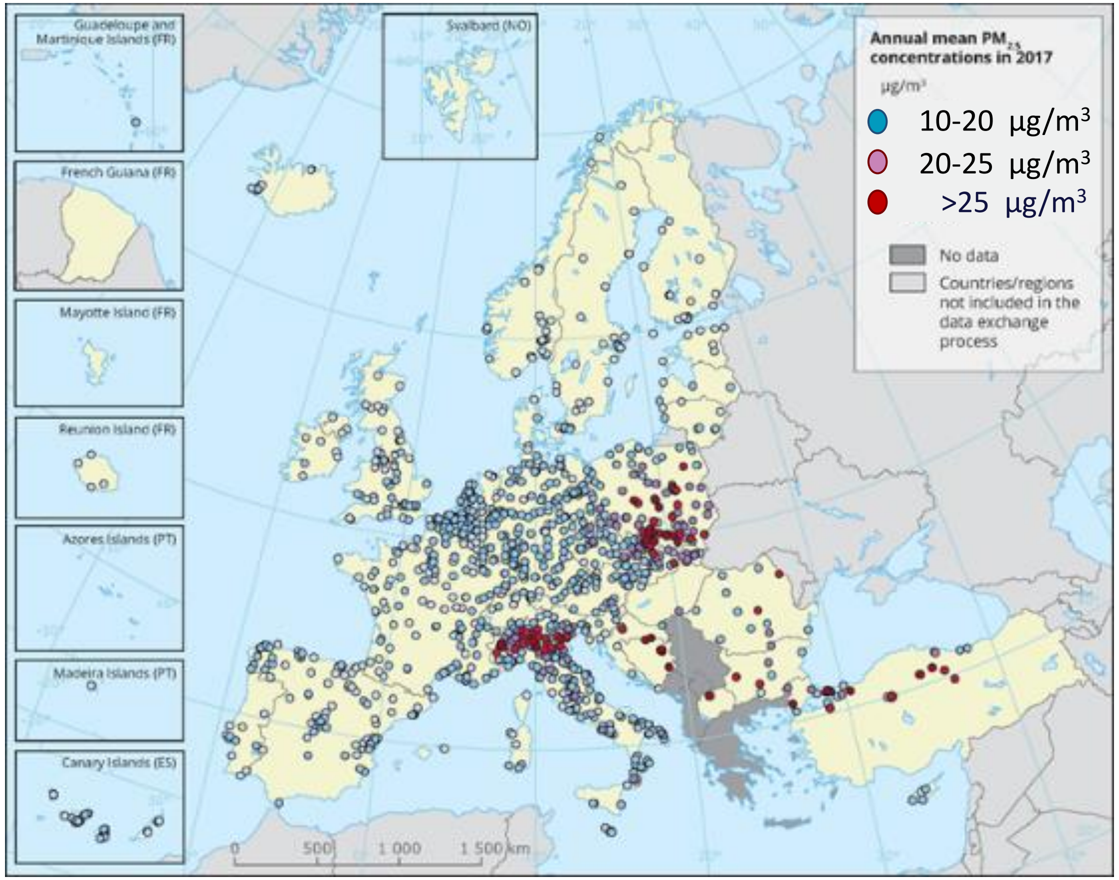
Outline

1. Transport and Air Pollution within the EU context
2. Vehicle exhaust emission control technology effects
3. New fuels
4. Exhaust vs Non-exhaust emissions
5. Vessel emissions
6. Concluding messages

TRANSPORT AND AIR POLLUTION WITHIN THE EU CONTEXT

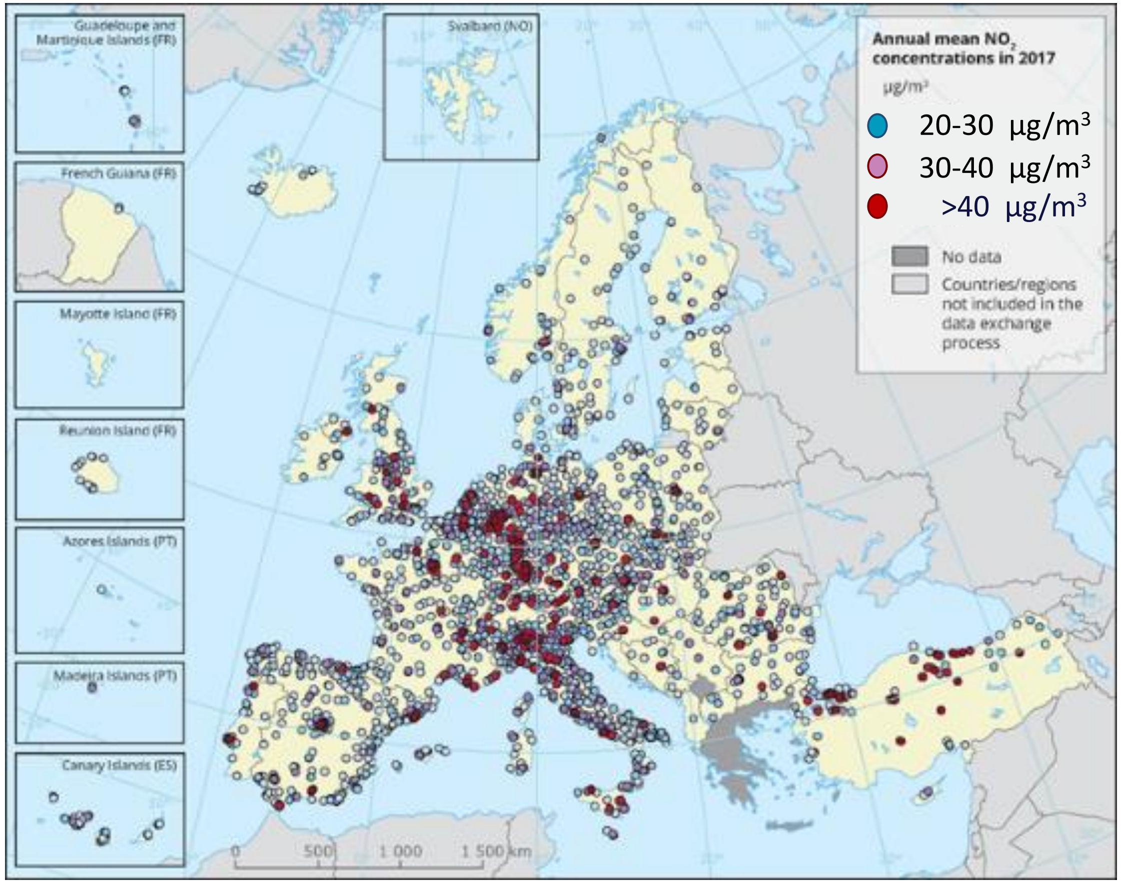
$PM_{2.5}$ and NO_2 Air Quality in the EU - 2017

$PM_{2.5}$ – Annual limit values



WHO Guideline:
10 µg/m³ (annual mean)
25 µg/m³ (24-h mean)

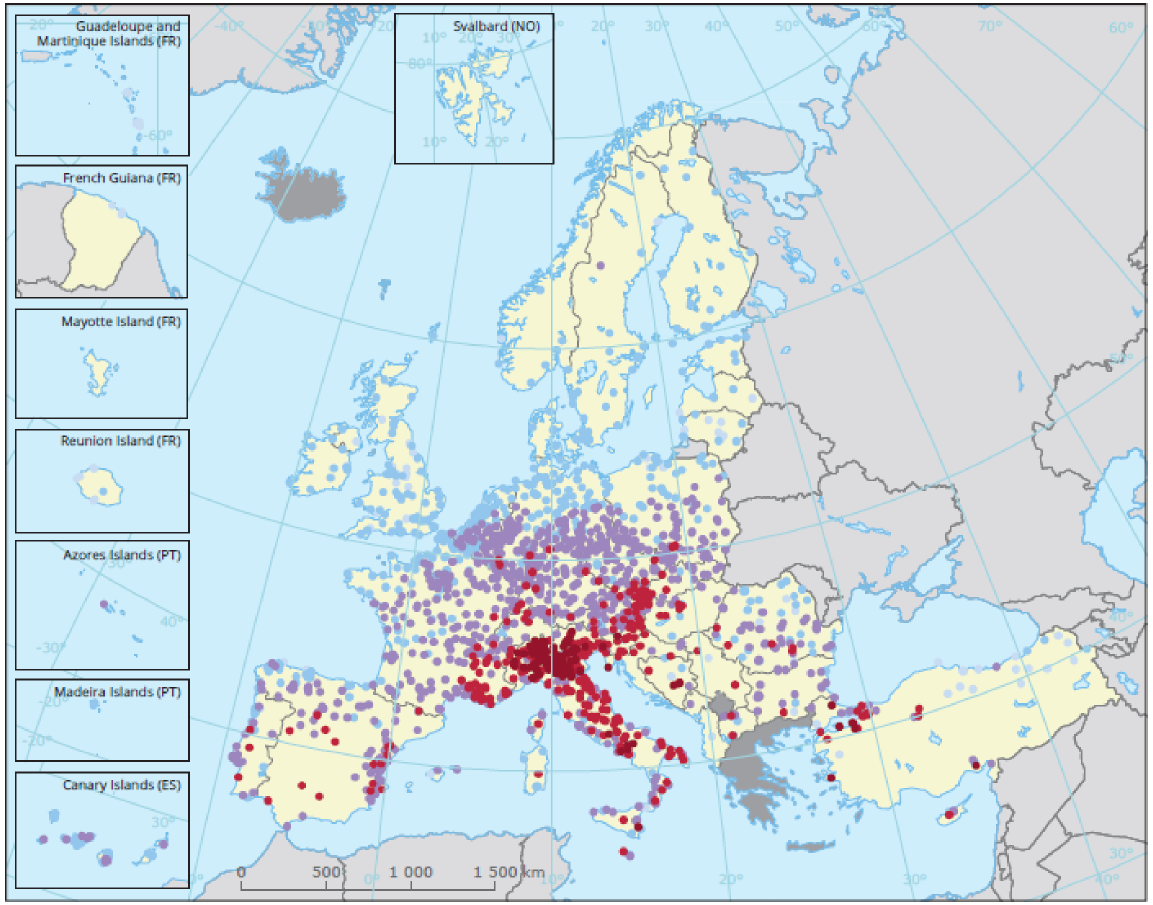
NO_2 – Annual limit values



WHO Guideline:
40 µg/m³ (annual mean)
200 µg/m³ (1-h mean)

Source: EEA, 2019

O_3 Air Quality in the EU - 2017



93.2 percentile of O_3 maximum daily 8-hour mean in 2017

μg/m³

- ≤ 80
- 80-100
- 100-120
- 120-140
- > 140

No data

Countries/regions not included in the data exchange process

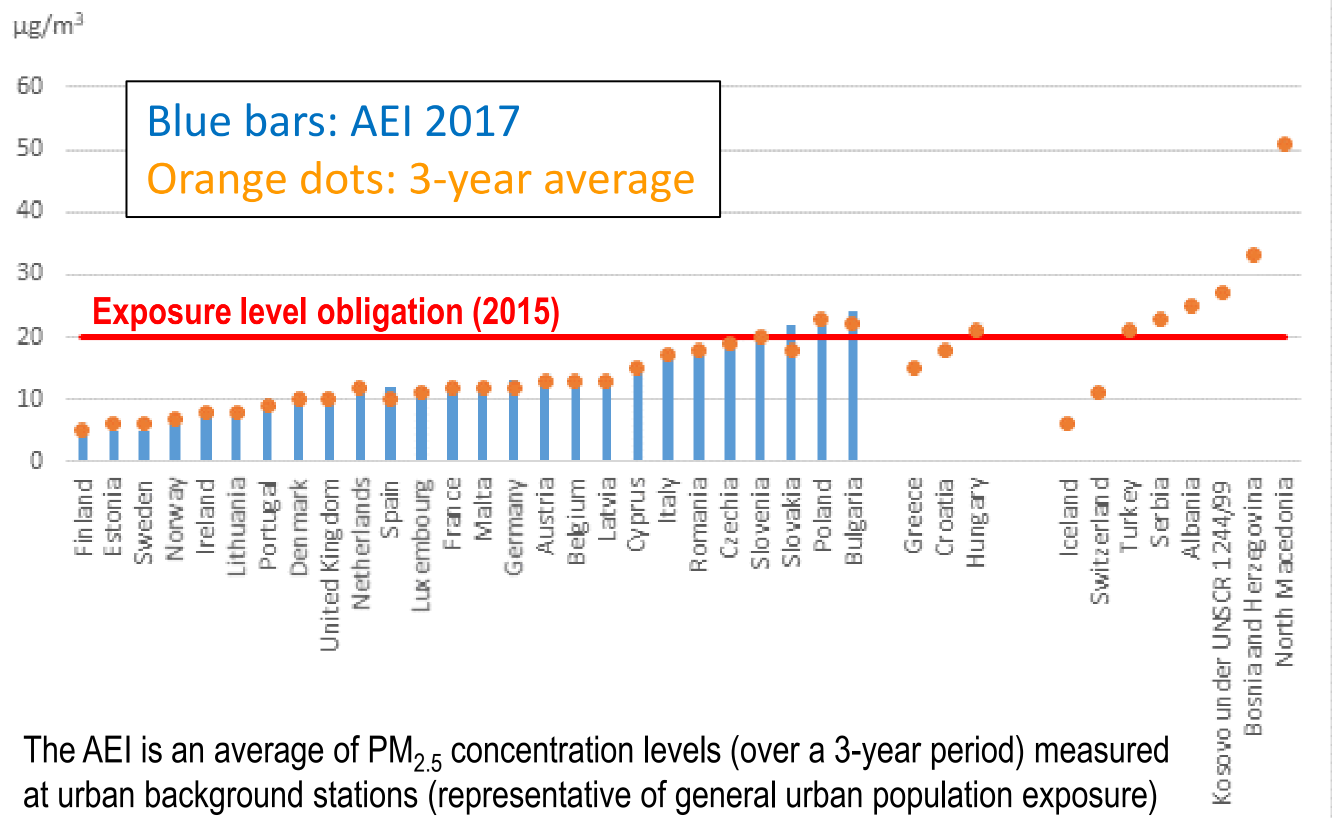
WHO Guideline:
100 μg/m³ (8-h mean)

Source: EEA, 2019

Exposure of population to air pollution

Fraction of urban EU28 population exposed to AP above EU limit and WHO AQG (min & max observed between 2015 and 2017)

