Engine design and operation

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Discussion topics

1

What is an internal combustion engine

- Four-stroke cycle engine – gasoline, natural gas and diesel
- Two-stroke cycle engine

2

Engine hardware and configurations

- Valvetrain configurations
- Power cylinder
- Pressure charging

3

Emissions control

- 3-way catalyst
- Aftertreatment systems

4

Summary

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1. The internal combustion engine

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What is an internal combustion engine?

The reciprocating internal combustion engine generates power by converting chemically bound energy into work by the use of reciprocating motion

Ideal Conditions

Fuel + Oxygen → Carbon dioxide + Water + Energy

Reality

Gasoline, Diesel, Natural Gas, Hydrogen or other liquid/gaseous fuel + Air 78% Nitrogen 21% Oxygen → CO / CO_2, SO_x, NO_x, HC, PM, VOC + Water + Energy

CO = Carbon monoxide
HC = Hydrocarbons

NO_x = Nitrogen oxides
SO_x = Sulfur oxides

PM = Particulate matter (soot)
VOC = Volatile organic compounds

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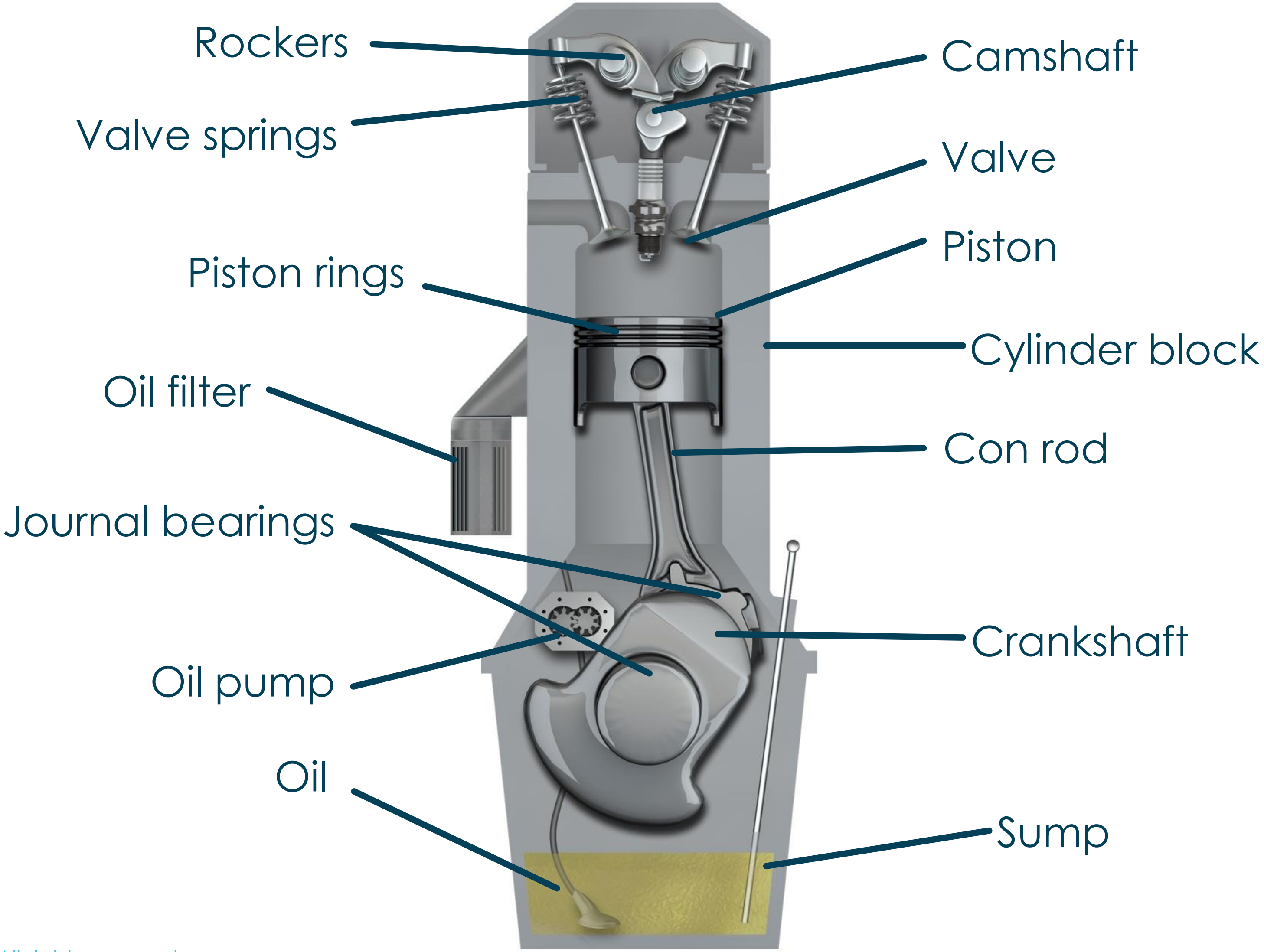
Main components of an internal combustion engine



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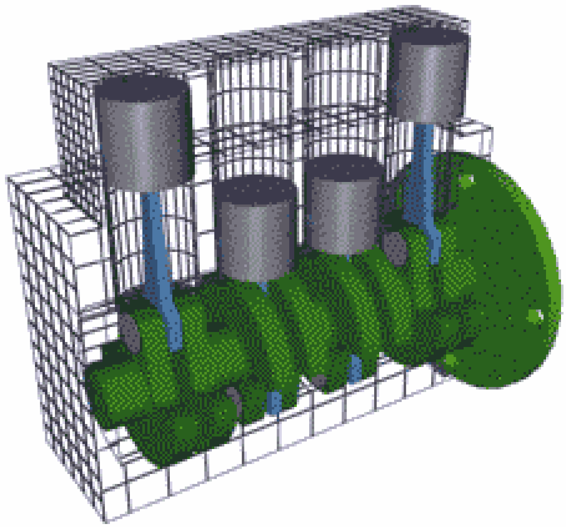
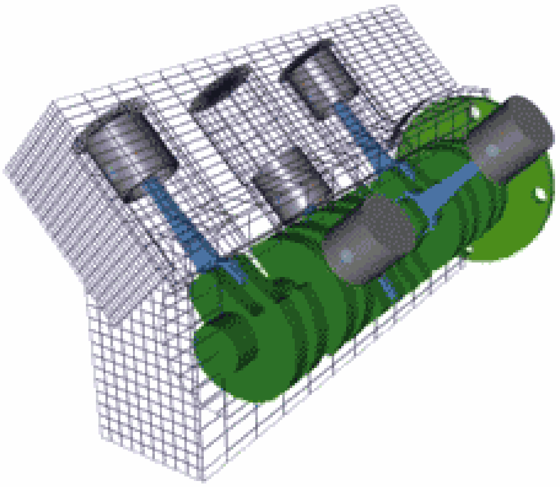
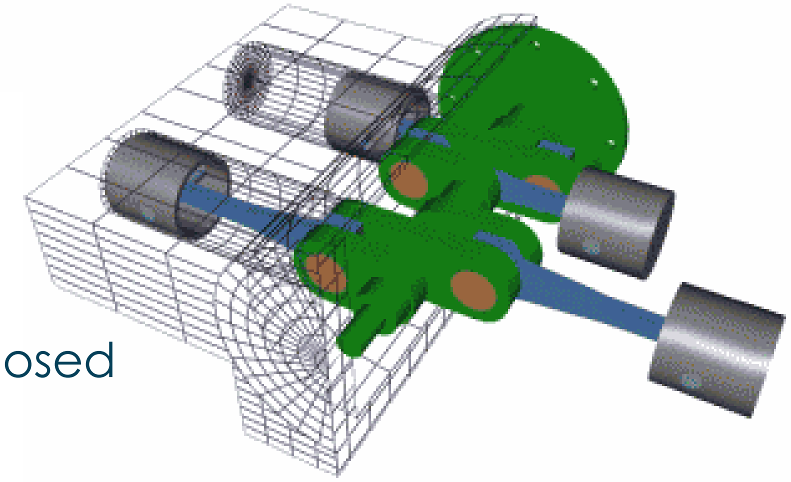
Standard configurations

Inline 4 (I4)



V6





Horizontally-opposed
(Boxer)

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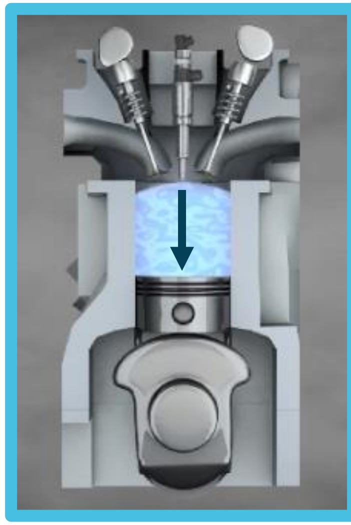
Four-stroke cycle engine

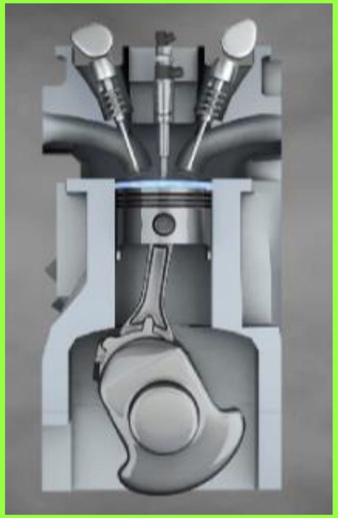


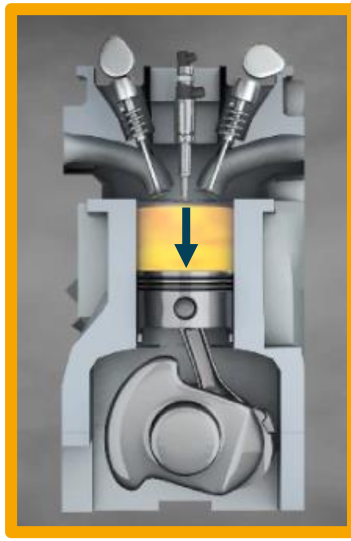
Intake

As piston moves down or toward crankcase, intake valve opens and partial vacuum is created in cylinder. Vaporized air-fuel mixture is forced into cylinder by atmospheric pressure.

Compression

Intake valve closes. As crankshaft rotates, piston moves up and compresses air-fuel mixture.



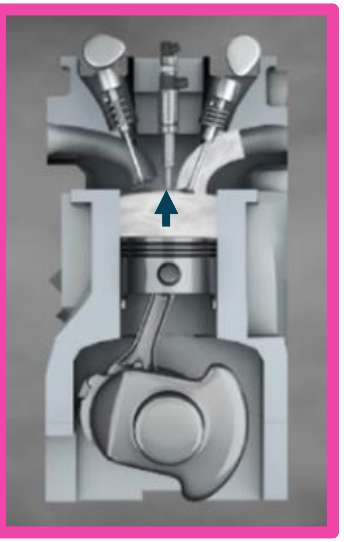


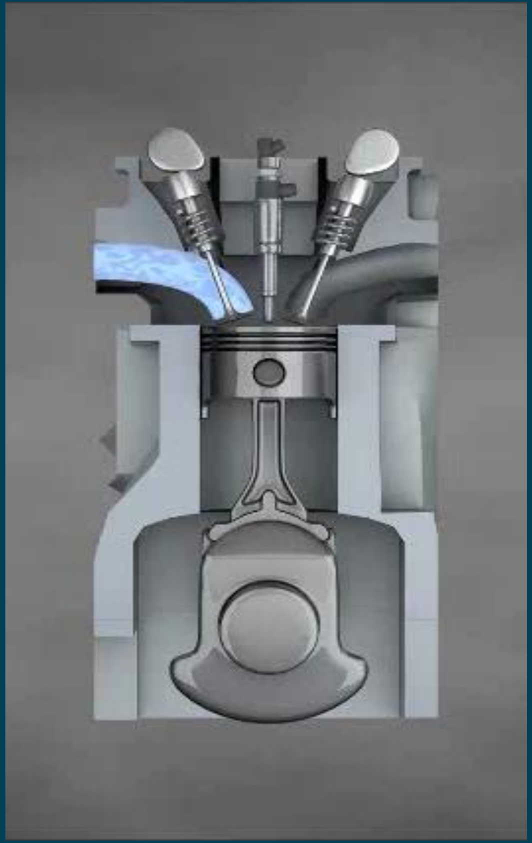
Power

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.

