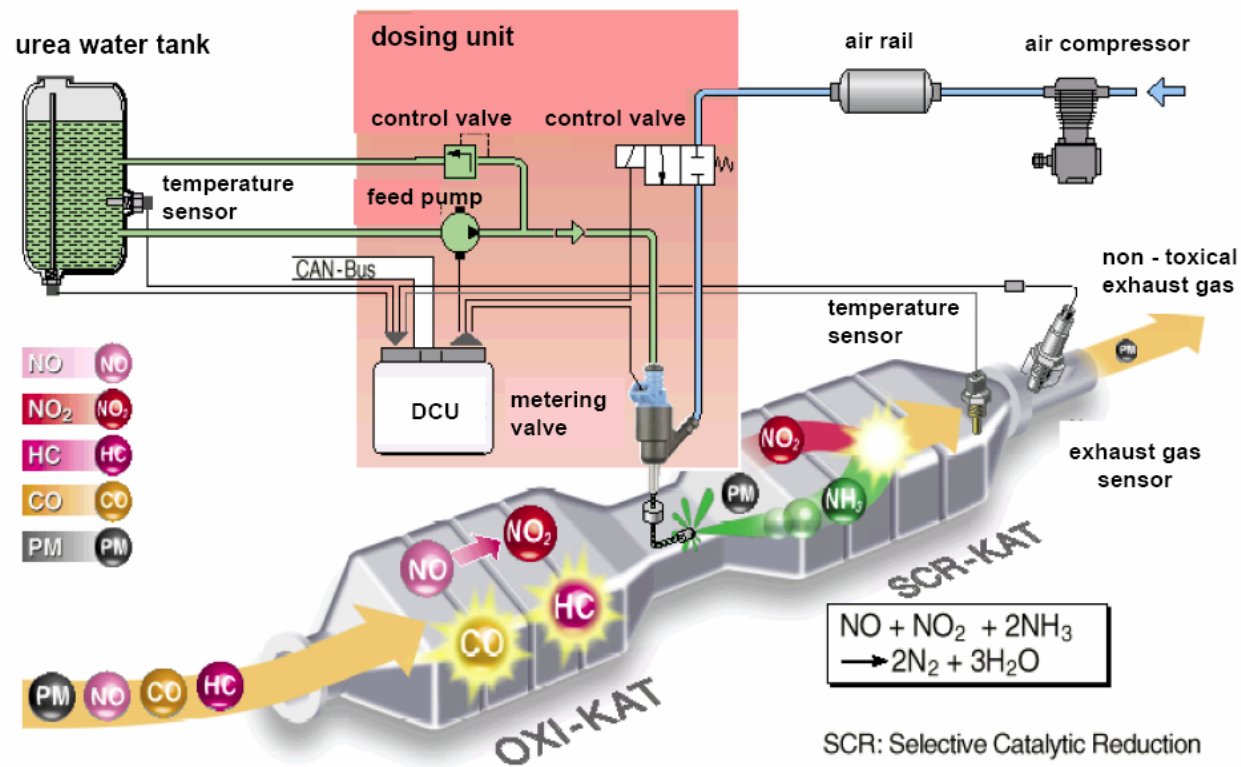




Engines

Chapter 6: Pollution Control & Abatement





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



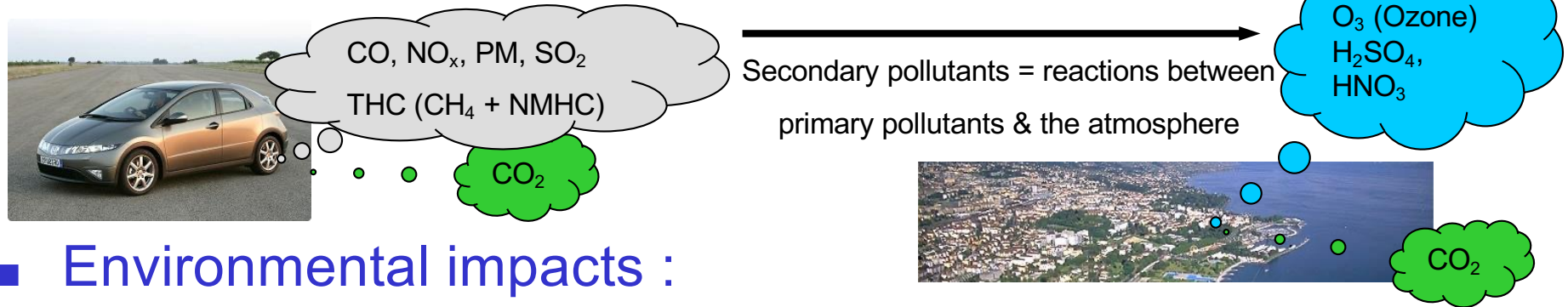
Content

- Pollutants
- 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)



Pollutants

■ Main primary and secondary pollutants



■ Environmental impacts :

- CO : toxic for breathing beings (↑ in high concentrations)
- HC : toxic (benzene and PAH are highly carcinogenic)
 - Ozone precursors (O₃) : contribute to “smog” formation
- CH₄ : greenhouse gas (GWP ≈ 20) : $CH_4 = THC - NMHC$
- NO : non-toxic gas but NO₂ precursor
- NO₂ : Ozone precursor (O₃) : contributes to “smog” formation, toxic for pulmonary system
- N₂O: greenhouse gas (GWP ≈ 300)
- PM : toxic for human beings (volatiles < 50 nm)



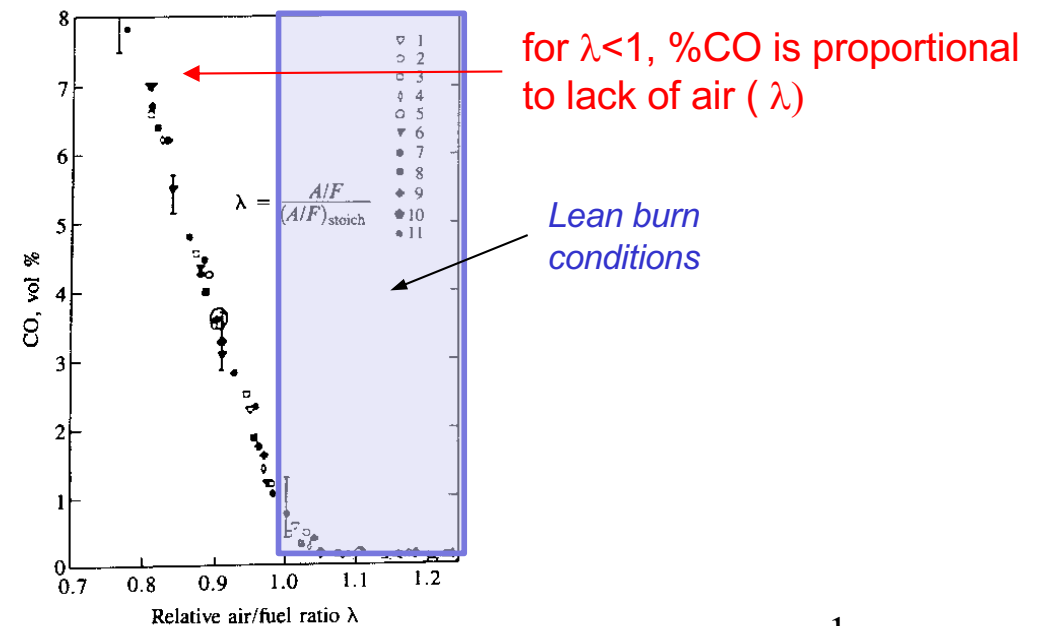
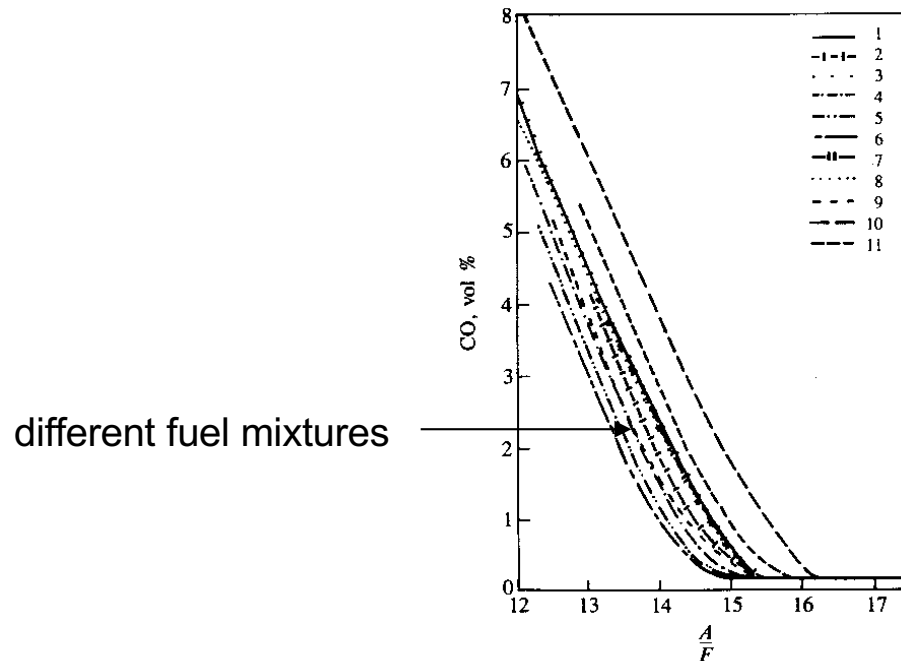
Pollutants (1)

■ Pollutant formation during the combustion process

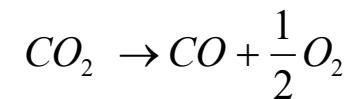
1) CO : formed by an **O₂ lack** $\Rightarrow$ O₂ is necessary in order to burn all carbon fully to CO₂

