Basics of Automotive Engineering

Part 2:

Basics of Reciprocating Internal Combustion Engines

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Chair for Engines and Vehicles
Basics of Reciprocating Internal Combustion Engines

Introduction
Introduction

Objectives

• To give a general introduction to RICE
• Get to know the main parameters used to evaluate the operation of these engines
• To explain what air management is
• To give an introduction to different concepts of combustion in ICEs
• Introduce you to the pollutant emissions
• Get to know the basics of RICE control
1. Introduction: Characteristics and parameters of R.I.C.E
2. Basics of air management
3. Combustion in internal combustion engines
4. Pollutant emissions
5. ICE Control
1. Introduction:
Characteristics and parameters of RICE
DEFINITION:

- A machine which, by means of the linear displacement of a piston obtains mechanical energy from thermal energy stored in a fluid as a consequence of an internal combustion process.

CLASSIFICATION:

- According to air-fuel mixture ignition:
  - Spark ignition engine (SIE)
  - Compression ignition engine (CIE)

- According to the working cycle:
  - Four stroke (4S)
  - Two stroke (2S)
1. Characteristics and parameters of RICE

Working processes:

- Intake
- Compression
- Combustion Expansion
- Exhaust
1. Characteristics and parameters of RICE

Basic geometric parameters of RICE

– Bore: \( D \)
– Stroke: \( S \)
– Stroke/bore ratio: \( S/D \)
– Piston area: \( \mathbf{A_p} = \pi \frac{D^2}{4} \)
– Displacement: \( \mathbf{V_d} = \mathbf{A_p} \cdot S \)
– Number of cylinders: \( z \)
– Total displacement: \( \mathbf{V_t} = z \cdot \mathbf{V_d} \)
– Combustion chamber volume: \( \mathbf{V_c} \)
– Compression ratio: \( \mathbf{r} = (\mathbf{V_d} + \mathbf{V_c}) / \mathbf{V_c} \)
– Engine speed: \( \mathbf{n} \) (in r.p.s.)
– Mean piston speed: \( \mathbf{c_m} = 2 \cdot S \cdot n \)
### Differences between SIE and CIE:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SIE</th>
<th>CIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture formation</td>
<td>During intake</td>
<td>End of compression</td>
</tr>
<tr>
<td>Mixture ignition</td>
<td>Electric spark</td>
<td>Fuel self-ignition</td>
</tr>
<tr>
<td>Load regulation</td>
<td>Quantitative</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Fuel</td>
<td>Gasoline, LGP, NG, ethanol, biogas</td>
<td>Gas-oil, fuel-oil, bio-fuels</td>
</tr>
<tr>
<td>Working fluid during intake</td>
<td>air+fuel</td>
<td>air</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>8 to 11</td>
<td>12 to 23</td>
</tr>
<tr>
<td>Mean piston speed (m/s)</td>
<td>8 - 16 passenger, 15 - 23 sport cars</td>
<td>9 - 13 automotive, 6 - 11 motionless</td>
</tr>
<tr>
<td>Engine speed (rpm)</td>
<td>5500 - 6500 automotive, 12 000 racing</td>
<td>1800 - 5000 automotive, 500 - 1500 motionless, 70 - 200 huge 2S</td>
</tr>
</tbody>
</table>
Engine operating parameters

- There are different types of parameters:
  - Indicated parameters (referred to the cycle).
  - Brake parameters (referred to the engine shaft).
  - Normalized parameters: parameters that do not depend on the engine size.
  - Other.
Indicated parameters

– Referred to the real closed cycle.

– Do not account for pumping work, mechanical friction or driving of auxiliary equipment.

**INDICATED WORK (\(W_i\)):**

– Work done in the closed cycle (area enclosed in the p-V diagram)

**INDICATED POWER (\(N_i\)):**

– Indicated work per unit time

\[
N_i [W] = z \cdot W_i \left[ \frac{J}{\text{cycle}} \right] \cdot i \left[ \frac{\text{cycle}}{\text{rev.}} \right] \cdot n \left[ \frac{\text{rev.}}{s} \right]
\]

\(i \equiv \text{no. cycles / rev.}\)

\(2S \rightarrow i=1\) \hspace{1cm} \(4S \rightarrow i=0.5\)

**INDICATED EFFICIENCY (\(\eta_i\)):**

– Ratio of the indicated power to the heat power delivered during the combustion process.

