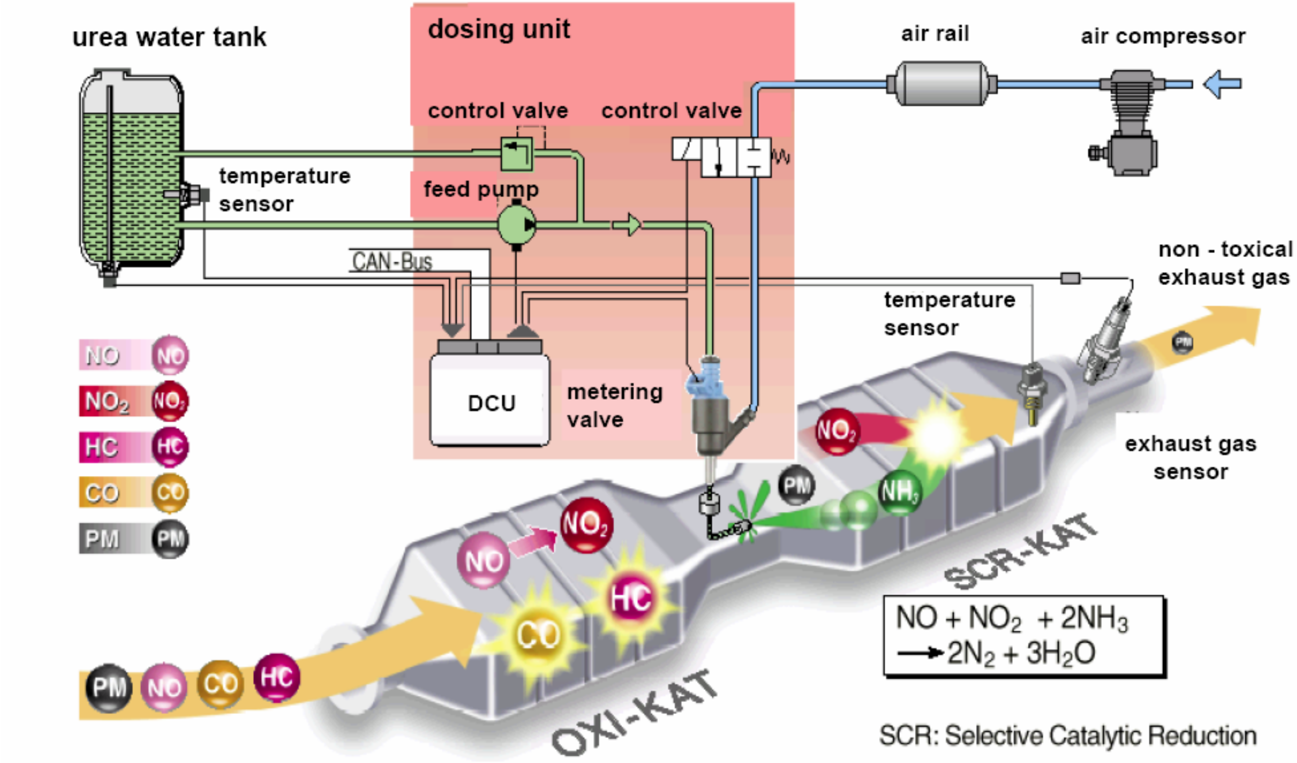
Chapter 6:
Pollution Control & Abatement



$$NO + NO_2 + 2NH_3 \longrightarrow 2N_2 + 3H_2O$$

SCR: Selective Catalytic Reduction

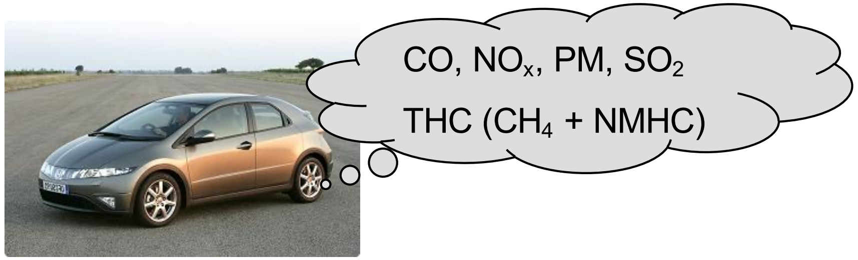
Learning objectives of Chapter 6

- ⇨ Know the characteristics of combustion gases for C.I. (Compressed Ignition) and S.I. (Spark Ignition) engines and the origins of pollutants
- ⇨ Recognize different “**upstream** methods” and the means of emissions reduction through the Electronic Control Unit (ECU)
- ⇨ Know the operating principles of after-treatment technology (“**downstream** methods”) like 3-way cat, SCR, DPF, NOx trap

Content

Pollutants

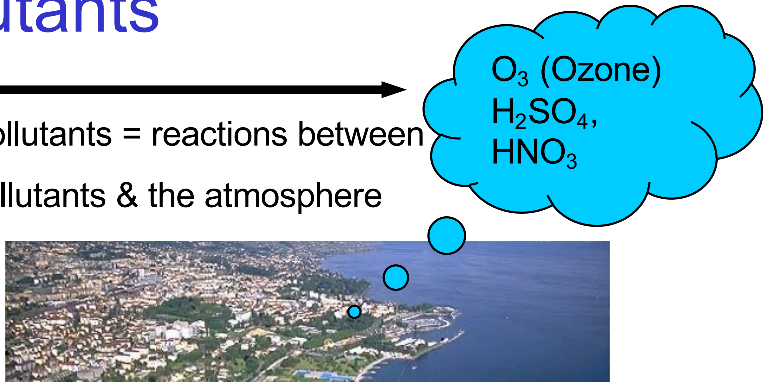
- Main primary and secondary pollutants



CO, NO_x, PM, SO_2

THC (CH_4 + NMHC)

Secondary pollutants = reactions between primary pollutants & the atmosphere



O_3 (Ozone)
H_2SO_4,
HNO_3

- Impacts :
  - CO : toxic (✝ in high concentrations)
  - HC : toxic (benzene and PAH are highly carcinogenic)
    Ozone precursors (O_3) : contribute to “smog” formation
  - CH_4 : fuel loss. $CH_4 = THC - NMHC$
  - NO : non-toxic but NO_2 precursor
  - NO_2 : Ozone precursor (O_3) : contributes to “smog” formation,
    toxic for pulmonary system
  - PM : toxic for humans (volatiles < 50 nm)

Pollutants (1)

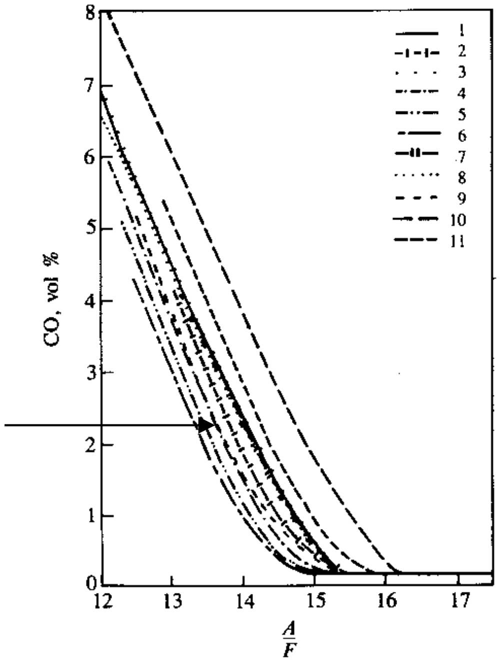
Pollutant formation during the combustion process

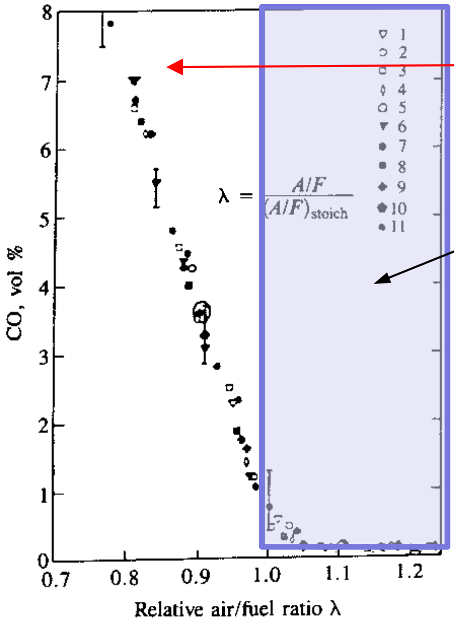
1) CO : formed by an **O_2 lack** ⇒ O_2 is necessary in order to burn all carbon fully to CO_2

Origin of formation :

1. **Combustion in rich (=fuel excess) burn mixture** ⇒ highly dependent on the λ ratio (A/F ratio)

different fuel mixtures





for λ<1, %CO is proportional to lack of air (λ)

Lean burn conditions

2. **For λ > 1, reactions of dissociation at high temperature**
   ⇒ oxidation reactions are frozen during the expansion stroke:

$$CO_2 \rightarrow CO + \frac{1}{2}O_2$$

$$CO + OH \cancel{\rightarrow} CO_2 + H$$

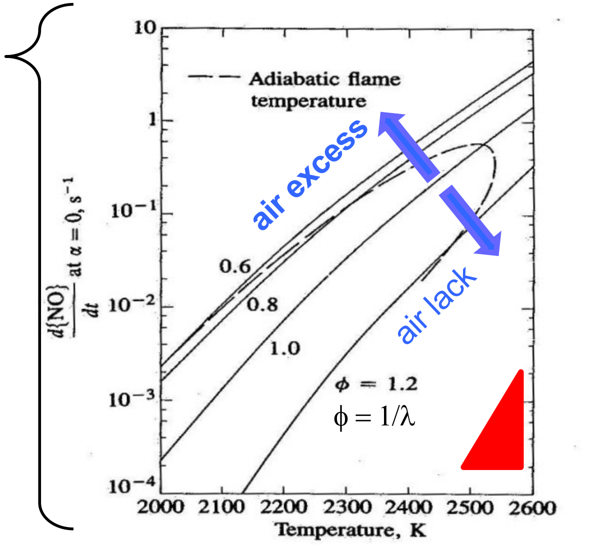
Pollutants (2)

- Pollutant formation <u>during</u> the combustion process

2) NO_x : NO_x are composed of NO (≈ 98% Otto, ≈ 70% Diesel) and NO_2

Formed in the burned gases zone at **high temperature** (> 2300K)

Ex : $$\frac{d[NO]}{dt}=\frac{6\cdot10^{16}}{T^{0.5}}\cdot\exp\left(\frac{-69090}{T}\right)\cdot[O_2]_e^{0.5}\cdot[N_2]_e$$



+100K=>NO*10 !

Origin of formation :

1.Formed by chemical reactions between N_2 (air) and O_2

NO = Zeldovich mechanism :

$$O+N_2\leftrightarrow NO+N \quad (1)$$
$$N+O_2\leftrightarrow NO+O \quad (2)$$
$$N+OH\leftrightarrow NO+H \quad (3)$$

NO_2 = NO oxidation reaction

⇒ **residence time*** at high temperature facilitates $[NO_x]$ concentration

2.These reactions are frozen with the cooling process of the combustion gases during the expansion stroke. (back-reduction of NO_x to N_2 is kinetically too slow)

⇒ $[NO]_{real}$ are higher than the theoretical values computed via chemical equilibrium

residence time longer with **diesel because of slower combustion process*

Pollutants (3)

- Pollutant formation <u>during</u> the combustion process

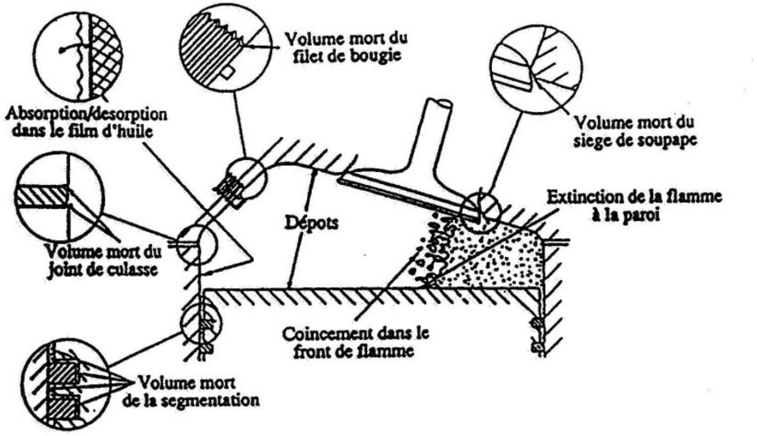
3) HC : formed mostly by an *incomplete* fuel combustion*

Origin of formation (for ***S.I.*** *engine) :*

1.Flame quenching / Trap zone within the combustion chamber :

Fuel/Air mixture penetrates into small clearance volumes (interstices) during compression stroke

Example: piston rings, spark-plug, head gasket
⇒ avoid the oxidation by flame propagation and
HC are released during expansion stroke



2.Fuel absorption/desorption phenomena in engine oil layer on cylinder walls
3.Incomplete combustion : flame propagation speed too slow or poor comb. quality
4.Combustion misfire (**cold start**) and rich burn mixture