Origin of formation :

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



2. **For $\lambda > 1$, reactions of dissociation at high temperature**
 $\Rightarrow$ oxidation reactions are frozen during the expansion stroke:





Pollutants (2)

■ Pollutant formation during the combustion process

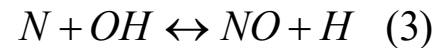
2) NO_x : NO_x are composed of NO ($\approx 98\%$ Otto, $\approx 70\%$ Diesel) and NO_2
 Formed in the burned gases zone at high temperature ($> 2300\text{K}$)

$$\text{Ex : } \frac{d[\text{NO}]}{dt} = \frac{6 \cdot 10^{16}}{T^{0.5}} \cdot \exp\left(\frac{-69090}{T}\right) \cdot [\text{O}_2]_e^{0.5} \cdot [\text{N}_2]_e$$

Origin of formation :

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

NO = Zeldovich mechanism :

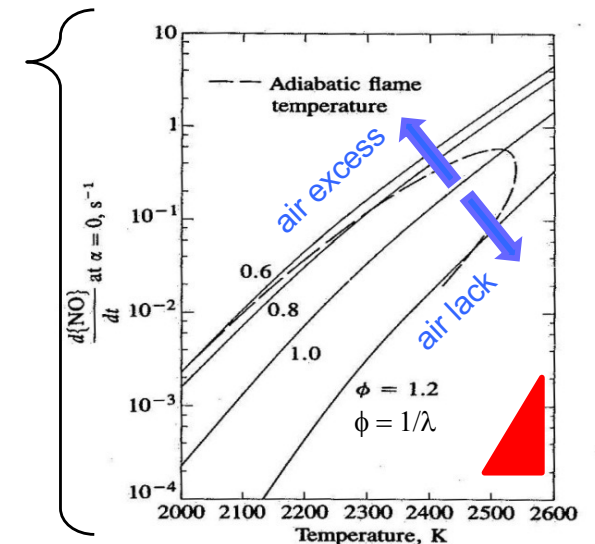


NO_2 = NO oxidation reaction

$\Rightarrow$ residence time at high temperature facilitates $[\text{NO}_x]$ 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)

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



+100K $\Rightarrow$ NO*10 !



Pollutants (3)

■ Pollutant formation during the combustion process

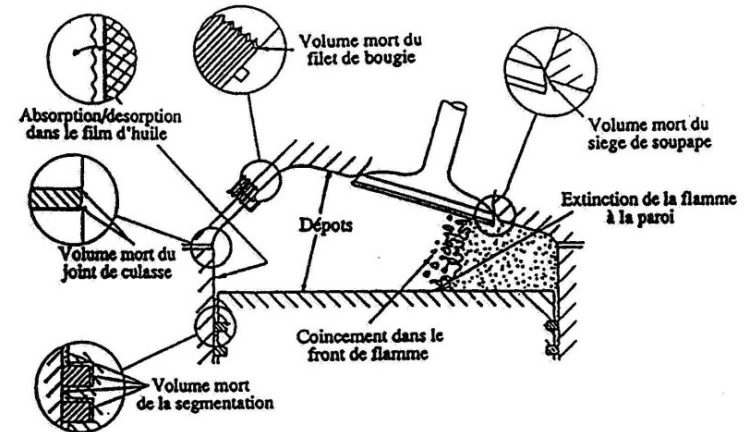
3) HC : formed mostly by an incomplete fuel combustion

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



Pollutants (4)

■ Pollutant formation during 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 fuel-rich and at high temperature

Origin of formation :

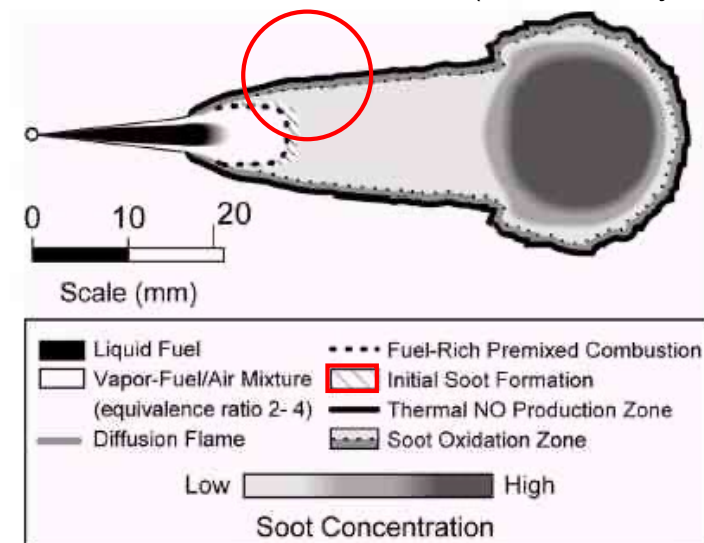
1. Process of PAH formation (Polycyclic Aromatic Hydrocarbons) :

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 during 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 ($\Rightarrow$ 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 ($\Rightarrow$ **post-injection**)

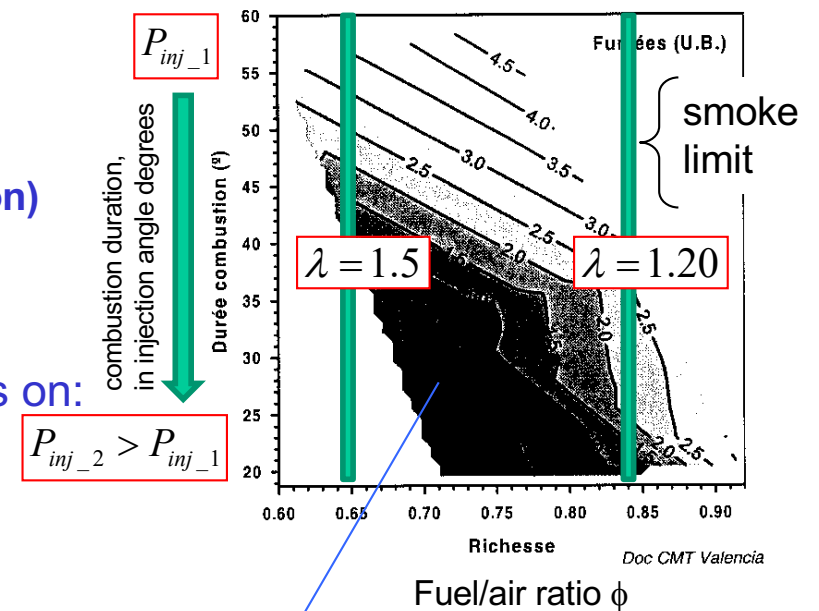
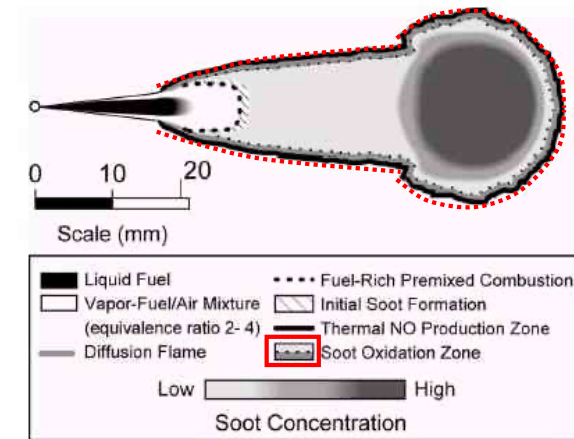
[PM] $\nearrow$ when P and T decrease too quickly before the end of the combustion, that depends on:

$\Rightarrow$ engine speed

$\Rightarrow$ delivery period / timing of the combustion

Soot is reduced the faster the combustion

$\Rightarrow$ act on fuel injection pressure



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] $\Rightarrow$ A/F ratio (λ)

S.I.

- [NO_x] $\Rightarrow$ [O₂] concentration (lean mixture), hence λ
 $\Rightarrow$ T (K) of combustion process
 $\Rightarrow$ residence time at high T

C.I.

- [HC] $\Rightarrow$ geometry / design of the combustion chamber
 $\Rightarrow$ combustion in rich mixture ($\lambda < 1$)

S.I.

- [PM] $\Rightarrow$ local F/A ratio (fuel atomisation, turbulence)
 $\Rightarrow$ combustion duration (residence time for post-oxidation)

C.I.



