UNITED

Engineering Knowledge Transfer Units to Increase Student´s Employability and Regional Development

2nd UNITED Training Melaka

From ICE to Alternative Powertrain (ICE SLOT 1)

Thomas Esch

Co-funded by the Erasmus+ Programme of the European Union

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WP 2 – Trainer Summary

Academic CV

- Adjunct professor at the Royal Melbourne University of Technology, Australia (since February 2013)
- Head of Institute "Applied Thermodynamics and Combustion Technology" at FH Aachen (since 1998)
- Head of Institute "Thermal Power and Heat Engines and Vehicle Mechanics" at the FH Aachen (1993 to 1998)
- FH Aachen: External lecturer in the field of internal combustion engines (1985 to 1993)
- RWTH Aachen University: Lecturer in the field of energy technology and internal combustion engines (1984 to 1989)
- Ph.D. (1992): Thesis title "Effect of cylinder design on the tribological properties of water-cooled four-stroke internal combustion engines", academic teaching adviser Prof. Dr. Franz Pischinger
- Academic study: Semester abroad at the University of Las Vegas, Solar Energy Systems Engineering (1984)
- Academic study: Dipl.-Ing. Mechanical Engineering "Process Engineering" at the RWTH Aachen (1979 to 1984)

Thomas F. Esch
Dean of Finance
Head of Master Course International Automotive Engineering

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WP 2 – Trainer Summary

Professional experience

- Consulting service to various companies, director of the “Competence Center for Electromagnetic Valve Train Systems”, senior project management, attestation engagements, seminar manager (since 1994)
- FEV Aachen: Various positions from group leader "Tribology" (1989 to 1990), assistant to the business head "Design and Development" (1990 to 1991) to the department head for "Engine Mechanics" (1991 to 1993)
- Institute for Applied Thermodynamics at RWTH Aachen University and FEV Aachen: Researcher and project engineer in the field of combustion engineering of ICE (1985 to 1989)
- Desert Research Institute, Boulder City (Nevada, USA): Research engineer in the field of latent heat storage technologies (1984 to 1985)

Publications and editorial activities

- More than 130 scientific publications and presentations
- R&D reporting of more than 150 industrial projects
- 52 national and international patents and patent applications
- Founder and editor of the book series "Applied Thermodynamics" (9 volumes)
- Co-founder and co-author of the technical book "Light and Heavy Duty Truck Technology"

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WP 2 – Trainer Summary

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Lectures at Aachen University of Applied Sciences (Institute of Applied Thermodynamics and Combustion Technology)

Undergraduate Study:

- **Fundamentals of Thermodynamics** (Ba – 3. Semester)
- **Vehicle Dynamics (Longitudinal !)** (Ba – 4. Semester)
- **Internal Combustion Engines** (Ba – 5. Semester)
- **Combustion Technology** (Ba – 6. Semester)
- **Space Propulsion Systems** (Ba – 6. Semester)

Graduate Study:

- **Environmental Effects of Vehicle Powertrains** (Ma – 1. Semester)

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WP 2 – Trainer Summary

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Lectures at Aachen University of Applied Sciences (Institute of Applied Thermodynamics and Combustion Technology)

By External Lecturers:

- **Patent Law for Engineers** (Ba – 6. Semester)
- **General Management of Automotive Suppliers** (Ma – 1. Semester)
- **Global Automotive Homologation and Mass Production Release** (Ma – 2. Semester)

General Competencies by External Lecturers:

- **Project Management** (Ba – 1. Semester)
- **Rhetoric for Engineers** (Ba – 1. Semester)
- **Leadership and Decision Making** (Ba – 2. Semester)

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WP 2 – Training Overview

- Slot 1: **Introduction and Overview of ICE Technology**
- Slot 1: **Thermodynamics of ICE**
- Slot 2: **ICE Characteristics and Mixture Formation**
- Slot 2: **ICE Gas Exchange and Performance Increase**

Seminar content (academia level) is targeted to students at the end of an undergraduate study and to professional lectures/curriculum managers of Automotive study courses

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WP 2 – Global Light-Duty Vehicles Sales

- In 2017, 90 million light-duty vehicles have been sold globally increasing to 118 million units by 2030.
- The three major automotive regions, Europe, USA and China, account for approximately 60 percent of the global market. Between 2017 and 2030, vehicle sales are likely to stay constant in Europe and the USA.
- For China and the rest of the world, an annual sales growth between 1.5 percent and 4 percent is forecasted. Sales of combustion engine based powertrains (including hybrid electric drivetrains) are expected to increase throughout 2025 reaching a maximum of approximately 100 million units, which represents a 12 percent increase compared to 2017.

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WP 2 – Global Light-Duty Vehicles Sales

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- In the base scenario, sales of combustion engines are expected to reach a plateau between 2025 and 2030 before declining in the long-term.
- Sales of electric powertrains are expected to increase significantly reaching 20 million units by 2030.
- This includes almost exclusively battery electric vehicles, while large scale market penetration of fuel cell based drivetrains is only expected for the period after 2030.
- In Europe, USA, and China, the transition from conventional to electrified powertrain systems will be happening significantly earlier than in less mature markets. As a result, the number of internal combustion engines sold in these three markets in 2030 is expected to be approximately 10 percent below the 2016 sales volume. Hybrid drivetrains (including mild hybridization with 48V technology) are expected to account for approximately 56 percent of sales in 2030.

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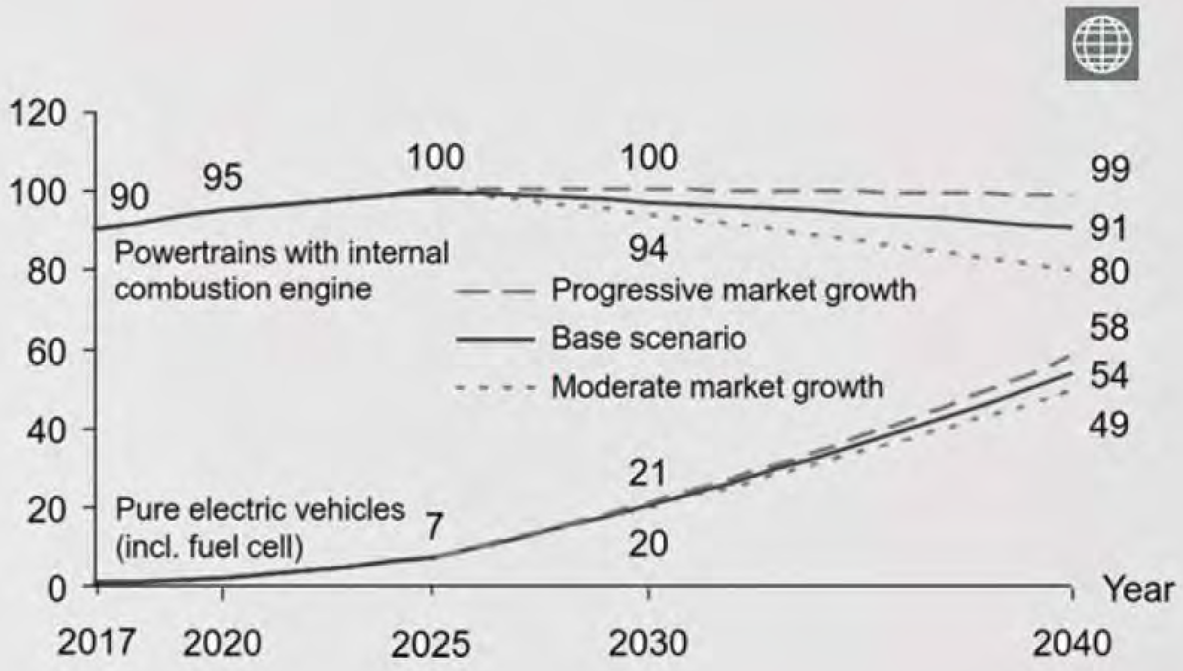
WP 2 – Global Light-Duty Vehicles Sales



Global light-duty vehicles sales forecast in million units
(Vehicle sales include passenger cars and light commercial vehicles up to 3.5 tons Source: FEV)

2030 light-duty vehicles sales
 # Base scenario

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[1]

WP 2 – Expected Global Sales Volume in 2030

- The technological change also affects other components of the powertrain. The average number of cylinders decreases by 8 percent from 4.3 to 4.0 due to an ongoing trend towards turbocharged three and four cylinder engines.
- Among the three key automotive regions, the pace of the transition towards electrified powertrains varies.
- In Europe, a share of 21 percent battery electric vehicles is forecasted for 2030. A main driver for this development is the regulation of CO2 emissions for newly registered vehicles, which every vehicle manufacturer has to abide by individually.
- In addition, aversion against combustion engine based vehicles is increasing in some parts of society and the acceptance of e-mobility is increasing.

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WP 2 – Expected Global Sales Volume in 2030

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- The expected investments into charging infrastructure and roll-out of electric vehicle portfolios by many manufacturers are likely to facilitate the transition. For the US market, a lower sales share of electric vehicles (9% in 2030) is expected for 2030. Compared to Europe, the US CO2 emission regulation is less stringent.

- In addition, electric vehicles are less suitable for average US customers, which prefer larger vehicles and are driving longer distances compared to Europe. However, in some regions of the USA, especially the coastal areas, a higher market share of electric vehicle is expected. In China, a comparably high electric vehicle share of 29 percent is expected for 2030.

- Main driver for the high market penetration is a variety of regulatory programs pushing electric vehicle sales, such as fuel economy targets, electric vehicle sales quotas ("NEV credit targets") and advantages for electric vehicles in license plate assignments.

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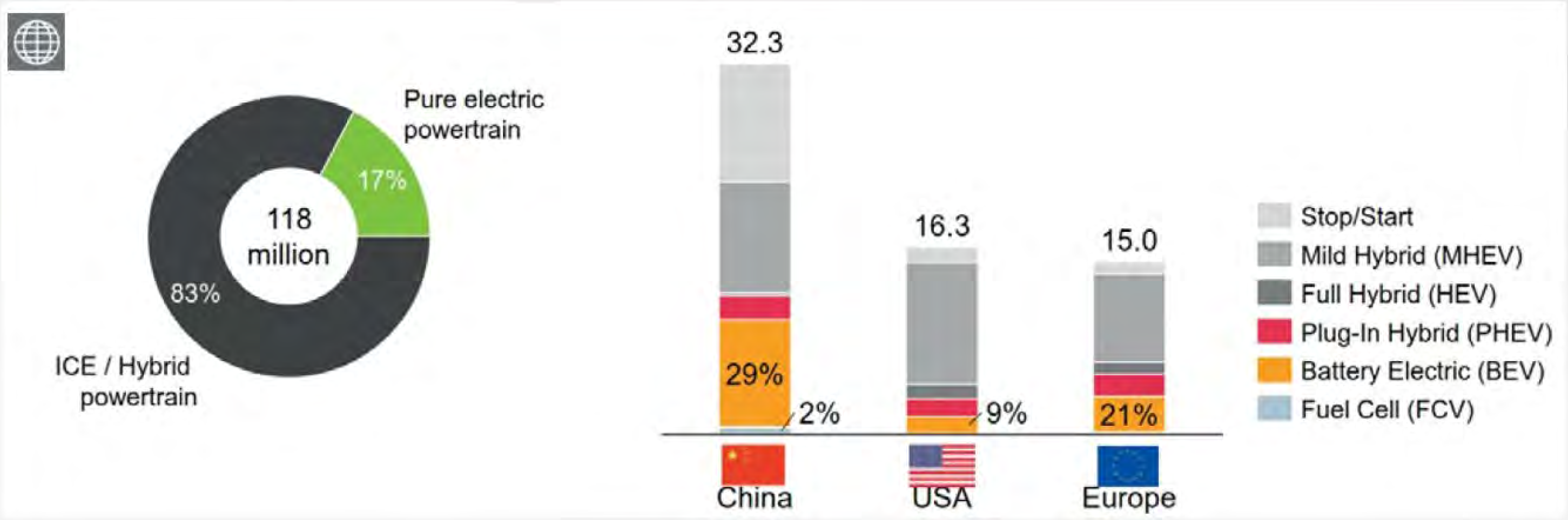
WP 2 – Expected Global Sales Volume in 2030



Expected global sales volume in 2030
(# Base scenario; vehicle sales include passenger cars and light commercial vehicles up to 3.5 tons, source: FEV)

Passenger car powertrain tupe forecast for 2030 in million units
(# Base scenario;)

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[1]

WP 2 – Malaka SLOT 1

- **Introduction** and Overview of ICE Technology (30 minutes)

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WP 2 - Germany: Look Back - Dieselgate Scandal Political

- September 2015: EPA found that TDI diesel engines activate emissions controls only during laboratory emissions testing
  - output meets US standards during regulatory testing, but up to 40 times more NO in real-world driving
  - regulators in multiple countries began to investigate Volkswagen
  - stock price fell in value by a third
  - VW Group CEO Martin Winterkorn resigned
- April 2016: Volkswagen announced plans in to spend €16.2 billion on rectifying the emissions issues
- January 2017: Volkswagen pleaded guilty to criminal charges
- April 2017: a US federal judge ordered Volkswagen to pay a $2.8 billion criminal fine
- 3 May 2018: Winterkorn was charged in the United States with fraud and conspiracy

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Defeat Device.

- A defeat device is a kind of manipulation, more precisely a function within a control unit with the purpose to changing or modulating any kind of exhaust emission related system, part or function.

- Similar but different definitions between EU and US legislation.
  - > One reason for different liability and concessions of VW

- Differences more or less about the exceptions of the prohibition of such a defeat device.
  - > EU definition offers a huge room of interpretation
  - > “Component protection”

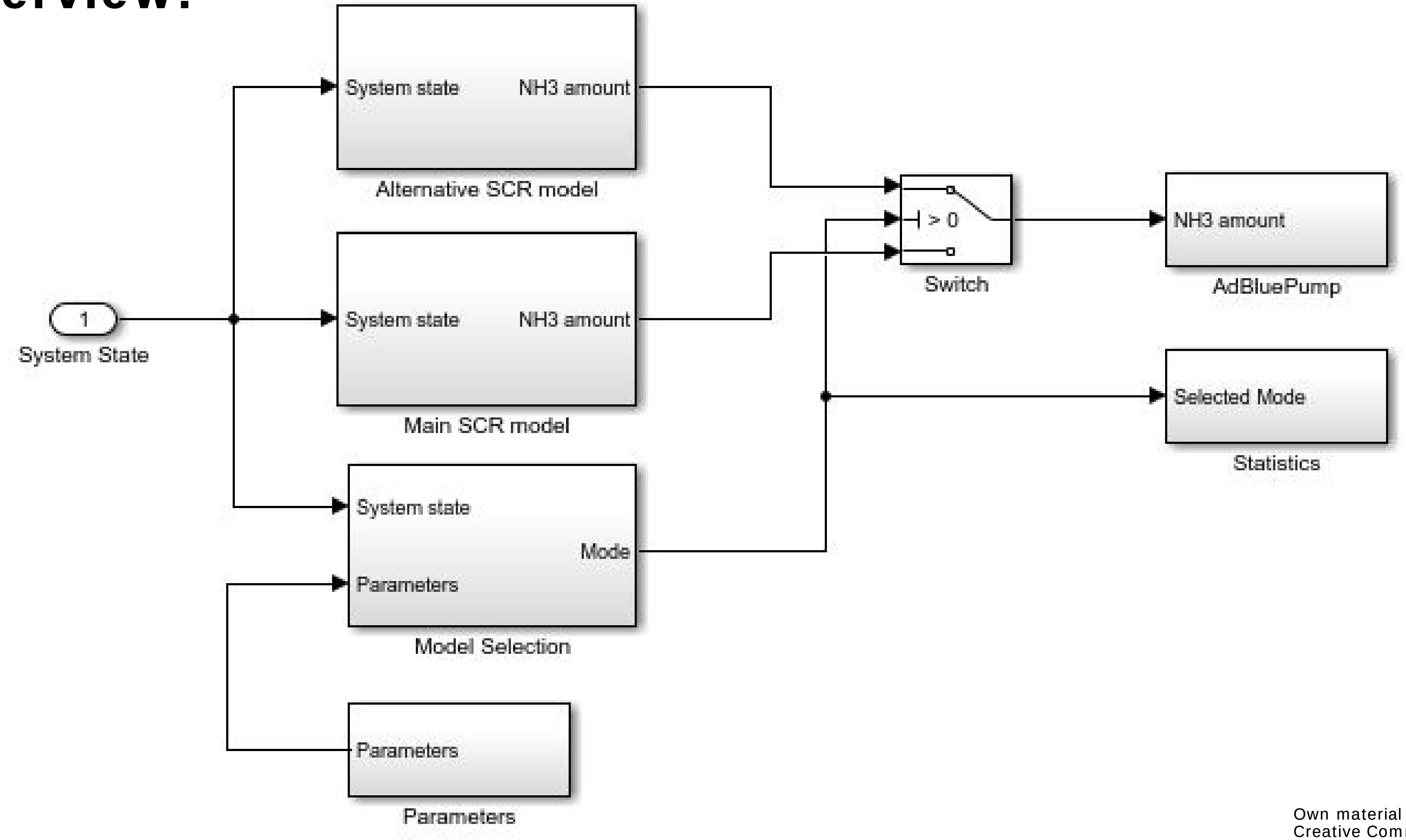
- Article 2 (10) and article 5 (2) of the EU regulation 715/2007

Defeat Device in the Diesel Exhaust Gas Scandal.

- Volkswagen cheated by deactivating NOx-reduction systems
  - Switching to rudimental calibration model (SCR catalyst)
  - Deactivating of DeNOx events (LNT)
- For manipulation a cycle detection is necessary
  - Emission tests are done on dynamometer under predefined conditions.
  - NEDC (EU), FTP 75 (US)
- Software structure, how it was implemented by VW, for manipulating the SCR system is shown on the next slides.

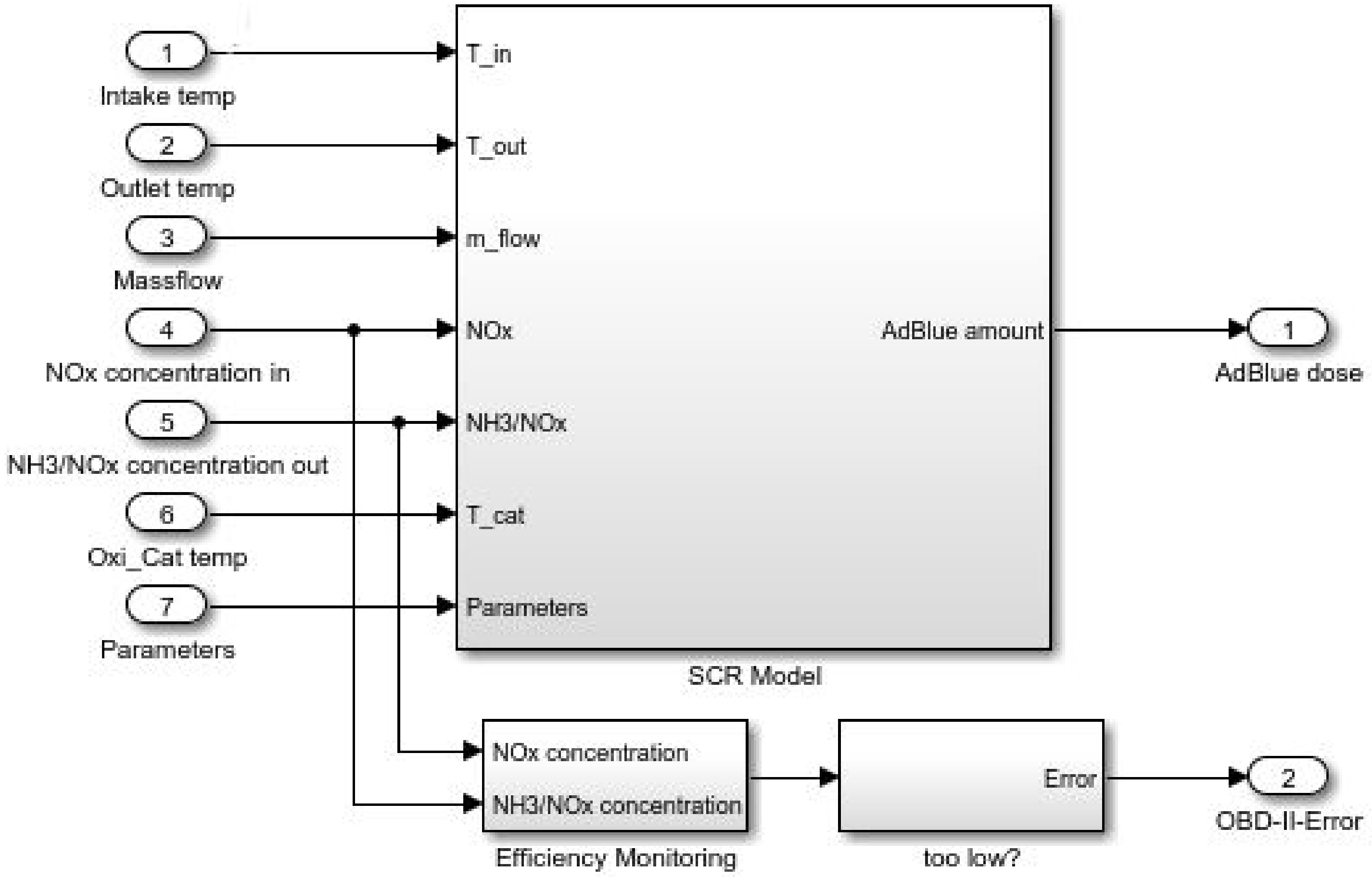
Defeat Device in the Diesel Exhaust Gas Scandal.