**not the case for diesel since always air excess (λ>1.2)*

Pollutants (4)

- Pollutant formation <u>during</u> the combustion process

4) PM : PM (Particulate Matter) are composed of :

⇒ carbonaceous material (soot)

⇒ other components coming from fuel or adsorbed lubricant on PM (sulfates, metallic oxides, heavy organic compounds)

Resulting from a complex chemistry in a mixture locally <u>fuel-rich</u> and at <u>high temperature</u>

Origin of formation :

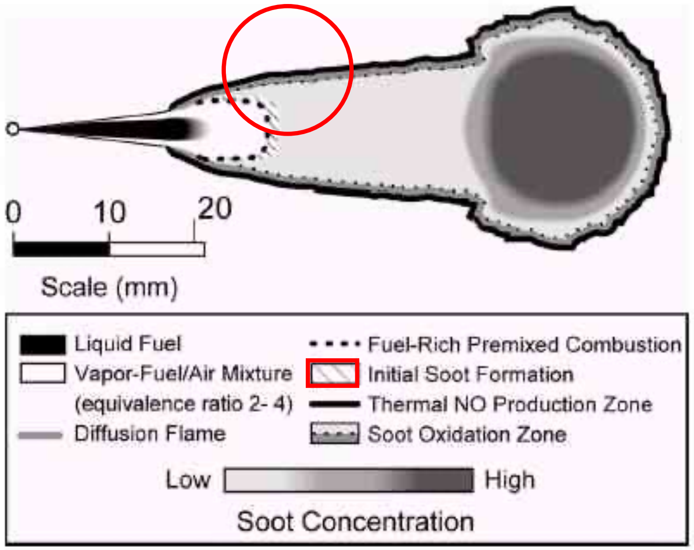
1.Process of PAH formation (Polycyclic Aromatic Hydrocarbons) :

After injection, the fuel temperature is elevated near the flame front and fuel molecules are oxidized and/or pyrolysed
This will form initial light products ($C_{2n}H_2$, PAH)
which will be the soot precursors in flames

⇒ depends on the mixture preparation:
$\nabla\lambda$, turbulence, fuel atomization

=> Fuel injection pressure is a means of action

Top view of a diesel fuel injector
(1 of the 6 or 8 jets)



Pollutants (4)

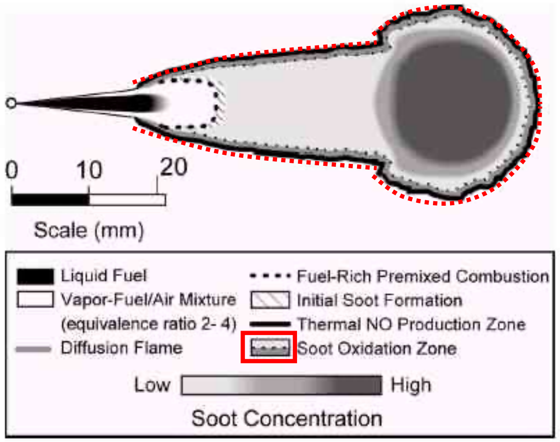
Pollutant formation <u>during</u> the combustion process

Origin of formation :

2. Soot particle growth

   Starting with two single types of molecules (precursors)

   Particles will grow by coagulation, aggregation and dehydrogenation (=> long C-chains)



3. Soot oxidation

   Soot is formed until the flame front extinction where they start to be oxidized with O_2 by air contact. Pressure, temperature, $[O_2]$ and residence time facilitate the **soot post-oxidation (=>post-injection)**

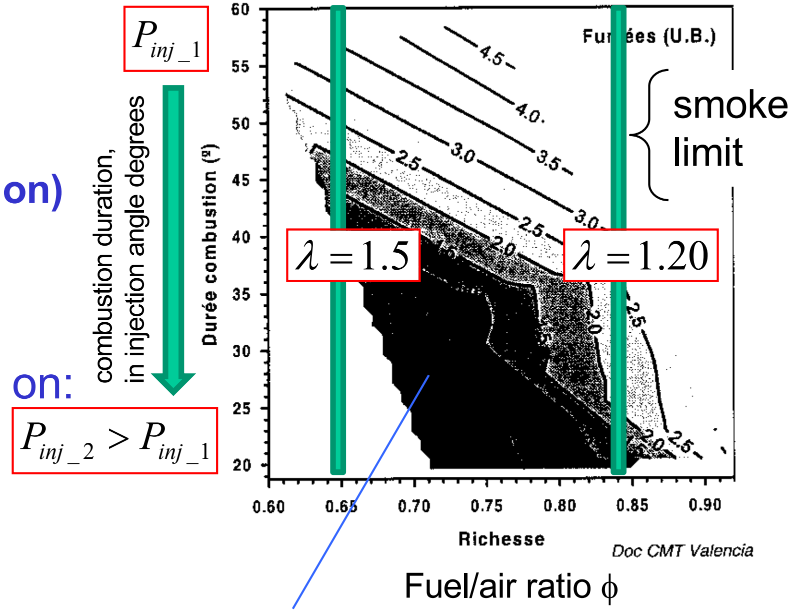
   [PM] ⬀ when P and T decrease too quickly before the end of the combustion, that depends on:

   ⇒ engine speed

   ⇒ delivery period / timing of the combustion

Soot is reduced the faster the combustion

=> act on fuel injection pressure



Doc CMT Valencia

smoke index >2.0 = soot
smoke index <2.0 = no soot

Pollutants (summary)

- Pollutant formation during the combustion process

  In summary, the formation of the 4 main pollutants depends on:

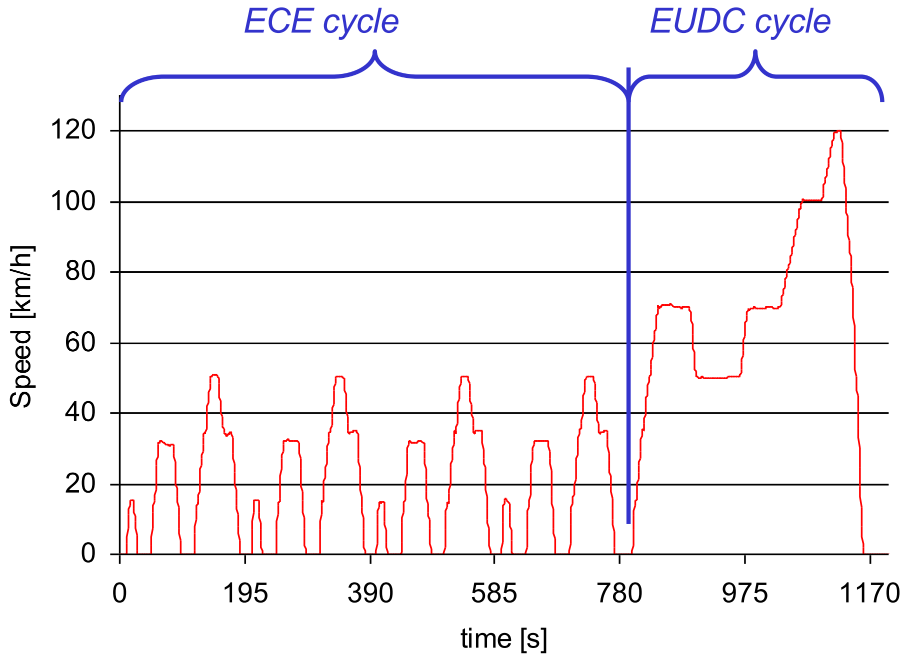
  - [CO] ⇒ A/F ratio (λ) S.I.
  - [NO_x] ⇒ [O_2] concentration (lean mixture), hence λ
    ⇒ T (K) of combustion process
    ⇒ residence time at high T C.I.
  - [HC] ⇒ geometry / design of the combustion chamber
    ⇒ combustion in rich mixture ($\lambda < 1$) S.I.
  - [PM] ⇒ local F/A ratio (fuel atomisation, turbulence)
    ⇒ combustion duration (residence time for post-oxidation) C.I.

Content

- Pollutants
- Emission standards
    - Passenger vehicles
    - Trucks and Off-Road vehicles
- Upstream pretreatment methods
    - Cylinder mixture dilution
    - Influence of ECU parameters
- Exhaust-gas after treatment systems
    - 3-way catalyst & λ regulation
    - Oxidation catalytic converter
    - NO_x treatment in lean-burn operation
    - Diesel Particulate Filter (DPF)

Emission standards

- Passenger vehicles
  - Pollutants are measured in [g/km] on a normalized cycle (>1990) including:



Urban driving cycle or **ECE 15**

⇒ 4 consecutive phases

(L ≈ 4 km, t = 780 s, v_{avg} = 18.7 km/h)

Extra-urban driving cycle or **EUDC**

(L ≈ 7 km, t = 400 s, v_{avg} = 62.6 km/h)

- Total of the mixed cycle : ECE + EUDC = **NEDC** *(or MVEG) >1990*

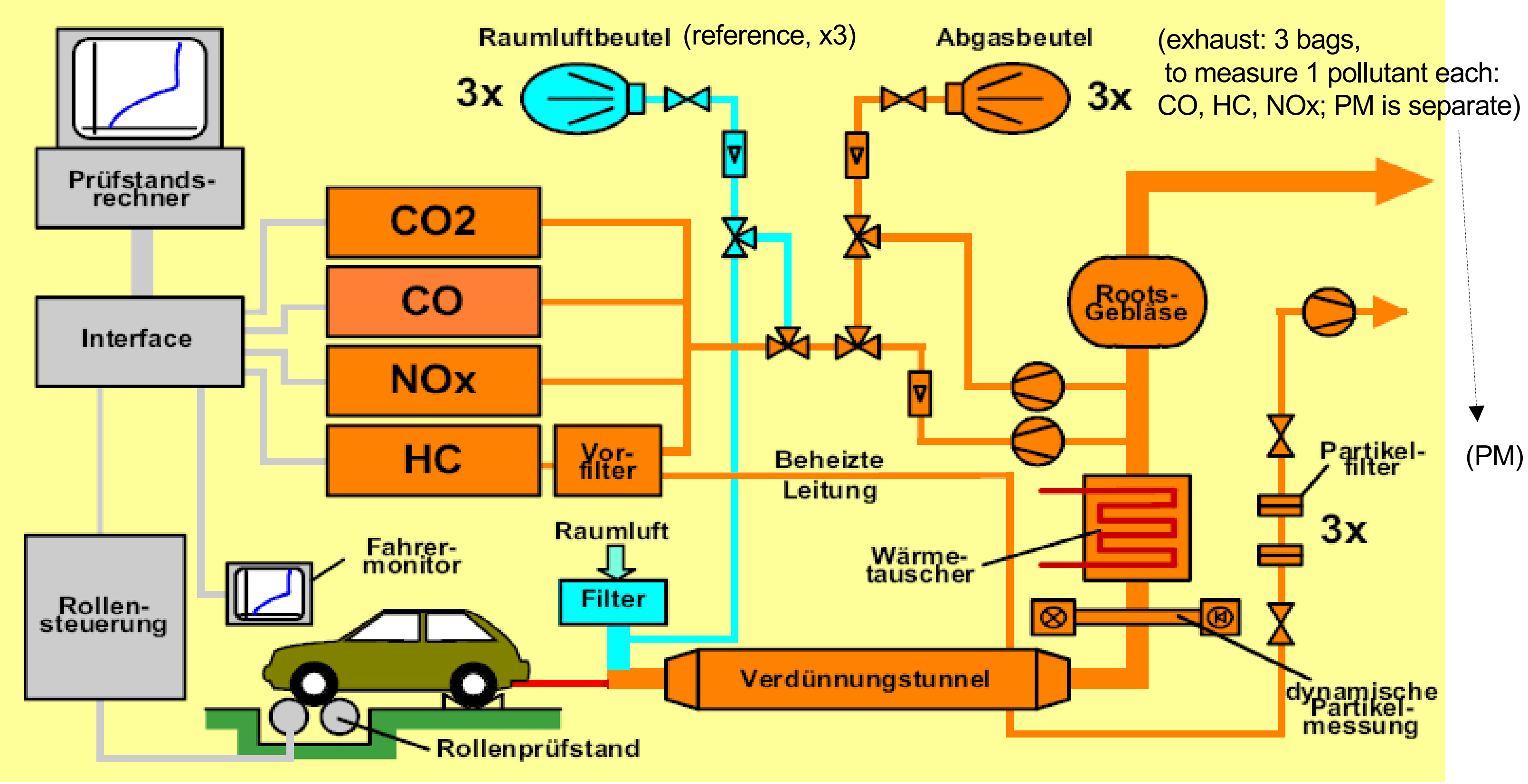
L = 11.0 km, t = 1180 s, v_{avg} = 32.5 km/h

➔ ***N**ew **E**uropean **D**riving **C**ycle*

➔ *(Motor Vehicles Emission Group)*

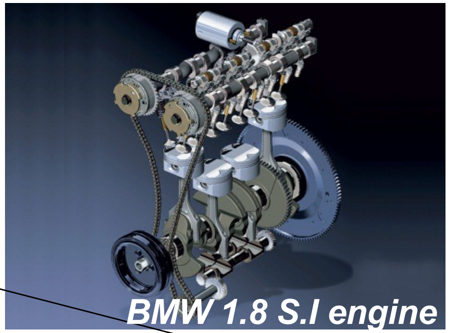
Emission standards

- Passenger vehicles
  - During the cycle, exhaust gases are stored into separated bags and analyzed at the end of the driving cycle (continuous measurements are also accomplished in real time for post-treatment and development)