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Emission standards

■ Passenger vehicles

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

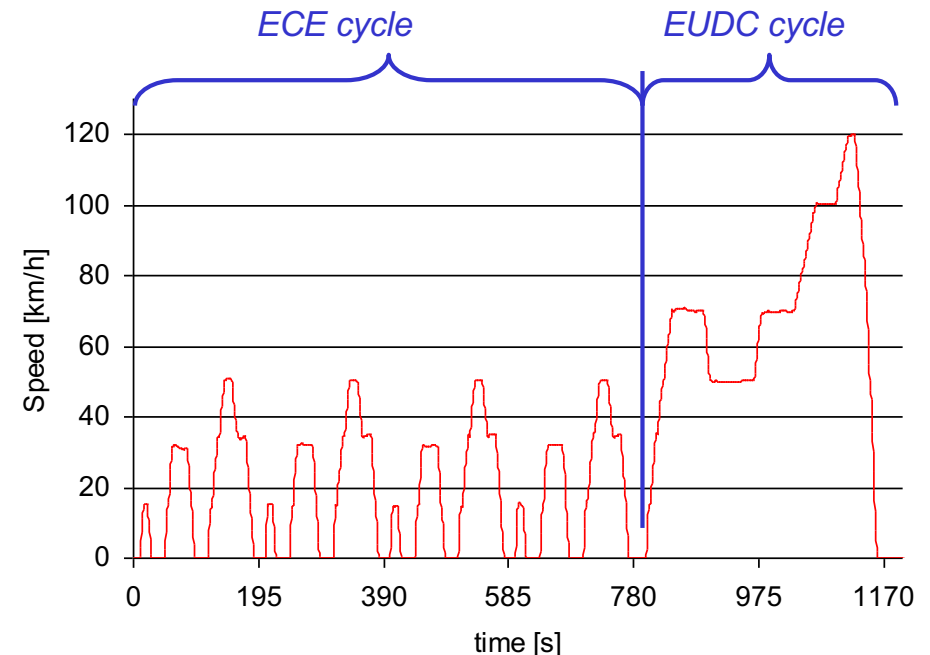
Urban driving cycle or **ECE 15**

⇒ 4 consecutive phases

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

Extra-urban driving cycle or **EUDC**

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



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

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

→ *New European Driving Cycle*

→ *(Motor Vehicles Emission Group)*



- 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

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

Gasoline vehicle

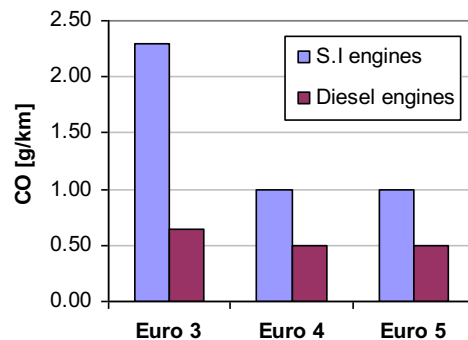
g/km	year	CO	HC	NO _x	PM
Euro 1	1992	2.72	Tot : 0.97		-
Euro 2	1996	2.20	Tot : 0.50		-
Euro 3	2000	2.30	0.20	0.15	-
Euro 4	2005	1.00	0.10	0.08	-
Euro 5	2009	1.00	0.10	0.07	0.005
Euro 6	2014	1.00	0.10	0.07	0.0045

Diesel vehicle

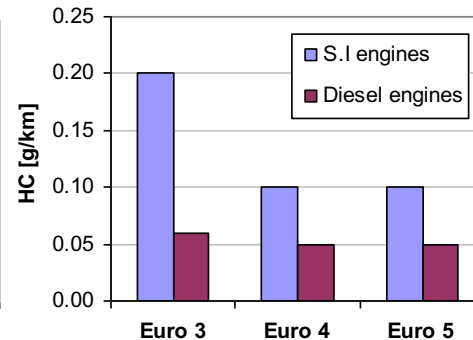
g/km	year	CO	HC+NO _x	NO _x	PM
Euro 1	1992	2.75	1.36	-	0.19
Euro 2	1996	1.00	0.90	-	0.10
Euro 3	2000	0.64	0.56	0.50	0.05
Euro 4	2005	0.50	0.30	0.25	0.025
Euro 5	2009	0.50	0.23	0.18	0.005
Euro 6	2014	0.50	0.17	0.08	0.005

- 50 %
- 50 %
- 50 %
- 80 %
- 50 % (NO_x)

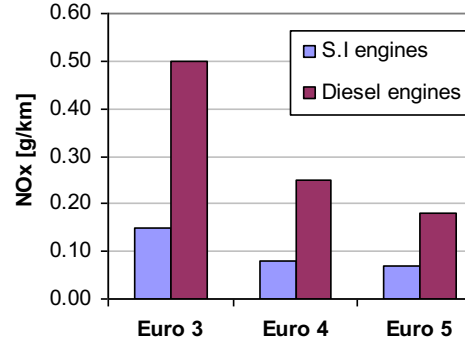
CO



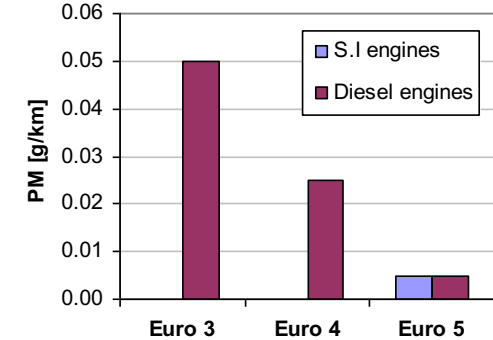
HC



NO_x



PM





Emission standards

- Passenger vehicles: now
 - In 2017, the NEDC cycle was replaced by the WLTP:
Worldwide harmonized Light vehicles Test Procedures

⇒ *harmonized (Worldwide)*
⇒ *more dynamic*
⇒ *3 different vehicle class defined by power-weight ratio: kW / ton*

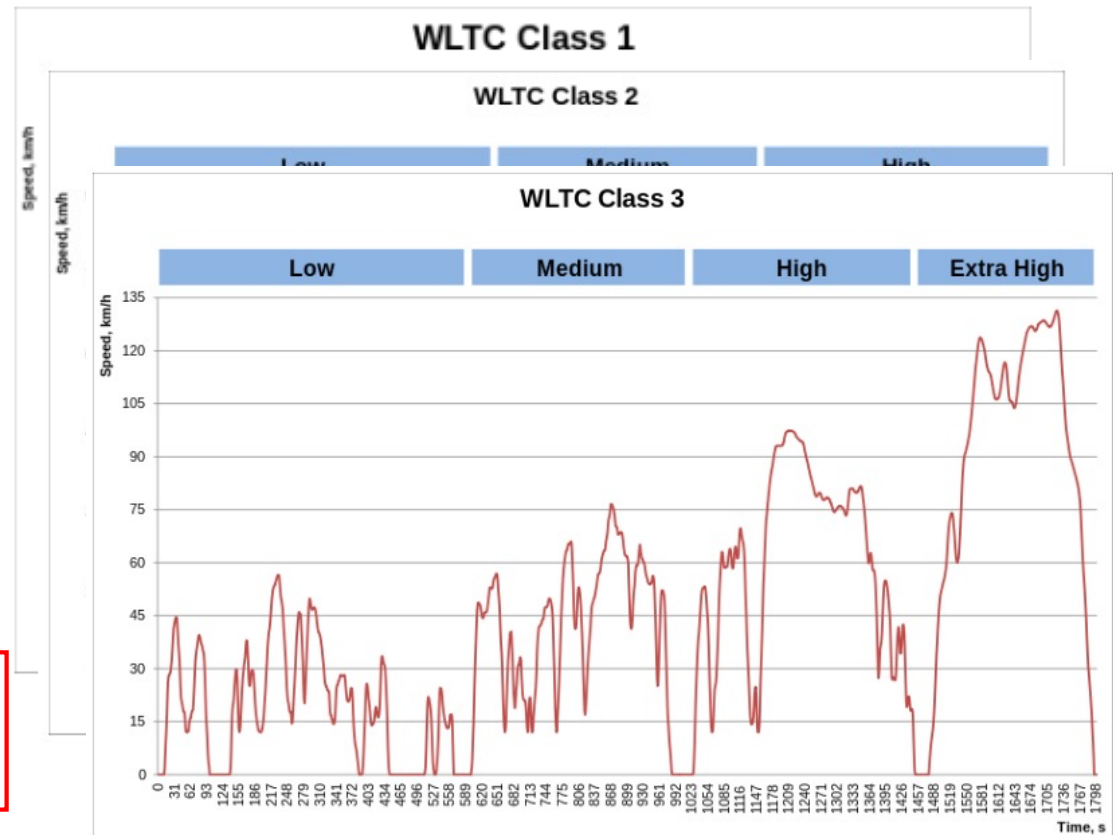
Class 1: $PW_r < 22$

Class 2: $22 < PW_r < 34$

Class 3: $PW_r > 34$

Actual cars in EU:

$40 < PW_r < 70$ kW/tons



test to be repeated every 10'000 km



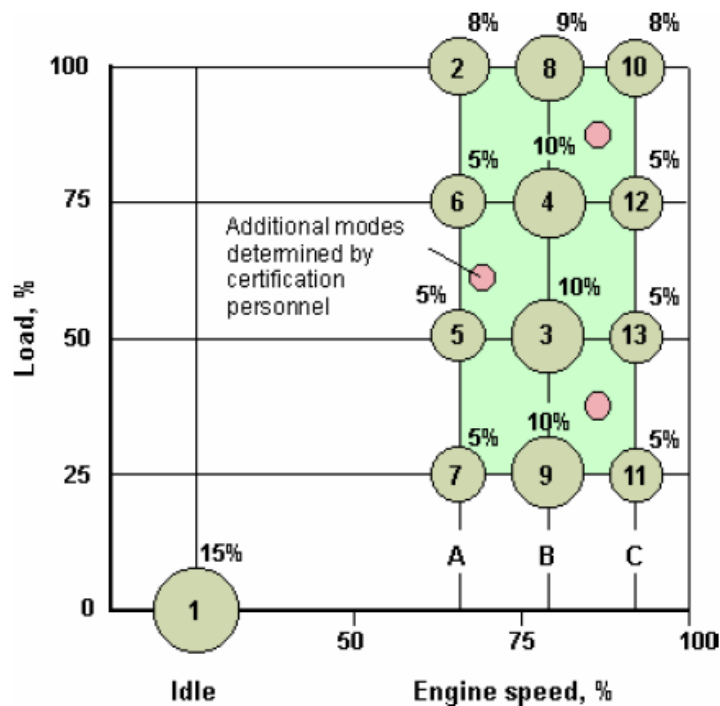
Emission standards

■ Trucks

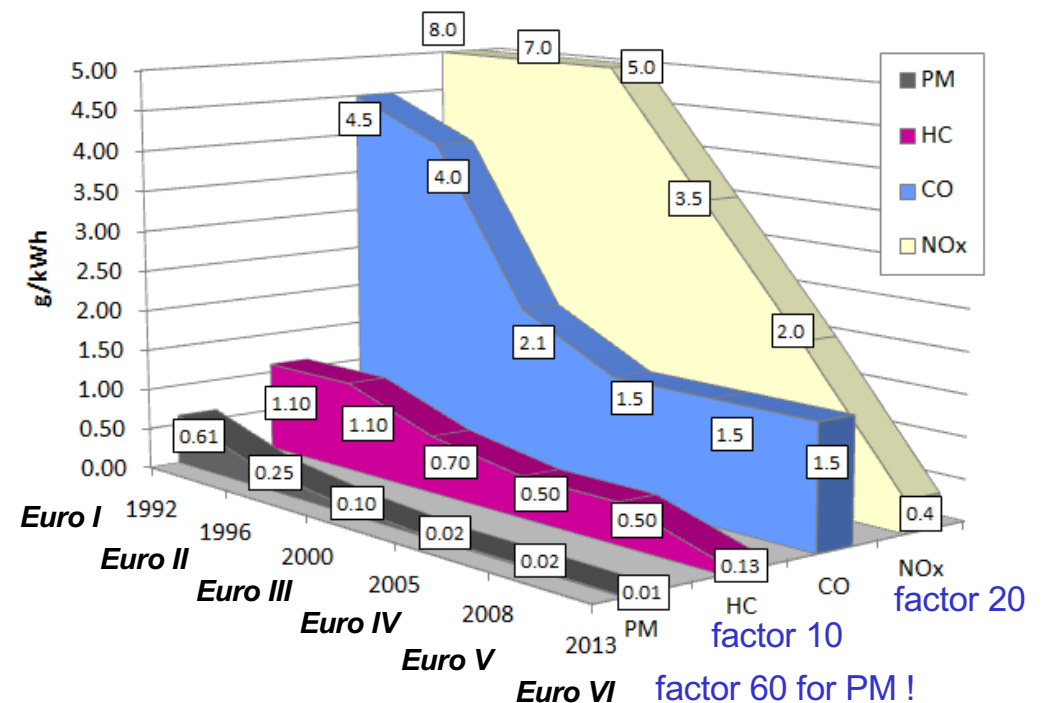
≠ g/km!

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

13 modes test cycle:



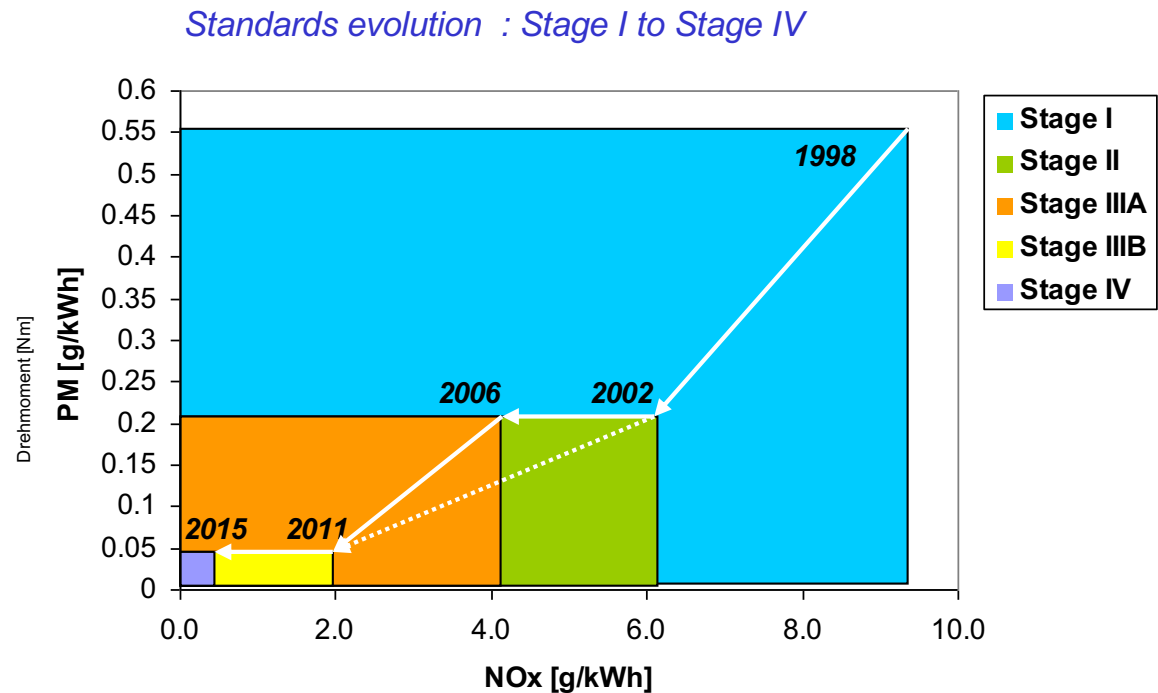
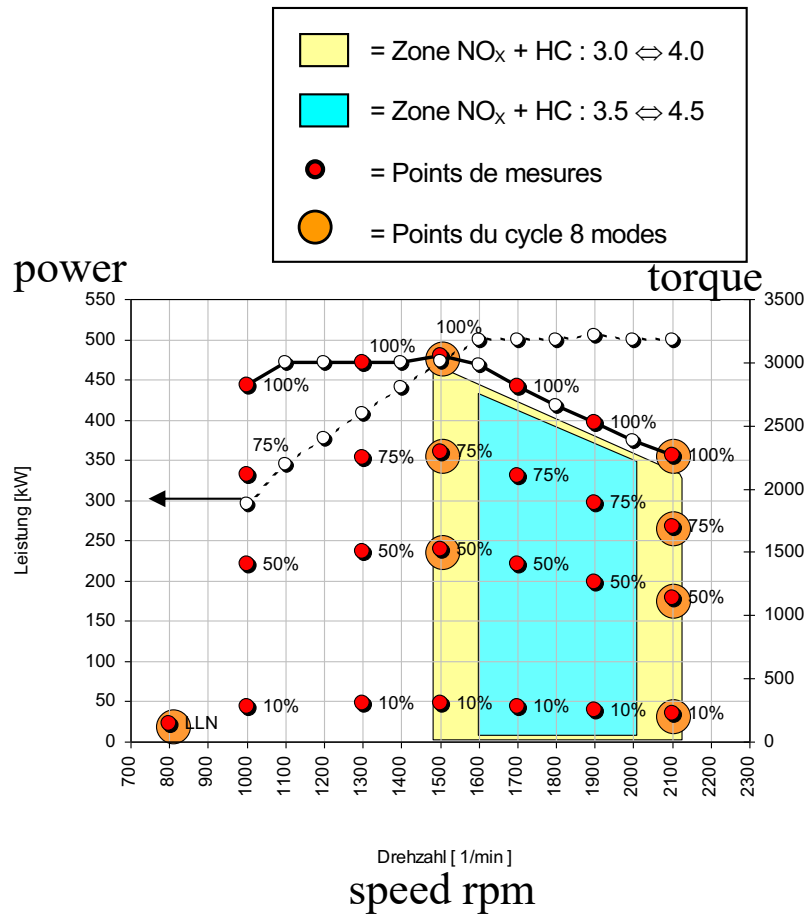
Standards evolution:





Emission standards

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





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

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



Vehicle @ 120 km/h
 $\Rightarrow P_{mean} \approx 20 \text{ kW}$

- 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



$\Rightarrow$ with a delay of 5 years offset, emission levels are quite identical !

$\Rightarrow$ from 2011, the standards on PM are all almost at the same level



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Upstream pretreatment methods

- “Pretreatment” $\Rightarrow$ 4 methods

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

1. Cylinder mixture dilution by air ($\lambda \nearrow$)

$\Rightarrow$ increase the oxygen fraction inside the combustion chamber by increasing the λ ratio

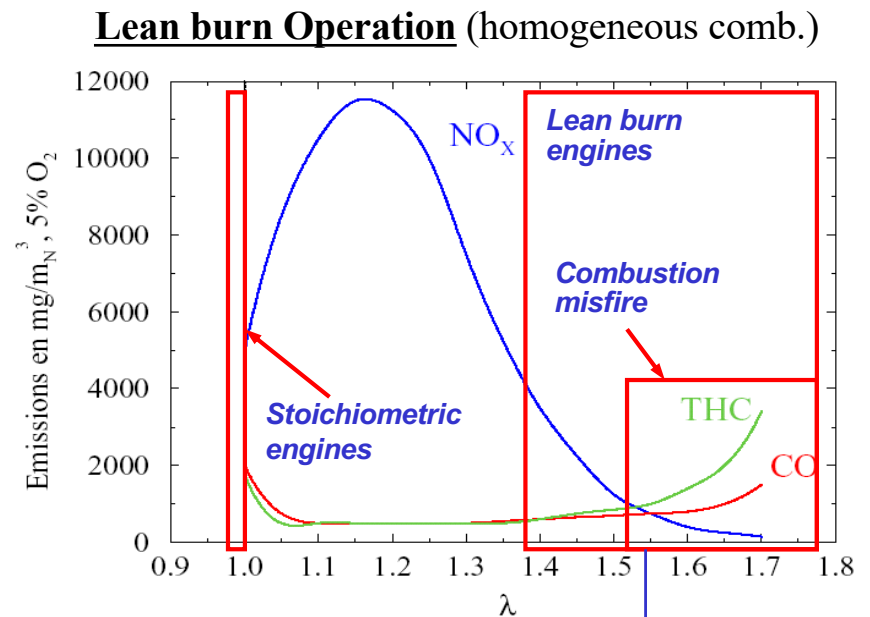
Reminder :

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

Consequence of a lean burn mixture:

$1 < \lambda < 1.5$: $[\text{NO}_x] \nearrow$ and $[\text{HC}], [\text{CO}] \searrow$

$\lambda > 1.5$: $[\text{NO}_x] \searrow$ and $[\text{HC}], [\text{CO}] \nearrow$





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 $\Rightarrow$ explains the higher $[\text{NO}_x]$ 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

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

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 $[\text{NO}_x]$

$\Rightarrow$ **NOx trap**



Upstream pretreatment methods

■ Pretreatment methods by cylinder mixture dilution

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

- Objective: NO_x reduction

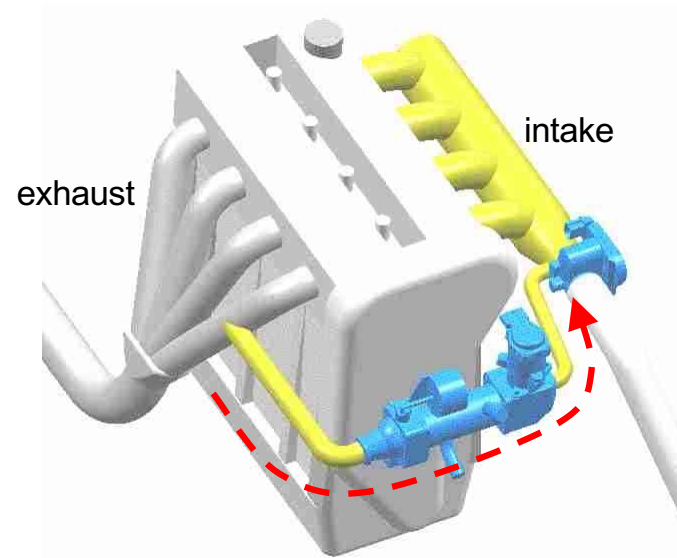
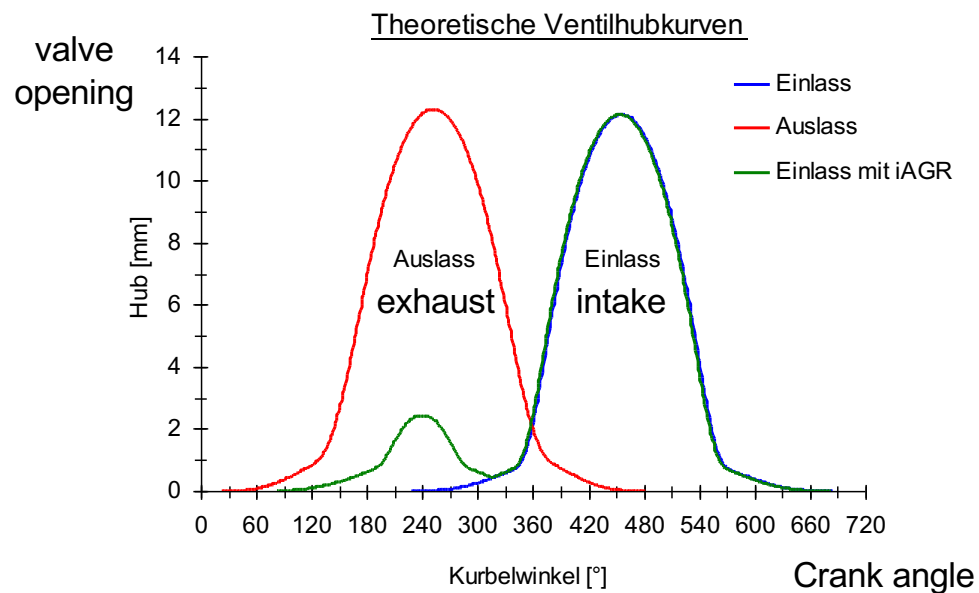
- Type of technology for exhaust gas recirculation (~10-30%):

A) Internal recirculation

⇒ with valve train system

B) External recirculation (cooled)

⇒ reintroduced at the intake





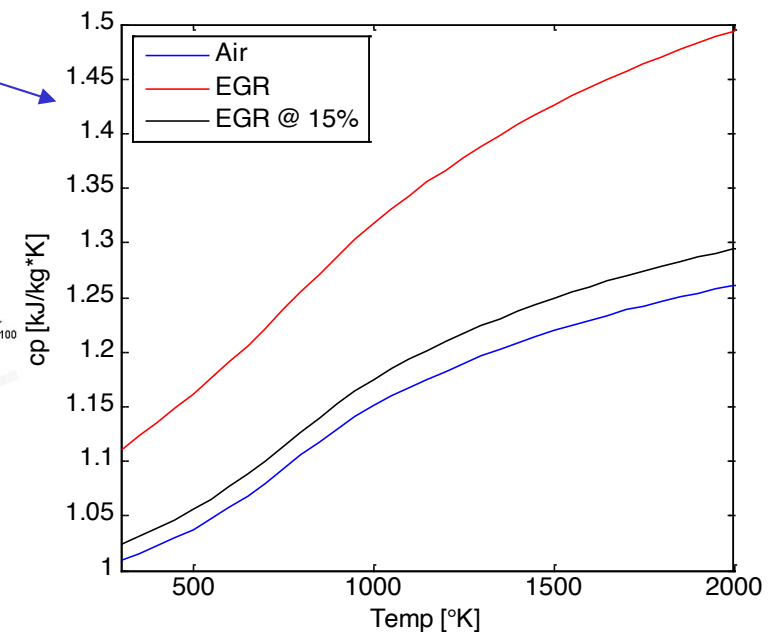
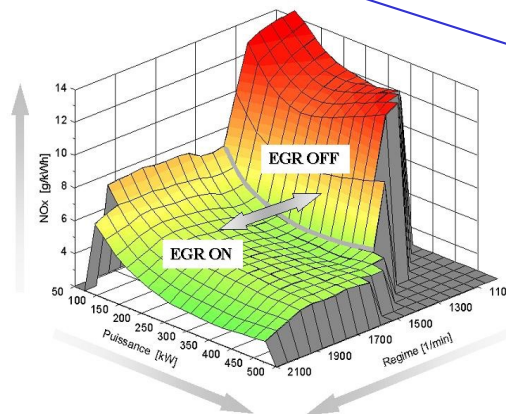
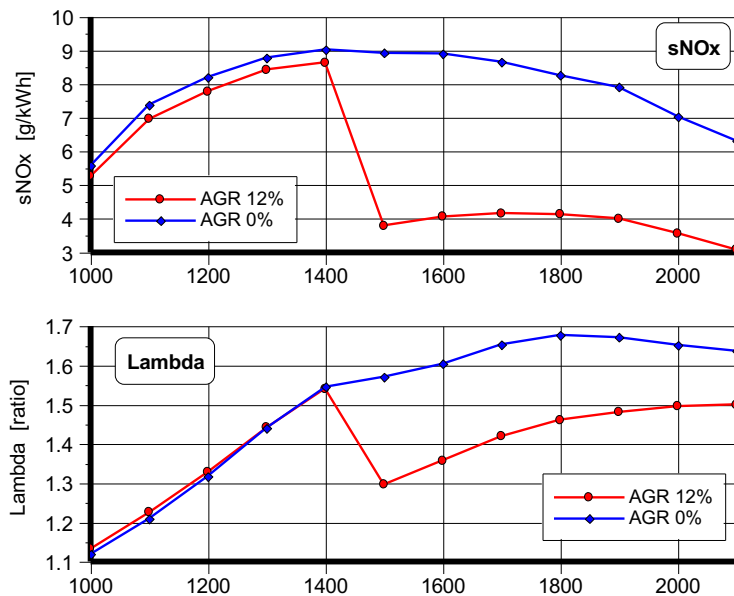
Upstream pretreatment methods

■ 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}



NOx divided by factor 2 (left), up to factor 5 (map)

EGR is now standard on all diesel cars



Upstream pretreatment methods

■ Pretreatment methods by engine parameters (ECU)

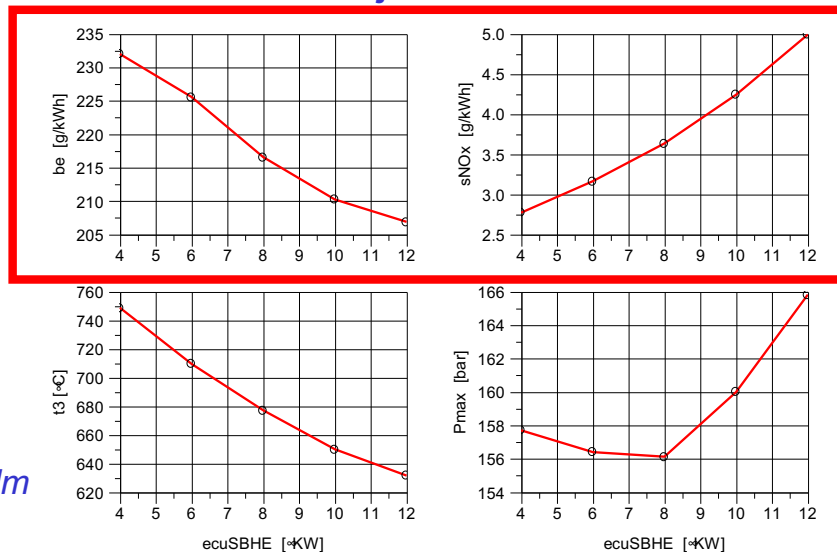
3. Combustion timing (=most important means of action)

- The timing of the combustion process in the engine cycle directly influences the cylinder temperature and pressure $\Rightarrow$ influence on the **[NO_x]**
- The increase of exhaust gases **T°** improves the post-oxidation $\Rightarrow$ influence on **[CO]** and **[PM]**