Overview:



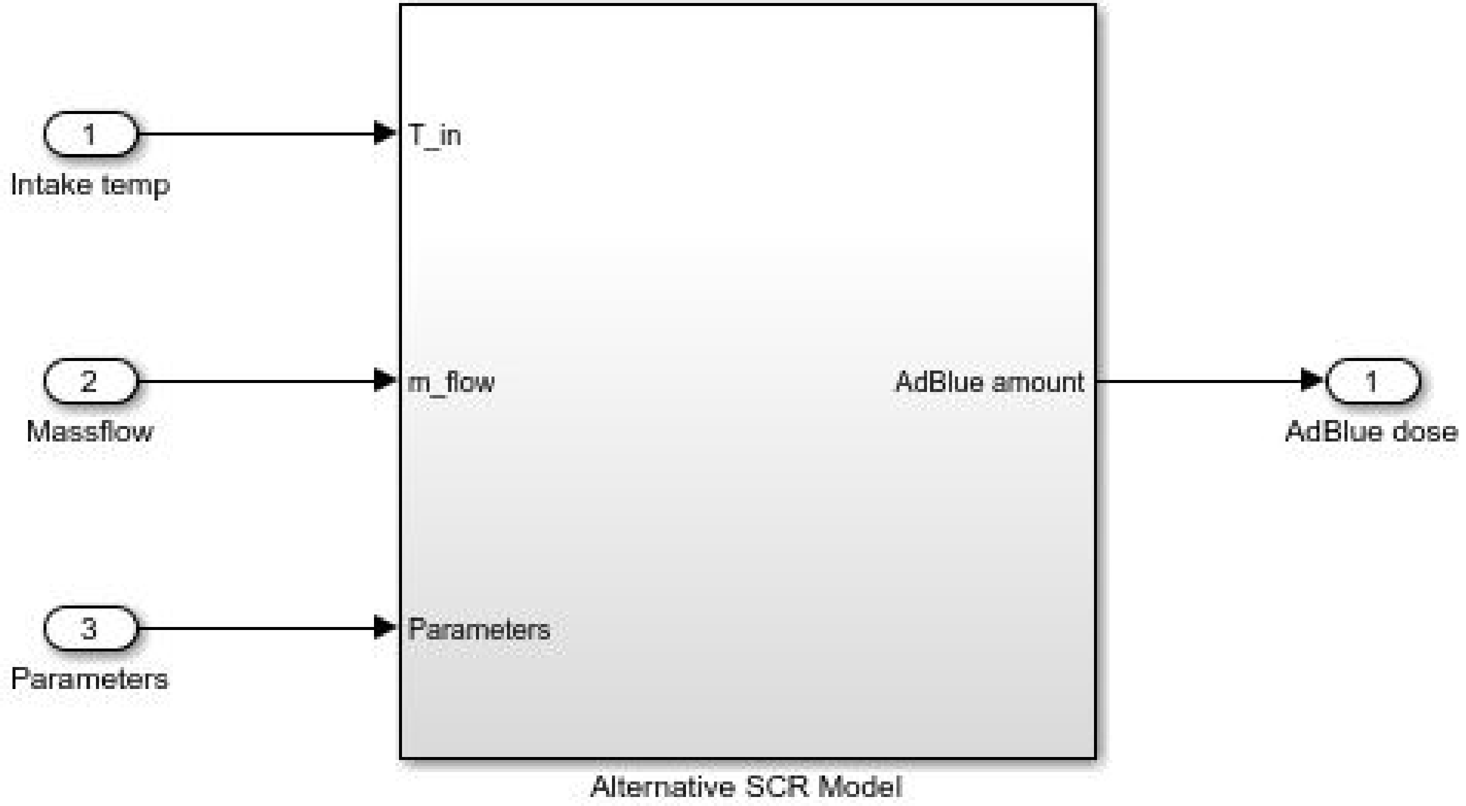
Defeat Device in the Diesel Exhaust Gas Scandal.

Regular SCR model:



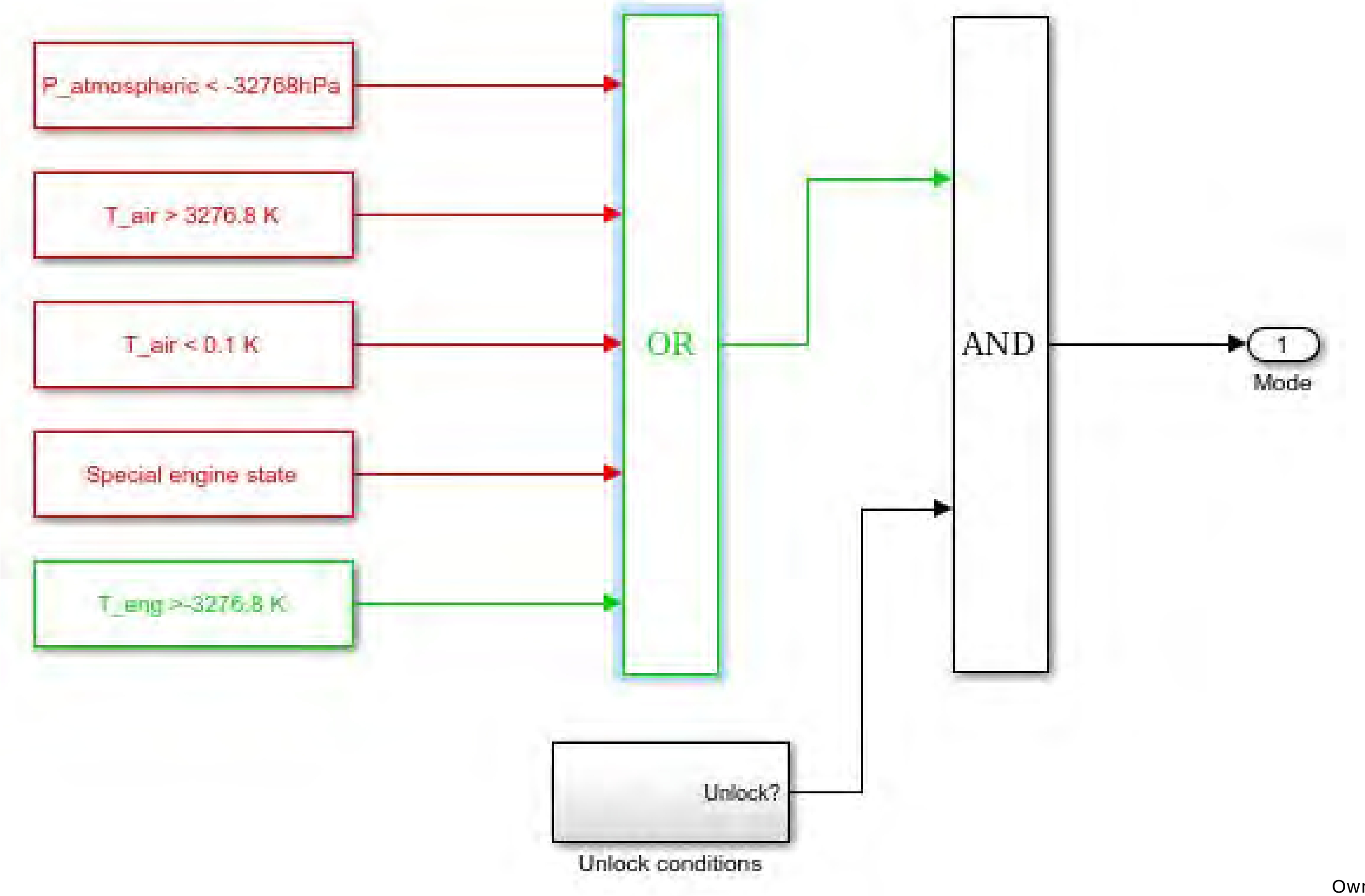
Defeat Device in the Diesel Exhaust Gas Scandal.

Alternative SCR model:



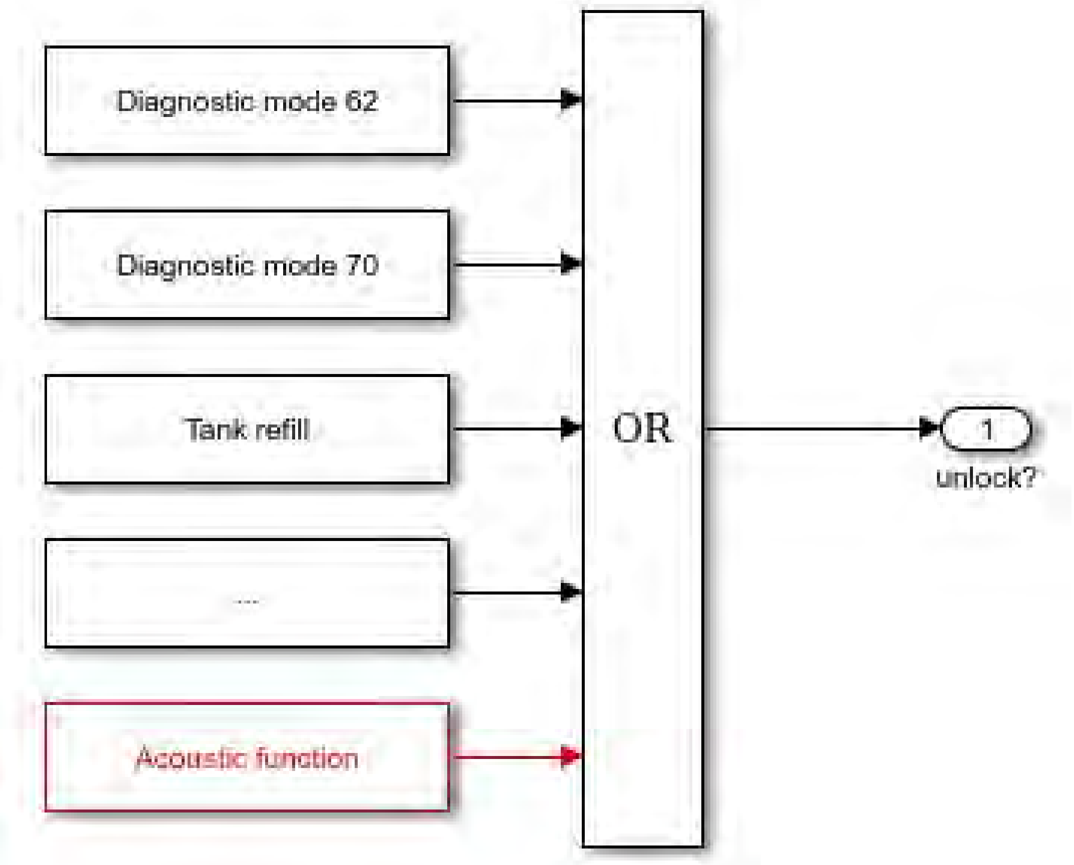
Defeat Device in the Diesel Exhaust Gas Scandal.

Selection model:

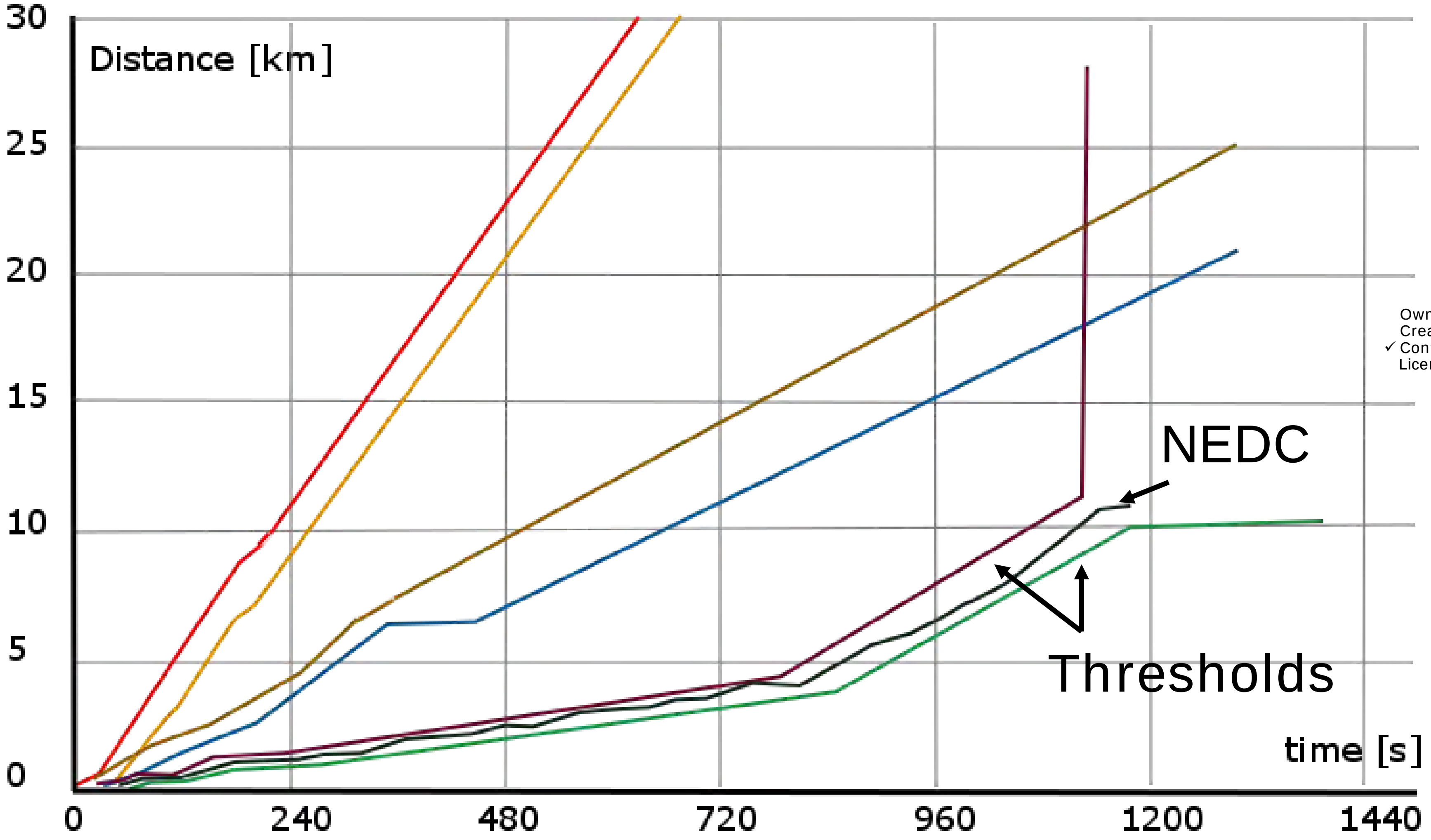


Defeat Device in the Diesel Exhaust Gas Scandal.

Unlock conditions:



Defeat Device in the Diesel Exhaust Gas Scandal.



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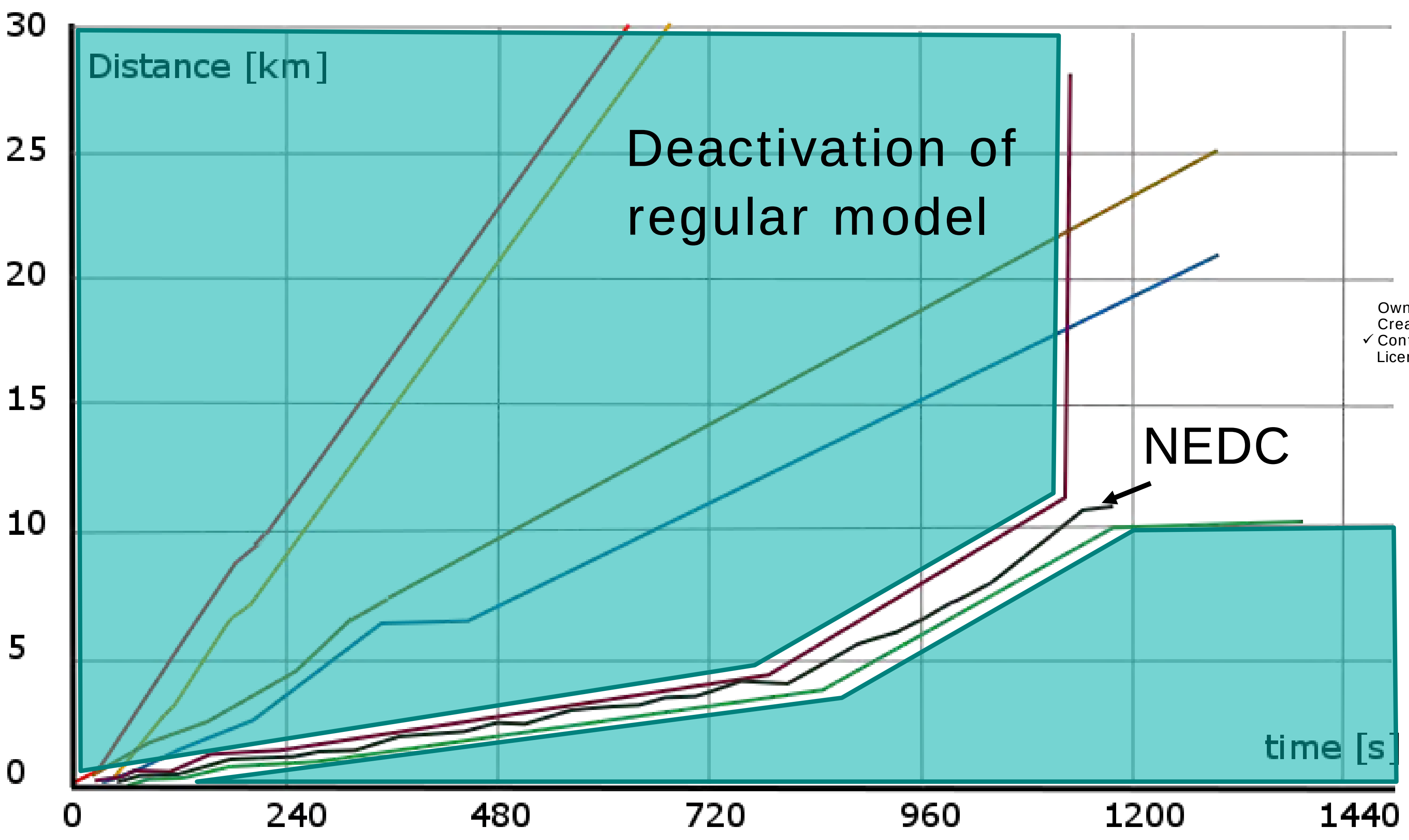
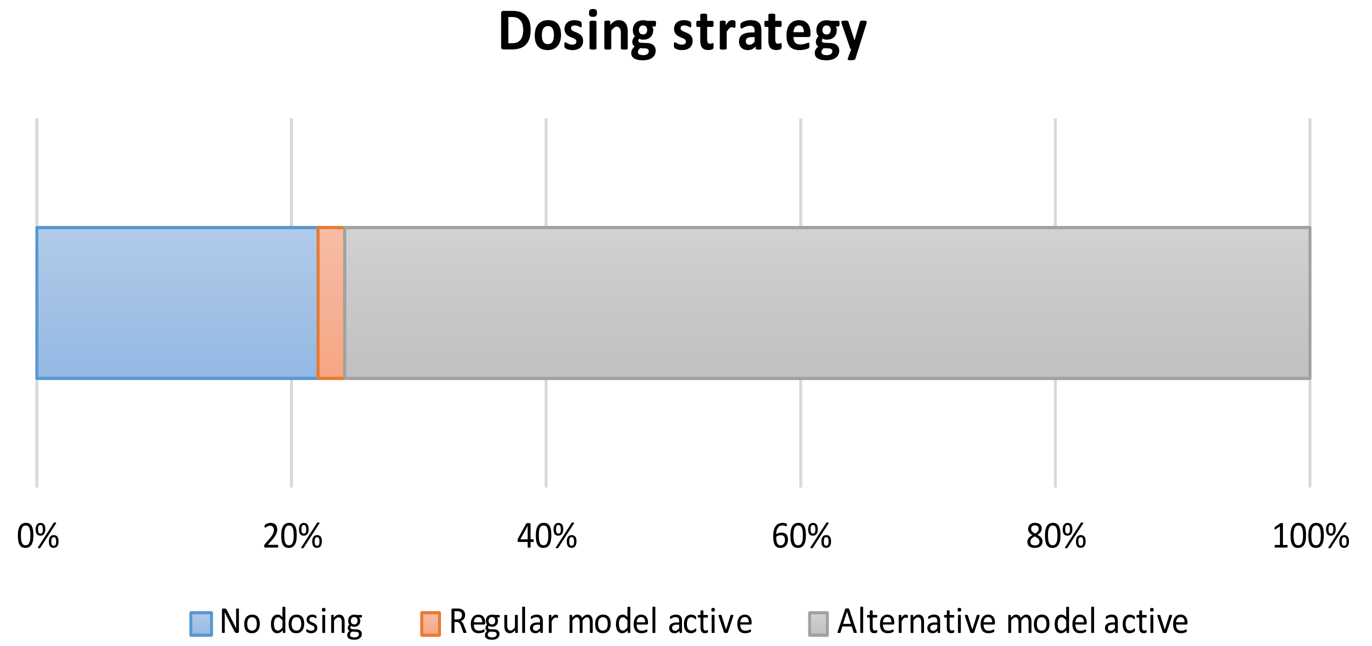
DieselGate – Exhaust Gas Scandal.