Exhaust

After fuel charge is burned, exhaust valve opens. Burned gases are forced out of cylinder by upward movement of piston.





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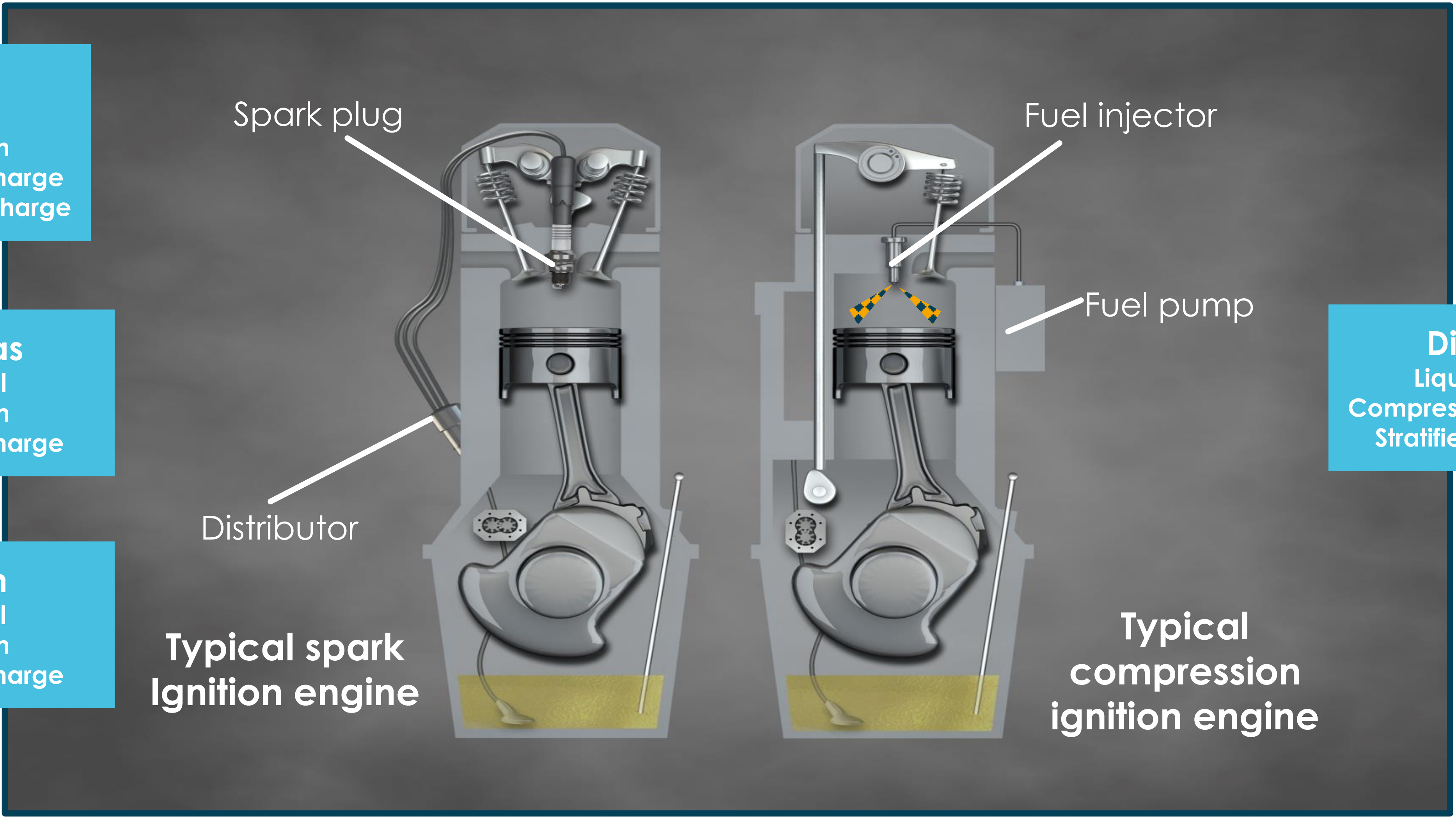
Additional components of internal combustion engines

Gasoline
Liquid fuel
Spark ignition
Homogeneous charge
and/or stratified charge

Natural Gas
Gaseous fuel
Spark ignition
Homogeneous charge

Hydrogen
Gaseous fuel
Spark ignition
Homogeneous charge



Diesel
Liquid fuel
Compression ignition
Stratified charge

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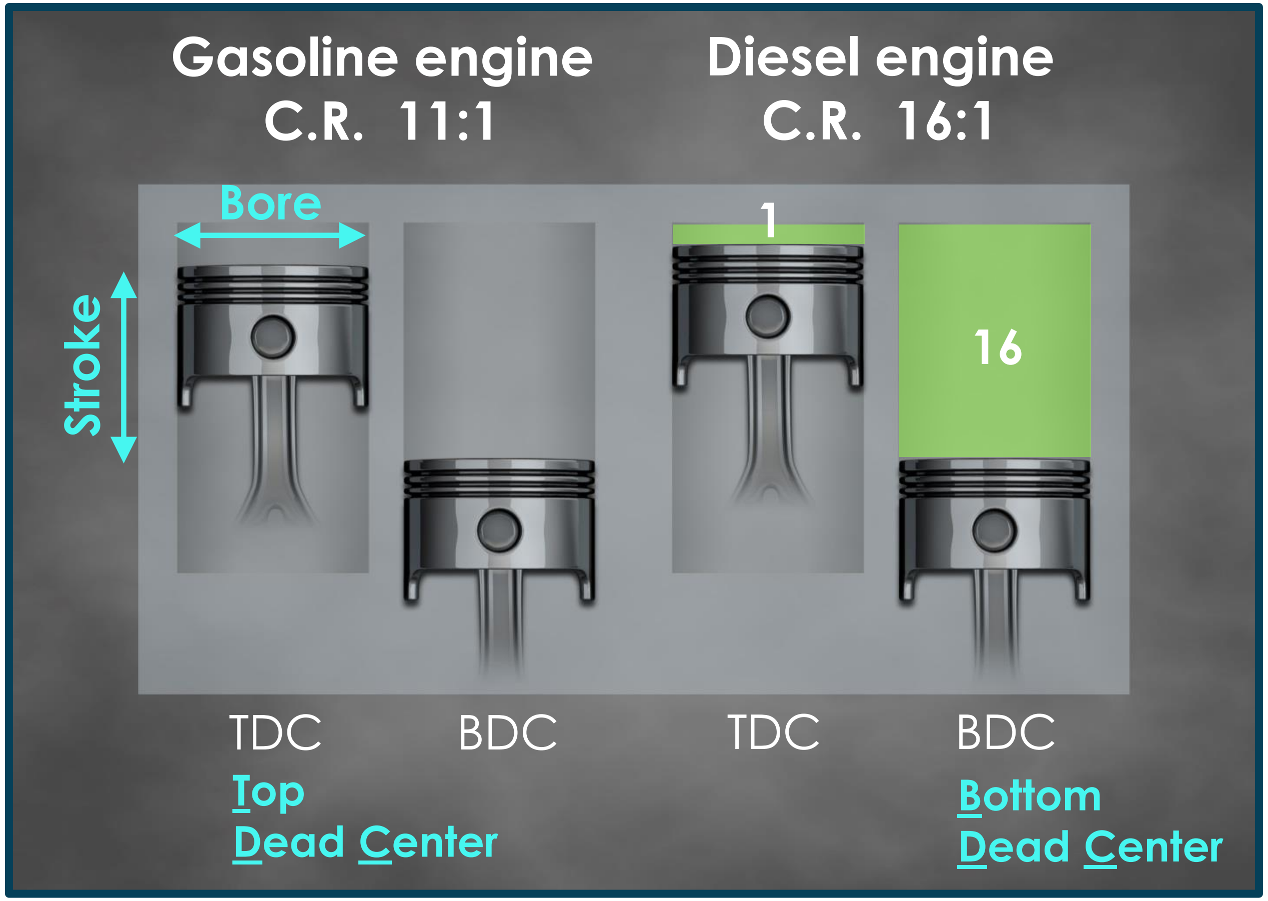
Comparison of engine ignition



C.R. = Compression Ratio

Lower to avoid pre-ignition

Higher for compression ignition

Ratio of the volume of the combustion chamber and cylinder volume measured when the piston is at the bottom of its stroke to the volume when the piston is at the top of its stroke

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Two-stroke cycle engine: Small engine

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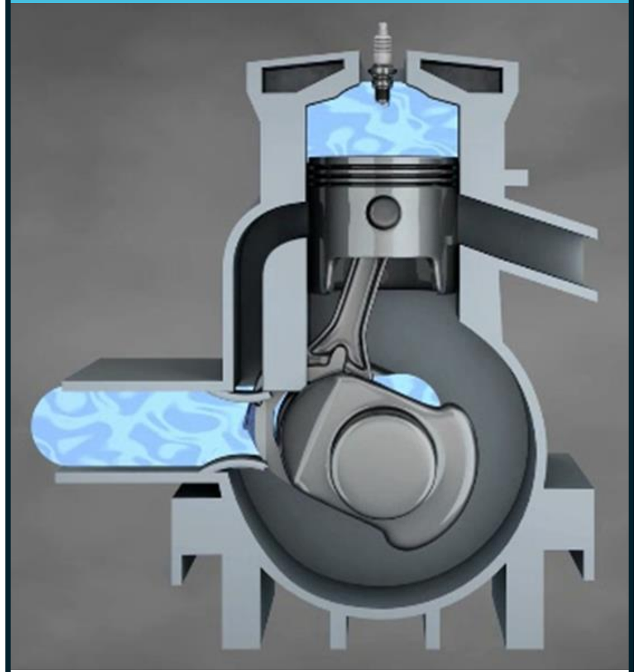
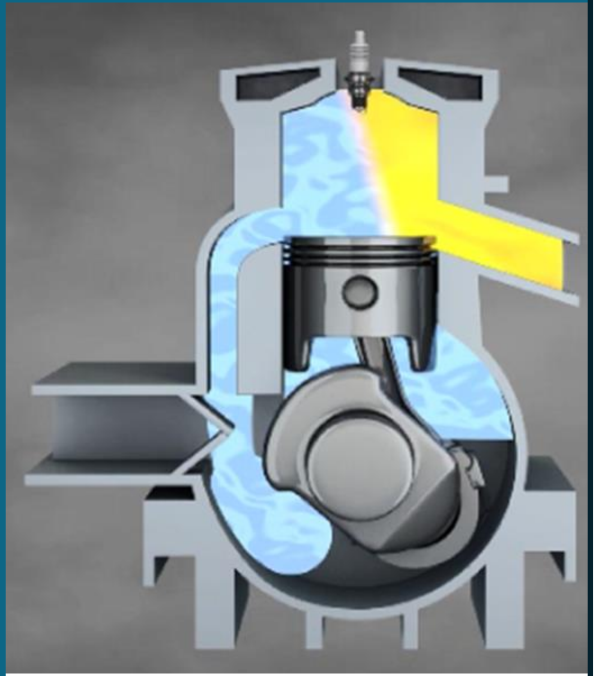
Piston ↑



- Compression
- Creates suction to draw fuel: air into crankcase

Piston ↓

- Power
- Pressurizes air: fuel in crankcase



- Exhaust
- Intake

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2. Engine hardware and configurations

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2.1 Valvetrain configurations