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

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

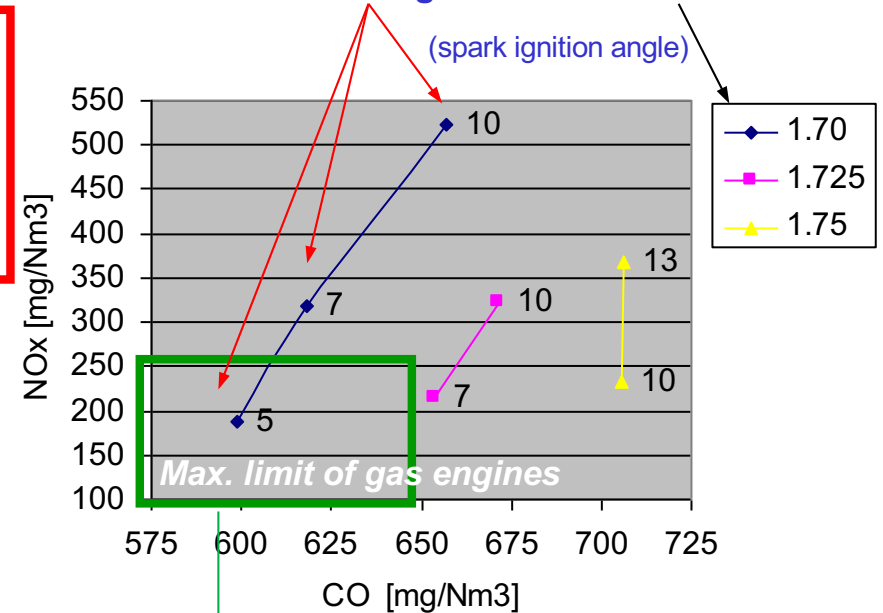
4 L Diesel engine
1800 1/min, 960 Nm



$\Rightarrow$ Compromise between BSFC $\Leftrightarrow$ NO_x

Otto : α_{ignition}

λ



Standard limits

$\Rightarrow$ today's exercise



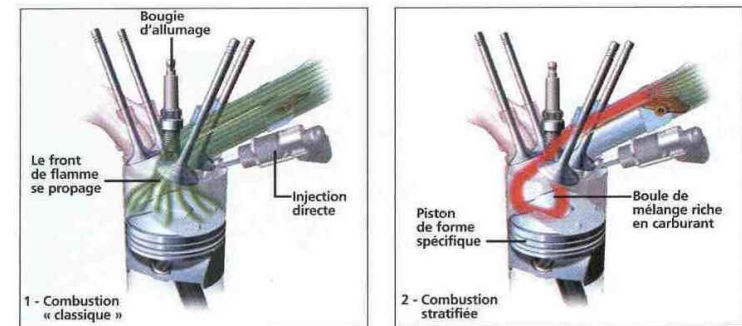
Upstream pretreatment methods

■ Pretreatment methods by engine parameters (ECU)

4. Combustion speed

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)

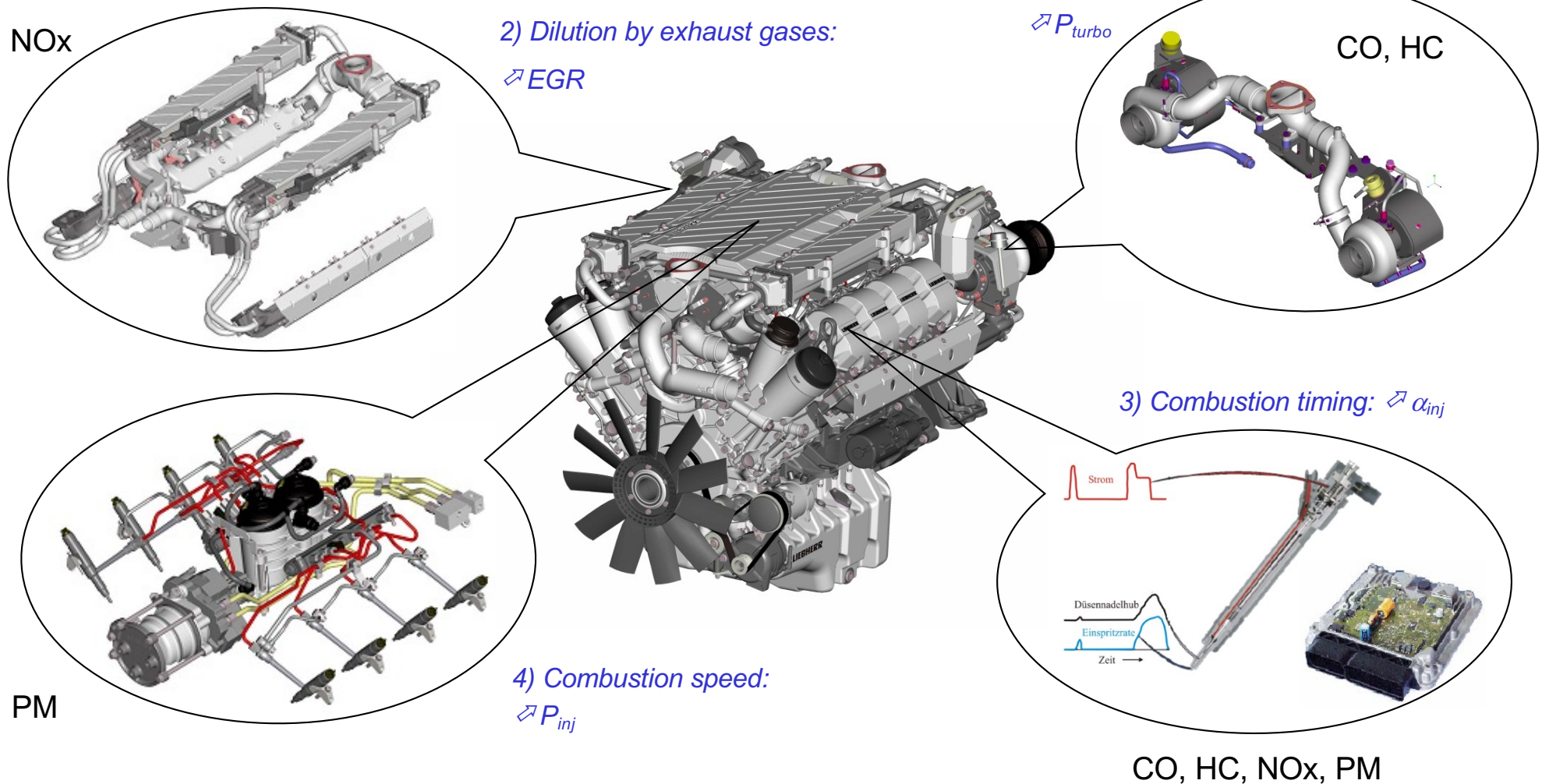
⇒ increase of P_{inj} in order to reduce the PM emissions



Upstream pretreatment methods: summary

■ Pretreatment methods by engine parameters (ECU)

Synthesis : example for a Diesel V8



(injection during expansion stroke to burn off PM)



Content

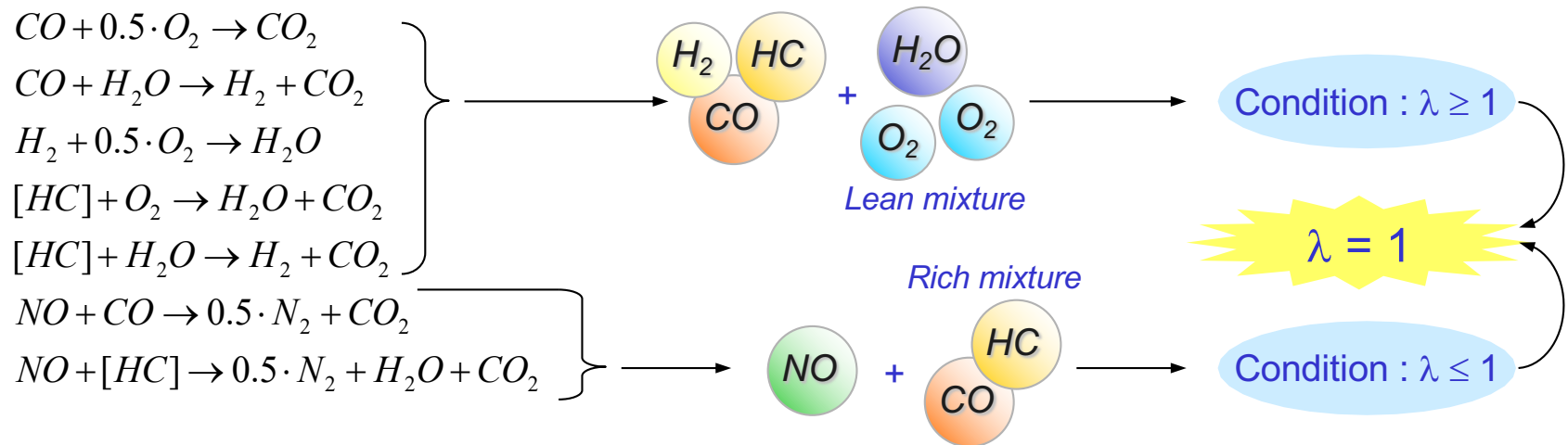
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Exhaust gas after-treatment systems

■ After-treatment systems: (1) 3-way catalyst (late 1980'ies)

- Simultaneous action on: CO, HC and NO_x ⇒ 3 pollutants
- Reactions to consider:



• 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 O₂ sensor (lambda sensor) close to the stoichiometric conditions

