Performance you can rely on.

Fundamentals of engine design and operation

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Outline

- General features
- Spark ignition engines
- Diesel engines
- Conclusion

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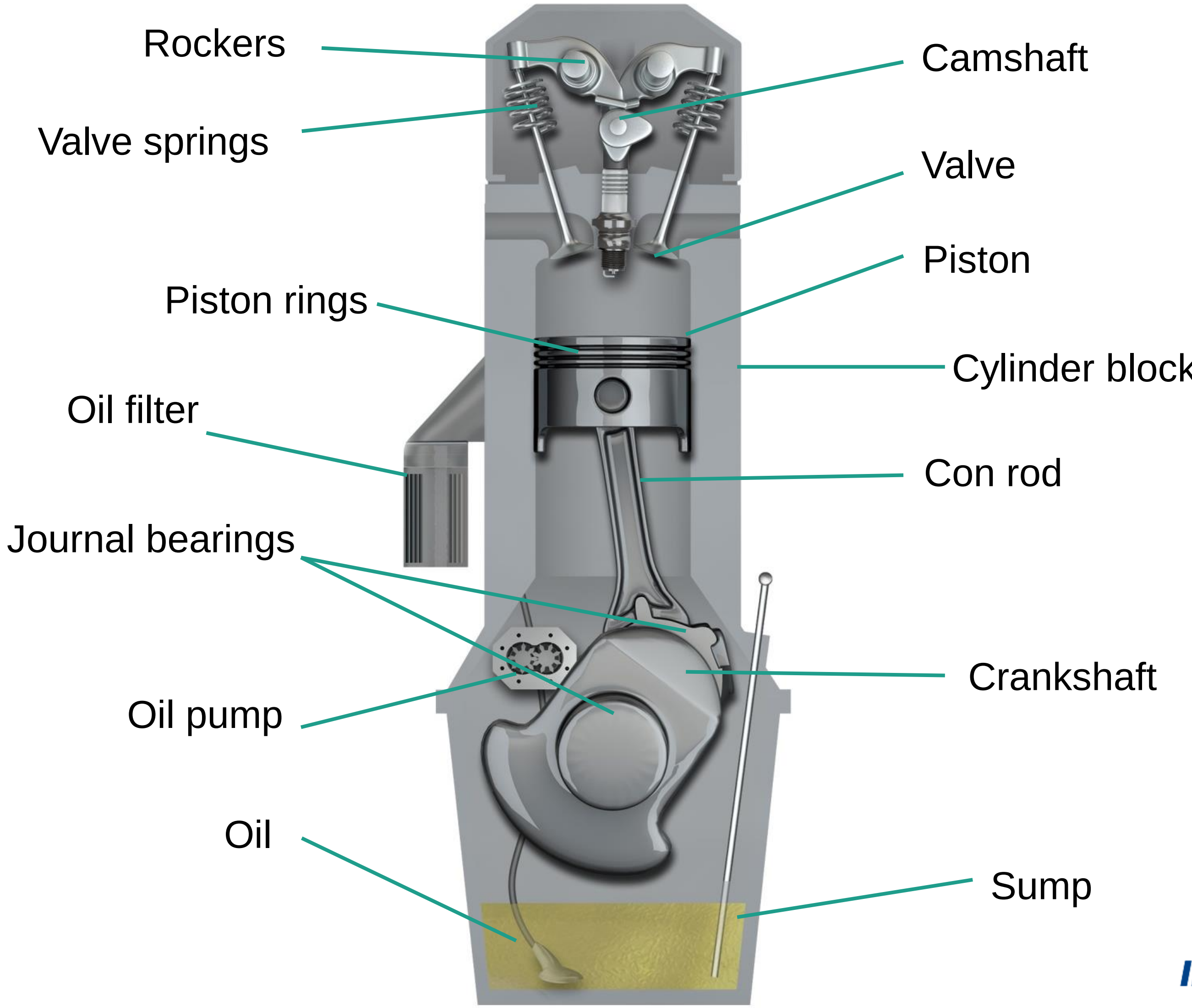
What is an internal combustion engine?

- Transform potential (chemical) energy into output work
- Today, energy comes from fuels (fossil or bio-source)

Main components of a 4-stroke internal combustion engine



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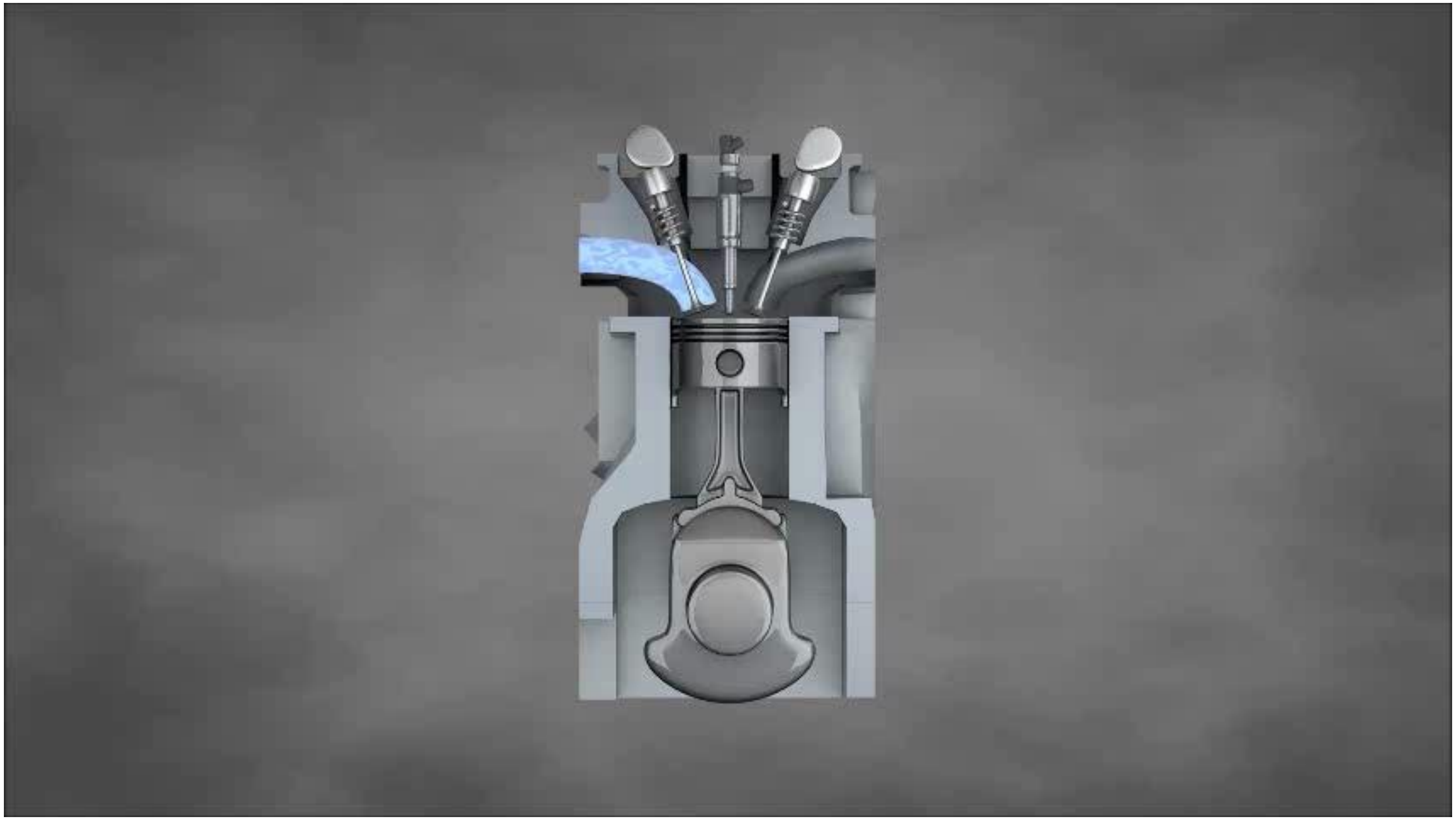
Four-stroke cycle – spark ignition (gasoline) engine



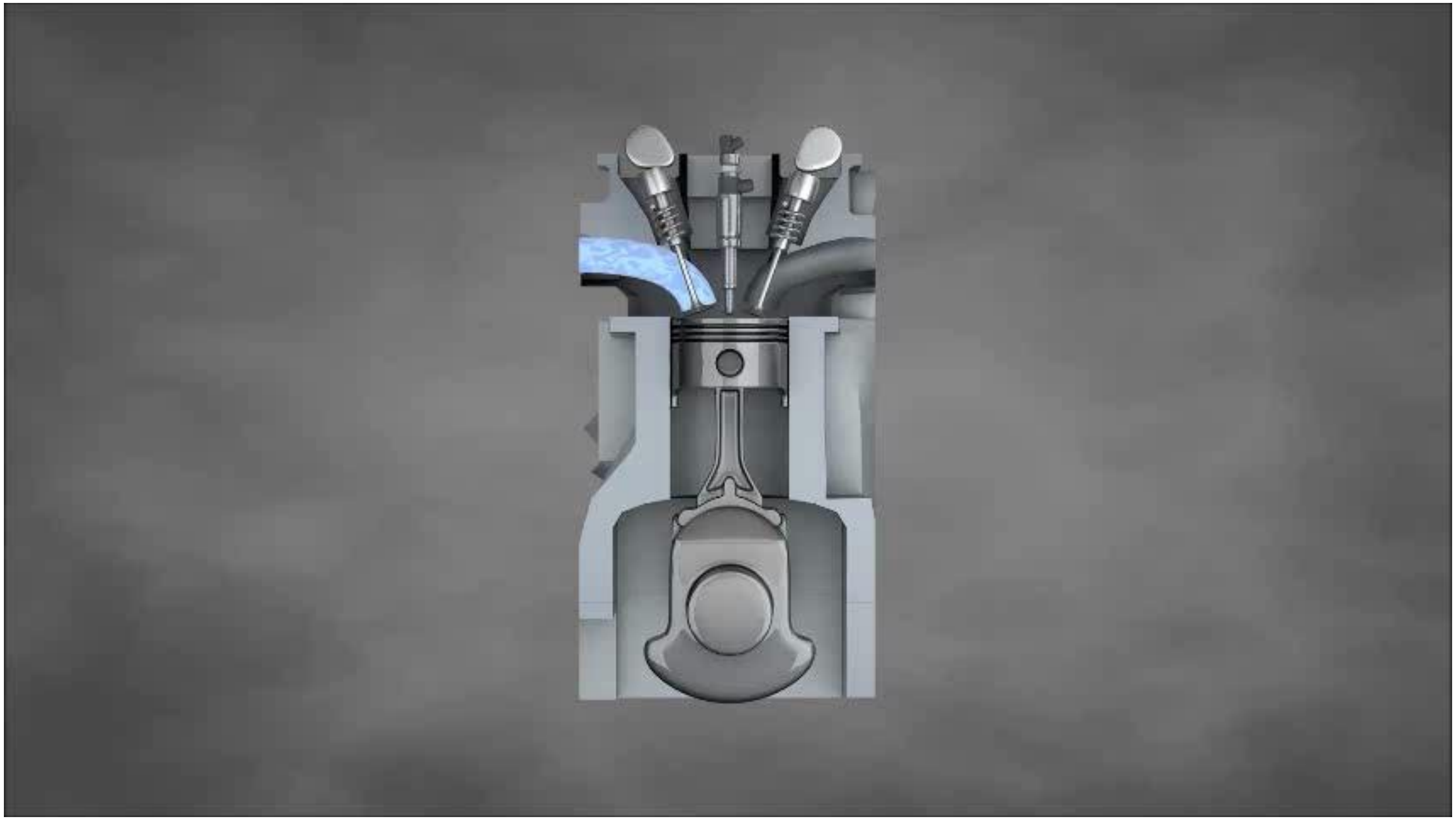
Intake-stroke: air induction

As piston moves down toward crankcase, intake valve(s) open(s). Pressure difference between intake and combustion chamber forces air (as well as fuel for port fuel injection) into cylinder.

Four-stroke cycle – spark ignition (gasoline) engine

Compression-stroke : mixture compression
Intake valve(s) close(s). As crankshaft rotates, piston moves up and compresses air-fuel mixture.

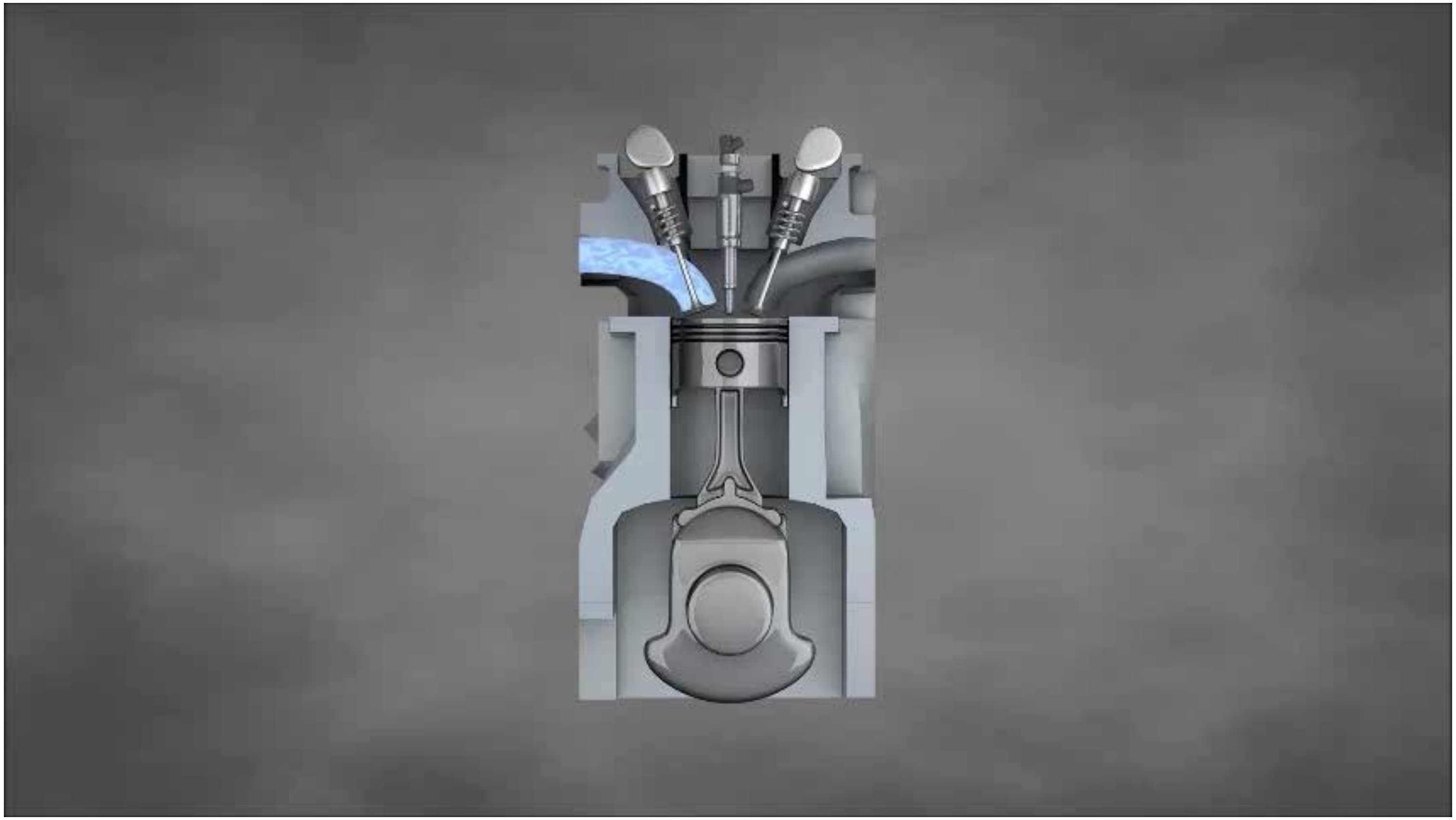
Four-stroke cycle – spark ignition (gasoline) engine



Expansion stroke: burn gas expansion (power)

Ignition system fires spark plug to ignite mixture just before piston reaches top of its travel. Expanding gases, which result from burning of fuel, force piston down to turn crankshaft.