Defeat Device in the Diesel Exhaust Gas Scandal.



Defeat Device in the Diesel Exhaust Gas Scandal.



- Under real driving conditions, the regular SCR model is chosen just about 5% of the time.
- At all other time, a reduced or almost no conversion of NOx

Mnemonics.

- The Diesel exhaust gas scandal roots in the accusations the Environmental Protection Agency (EPA) had against Volkswagen in 2015, wherein they indicted VW to cheat in the emission tests by using a so-called defeat device.

- Worldwide over 11 million vehicles and at least 2.5 million vehicles in Germany are involved. All these vehicles are equipped with the EA 189 Diesel engine, which is designed as a 1.6 l and a 2.0 l engine.

- A defeat device is a measure which is implemented to a control unit, for example the ECU, with the purpose of modifying, changing or deactivating an exhaust emission related function.

- Defeat devices are used within the Diesel exhaust gas scandal for deactivating or at least reducing the efficiency of the nitrogen oxide reduction systems (increase of the nitrogen oxides).

Mnemonics.

- For the defeat device, how it is implemented by Volkswagen (SCR manipulation), a cycle detection is necessary.
- The motivations for cheating in this case are wide but mainly describable with the diminution of calibration effort, the reduction of fuel and AdBlue consumption and the maintaining of the benefits of a Diesel engine.
- Only some examples of a defeat device are the deactivation of the EGR-system in special temperature windows, the manipulation of the LNT-catalyst via restraining the DeNOx event, or the reduction of the AdBlue dosing in case of a SCR catalyst.

Mnemonics.

- That means, that a function on the ECU, VW called it "Acoustic function", detects the driven distance regarding time and evaluates, if the vehicle is driving a test cycle, for example the NEDC, within an emission test or not.
- If the cycle detection delivers a "true" value, an optimized emission strategy is chosen and if the result is a "false" value, a rudimental alternative strategy becomes active.
- An investigation of the German authority regarding the Dieselgate discloses the suggested suspicion, that Volkswagen is not the only car manufacturer, who manipulated their emission test results and pollutes more exhaust emissions than it is allowed in the regulations.

WP 2 - Germany: Dieselgate Scandal

- The result of the complete Diesel exhaust gas scandal is a huge image damage for Volkswagen and the Diesel engine itself.

- It raised highest public awareness over the extensive levels of pollution emitted by all diesel-powered vehicles below EURO 6d (temp) especially in Germany and the US.

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WP 2 - The Future of Combustion Engines

- Discussion in 2017 in Germany, which included pronounced and partly justified criticism of Diesel engines, developed its own momentum.
- **It culminated in a general discussion about banning ICE in motor vehicles.**
- For this reason, the “Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik” (Scientific Society for Automotive and ICE Technology =WKM) has drawn up three core statements on these events and on the future of the internal combustion engine, which were formulated on the basis of the state of scientific knowledge.

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WP 2 - ICE WKM Core Statements

a. The internal combustion engine was and is the engine of mobility, freight traffic and mobile machinery. This role is supplemented, but not replaced, by electric drives. A technology-open further development of drive systems is a prerequisite for a successful climate policy in a prospering society. Bans have the opposite effect.

b. Due to very low combustion engine contributions, the issue of emissions and especially immissions will not be an argument against diesel or petrol engines in the future! The current state of technology already ensures that emission limit values can be adhered to without exception. Weak points identified in retrospect are no longer relevant for the future. On the basis of intensive research, completely environmentally neutral combustion-engine drives can be presented.

[2]

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WP 2 - ICE WKM Core Statements

c. The particular advantage of the internal combustion engine lies in the efficient and flexible use of fuels with high energy density and excellent storage and distribution options. With this fundamental characteristic, the combustion engine has constantly reinvented itself and, when considering the overall system, enables lower CO_2 emissions than alternative technologies. The potential to be able to flexibly use non-fossil and thus CO_2-neutral fuels is a further guarantee for a long-term, sustainable future technology.

[2]

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WP 2 - Political Parties in Germany about ICE Future

Strengthen public transport,
Linke

Thinking open to technology - culture of innovation instead of prohibition,
CDU

Yes, to diesel,
AfD

As of 2030 all new cars should be emission-free,
Die Grünen

Driving bans are yesterday's policy,
FDP

Diesel has a future, especially in rural areas,
CSU

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WP 2 - Ban of New Vehicle Sales with Diesel or Petrol Engines in Europe

Country	Ban announced	Ban commences
Denmark	2019	2030
France	2017	2040
Iceland	2018	2030
Ireland	2018	2030
Netherlands	2017	2030
Norway	2017	2025
United Kingdom	2017	2040 – England, Wales, Northern Ireland 2032 – Scotland
Sweden	2018	2030

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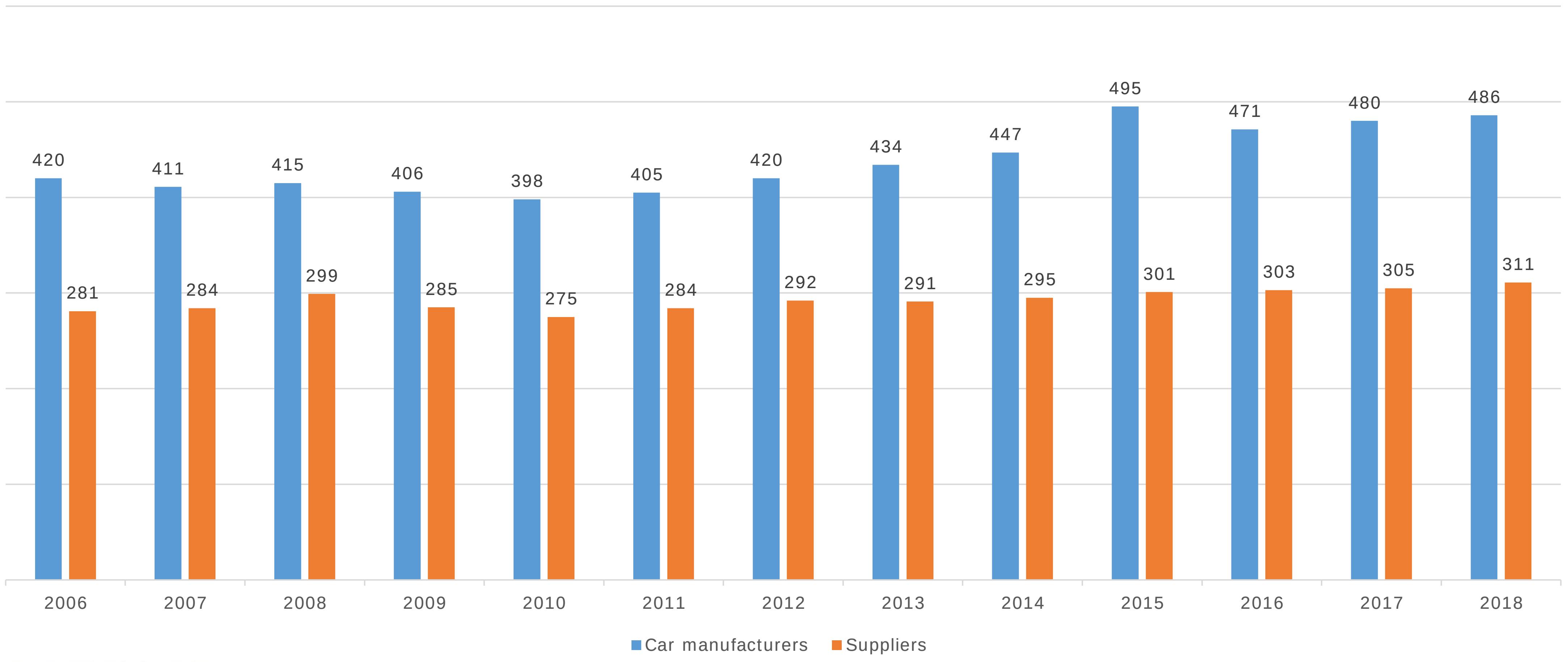
[3]

WP 2 - Annual Average Number of Employees in German Automotive Industry in 1000



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[4]

WP 2 – Training Overview

- Q&A, Discussion SLOT 1

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WP 2 – Malaka SLOT 1

- Introduction and **Overview of ICE Technology** (10 minutes)

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WP 2 – ICE Systematics

1. Method of working cycle
   - closed (external combustion)
   - open (internal combustion)
2. Combustion process
   - continuous
   - intermittent
3. Method of gas exchange
   - Four-stroke
   - Two-stroke
4. Charge pressure level (open process!)
   - Naturally aspirated engine
   - Boosted engine
5. Time of mixture generation
   - Air compression
   - Mixture compression
6. Location of mixture generation
   - Inner mixture generation
   - Outer mixture generation
7. Method of power control
   - Quantity control
   - Quality control
8. Method of ignition
   - Spark ignition (gasoline engine)
   - Compression ignition (diesel engine)

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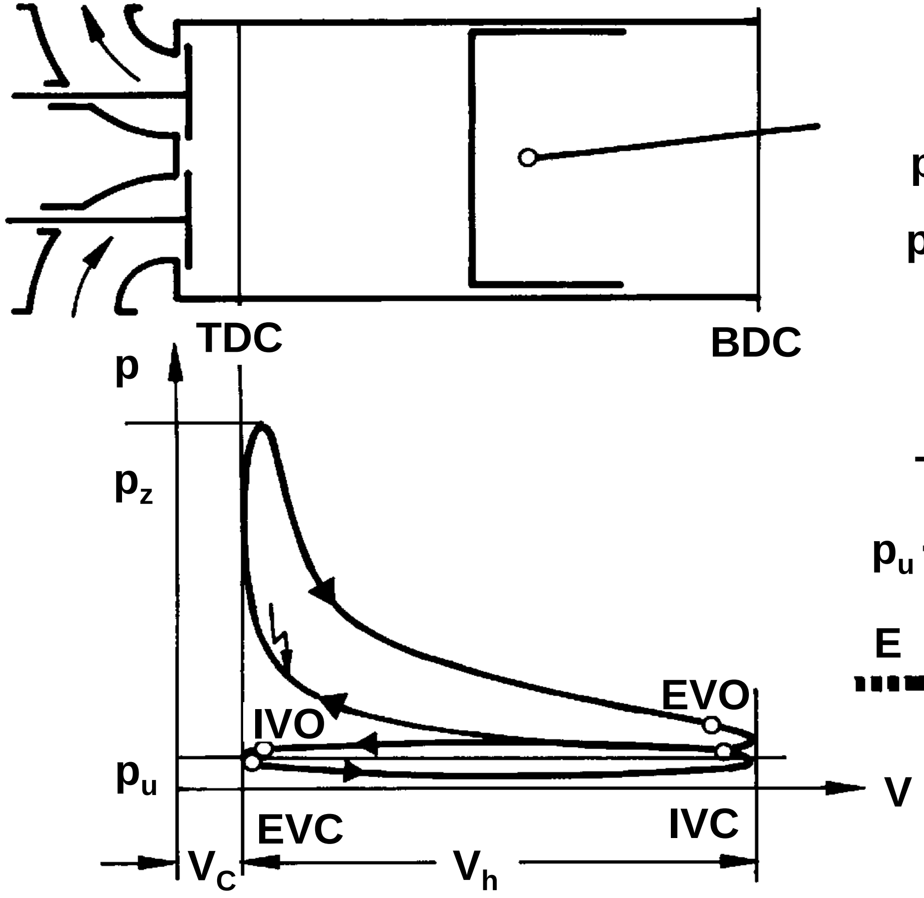
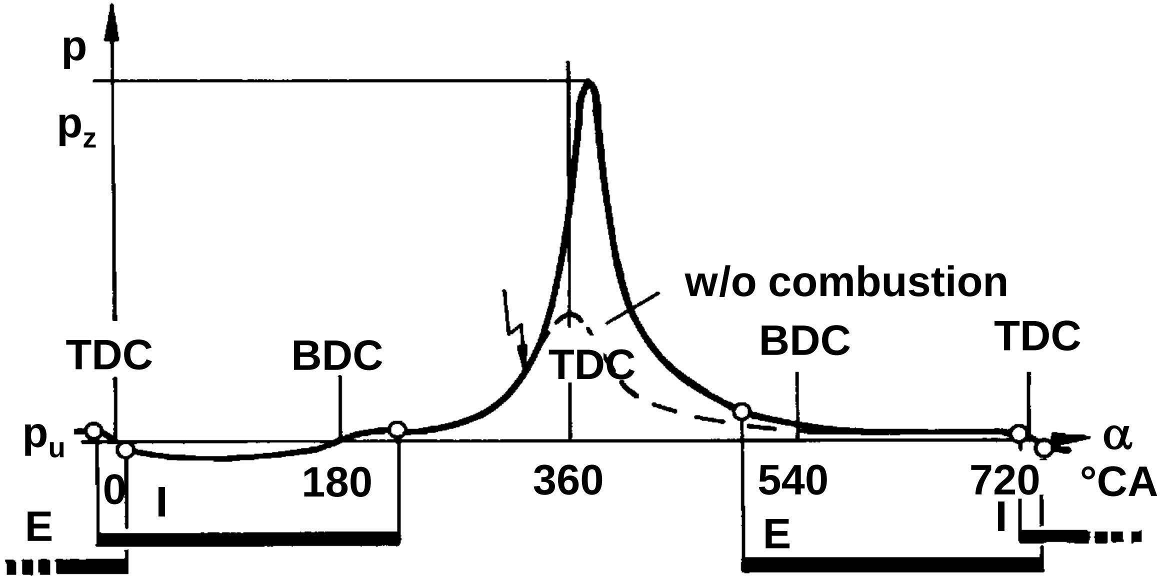
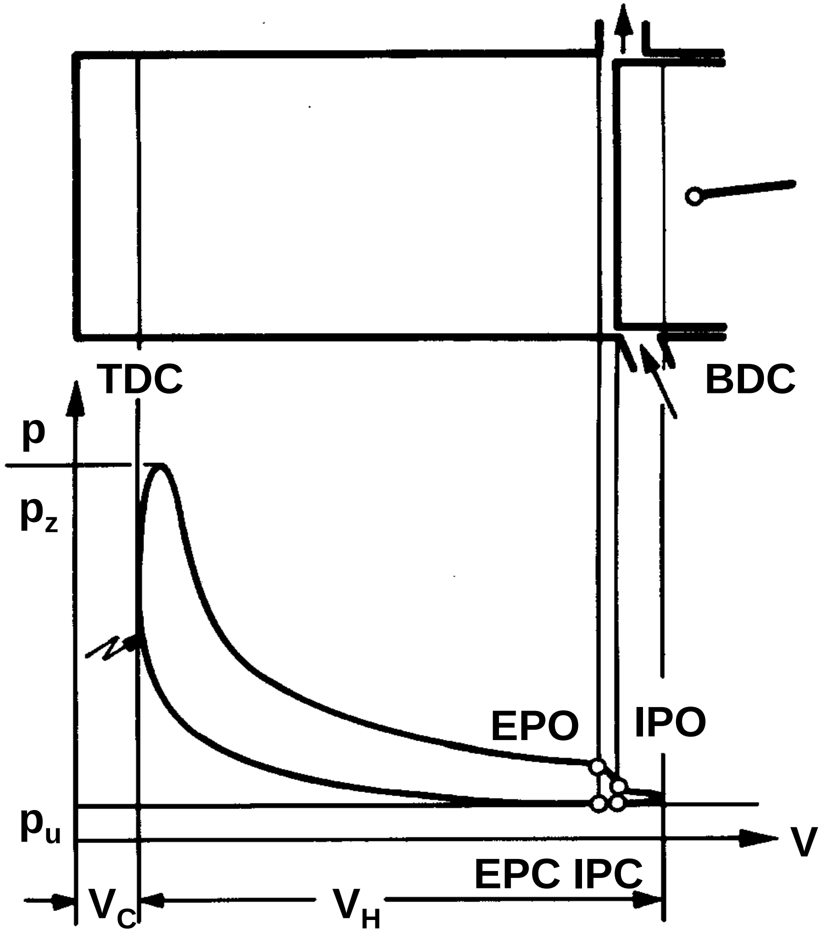
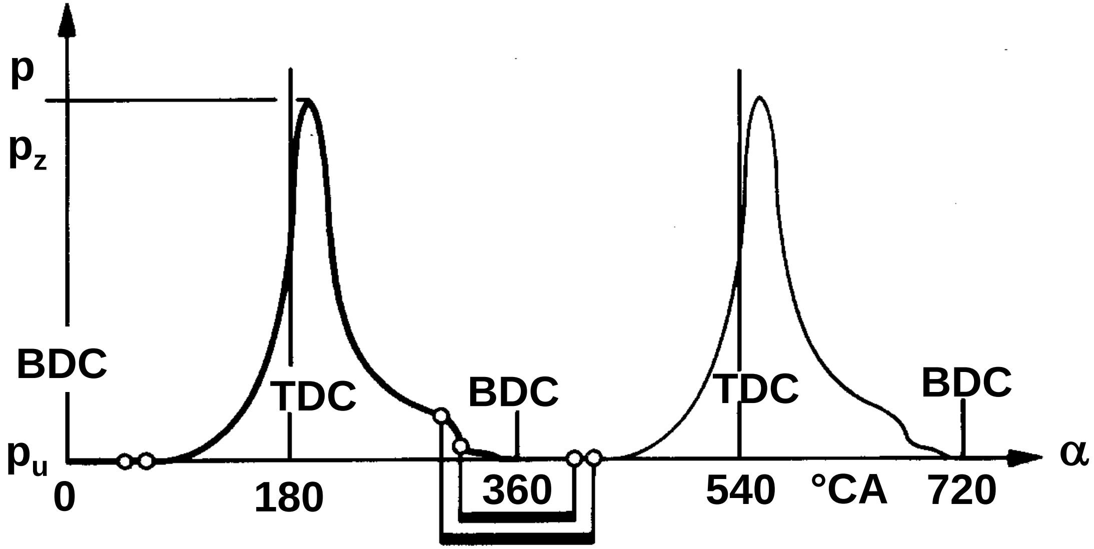
WP 2 – Four Stroke Operating Cycle