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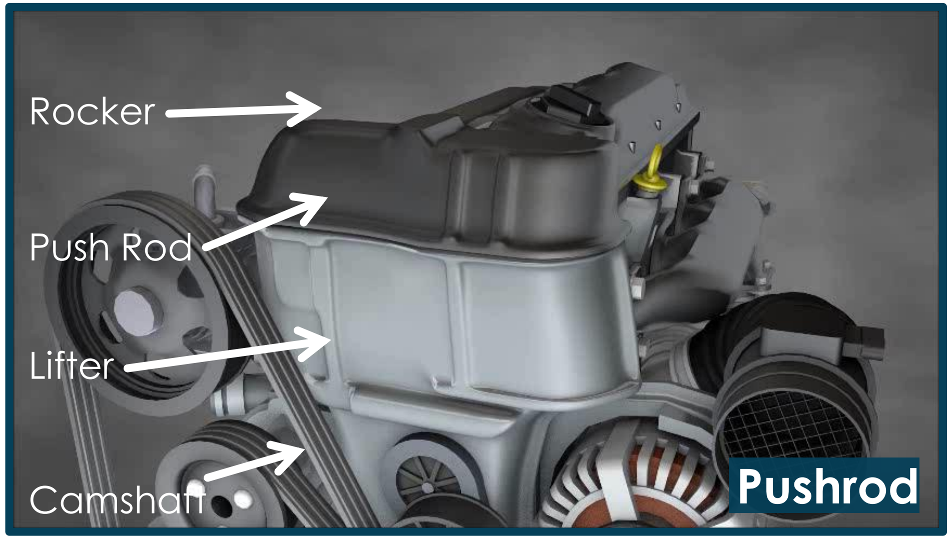
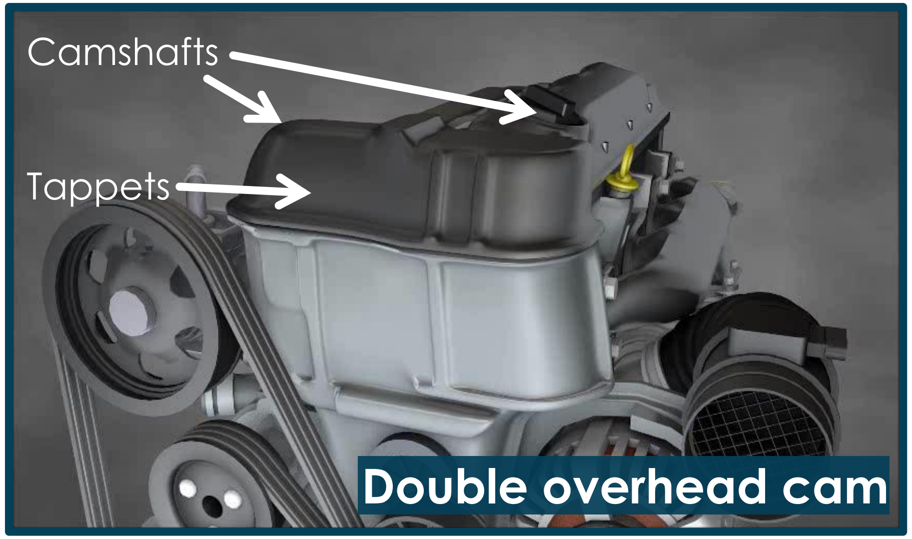
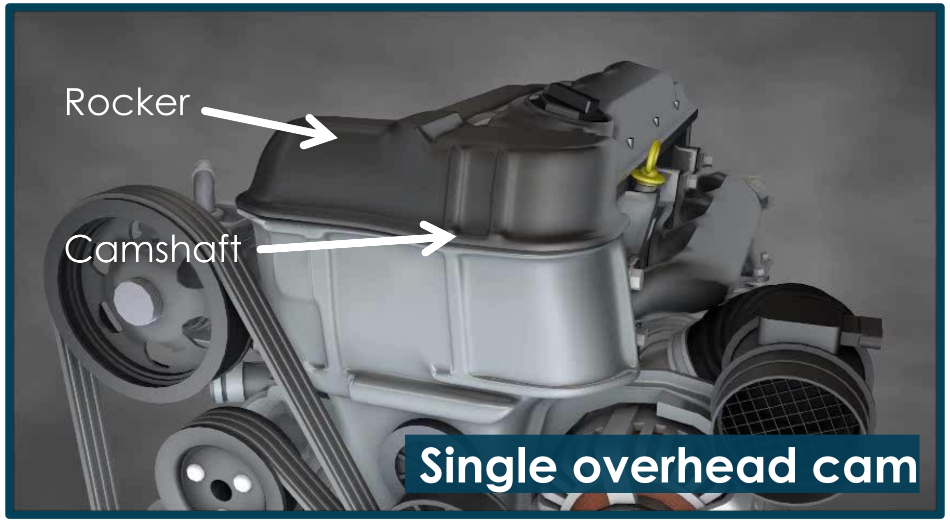
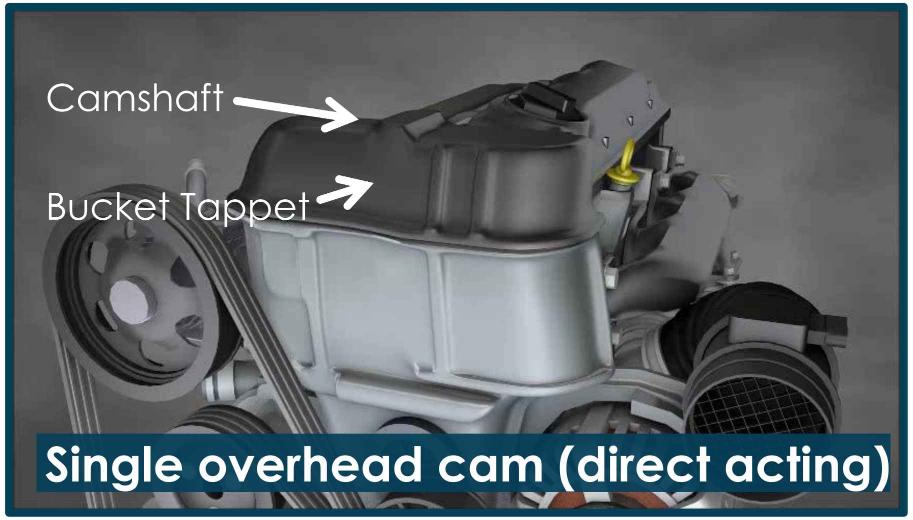
Different valve configurations









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Variable valve timing (VVT)

- Valves open and close at different times in the cycle and to varying amounts of lift depending on the engine speed and load
- Engines perform well across wide range of engine speeds and loads
- Less compromise between efficiency and performance
- Many different mechanical, hydraulic, and electronic options have been developed for VVT

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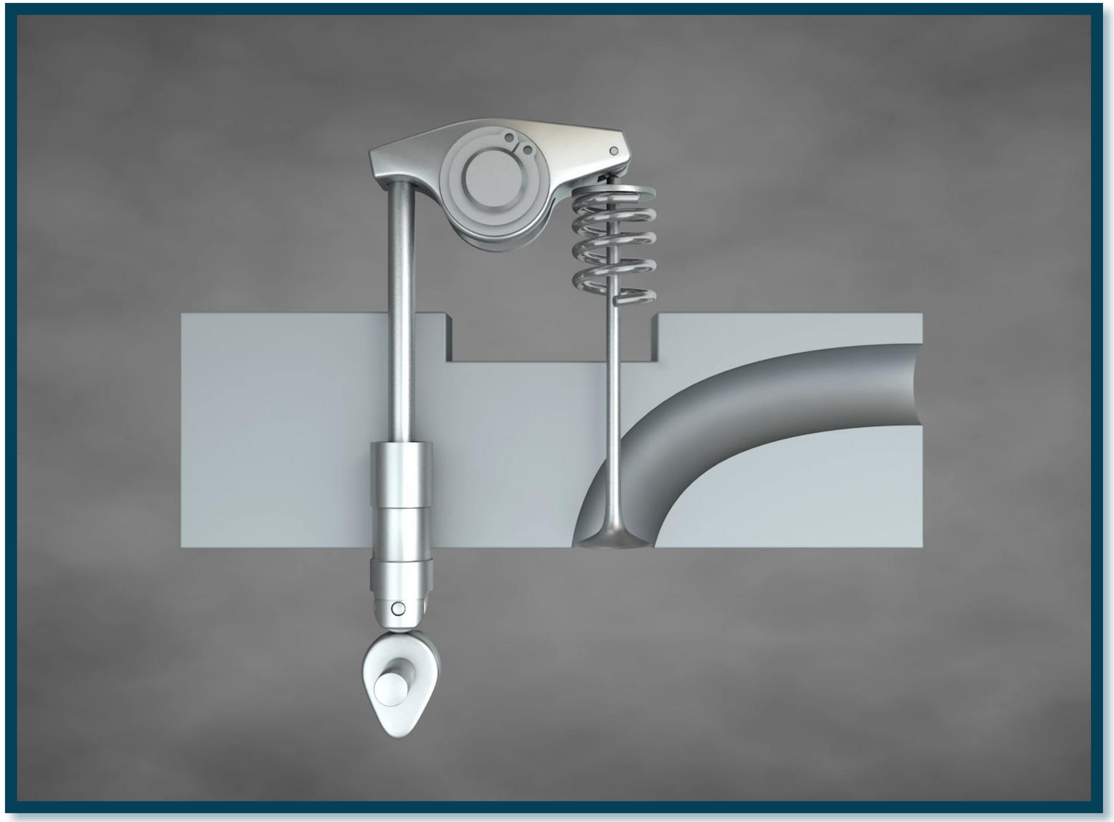
Cylinder deactivation



- Intake and exhaust valves are closed, shutting off cylinder(s)
- Creates a lower displacement engine out of a larger engine
- Reduces pumping losses when cruising at steady higher speeds
- Used as a means to increase fuel economy and reduce emissions
- For heavy duty diesel used to increase the temperature of the aftertreatment system to improve NOx reduction

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2.2 Power cylinder

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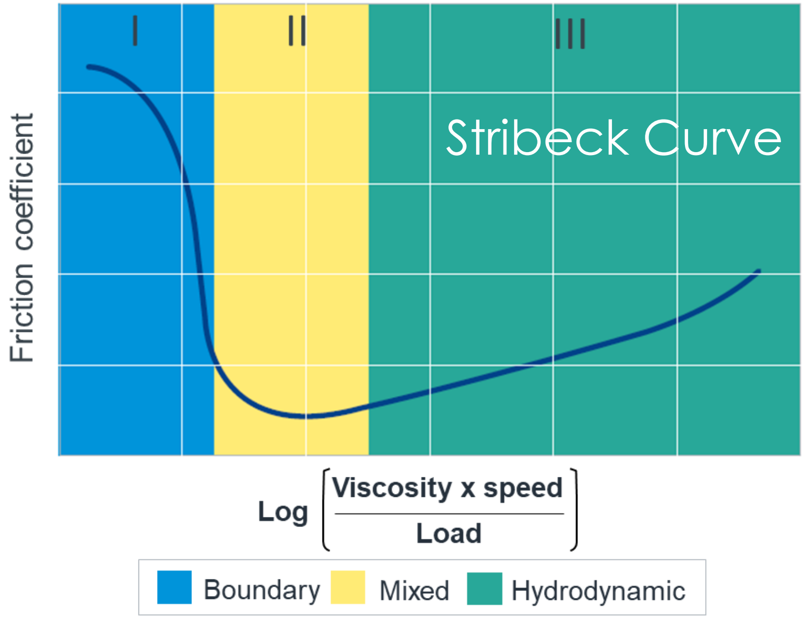
Engine lubrication regimes

CONFORMING SURFACES

- **Hydrodynamic** – moving surfaces completely separated by a film of lubricant
  - Piston rings, bearings
- **Mixed** – surfaces are still separated but asperities occasionally interact
  - Piston rings, gears
- **Boundary** – surfaces come into closer contact, asperities start to break off, intense localized heat begins to activate anti-wear additives in the lubricant to form protective films
  - Piston rings, gears