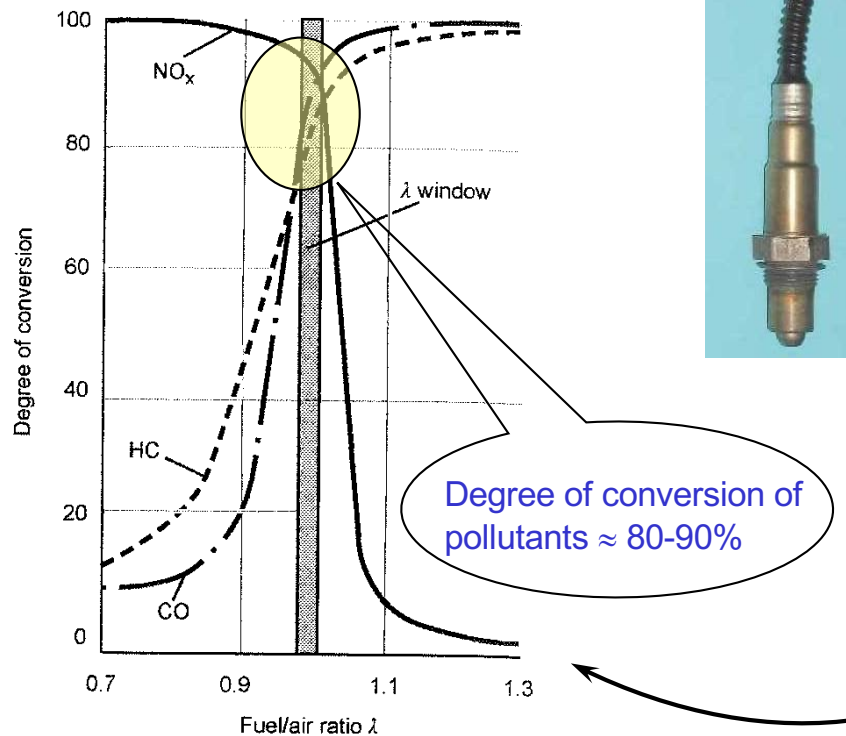


Exhaust gas after-treatment systems

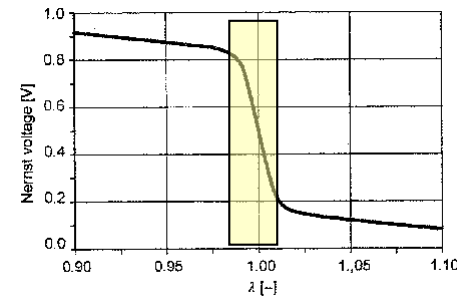
■ After-treatment systems: 3-way catalyst & λ regulation

- Regulation at $\lambda = 1$ possible only on S.I. stoichiometric engines
- The F/A ratio regulation is controlled by a *lambda* sensor :

Window of the λ regulation:



λ sensor

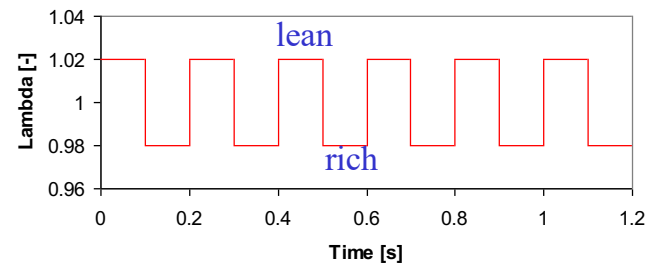


Signal specifications of a λ sensor

ECU



Signal oscillation at $\pm 2\%$, $f \approx 10$ Hz :

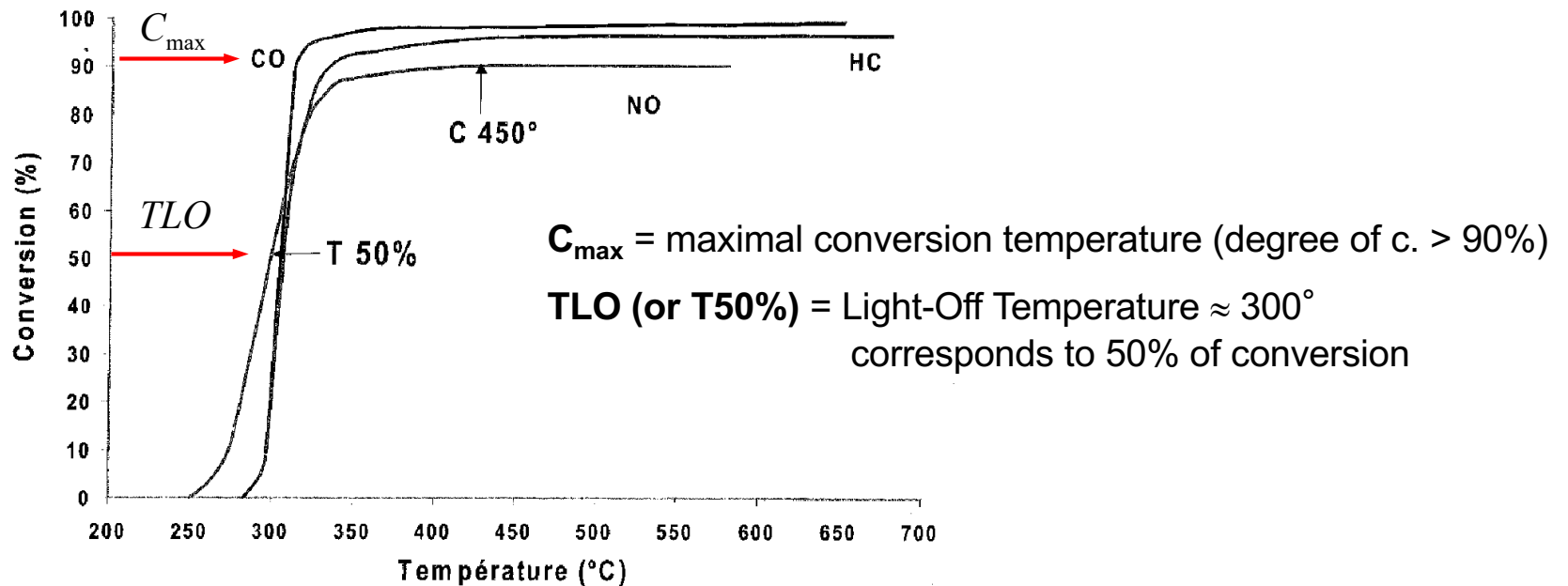


Correction on t_{inj}
(more, or less, fuel)



Exhaust gas after-treatment systems

- After-treatment systems: 3-way catalyst
 - Influence of the main parameters:
 - Temperature of combustion gases at the catalyst inlet



⇒ 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)

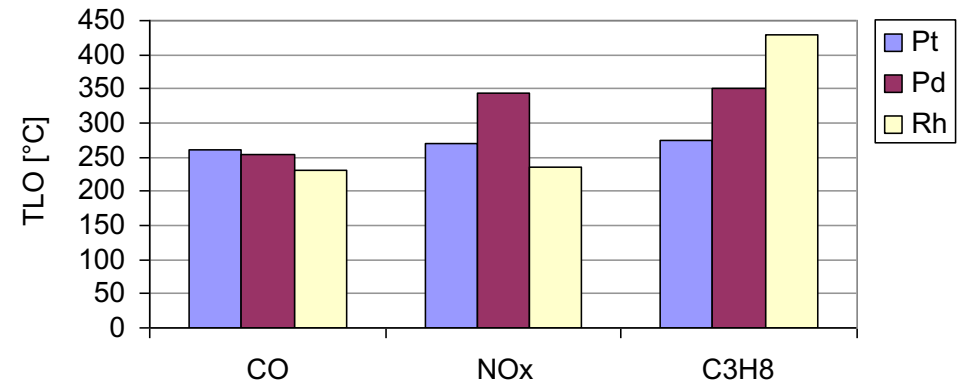


Exhaust gas after-treatment systems

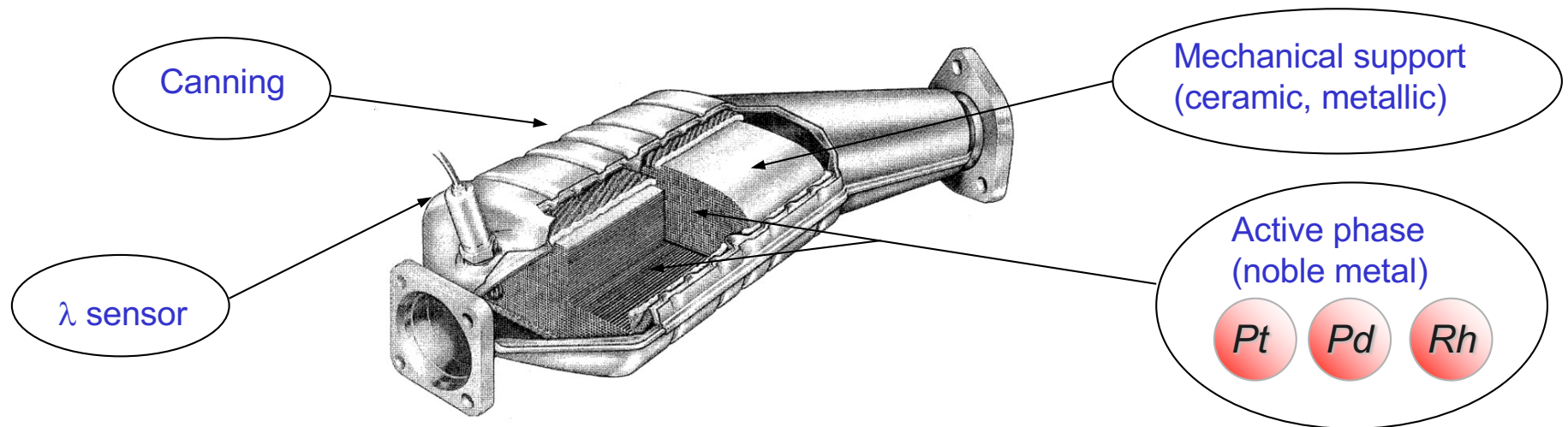
■ After-treatment systems: 3-way catalyst