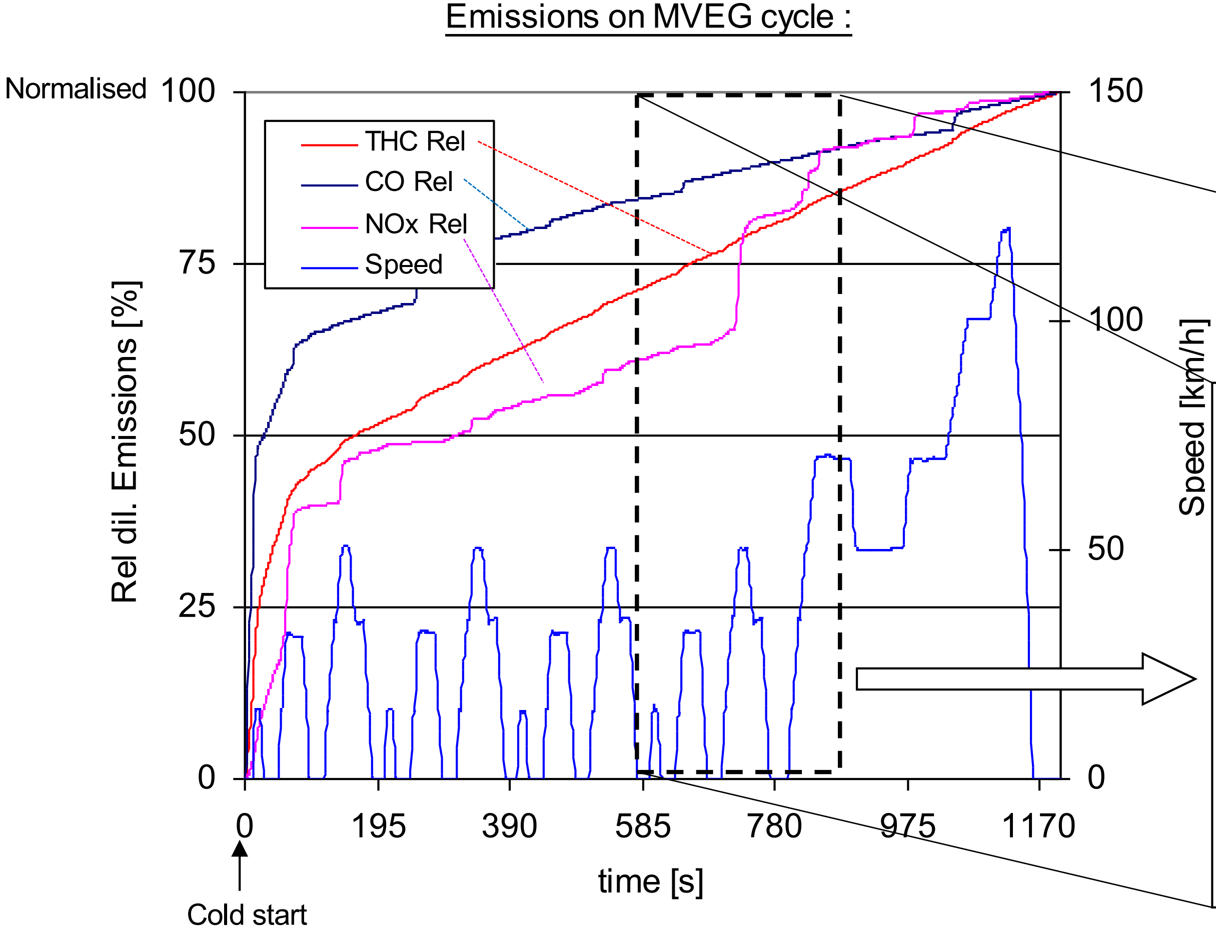


Emission standards

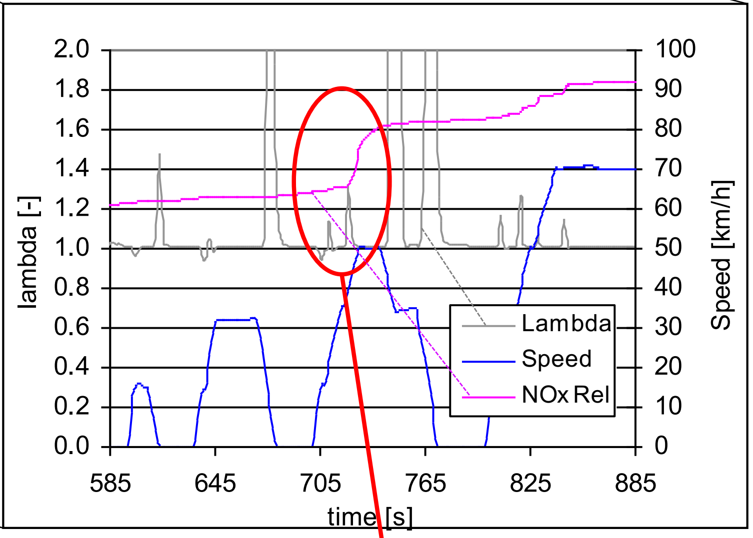
- Passenger vehicles
  - Analysis of the NEDC cycle : example on a BMW 318i Valvetronic



Emissions on MVEG cycle :



zoom



Lean-burn condition: NOx-spike

Emission standards

Passenger vehicles

- Maximal permissible values (for European Union) – in g/km :

Gasoline vehicle

g/km	year	CO	HC	NO_x	PM
Euro 1	1992	2.72	Tot : 0.97		-
Euro 2	1996	2.20	Tot : 0.50		-
Euro 3	2000	2.30	0.20	0.15	-
Euro 4	2005	1.00	0.10	0.08	-
Euro 5	2009	1.00	0.10	0.07	0.005
Euro 6	2014	1.00	0.10	0.07	0.0045

Diesel vehicle

g/km	year	CO	$HC+NO_x$	NO_x	PM
Euro 1	1992	2.75	1.36	-	0.19
Euro 2	1996	1.00	0.90	-	0.10
Euro 3	2000	0.64	0.56	0.50	0.05
Euro 4	2005	0.50	0.30	0.25	0.025
Euro 5	2009	0.50	0.23	0.18	0.005
Euro 6	2014	0.50	0.17	0.08	0.005

- 50 %

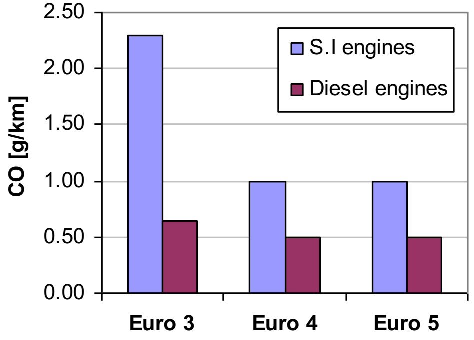
- 50 %

- 50 %

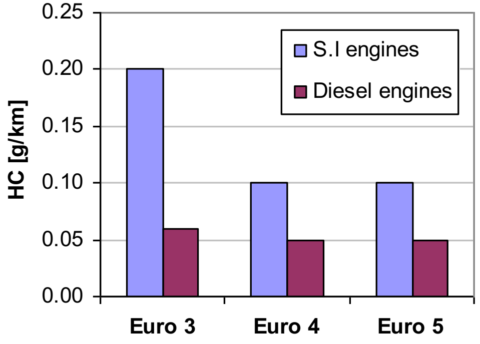
- 80 %

- 50 %
(NOx)

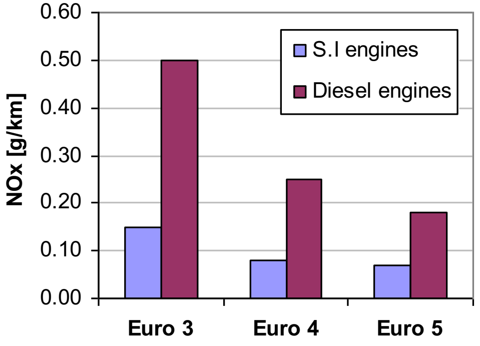
CO



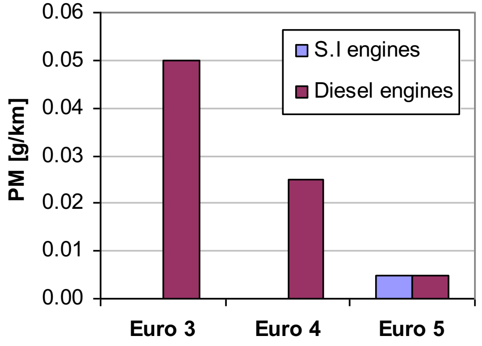
HC



NO_x



PM



Emission standards

- Passenger vehicles: now
  - In 2017, the NEDC cycle was replaced by the WLTP:

    ***W**orldwide harmonized **L**ight vehicles **T**est **P**rocedures*

⇒ *harmonized (Worldwide)*

⇒ *more dynamic*

⇒ *3 different vehicle class defined by power-weight ratio: kW / ton*

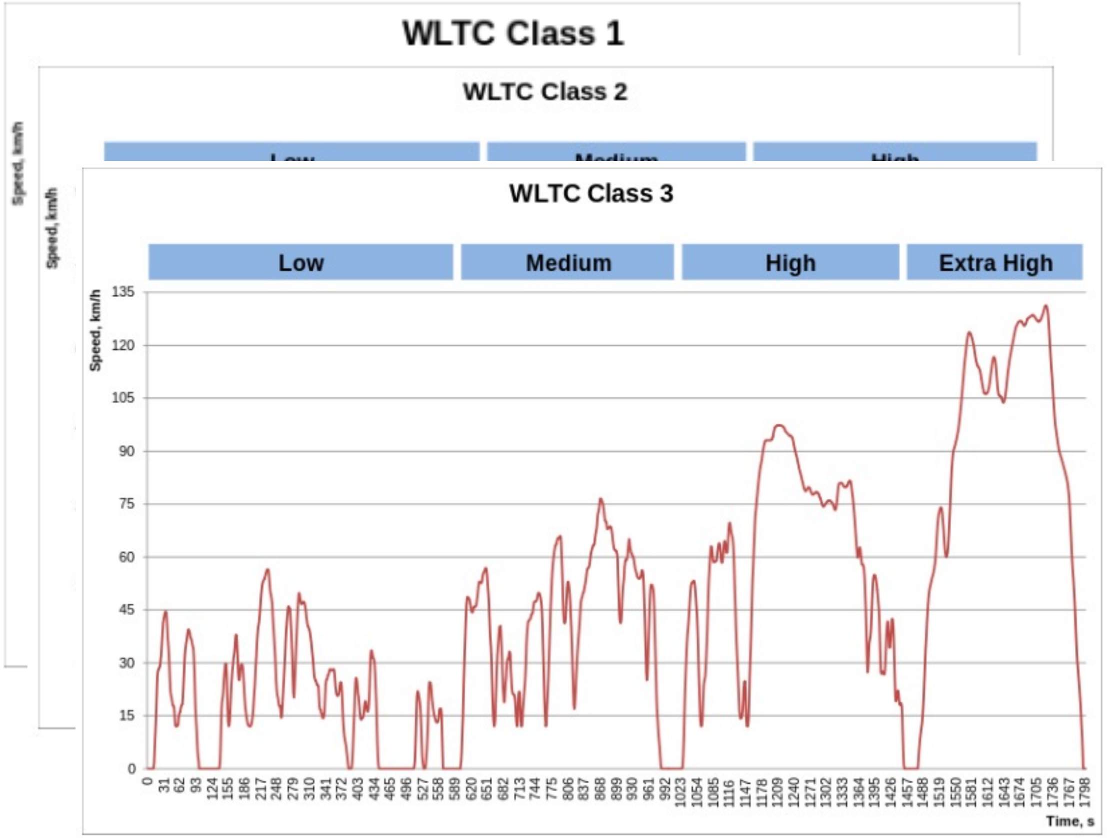
Class 1: PWr < 22

Class 2: 22 < PWr < 34

Class 3: PWr > 34

Actual cars in EU:

40 < PWr < 70 kW/tons



test to be repeated every 10’000 km

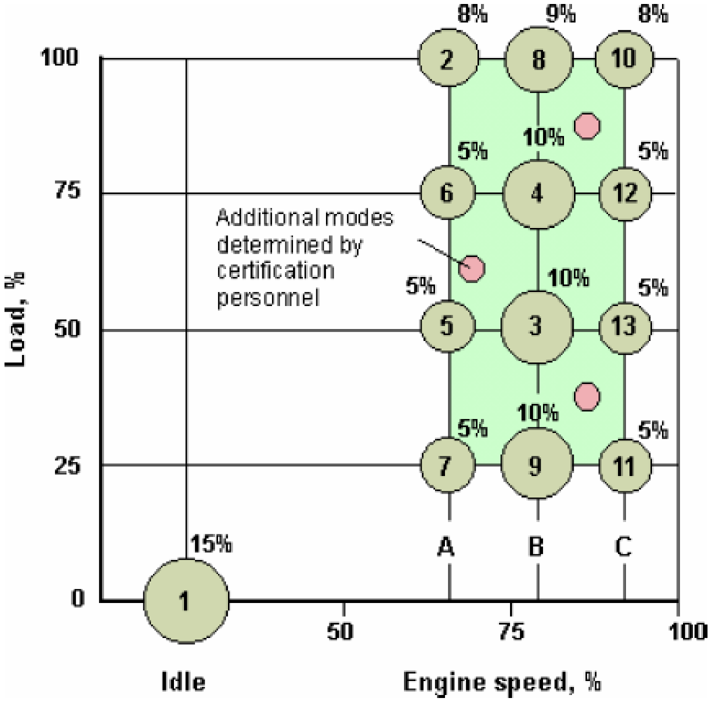
Emission standards

- Trucks

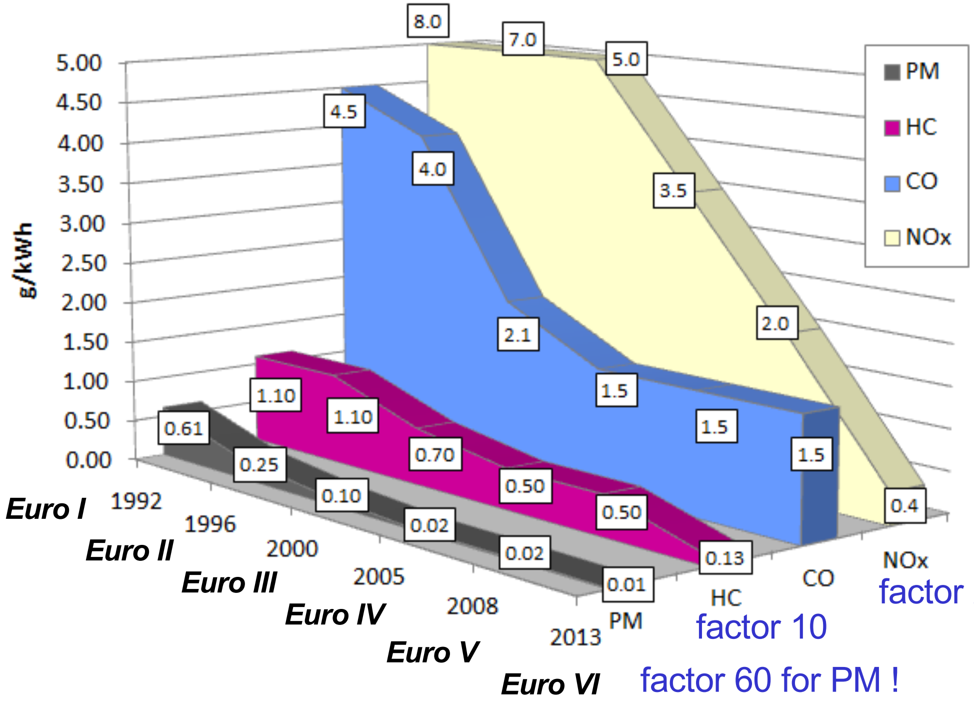
  ≠ g/km!

  - Pollutants are measured in [g/kWh] on a 13 modes cycle:

13 modes test cycle:



Standards evolution:



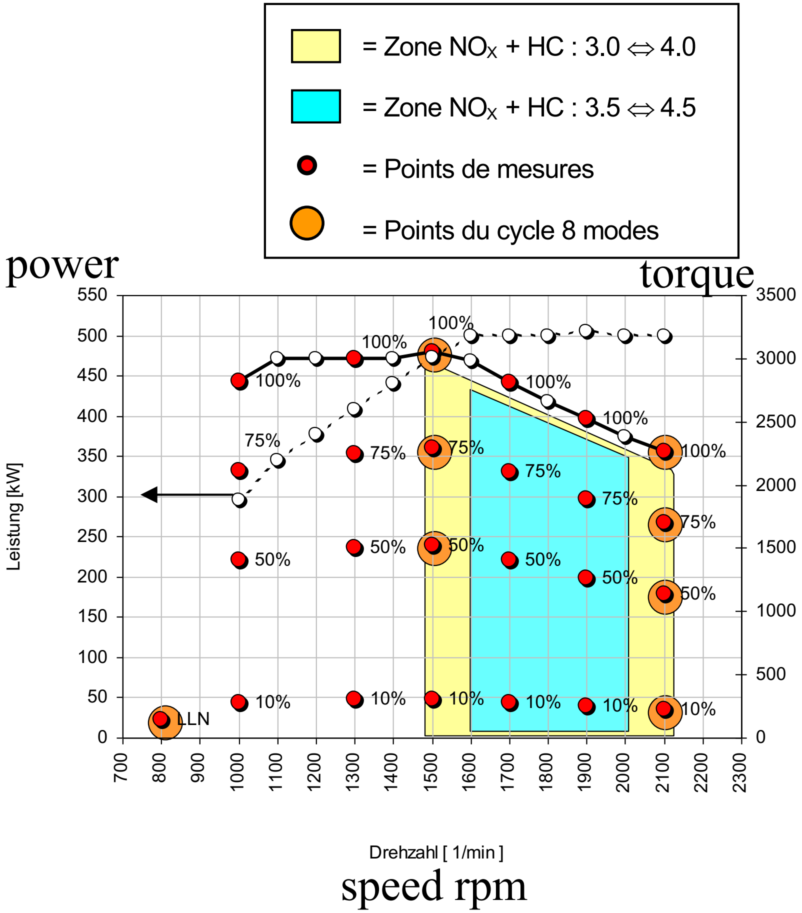
factor 20

factor 10

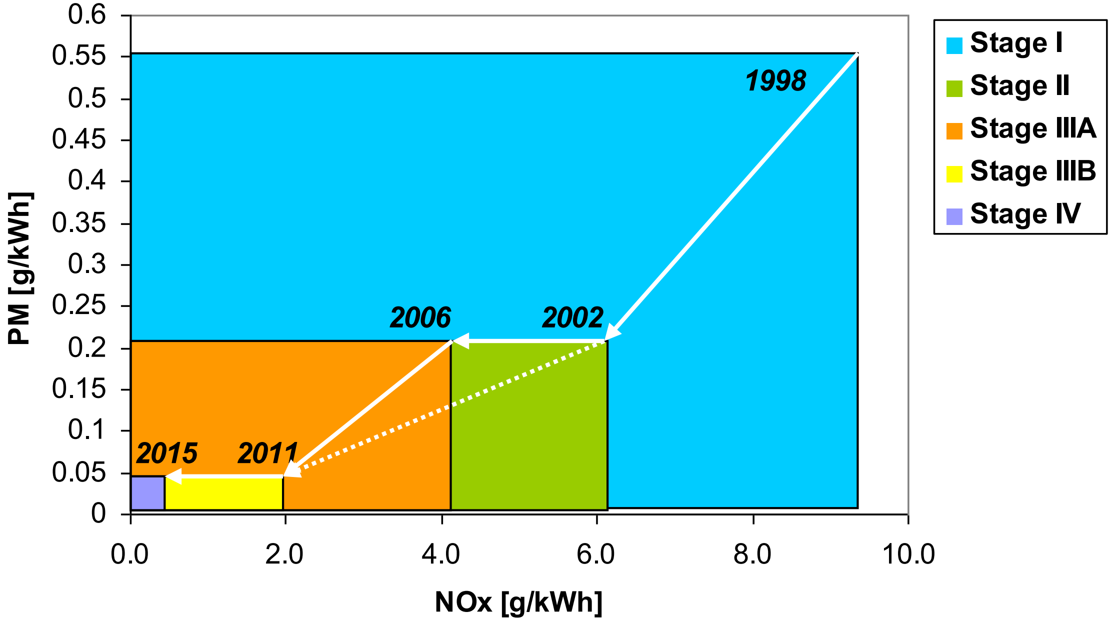
factor 60 for PM !

Emission standards

- Off-road vehicles (=> diesel => NOx, PM)
  - Pollutants are measured in [g/kWh] on a 8-modes cycle:



Standards evolution : Stage I to Stage IV



Emission standards

- Off-road vehicles
  - Comparison of Emission Standards: passenger car / off-road vehicles
    - Passenger vehicles (Diesel engine): **[g/km]**

Available from:	Name	Unit	CO	NO_x + HC	PM
> 2000	Euro 3	g/km	0.64	0.56	0.05
> 2005	Euro 4	g/km	0.50	0.30	0.025

Vehicle @ 120 km/h

⇒ *P_{mean} ≈* ***20 kW***

> 2000	Eq. EU3	g/kWh	3.84	3.36	0.30
> 2005	Eq. EU4	g/kWh	3.00	1.80	0.15

- Off-road vehicle (Diesel engine): **[g/kWh]**

> 2006	Stage 3A	g/kWh	3.5	4.0	0.20
> 2011	Stage 3B	g/kWh	3.5	2.0 + 0.19	0.025

⇒ with a delay of 5 years offset, emission levels are quite identical

⇒ from 2011, the standards on PM are all almost at the same level

Content of Chapter 6

- Pollutants
- Emission standards
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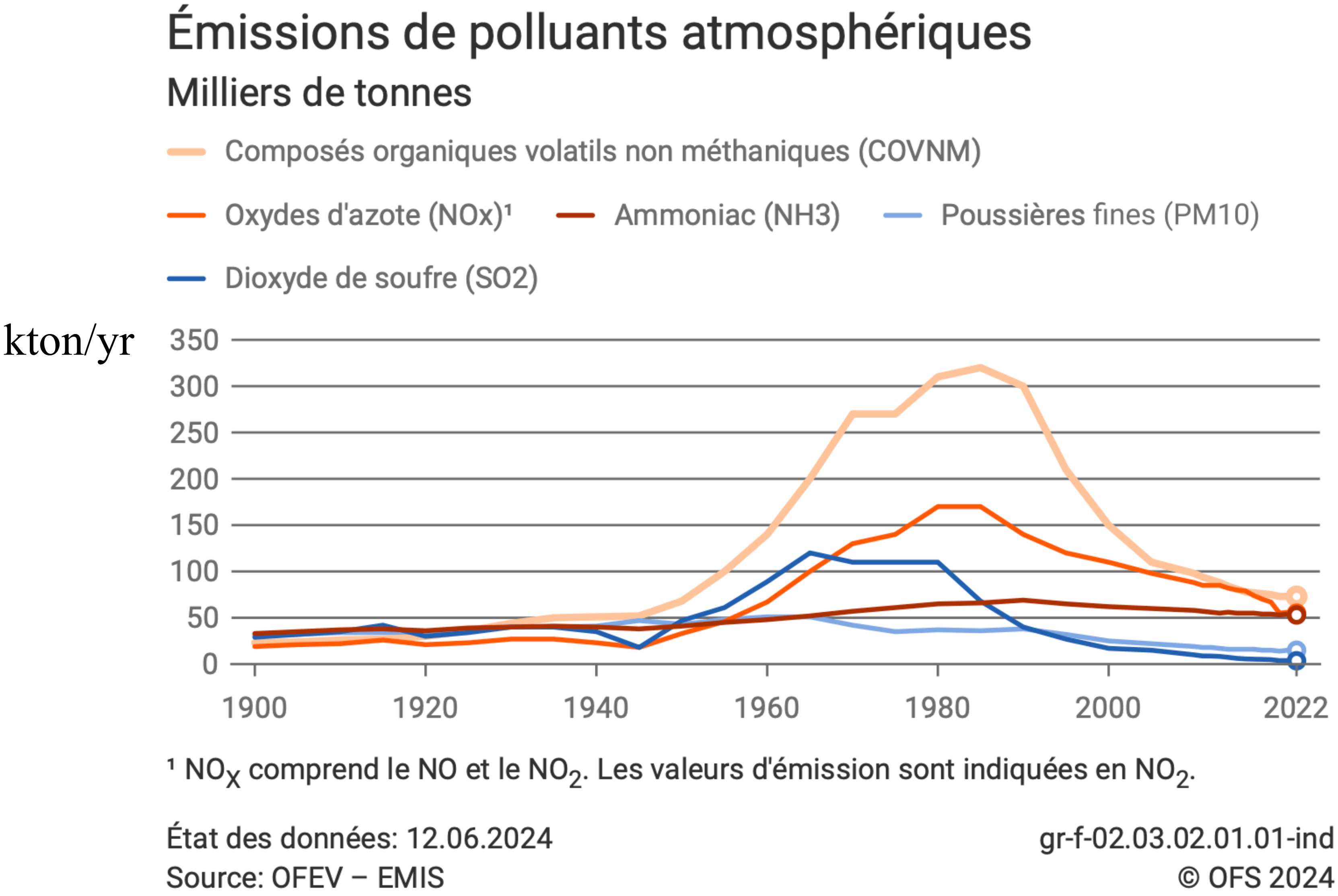
  - Trucks and Off-Road vehicles
- Upstream pre-treatment methods
  - Cylinder mixture dilution
  - Influence of ECU parameters
- Exhaust-gas after-treatment systems
  - 3-way catalyst & λ regulation
  - Oxidation catalytic converter
  - NO_x treatment in lean-burn operation
  - Diesel Particulate Filter (DPF)

Positive impact ✅ on air quality



Émissions de polluants atmosphériques

Milliers de tonnes

¹ NO_X comprend le NO et le NO_2. Les valeurs d'émission sont indiquées en NO_2.