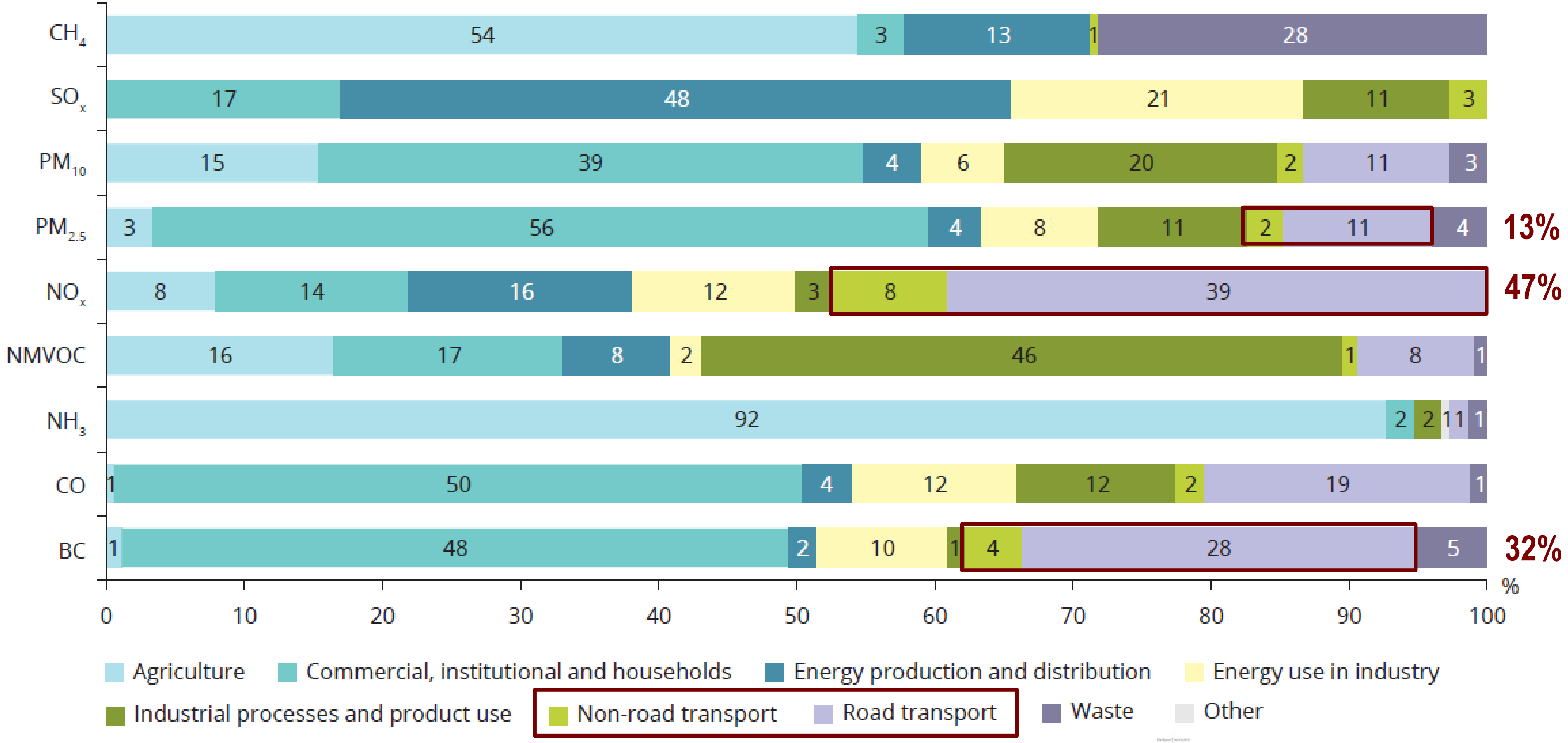
	EU limit ($\mu g/m^3$)	Exposure estimate (%)	WHO AQG ($\mu g/m^3$)	WHO Exposure estimate (%)
$PM_{2.5}$	Year (25)	6-8	Year (10)	74-81
PM_{10}	Day (50)	13-19	Year (20)	42-52
O_3	8-hour (120)	12-30	8-hour (100)	95-98
NO_2	Year (40)	7-8	Year (40)	7-8
BaP	Year (1)	17-20	Year (0.12) estimate	83-90
SO_2	Day (125)	< 1	Day (20)	21-31



The AEI is an average of $PM_{2.5}$ concentration levels (over a 3-year period) measured at urban background stations (representative of general urban population exposure)

Source: EEA, 2019

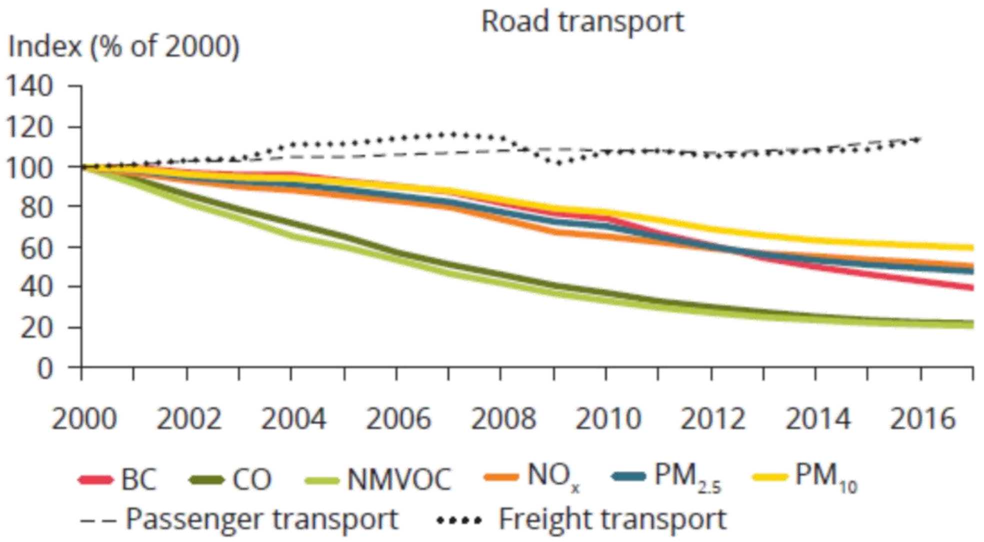
Contribution of sources to pollutants inventories

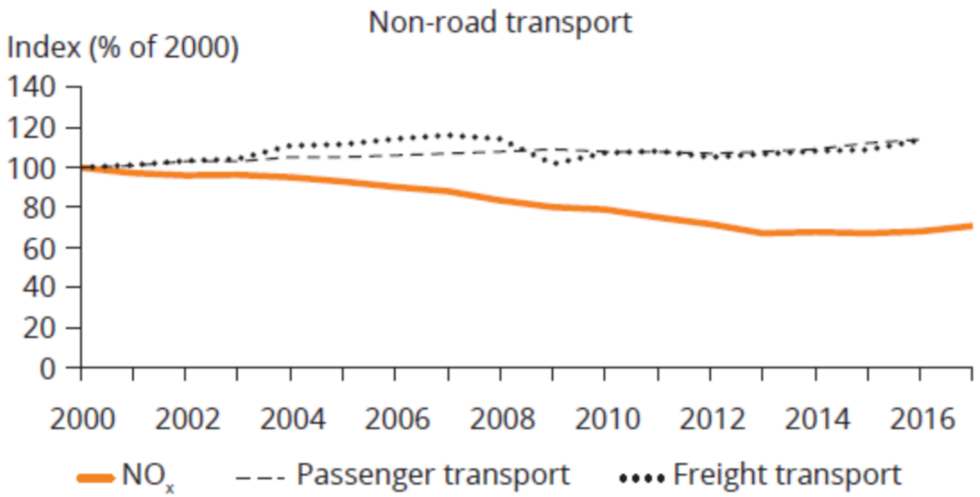


Year considered: 2017
Non-road: Rail, Inland Waterways, Intra-EU Air and Sea

Source: European Environment Agency – Air Quality in EU 2019

Evolution of emissions from transport modes

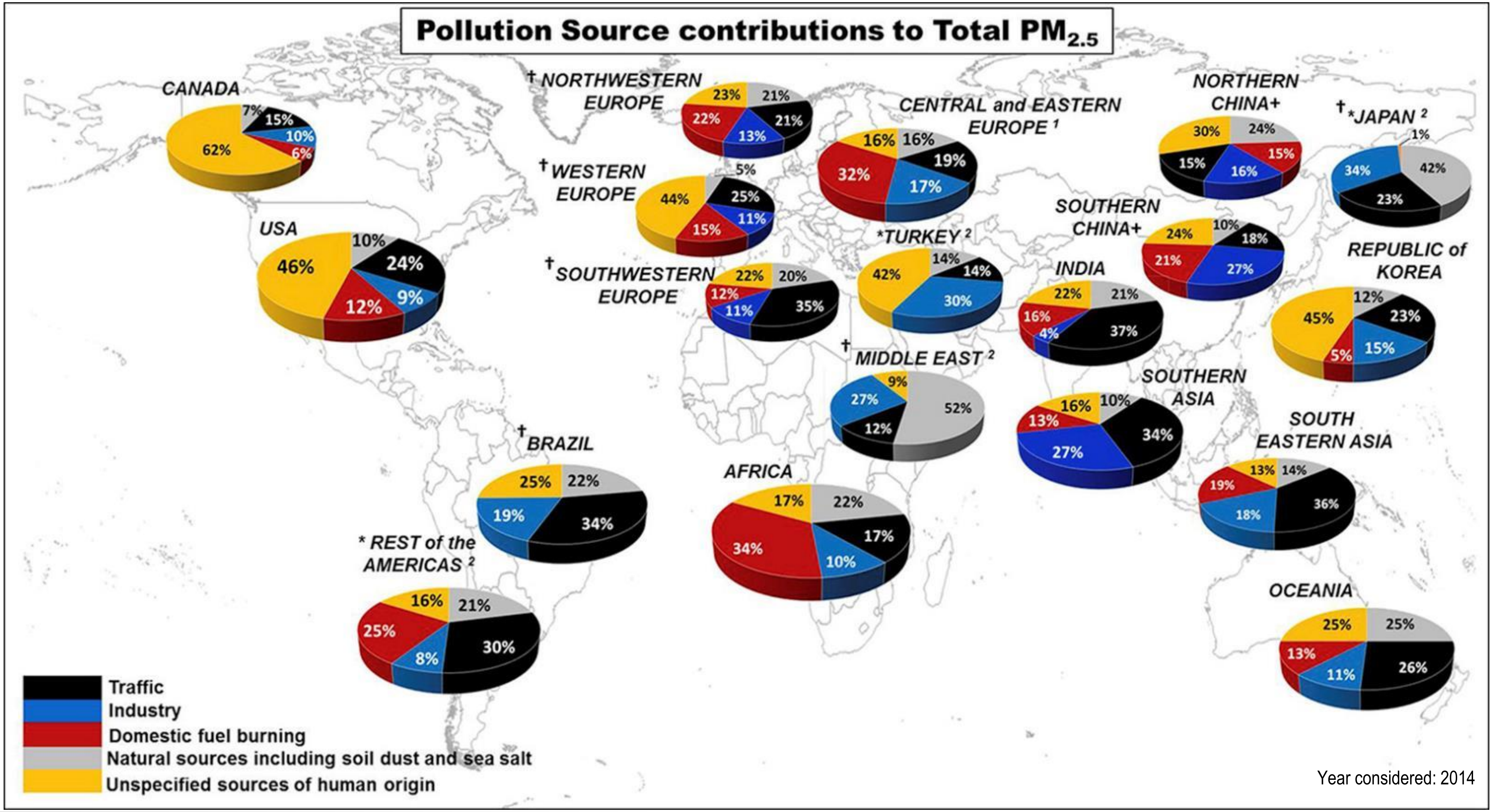




Despite emission control inefficiencies, significant reductions in air pollutants emissions have been achieved but exceedances of air pollution are still present

Source: European Environment Agency – Air Quality in EU 2019

Source apportionment of urban $PM_{2.5}$



Karagulian et al. (2015), DOI: 10.1016/j.atmosenv.2015.08.087

Source apportionment of urban O_3

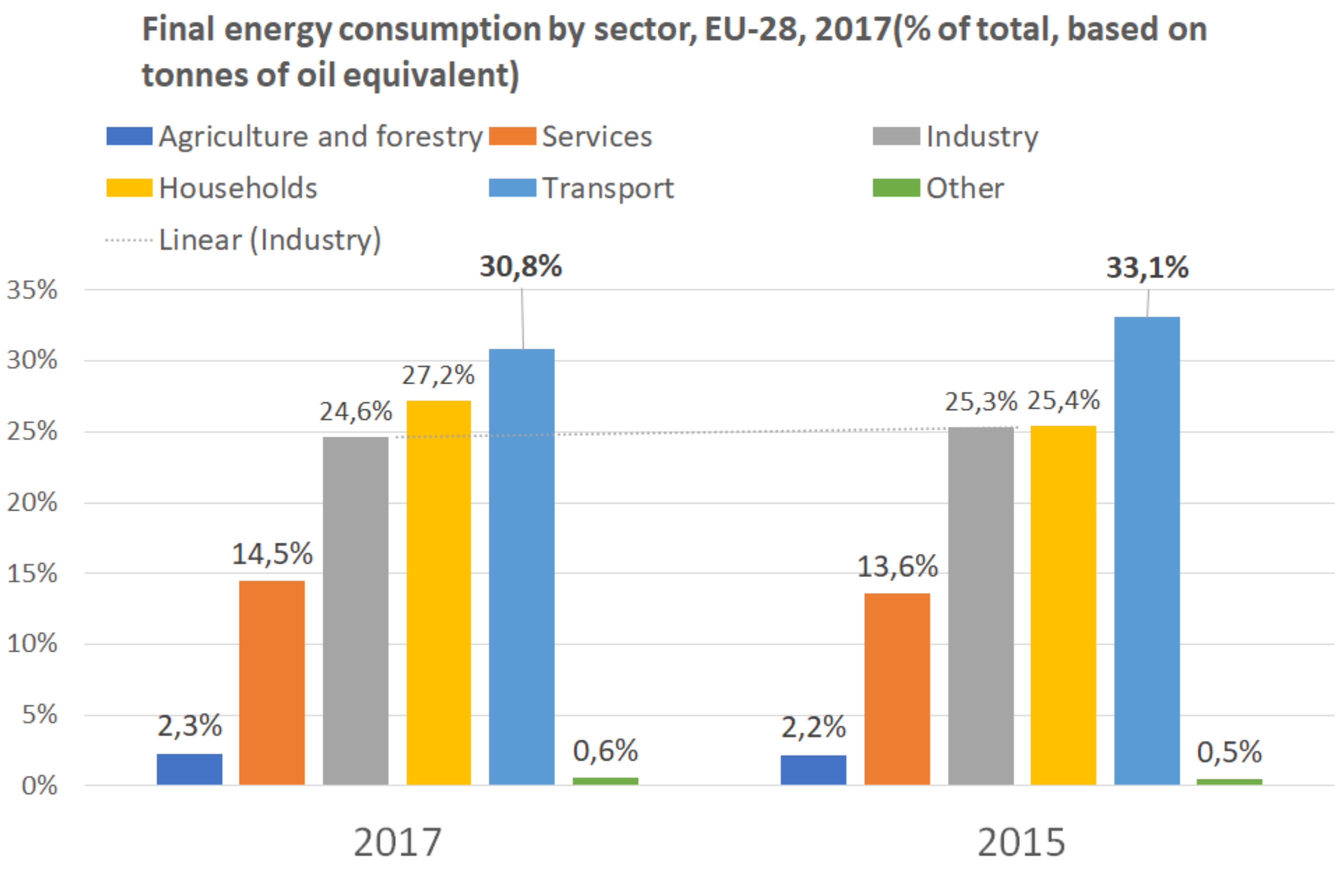
City ($\mu g\,m^{-3}$)	Sector* contributions (%)						
Lisbon (13)	SOA (47)	SNAP 2 (15)	SNAP 8 (13)	SNAP 7 (7)	SNAP 34 (6)	–	–	–
Barcelona (13)	SNAP 8 (21)	SOA (18)	SNAP 7 (18)	SNAP 2 (17)	SNAP 10 (7)	SNAP 1 (7)	SNAP 34 (7)	–
Athens (15)	SNAP 2 (20)	SNAP 8 (17)	SOA (13)	BC (12)	Dust (10)	SNAP 7 (10)	SNAP 1 (9)	–
Istanbul (26)	SNAP 2 (25)	SNAP 7 (11)	BC (11)	SNAP 34 (11)	SNAP 1 (10)	SNAP 8 (10)	SNAP 10 (9)	SOA (6)
Budapest (30)	SNAP 2 (29)	SNAP 7 (18)	SNAP 1 (17)	SNAP 10 (15)	SNAP 8 (7)	SNAP 34 (7)	–	–
Minsk (30)	SNAP 2 (33)	SNAP 10 (16)	SNAP 1 (13)	SNAP 7 (12)	SNAP 8 (10)	SNAP 34 (7)	–	–
Kiev (31)	SNAP 2 (37)	SNAP 10 (12)	SNAP 1 (11)	SNAP 8 (10)	SNAP 7 (10)	SNAP 34 (9)	–	–
Warsaw (38)	SNAP 2 (34)	SNAP 7 (17)	SNAP 10 (16)	SNAP 1 (12)	SNAP 8 (7)	SNAP 34 (6)	–	–
London (21)	SNAP 8 (23)	SOA (23)	SNAP 7 (19)	SNAP 2 (11)	SNAP 10 (7)	SNAP 1 (6)	–	–
Paris (25)	SNAP 2 (30)	SOA (16)	SNAP 7 (16)	SNAP 8 (13)	SNAP 10 (8)	SNAP 1 (6)	SNAP 34 (6)	–
Amsterdam (26)	SNAP 7 (19)	SNAP 8 (18)	SNAP 2 (16)	SNAP 10 (13)	SOA (12)	SNAP 1 (10)	SNAP 34 (7)	–
Berlin (32)	SNAP 2 (24)	SNAP 7 (18)	SNAP 10 (15)	SNAP 1 (12)	SNAP 8 (11)	SNAP 34 (7)	SOA (6)	–
Stockholm (17)	SNAP 7 (22)	SNAP 2 (19)	SNAP 8 (16)	SOA (14)	SNAP 1 (10)	SNAP 10 (7)	SNAP 34 (6)	–
Oslo (19)	SNAP 2 (47)	SNAP 8 (16)	SNAP 7 (11)	SOA (7)	SNAP 1 (6)	SNAP 10 (5)	–	–
Helsinki (21)	SNAP 2 (33)	SNAP 7 (18)	SNAP 8 (14)	SNAP 1 (9)	SOA (9)	SNAP 10 (7)	SNAP 34 (5)	–
Copenhagen (24)	SNAP 2 (20)	SNAP 8 (19)	SNAP 7 (14)	SNAP 10 (12)	SNAP 1 (12)	SOA (11)	SNAP 34 (6)	–