Four-stroke cycle – spark ignition (gasoline) engine



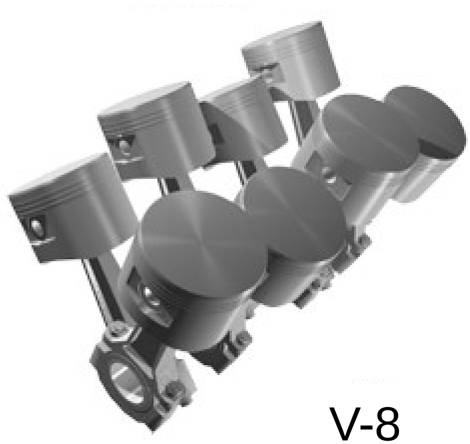
Exhaust stroke: burnt gas removal

After fuel charge is burned, exhaust valve(s) open(s). Due to pressure difference between combustion chamber and exhaust, Burned gases are removed out of cylinder.

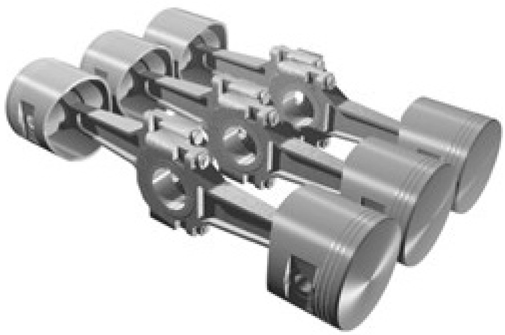
Engine capacity and configuration

- The capacity of the engine is the total displacement volume of all cylinders
- Configurations are normally referred to by their shape and number of cylinders
- Below are some common engine configurations

Straight/In-Line 4



V-8



Flat/Boxer-6

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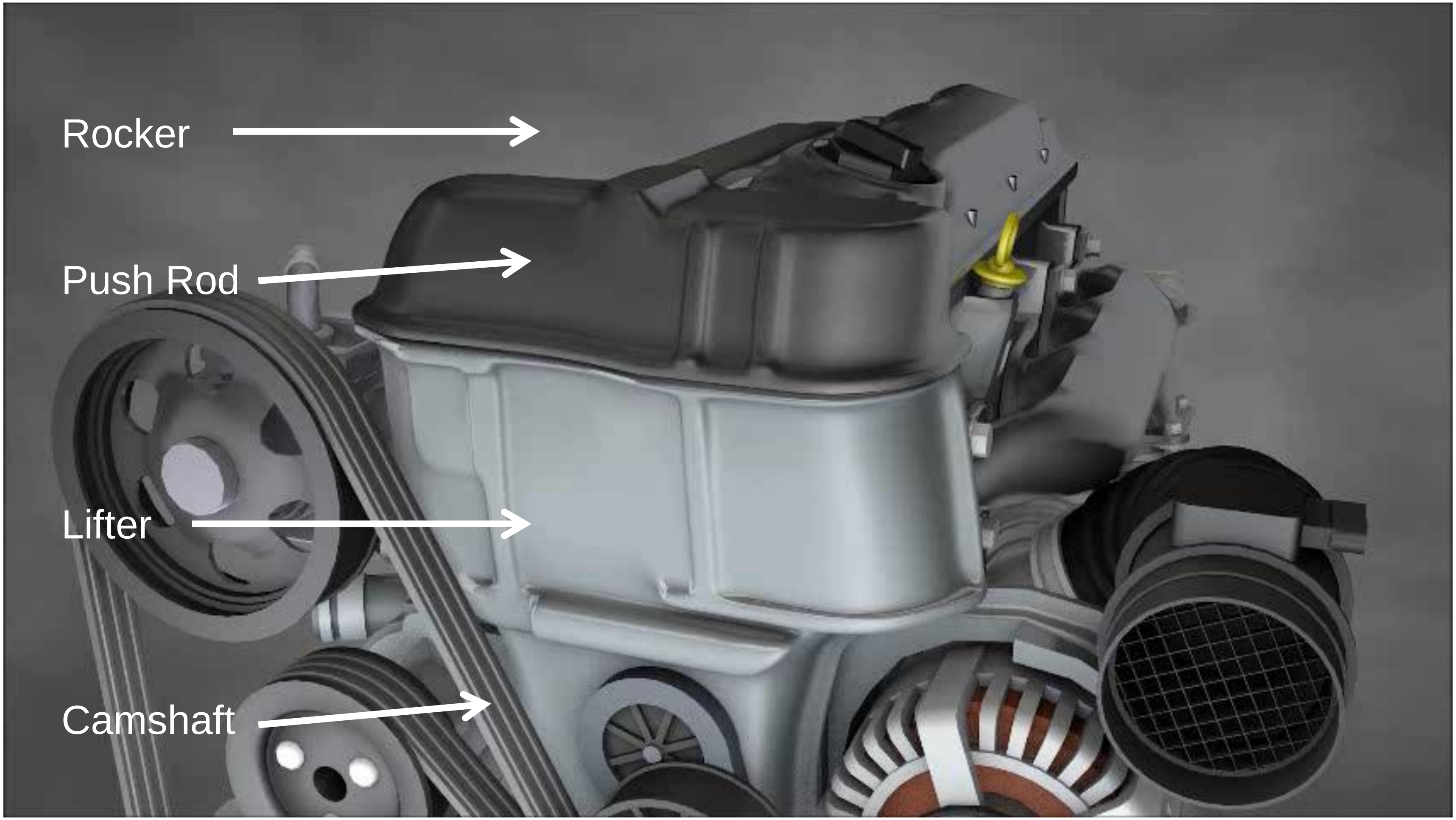
Different valve configurations

Pushrod



Different valve configurations

Single overhead cam (direct acting)

Different valve configurations

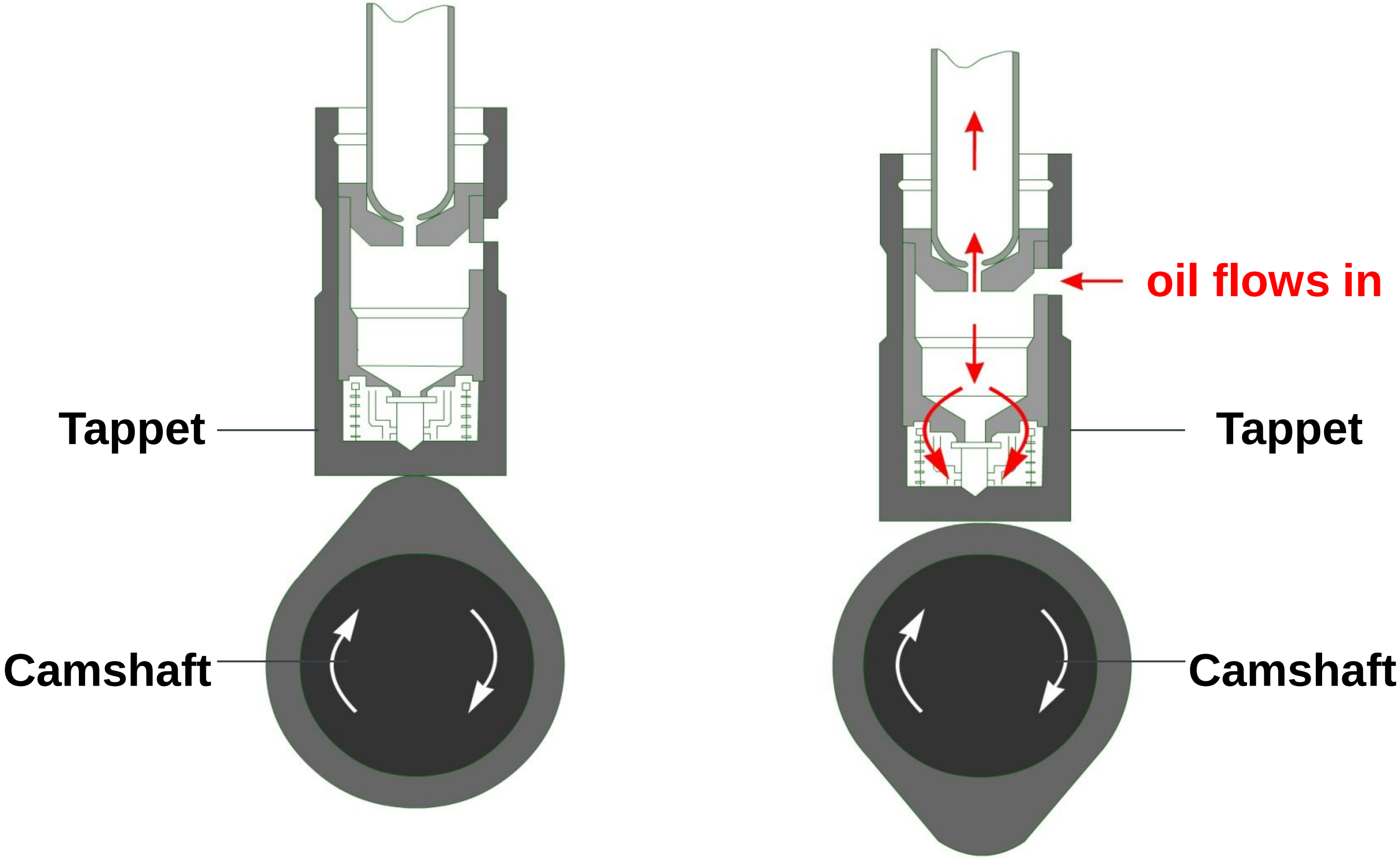
Single overhead cam

Different valve configurations

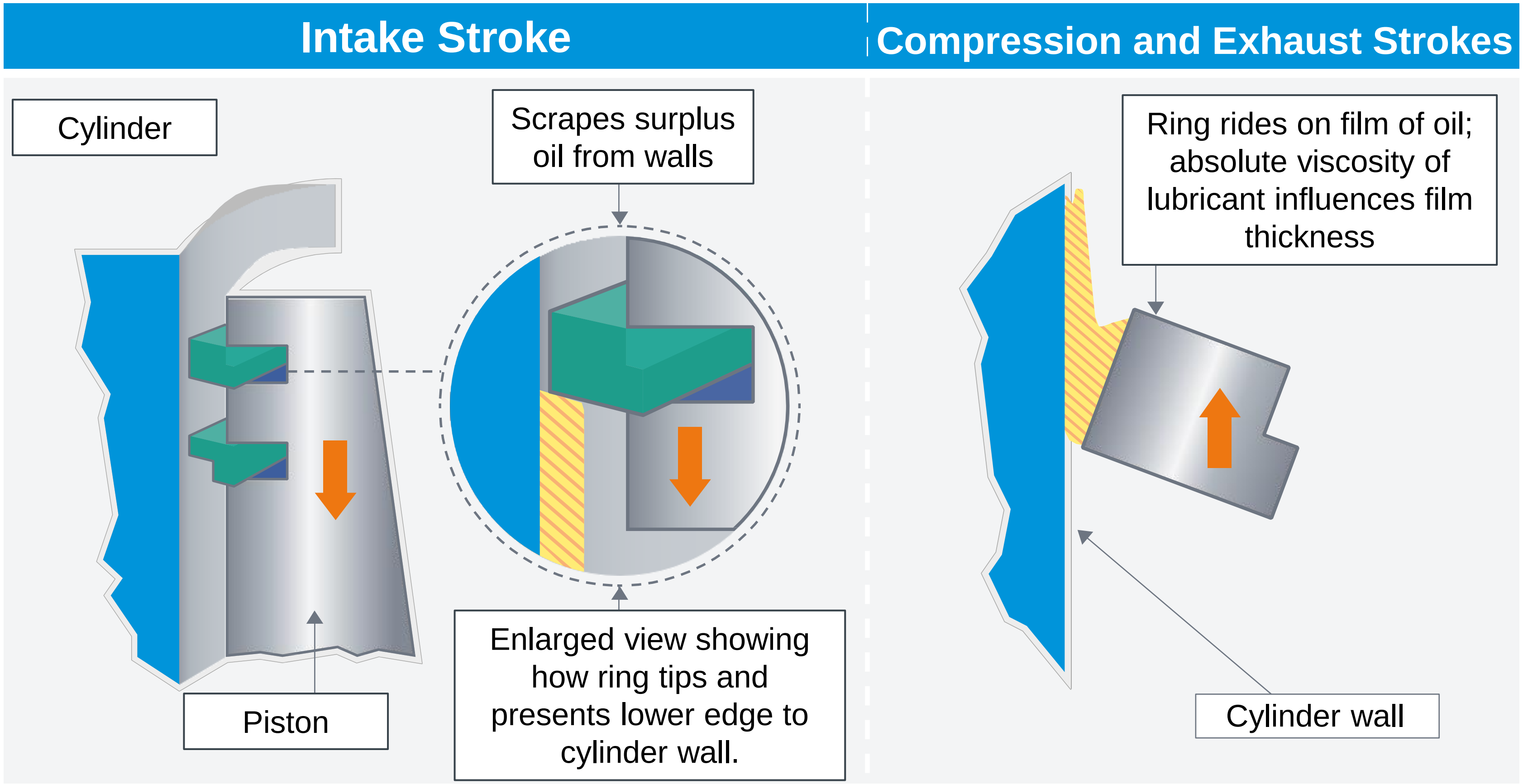
Double overhead cam

Variable valve timing (VVT)