WP 2 – Two Stroke Operating Cycle





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WP 2 – Characteristics of Engine Processes

	Gasoline engine (conventional)	Diesel engine
Compression	(1) Gas mixture	(a) Air
Charge mixture state	(2) homogeneous	(b) inhomogeneous
Ignition	(3) Spark-ignition	(c) Compression-ignition
Load control	(4) Fuel and air flow	(d) Fuel flow

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WP 2 – Requirements for Passenger Vehicle Powertrains / Motivation

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Customer use

- Driving pleasure
- Low vehicle and operational costs
- Quality/reliability
- Comfort

Environmental demands/laws

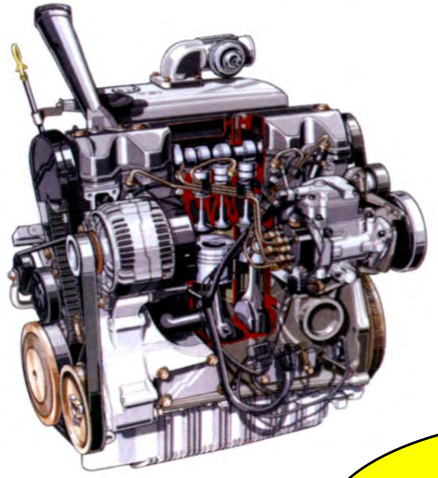
- Emissions (local/global)
- CO_2 emissions (Green house effect)
- Recycling
- Conserving resources

Durability

High spec. power and torque

Compact, lightweight

Low production costs



Low fuel consumption

Low CO_2 and pollutant emissions

Low noise and vibration

Short development times

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WP 2 – Malaka SLOT 1

- **Thermodynamics of ICE** (30 minutes)

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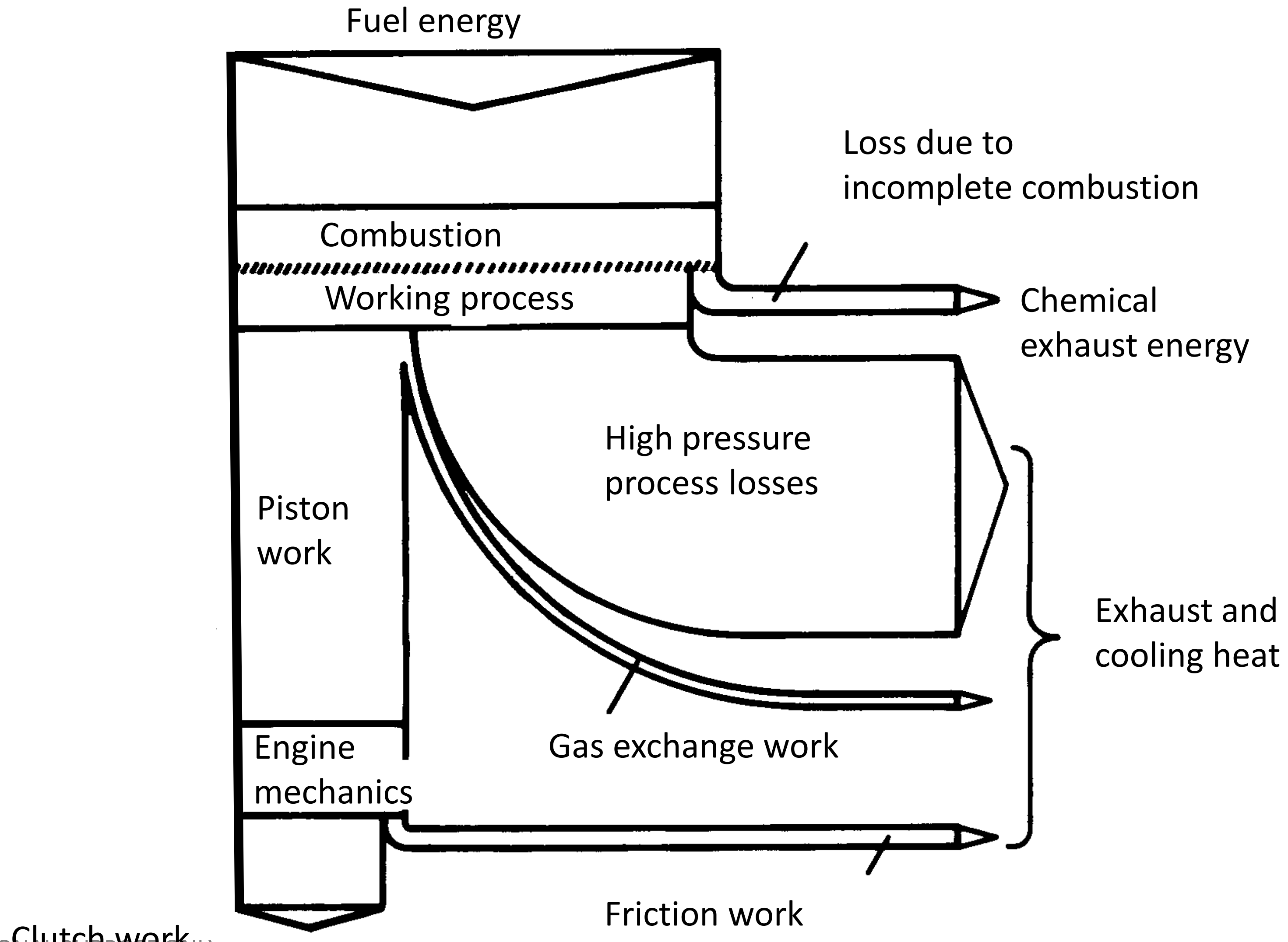
WP 2 - Energy Conversion in ICE

UNITED



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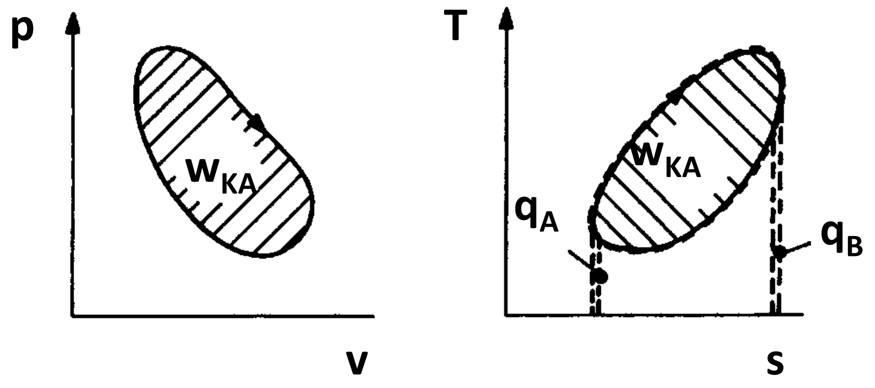
WP 2 - Working Cycle Assumptions

- Adiabatic compression and expansion
- Combustion replaced with heat supply
- Gas exchange replaced with heat reduction
- Fluid homogeneous
- No irreversibilities

$$\eta_{th} = \frac{W_{KA}}{Q_B} = \frac{w_{KA}}{q_B}$$



$$\longrightarrow \eta_{th} = 1 - \frac{q_A}{q_B}$$

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WP 2 - Assumptions of the Thermodynamic Cycles

- Internal combustion is replaced by an external heat addition q_B.
- Gas exchange process is replaced by an external heat rejection q_A.
- Gas composition remains unchanged during the operating cycles.
- The mass of working fluid remains unchanged throughout the process.
- Specific heat capacities are independent of the state of the gas.

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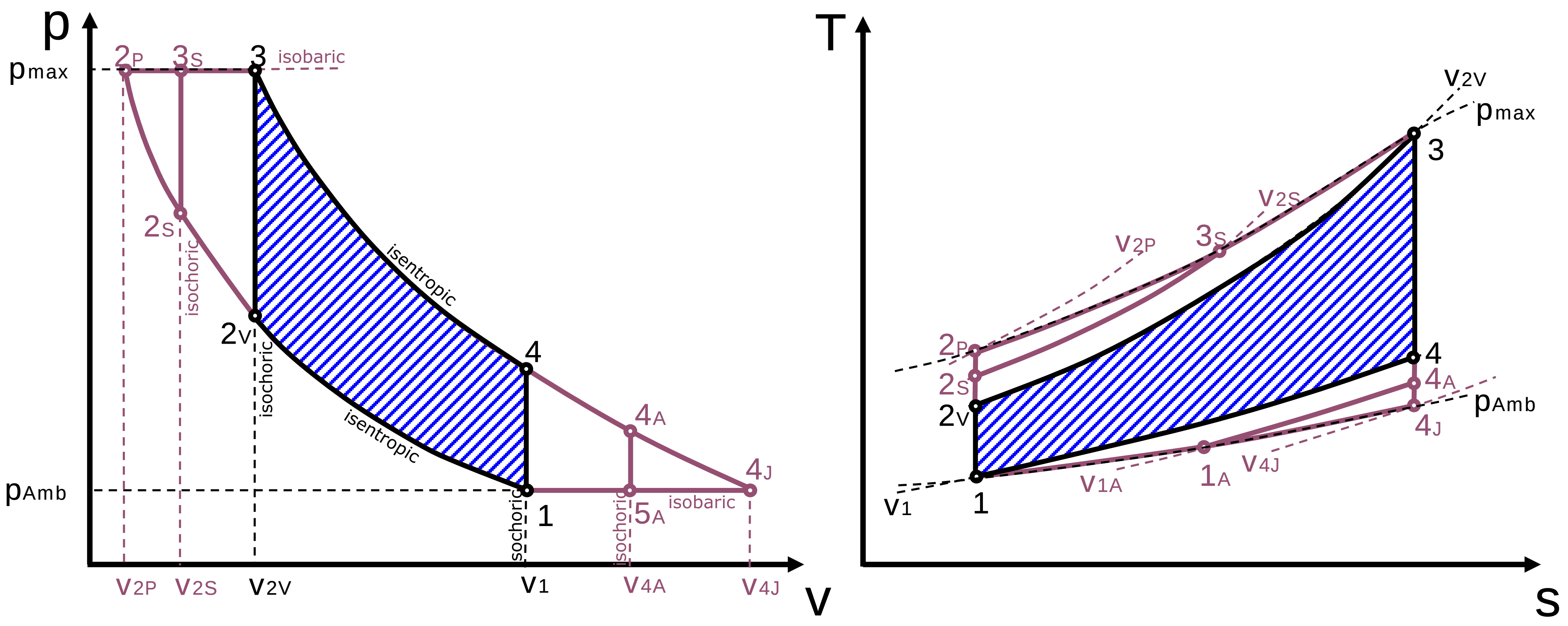
WP 2 - Constant Volume Engine Cycle in T-S and p-V Diagram



Constant volume cycle

1-2v-3-4-1 Cycle work:

1→2v	Isentropic compression
2v→ 3	Isochoric heat supply
3 → 4	Isentropic expansion
4 → 1	Isochoric heat derivation

WP 2 - Thermal Efficiency of Constant-Volume Engine Cycle

$$\eta_{th} = 1 - \frac{q_A}{q_B}$$

$$\eta_{th,v} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\kappa-1} = \left(\frac{v_3}{v_4}\right)^{\kappa-1} = \frac{T_4}{T_3}$$

$$\eta_{th,v} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{v_2}{v_1}\right)^{\kappa-1}$$

$$\boxed{\eta_{th,v} = 1 - \frac{1}{\varepsilon^{\kappa-1}}}$$

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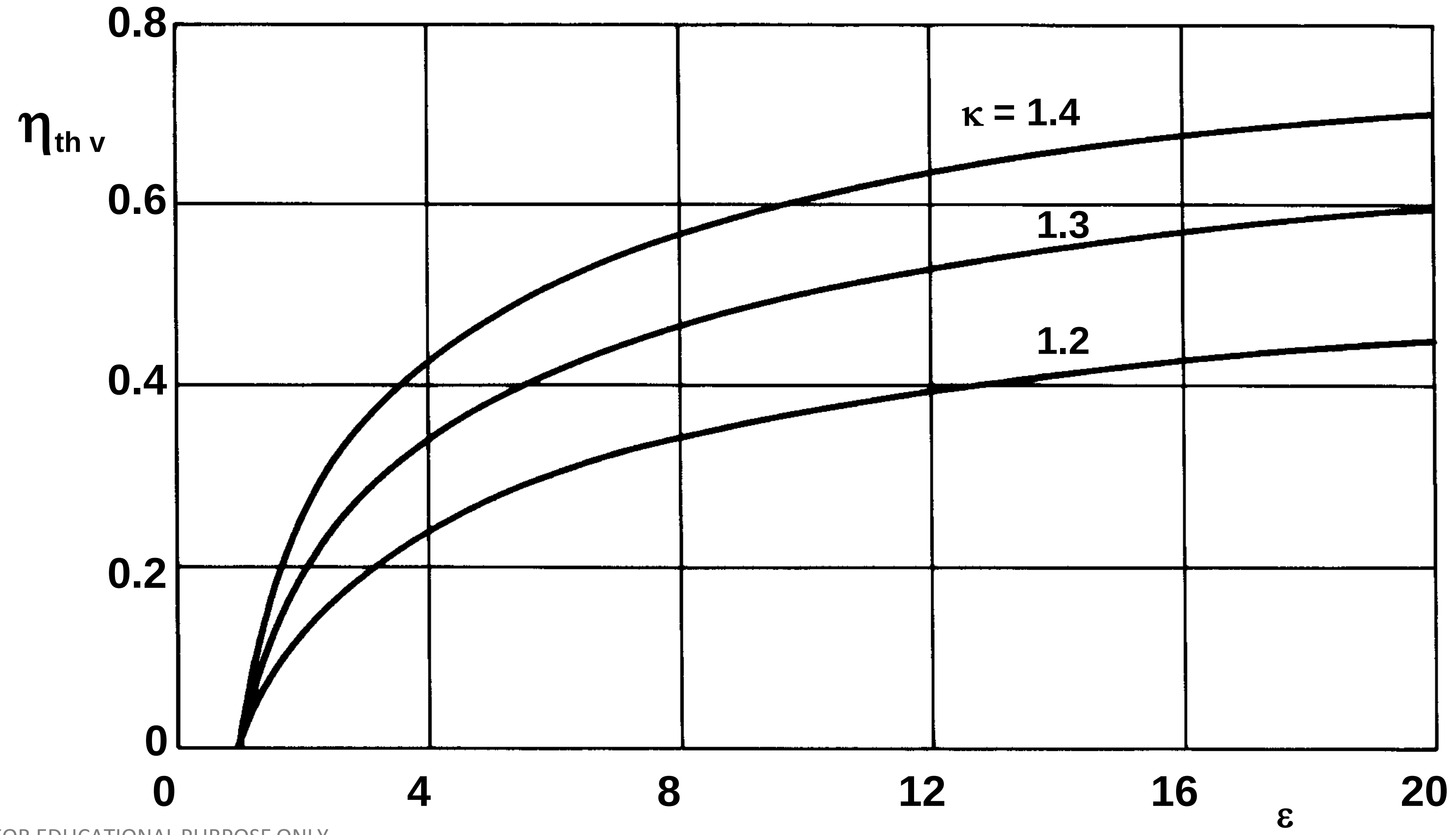
WP 2 - Thermal Efficiency of Constant-Volume Engine Cycle



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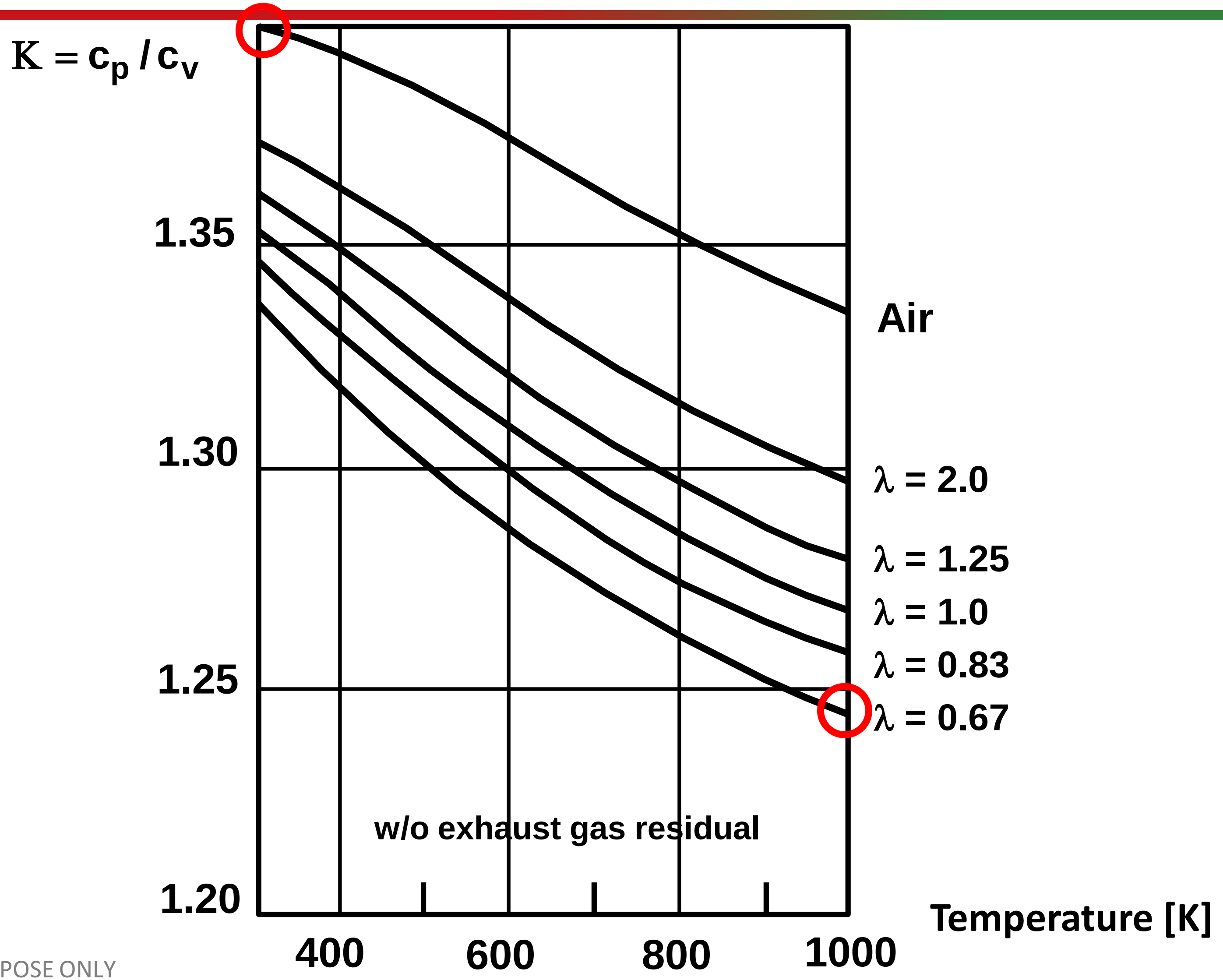
WP 2 - Isentropic Exponent κ for Air and Air Fuel Mixture