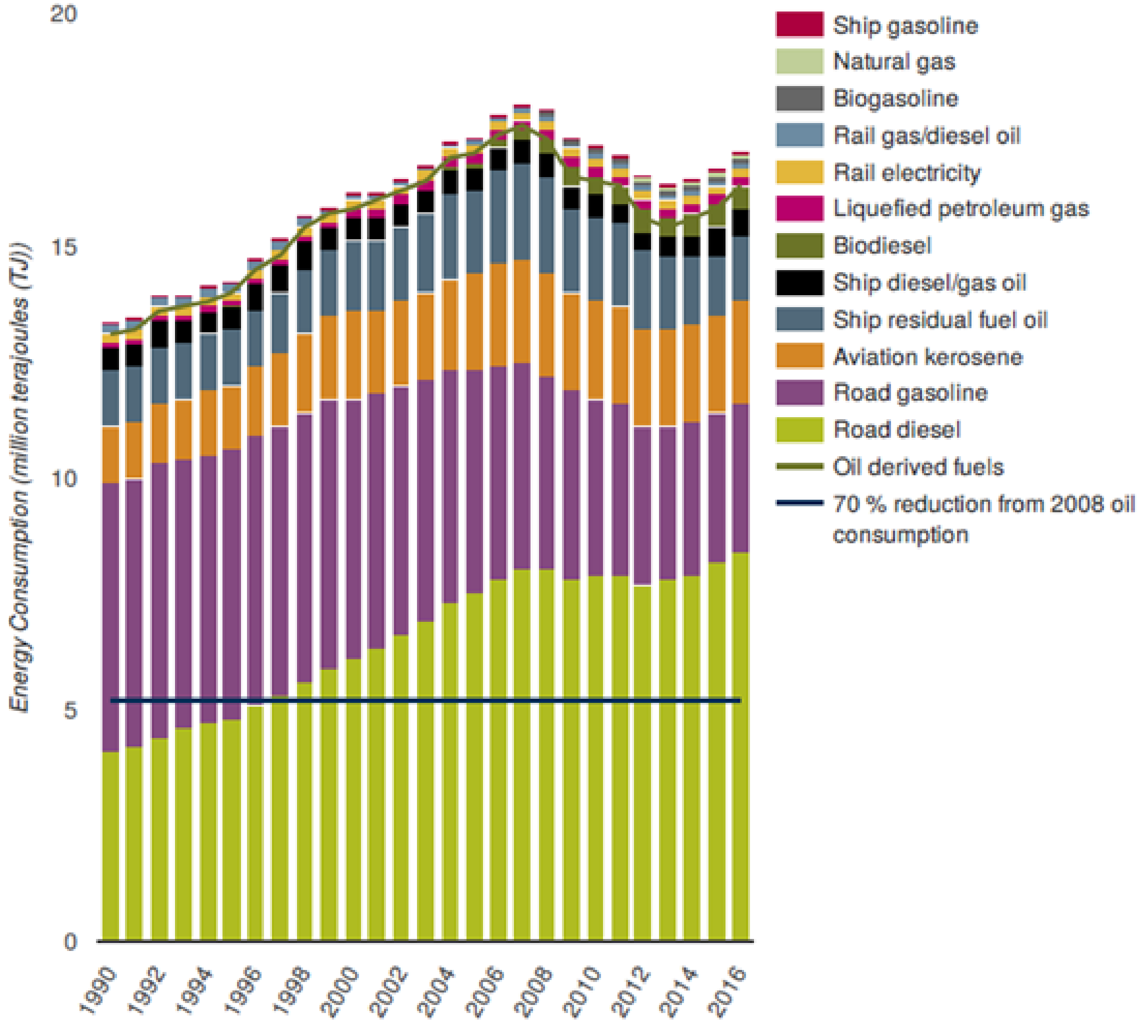
Year considered: 2010

01	Combustion in the production and transformation of energy	07	Road Transport
02	Non-industrial combustion plants	08	Other mobile sources and machinery
03	Industrial combustion plants	09	Waste treatment and disposal
04	Industrial processes without combustion	10	Agriculture
05	Extraction and distribution of fossil fuels and geothermal energy	11	Other sources and sinks (nature)
06	Use of solvents and other products		

Karamchadani et al. (2017), DOI:10.5194/acp-17-5643-2017

Statistics of transport energy consumption



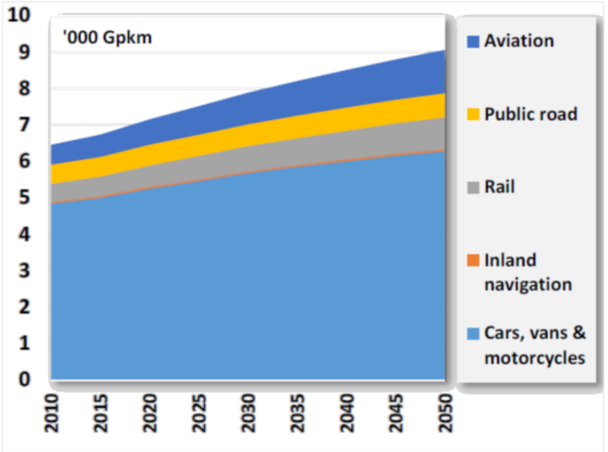


- Road transport accounts for the largest share of final energy consumption
- A decrease of about 7% in 2017 consumption vs. 2015 consumption
- However, consumption in 2017 was still 20% higher than in 1990
- The fraction of diesel used in road transport has continued to increase, amounting to 74 % of total fuel sales in 2016

Source: EEA 2019, EEA 2017, Eurostat 2018

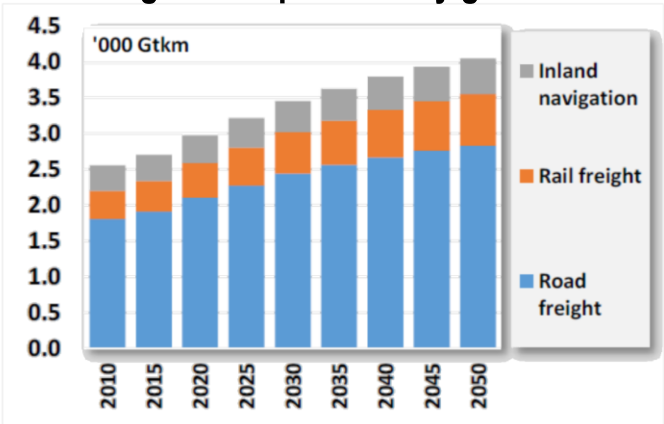
Our ‘reference’ estimate about energy evolution in transport

Passenger Transport activity growth

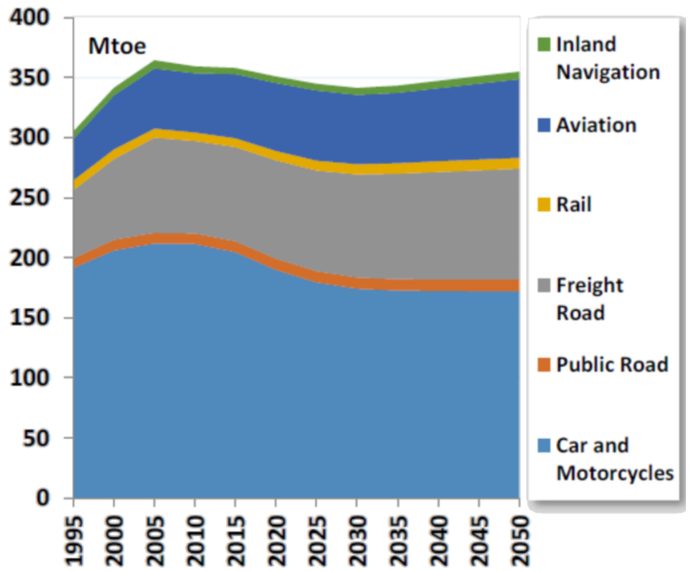


Note: The figure reports the aviation activity related to the domestic and inter-national intra-EU flights to maintain comparability with usual reported statistics

Freight Transport activity growth

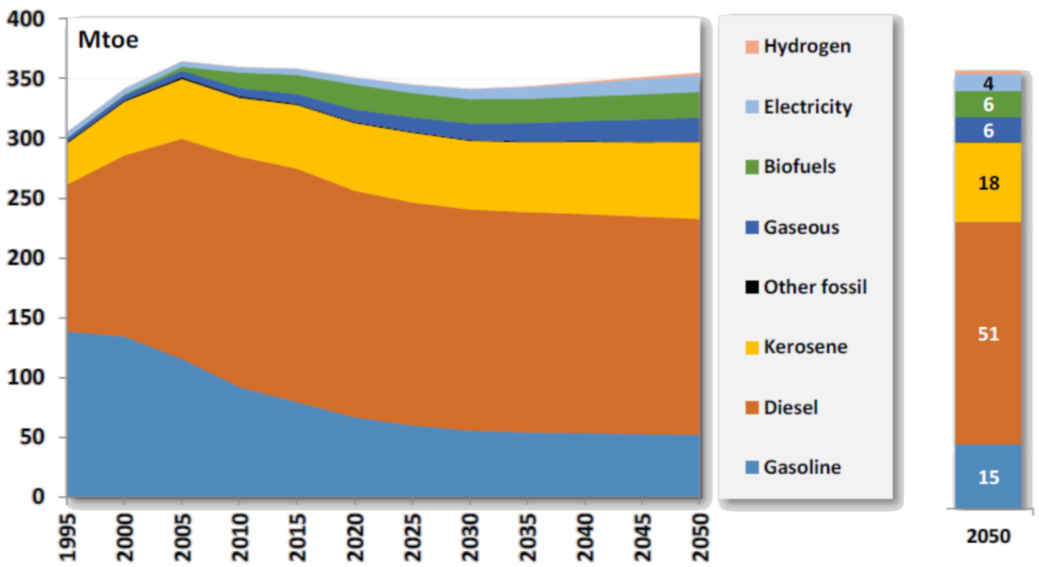


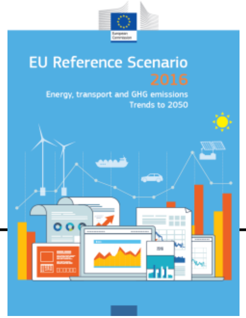
Total energy demand projection



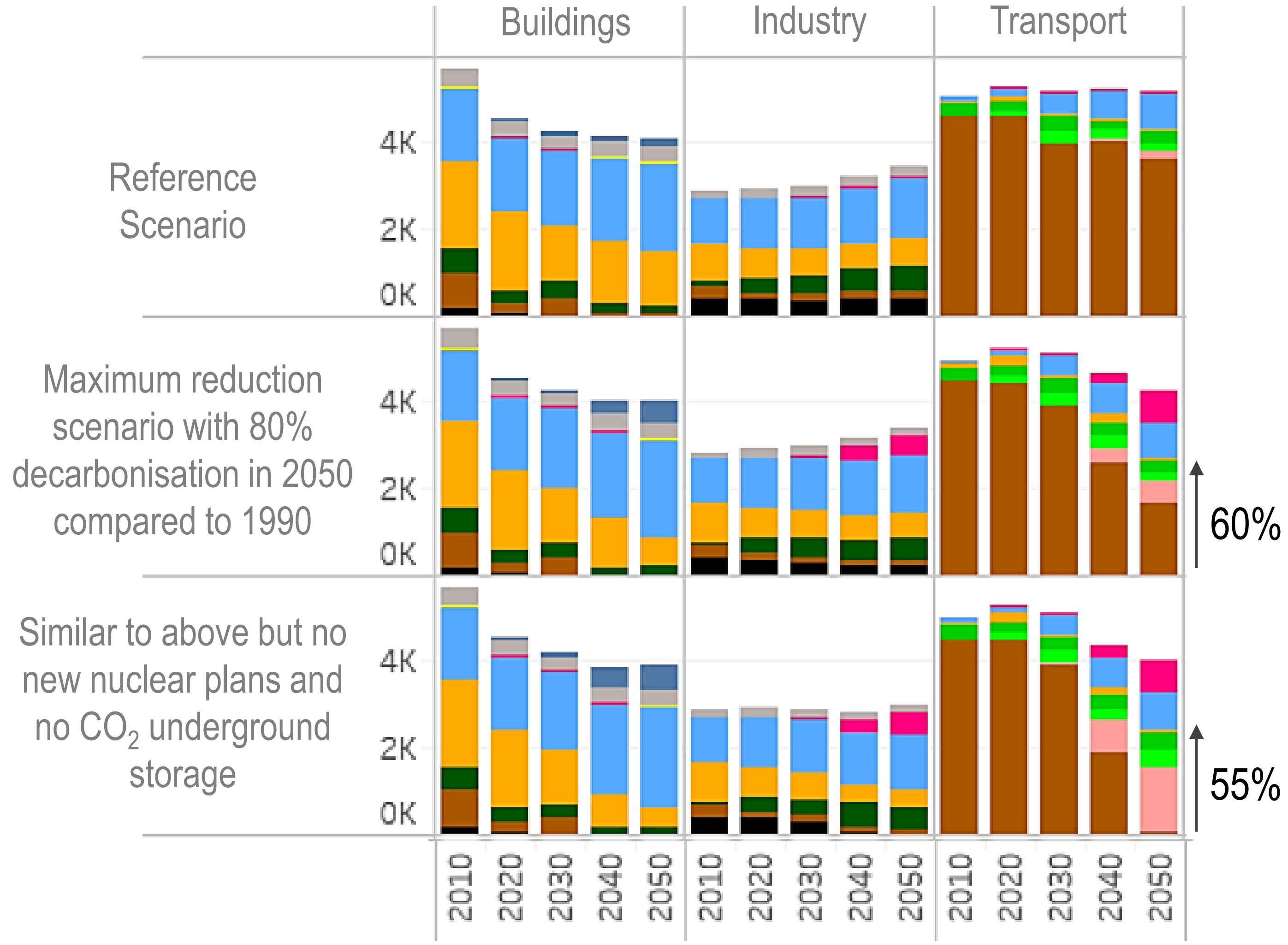
Note: Does not include bunger fuel used for international maritime transport (~50 Mtoe)