Hydraulic valve lifter



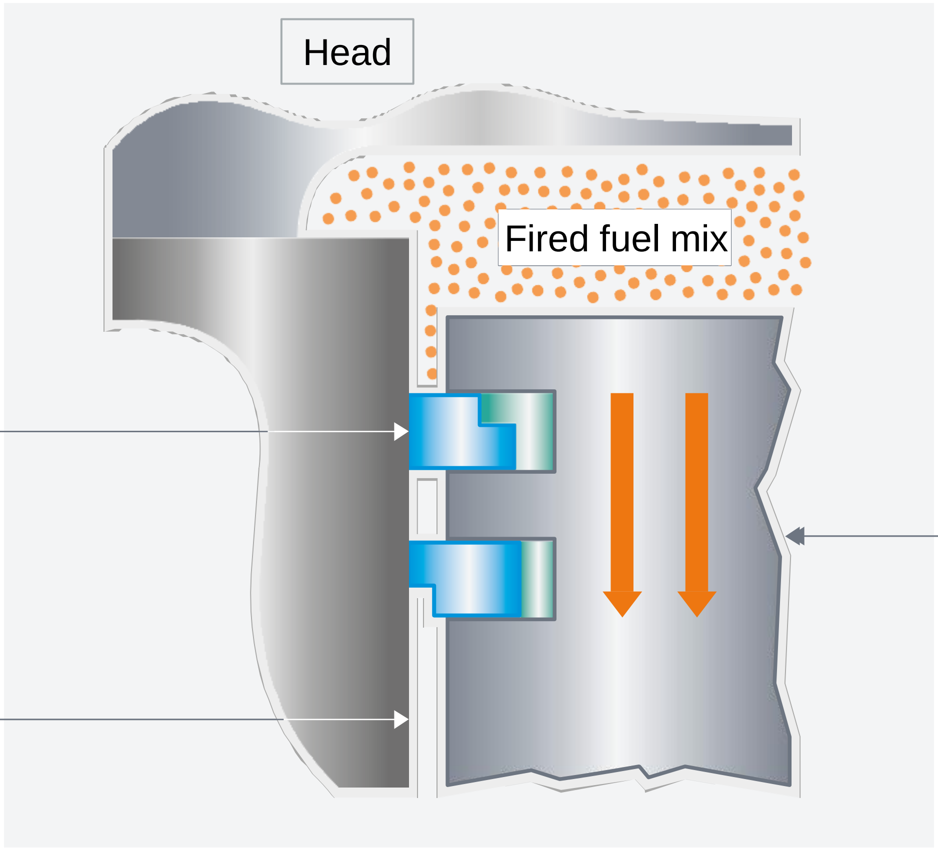
Piston ring action



Piston ring action

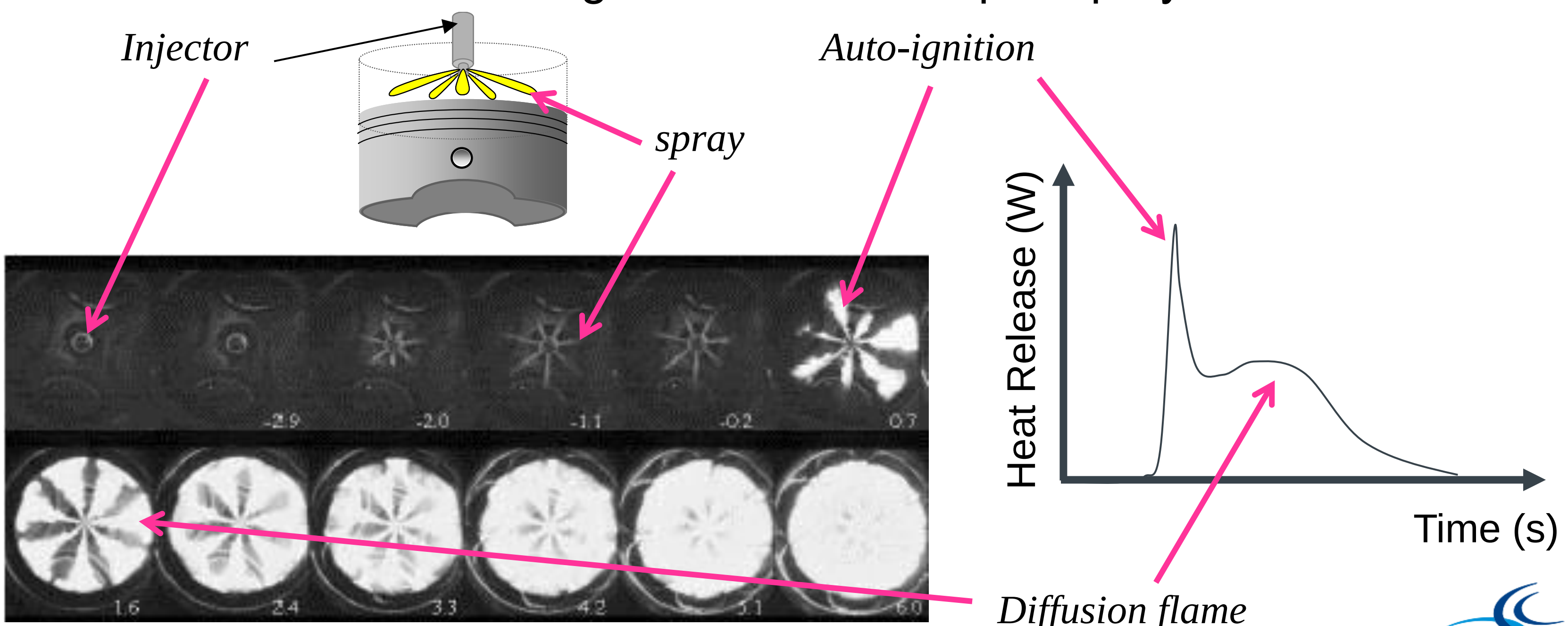
Firing Stroke

Firing pressure pushes ring down until entire ring face engages cylinder wall



Diesel engines – Basics

- Air (only) charging
- Fuel injection near the Top-Dead-Centre leading to a local fuel/air mixing
- Kinetic energy coming from spray injection (P_{inj}~2000 bars, V_{inj}~600m.s^{-1}) is converted into turbulent kinetic energy
- Auto-ignition of favourable mixture
- Combustion in a “diffusion” regime around the liquid spray



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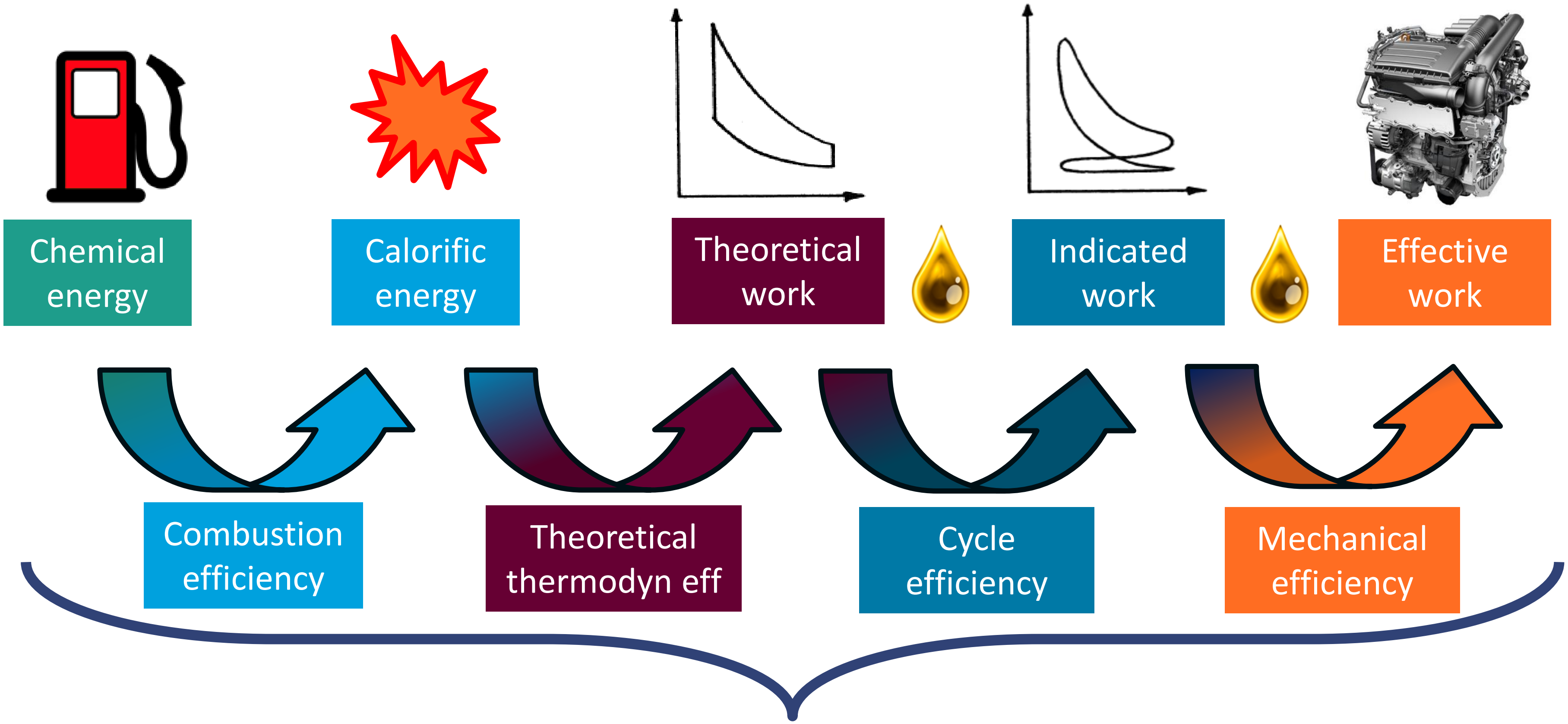
Efficiency

Overall efficiency is split in several efficiencies.
Efforts shall be made to increase each of them!



Overall efficiency

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Combustion process

- Ideal combustion is:

$$C_xH_y + \mathscr{R}\, O_2 + \alpha \mathscr{R}\, N_2 \rightarrow x\, CO_2 + y/2\, H_2O + \alpha \mathscr{R}\, N_2$$

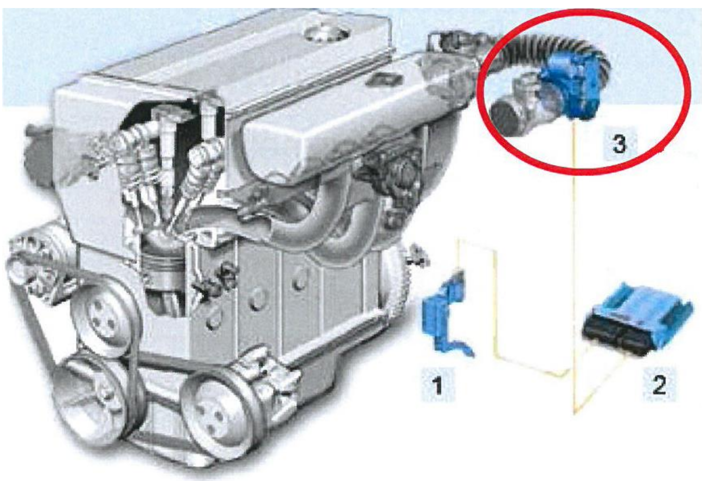
Where $\mathscr{R} = x + y/4$ and $\alpha = 0.79/0.21 \approx 3.76$

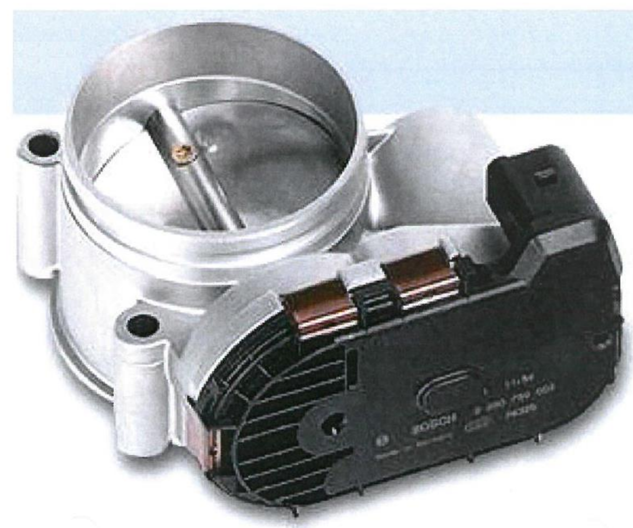
- Ideal burnt gases is an unreachable state because it contradicts chemical equilibrium theory
  - At best, chemical equilibrium can be reached, not complete fuel conversion into CO_2 and H_2O
- In reality, combustion products are:
  - C_xH_y, CO_2, CO, H_2O, H_2, N_2, NO, NO_2, etc.
  - Among which C_xH_y, CO, NO, NO_2 are pollutants

Spark Ignition engines

Fuel-Air mixing - throttling

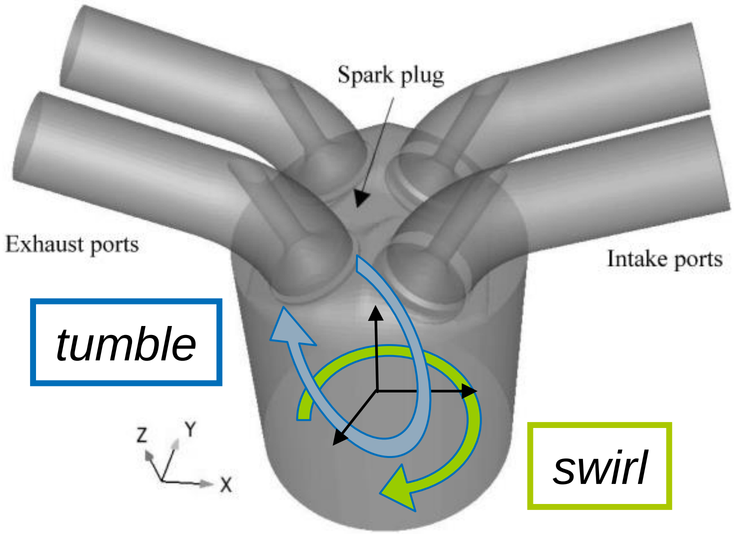
- Gasoline engines only combust in a relatively reduced range of air/fuel mixtures
- To control load, the throttle controls the air flow into a gasoline engine





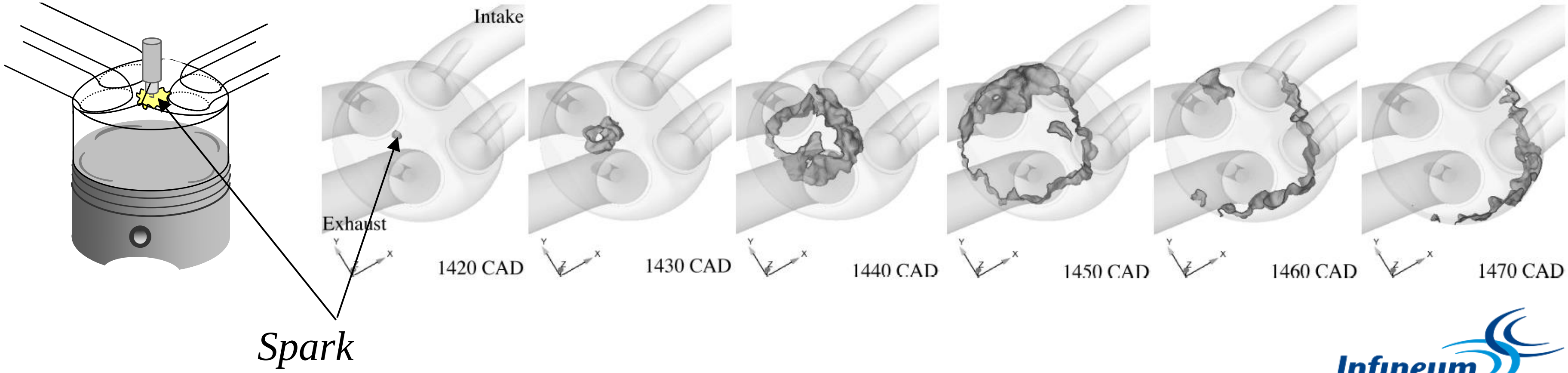
Fuel-Air mixing – air motion

- Main flow motion is tumble
  - Near Top Dead Centre, tumble motion is converted into turbulence
  - High turbulence level allows rapid flame propagation
    - Favourable for efficiency and stability



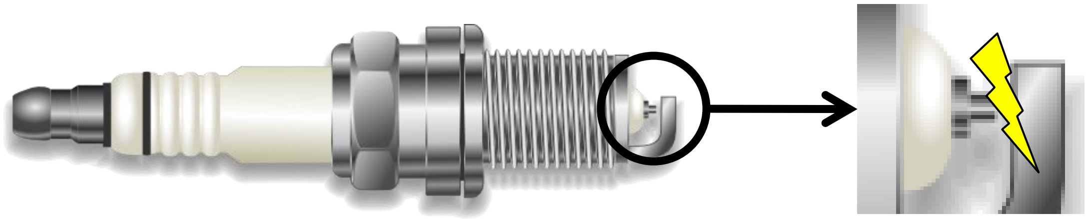
Spark-Ignited Engines - Basics

- Fuel (commercial gasoline, gas, etc.) can be directly injected within the combustion chamber (DI for Direct Injection) or within the air-path (PFI for Port Fuel Injection)
- Ignition is caused by a “spark” near the Top Dead Centre (TDC)
- Main combustion regime is the premixed flame regime
- Just after the ignition, initially spherical flame kernel propagates and is progressively wrinkled and accelerate by the turbulence



Ignition

- In Spark-Ignited engines, combustion is initiated by a controlled spark, generally a spark plug (usually electronic system)
  – External source of energy for the air-fuel mixture



- Delivered ignition energy usually far greater than “needed energy” to avoid any misfire and good combustion stability

Development of technology over time

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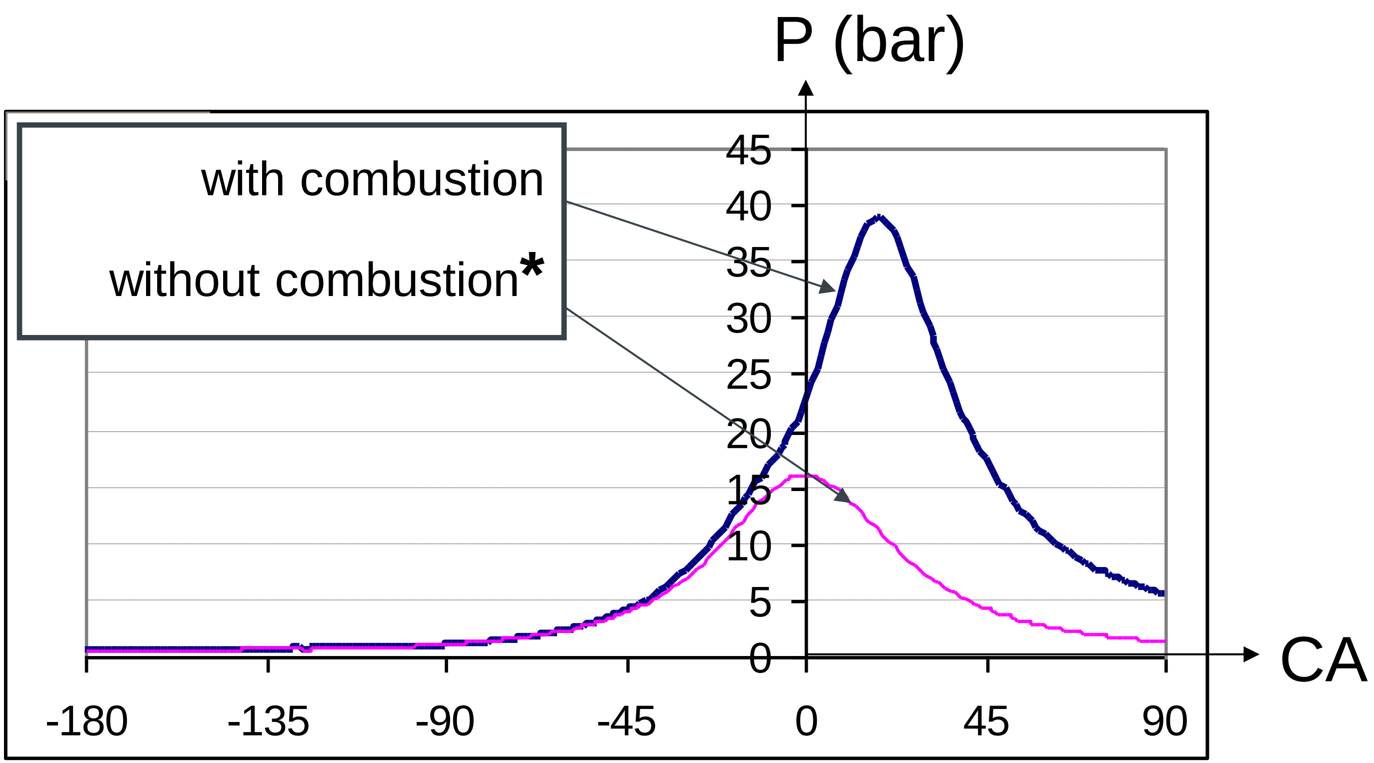
SI engine In-cylinder pressure