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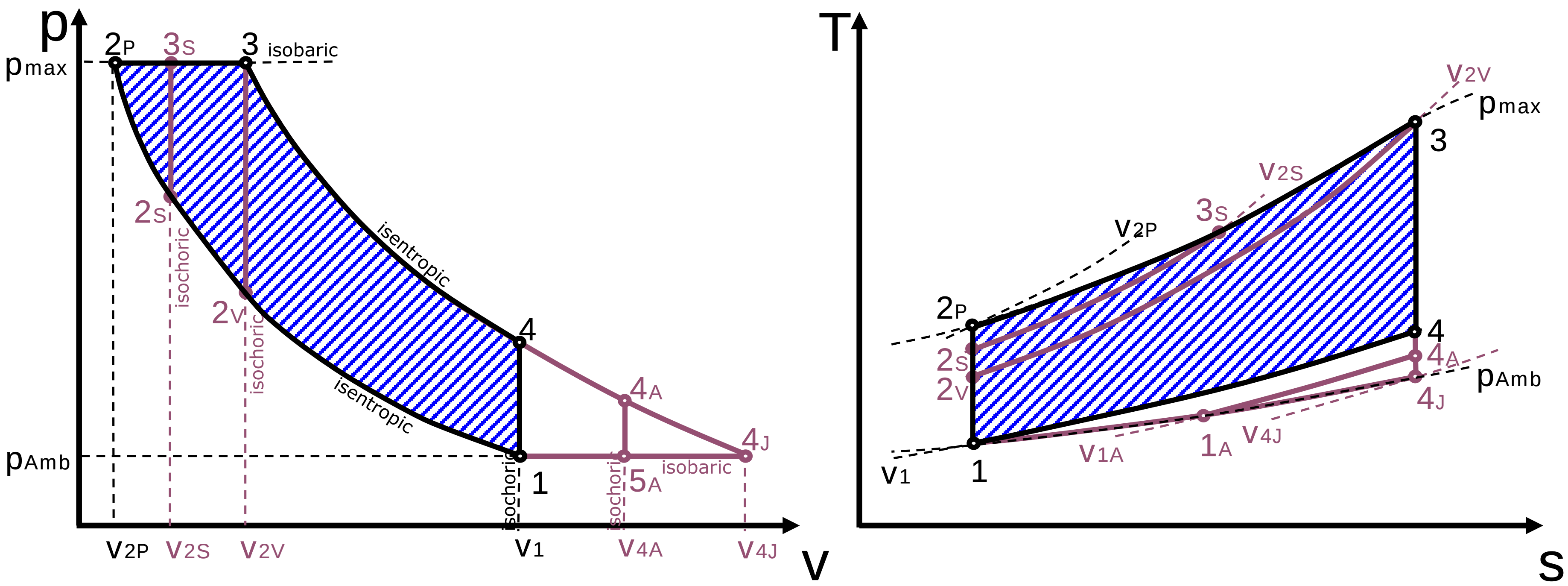
WP 2 - Constant-Pressure Engine Cycle



Constant pressure cycle 1-2P-3-4-1 cycle work:

1→2P Isentropic compression
2P→3 Isobaric heat supply
3 →4 Isentropic expansion
4 →1 Isochoric heat derivation

WP 2 - Thermal Efficiency of Constant Pressure Engine Cycle

$$\eta_{th} = 1 - \frac{q_A}{q_B}$$

$$\eta_{th,p} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

$$\eta_{th,p} = 1 - \frac{1}{\kappa q^*}\left[\left(\frac{q^*}{\varepsilon^{\kappa-1}} + 1\right)^{\kappa} - 1\right] \quad \text{with} \quad q^* = \frac{q_B}{c_p T_1}$$

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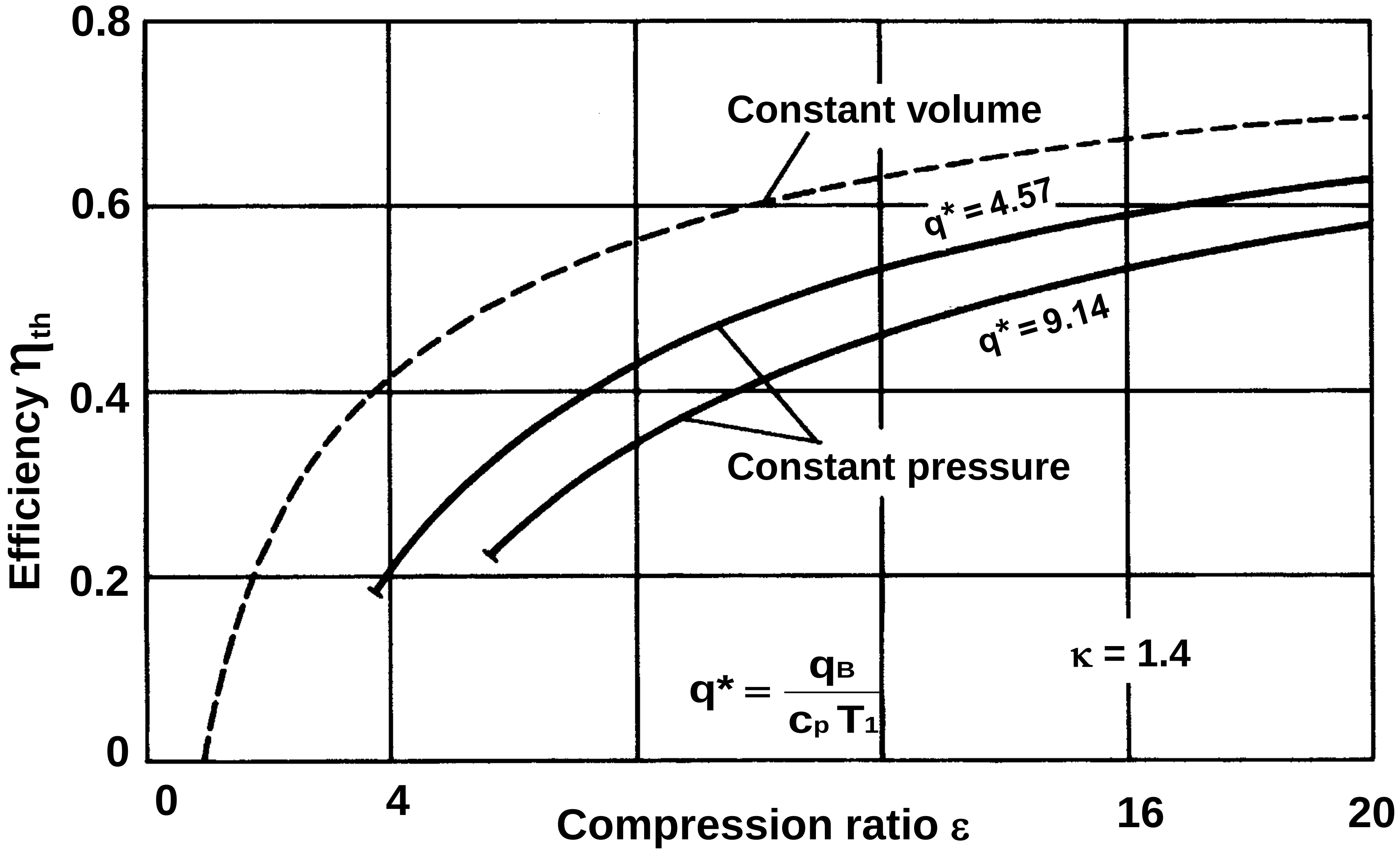
WP 2 - Simplified Constant-p and V Engine Cycles



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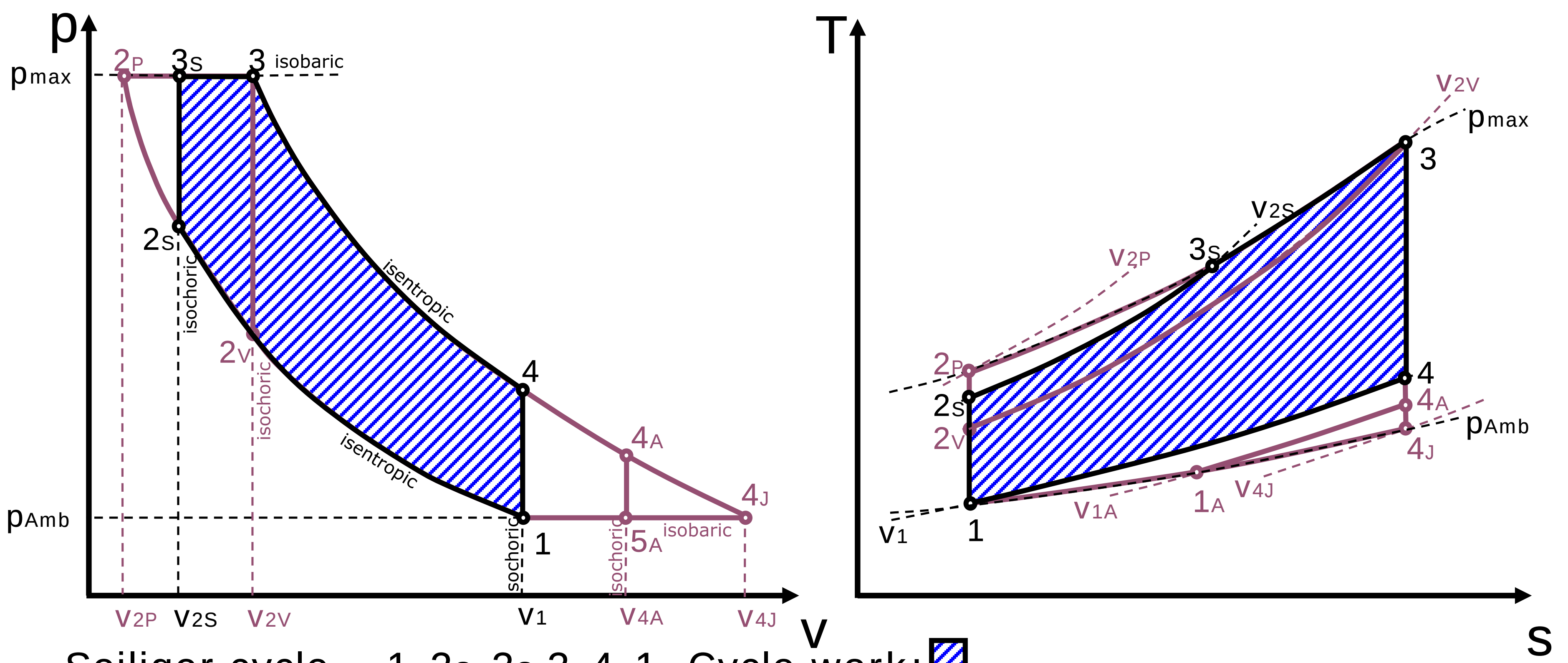
WP 2 - Limited Pressure Engine Cycle

UNITED



Seiliger cycle $1\text{-}2_s\text{-}3_s\text{-}3\text{-}4\text{-}1$ Cycle work:

$1 \rightarrow 2_s$	Isentropic compression
$2_s \rightarrow 3_s$	Isochoric heat supply
$3_s \rightarrow 3$	Isobaric heat supply
$3 \rightarrow 4$	Isentropic expansion
$4 \rightarrow 1$	Isochoric heat derivation

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WP 2 - Thermal Efficiency of Limited Pressure Cycle

$$\eta_{th} = 1 - \frac{1}{\kappa q^*}\left\{\left[q^* - \frac{1}{\kappa\varepsilon}\left(\frac{p_3}{p_1} - \varepsilon^{\kappa}\right) + \frac{p_3}{\varepsilon p_1}\right]^{\kappa}\left(\frac{p_1}{p_3}\right)^{\kappa-1} - 1\right\} \quad \text{with} \quad q^* = \frac{q_B}{c_p T_1}$$

$$\eta_{th} = \eta_{th,Diesel} = 1 - \frac{1}{\varepsilon^{\kappa-1}} \cdot \frac{\pi \cdot \tau^{\kappa} - \varepsilon^{\kappa}}{\pi - \varepsilon^{\kappa} + \kappa \cdot \pi(\tau - 1)}$$

with

$$\varepsilon = \frac{V_1}{V_2}$$

$$\pi = \frac{p_3}{p_1}$$

$$\tau = \frac{T_3}{T_{3s}}$$

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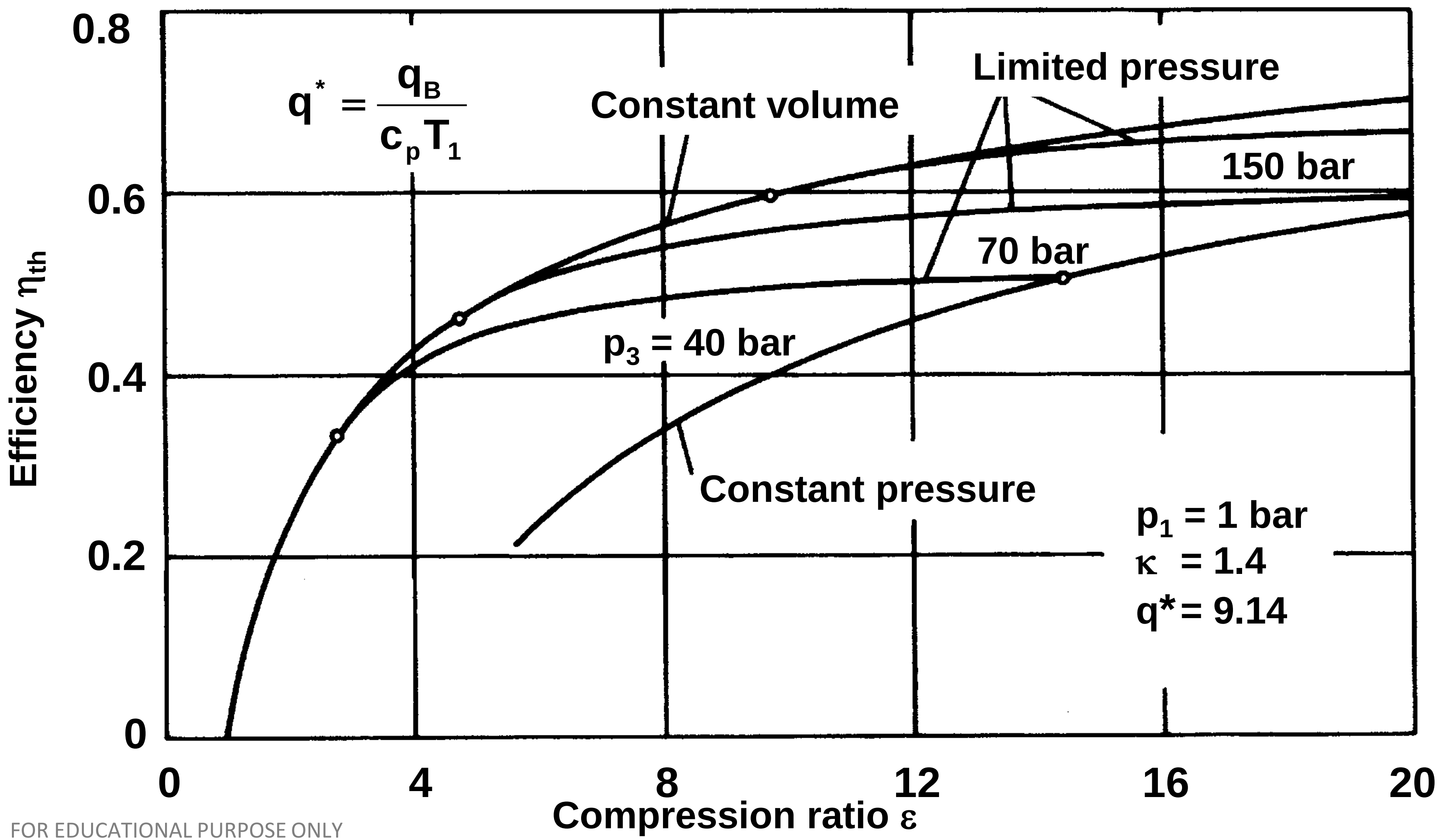
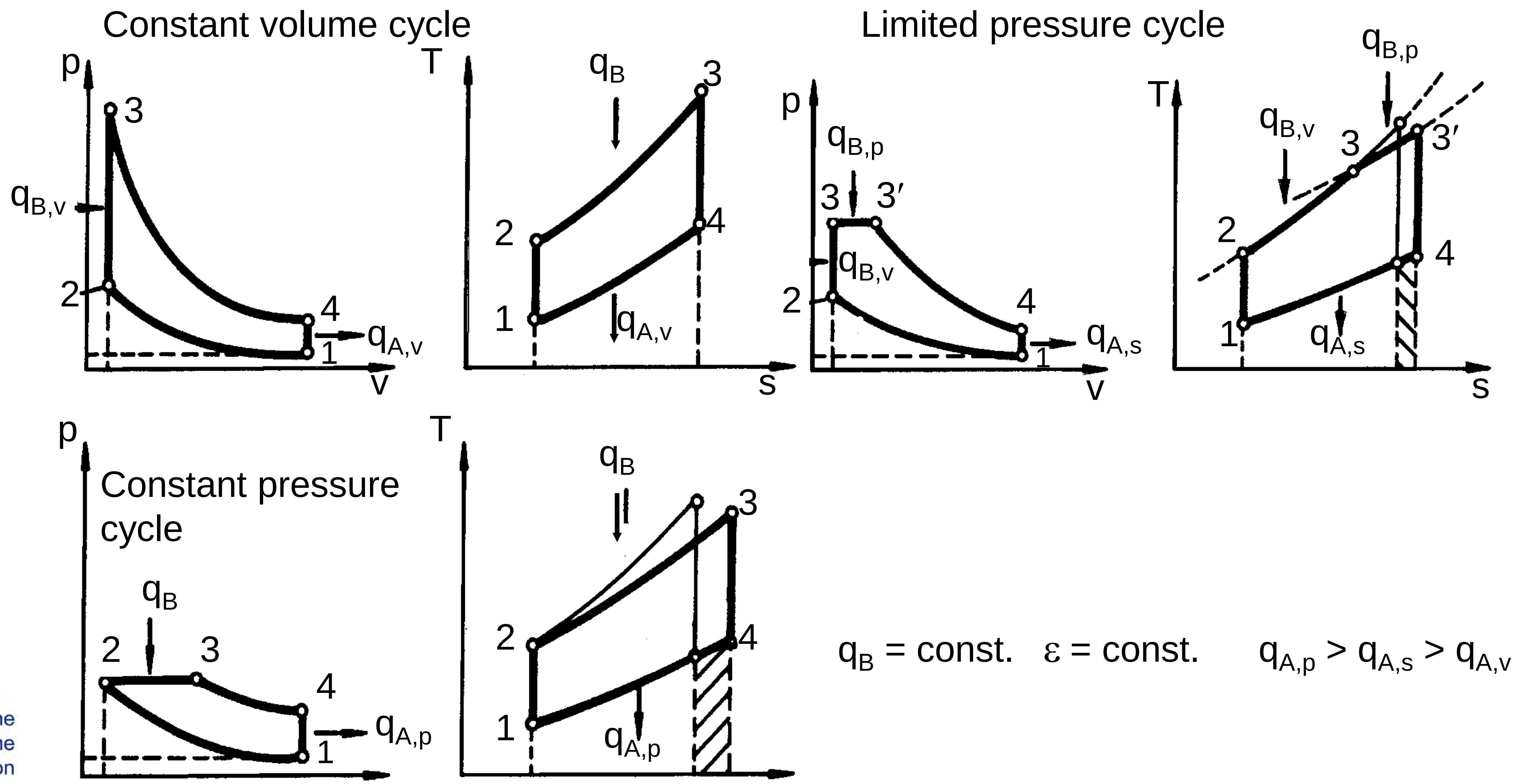
WP 2 - Thermal Efficiency as a Function of ε