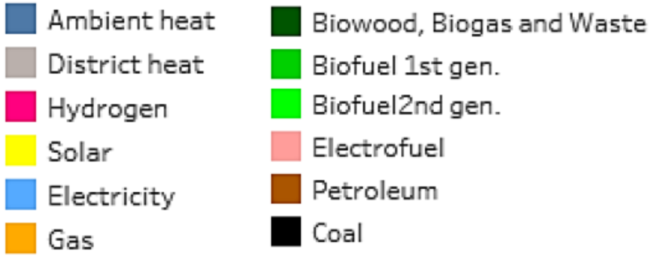
Energy demand by fuel



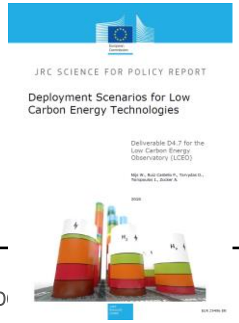


Alternative estimates on future energy projections





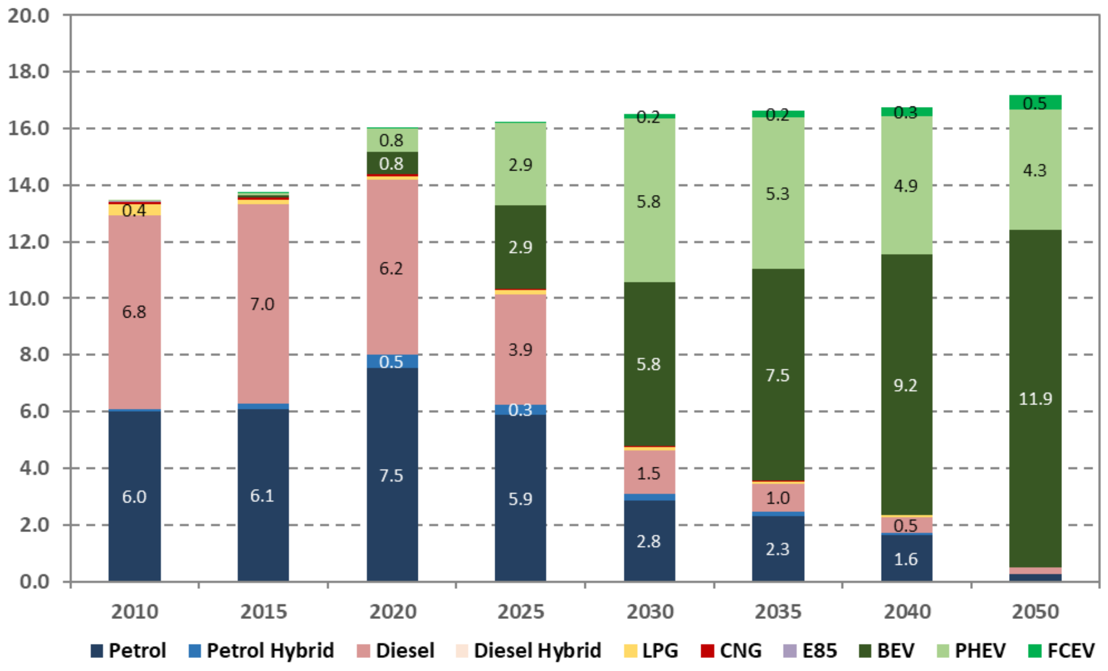
Even in the most advanced scenarios, the majority of transport activity is served by Internal Combustion Engines, up to 2050



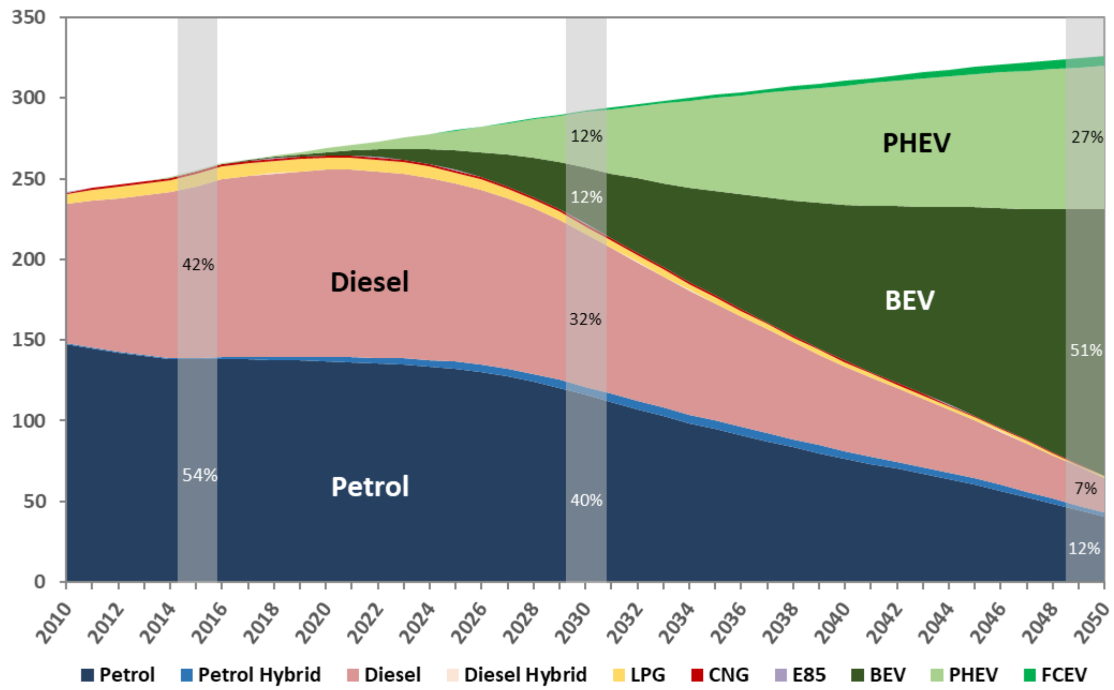
Source: Nijs et al. (2018), EC Joint Research Centre projections with the TIMES to

How the future car fleet may look like

Car sales



Fleet structure



11.6M BEV+PHEV sales in 2030, increasing to 16.2M in 2050

2.8M petrol sales in 2030, declining to <0.3M in 2050

1.5M diesel sales in 2030, declining to <0.1M in 2050

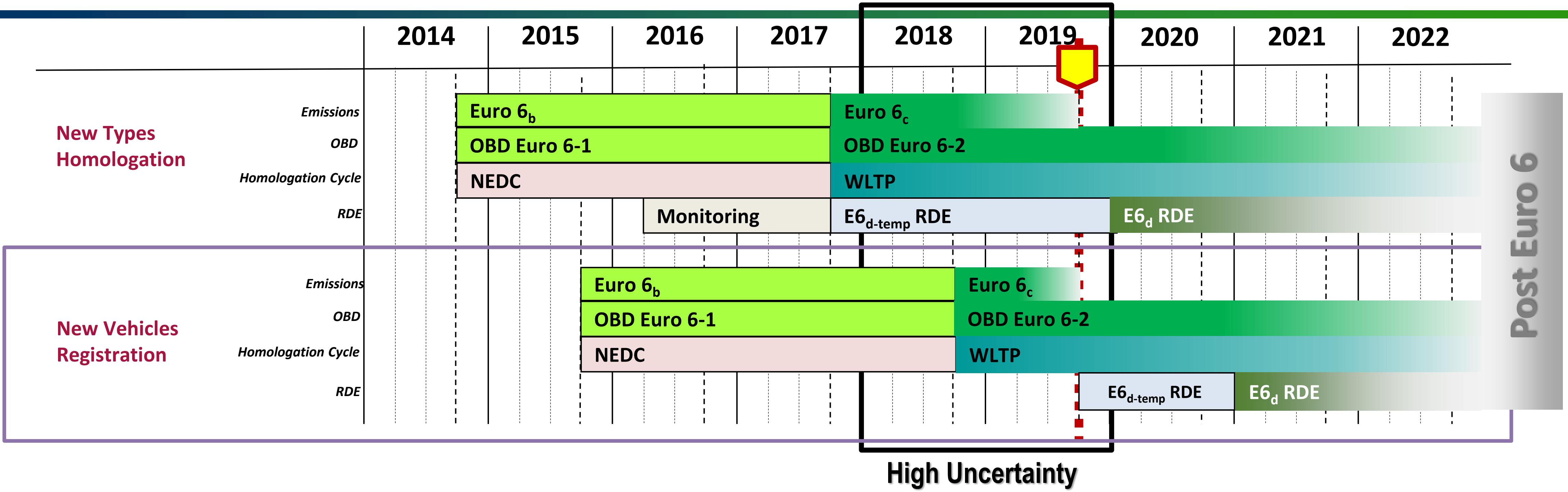
24% BEV+PHEV in 2030 increasing to 78% in 2050

76% ICE vehicles in 2030, decreasing to 20% in 2050

Market and fleet estimates: sibyl

VEHICLE EXHAUST EMISSION CONTROL TECHNOLOGY EFFECTS

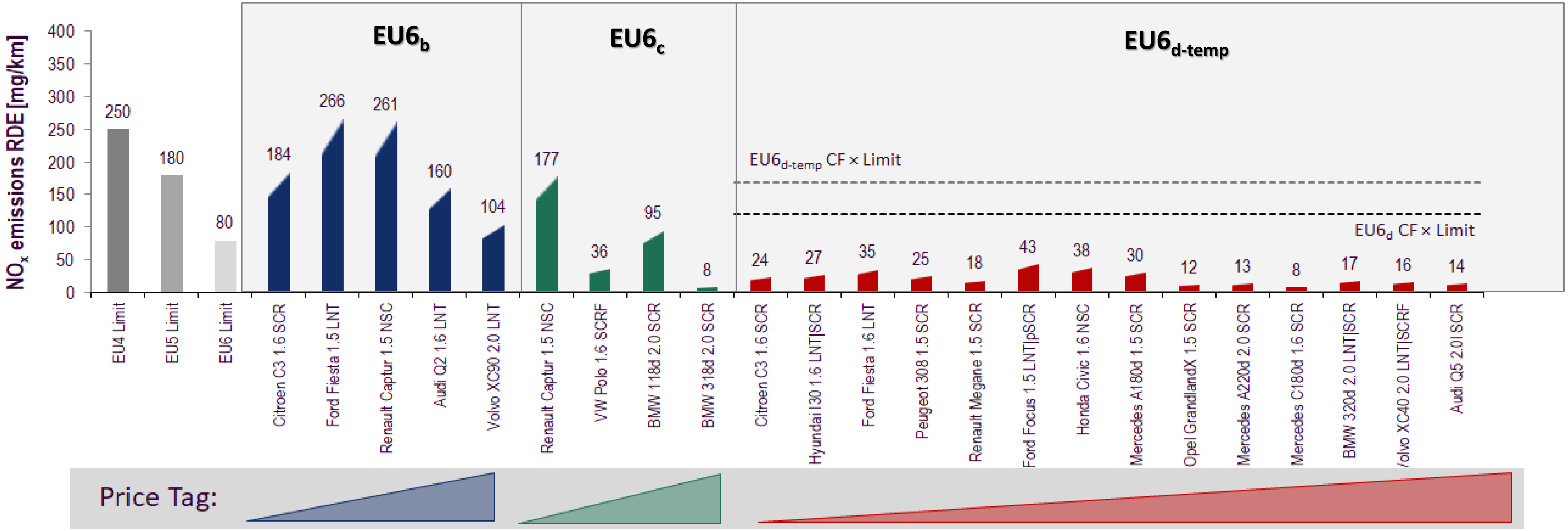
Emissions standards evolution



Euro 6c/d compliance requirements:

- **Particle Number (PN) limit** for GDI aligned with the diesel one: $\mathbf{6 \times 10^{11}}$ **#/km**
- **OBD** thresholds reduction both for NOx and Particulate Matter (PM)
- **WLTP** replaced **NEDC**
- **RDE (Real Driving Emissions)** with Conformity Factors (CF) to account for measurement uncertainty :
  - **NO_x** 2.1 Euro $6_{d\text{-}temp}$| 1.43 Euro 6_d
  - **PN** 1.5

The impact of RDE on diesel NOx



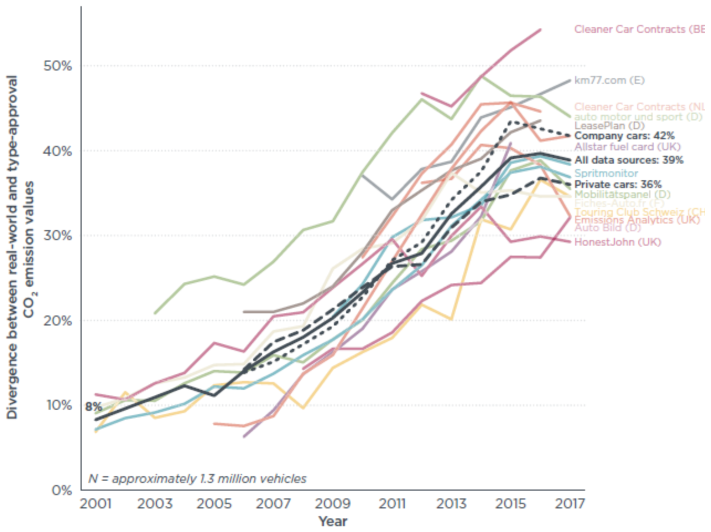
Official RDE results from public database:

- Euro 6 diesel before RDE continued to emit much higher than limit
- Latest Euro 6d-temp already by far fulfil Euro 6d