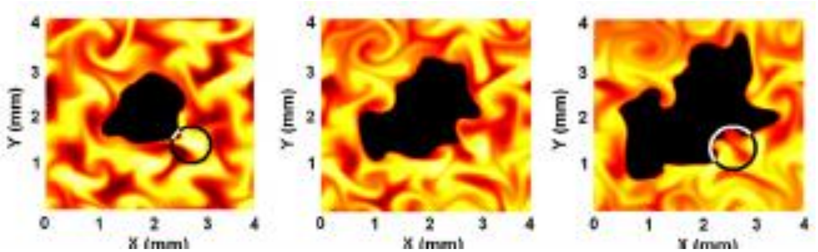


* *In that case, pressure increase is only due to piston movement.*

SI engine - Combustion process

- 1st step: ignition
  - Electrical energy is released at the spark plug at a given time ("spark timing")
  - Delivered energy typically 20 to 100 mJ, depending on the difficulty to ignite the mixture
  - Ignition process more difficult in:
    - lean mixture
    - fouled spark plug

- 2nd step: flame occurrence
  - Plasma kernel evolution toward early kernel flame
  - Propagation thanks to diffusion of chemical radicals and heat ahead of flame front



- 3rd step: flame propagation
- 4th step: flame extinction, flame can disappear because of:
  - Lack of reactant (unsuitable local air / fuel ratio)
  - Heat losses at the wall
  - Dead volume (crevice, piston rings, …)

➡ This results in emissions of unburnt hydrocarbons (HC)

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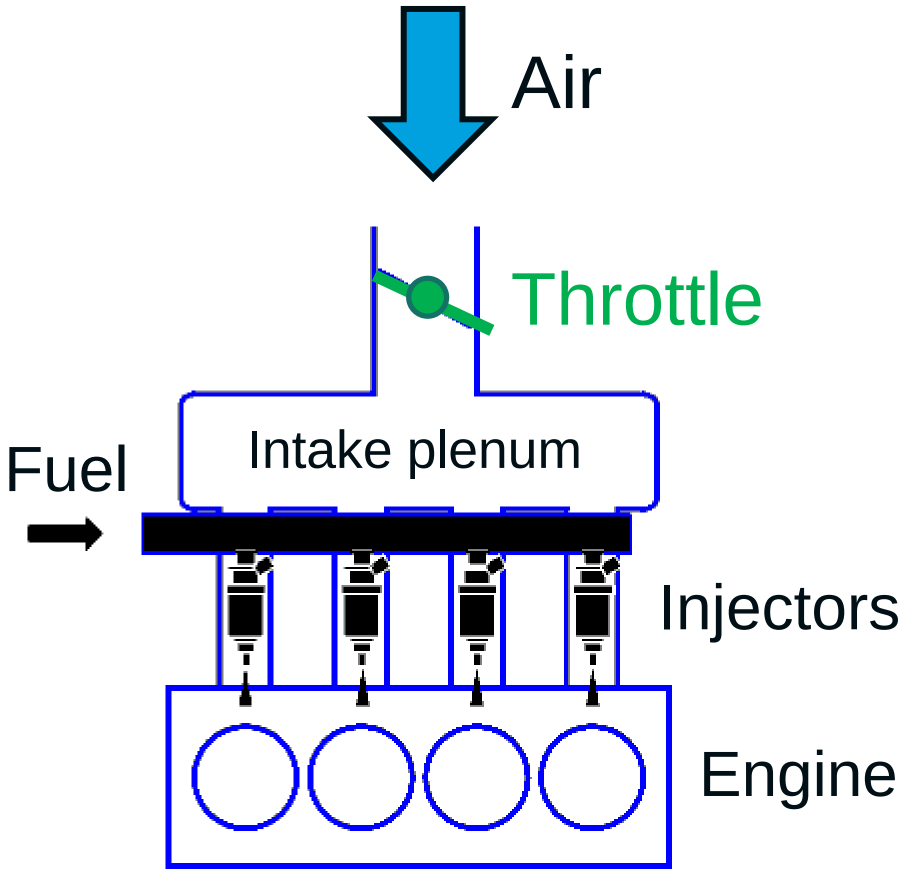
Fuel-air mixing - Multi-point fuel injection



- Single injector is obsolete
- For better control of fuel distribution from cylinder to cylinder, multipoint injection (MPI) is preferably used
- Fuel is injected into the inlet port, usually whilst the inlet valve is closed
- Generally targeted on the back of the valve to maximise heat transfer

Ignition

- Higher energy deposit
- Better control on spark distribution to appropriate cylinder by electronics
- Variable level of energy
- Last generation: Corona Discharge Ignition (CDI)
  - More powerful ignition source
  - Fuel/air mixture is ionised and forms a plasma
  - Improved lean and stratified ignition ability
  - Higher dilution (EGR) tolerance
  - Higher pressure
  - Faster burn rates for combustion stability

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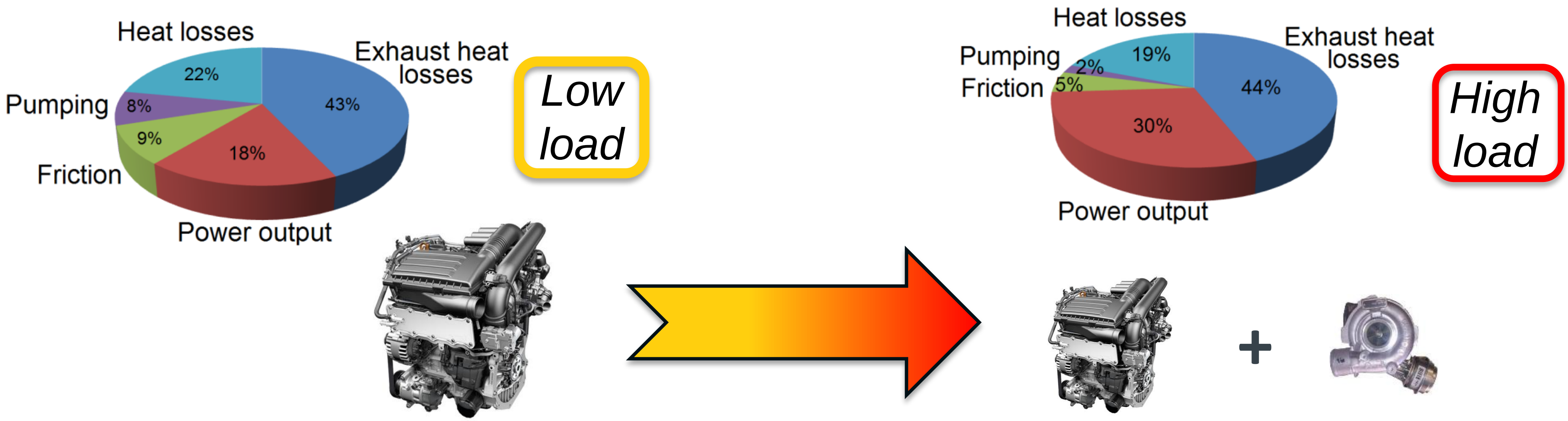
Downsizing engines



- Smaller engine while maintaining performance
  - Shift from low to high loads
    - Reduction of pumping losses
    - Better efficiency
  - Fuel economy
- Additional technologies:
  - Mostly achieved through increased use of boosting technologies
  - Often coupled with GDI (Gasoline Direct Injection)
- Today, typical gain is about 10 to 20% in fuel consumption

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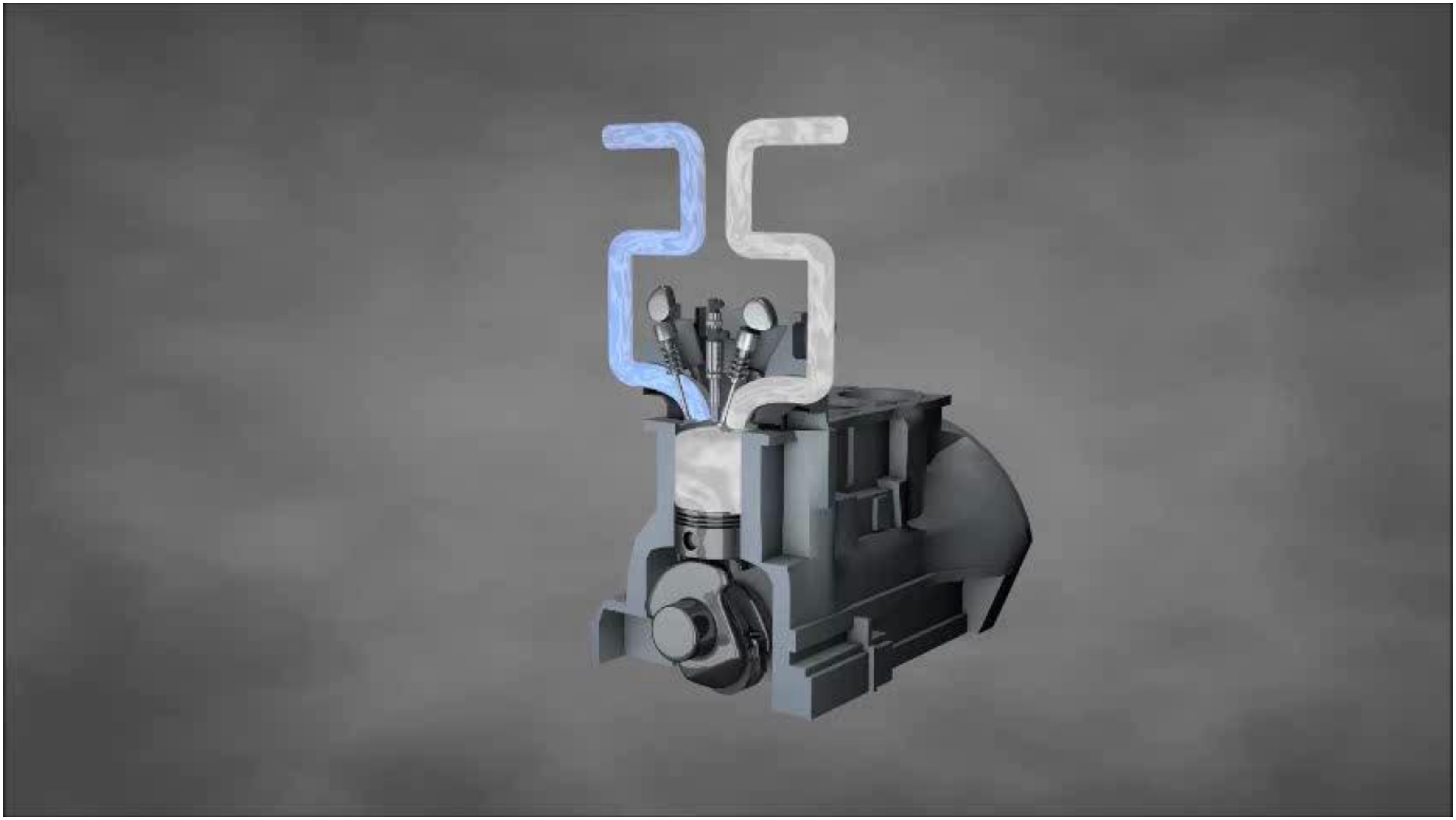
Turbocharging and supercharging



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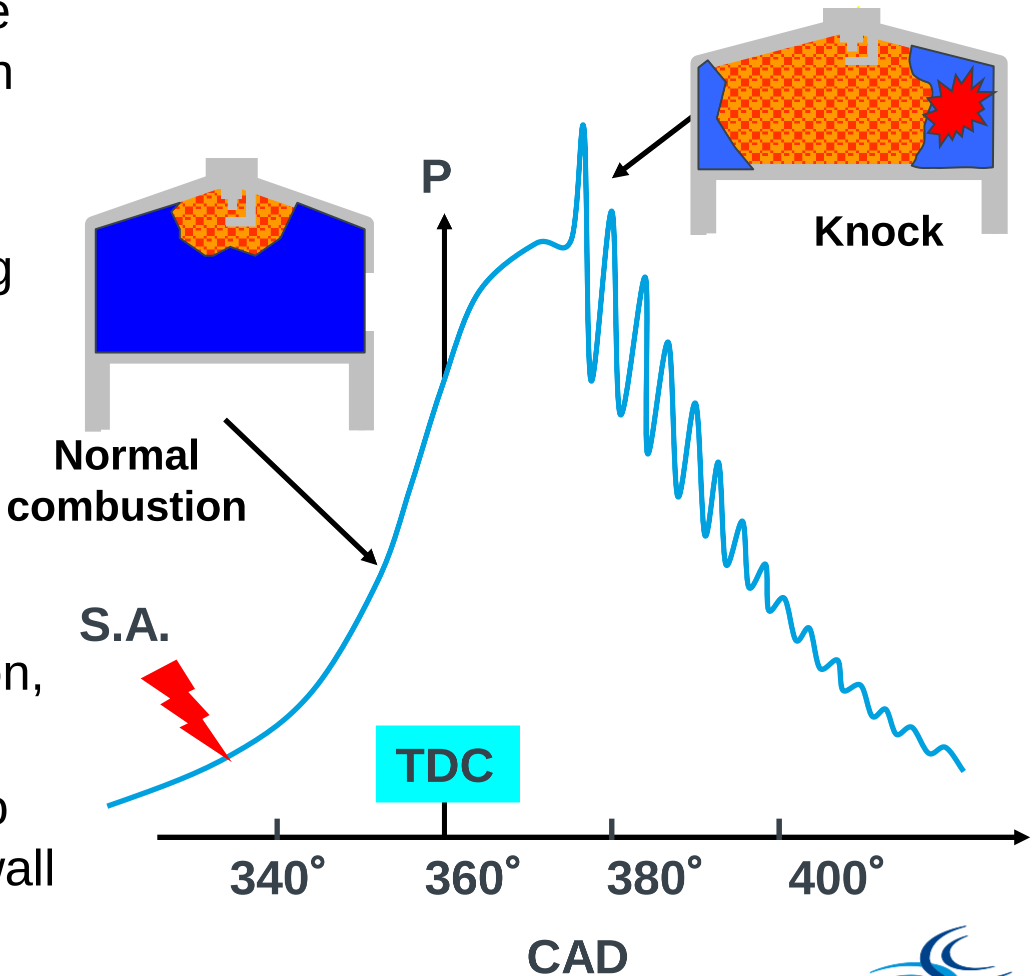
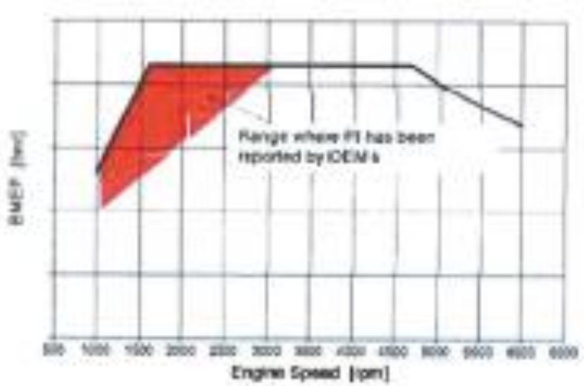
Downsizing engines - Knock