\[
\eta_i = \frac{N_i}{m_f \cdot H_c}
\]
INDICATED MEAN EFFECTIVE PRESSURE (imep):

- Equivalent constant pressure that would produce, along a stroke, the indicated work.

\[
\text{imep} = \frac{W_i}{V_d}
\]

RELATIONSHIP WITH \( N_i \):

\[
N_i = \text{imep} \cdot z \cdot V_d \cdot n \cdot i
\]
\[
N_i = \text{imep} \cdot V_T \cdot n \cdot i
\]

\( i = \text{no. cycles / rev.} \)
1. Characteristics and parameters of RICE

Break parameters

- Referred to the engine shaft. They include:
  - Closed cycle (indicated parameters).
  - The pumping loop.
  - Friction.
  - Auxiliary equipment operation (according to standards).

**BRAKE WORK** \((W_e)\): 

- Indicated work minus mechanical losses.

\[
W_e = W_i - W_{ml}
\]

**BRAKE POWER** \((N_e)\):

- Brake work per unit time.
BRAKE MEAN EFFECTIVE PRESSURE (bmep):

- Equivalent constant pressure that would produce, along a stroke, the brake work.

\[
bmep = \frac{W_e}{V_d} = \frac{W_i - W_{ml}}{V_d} = imep - mlmep
\]

RELATIONSHIP WITH \(N_e\):

\[
N_e = bmep \cdot z \cdot V_d \cdot n \cdot i
\]

- A **pumping mean effective pressure** may be defined as:

\[
pmepe = \frac{W_b}{V_d}
\]
1. Characteristics and parameters of RICE

TYPICAL maximum bmep VALUES (in bar)

<table>
<thead>
<tr>
<th>Type</th>
<th>Nat. asp.</th>
<th>Superch.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIE passenger:</td>
<td>8 – 12</td>
<td>13 – 17</td>
</tr>
<tr>
<td>SIE sport:</td>
<td>8.5 – 14</td>
<td>16 – 25</td>
</tr>
<tr>
<td>CIE automotive:</td>
<td>6 – 10</td>
<td>12 – 23</td>
</tr>
<tr>
<td>4S CIE trucks:</td>
<td>5.5 – 9</td>
<td>14 – 28</td>
</tr>
<tr>
<td>2S CIE low-speed:</td>
<td>–</td>
<td>10 – 18</td>
</tr>
</tbody>
</table>

BRAKE TORQUE ($M_e$):

–Mechanical torque obtained at the engine shaft:

$$M_e = \frac{N_e}{\omega} = \frac{N_e}{2\pi \cdot n} = \frac{bmep \cdot V_T \cdot i}{2\pi}$$

–Proportional to total displacement and bmep (and, consequently, to the brake work).
BRAKE EFFICIENCY ($\eta_e$):

- Ratio of the brake power to the heat power delivered during the combustion process.
  
  $$\eta_e = \frac{N_e}{\dot{m}_f \cdot H_c}$$

- **Maximum brake efficiency** values are reached only in certain operating conditions. Maximum values:
  
  - SIE: 0.25 – 0.35
  - CIE: 0.30 – 0.50
1. Characteristics and parameters of RICE

MECHANICAL EFFICIENCY ($\eta_m$):
- The mechanical efficiency is defined from the indicated and brake efficiencies:

$$\eta_m = \frac{N_e}{N_i} = \frac{bmep}{imep} = \frac{\eta_e}{\eta_i}$$

BRAKE SPECIFIC FUEL CONSUMPTION ($g_{ef}$, bsfc):
- Ratio of the consumed fuel to the delivered power.

$$g_{ef} = \frac{m_f}{N_e} = \frac{1}{\eta_e \cdot H_c}$$

Typical values (minimum $g_{ef}$):
- CIE: 280 - 170 g/kWh
- SIE: 330 - 240 g/kWh
There are two other interesting operating parameters:

The fuel-air ratio (absolute):

\[ F = \frac{\dot{m}_f}{\dot{m}_a} \implies \dot{m}_f = F \cdot \dot{m}_a \]

The relative fuel-air ratio can also be defined:

\[ F_R = \frac{F}{F_e} \implies \dot{m}_f = F_R \cdot F_e \cdot \dot{m}_a \]

(with \( F_e \) = stoichiometric fuel-air ratio)