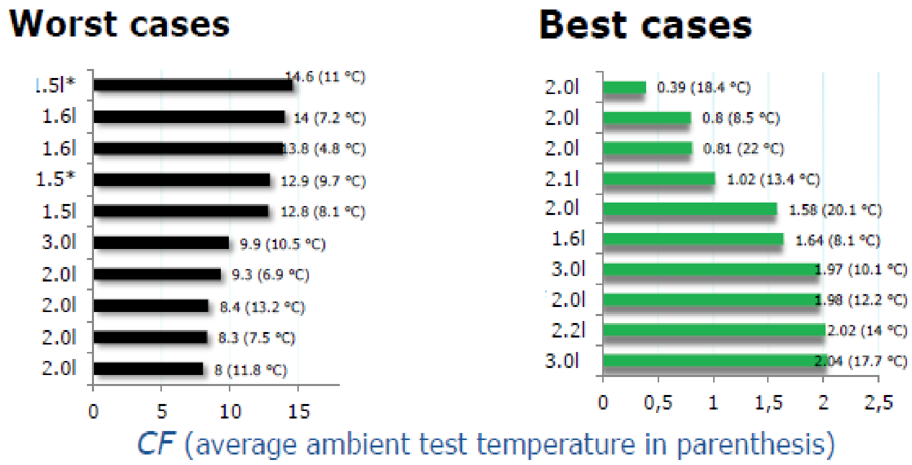
source: //www.acea.be/publications/article/access-to-euro-6-rde-monitoring-data

Real world emissions

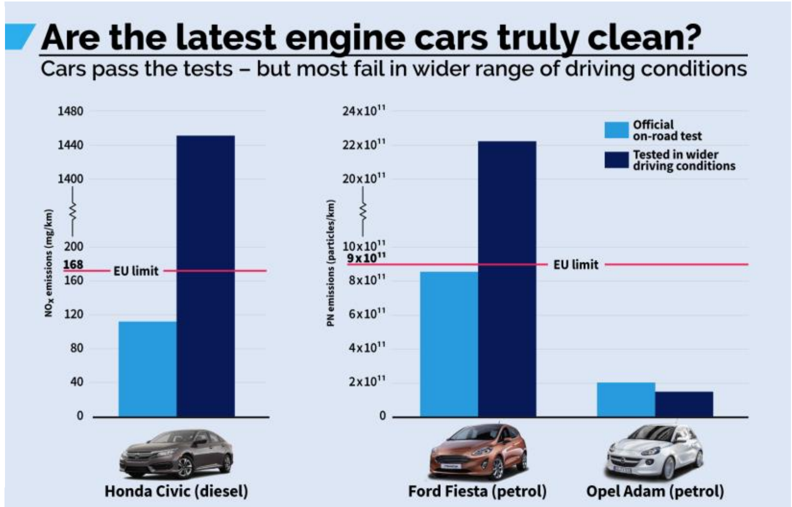
Divergence between real-world and type-approval CO_2 emission values



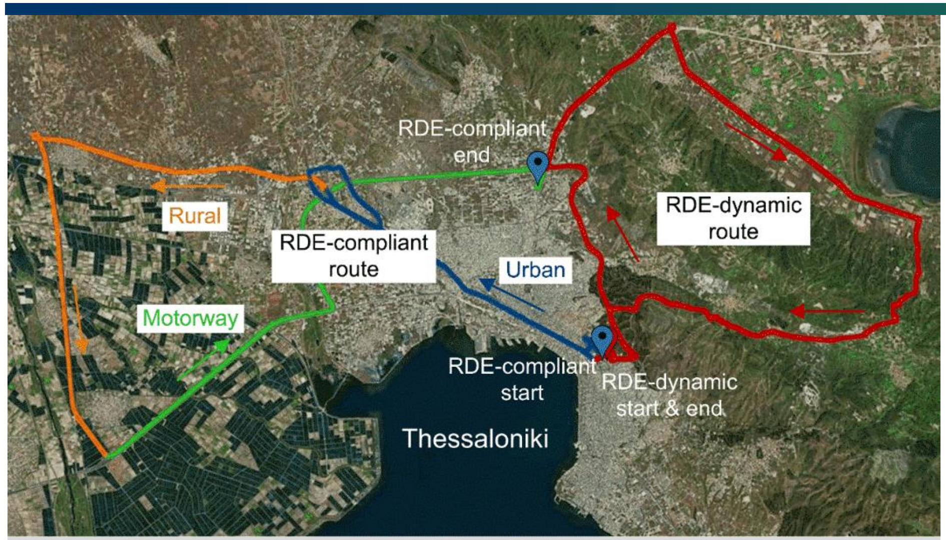
EURO 6 Diesel RDE test results for pre-RDE vehicles



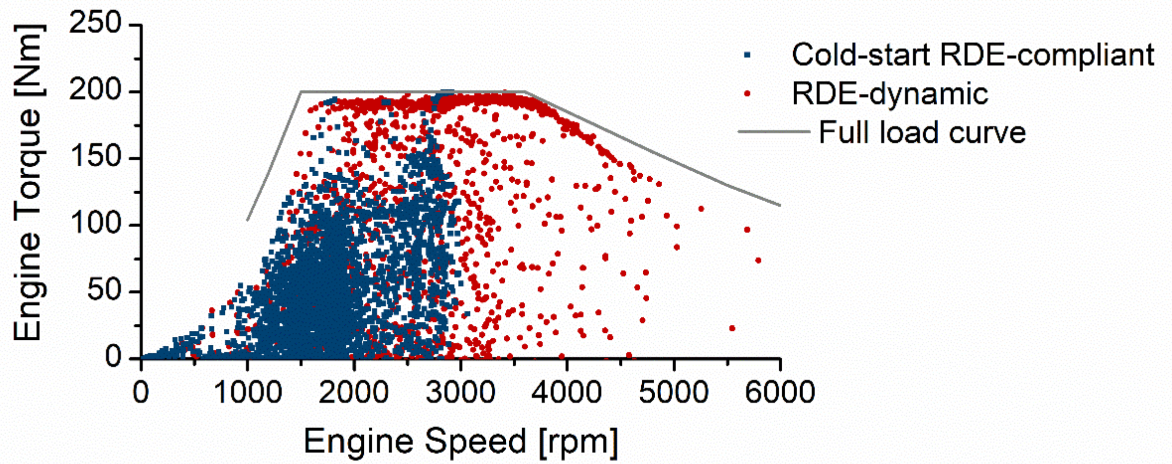
EURO 6 Testing outside of RDE



Different driving conditions examined - Thessaloniki



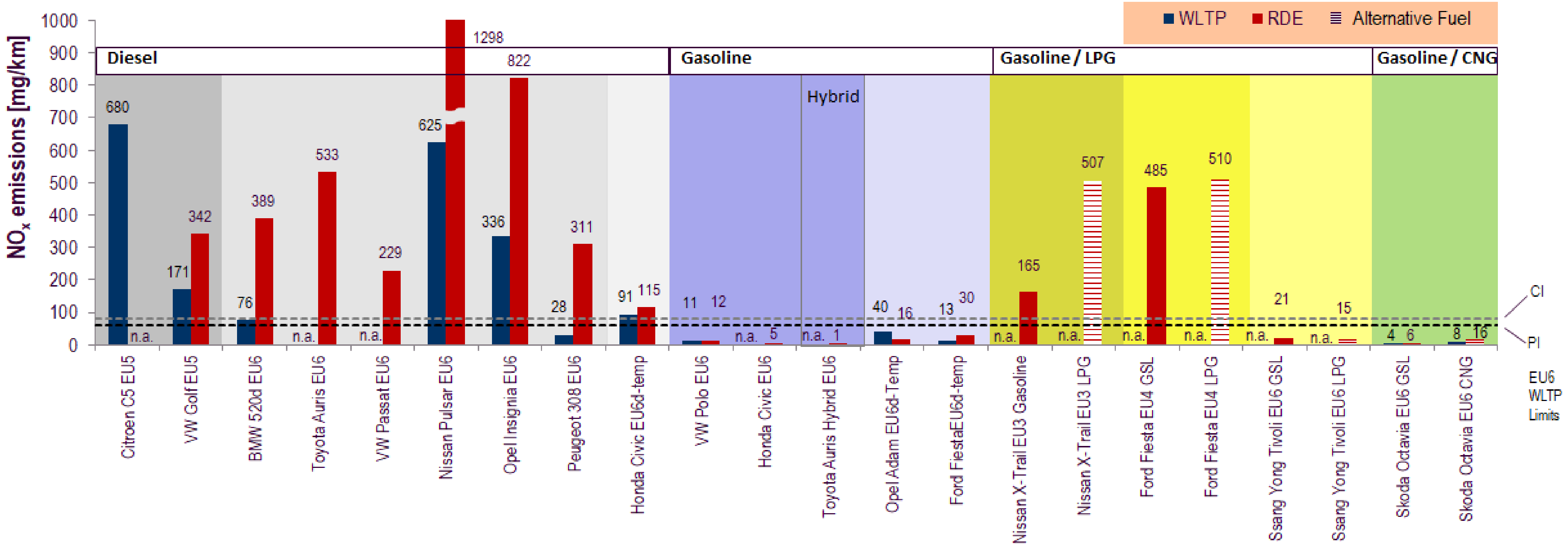
RDE route fully respects regulatory requirements
DYN is a route of demanding driving, incl. uphill



Trip characteristics	RDE	DYN	Regulation boundaries
Trip duration [min]	110	60	90 – 120
Stop duration [% of trip]	22	20	> 10
Trip distance [km]	77	77	> 46
Urban distance share [%]	37	30	29 – 44
Rural distance share [%]	29	36	23 – 43
Motorway distance share [%]	34	34	23 – 43
Urban av. speed [km/h]	21	30	15 – 30
Rural av. speed [km/h]	83	75	60 – 90
Motorway av. speed [km/h]	118	110	100 – 145
Max altitude [m]	115	530	< 700
Positive el. gain [m/100km]	507	1600	<1200
Total altitude gain [m]	-7	0	± 100

Source: LAT, 2019

NO_x emission levels



Independent tests confirm NO_x reduction with diesel Euro $6_{d\text{-}temp}$. More tests are needed.

- Not much difference between EU5 and EU6 pre-RDE
- Occasional big deviations between lab (WLTP) and RDE for pre-RDE Euro 6

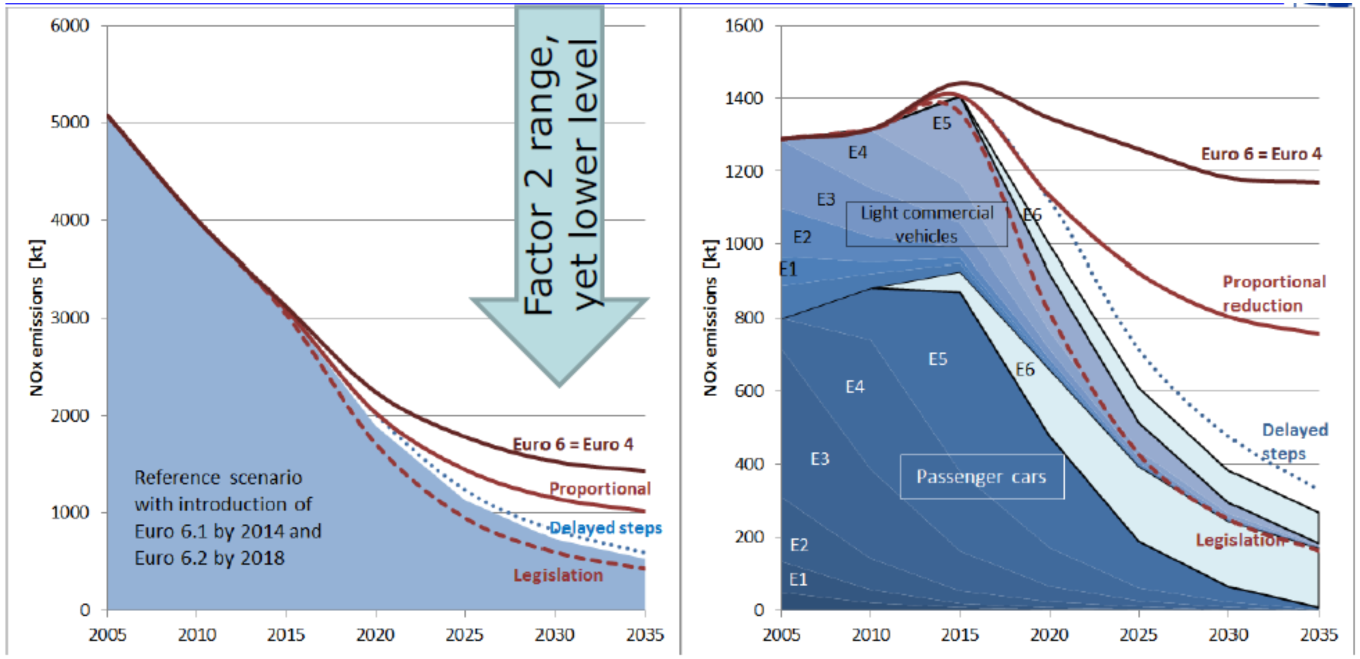
Latest positive-ignition still below diesel. Hybrid at detection limit over RDE.

- Impact of LPG or CNG uncertain on already low emission levels

LPG retrofits on older gasoline cars lead to very high NOx levels!

What can be the impact of (real) low limits?