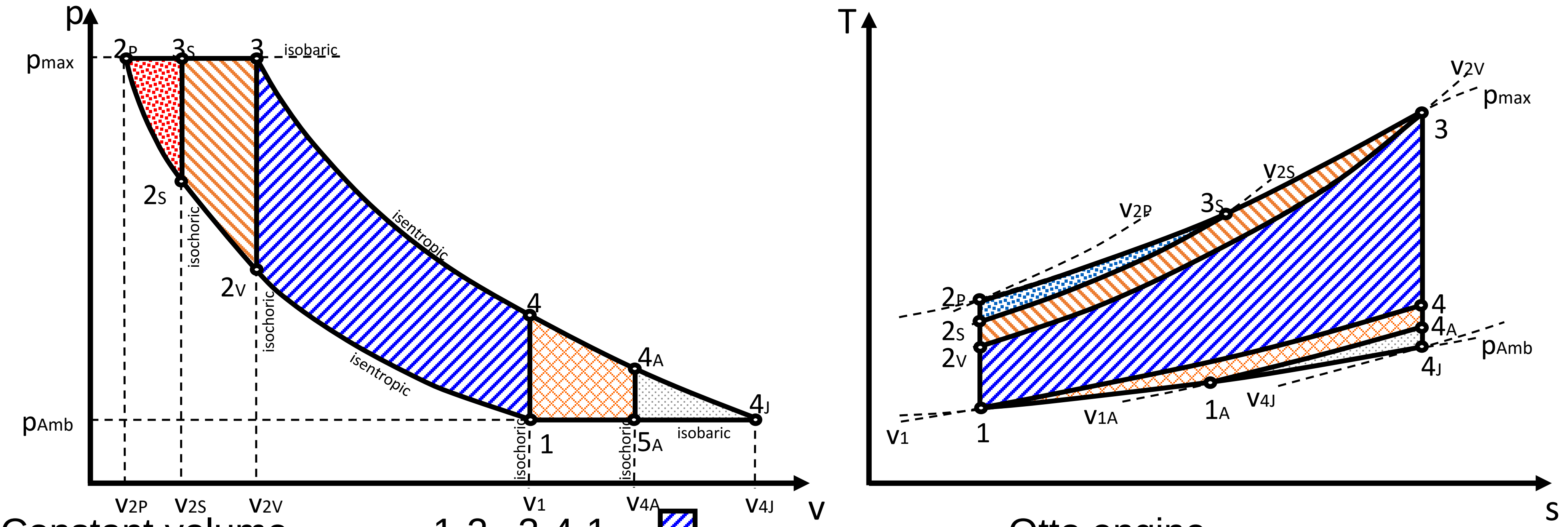


WP 2 - Overview Engine Working Cycles



q_B = const. ε = const. $q_{A,p} > q_{A,s} > q_{A,v}$

WP 2 - Overview Engine Working Cycles



Constant volume	1-2$_V$-3-4-1	Otto engine
Seiliger	1-2$_S$-3$_S$-3-4-1	Diesel engine
Constant pressure	1-2$_P$-3-4-1	icc - engine / Diesel
Const. vol - Atkinson	1-2$_V$-3-4$_A$-5$_A$-	Otto with extended expansion
Seiliger - Atkinson	1-2$_S$-3-4$_A$-5$_A$-	Diesel with extended expansion
Const. pres. - Atkinson	1-2$_P$-3-4$_A$-5$_A$-	Diesel / icc with extended expansion
Joule	1-2$_P$-3-4$_J$-1 + + + +	open cycle gas turbines

WP 2 - Working Cycle Characteristics: Efficiency of Atkinson Cycle

Efficiency of constant volume Atkinson cycle with $p_4 = p_1$ (optimum)

$$\eta_{th} = 1 - \frac{q_A}{q_B} = 1 - \frac{c_p \cdot (T_4 - T_1)}{c_v \cdot (T_3 - T_2)} = 1 - \kappa \cdot \frac{T_1}{T_3 - T_2} \cdot \left(\frac{T_4}{T_1} - 1\right)$$

$$T_3 - T_2 = \frac{q_B}{c_v} = \kappa q^* \cdot T_1 \quad \text{with } q^* = \frac{q_B}{c_p T_1}$$

$$\eta_{th} = 1 - \frac{1}{q^*}\left(\frac{T_4}{T_1} - 1\right)$$

$$\frac{T_4}{T_1} = \frac{T_4}{T_3} \cdot \frac{T_3}{T_2} \cdot \frac{T_2}{T_1} = \frac{1}{\varepsilon_E^{\kappa-1}} \cdot \frac{T_3}{T_2} \cdot \varepsilon_V^{\kappa-1} = \frac{T_3}{T_2} \cdot \left(\frac{\varepsilon_V}{\varepsilon_E}\right)^{\kappa-1}$$

$$\varepsilon_E = \left(\frac{p_3}{p_4}\right)^{\frac{1}{\kappa}} = \left(\frac{p_3}{p_1}\right)^{\frac{1}{\kappa}} = \left(\frac{p_3}{p_2} \cdot \frac{p_2}{p_1}\right)^{\frac{1}{\kappa}} = \varepsilon_V \cdot \left(\frac{T_3}{T_2}\right)^{\frac{1}{\kappa}} \quad \text{with } \frac{p_3}{p_2} = \frac{T_3}{T_2}$$

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \cdot \left(\frac{T_3}{T_2}\right)^{\frac{1-\kappa}{\kappa}} = \left(\frac{T_3}{T_2}\right)^{\frac{1}{\kappa}}$$

$$\frac{T_3}{T_2} = \kappa q^* \cdot \frac{T_1}{T_2} + 1 = \frac{\kappa q^*}{\varepsilon_V^{\kappa-1}} + 1$$

$$\eta_{th} = 1 - \frac{1}{q^*}\left[\left(\frac{\kappa q^*}{\varepsilon_V^{\kappa-1}} + 1\right)^{\frac{1}{\kappa}} - 1\right] \quad \text{with } q^* = \frac{q_B}{c_p T_1}$$

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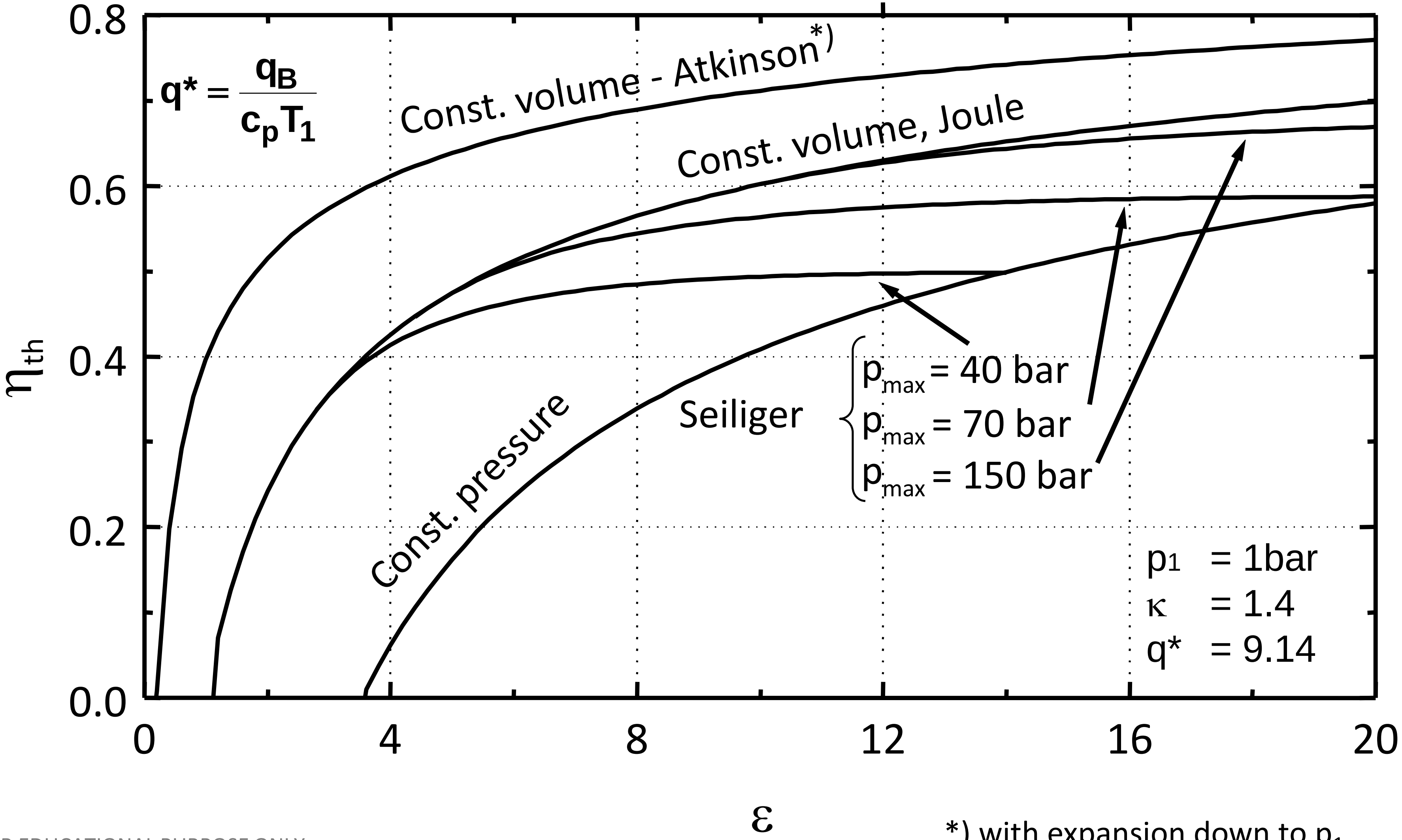
WP 2 - Working Cycle Characteristics: Comparison of Cycle Efficiencies



*) with expansion down to p_1

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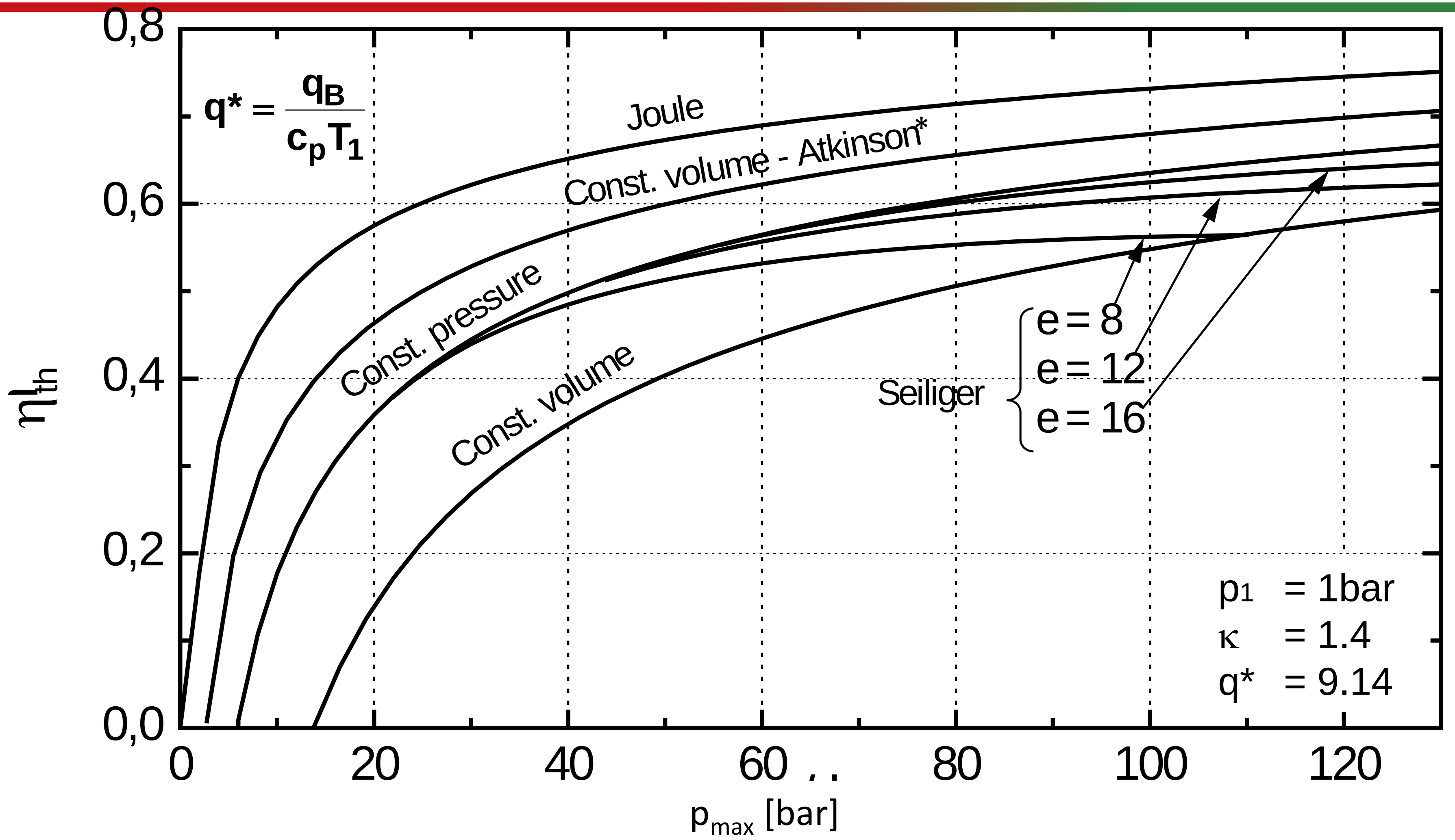
WP 2 - Working Cycle Characteristics: Comparison of Cycle Efficiencies



* with expansion down to p_1

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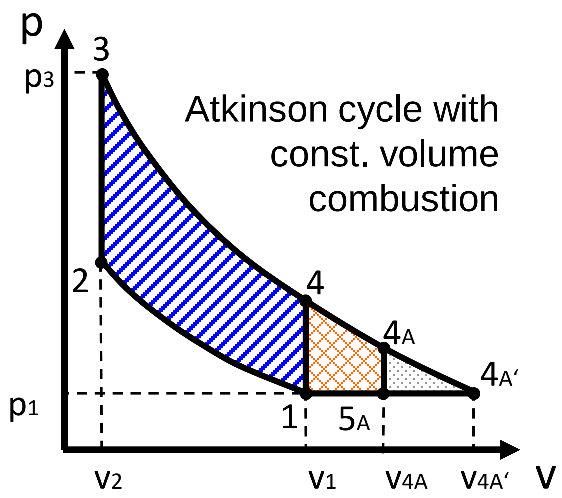
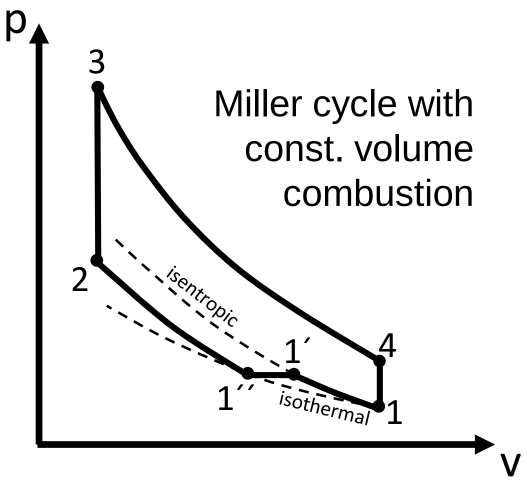
WP 2 - Working Cycle Characteristics: Atkinson & Miller Cycle (1)

- Atkinson and Miller cycle feature an extended expansion compared to the compression.



- The example to the right (constant volume cycle) shows, that with an expansion beyond „4" to „4_A" the additional work can be realized with equal heat supply. The best case with $p_{4A} = p_{4A'} = p_1$ additionally yields the work .
- This results in an increase of the thermal efficiency.
- For the Miller cycle the air supplied for the engine is externally compressed from 1 to 1´ and then intercooled down to 1´´. This results in lower gas temperatures at the end of the compression (lower stress).
- This equals an approximation of an isothermal compression from 1 to 1´´.



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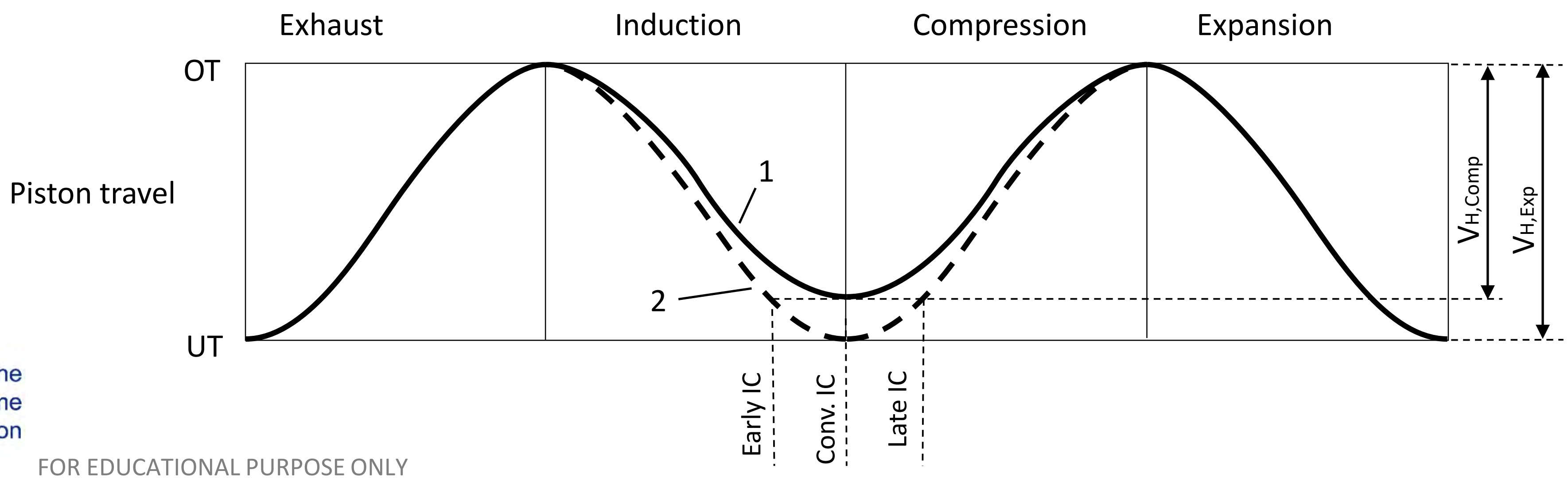
WP 2 - Working Cycle Characteristics: Atkinson & Miller Cycle (2)

- The extended expansion can be realised with the following methods:
  1. Construction of an engine with reduced piston travel for the induction and compression strokes. (e.g. use of cam track or elaborate crank train)
  2. Valve train design with option for late or early intake closure (i.e. EMV)
     - With early intake closure the loaded air is isentropically expanded and recompressed.
     - With late intake closure a part of the loaded air is pushed back into the intake port after the induction stroke before the start of the compression.