### Typical values:

<table>
<thead>
<tr>
<th>( F_e )</th>
<th>Natural Gas</th>
<th>1 / 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1 / 14.6</td>
<td></td>
</tr>
<tr>
<td>Gas-oil</td>
<td>1 / 14.5</td>
<td></td>
</tr>
<tr>
<td>Fuel-oil</td>
<td>1 / 13.8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( F_R )</th>
<th>SIE</th>
<th>( \approx 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIE</td>
<td>( \leq 0.8 ) [global]</td>
<td></td>
</tr>
</tbody>
</table>
The **volumetric efficiency** (it is a measure of the cylinder filling):

\[
\eta_V = \frac{\dot{m}_a}{\dot{m}_{ref}} = \frac{\dot{m}_a}{\rho_{ref} \cdot V_T \cdot n \cdot i}
\]

– The real air mass flow is related to a reference air mass flow (a “theoretical” value).

– This parameter is very important, since the cylinder filling (with air) is the factor that limits the engine power.

\[
N_e = \eta_e \cdot \dot{m}_f \cdot H_c = \eta_e \cdot F_R \cdot F_e \cdot \dot{m}_a \cdot H_c
\]
1. Characteristics and parameters of RICE

- There are three important engine parameters, all of them related by the following equation:

\[ Ne = Me \cdot \sigma = Me \cdot 2 \cdot \pi \cdot n \]

- Engine power (Ne): ability to perform work.
- Engine torque (Me): engine “force”.
- Engine speed (n): engine “velocity”.

- All these parameters strongly depend on the engine size (and type). How can we remove the effect of the engine size?
  - Engine torque (Me): the corresponding normalized parameter is the bmep.
  - Engine speed (n): the corresponding normalized parameter is the mean piston speed \( c_m \).
  - Engine power (Ne): the specific power, defined as follows:

\[
Ne = \text{bmep} \cdot V_T \cdot n \cdot i = \text{bmep} \cdot z \cdot A_P \cdot c_m \cdot \frac{i}{2}
\]

\[
\frac{Ne}{z \cdot A_P} = \frac{\text{bmep} \cdot c_m \cdot i}{2}
\]
1. Characteristics and parameters of RICE

- Engine operation is characterized by:
  - **Engine speed** \((n, C_m)\).
  - **Load** (torque, bmep): ratio between the torque (bmep) delivered and the maximum torque (max bmep) at a given engine speed.

**ENGINE SPEED CHARACTERISTIC CURVES**

- Variation of engine characteristic magnitudes \((N_e, M_e, g_{ef}, \eta_v\ldots)\) as a function of engine speed \((n, C_m)\) at constant load.

**Full-load curves**

**Part-load curves**
1. Characteristics and parameters of RICE

**Opel 2.5TD**

**TDI 150 CV**
1. Characteristics and parameters of RICE

**A8 4.2 l.**

![Graph for A8 4.2 l.](image)

**CBR 600F**

![Graph for CBR 600F](image)
1. Characteristics and parameters of RICE

**Torque**

- 300 Nm

**BMEP**

- 0 - 4000 - 8000 - 12000

- BMEP vs. rpm

- A8 4.2 l
- CBR 600 F4i
- Opel 2.5TD
- TDI 150 CV
1. Characteristics and parameters of RICE

**Ne**

- Potencia [kW] vs. Régimen [r.p.m.]

**Specific Ne**

- Pot. Exp. [kW/m²] vs. Cm [m/s]

Graphs showing the performance characteristics of different models:
- A8 4.2i
- CBR 600 F4i
- Opel 2.5TD
- TDI 150 CV
A RICE delivers mechanical energy from the thermal energy supplied to the working fluid by a combustion process; that energy is transmitted by means of the linear displacement of a piston.

- Depending on the number of strokes required to complete an engine cycle, there are four-stroke (4S) and two-stroke (2S) RICE.

- Depending on the combustion process, there exist spark-ignition engines (SIE) and compression-ignition engines (CIE).
1. Characteristics and parameters of RICE

- **Indicated parameters** (work, mean effective pressure and power) refer to the closed cycle in the real p-V diagram of the engine.

- **Brake parameters** are referred to the engine shaft.

- **Normalized parameters** are really useful to remove the effect of engine size on a given aspect.

- **Engine speed** and **engine load** are the main operating variables of an engine.