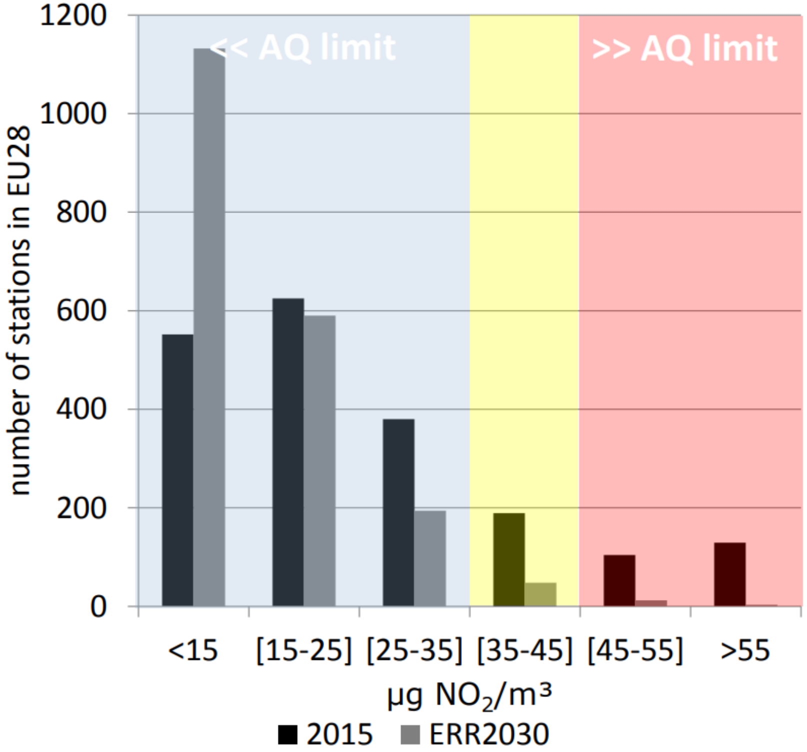
NO_x emission evolution



"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

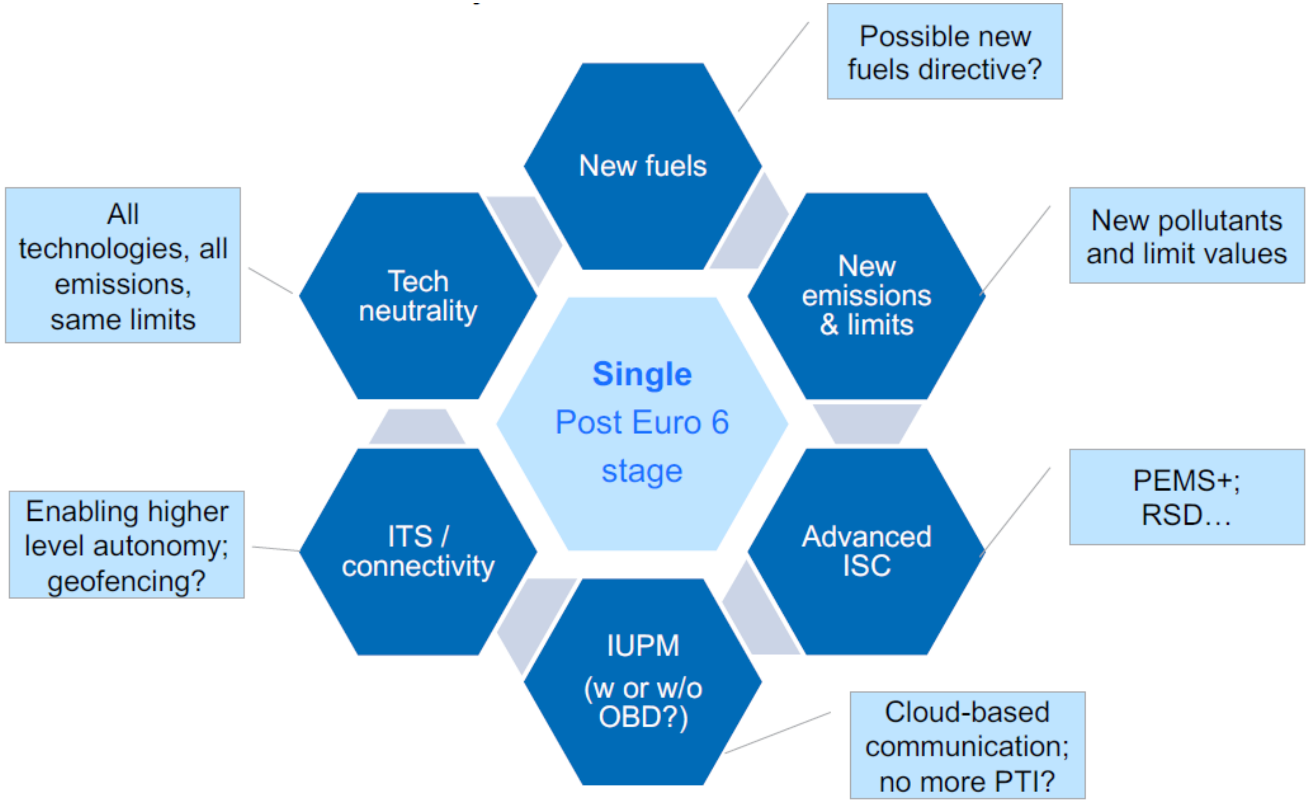
NO_2 concentration exceedances



Source: Amann (2018)

Emission control technologies that deliver emission levels on the road as designed by the emission standards can lead to zero exceedances (in this case NO_2) in urban conditions

Next regulatory stage: Post Euro 6/VI



EU consider that the next stage will be the last stage with all the objectives included

Major lines of consensus

- In use performance monitoring for compliance and enforcement over the lifetime of the vehicle
- Pollutant emissions to be considered along with CO2/GHG emissions
- Non regulated emissions to be also included in the regulations

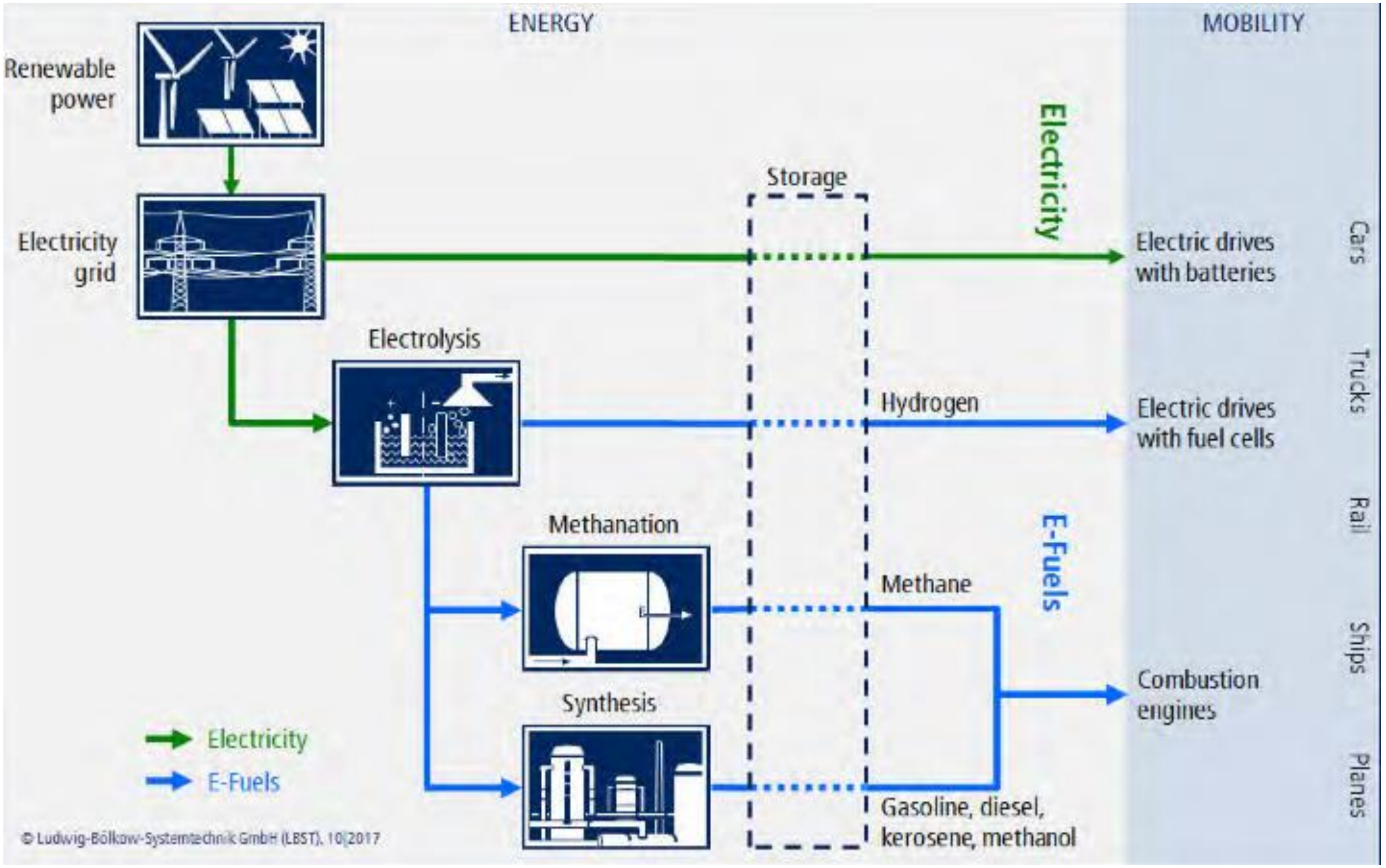
Source: Ricardo,2019

NEW FUELS

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
- **2^{nd} – 3^{rd} generation biofuels**
  - Target is a 20% reduction to CO_2 emissions
  - Adapted engines and vehicles are being studied in H2020
- **E-fuels**
  - Produced with renewable energy (H_2, CH_4, FT-Hydrocarbons)
  - High specific energy, designed properties, no contaminants
  - High cost (4 € / l)

Synthetic fuels



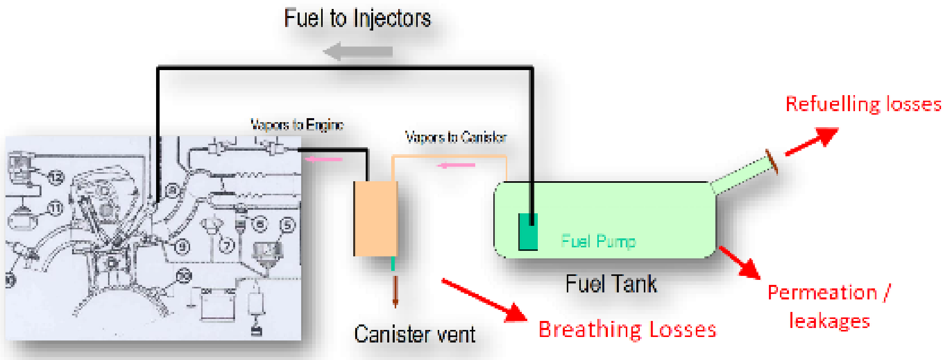
Renewable synthetic fuels

- e-fuels are gaseous and liquid fuels such as hydrogen, methane, synthetic petrol, and diesel fuels generated from renewable electricity

EXHAUST VS NON-EXHAUST EMISSIONS

Exhaust emissions vs non exhaust emissions

- **Total Exhaust Emissions:** $E_{EXH} = E_{HOT} + E_{COLD}$
  - Hot (stabilized engine temperature): $E_{HOT} = N \cdot M \cdot e_{HOT}$
  - Cold-start emissions: $E_{COLD} = \beta \cdot N \cdot M \cdot e_{HOT} \cdot (e^{COLD}/e^{HOT}-1)$



Mechanisms causing evaporation emissions

- Diurnal emissions
- Hot soak emissions

→ **Parked vehicle**

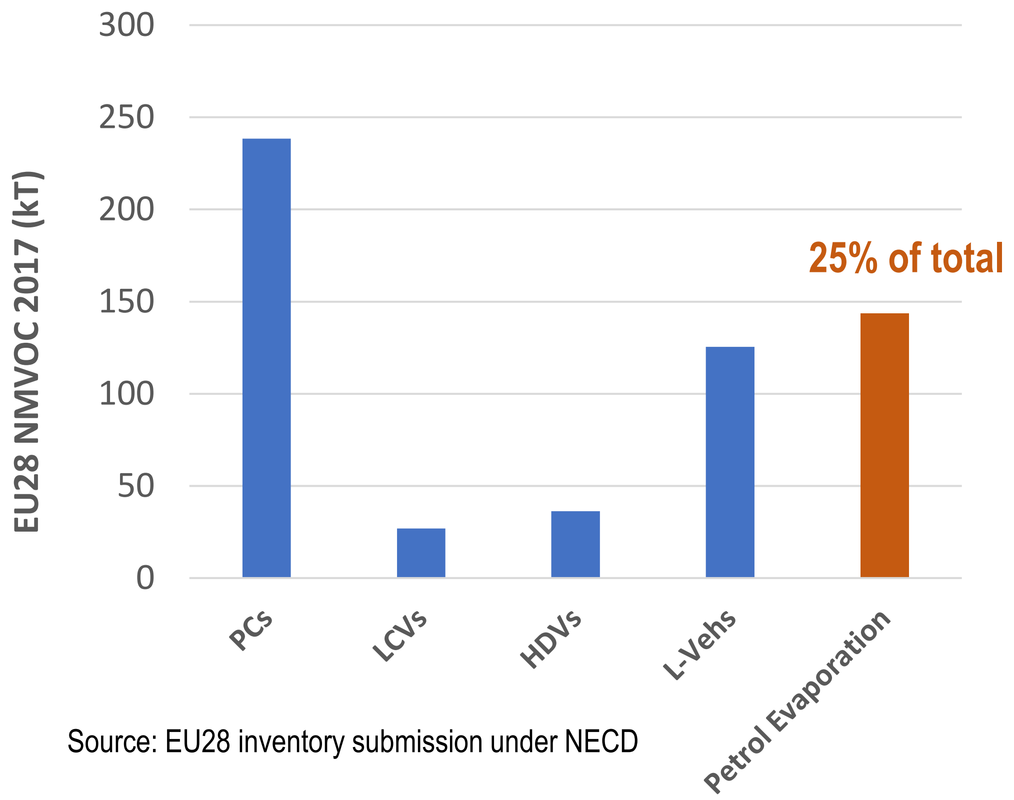
- Running losses

→ **Engine running**

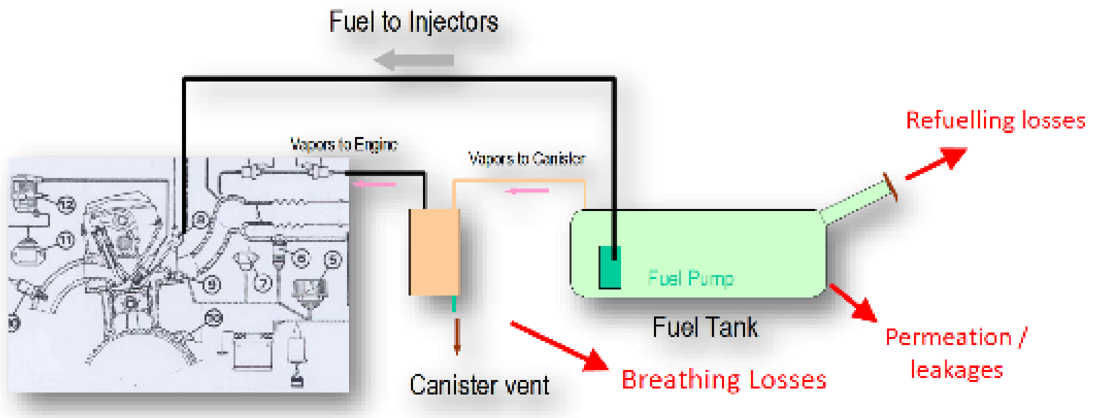
Only relevant for Gasoline!