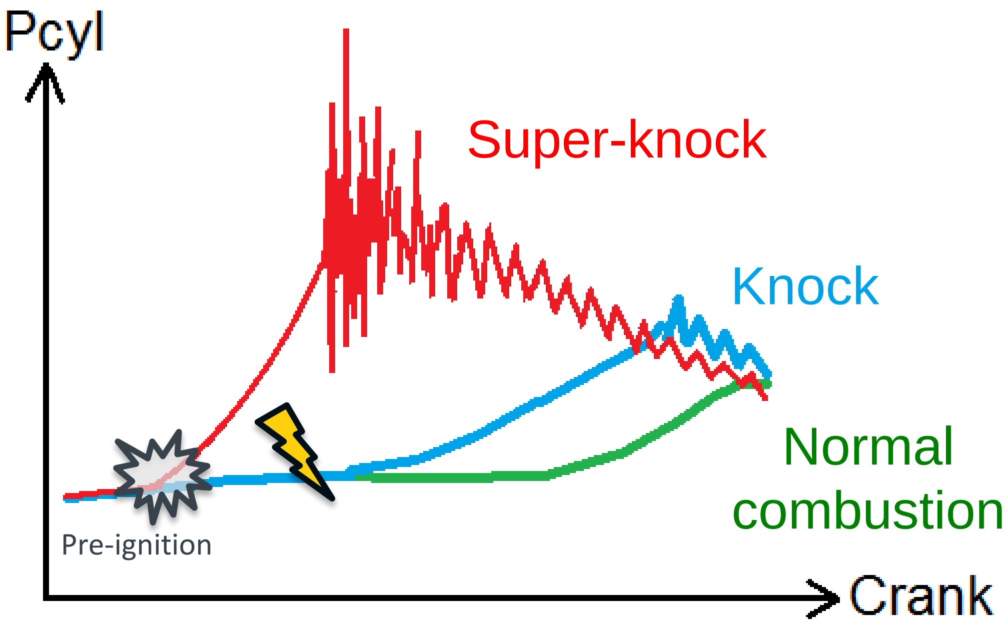
- Spontaneous combustion of the unburnt charge (end-gas) which has not yet passed through the flame front
- Apparition after spark plug firing
- Very quick combustion
- Pressure waves causing characteristic metallic pinging sound
- Damage to the combustion chamber, generally on the piston, the valves, the cylinder head…
- These degradations can lead to valve, piston or cylinder head wall piercing



Downsizing engines - LSPI (Low-Speed Pre-Ignition)

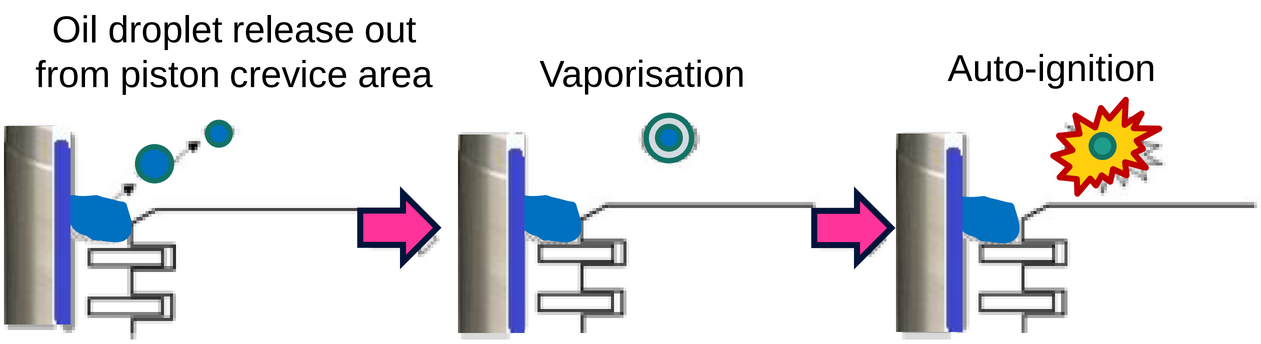
- LSPI is a pre-ignition event often followed by heavy-knock
  - Very early stage of combustion (before spark was triggered = pre-ignition)
  - Initial combustion is relatively slow and similar to normal SI combustion
  - Sudden increase in combustion speed = super-knock
- LSPI events appear sporadically and disappears without the uses of engine control system

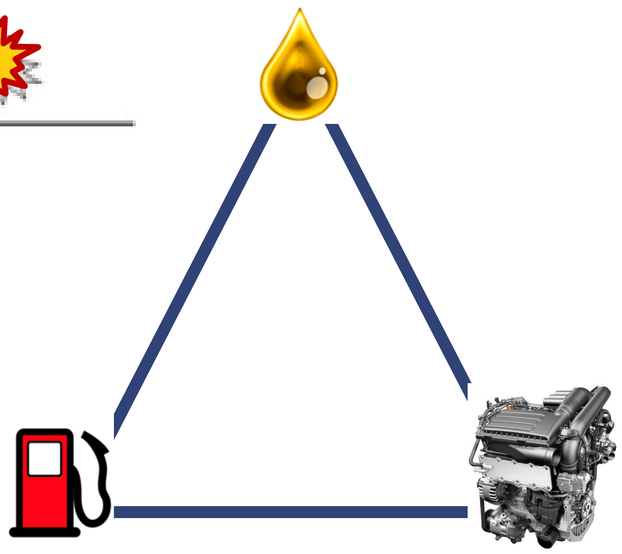




Downsizing engines - LSPI (Low-Speed Pre-Ignition)

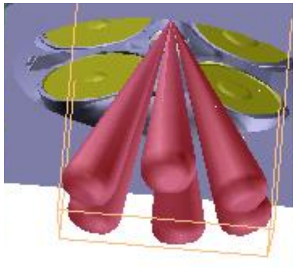
- LSPI events are rare (few LSPI events over 10,000 cycles)
- There are many theories for explaining LSPI sources
- The prevailing theory to date is the auto-ignition triggered by oil

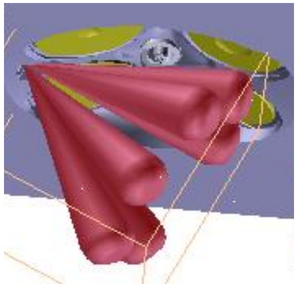




Gasoline Direct Injection (GDI)

- Injection takes place inside the combustion chamber, thanks to an injector specially designed
- The injector may be located
  - in central position
  - in lateral position





- Phasing of the injection (start of injection) has great impact on performance
  - Too early injection creates a fuel impact on the piston smoke emissions
  - Too late injection leads to poor homogenisation (and impact on piston)
- Pressure injection is typically 100-200 bar to ensure:
  - Homogenisation at low load
  - Short time to inject the whole charge (only during the intake stroke) at high speed – high load

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Gasoline Direct Injection (GDI)

- Advantage: fuel droplet vaporisation requires heat taken from the in-cylinder air
  - Air is cooled down: it is called "cooling effect".
    - Reduction of knock
    - Better volumetric efficiency (air density is increased)
  - increased torque (~ 5%)
  - greater downsizing can be achieved
- Drawbacks: cost and complexity
  - Degraded homogenisation compared to PFI engines
    - CO emissions, combustion stability
  - Risk of fuel impact on the piston
    - Smoke and particle emissions
  - Injector fouling must be avoided

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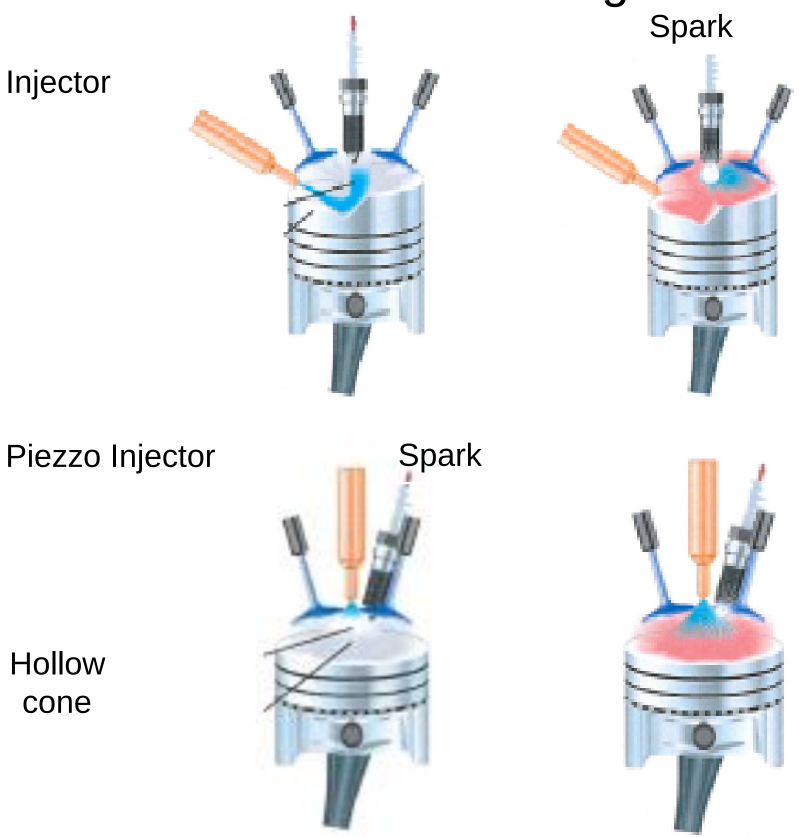
Gasoline Direct Injection (GDI)

- Charge cooling effect allows higher compression ratio (fuel efficiency)
- Fuelling control permits to reduce transient issues and to pollutant emissions
- Limit knock
- There exist different strategies:



Wall-guided GDI

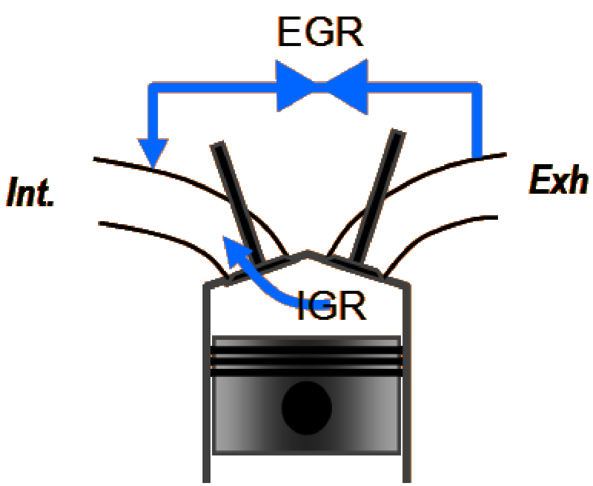
- Injected fuel is swirled around when it hits the piston floor

Spray-guided GDI

- Injected fuel is sprayed onto piston head

Exhaust Gas Recirculation (EGR)

- 2 ways for increasing dilution by inert species
  - (External) Exhaust Gas Recirculation (EGR)
  - Internal Gas Recirculation (IGR) which requires variable valve timing + valve overlap



- EGR is widely used at part load because of
  - NOx reduction (lower combustion T)
  - Heat transfers and pumping reduction
- A major difficulty is to achieve a high EGR rate at high load
- Decrease knock intensity and LSPI probability
- But:
  - Degradation of combustion stability at low loads
  - Management of transients

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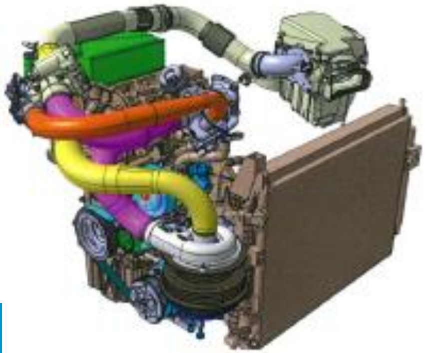
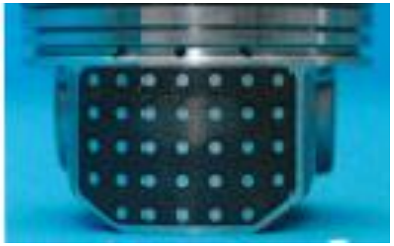
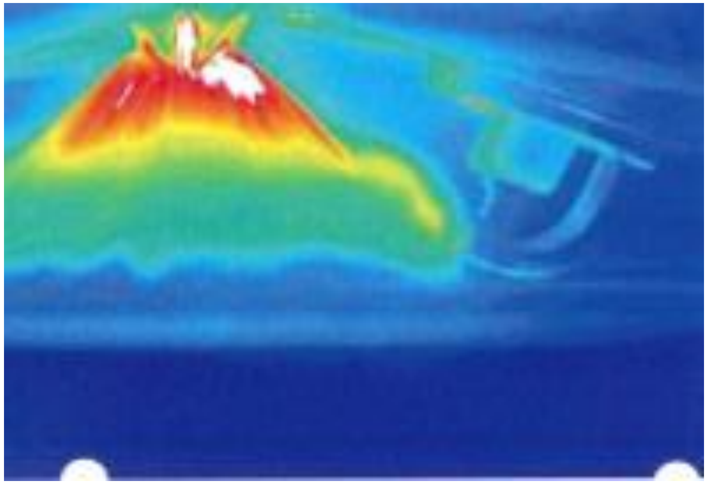
Other SI engine technology developments

- Increasing use of bio-fuel
- Hyboost: combination of downsizing, e-boost, economical energy storage and micro-hybrid (stop-and-start)
- New low-friction material design
- Stratified lean combustion







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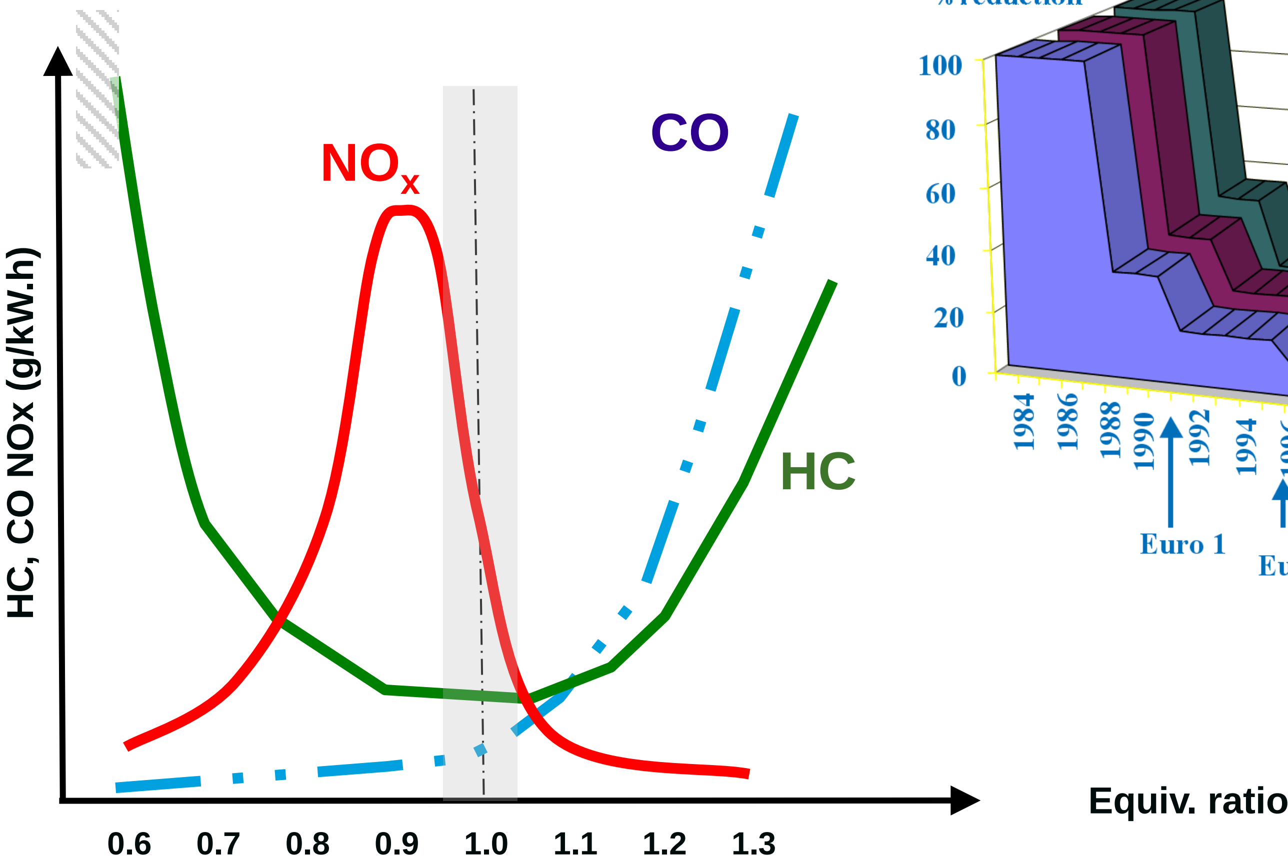
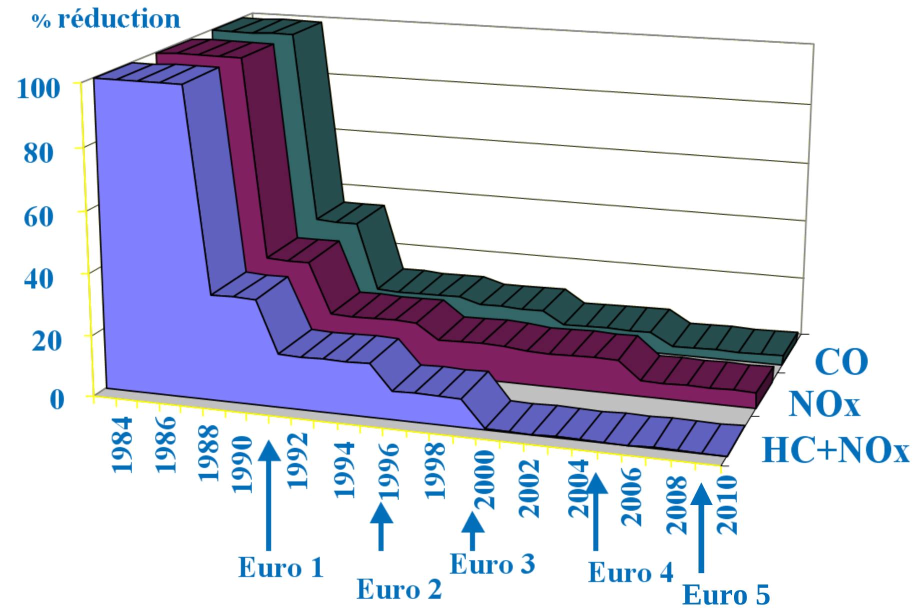
Raw emissions