- The **characteristic curves** give a graphical representation of the variation of a magnitude as a function of engine speed and load.
2. Basics of air management
Process definition and description:

- Air management is a process aimed to the replacement of burned gases with fresh air (or air-fuel mixture)
Characteristic parameters:

Volumetric efficiency:

\[ \eta_v = \frac{\dot{m}_m}{\frac{n}{2} V_T \rho_{im}} \approx \frac{\dot{m}_a}{\frac{n}{2} V_T \rho_{ia}} \]

Reference conditions:

Elements downstream of reference points are evaluated
Characteristic parameters:

- Residual gasses → effect on trapped mass and composition
- Short circuiting mass
- Pumping mean effective pressure

Work required for air management
Important phenomena that affect air management:

- Pressure drop
- Gas inertia
- Gas heating
Effects of pressure drop:

- Pressure drop at different elements (filter, ducts, throttle valve, valves and ports) affect the pumping work.

- The pressure drops during intake leads to density reduction, therefore the volumetric efficiency diminishes.
2. Basics of air management

Effects of gas inertia:

- **Valve overlap:**
  - Period in which intake and exhaust valves are opened simultaneously
    - Short circuiting can happen (fresh mass goes out of the cylinder)
  - Valve piston interaction must be taken into account
  - Inertia of intake fresh gasses and exiting burned gasses can be used to improve burned gas replacement with fresh gasses
Effects of gas heating:

Heat transfer affects gas density during intake process

- The heat transfer depends on:
  - Ports area
  - Residence time
  - Gas-wall temperature difference

- Residence time is affected by engine speed
- Temperature difference is affected by ambient temperature and engine load
Summary

- The best parameter to characterize the air management process is the volumetric efficiency.
- Air management has a big influence on engine performance.
- The most relevant phenomena involved in the process are:
  - Pressure drop
  - Gas inertia
  - Gas heating
- Engine components with the greatest importance are:
  - Ports and valves
  - Valve timing
  - Intake and exhaust manifolds
Basics of Reciprocating Internal Combustion Engines

3. Combustion in internal combustion engines
Why is combustion important in an ICE?

- Engine power output:
  \[ Ne = n \cdot i \cdot \eta_m \cdot W_i \]
  Where:
  - \( n \) – engine speed
  - \( i \) – number of cycles per engine revolution
  - \( \eta_m \) – mechanical efficiency
  - \( W_i \) – indicated work (area closed by the pV diagram)

Compression/ \textsc{Combustion}/Expansion

- Pollutant emission formation
3. Combustion in ICE

Definitions:

- Rapid oxidation generating heat, or both light and heat
- Transformation of some chemical species (reactants) into others (products)
- A process in which the chemical energy imbalance is released in the form of thermal energy (heat)

Combustion classification criteria:

- Reaction initiation
- Propagation speed
Combustion is a chemical reaction... How is it started?

- **Induced-ignition**
  An external source rises local temperature until achieving chemical reaction initiation
  - Electrical arch, hot point, laser...

**Spontaneous**

**Self-ignition**: Fuel-air mixture is chemically unstable, and chemical reaction occur
3. Combustion in ICE

Propagation speed

A reaction front propagates at a combustion speed $u_c$

- **Explosion**: infinite velocity $u_c \to \infty$
- **Detonation**: $u_c \geq a$ (a – speed of sound)
- **Deflagration**: flames $u_c < a$
  
  - Premixed - fuel-air mixture already exists
  - Diffusion (non-premixed) – mixing and combustion occur at the same time
### Combustion classification criteria applied to engines

- **Reaction initiation:**
  - Spark ignition (SI)
  - Compression ignition (CI)

- **Propagation speed: Deflagration**

<table>
<thead>
<tr>
<th>Initiation</th>
<th>Premixed</th>
<th>Non-premixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-ignition</td>
<td></td>
<td>Conventional CI</td>
</tr>
<tr>
<td>Induced-ignition</td>
<td></td>
<td>Conventional SI</td>
</tr>
</tbody>
</table>
Conventional SI combustion
3. Combustion in ICE

Conventional SI combustion

Phases:
• **Ignition**: electrical discharge
• **Initial phase (5% fuel burnt)**: from spark discharge to the deviation from motored pressure. Laminar combustion.
• **Main phase (90% fuel burnt)**: Turbulent combustion
• **Final phase (5% fuel burnt)**: Laminar combustion. Burning of mixture close to the cylinder walls
• **Extinction**
3. Combustion in ICE