● Influence of the main parameters:

- type of noble metal used on catalytic support $\Rightarrow$



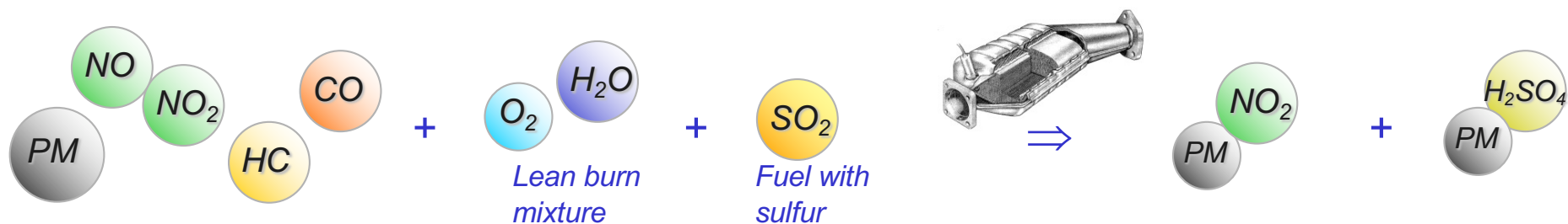
● Converter components :





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 N₂ 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



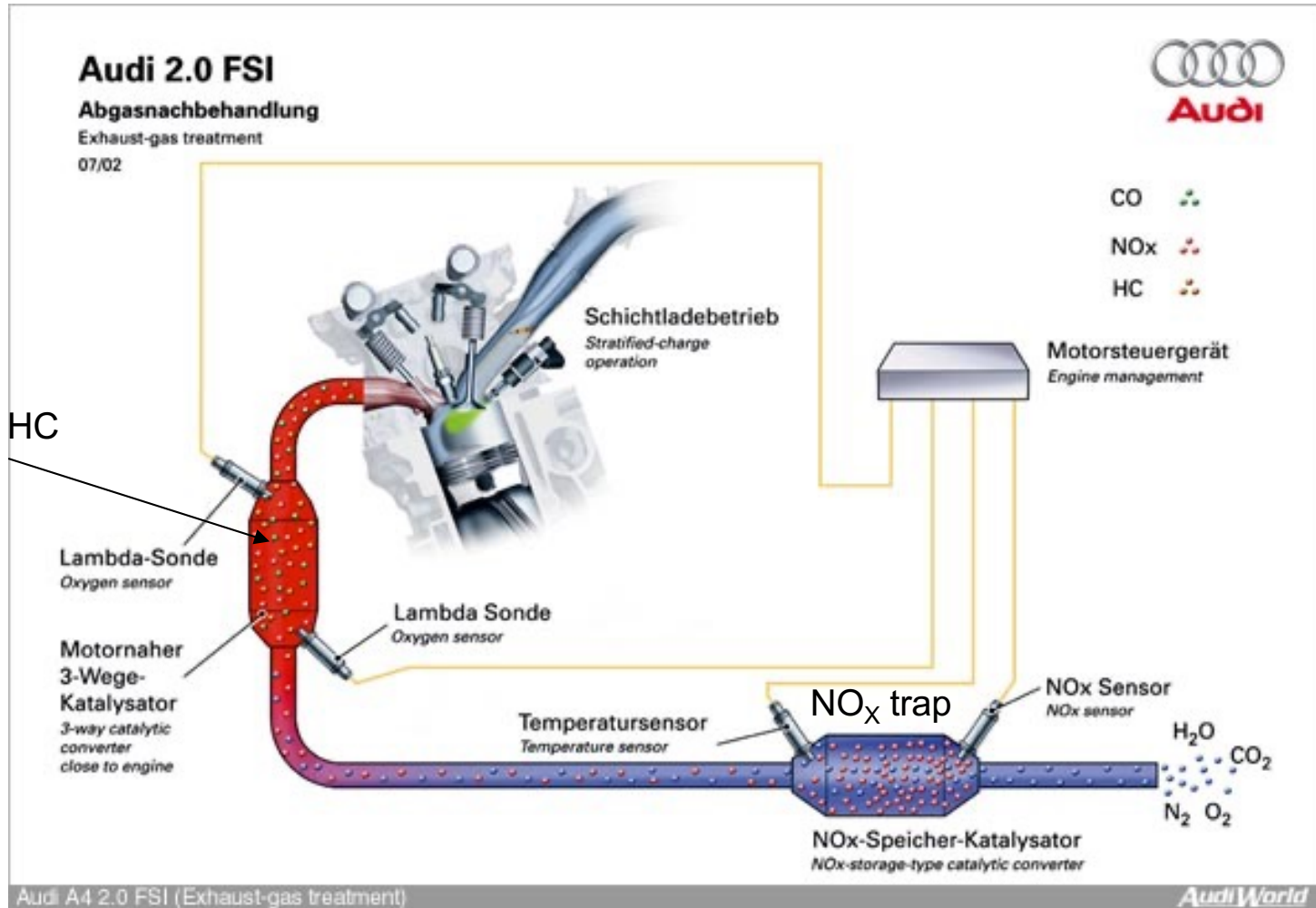
Exhaust gas after-treatment systems

- (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 $\lambda=1$
At $\lambda>1$, it can only oxidize CO, HC, hence NO_x pass through.



(maybe
+PM filter
in future)

Cost : 3 kFr
Life : 8-10 yrs

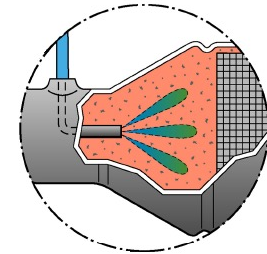
NO_x trap filled during lean burn $\lambda>1$.
The trap is cleaned to N₂ by a short rich burn phase $\lambda<1$ every 10 min. or so.



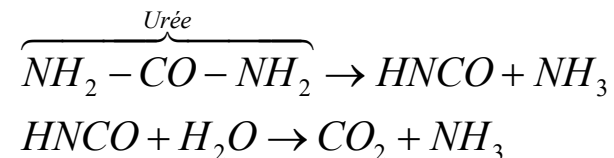
Exhaust gas after-treatment systems

■ (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 (NH₃)



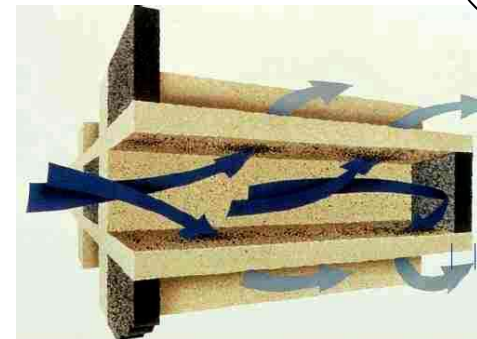
2. NO_x reduction thanks to ammonia (NH₃)
- The use of (toxic) ammonia directly is avoided
 - High conversion degree of the system ≈ 90%



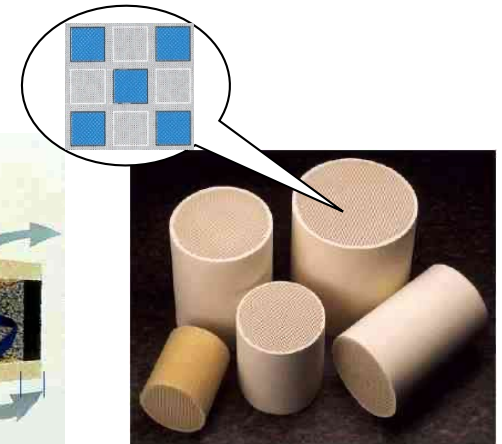
Exhaust gas after-treatment systems

■ 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

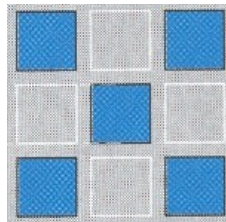


Exhaust gas after-treatment systems

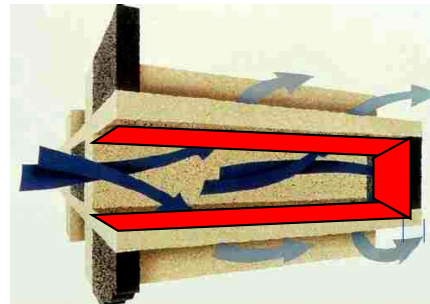
■ After-treatment systems: Diesel Particulate Filter (DPF)

- 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
 $\Rightarrow$ regeneration is needed (=burn-off of soot by filter heating)

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



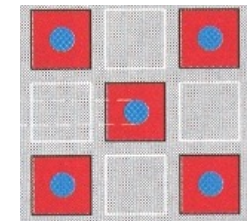
$P_{\text{éch}}$



P_0

Used filter:

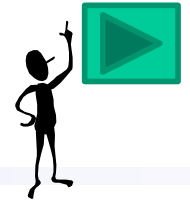
$P_{\text{exh}} \Rightarrow + 200 \text{ mbar}$



- DPF regeneration strategy (PM are composed of carbon: $T_{\text{comb}} \approx 500\text{-}600^\circ \text{ C}$) :
 - $\Rightarrow$ Increase the exhaust-gas temperature (burn-off soot) by **post-injection**
 - $\Rightarrow$ 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 $\alpha_{\text{injection}}$)
 - Post-injection
 - injection at or close to *BDC* (fuel combustion into the oxidation catalytic converter)