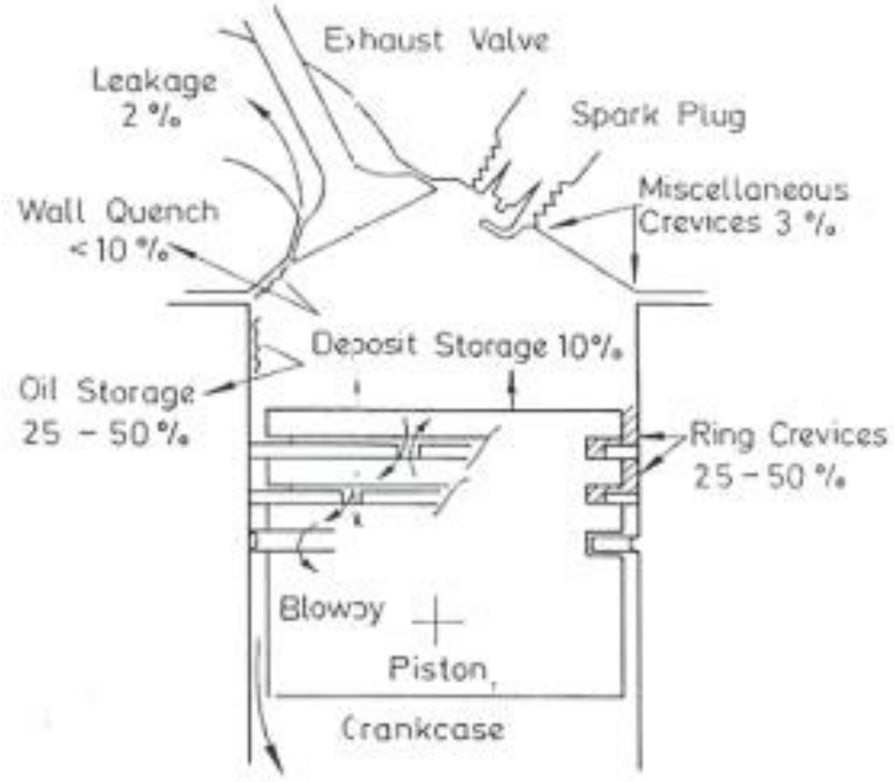
- Main pollutants from SI engines are CO, HC and NOx





Raw emissions - HC formation process

- Storage of the air/fuel mixture in the combustion chamber "dead" zones during the compression stroke
- Adsorption/desorption of HCs into the oil layer
- Trapping of the air/fuel mixture in the combustion chamber deposits
- Flame quenching at the cylinder wall
- HC formation increased the impact of liquid fuel on the chamber walls



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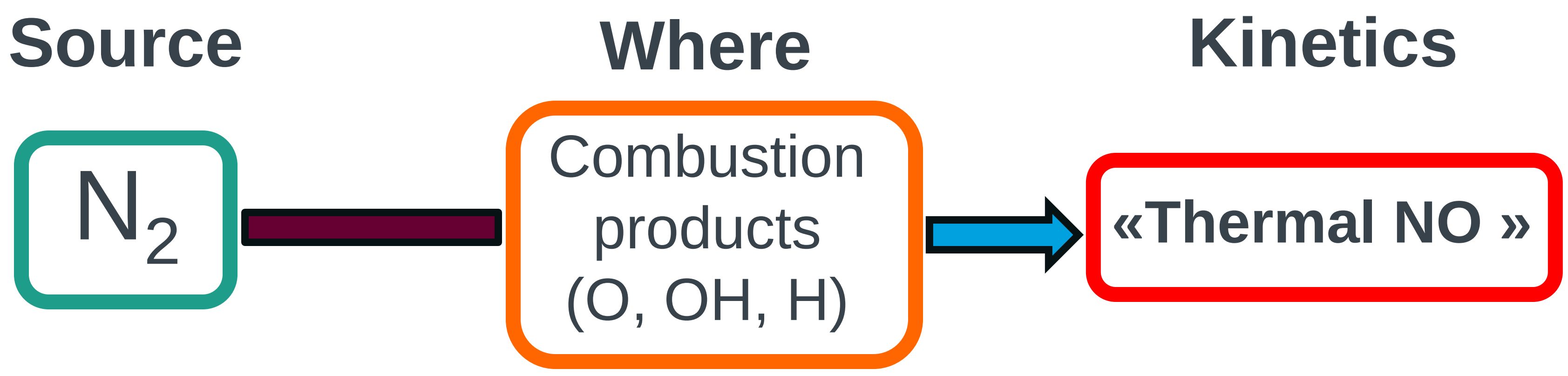
Raw emissions - NOx

- NOx are mainly formed thought a “Thermal” process
  - The main source is N_2 in the air
  - High temperatures prone NOx formation
  - Everything that dampens in-cylinder temperature reduces NOx
    - Introduction of dilution by EGR



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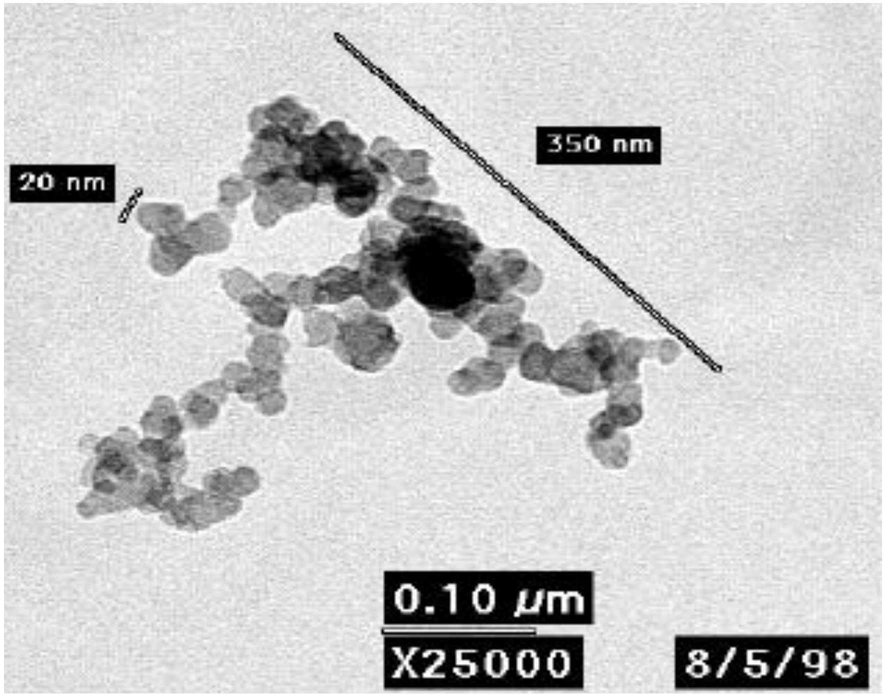
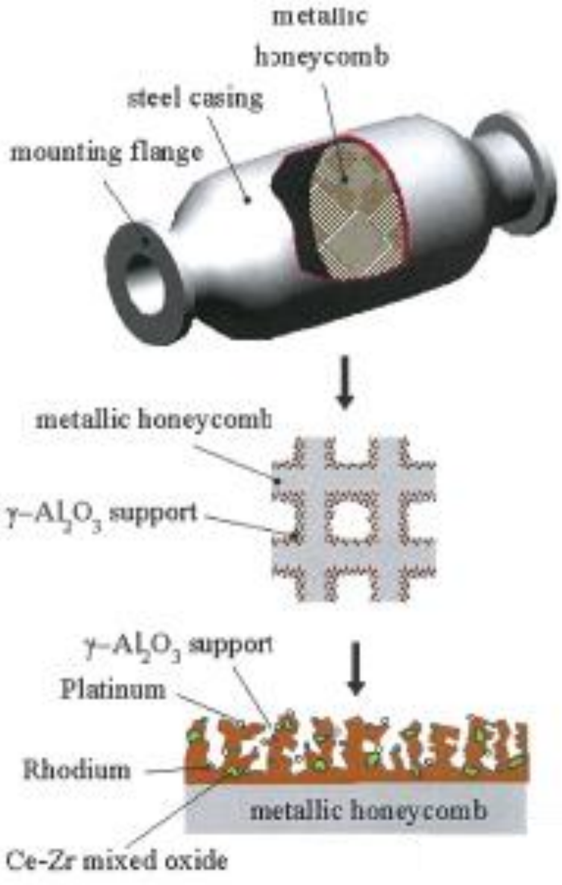
Raw emissions - Particles

- Locally rich mixtures create smoke inside the combustion chamber
- Smoke and particle emissions may be an issue for GDI engine
- A regulation will appear with next European regulation on pollutant emission:
  - limitation of the mass of particles emitted: < 5 mg/km (Euro5)
  - limitation of the number of particles emitted (Φ>23nm):
    - 6.10^{12} particles/km (Euro6b in 2014)
    - 6.10^{11} particles/km (Euro6c in 2017)



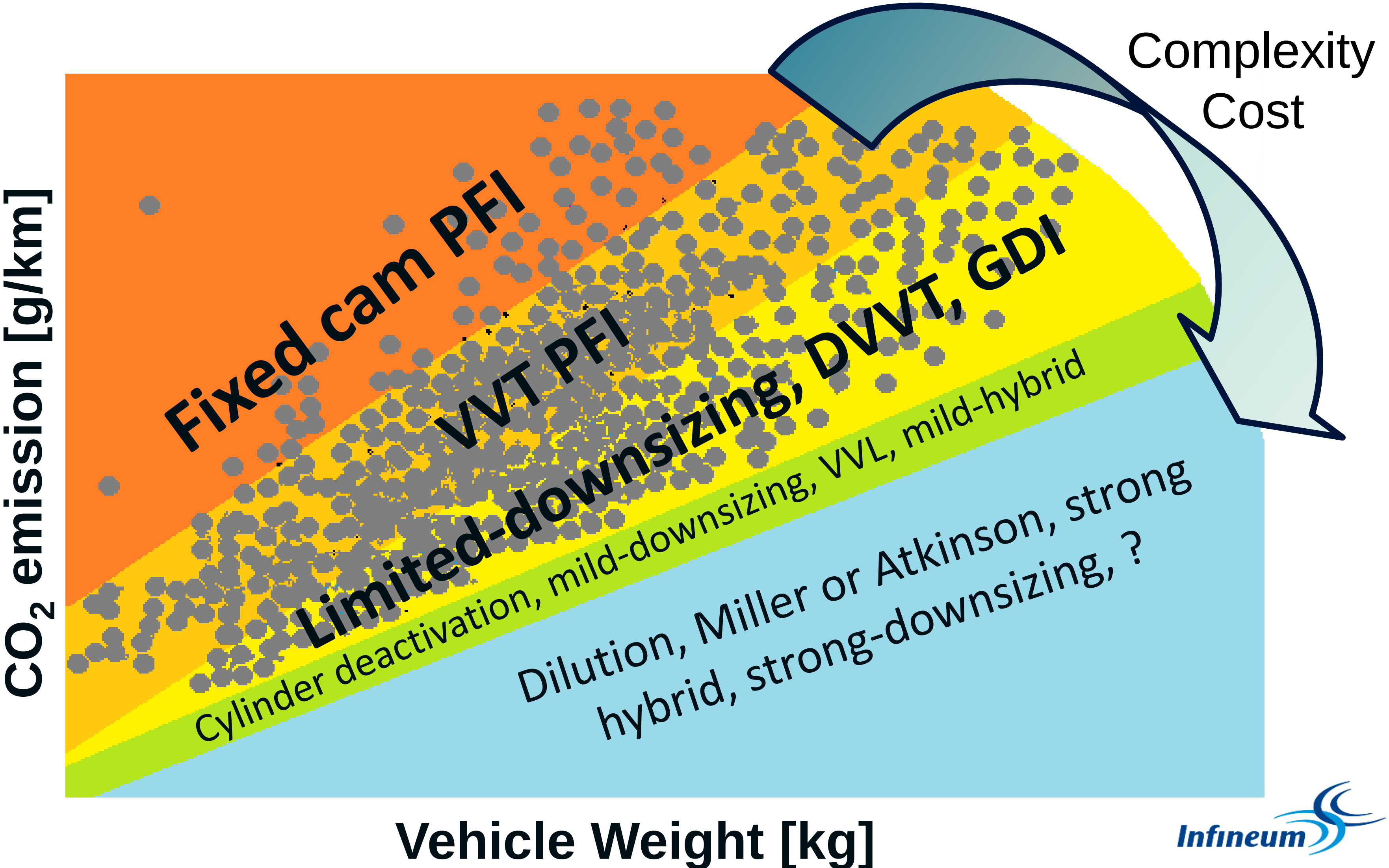
Raw emissions - Catalytic converter

- A 3-way catalyst can simultaneously convert HC, CO and NOx
- Very close stoichiometry mixture (± 0.5%) is needed
- TWC contains precious metal (Pt, Rh, Pd, etc.)
- TWC is only efficient after reaching a suitable temperature
- For cold start, dedicated engine strategy is needed
- Temperature is achieved after few seconds (about 15-60 s)



Source [Ricardo]

SI engines conclusion
Evolution of technology



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Diesel engines

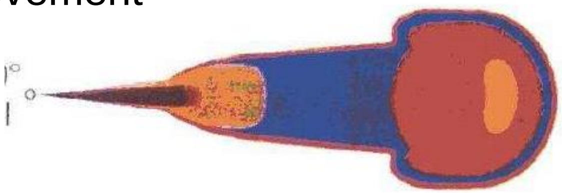
Diesel combustion

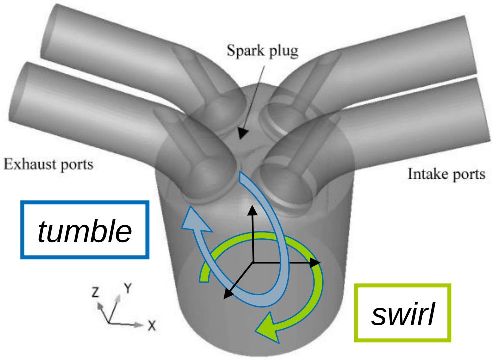
- Combustion is initiated by spontaneous self-sufficient auto-ignition
- Combustion spreading is controlled by
  - Injection timing(s)
  - The number of injection(s)
  - Injection duration
  - Dilution (EGR) inside the cylinder