- **Non-Exhaust Emissions**
  - NMVOC from Fuel Evaporation: $E_{EVAP} = E_{DIURNAL} + E_{SOAK} + E_{RUNNING}$
  - PM from tyre and brake attrition: $E_{T\&B} = N \cdot M \cdot e_{PM,T\&B}$

The significance of fuel evaporation



Source: EU28 inventory submission under NECD



Mechanisms causing evaporation emissions

- Diurnal emissions
- Hot soak emissions

→ **Parked vehicle**

- Running losses

→ **Engine running**

Only relevant for Gasoline!

emisia

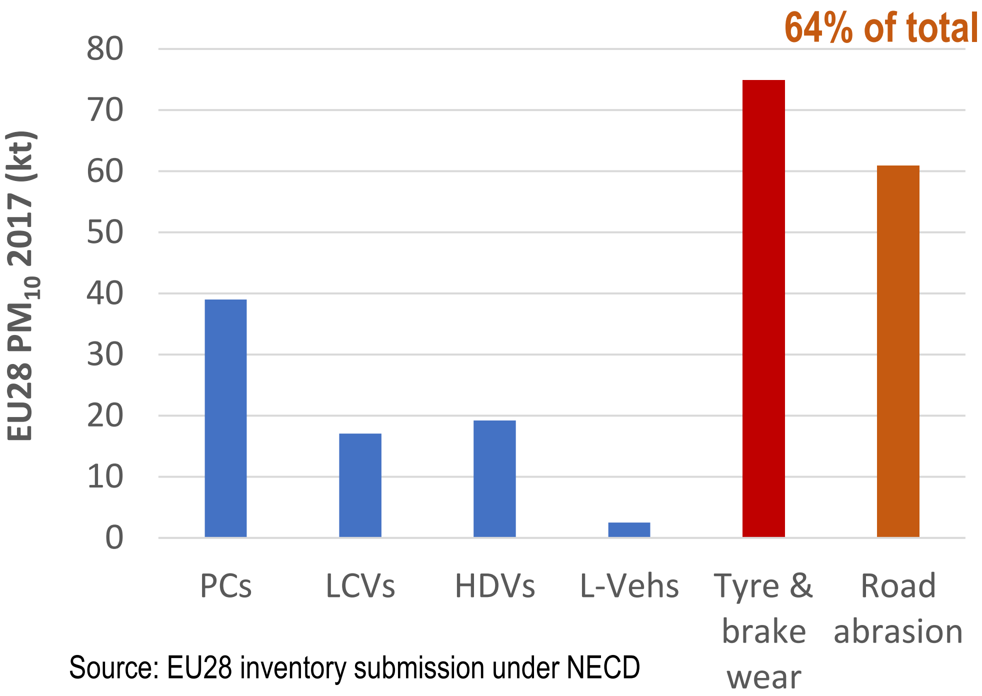
European Topic Centre on Air

Notes:

- Calculations do not include refuelling losses, no ORVR control in the EU
- No reliable estimate of running losses

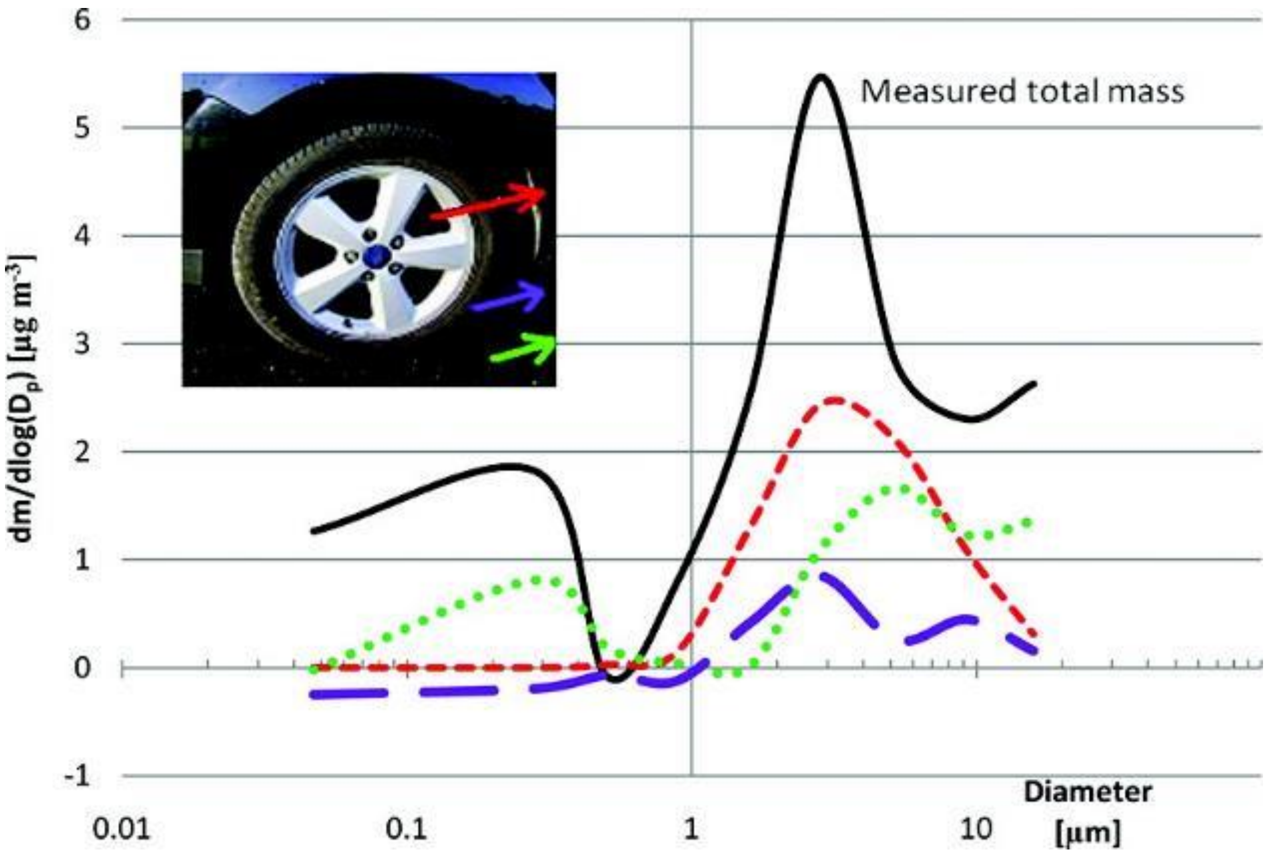
LAT

Exhaust vs non-exhaust PM emissions



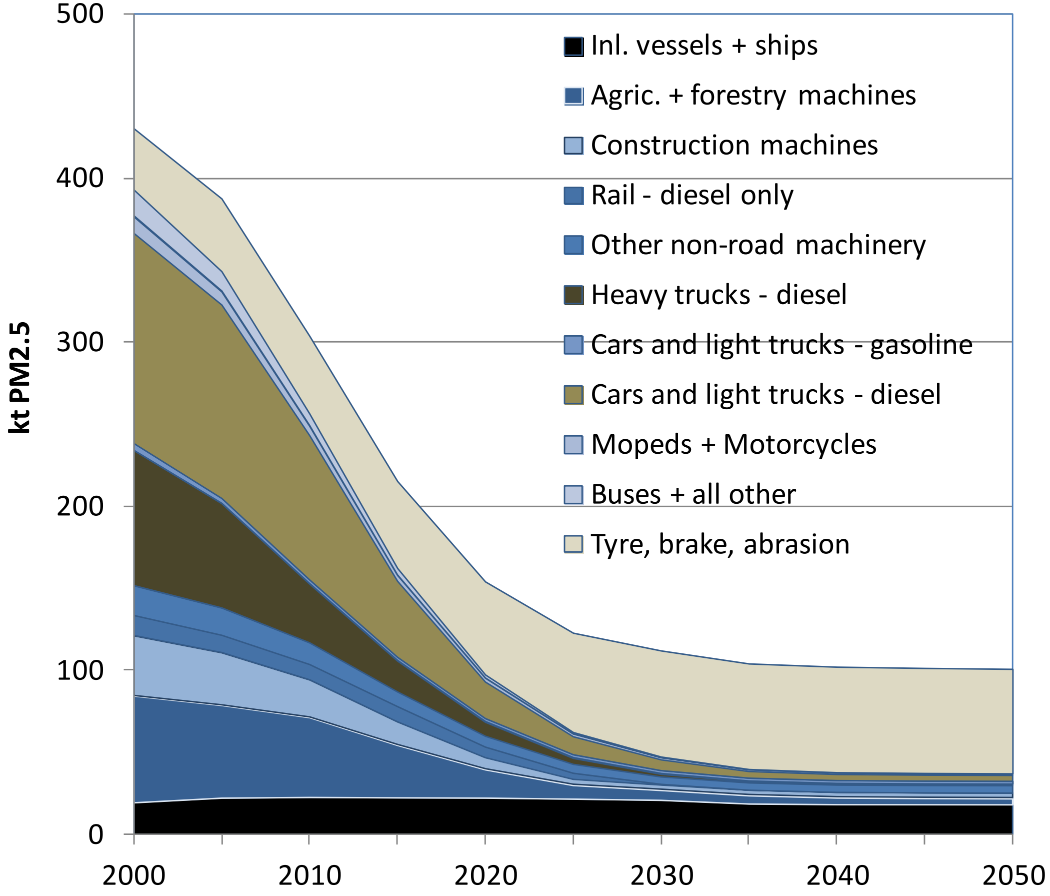
Source: EU28 inventory submission under NECD

Vehicle class (j)	Particle source(s)			
	Tyre wear (g/km)	Brake Wear (g/km)	Road surface wear (g/km)	Exhaust emission rate (g/km)*
Two-wheelers	0.0028	0.0037	0.0030	0.060 (two-stroke)
Passenger cars	0.0064	0.0073	0.0075	0.0005 (dpf or petrol)
Light duty trucks	0.0101	0.0115	0.0075	0.0008 (dpf or petrol)
Heavy vehicles	0.0270	0.0320	0.0380	0.0010 (dpf)



Source: Harrison et al. (2012), DOI: 10.1021/es300894r

$PM_{2.5}$ projections

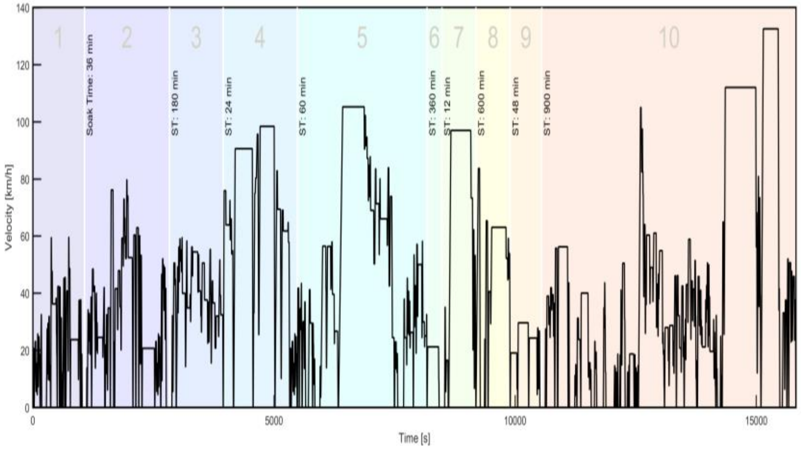


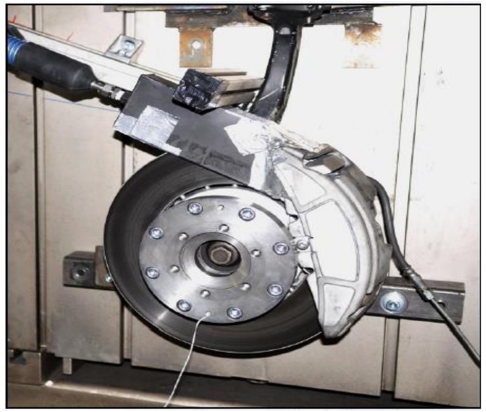
- **Baseline:**
  - Reductions until 2030 vs. 2005
    >90%: diesel HDV&LDV, locos, NRMM
    ~70% other mobile machines
  - Road abrasion, tyre, clutch and brake wear increase with traffic volume,
    >80% of emissions from road vehicles in 2030

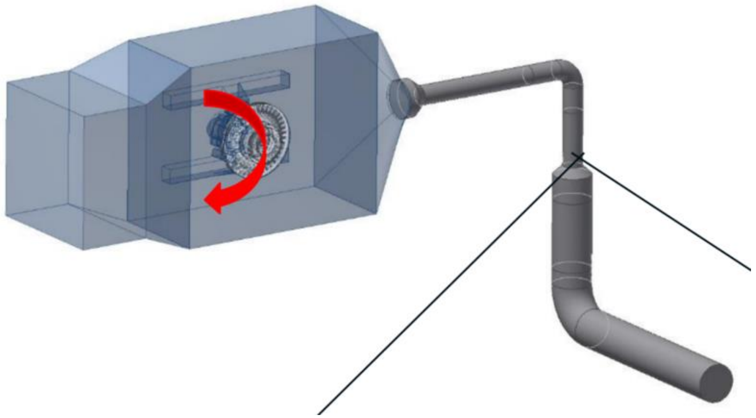
Source: Kleefeld and Ntziachristos (2012) TSAP Review

Current PMP activities for non-exhaust PM

- ➢ Reepsentative braking driving cycle under development
- ➢ Particle sampling and measurement system under development
- ➢ Metric still unknown (PM and PN)
- ➢ Tyre emissions considered but little activity as yet





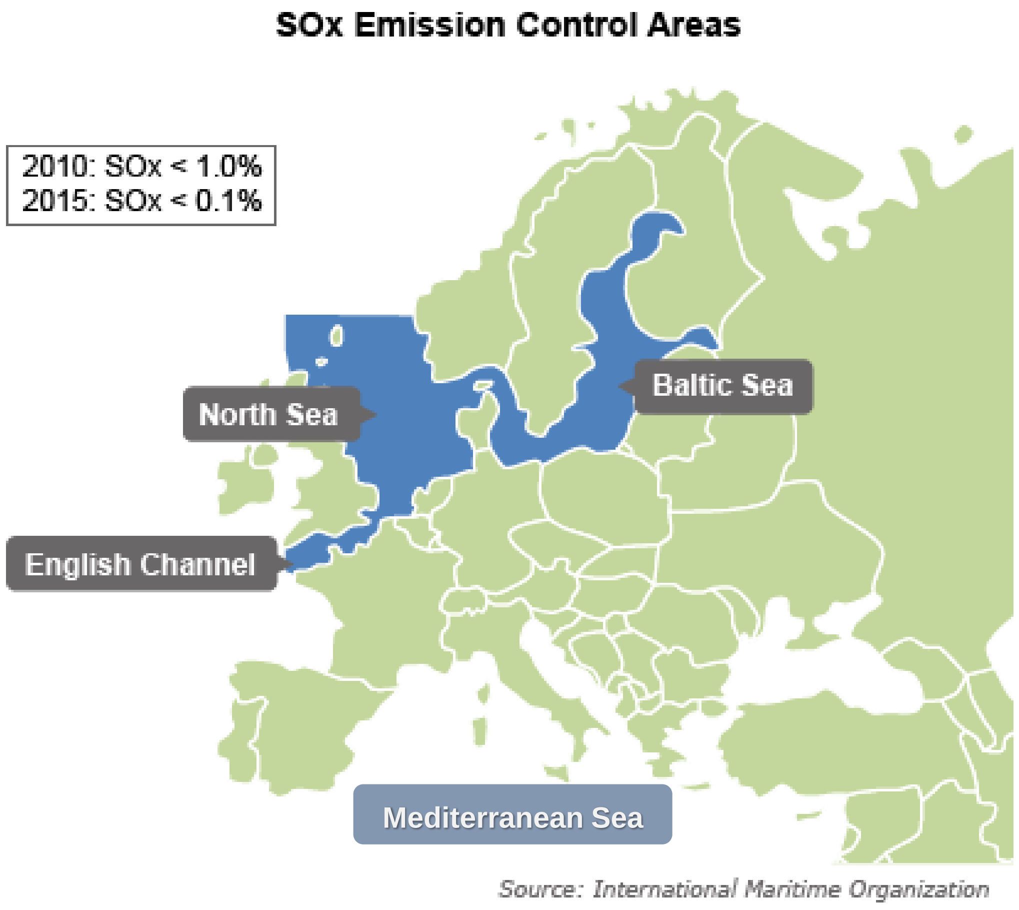


Source: Presentations from PMP group

VESSEL EMISSIONS

ECAs in EU waters

- Currently three regions:
  - Baltic Sea
  - North Sea
  - English Channel
- Limits
  - 0.1% max S since 1.1.2015
  - Baltic and North Seas NO_x Tier III ECAs from 1.1.2021 on
- Developments
  - On-going discussion for inclusion of the Mediterranean region as a SO_x - ECA