État des données: 12.06.2024
Source: OFEV – EMIS

gr-f-02.03.02.01.01-ind
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Swiss Federal Office of Environment

Upstream pretreatment methods

- “Pretreatment” ⇒ 4 methods

Objective : reducing the emission values before the after-treatment itself, i.e. <u>inside</u> the combustion chamber

1. Cylinder mixture dilution by air (λ ↗)

⇒ increase the oxygen fraction inside the combustion chamber by increasing the λ ratio

Reminder :

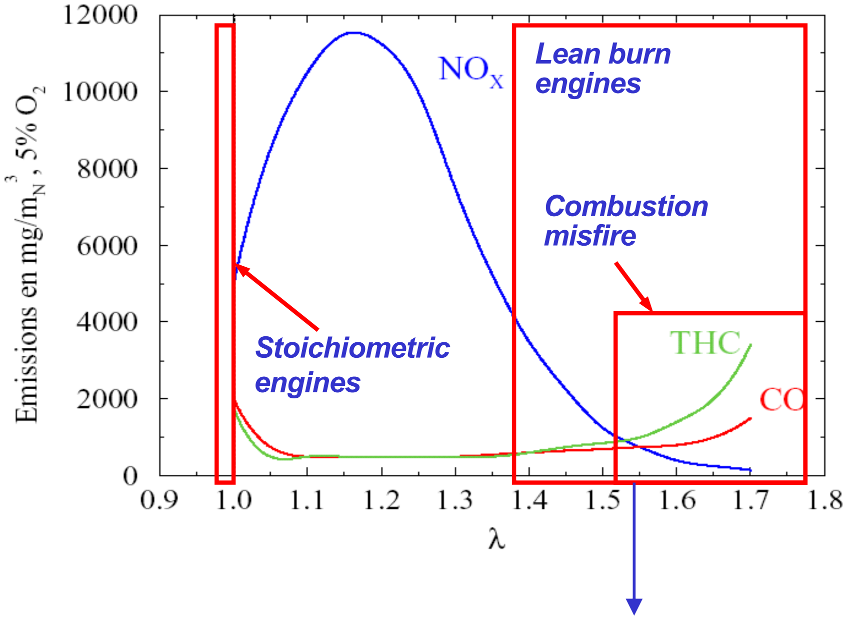
$$\lambda = \frac{R_{A/F}}{R_{A/F,sto}} = \frac{\left(\frac{M_A}{M_F}\right)}{\left(\frac{M_{A,sto}}{M_F}\right)} = \frac{M_A}{M_{A,sto}}$$

Consequence of a lean burn mixture:

$1 < \lambda < 1.5$: [NO_x] ↗ and [HC], [CO] ↘

$\lambda > 1.5$: [NO_x] ↘ and [HC], [CO] ↗

<u>Lean burn Operation</u> (homogeneous comb.)



local optimum of λ 1.55 (lean-burn engines without 3-way catalyst)

Upstream pretreatment methods

- Pretreatment methods by cylinder mixture dilution

1. Cylinder mixture dilution by air (continued)

   ***Diesel** engine:*

   Permanent operation in air excess (lean burn) to avoid the formation of black smoke ⇒ explains the higher [NO_x] concentration for C.I. engines

   ***Otto** engine (non-stoichiometric)*

   This type of operation is called **lean burn**, we find 2 types :

   A) **Homogeneous lean burn** engines

   ⇒ beware at the « lean flammability range », so $\lambda_{max} \approx 1.5\text{-}1.7$

   Example : gas engine with a prechamber

   B) **Stratified lean burn** engines

   Need the use of a direct injection system (for the mixture air/fuel stratification) and an after-treatment system for the [NO_x]

   => **NOx trap**

Upstream pretreatment methods

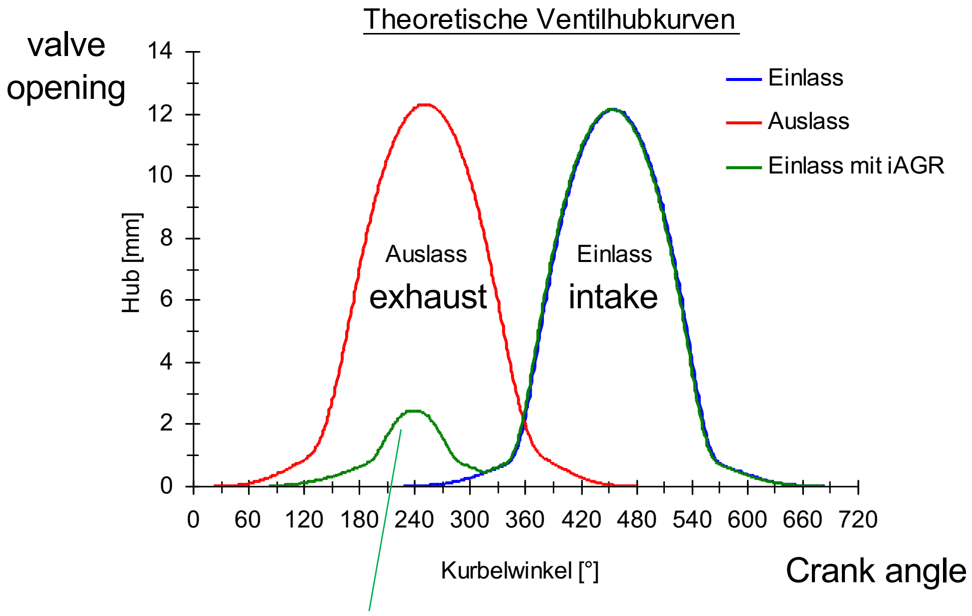
- Pretreatment methods by cylinder mixture dilution

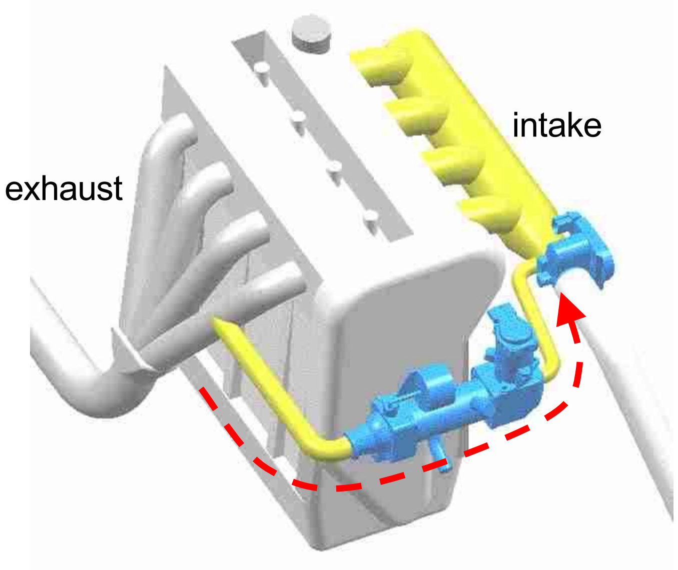
2. Cylinder mixture dilution by exhaust gas recirculation (**EGR**)

   - Objective: NO_x reduction
   - Type of technology for exhaust gas recirculation (~10-30%):

   A) *Internal* recirculation
   ⇒ with valve train system

   B) *External* recirculation (cooled)
   ⇒ reintroduced at the intake





Piston moves up for exhaust stroke but pushes some exhaust gases back to the inlet if the inlet valve is opened slightly

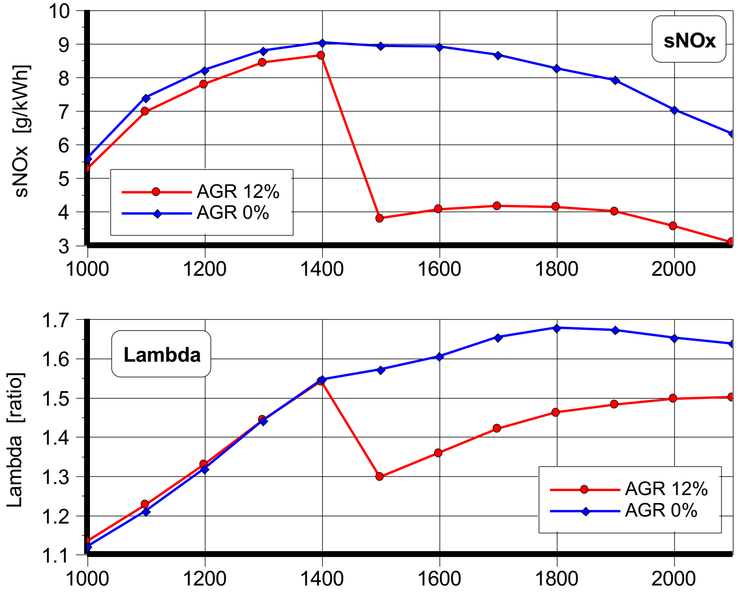
Upstream pretreatment methods

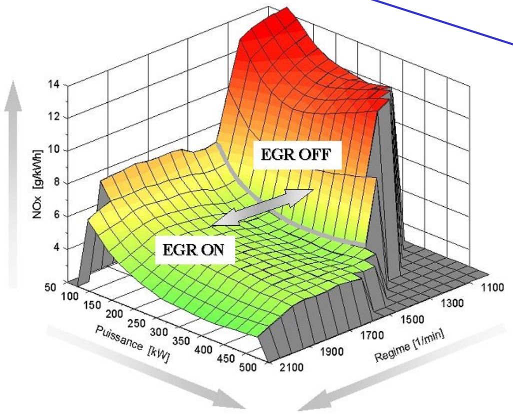
- Pretreatment methods by cylinder mixture dilution
  2. Cylinder mixture dilution by exhaust gas recirculation (**EGR**)

     The fresh gases dilution by the combustion gases has 2 consequences:

     - Reduction of $[O_2] \Rightarrow$ reduction of the λ ratio

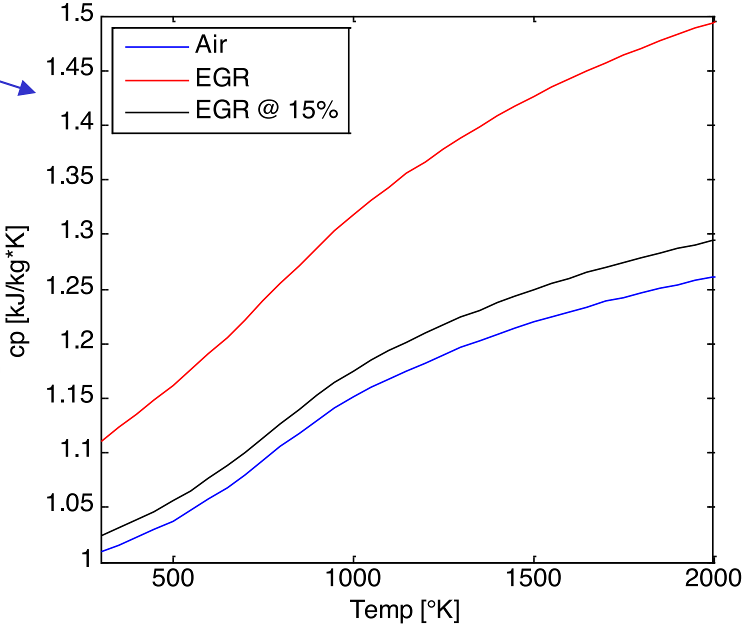
     - Increase of the c_p (of the introduced mixture) $\Rightarrow$ reduction of T_{max}





V8 500kW engine:

Full load and operating map



NOx divided by factor 2 (left), even downto factor 5 (map)

EGR is now standard on all diesel cars

Upstream pretreatment methods

- Pretreatment methods by engine parameters (ECU)

3. Combustion timing (=most important means of action)
   - The timing of the combustion process in the engine cycle directly influences the cylinder temperature and pressure ⇒ influence on **[NO$_x$]**
   - The increase of exhaust gases **T°** improves the post-oxidation ⇒ influence on **[CO] and [PM]**