NON-CONFORMING SURFACES

- **Elasto-hydrodynamic** – rolling contact surfaces are separated but undergo
  elastic deformation
  - Valvetrain, cam and followers



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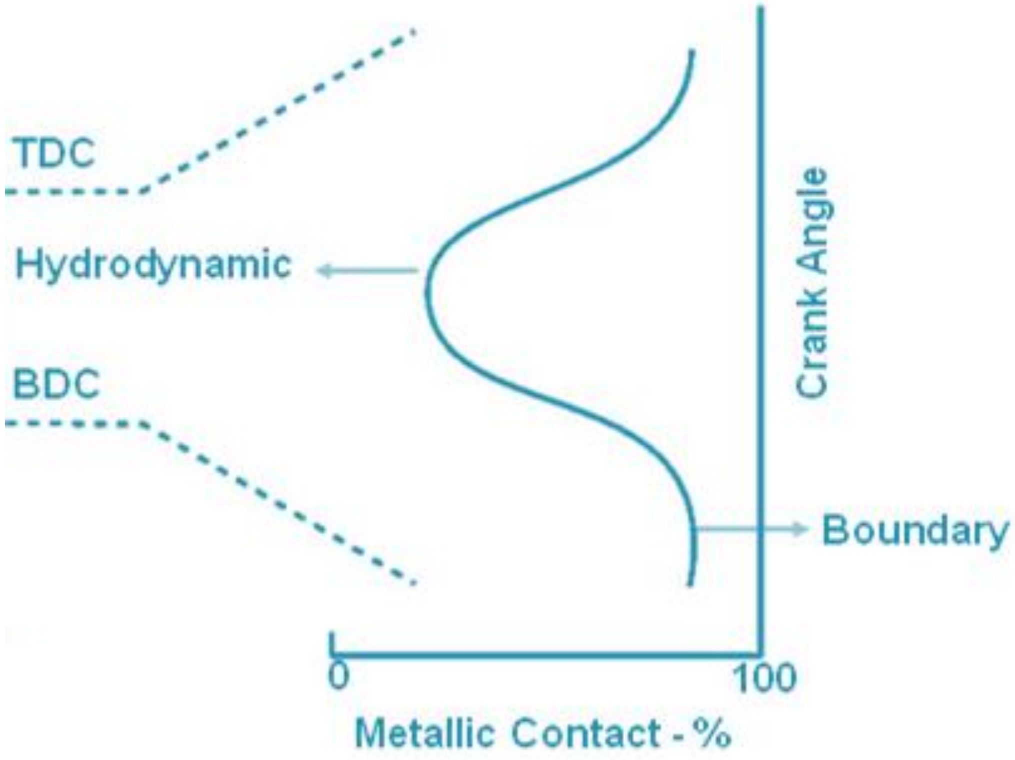
Piston ring and cylinder lubrication mode

50% **of engine friction is between piston rings and liner**



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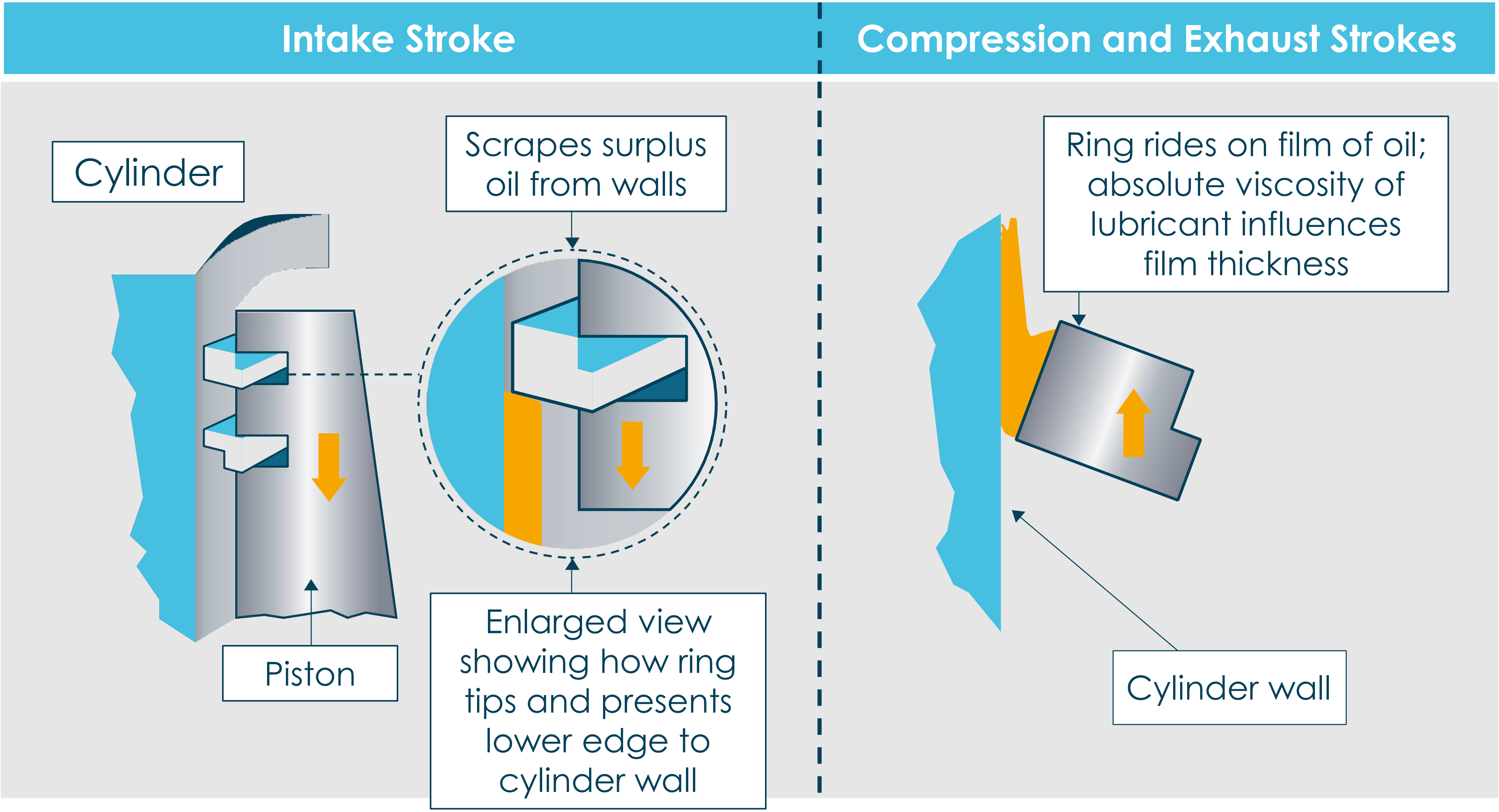
Piston ring action



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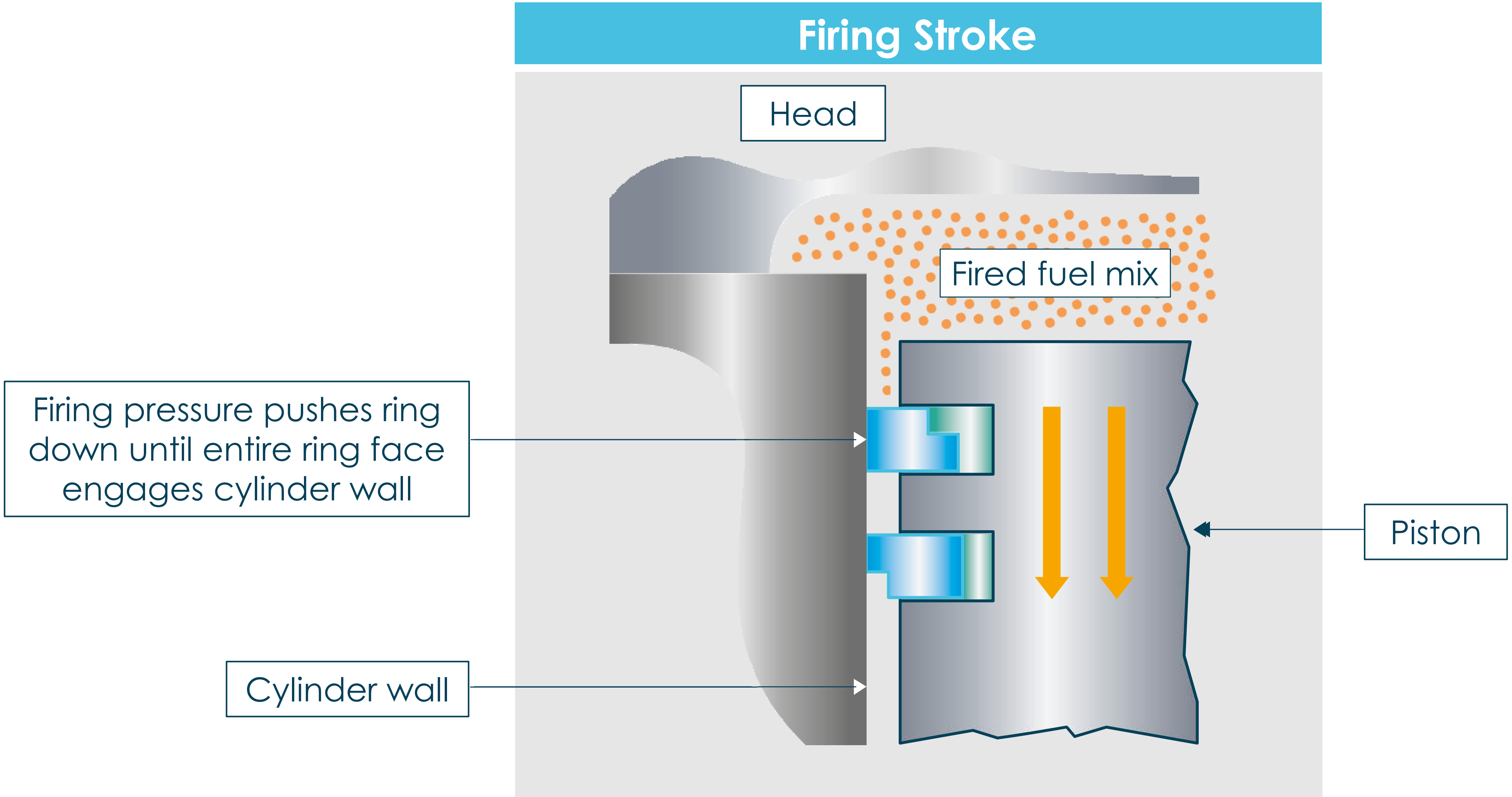
Piston ring action