Abnormal SI combustion

- Undesirable uncontrolled combustion
- Reduces engine performance
- Can damage the engine

Types:
- Knocking
- Surface ignition
3. Combustion in ICE

Knocking (detonation)

- Autoignition of the end-gas mixture, due to the increase in pressure and temperature due to the combustion
- Autoignition is followed by detonation waves. As a consequence, violent vibration of the gas and mechanical elements occurs.
3. Combustion in ICE

Surface ignition

Hotspots in the combustion chamber can generate flame fronts at any time

- **Pre-ignition:** occurs before the spark. Usually leads to knock.
- **Post-ignition:** occurs after the spark.
3. Combustion in ICE

**CI Combustion**

- **Diffusion (non-premixed) flames**
  - Fuel and air are supplied separated to the combustion chamber
  - Mixing process due to:
    - Momentum flux exchanged between fuel and ambient air
    - Natural convection
  - Relative fuel-air ration and T change spatially
  - Chemical reaction in the flame front
    - Max T $\rightarrow$ Tad ($\phi = 1$)
3. Combustion in ICE

CI Combustion

Diffusion combustion

- Two phenomena are controlling the process:
  - Chemical reaction rate is fast and similar to the premixed flames
  - Combustion process controlled by fuel and O2 mixing process

- Very complex problem…2 stages:
  - Inert spray (mixing)
  - Reactive spray (mixing + reaction)
3. Combustion in ICE

- Implications on engine hardware and settings:
  - Atomization + mixing process up to auto-ignition \(\rightarrow\) *slow process compared to SI*
    - Limited engine speed *(up to 4000 rpm)*
    - Lean air-fuel ratio to get soot free combustion *(0.2 up to 0.9)*
  - Auto-ignition process:
    - High Thermodynamic conditions *(P & T) \(\rightarrow\)* *High compression ratio compared to SI (up to CR 18)*
    - Fuels with low octane number *(Diesel; biodiesel, Fischer Tropsch)*
3. Combustion in ICE

3 different stages:

- Fuel mass flow
- Heat Release
- Pressure
- Rate of HR

- Injected
- Burned
3. Combustion in ICE

3 different stages:
- Ignition delay (I)
  The time spent between the end of injection to the start of combustion
- Premixed combustion (II)
  Fuel mixed and vaporized during ignition delay is auto-ignited
- Diffusion combustion (III)
  Fuel mixes and burns at the same time

![Diagram showing stages of combustion](image)
UNDERTHEHOOD

Basics of Reciprocating Internal Combustion Engines

4. Pollutant emissions
4. Pollutant emissions

Pollution sources in RICE

Acoustic pollution. Noise emission as a result of:

- Gas exchange process
- Combustion process
- Moving parts

Chemical pollution. Sources and substances:

- Fuel tank: unburned fuel vapour
  - can be eliminated by adsorption
- Carter: oil vapour
  - Conducted to the intake

Combustion process

- Chemical substances
4. Pollutant emissions

Problems caused by pollution

Urban area air quality:

- CO, HC, NOx, PM, O₃, noise

&

Global environmental issues:

- CO₂, CH₄, N₂O, depletion of fossil fuels,...
4. Pollutant emissions

Exhaust gas composition

- Ideal hydrocarbon combustion: $\text{CO}_2 + \text{H}_2\text{O}$
-Incomplete combustion: CO+HC
- Nitrogen by-products: NOx
- Fuel carbonisation + oil adsorption + others: Particulate matter (solid substances)

SI Engine:

CI Engine:
- Large amount of particulate matter and soot
4. Pollutant emissions

Exhaust gas composition

- Carbon monoxide (CO) is toxic
  @ 0.3% volume fraction in air ➞ death in 30 minutes
- Unburned Hydrocarbons (HC)
  cause smog formation, some cause cancer
- Nitrogen oxides (NO$_x$) NO and NO$_2$
  Smog and acid rain formation
  NO ➞ contributes to ozone reduction in the stratosphere
  NO$_2$ ➞ toxic, irritates the respiratory system, greenhouse effect precursor
- Particulate matter
  environment pollution and dirtiness
  health problems: deposition in lungs, with long term exposure can cause cancer
4. Pollutant emissions

How much emissions are from transport?