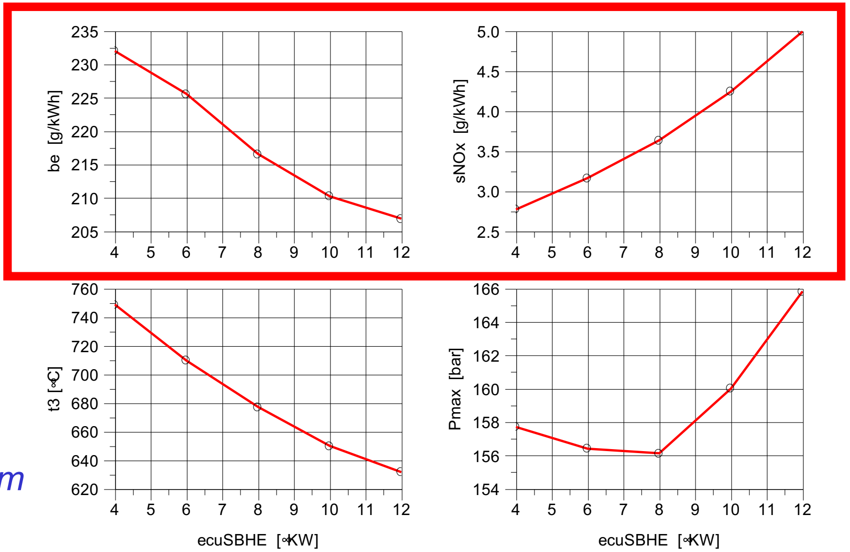
***Diesel** :* $\alpha_{\textbf{injection}}$ (before TDC)

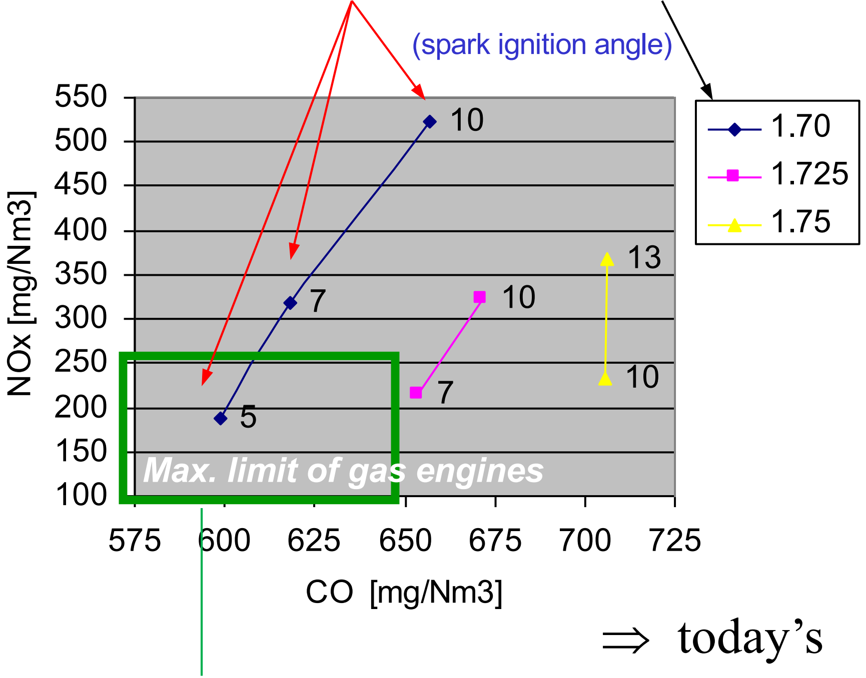
Otto : $\alpha_{\textbf{ignition}}$ λ

by 8° fuel injection angle change before TDC (1 mm piston displacement), fuel consumption is reduced by 10%, but NOx is increased by factor 2

4 L Diesel engine

1800 1/min, 960 Nm





⇒ Compromise between BSFC ⇔ NO$_x$

Standard limits

⇒ today's exercise

Upstream pretreatment methods

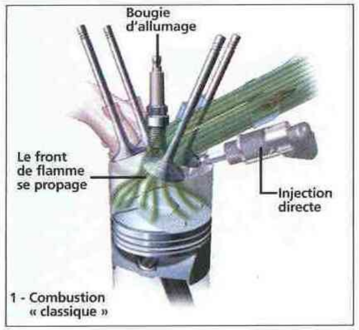
- Pretreatment methods by engine parameters (ECU)

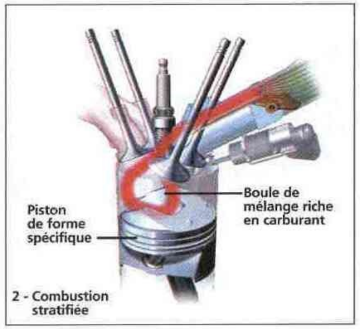
  4. Combustion <u>speed</u>

     Reminder: an increase of the turbulence intensity involves an increase of the flame propagation speed (therefore the combustion speed)

(*Otto :*) Influence on [CO] and [HC]

with lean burn engines
(combustion becomes more stable)





⇒ Turbulence generator enable / disable (swirl or tumble)

Diesel : Influence on [PM]

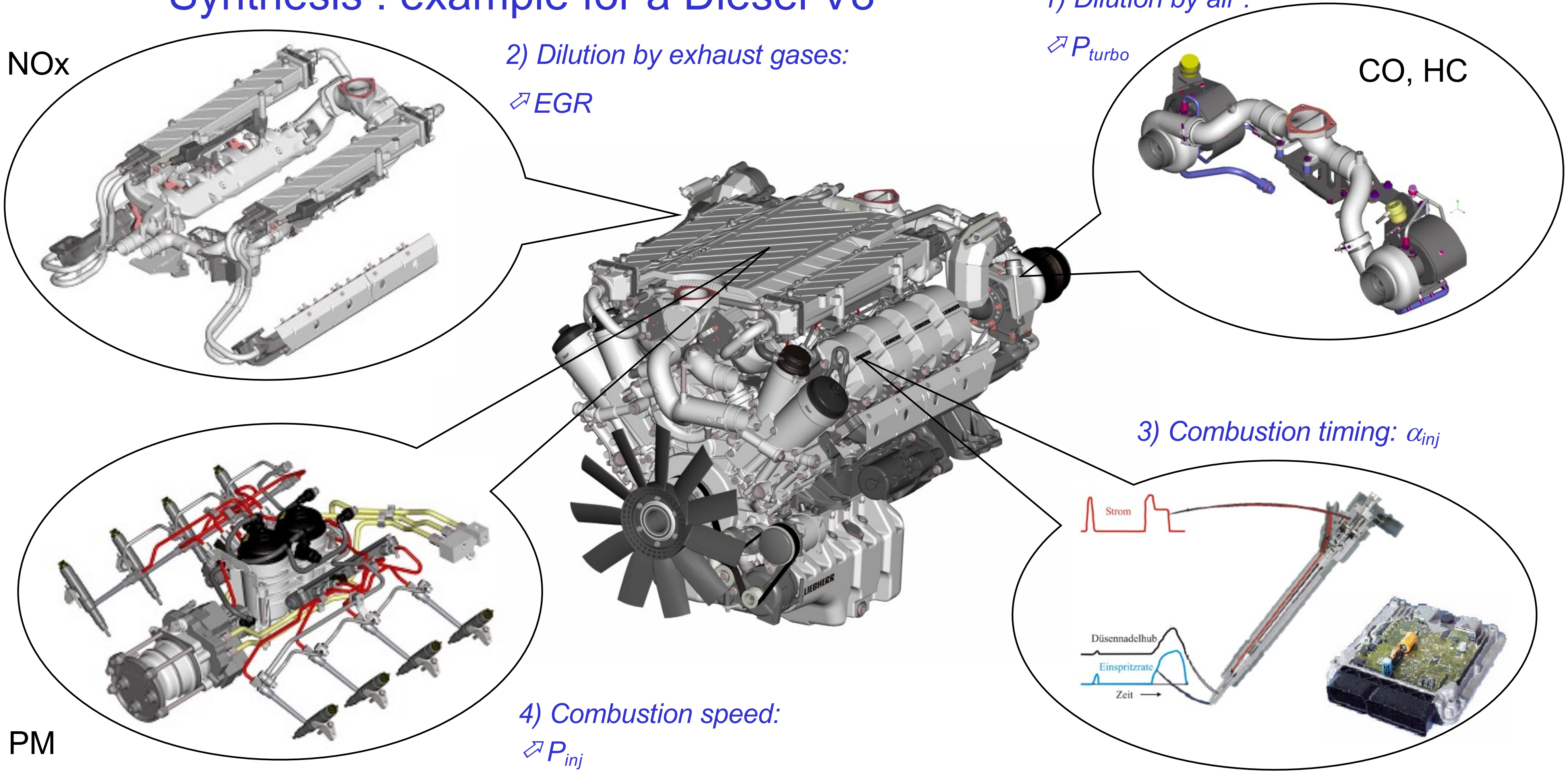
On Diesel engines, the combustion **duration is reduced** if the injection duration of the fuel is reduced by an **increase of the injection pressure** (⇒ better atomisation)

⇒ increase of P_{inj} in order to reduce the PM emissions

Upstream pretreatment methods: summary

- Pretreatment methods by engine parameters (ECU)

  Synthesis : example for a Diesel V8



NOx

2) Dilution by exhaust gases:

$\nearrow$ *EGR*

1) Dilution by air :

$\nearrow P_{turbo}$

CO, HC

3) Combustion timing: α_{inj}

PM

4) Combustion speed:

$\nearrow P_{inj}$

CO, HC, NOx, PM

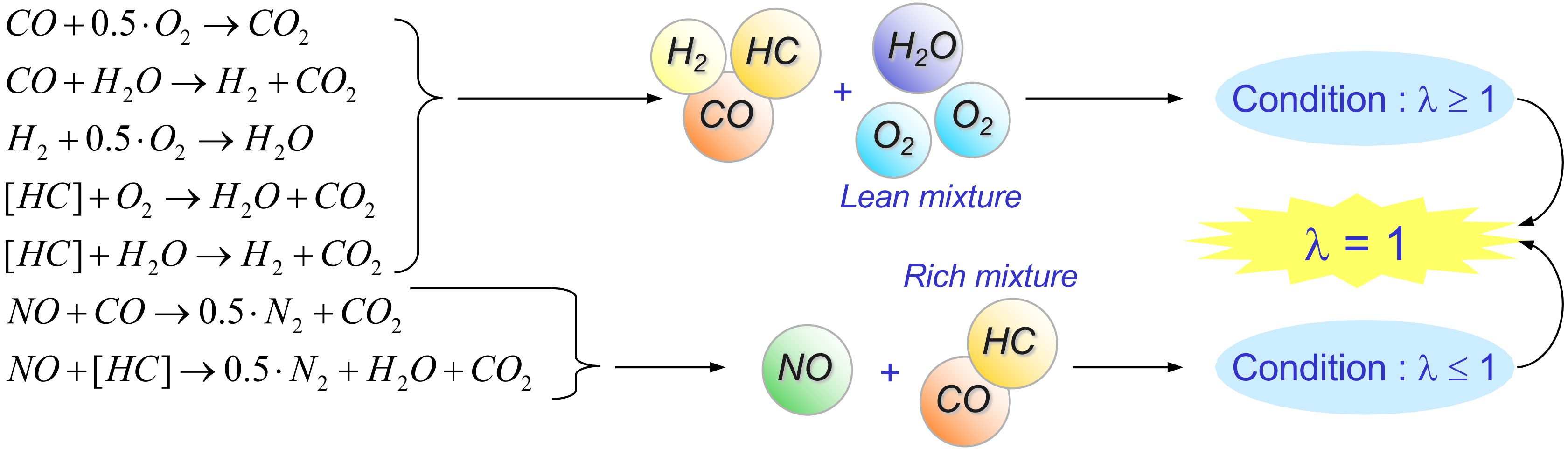
(injection during expansion stroke to burn off PM)

Content

- Pollutants
- Emission standards
  - Passenger Vehicles
  - Trucks and Off-Road vehicles
- “Upstream” pre-treatment methods
  - Cylinder mixture dilution
  - Influence of ECU parameters
- Exhaust gas ***after***-treatment systems
  - 3-way catalyst & λ regulation
  - Oxidation catalytic converter
  - NO_x treatment in lean-burn operation
  - Diesel Particulate Filter (DPF)

Exhaust gas after-treatment systems

- After-treatment systems: (1) 3-way catalyst (late 1980'ies)
  - Simultaneous action on: CO, HC and NO_x ⇒ 3 pollutants
  - Reactions to consider:



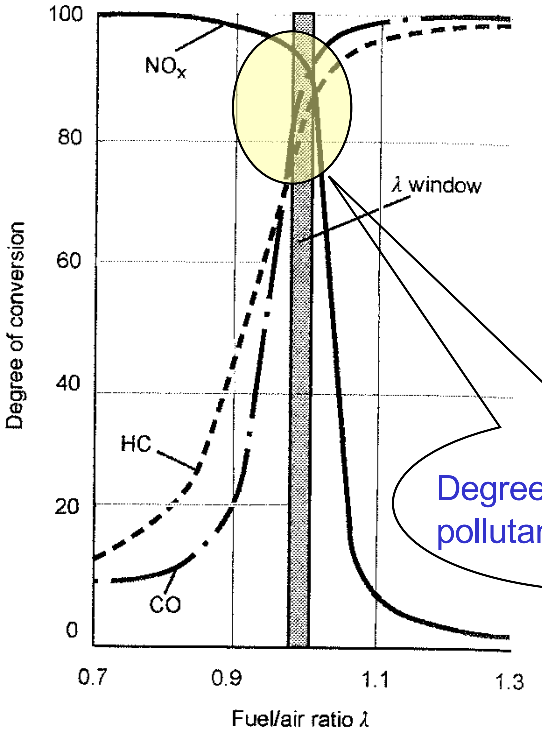
$$CO + 0.5 \cdot O_2 \rightarrow CO_2$$
$$CO + H_2O \rightarrow H_2 + CO_2$$
$$H_2 + 0.5 \cdot O_2 \rightarrow H_2O$$
$$[HC] + O_2 \rightarrow H_2O + CO_2$$
$$[HC] + H_2O \rightarrow H_2 + CO_2$$
$$NO + CO \rightarrow 0.5 \cdot N_2 + CO_2$$
$$NO + [HC] \rightarrow 0.5 \cdot N_2 + H_2O + CO_2$$