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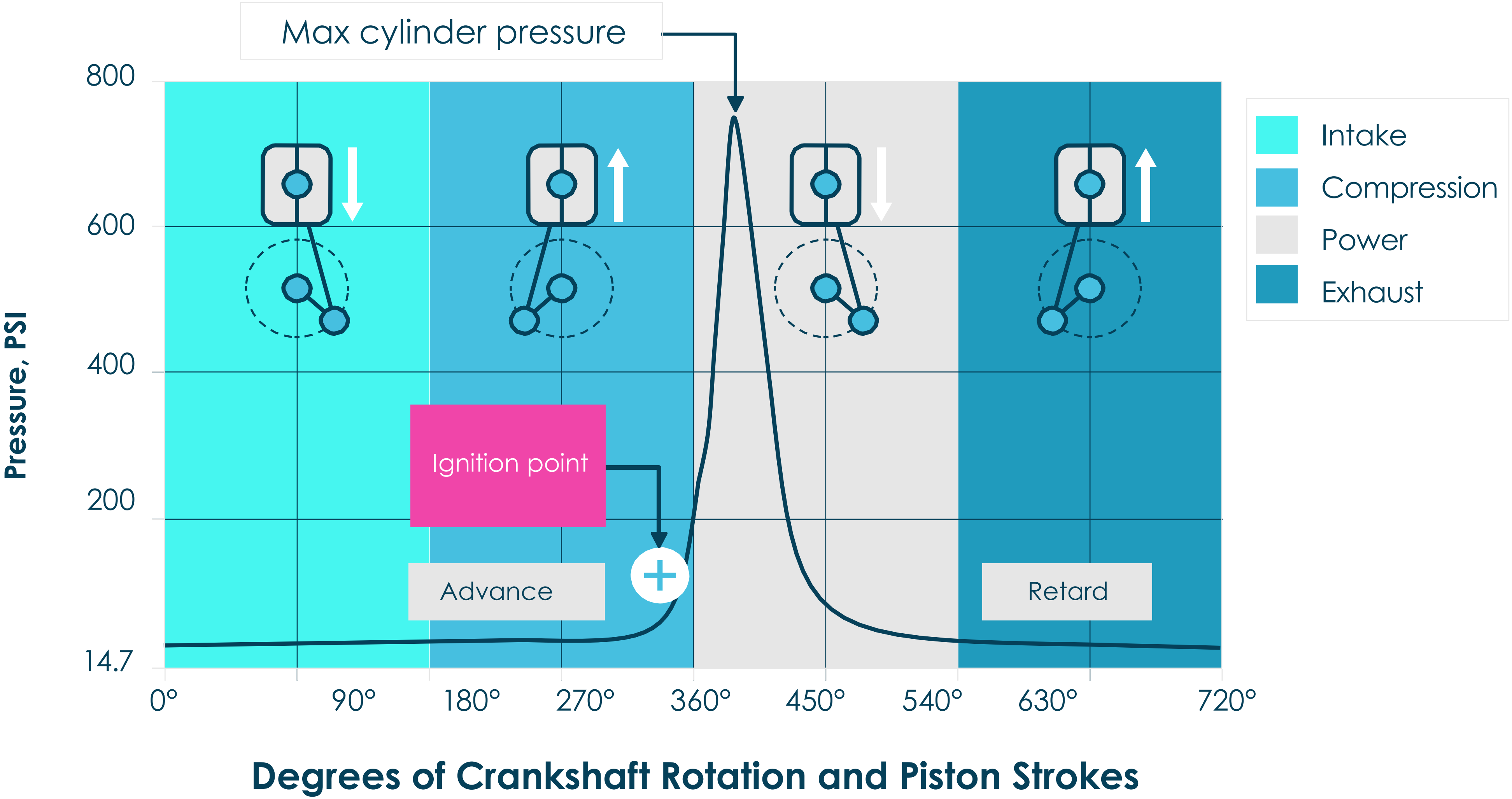
Pressures in an engine cylinder



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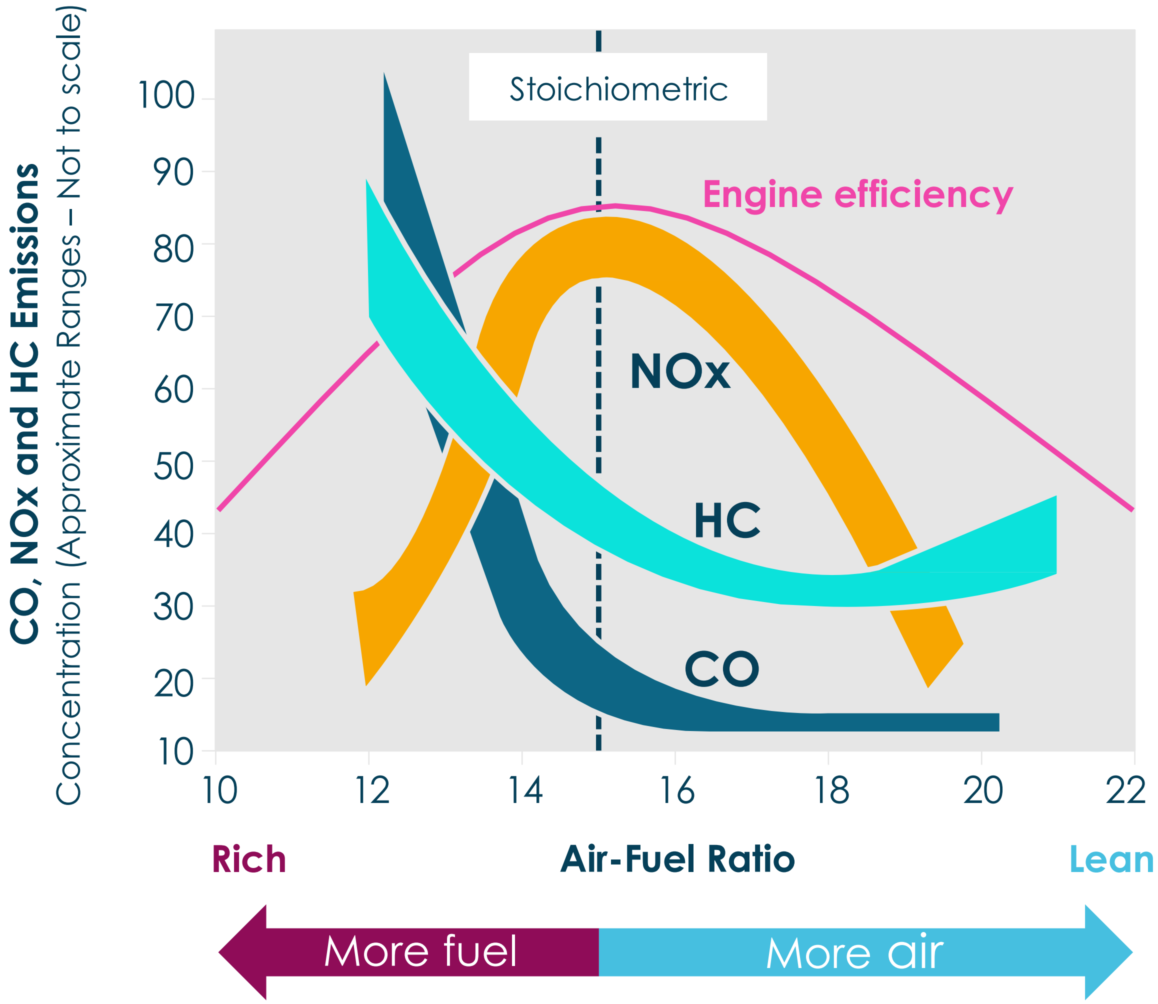
Effect of air/fuel ratio on combustion gas composition



Stoichiometric = 14.7 parts air to 1 part fuel

NOx – caused by high in-cylinder temperatures experienced under moderate to heavy load

HC – unburned hydrocarbons (fuel)

CO – carbon monoxide results from incomplete combustion of fuel in a low oxygen environment

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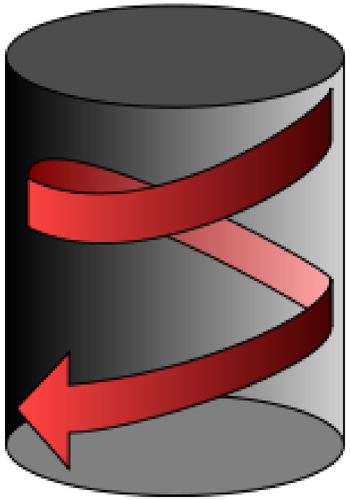
Mixing of air and fuel

On Intake

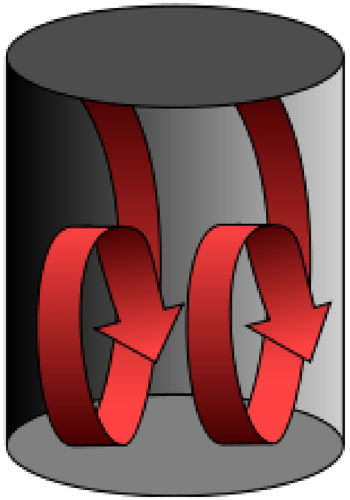
Swirl



Due to a tangential proponent to the flow of air into the cylinder on intake a vortex forms

On Compression

Tumble



As the piston reaches top dead center a secondary flow is created by the piston bowl creating a barrel swirl

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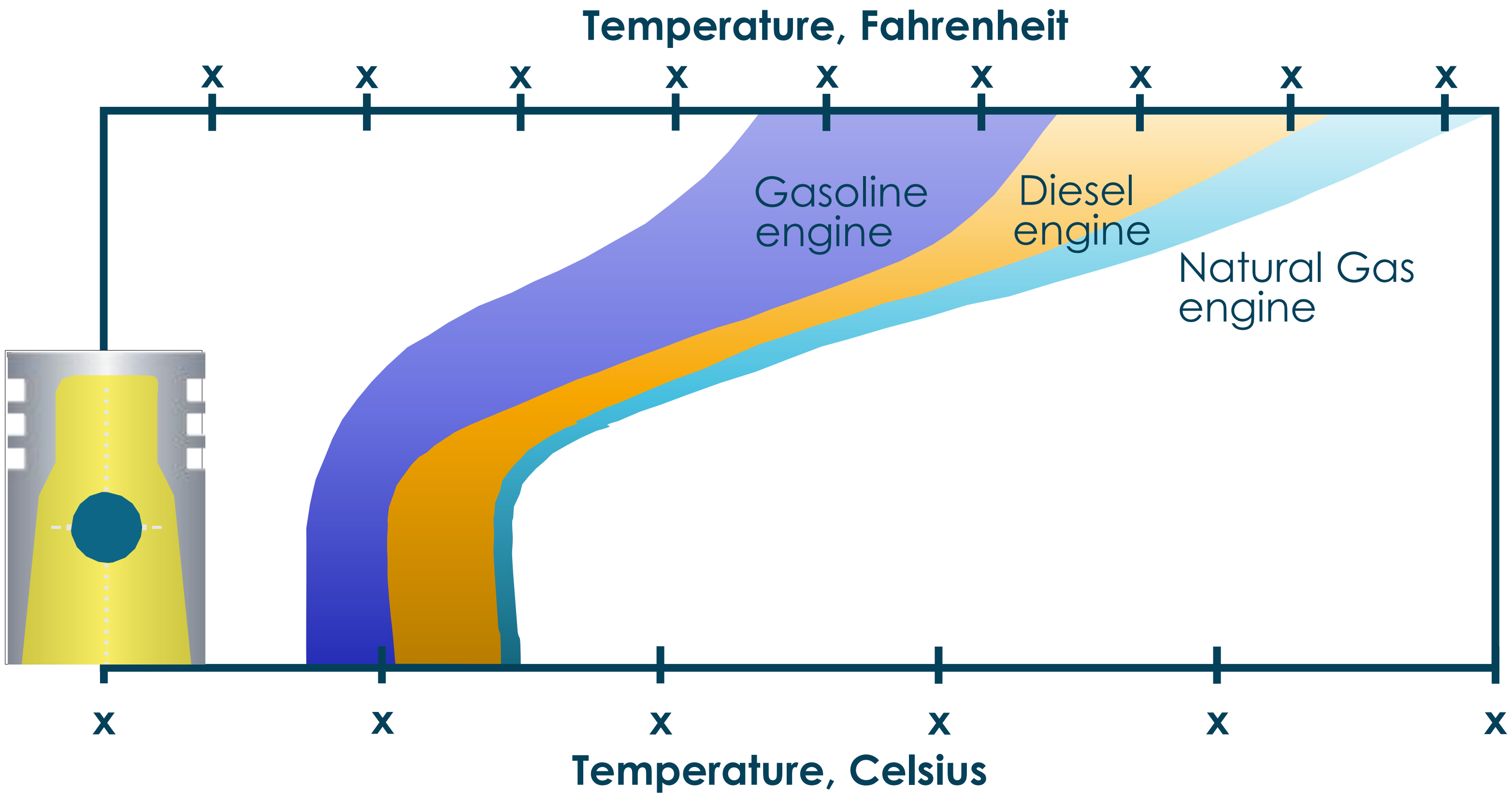
Temperature distribution of pistons

Median distribution temperature of light alloy pistons

- Structural and functional characteristics influence temperatures



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2.3 Pressure charging

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Engine breathing systems

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Power output depends on quantity of fuel burned.
Which depends on the quantity of air “inhaled” (“breathing”)