Data 2010 – EEA-32

source: European Environment Agency
# 4. Pollutant emissions

## Standards and regulations historical review

### USA

<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>California</td>
<td>Crankcase emissions and atmosphere concentration</td>
</tr>
<tr>
<td>1963</td>
<td>Rest of USA</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>FTP Cycle</td>
<td>HC, CO (concentration)</td>
</tr>
<tr>
<td>1972</td>
<td>FTP - 72</td>
<td>HC, CO, NO(_x) (mass per distance)</td>
</tr>
<tr>
<td>1975</td>
<td>FTP - 75</td>
<td>HC, CO, NO(_x) (mass per distance)</td>
</tr>
</tbody>
</table>

### Europe

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>VDI (Germany)</td>
<td>1er Directive draft</td>
</tr>
<tr>
<td>1963</td>
<td>France</td>
<td>1a regulacion of smoke</td>
</tr>
<tr>
<td>1964</td>
<td>France</td>
<td>1a regulacion of crankcase vapour</td>
</tr>
<tr>
<td>1969</td>
<td>France</td>
<td>Regulation of CO at idle</td>
</tr>
<tr>
<td>1976</td>
<td></td>
<td>Regulation of NO(_x)</td>
</tr>
</tbody>
</table>

### Japan

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>CO (concentration and mass)</td>
</tr>
<tr>
<td>1973</td>
<td>HC and NO(_x)</td>
</tr>
</tbody>
</table>
Standards and regulations historical review

European limits evolution (passenger cars)
Current EU regulations for emission control

- Limits of exhaust emissions for:
  - CO, HC, NO$_x$, PM mass and number, CO$_2$
  - Smoke (only diesel)

- Regulations for fuel quality:
  - Maximum Sulphur content: 10 ppm
  - Minimum Diesel cetane number of 51
  - Aromatic compounds content

- Durability, OBD (on board diagnostics), secondary emissions with advanced aftertreatment (NH$_3$, …)
4. Pollutant emissions

European standards: Passenger cars

- Test type:
  - Vehicle test in chassis dynamometer:
  - gr/test or g/km
  - CO, HC, NO\textsubscript{x}, PM
  - Transient cycle (NEDC cycle)

Chassis dynamometer test
## European standards: Passenger cars

**NEDC**
(New European Driving Cycle)

<table>
<thead>
<tr>
<th></th>
<th>Urban</th>
<th>Extra-urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [km]</td>
<td>4x1.013</td>
<td>6.955</td>
</tr>
<tr>
<td>Duration [s]</td>
<td>4x195</td>
<td>400</td>
</tr>
<tr>
<td>Mean speed [km/h]</td>
<td>18.7</td>
<td>62.6</td>
</tr>
<tr>
<td>Max speed [km/h]</td>
<td>50</td>
<td>120</td>
</tr>
</tbody>
</table>
### European standards: Passenger cars

<table>
<thead>
<tr>
<th>Tier</th>
<th>Date</th>
<th>Type</th>
<th>CO (g/km)</th>
<th>HC (g/km)</th>
<th>NOx (g/km)</th>
<th>HC+NOx (g/km)</th>
<th>Particulates (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO1</td>
<td>10/07/1992</td>
<td>Gasoline</td>
<td>2.72</td>
<td>-</td>
<td>-</td>
<td>0.97</td>
<td>-</td>
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<tr>
<td></td>
<td>01/07/1992</td>
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<td>-</td>
<td>-</td>
<td>0.97</td>
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<td>01/07/92-94</td>
<td>DI</td>
<td>2.72</td>
<td>-</td>
<td>-</td>
<td>1.358</td>
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<td>1996</td>
<td>Gasoline</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
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<tr>
<td></td>
<td>1996</td>
<td>IDI</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>0.08</td>
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<td></td>
<td>1996-99</td>
<td>DI</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
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<td>EURO3</td>
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<td>Gasoline</td>
<td>2.3</td>
<td>0.2</td>
<td>0.15</td>
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<td></td>
<td>2000</td>
<td>IDI/DI</td>
<td>0.64</td>
<td>-</td>
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<td>EURO4</td>
<td>2005</td>
<td>Gasoline</td>
<td>1.0</td>
<td>0.1</td>
<td>0.08</td>
<td>-</td>
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<tr>
<td></td>
<td>2005</td>
<td>IDI/DI</td>
<td>0.5</td>
<td>-</td>
<td>0.25</td>
<td>0.3</td>
<td>0.025</td>
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<td>EURO 5</td>
<td>2009</td>
<td>Gasoline</td>
<td>1.0</td>
<td>0.1</td>
<td>0.06</td>
<td>0.005</td>
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<td>2009</td>
<td>Diesel</td>
<td>0.5</td>
<td>-</td>
<td>0.18</td>
<td>0.23</td>
<td>0.005</td>
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<td>EURO 6</td>
<td>2014</td>
<td>Gasoline</td>
<td>1.0</td>
<td>0.1</td>
<td>0.06</td>
<td>0.005 + PN</td>
<td>-</td>
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<tr>
<td></td>
<td>2014</td>
<td>Diesel</td>
<td>0.5</td>
<td>-</td>
<td>0.08</td>
<td>0.17</td>
<td>0.005 + PN</td>
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</table>
4. Pollutant emissions