  - Problem:
    - Kinetic constraints: the required time for (homogeneous) reactions is longer than the residence time of the gases in the exhaust line (< 1s)
      ⇒ acceleration of the reactions thanks to a catalyst
    - Needs an operation in both lean burn AND rich burn conditions
      ⇒ regulation by an O_2 sensor (lambda sensor) close to the stoichiometric conditions

Exhaust gas after-treatment systems

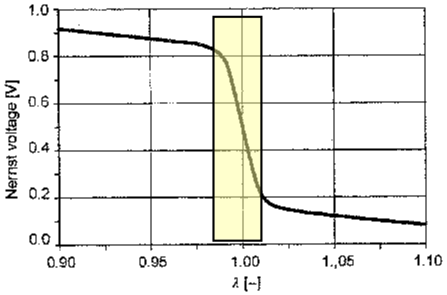
- After-treatment systems: 3-way catalyst & λ regulation
  - Regulation at λ = 1 possible only on S.I. stoichiometric engines
  - The F/A ratio regulation is controlled by a *lambda sensor* :

Window of the λ regulation:



Degree of conversion of pollutants ≈ 80-90%

λ sensor



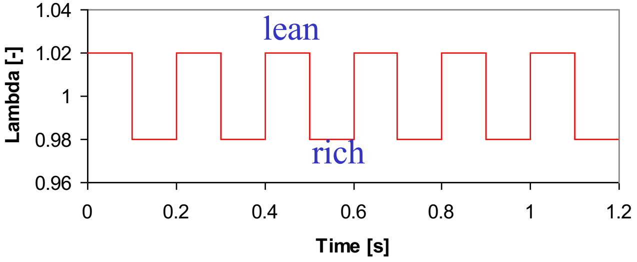
Signal specifications of a λ sensor

ECU

Correction on t_{inj}

(more, or less, fuel)

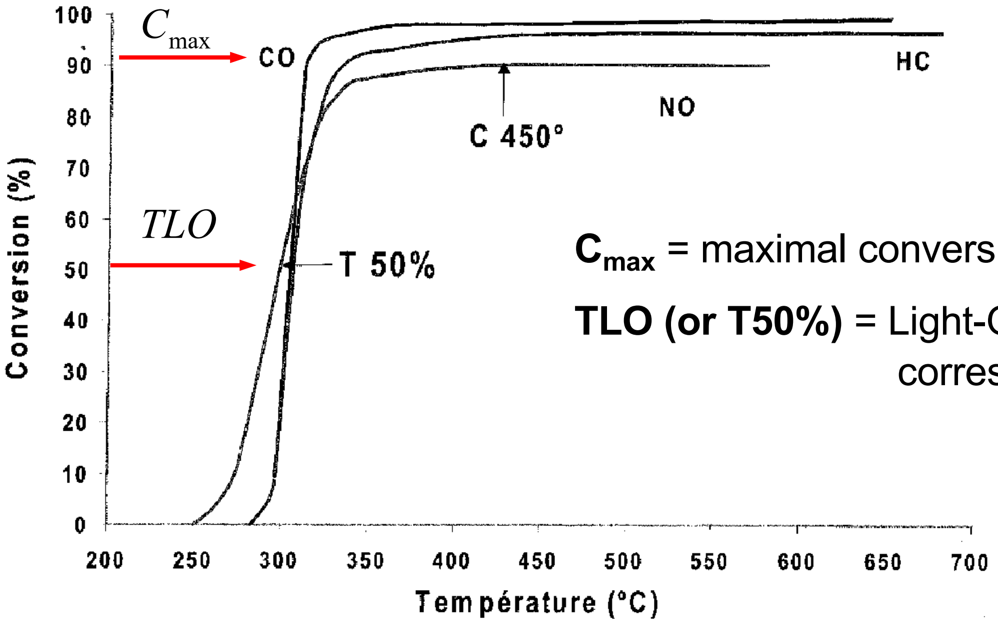
Signal oscillation at ± 2%, *f* ≈ 10 Hz :



Exhaust gas after-treatment systems

After-treatment systems: 3-way catalyst

- Influence of the main parameters:
  - Temperature of combustion gases at the catalyst inlet



C_{max} = maximal conversion temperature (degree of c. > 90%)

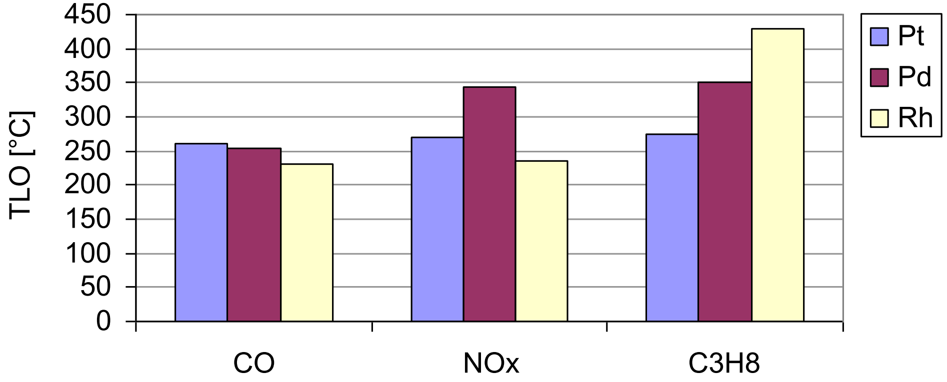
TLO (or T50%) = Light-Off Temperature ≈ 300°
corresponds to 50% of conversion

⇒ 90% of the measured emissions on the normalized cycle are generated during the 200 first seconds before catalyst Light-Off (when $T_{exhaust}$ < TLO) (= cold start)

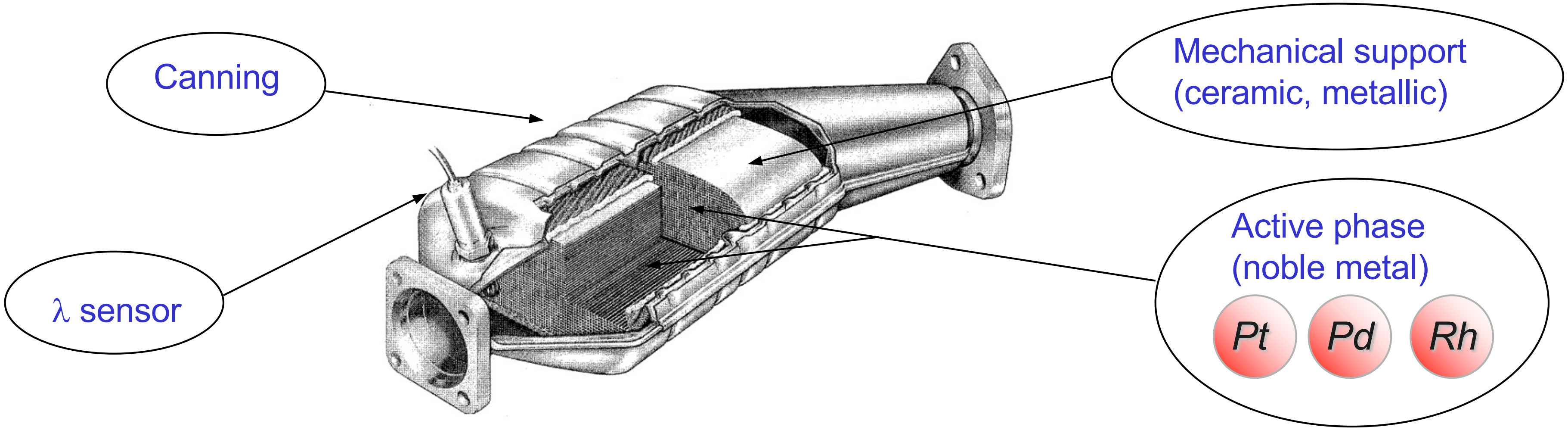
Exhaust gas after-treatment systems

After-treatment systems: 3-way catalyst

- Influence of the main parameters:
  - type of noble metal used on catalytic support ⇒



- Converter components :



Canning

λ sensor

Mechanical support (ceramic, metallic)

Active phase (noble metal)

Pt Pd Rh

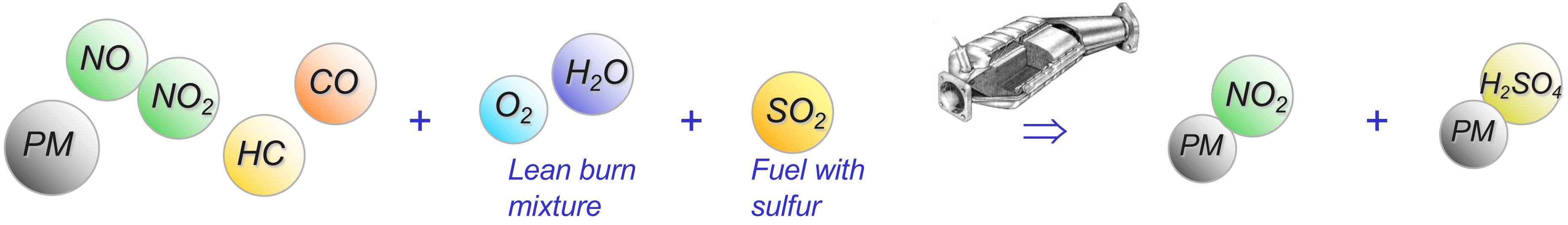
Half of the Pt world production goes into the automotive catalyst industry

Exhaust gas after-treatment systems

- After-treatment systems: (2) Oxidation catalytic converter
  - Operation in lean burn condition

    ⇒ application for **Diesel** engines (with a constant operation at $\lambda>1.2$)
  - Composition of the combustion gases for Diesel engines (with respect to stoichiometric engines) :
    - **CO and HC** content clearly lower
    - NO_x level slightly higher
    - O_2 always in excess
    - presence of particulates (PM)
    - T° of exhaust gases lower

    ⇒ 3-way catalyst is impossible because of O_2 presence:



Exhaust gas after-treatment systems

- (3) 'NO$_x$ treatment in lean-burn operation' (=intrinsically contradictory)
  - The NO$_x$ treatment by catalyst requires a stoichiometric regulation (NO$_x$ reduction is impossible in an oxidizing environment)

    ⇒ Problem for lean-burn engines:

    1. Spark ignition engines with lean burn operation (FSI)
    2. Diesel engines

  - The reduction of emission standards caused upstream pretreatment measures to be insufficient (for example: EGR, late combustion timing) and required specific new after-treatment solutions:

    ⇒ (a) NO$_x$ trap (S.I.)

    ⇒ (b) Selective Catalytic Reduction (SCR) (C.I.)

Exhaust gas after-treatment systems

- (3) NO_x treatment in lean-burn operation:

  (a) NO_x trap / absorber

  - Principle:
    1. Catch the NO_x on an absorbent material during the lean-burn operating phases (storage (few min) on the catalyst surface like a sponge filled with water)
    2. Release the NO_x and reduce them to N_2 during short transitions in **rich burn operation** (similar mechanism to the one used for the 3-way catalyst)

  - Adaptation on **S.I.** engines:
    - The change of the A/F ratio is done by switching from one combustion mode to another :

      lean burn (stratified or homogeneous) ⇔ stoichiometric
    - Strategies of regeneration occur e.g. during vehicle accelerations (rich burn)