Two types of engine breathing:

Naturally aspirated:

- Uses suction from the engine (“intake stroke”)
- Limited by atmospheric pressure

Pressure charging:

- Forcing air into the cylinder
- More air → more fuel can be added → more power

Two types of pressure chargers

Supercharger
Driven by the engine or external motor

Turbocharger
Driven by exhaust gases

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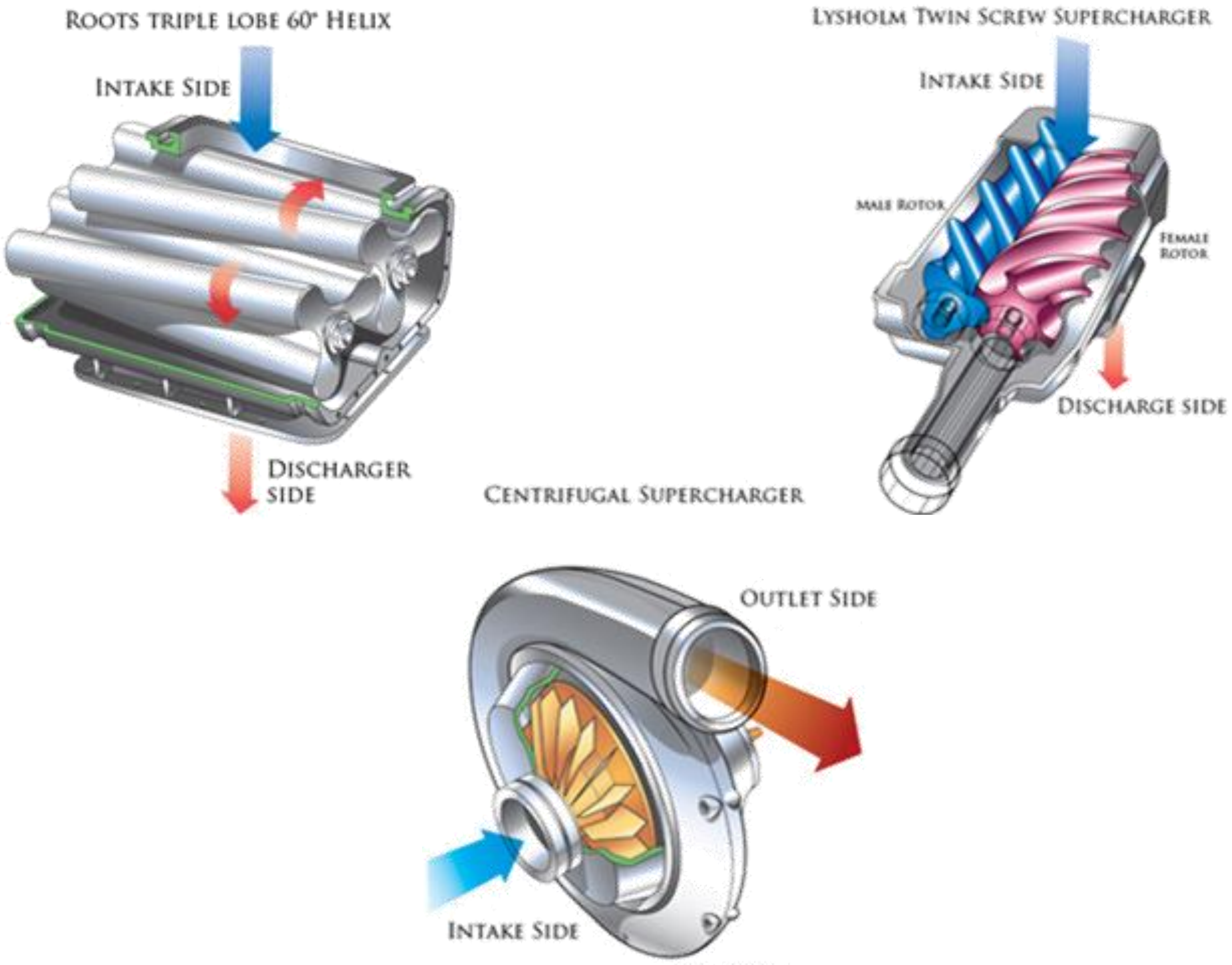
Supercharging

Supercharger

Compressed
by motor/engine



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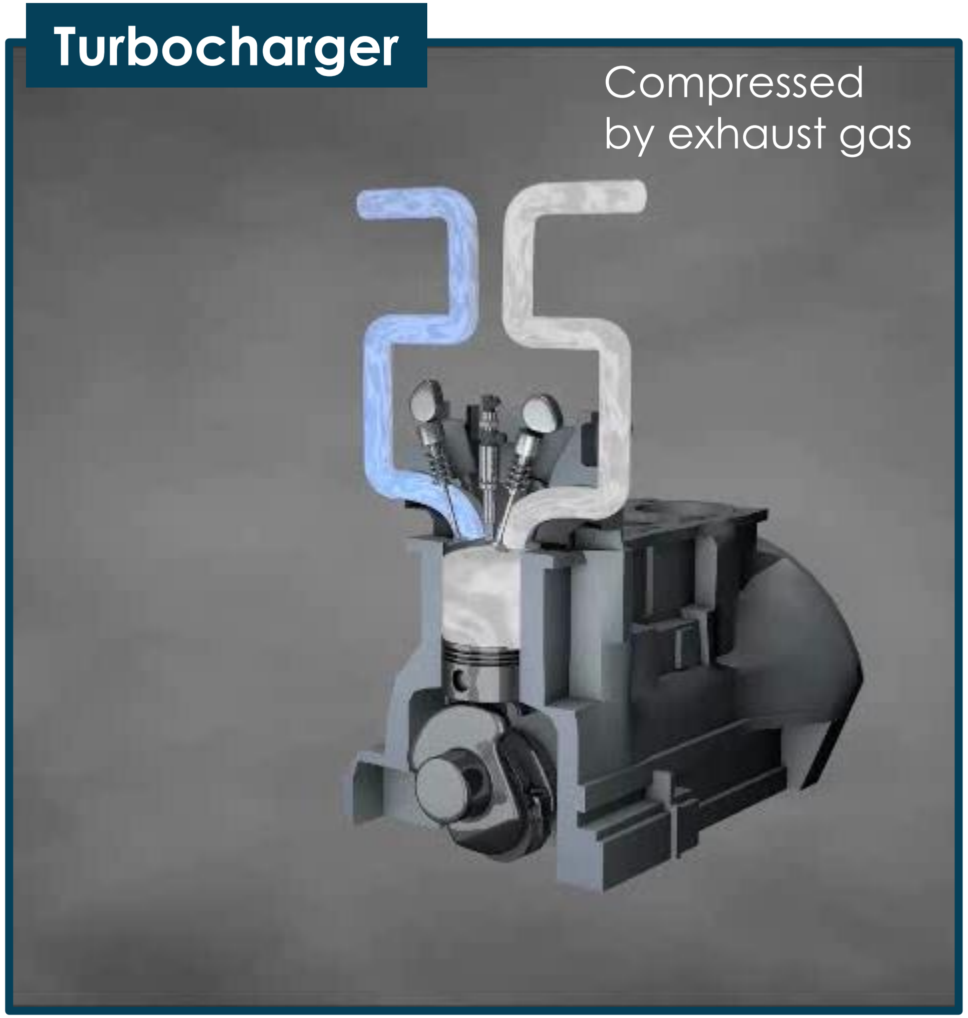
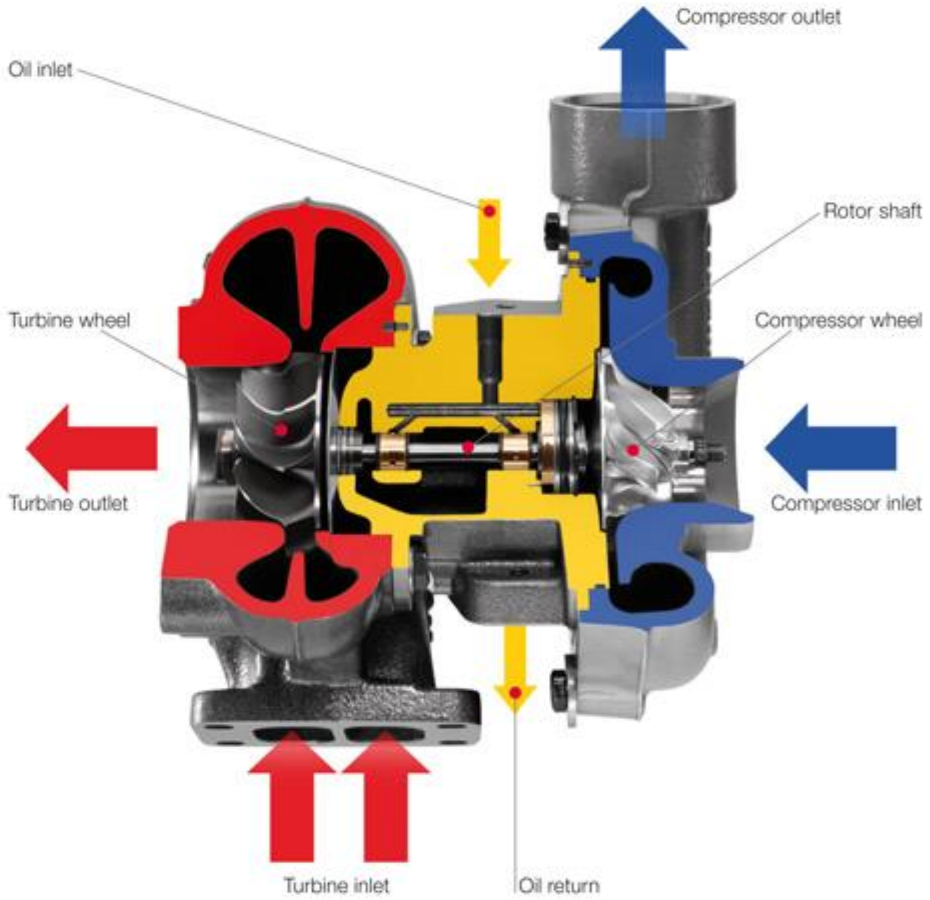
Turbocharging