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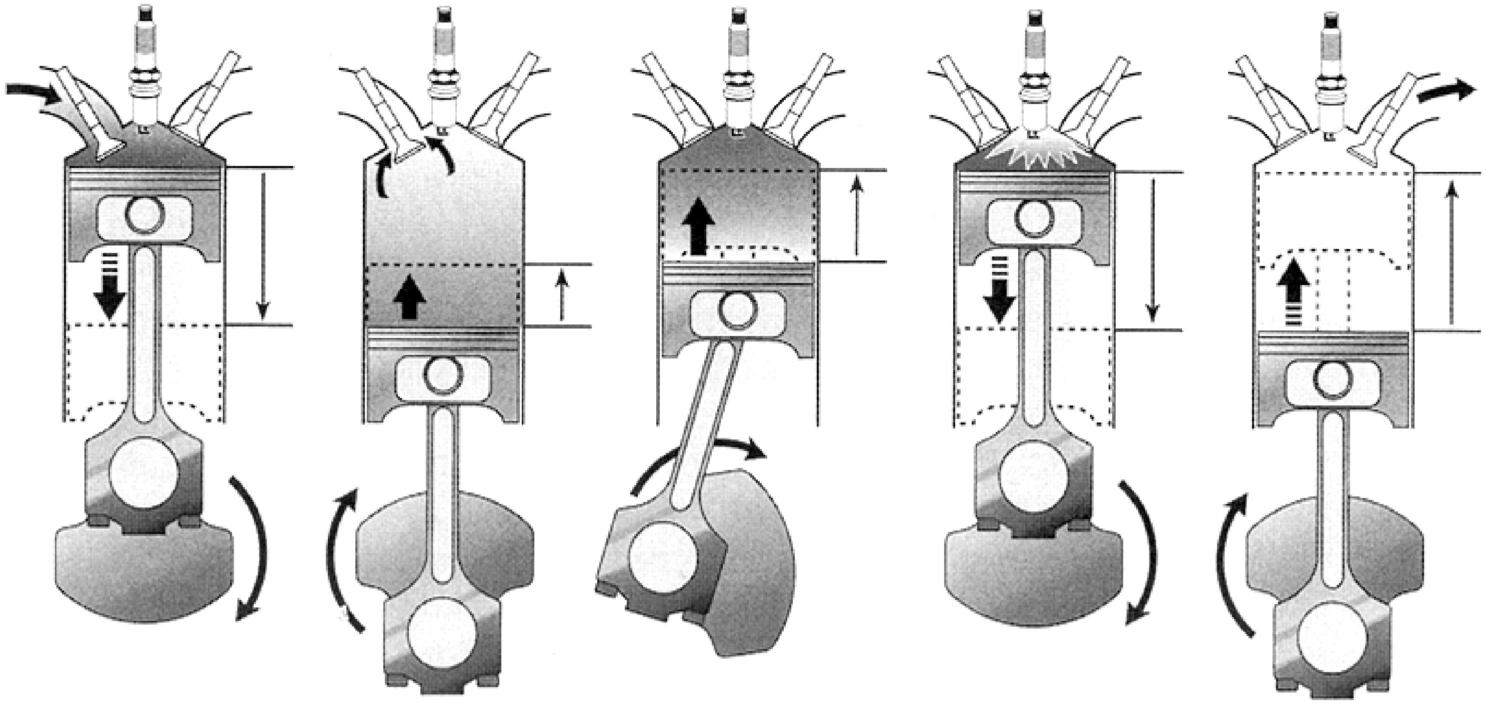
WP 2 - Working Cycle Characteristics: Miller Cycle of the Mazda 2.3l V6 - Engine



Miller cycle as implemented in the Mazda 2.3 l V6 - engine: The intake valve closes significantly after BDC. Therefore part of the loaded air is pushed back into the induction system during the compression stroke. The charge loss is compensated by Mazda by boosting the inducted air.

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WP 2 - Working Cycle Characteristics: Atkinson & Miller Cycle (3)

Evaluation:

- Actual implementations of Atkinson or Miller cycles don’t really feature an extended expansion but rather a reduced compression.
- The longer expansion stroke leads to an increase in engine size. This additional size results in bigger friction losses, which reduce the efficiency gain of the cycle modification.
- Usage of the complete expansion volume for the compression would result in a lower thermal efficiency but yield a higher specific power.
- Therefore the implementation of the Atkinson cycle is promising primarily for part load operation. This can only be achieved with variable valve timings.
- The Miller cycle additionally offers an engine power increase due to the charging and intercooling of the induced air.

Alternative solution:

- The energy contained in the exhaust gases of conventional engine cycles can be utilized with a turbocharger. This is state of the art and commonly used in Diesel engines.

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WP 2 - Assumptions for Ideal Thermodynamics Cycles

- Isentropic compression of fuel vapour/air mixture
- Combustion process as specified
- Isentropic expansion in chemical equilibrium of exhaust gases
- Geometry, cylinder charge and λ same as the real cycle
- Adiabatic process control
- Gas exchange process with zero dissipation

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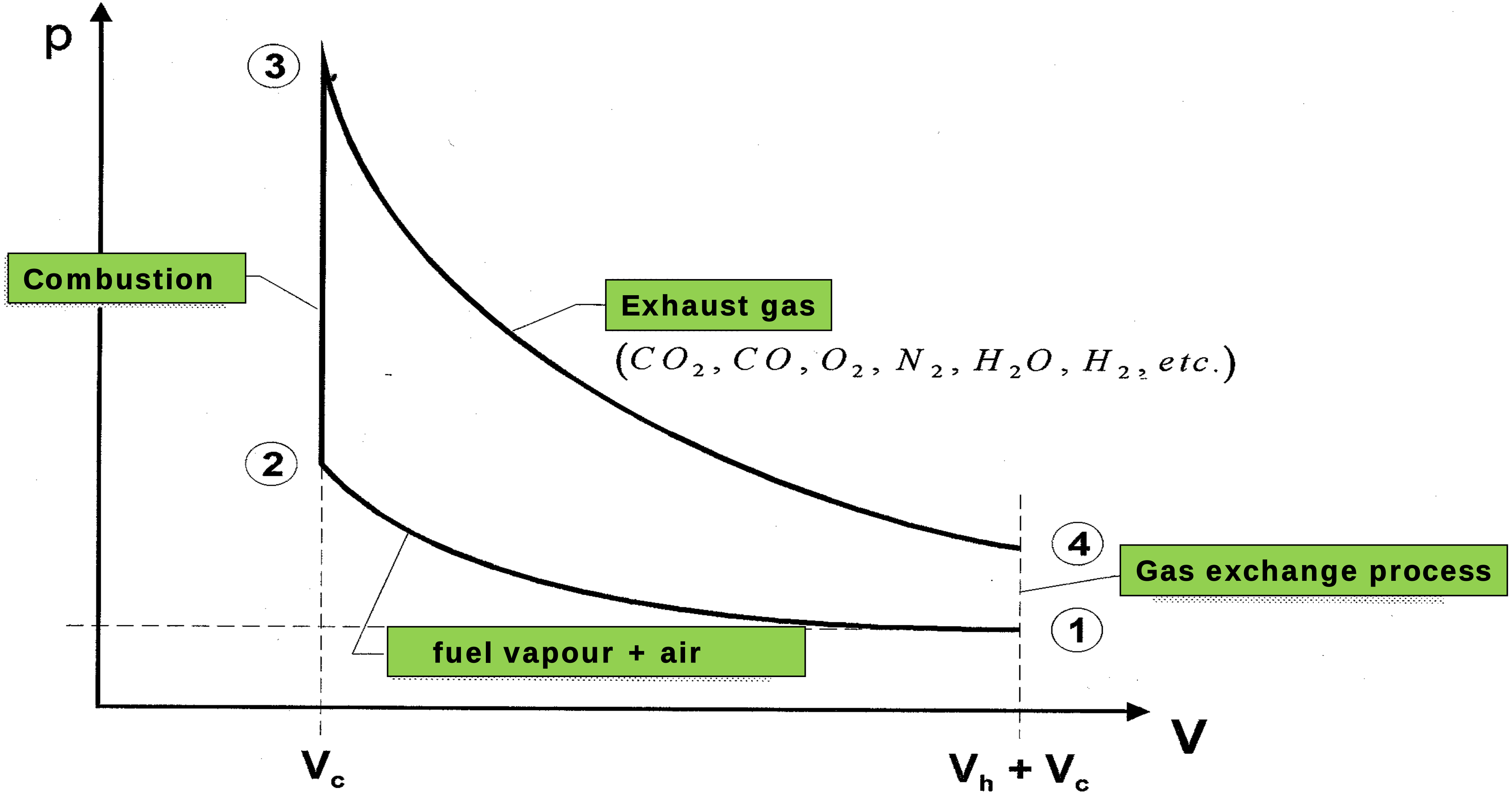
WP 2 - Ideal Engine in a Constant-Volume Engine Cycle



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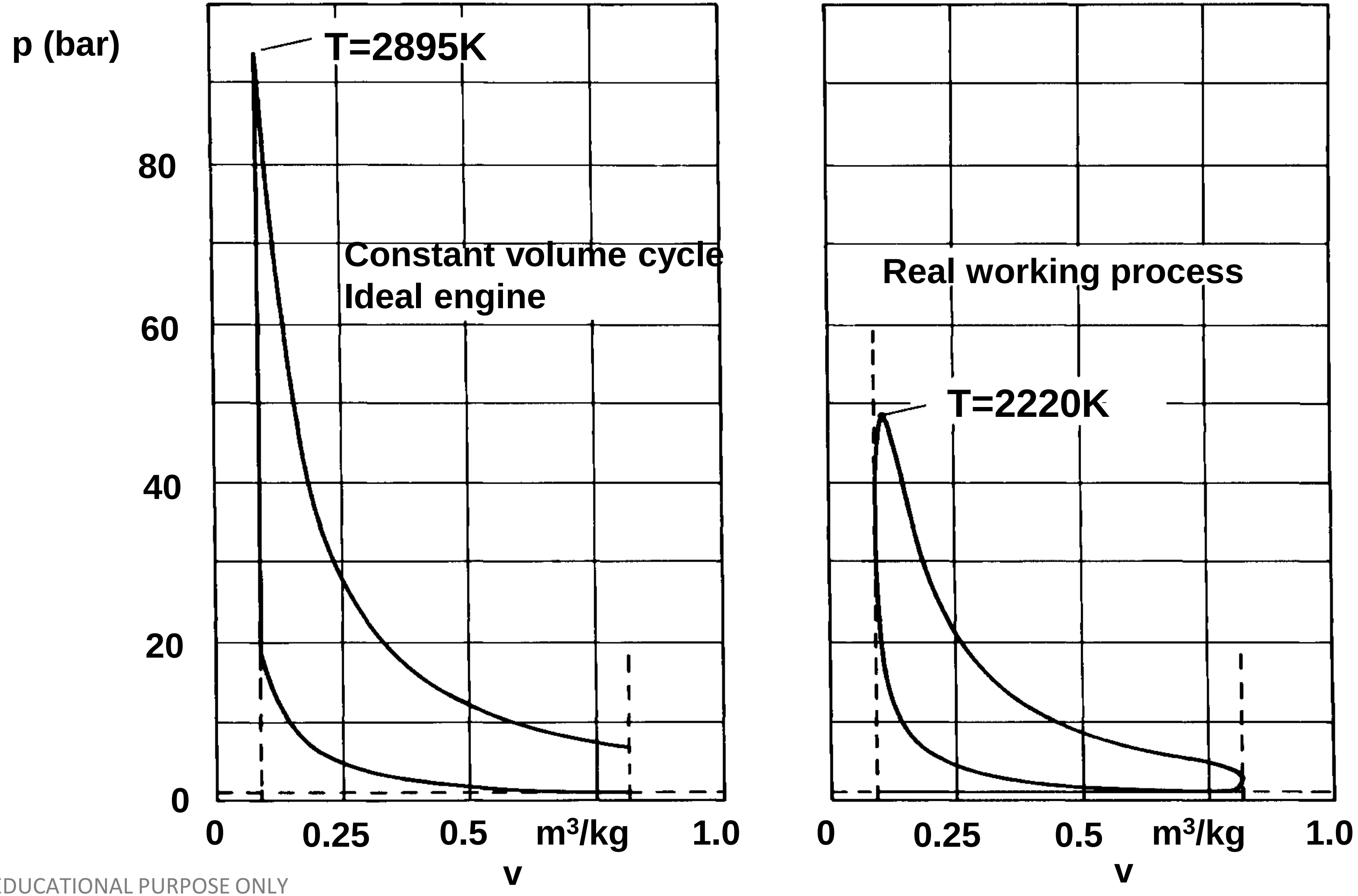
WP 2 - p-V-Diagram of a Petrol Engine (ε = 9.0)



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WP 2 - Efficiency Losses of a Real Working Process

inner losses

Efficiency of ideal engine, Losses of ideal process (exhaust)

- Non-ideal combustion (real combustion development, incomplete combustion)
- Leakage
- Wall-heat losses
- Gas exchange work
- Friction work

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WP 2 - Efficiency Losses for a Real Working Process

$$\eta_e = \overbrace{\underbrace{\eta_V - \Delta\eta_{BV} - \Delta\eta_U - \Delta\eta_W}_{\eta_{i,HD}} - \Delta\eta_{LW}}^{\eta_i} - \Delta\eta_R$$

Loss of efficiency from the state of an ideal engine operation with η_V:

$\Delta\eta_{BV}$: Real (non ideal) combustion process

$\Delta\eta_U$: Leakage

$\Delta\eta_W$: Heat dissipation losses through cylinder wall

$\Delta\eta_{LW}$: Gas exchange work

$\Delta\eta_R$: Friction work

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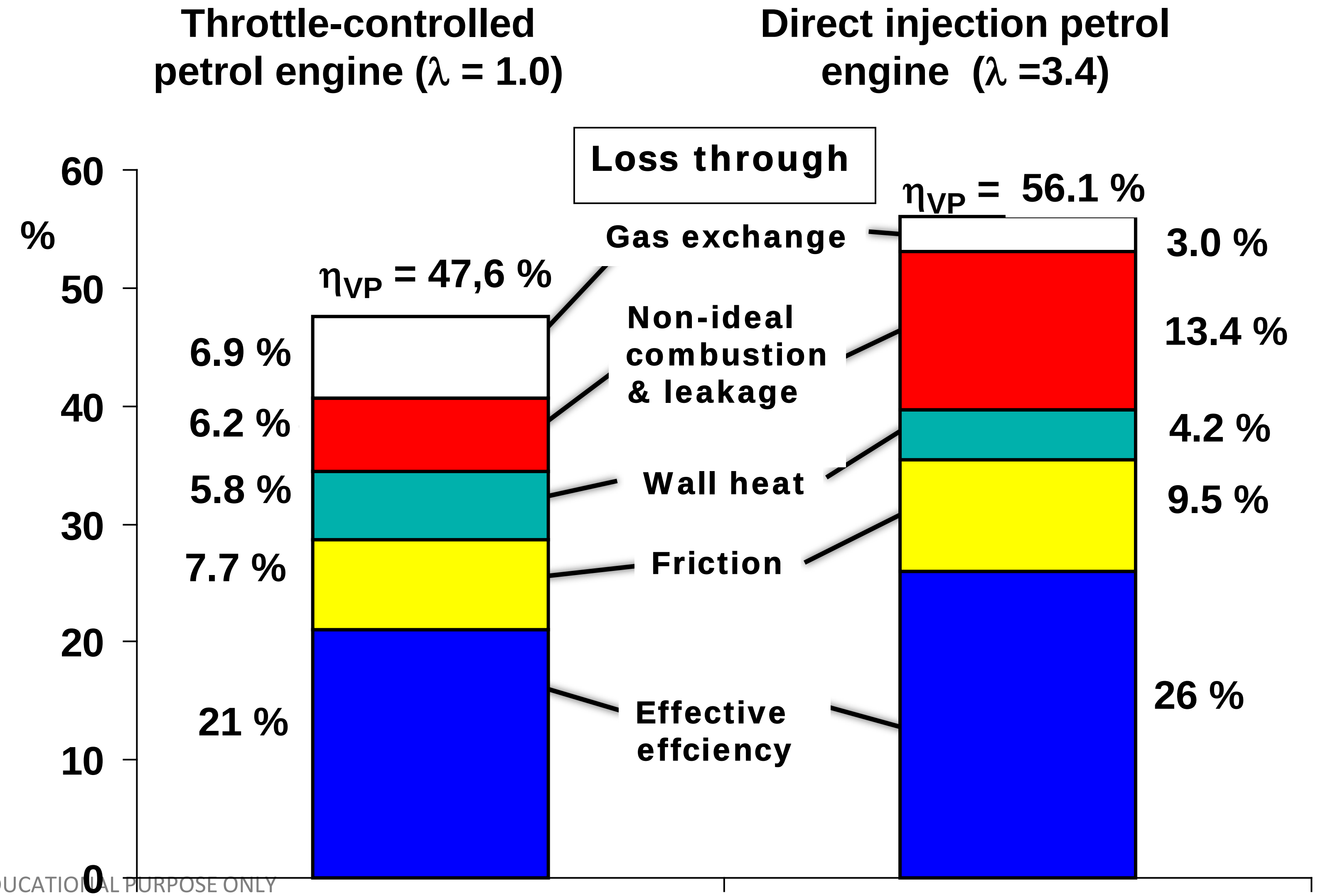
WP 2 - Breakdown of Processes of Petrol Engines (2000 1/min, 2 bar pme)



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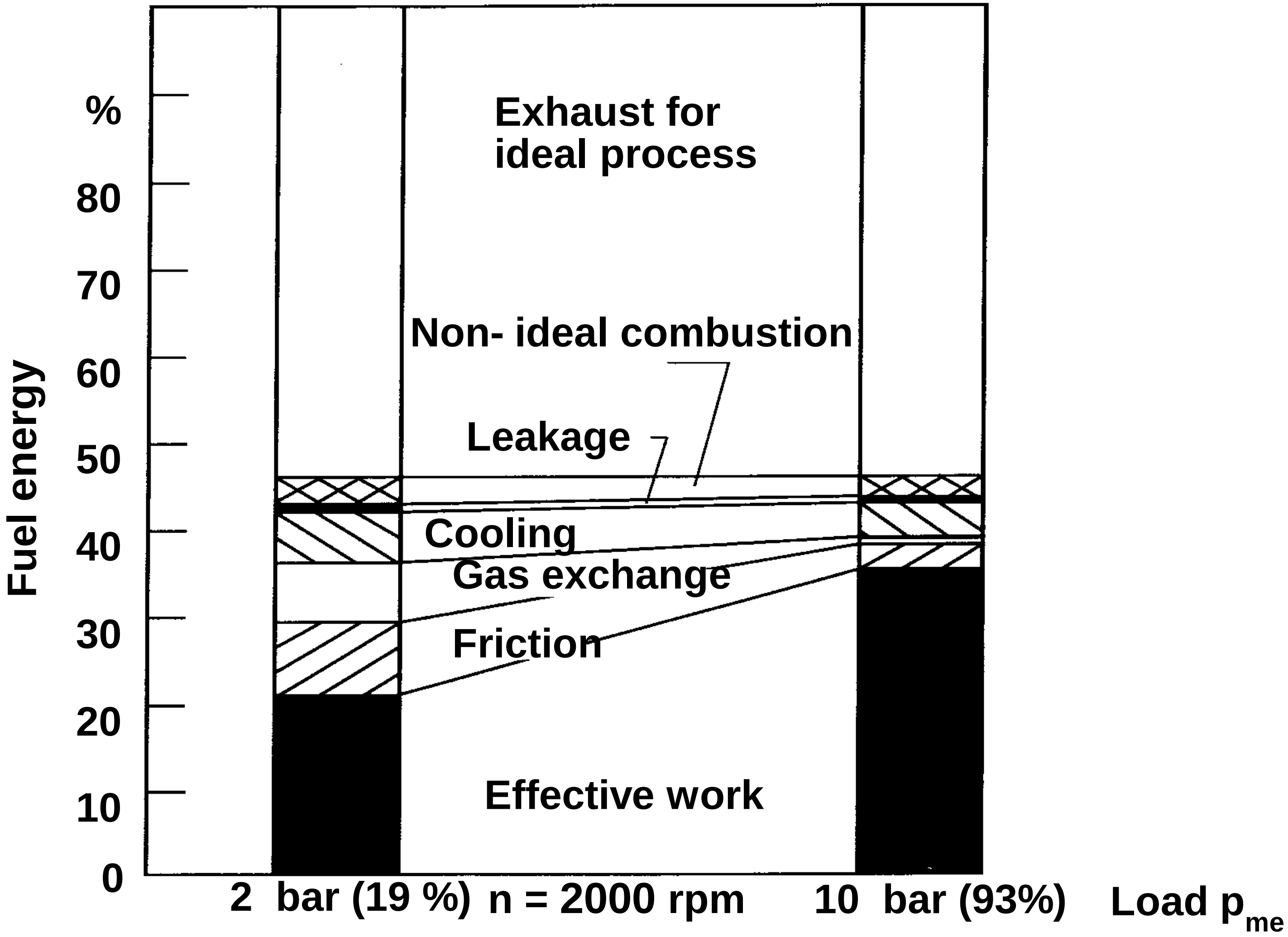
WP 2 - Efficiency Losses of a Throttle Controlled Petrol Engine