Diesel – combustion process

- 1st step: injection/vaporisation
  - Fuel, forced through small holes under very high pressure, is torn-up into small droplets (so-called "atomisation")
  - Air is "entrained" into this jet
  - Evaporation occurs at the fringes so that droplets become non-uniform clouds of vapour and air
  - Local premixed fuel/air mixture is created
- 2nd step: auto-ignition / premixed
  - Auto-ignition delay and combustion heat release are triggered by fuel characteristics
- 3rd step: diffusion of the combustion to the rest of the chamber
  - Depends on engine geometry (bowl)
  - Turbulence and combustion spreading are linked to the spray and the swirl movement

[source: CORIA]

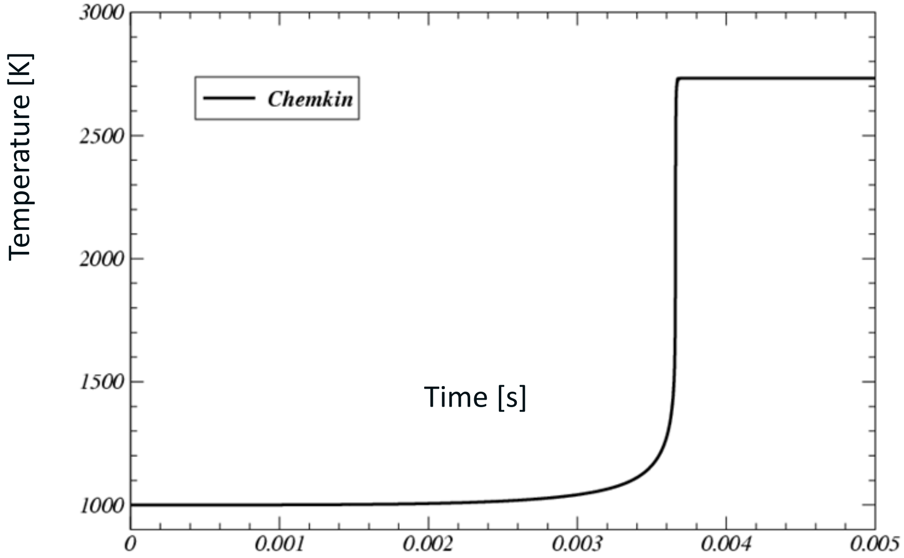




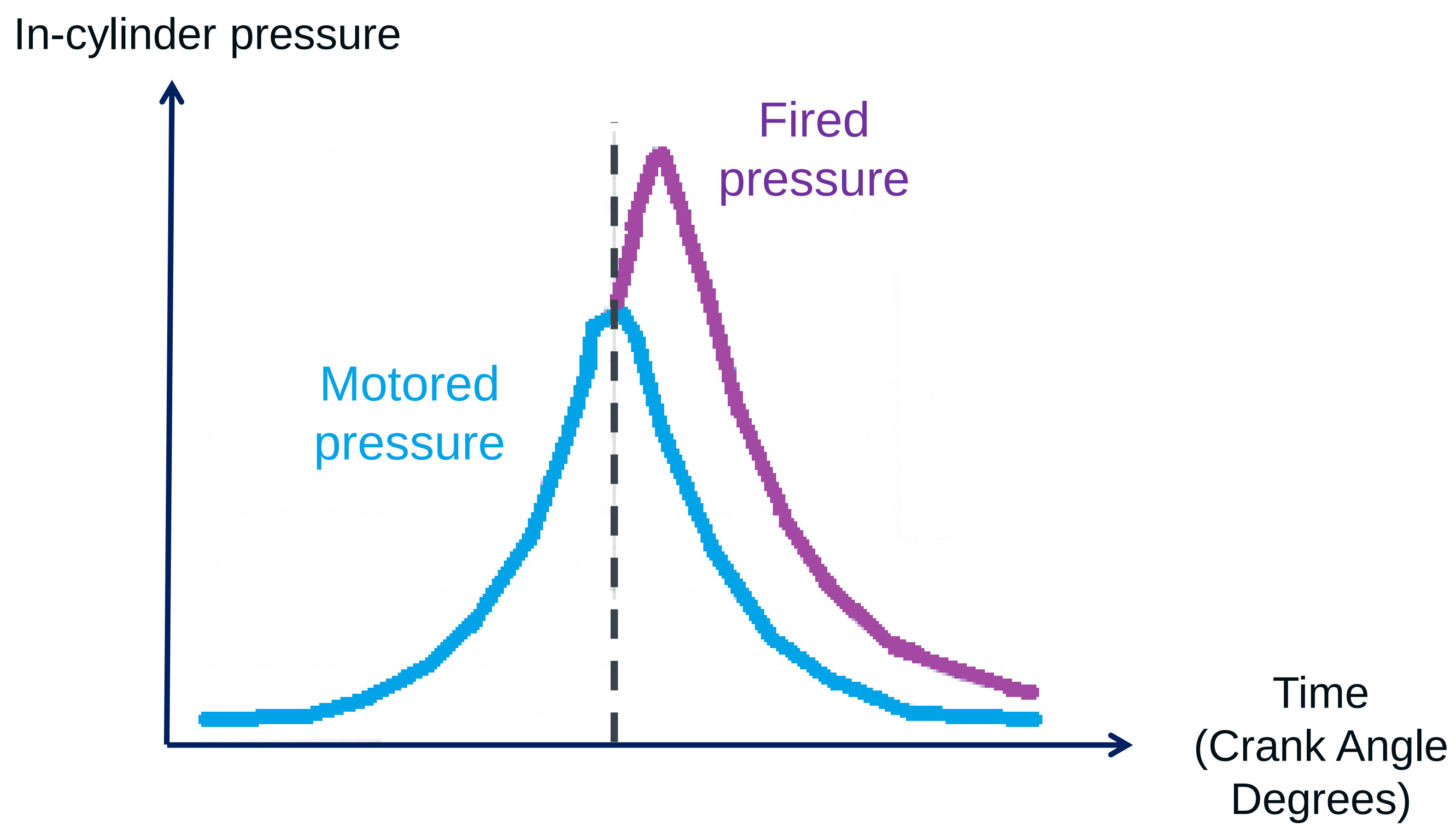
Diesel – combustion process

- Auto-ignition depends on:
  - Pressure
  - Temperature
  - Fuel/Air equivalence ratio
  - Dilution
  - Nature of the fuel
  - Turbulence (micro-mixing)

N-heptane/air 20 bar stoichiometric mixture

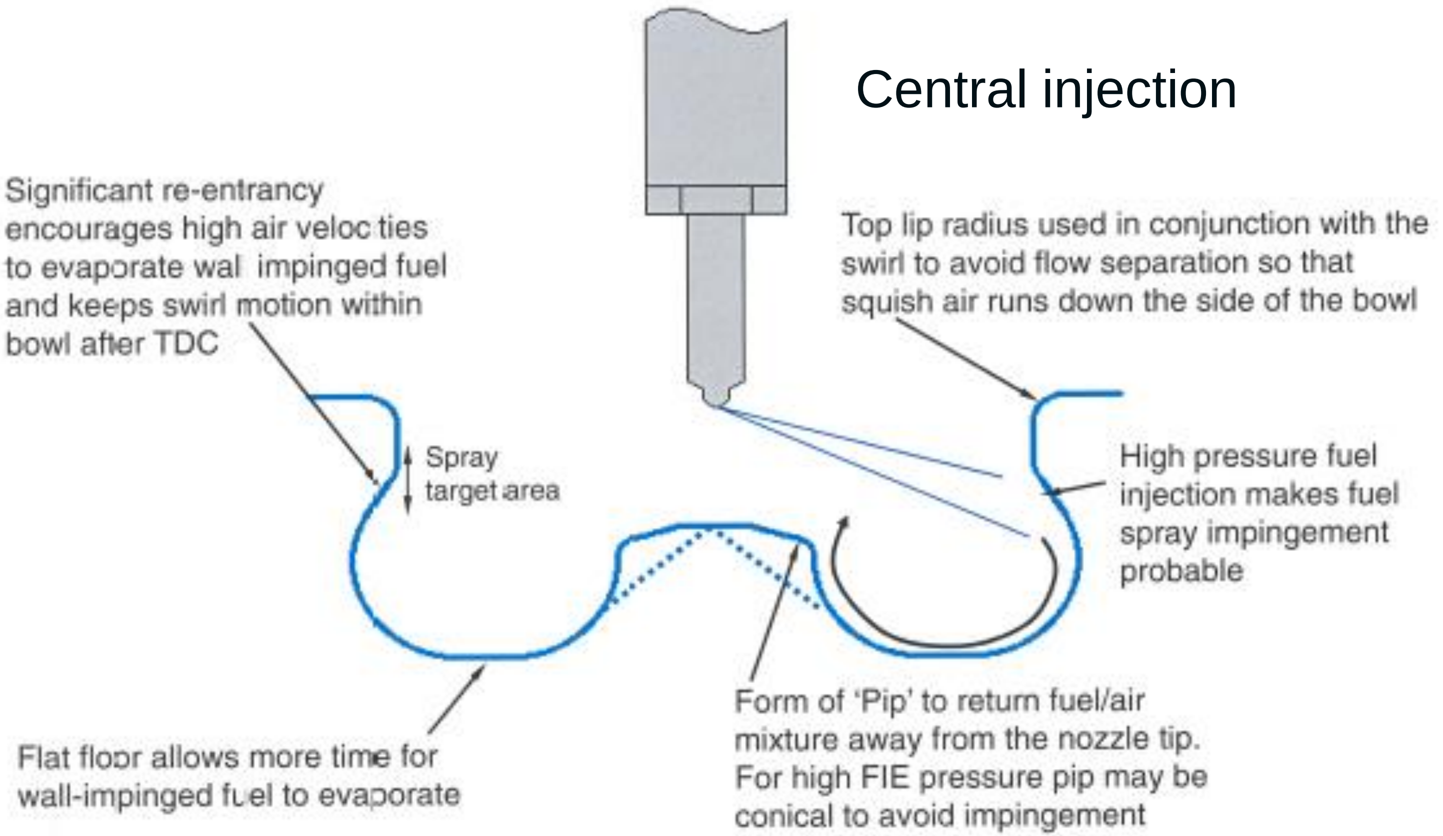


Diesel – combustion process



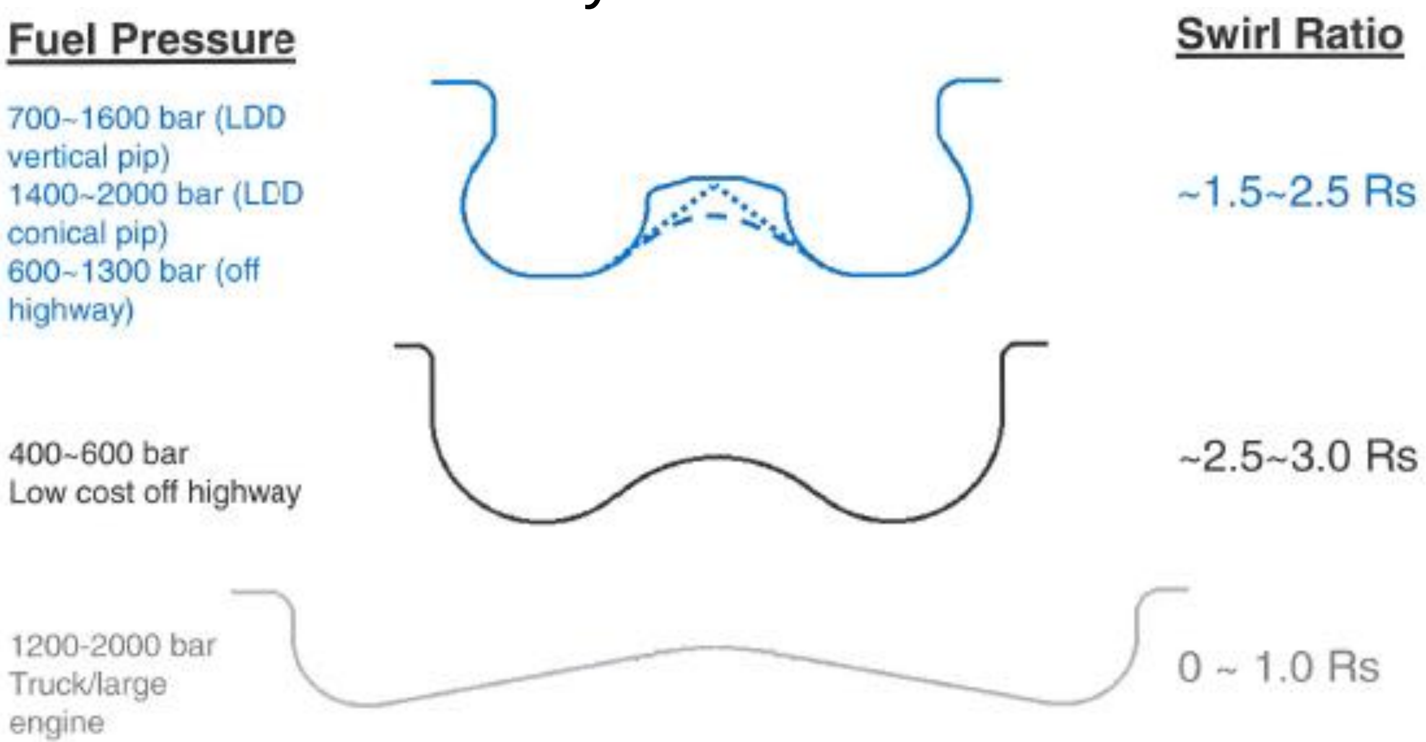
Diesel – standard technology combustion chamber

LDD passenger car applications typically use a re-entrant combustion bowl



Diesel – standard technology combustion chamber

The key feature of diesel combustion chamber is that the combustion space is contained within the piston not the cylinder head



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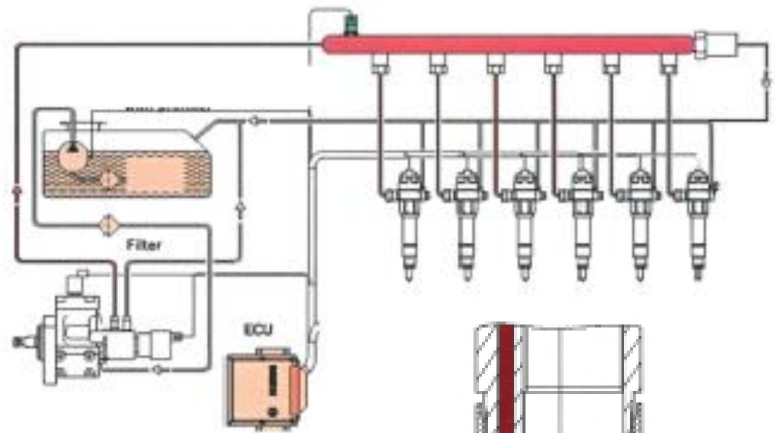
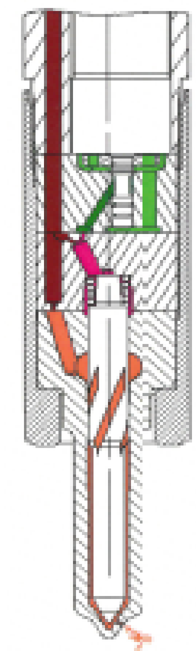
Diesel – standard technology combustion chamber

- Almost all current production use "Common Rail" fuel injection systems
- It maintains a "rail" or accumulator of fuel at the required high pressure
  – Current research up to 3000 bar
- It releases the fuel into the injection orifice with fast electric solenoid valves for control





- It facilitates re-opening of the solenoid valves and allow multiple injections per cycle
- It allows electronically control of:
  – Number of injections
  – Injection start
  – Injection duration
  – Injection pressure

Diesel – multiple injection strategy

- Diesel fuel injection controls pollutant emissions (particles and NOx) but also fuel economy and combustion noise and torque
- Multiple injections may include:
  - Pilot injection(s): small volume of fuel before the main injection starts
    - This creates a small initial combustion allowing a small (controlled) increase of pressure and temperature which results in quieter engine operation
  - Main injection
  - Post-injection(s): short injections after a longer main injection
    - Soot reduction