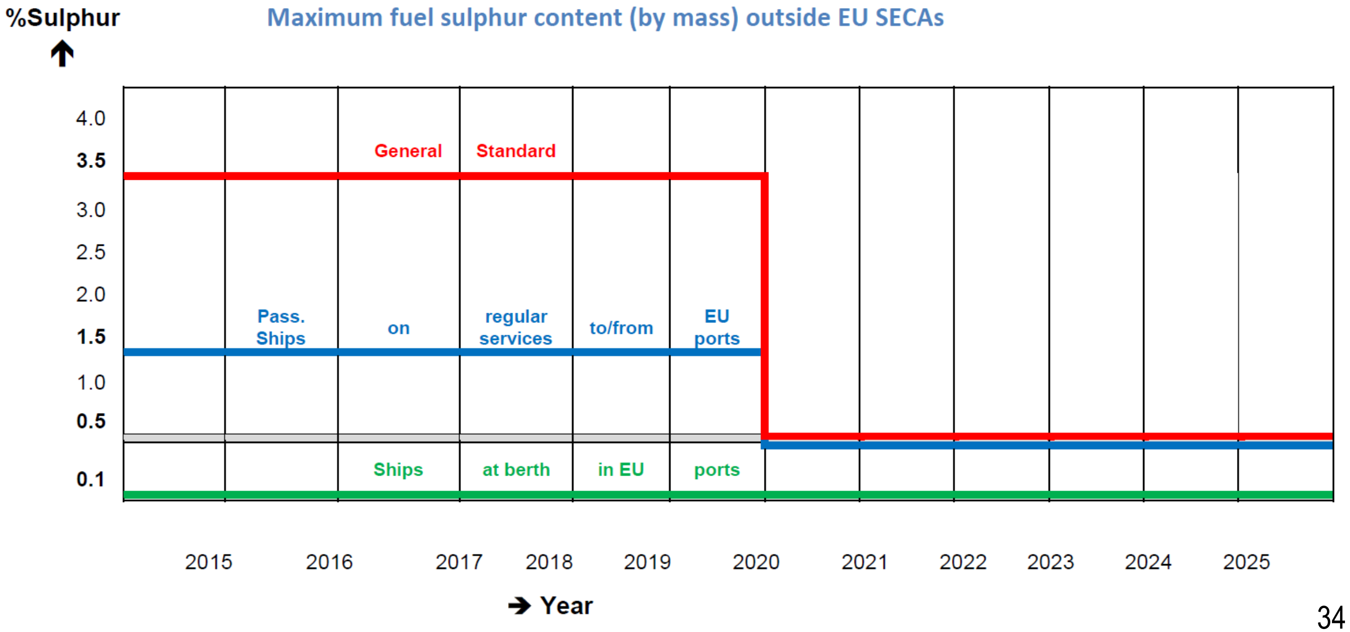
SO_x limits in EU

SO_x - ECA vs non ECA zones

Maximum fuel sulphur content (by mass - % m/m*) established by the Directive

	outside EU SECAs**	**inside** EU SECAs**	Exceptions
Ships at berth in EU ports (includes at anchor)	**0.10%** Not if timetable < 2 hrs or engines switch off and shore-side electricity		Ships using Approved Emission Abatement Methods****
Passenger ships on regular services to/from EU ports	Until 01-01-2020 1.5% From 01-01-2020 **0.50%**	From 01-01-2015 **0.10%**	
Other ships/cases	From 18-06-2014 **3.50%***** From 01-01-2020 **0.50%**		

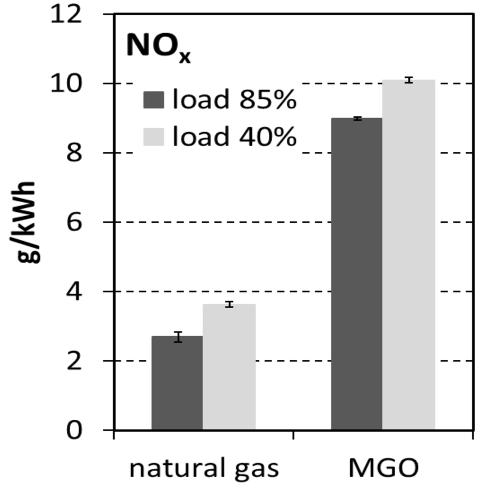
Permissible SO_x levels outside SO_x - ECA for different shipping activities

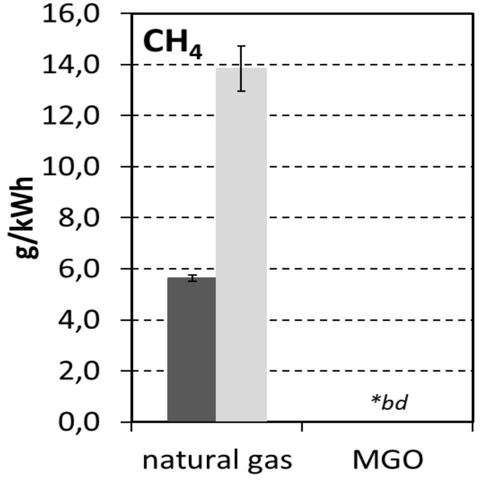


Source: Directive (EU) 2016/802: The sulphur directive

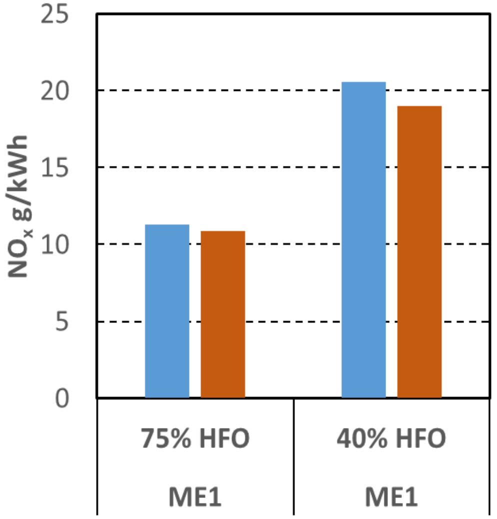
NOx emissions with different technologies

Tier II MSD

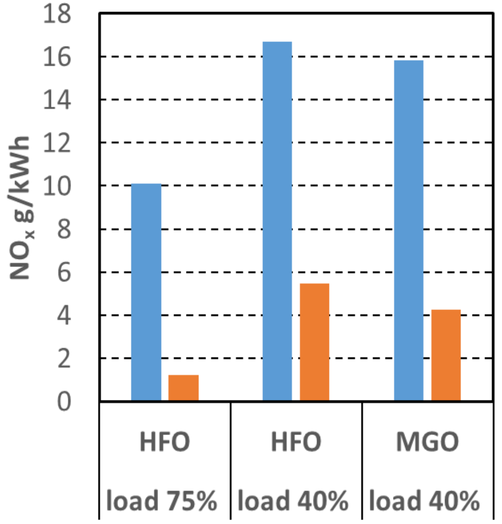




Tier II MSD + Scrubber



Tier II MSD + SCR = **Tier III**

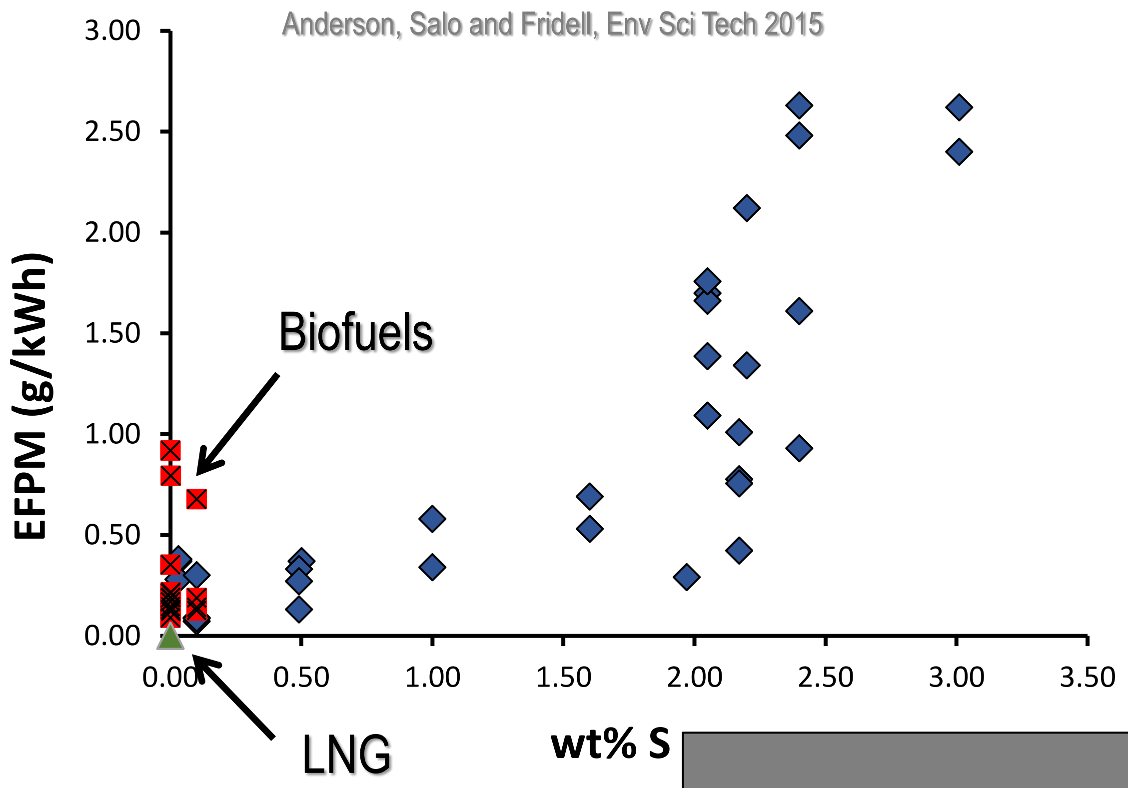


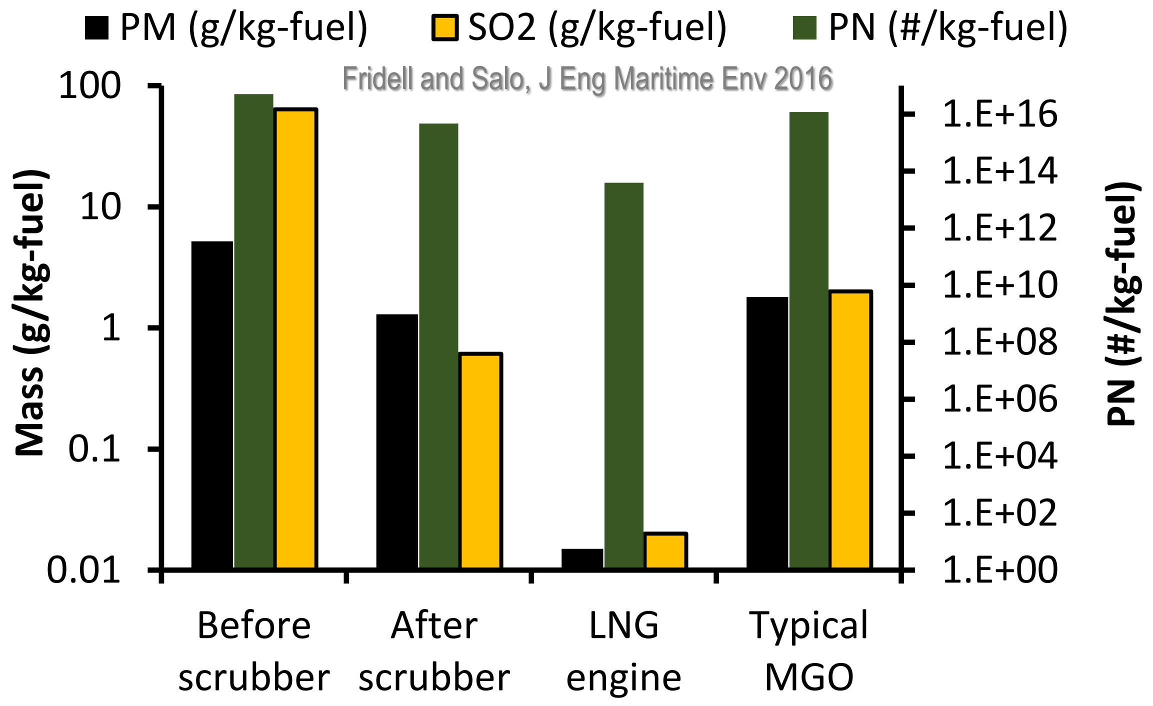
An order of magnitude comparison

Category	NOx (g/kg-fuel)
Diesel PC Euro $6_{d\text{-}temp}$	1.5
Diesel Truck Euro VI	0.5
MSD Tier II	60
MSD Tier III	6

Lehtoranta et al., CIMAC 2019

PM from ships as a function of fuel sulphur content



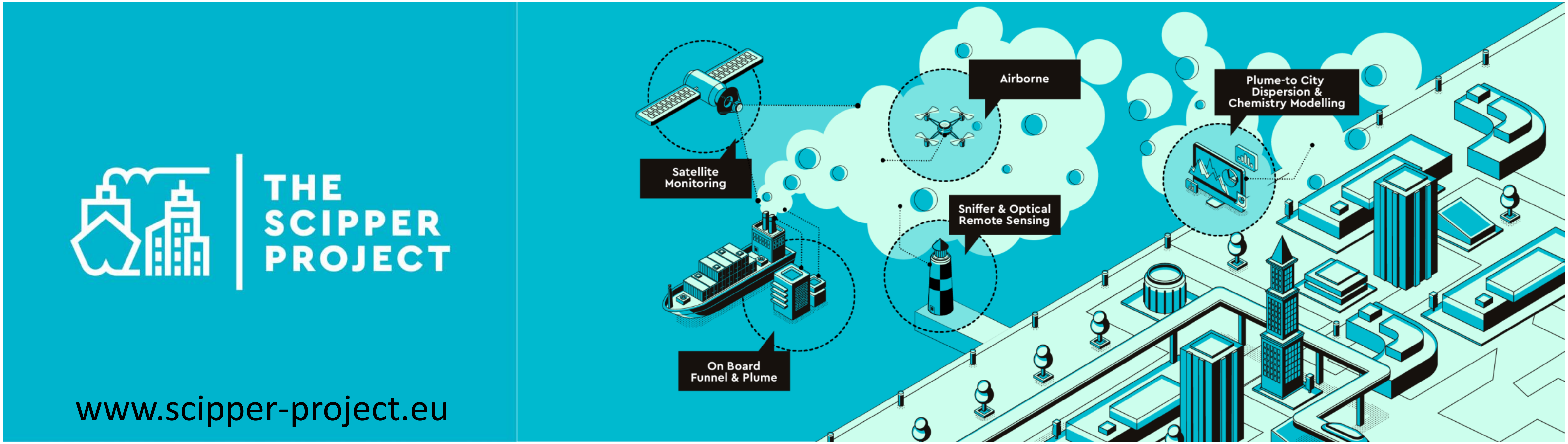


An order of magnitude comparison

Category	PM (mg/kg-fuel)
Diesel PC Euro $6_{d\text{-temp}}$	6
Diesel Truck Euro VI	5
MSD Tier II + MGO	1400
SSD Tier II + HFO	7400

Aakko-Saksa et al., TRA 2020

The SCIPPER Project



- Deployment of five measurement techniques for enforcing environmental regulations of shipping
- Testing of techniques in five real-world campaigns

CONCLUDING MESSAGES

Key messages

- **Air pollution and GHG**
  - Transport remains significant source for urban air pollution
  - Air quality expected to improve, provided standards deliver reductions on the road
  - Fuels significant to achieve sustainability also in terms of GHG
- **Vehicles**
  - Post Euro 6 likely to be massive and change of approach
  - Will include new pollutants, enhanced on-board monitoring and in-service conformity
  - Connecting the car with rest of the ecosystem is crucial to AP/GHG success
- **Vessels**
  - Environmental regulations become stringent
  - Fuel refinement and emission aftertreatment deemed to bring significant reductions
  - Real –world measurement-based enforcement is required

Thank you!

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