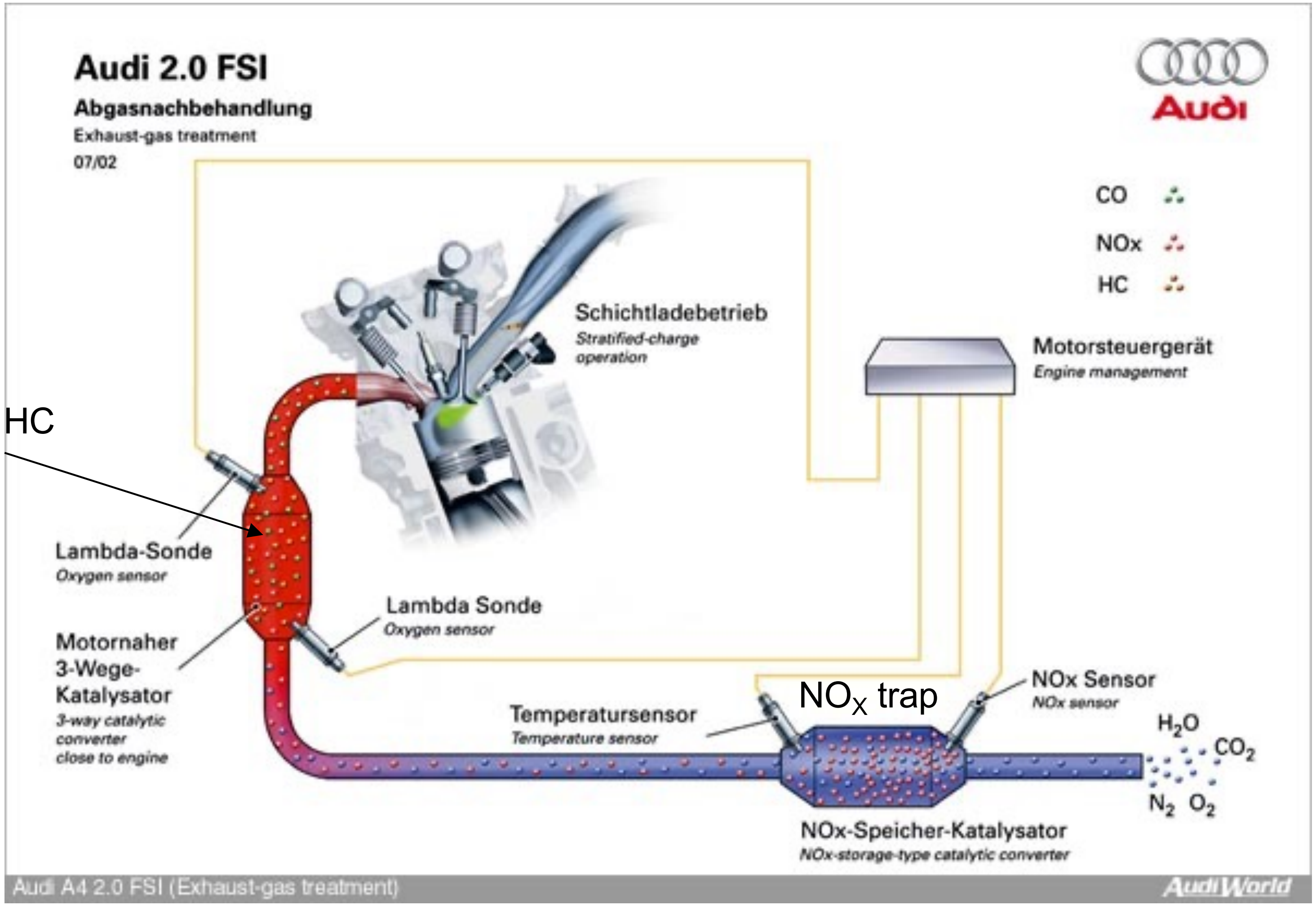
  - (Adaptation on Diesel)
    - More difficult because black smoke emissions are enormous at $\lambda < 1$

      ⇒ Combination of NO_x trap & Particulate filter

Exhaust gas after-treatment systems

- (3) NO_x treatment in lean-burn operation: (a) NO_x trap / absorber

Only for S.I.E.



oxidation of CO, HC

3-way cat works normally at λ=1
At λ>1, it can only oxidize CO, HC, hence NOx pass through.

(maybe +PM filter in future)

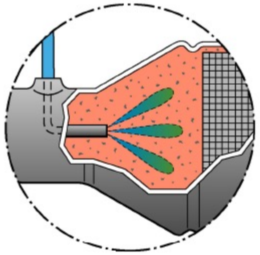
Cost : 3 kFr
Life : 8-10 yrs

NOx trap filled during lean burn λ>1. The trap is cleaned to N_2 by a short rich burn phase λ<1 every 10 min. or so.

Exhaust gas after-treatment systems

- (3) NO_x treatment in lean-burn operation: (b) SCR (for **Diesel**)
  - Principle of selective catalytic reduction (SCR) :

    ⇒ Injection at the exhaust system of a reducing agent having a strong selectivity towards NO_x :



  - Reducing agent mostly used: urea (=>ammonia after dissociation) ‘**ADBLUE**’
    1. Thermal dissociation of urea and hydrolysis into ammonia (NH_3)

$$\overbrace{NH_2-CO-NH_2}^{Urée} \rightarrow HNCO + NH_3$$

$$HNCO + H_2O \rightarrow CO_2 + NH_3$$

    2. NO_x reduction thanks to ammonia (NH_3)

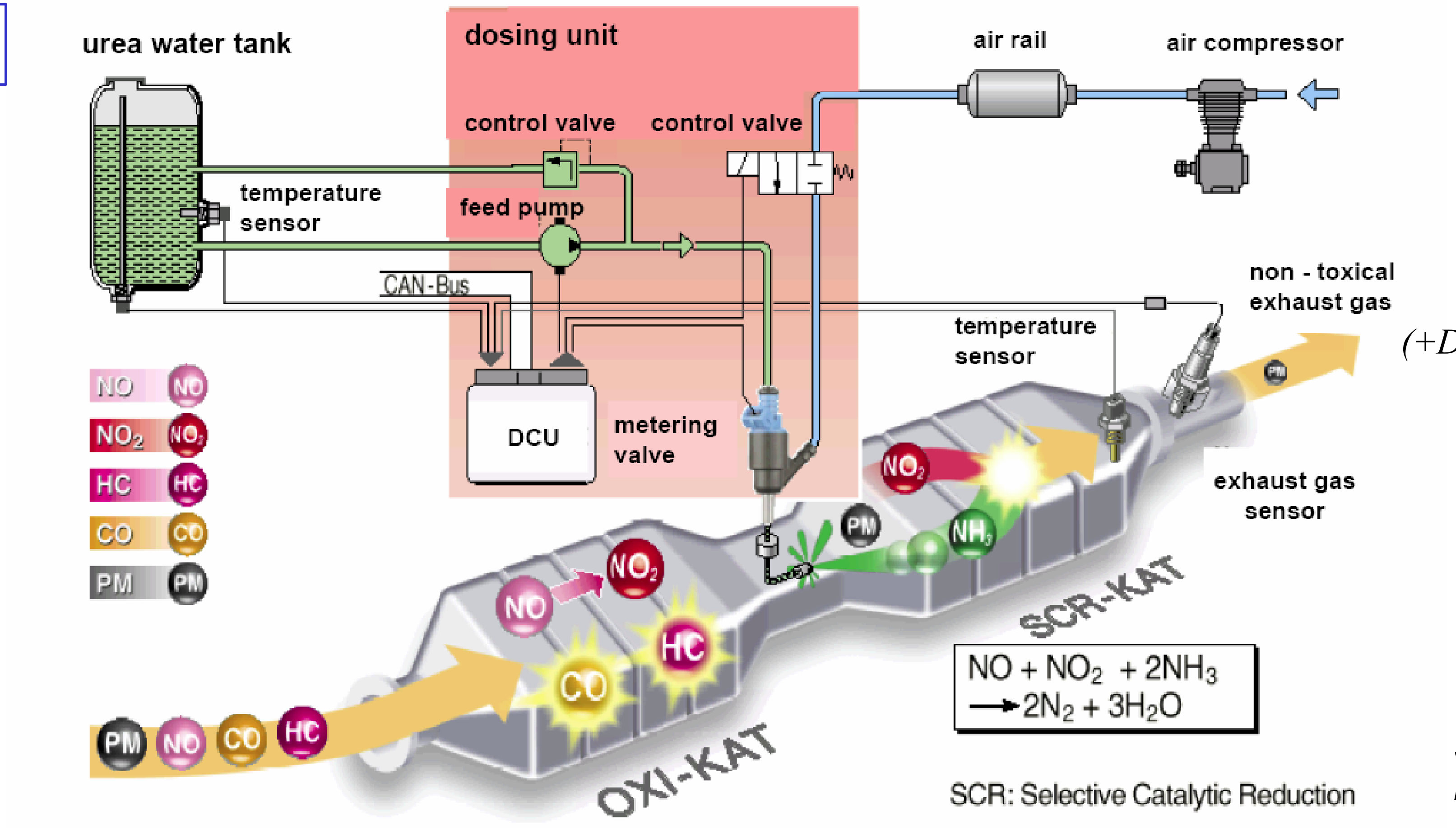
  - The use of (toxic) ammonia directly is avoided

  - High conversion degree of the system ≈ 90%

Exhaust gas after-treatment systems

- (3) NO_x treatment in lean-burn operation: (b) SCR
  - Example of a SCR system with urea injection:

C.I.E.



$$NO + NO_2 + 2NH_3 \longrightarrow 2N_2 + 3H_2O$$

SCR: Selective Catalytic Reduction

(+DPF)

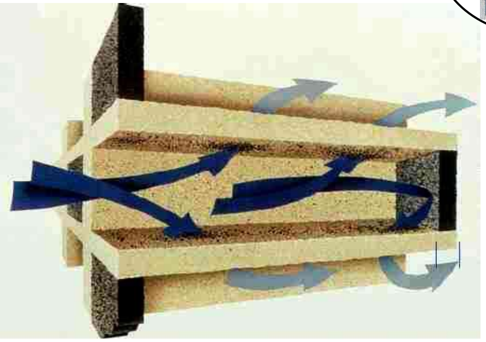
Source BOSCH

Exhaust gas after-treatment systems

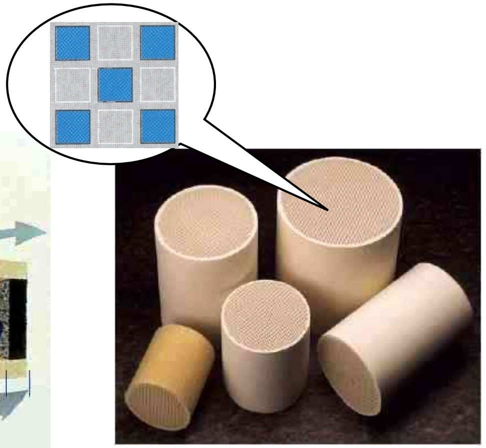
- After-treatment systems:(4) Diesel Particulate Filter (DPF)
  - Utilization only on Diesel engines
  - Due to a massive reduction of the PM emission limit, the upstream pretreatment measures (like increase of injection pressure) reached its limits

    ⇒ need to equip with Particulate Filters all the Diesel engines of the market (Passenger vehicles, Trucks, Heavy-duty machines, cogeneration)
  - Principle : solid particles present in the exhaust gases are retained on a porous material until a regeneration phase
  - Type of filtration : « Wall-Flow »

    The hot gases pass through a porous wall (ex. : ceramic monoliths) and leave the particles behind ⇒



Filtering « Wall-Flow »



Ceramic monoliths

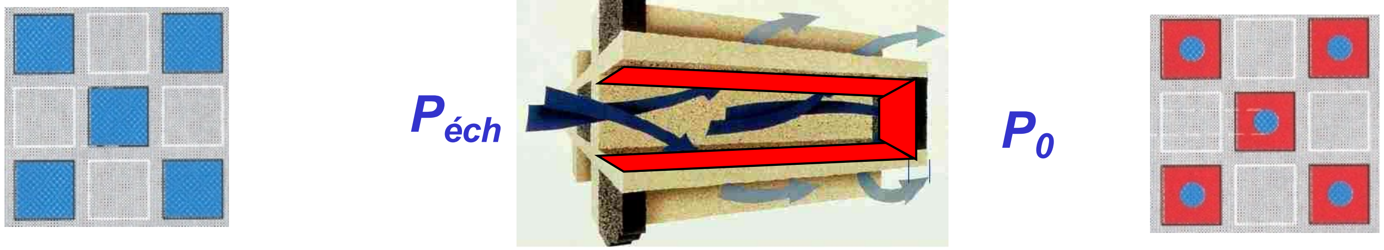
Exhaust gas after-treatment systems

After-treatment systems: Diesel Particulate Filter (DPF)

- Degree of filtration : > 90% in mass of all particles

- Filter regeneration:
  - The accumulation of particles causes an increase in back-pressure at the exhaust, penalizing the engine operation

    ⇒ regeneration is needed (=burn-off of soot by filter heating)



Clean filter: $P_{exhaust} \Rightarrow$ OK

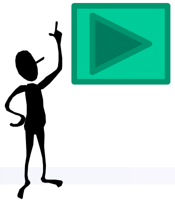
Used filter:
$P_{exh} \Rightarrow$ + 200 mbar

  - DPF regeneration strategy (PM are composed of carbon: $T_{comb} \approx$ 500-600° C) :

    ⇒ Increase the exhaust-gas temperature (burn-off soot) by **post-injection**

    ⇒ Decrease the soot combustion temperature

Exhaust gas after-treatment systems



- After treatment systems: Diesel Particulate Filter (DPF)
  - The regeneration strategy depends on the filter type:

Passive filters :	Utilization of additives mixed in the fuel in order to reduce the temperature of soot combustion and so accelerate the combustion process ⇒ the filter is « passive » for the engine
Active filters :	The engine management knows the charge load of the filter (by measuring the ΔP_{exh}) and is able to elaborate strategies to increase the exhaust-gas temperature if a regeneration phase is required: ⇒ action on engine parameters or external heating (electrical or thermal)

  - Example of possible modifications on the engine parameters:
    - Reduction of λ ratio (EGR *or* air throttle)
    - Combustion timing (reduction of $\alpha_{injection}$)
    - Post-injection
    - injection at or close to *BDC* (fuel combustion into the oxidation catalytic converter)