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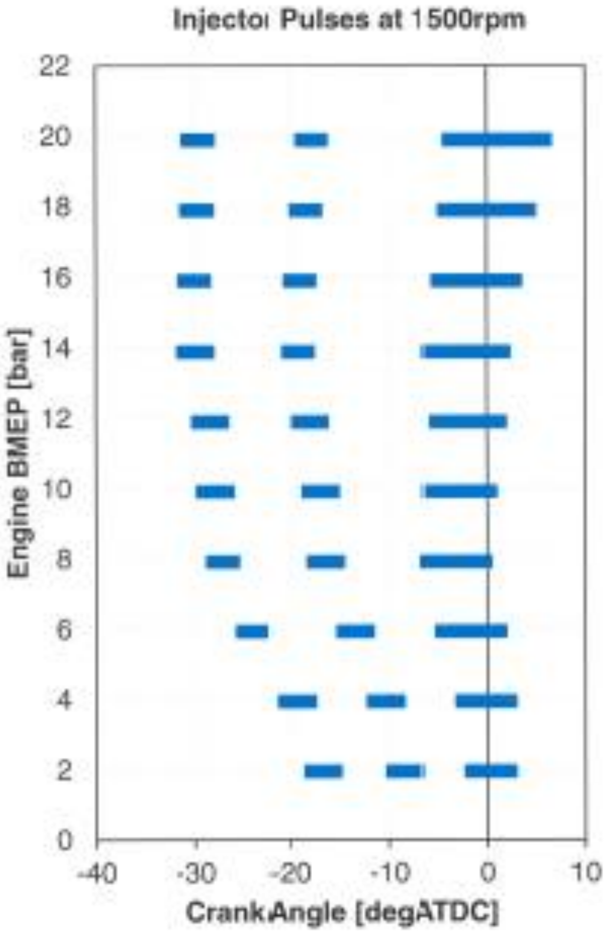
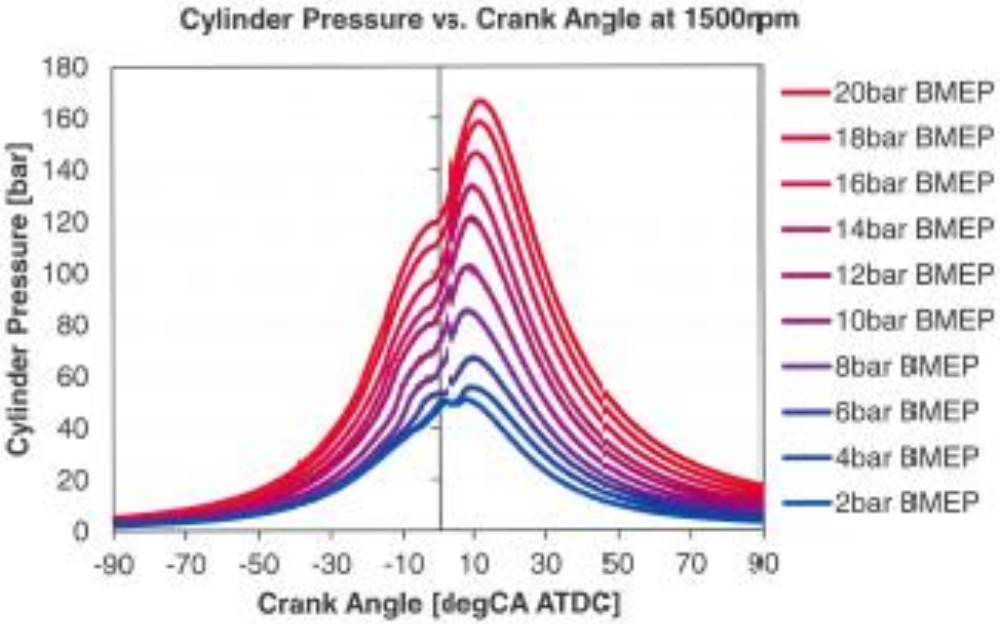
Diesel – multiple injection strategy example

Example cylinder pressure and injection strategy, varying load (EU5 Diesel)





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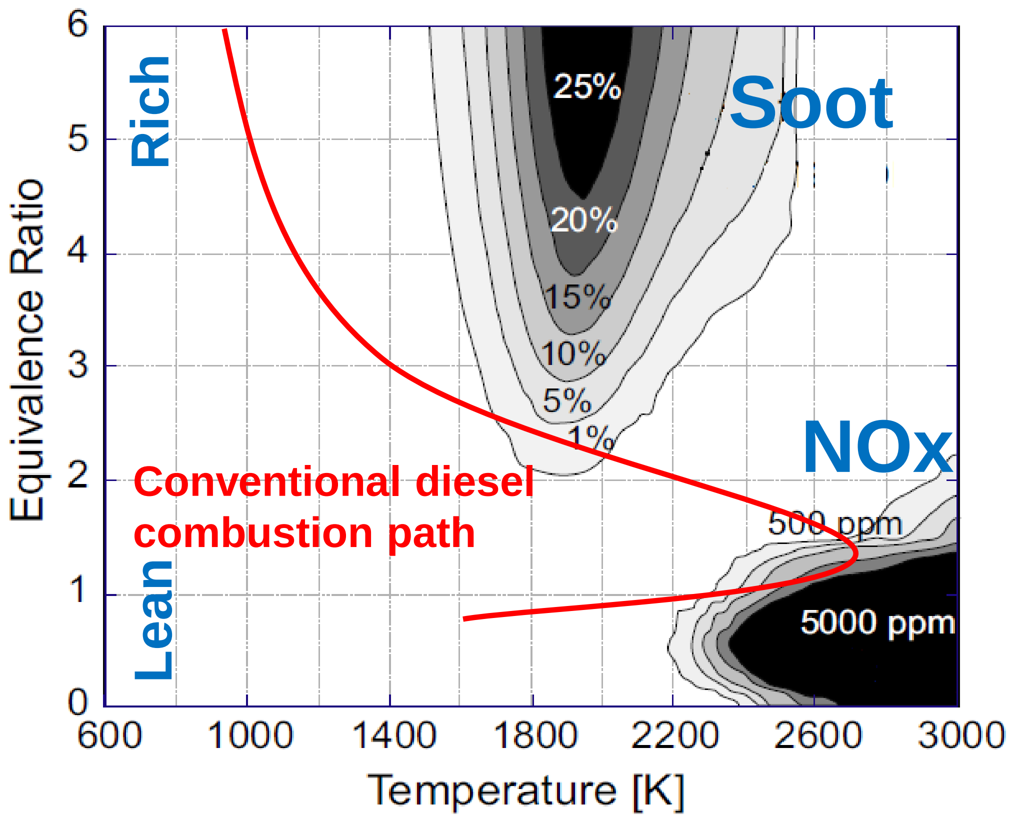
- As load increases:
  - Boost pressure is increased
  - Injection are advanced and injection durations are increased

Diesel – pollutant emissions

Diesel combustion is globally lean (Φ ≈ 0.7) but it is LOCALLY rich



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Diesel – pollutant emissions

- Soot formation cannot be avoid because mechanism is linked to rich mixture
  - Very rich regions at combustion starting create soot that are oxidised as more air is found
  - Small droplet size (injected fuel spray) and high turbulence minimise soot
    - High injection pressures and small nozzle holes
  - Majority of soot are oxidised in the combustion chamber (up to 95%)

- Particulate mater (PM) is measured by passing a sample of exhaust over a filter paper
  - Soot, unburnt HC
  - Condensed sulphates
  - Wear particles
  - Other solid or condensed ash materials from lube oil additives (Zn, Ca, …)

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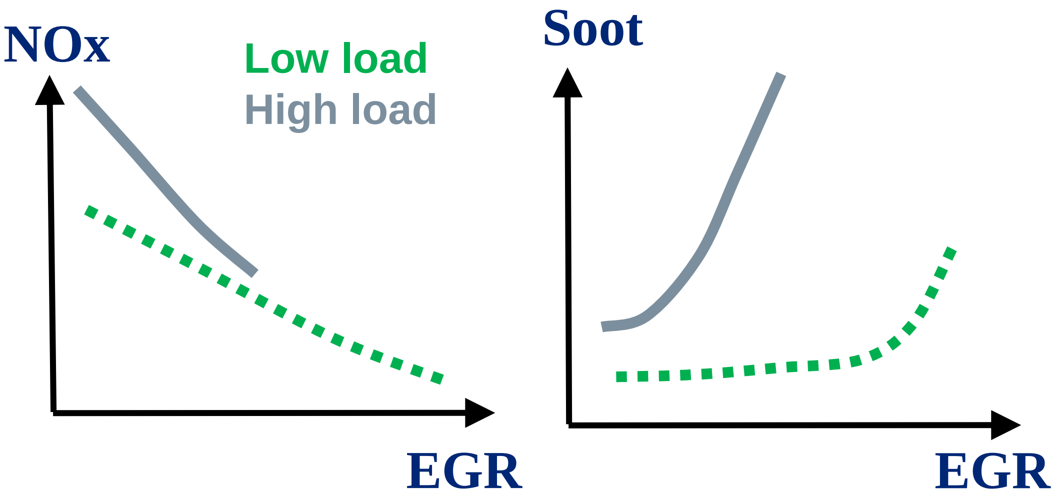
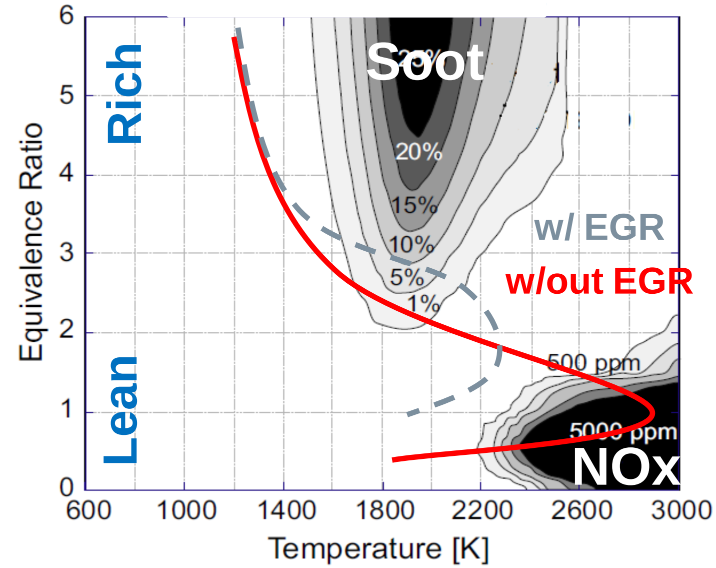
Diesel – pollutant emissions





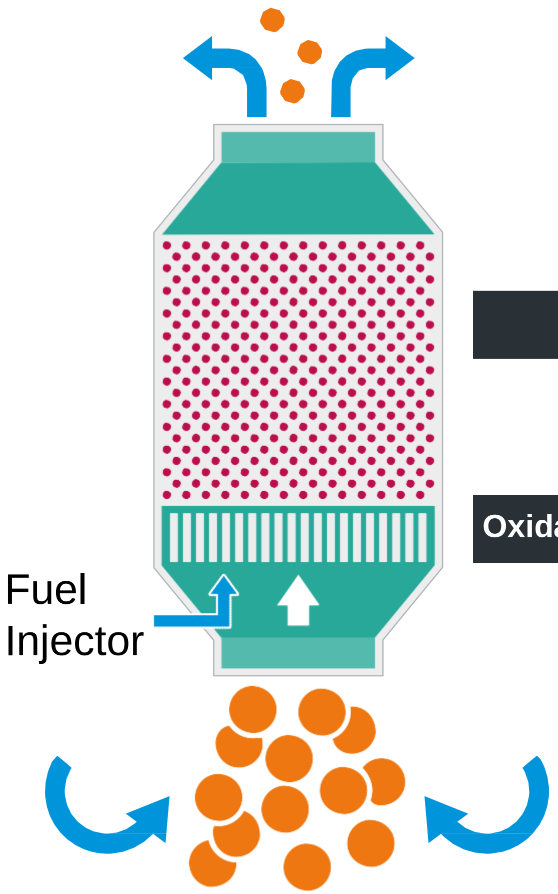
- The amount of NOx is governed by the residence tie of in-cylinder gases at high temperature (T>2000 K)
  - Peak temperature can be reduced by dilution
    - EGR on passenger cars and trucks
    - Water on large engines
- But negative effect on soot, HC and CO
- Optimising global emissions becomes a difficult balancing act

Diesel – after-treatment

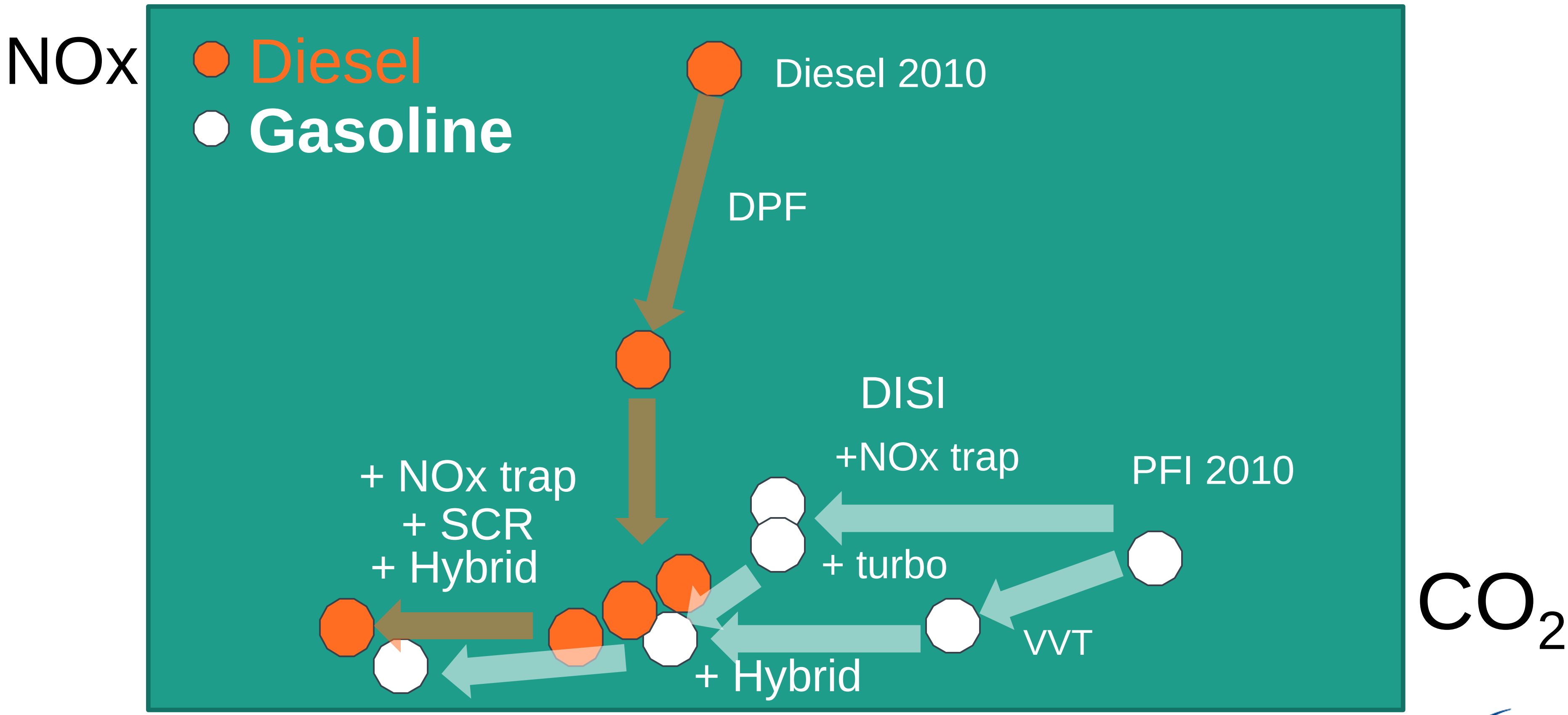
- DOC (Diesel Oxidation Catalyst)
  - Oxidises HC and CO to CO_2 and H_2O
  - Used for exothermic generation to raise exhaust temperature for other after-treatment components
  - Oxidises NO to NO_2
- LNT: Lean NOx trap
  - Used to reduce NOx emissions. Stores NOx on the brick during lean operation, chemically reduces NOx to N_2 during rich operation
- SCR: Selective Catalytic Reduction
  - Uses a reducing agent, usually ammonia (carried as urea)

Diesel – after-treatment

- DPF: Diesel Particulate Filter
  - Used to trap particulates. Trapped particulates are periodically "burned off" during an active regeneration
  - Organic matter is burned off leaving small amount of incombustible ash
  - As filter fills with soot, back pressure builds
  - Catalysed Diesel Particulate Filter is current technology on passenger cars



Conclusion


NOx
Diesel
Gasoline
Diesel 2010
DPF
DISI
+NOx trap
PFI 2010
+ NOx trap
+ SCR
+ Hybrid
+ turbo
VVT
+ Hybrid
CO_2