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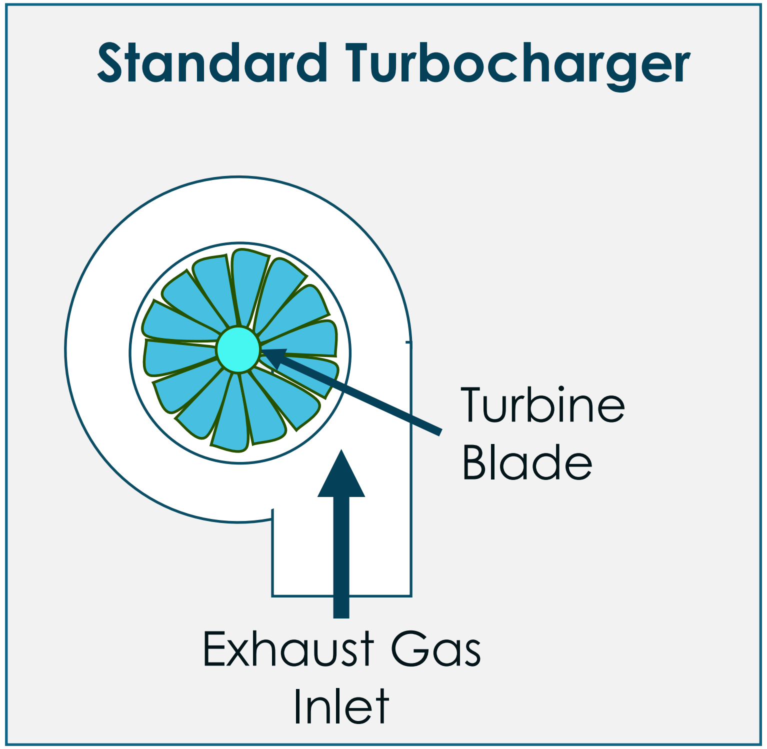
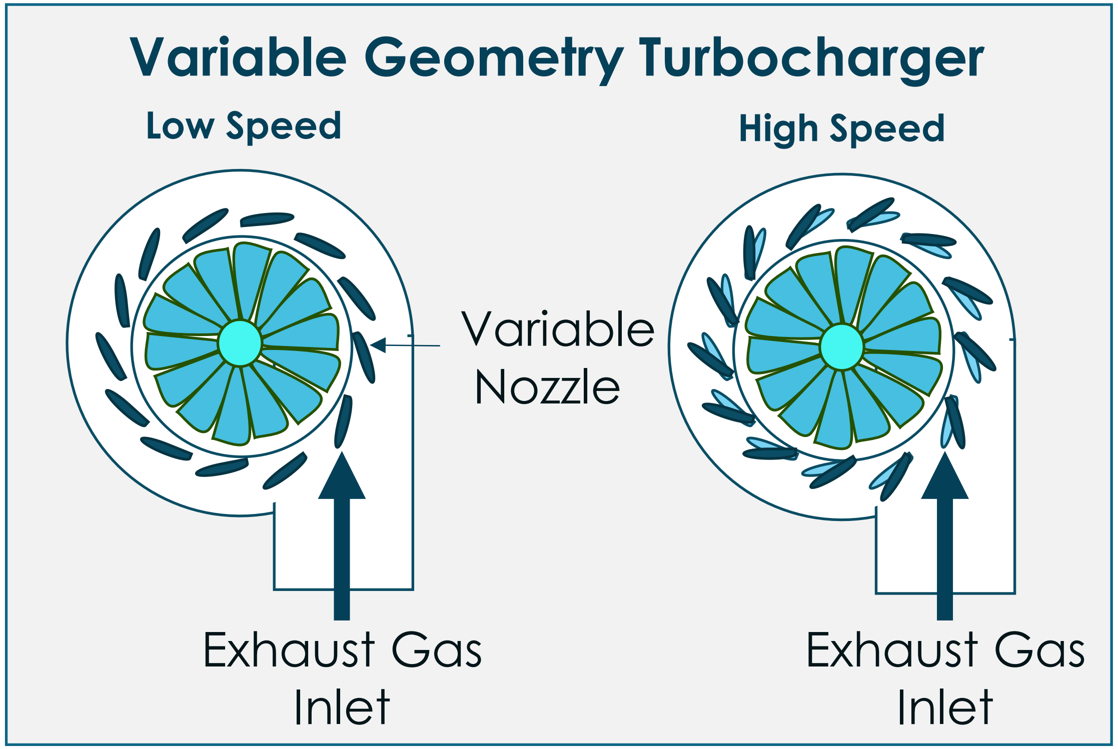
Variable geometry turbochargers





- At low rotation speed, variable nozzles rotate to a narrow opening to reduce turbo lag
- At high rotation speed, variable nozzles rotate open to allow in more exhaust gas
- A variable geometry turbocharger extends the boost range of the engine

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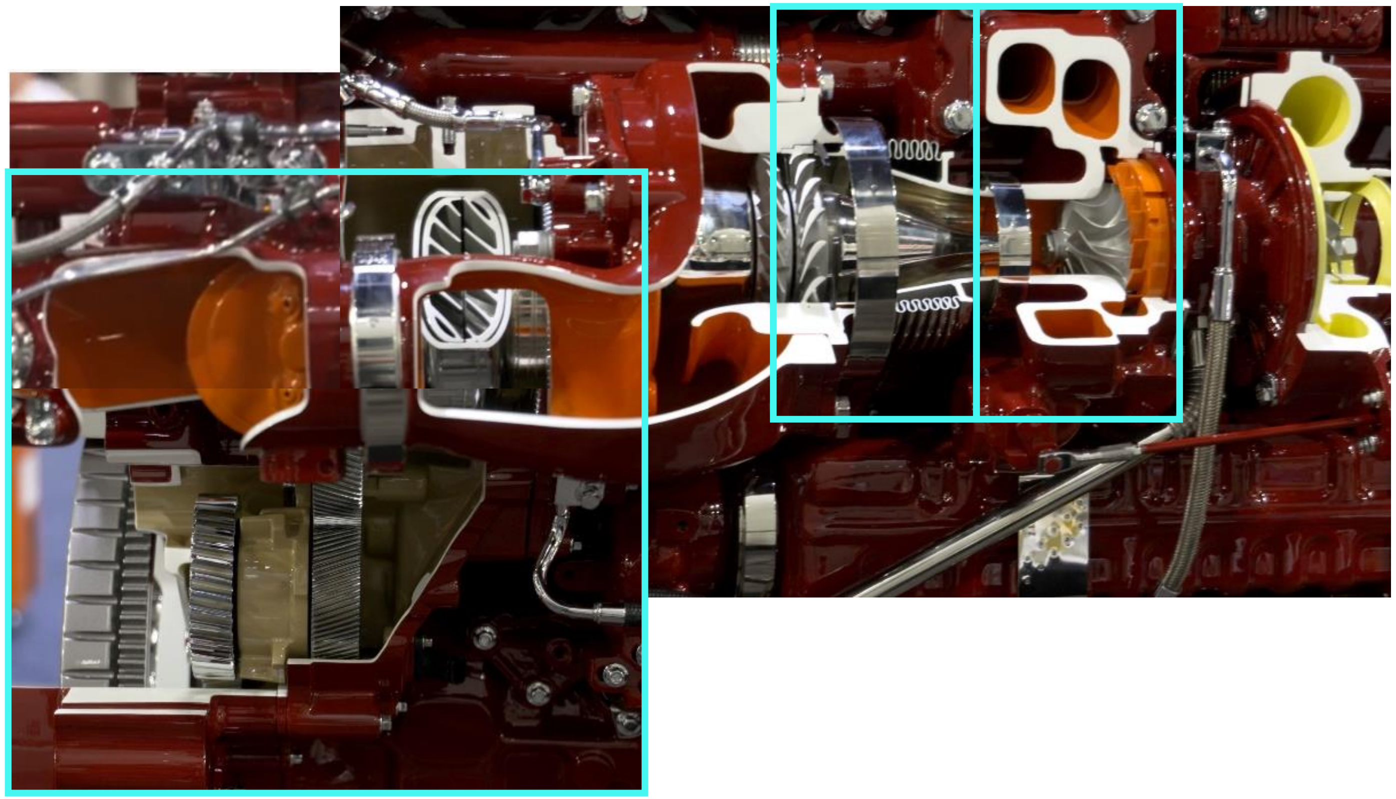
Turbo compounding / waste heat energy recovery

Converts energy from exhaust gas to mechanical energy and delivers it back to the crankshaft as torque



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3. Emissions control

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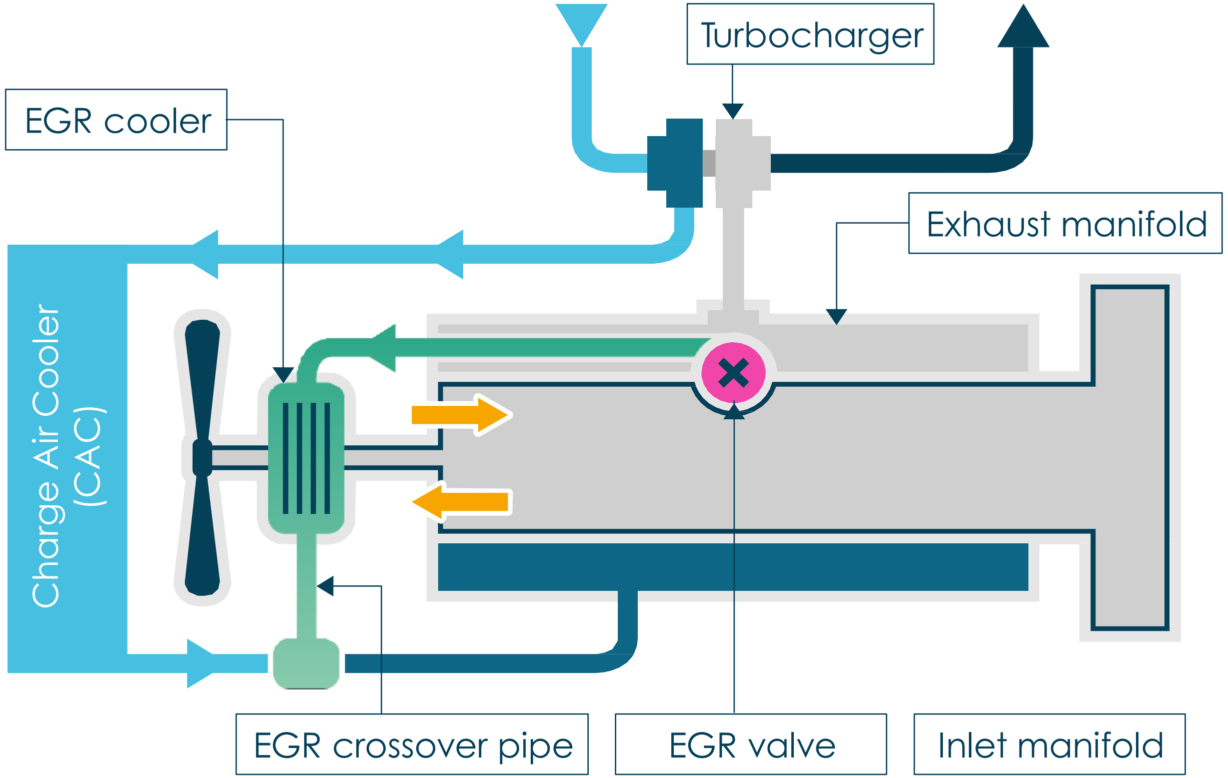
Exhaust gas recirculation (EGR) for NOx control

- Nitrogen oxides **NOx** are formed at high combustion temperatures
- Exhaust gas has a **high heat capacity**
- **EGR consequences:**
  - reduces engine efficiency
  - increases soot production
- **EGR used to meet NOx emission limits**
  - 2002 Light EGR (10-20%)
  - 2007 Heavy EGR (20-35%)



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EGR routed from exhaust manifold to intake manifold

NOTE: In use since 2002

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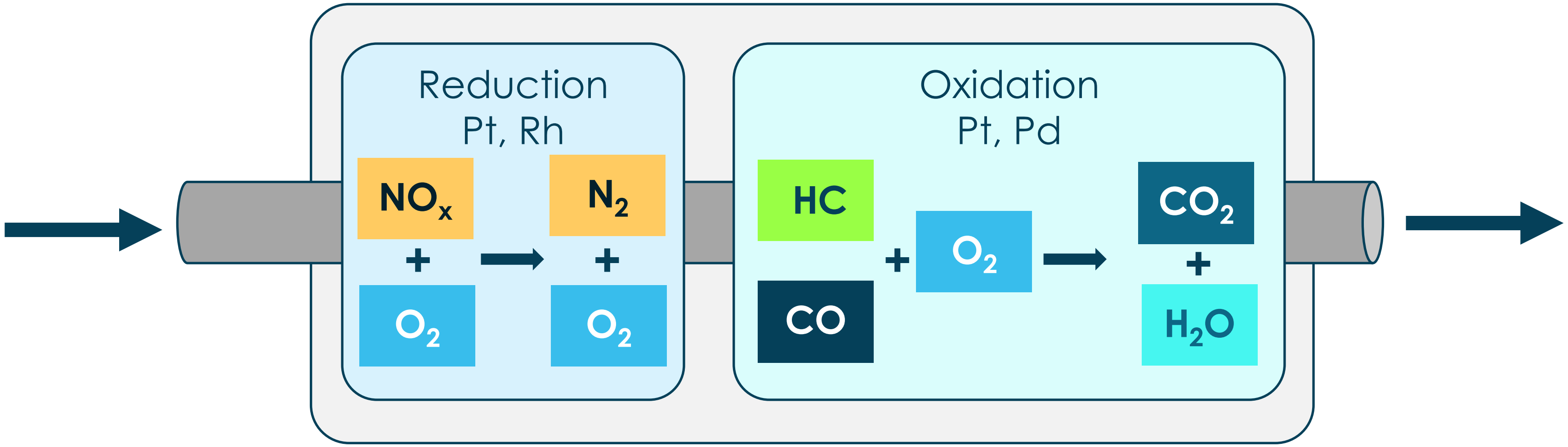
Three-way catalyst for removal of NOx, CO, and hydrocarbons