Technology evolution in passenger cars to meet past limits

- 3 way Catalytic Converter >2L
- Lambda Sensor
- Electronic fuel injection
- 3-way Catalytic Converter generalisation
- MPI
- EGR on/off
- Oxidation catalyst
- DI
- Turbo
- Common Rail
- Cooled elect. EGR
- Cold start tuning strategy

- IDI
- Mechanical pump with elec. control
- Engine out emissions
- After treatment improvement
- Common Rail with Piezo inject.
- Opti. Combustion chamber
- In some cases, DPI or NOxtrap

- Unleaded Petrol

- Lubricity
- Lead phaseout
- Gasoline S<150 ppm
- Aromatics, RVP...
- Diesel S<350ppm
- Cetane, T95...

- Oil Industry
- Diesel S<500 ppm

Source: EUCAR

EURO I 1985
EURO II 1993
EURO IV 2005

<50ppm & Sulfur free fuels
Basics of Reciprocating Internal Combustion Engines

5. ICE Control
Historical review
5. ICE Control

Historical review

- **Manual Regulation**
  - Driver

- **Mechanical Systems**
  - Driver

- **Electronic Control**
  - Driver
  - Environment
  - Other Sist.
Control systems fundamentals

- Classification:
  - Open loop: The control system does not take into account the difference between the actual and desired value of the variable to be controlled (does not guarantee a minimum error)
  - Closed loop: The control system takes into account the difference between the actual and desired value of the variable to be controlled (PID is the most usual closed loop control system, and can guarantee a minimum error under some assumptions)
- The control strategy is strongly dependent on the information available (sensors)
- There are other criteria than accuracy to be taken into account: stability, robustness…
5. ICE Control

Systems to be controlled in ICEs

- **Air loop elements:**
  - Intake throttle, variable geometry turbine, variable valve timing...
- **Injection system:**
  - Injection pressure, timing and profile...
- **Spark management:**
  - Spark timing, spark energy
- **Thermal management:**
  - Radiator bypass, electro fan, glow plugs...
- **Exhaust gas after-treatment system**
- **Vehicle/powetrain:**
  - Dashboard panel, ABS, gearbox...
General engine control system structure (HW + SW)
5. ICE Control

Sensors

- Position sensors:
  Pedal position, crankshaft position and speed...

- Pressure sensors:
  Intake pressure, fuel rail pressure, turbo pressure, ...

- Temperature sensors:
  Coolant temperature, oil, fuel, intake air...

- Air mass flow sensor

- Lambda sensor:
  Used for air-fuel ratio control
Actuators (a few examples)

- Variable valve timing
- Electronic throttle control
- Variable geometry turbine
- Fuel rail pressure regulators
- Many more
5. ICE Control

Wiring

- Conventional wiring has been replaced by data bus wiring – CAN (controller area network) or Flex Ray

Diagram showing FlexRay Channel A and B, ECU, Gearbox CU, ABS CU, and Data bus cables.
5. ICE Control

ECU hardware

➢ ECU (engine control unit) or PCM (powertrain control module)
5. ICE Control

Software

- The ECU is programmed in different levels
5. ICE Control

Software

- Extended use of engine maps: 2D or 3D tables that contain characteristic values of the control variables as a function of other engine variables (typically engine speed and load or other sensor values)
Example

- Air-fuel ratio control in SI internal combustion engines
THE END
THANKS FOR YOUR ATTENTION

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