Gasoline and natural gas engine major emissions are:

- **CO** Carbon monoxide
- **NO_X** Nitrogen oxides
- **HC** Hydrocarbons

Emission control mechanisms

- **TWC** = Three-Way Catalyst



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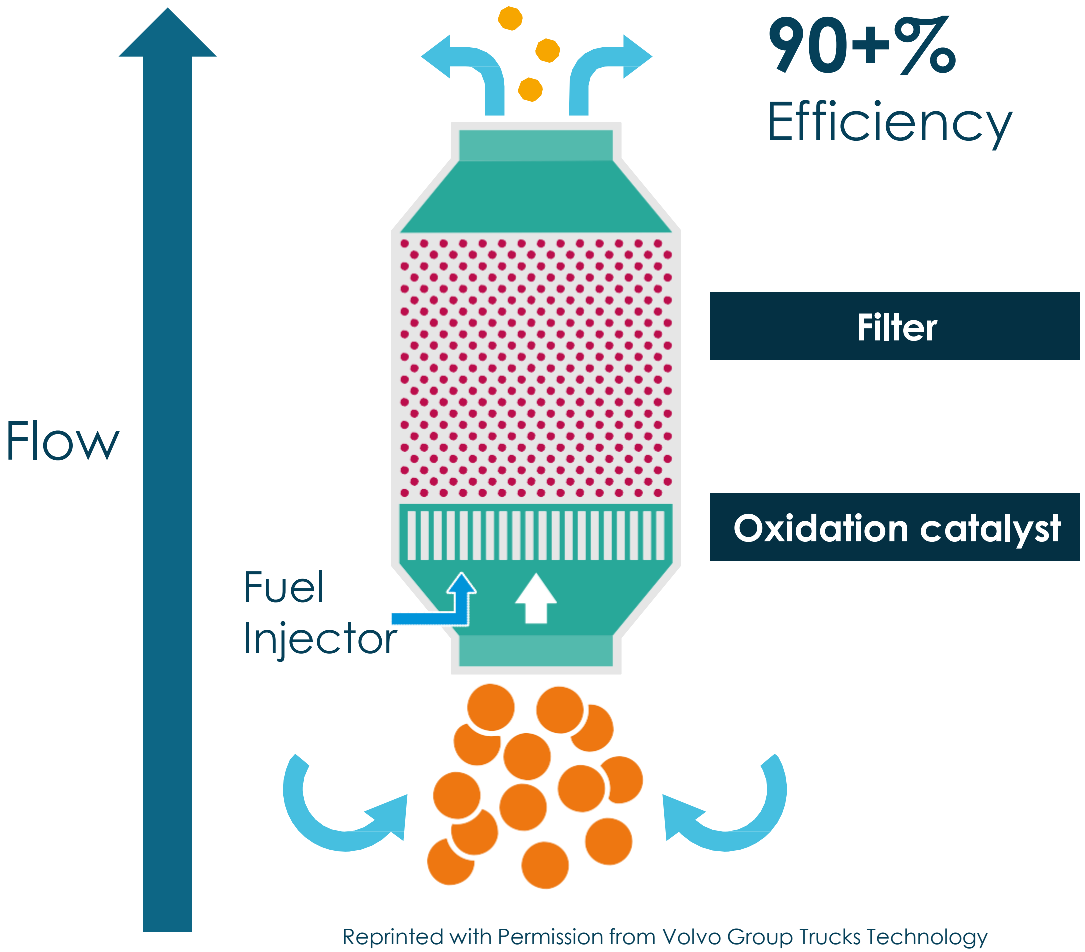
Particulate filters reduce exhaust soot

- **Filter service** is required to remove ash build-up
- **Filter Regeneration**
  - **Passive**
  - **Active**
  - Organic matter is burned off leaving small amount of incombustible **ash**
- As filter fills with soot **back pressure** builds
- Particulate matter ‘**soot’** enters the filter
- First came into use as Diesel Particulate Filter (DPF)
- Due to heavier usage of gasoline direct injection and new global regulations on particle number, Gasoline Particulate Filters (GPF) have also been introduced



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Selective catalytic reduction (SCR) for NOx control

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Key Components
- Hot Exhaust gas
- Diesel Exhaust Fluid (DEF)
- Catalyst

DEF injected after DPF
- DEF vaporizes and decomposes into ammonia

Ammonia + NOx pass over catalyst and form N_2 and water vapor

SCR - key advantage OEMs could re-advance injection timing

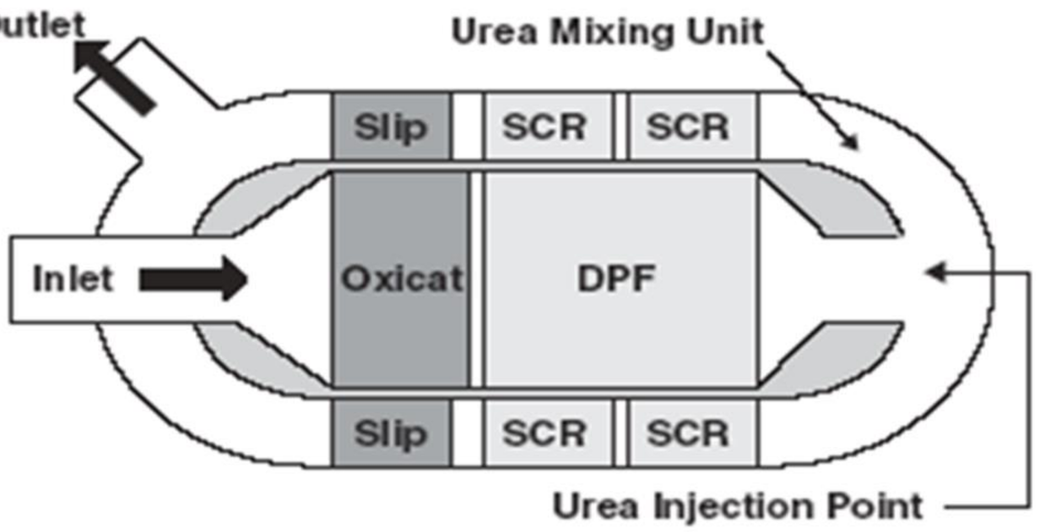

Figure 2 - Schematic representation of compact DPF-SCR system.

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DOC – Diesel Oxidation Catalyst
DPF – Diesel Particulate Filter
DEF – Diesel Exhaust Fluid (Urea)

SCR – Select Catalytic Reduction
ASC – Ammonia "Slip" Catalyst

NOTE: In use since 2010

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Exhaust after treatment systems

Mack Cleartech™ one 2017+

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- Current emission aftertreatment systems are being packaged as 1 box solutions which weigh significantly less and takes up less space than having the blocks separate
- New copper-zeolite coating improves low temperature NOx conversion for improved emissions control

Some current diesel aftertreatment systems:

- Mack – Cleartech™ one
- Cummins – Single Module™
- Detroit Diesel – 1-box aftertreatment

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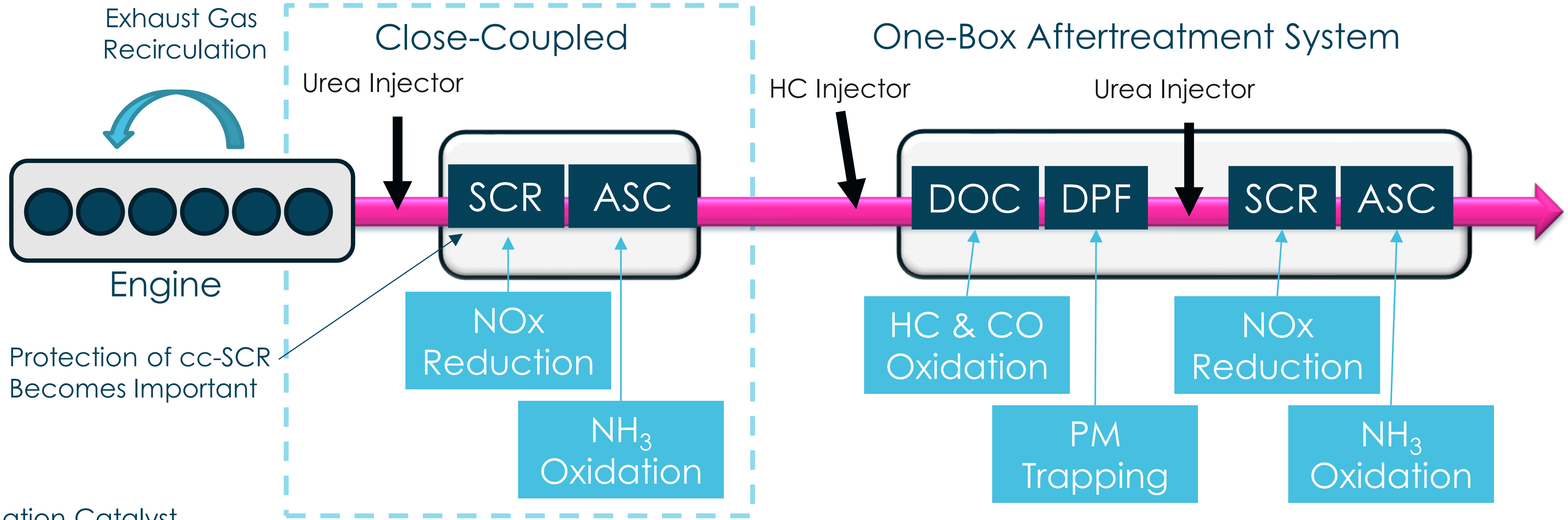
For future emissions standards more complex aftertreatment systems will be required

Aftertreatment System of Tomorrow*

More complex aftertreatment systems will be necessary for on-road HDD vehicles in 2027



DOC – Diesel Oxidation Catalyst
DPF – Diesel Particulate Filter
DEF – Diesel Exhaust Fluid (Urea)
SCR – Select Catalytic Reduction
ASC – Ammonia "Slip" Catalyst

CO – Carbon Monoxide
HC - Hydrocarbon
NH_3 – Ammonia
NO_x – Nitrogen Oxides

*Based on possible solution for Class 8 Truck proposed by CARB/EPA research

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Continuing hardware changes will affect future formulations

Design change	Resulted in change
Higher top rings	Higher upper piston temperatures
Exhaust gas recirculation	Higher oil temperatures
Increased BMEP	Need for better oxidation stability
Higher fuel injector pressures	Greater stress on oil in crankcase
Timing changes	Adjust soot loading in oil
Lower oil consumption	Less fresh make-up oil
Exhaust after treatment devices	Chemical limits on oil formulation
Engine downsizing + Turbocharging + Gasoline direct injection	Higher oxidation, pre-ignition (LSPI), soot

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4. Summary

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Summary

1. Internal combustion engines convert **chemical energy into work**
   - 4 stroke process:
     Intake, compression, power, exhaust

2. Modern gasoline and diesel engines have **many common parts** but differ in **ignition** source, engine **temperatures** and **pressures**, plus **combustion chemistry**, making the diesel lubricating environment more severe

3. Heavy-duty diesel **emissions requirements** are having a significant impact on engine design and lubricant formulation

4. Engine oil has many **responsibilities** (bearings, ring and liner, valvetrain, turbo, etc.) a balance of **viscometric properties and additive chemistry** is required to provide satisfactory lubrication in all phases of engine operation

5. Engine design and operating conditions are **constantly evolving**, placing ever more stringent demands on the crankcase lubricant

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