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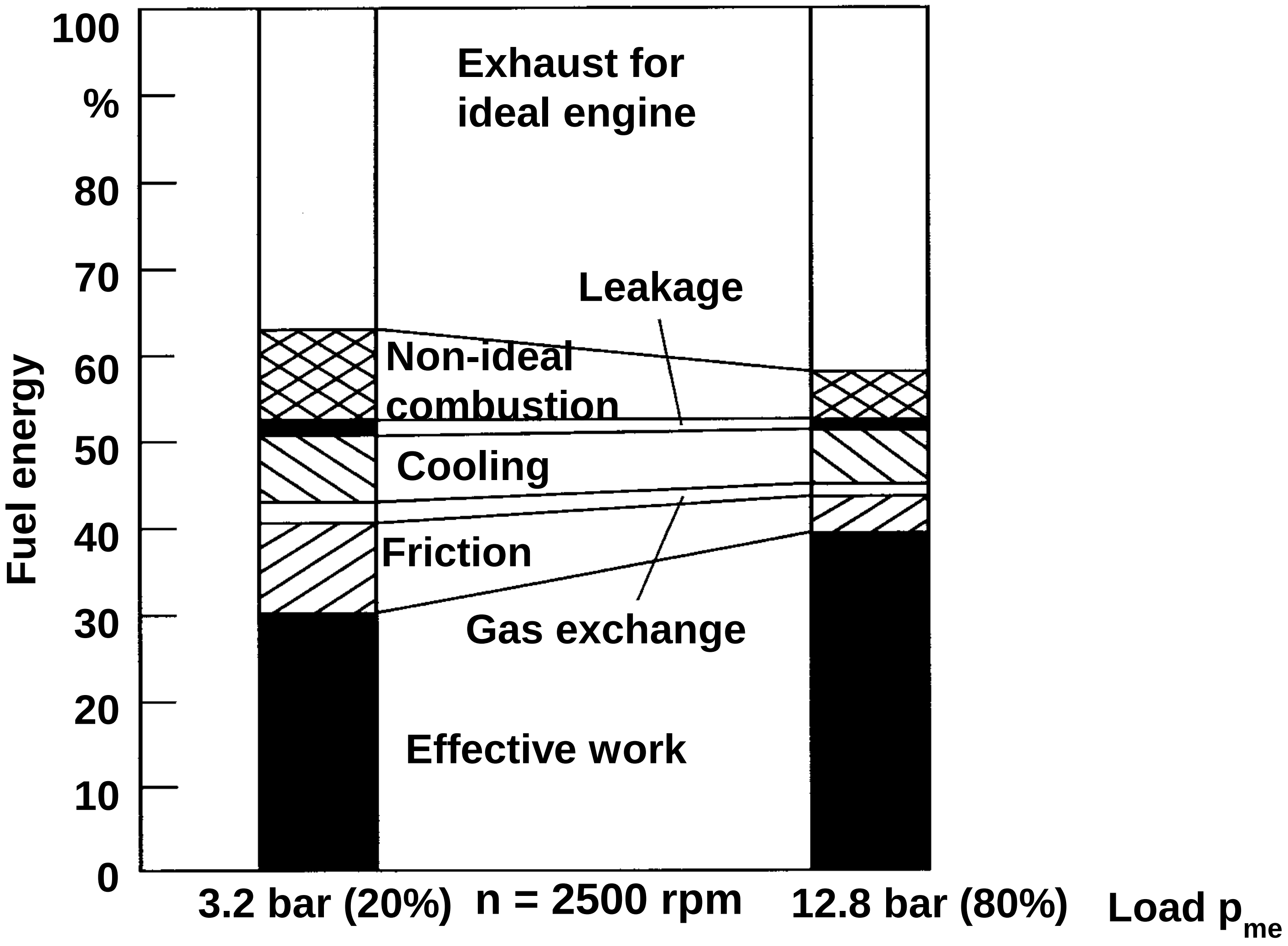
WP 2 - Efficiency Losses of a DI Turbocharged Diesel Engine



WP 2 – Training Overview

- Q&A, Discussion SLOT 1

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WP 2 – Training Overview

More lectures on ICE (w/o transmission) at our University

- Construction elements of ICE
- Exhaust aftertreatment systems of ICE (environmental effects)
- Noise Vibration Harshness of ICE
- Calibration of ICE performance
- Measuring and testing techniques in the powertrain sector (RDE-PEMS)

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WP 2 – Training Overview

My practical exercises (lab experiments) in ICE modules:

- Partial assembly and checking of the basic setting of a combustion engine
- Operating characteristics of a turbocharged direct injection petrol engine
- Internal efficiency of a turbocharged, direct injection gasoline engine
- Exhaust emissions of a petrol engine (λ-variation, spark timing, cat efficiency)
- Analysis of the exhaust emission behaviour of a diesel engine
- Analysis for European Driving Cycle NEDC – fuel consumption and emission measurement for a passenger vehicle
- Portable Emissions Measurement System (PEMS) vehicle testing – ICE emissions

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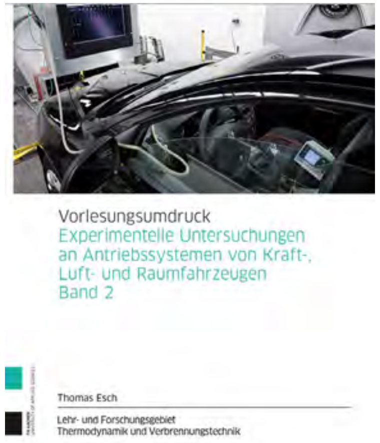
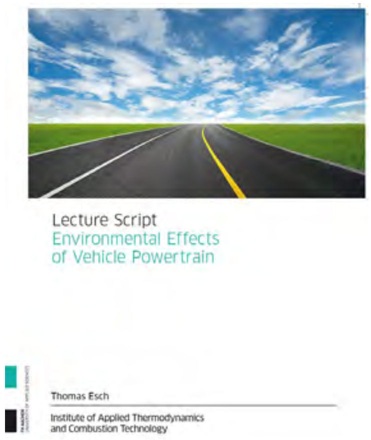
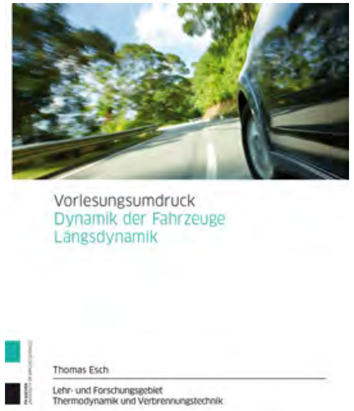
WP 2 – Training Overview

My lecture books at the University:







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UNITED

Engineering Knowledge Transfer Units to Increase Student´s Employability and Regional Development

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598710-EPP-1-2018-1-AT-EPPKA2-CBHE-JP

Engineering Knowledge Transfer Units to Increase Student´s Employability and Regional Development

2nd UNITED Training Melaka

From ICE to Alternative Powertrain (ICE SLOT 2)

Thomas Esch

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WP 2 – Malaka SLOT 2

- **ICE characteristics** and mixture formation (20 minutes)

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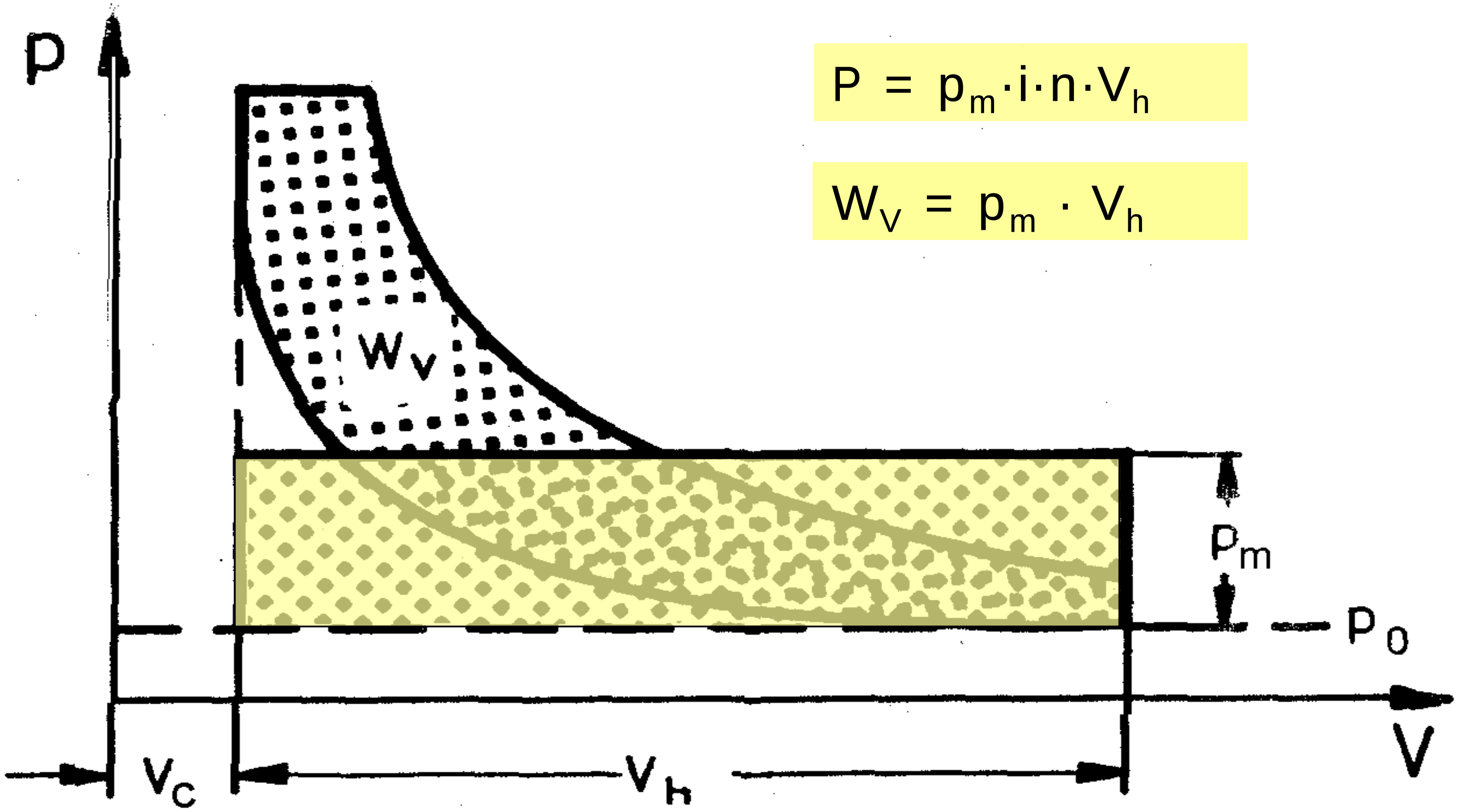
WP 2 - Definition of the Mean Pressure (schematic)



$P = p_m \cdot i \cdot n \cdot V_h$

$W_V = p_m \cdot V_h$

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WP 2 - Engine Power Equations

$$P_{iz} = i \cdot n \cdot W_{KA} = i \cdot n \cdot p_{mi} \cdot V_h$$

Indicated cylinder power (one cylinder)

2 - stroke: i = 1
4 - stroke: i = 0.5

$$P_i = i \cdot n \cdot p_{mi} \cdot V_H$$

Indicated power (complete engine)

p_{mi} : **Indicated mean eff. pressure (IMEP)**

$$P_e = i \cdot n \cdot p_{me} \cdot V_H$$

Effective power (complete engine)

p_{me} : **Brake mean eff. pressure (BMEP)**

$$P_r = P_i - P_e$$

$$= i \cdot n \cdot (p_{mi} - p_{me}) \cdot V_H$$

Friction power (complete engine)

$$P_r = i \cdot n \cdot p_{mr} \cdot V_H$$

p_{mr} : **Friction mean eff. Pressure (FMEP)**

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WP 2 - Torque and Brake Mean Effective Pressure

$$P_e = M \cdot \omega = M \cdot 2\pi n = i \cdot n \cdot p_{me} \cdot V_H$$

Angular velocity (ω)

Torque (M)

$$M = \frac{i}{2\pi} \cdot p_{me} \cdot V_H \qquad (M \sim p_{me})$$

Reference state: -DIN 70020
-EWG Norm 0158

$$p_{me} = \frac{2\pi}{i} \cdot \frac{M}{V_H}$$

Example: Four-stroke engine, $V_H = 2\ dm^3$

$n = 5000\ rpm,\ M = 126\ Nm$

$$p_{me} = \frac{2\pi}{0{,}5} \cdot \frac{126\ Nm}{2\ dm^3} = \frac{2\pi}{0{,}5} \cdot \frac{126\ Nm}{2 \cdot 10^{-3} m^3}$$

$$p_{me} = 792000 \frac{N}{m^2} = 7{,}92\ bar = 0{,}792 \frac{kJ}{dm^3}$$

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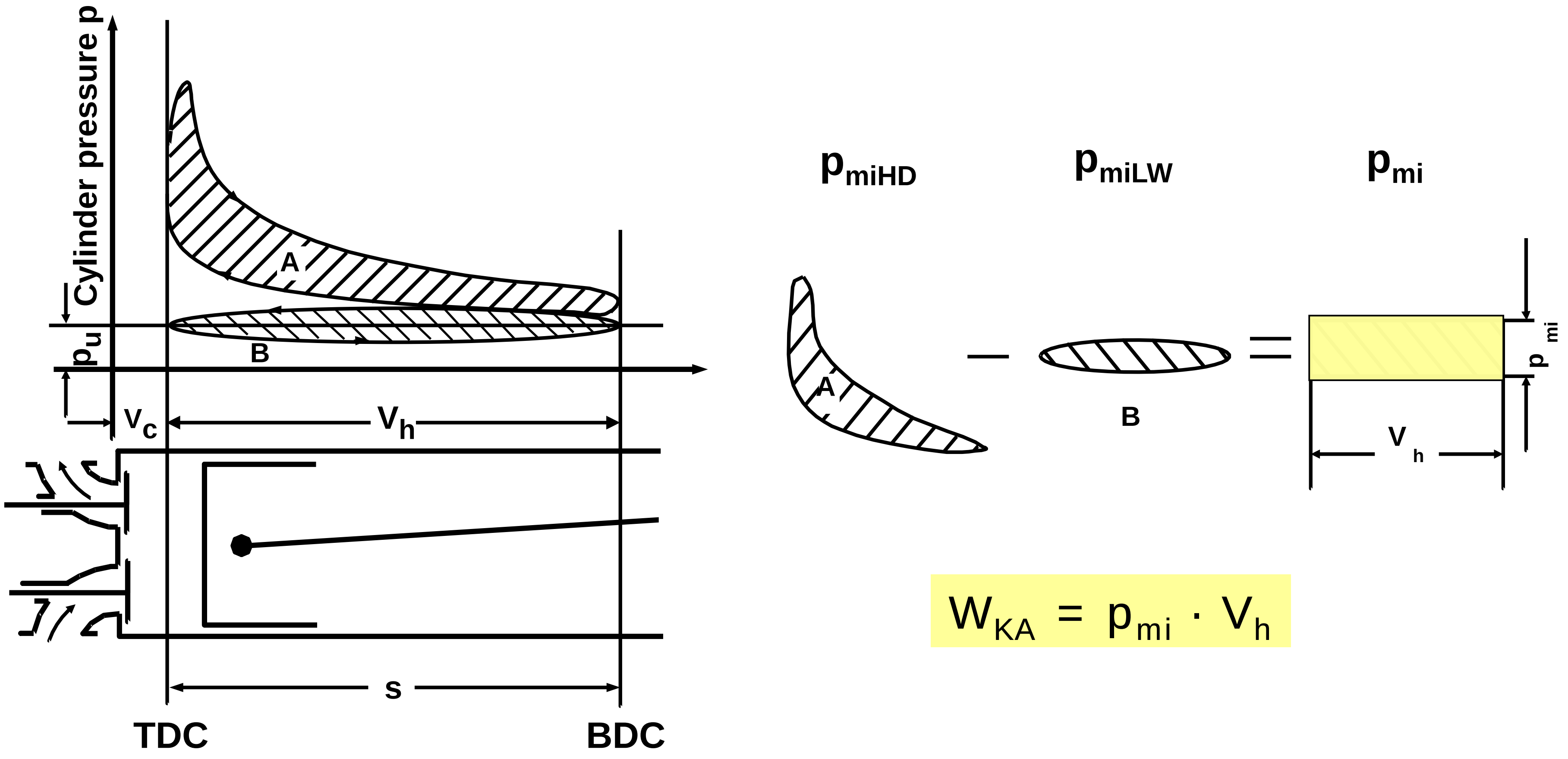
WP 2 - Establishing IMEP from p-V Diagram (4-stroke)



$$W_{KA} = p_{mi} \cdot V_h$$

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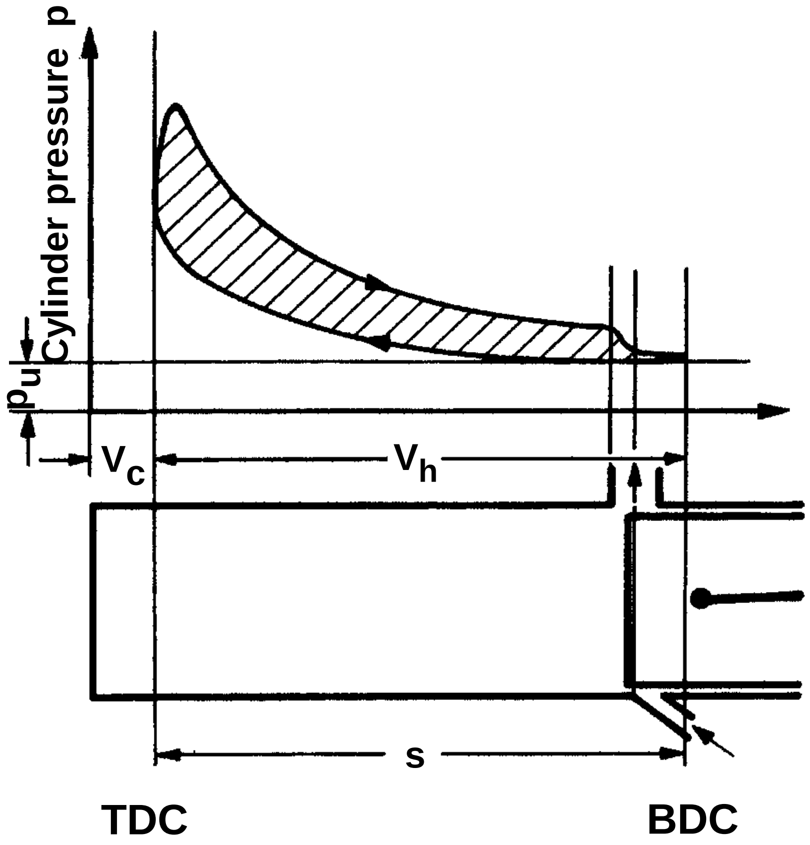
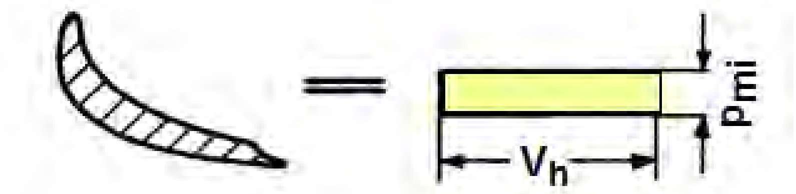
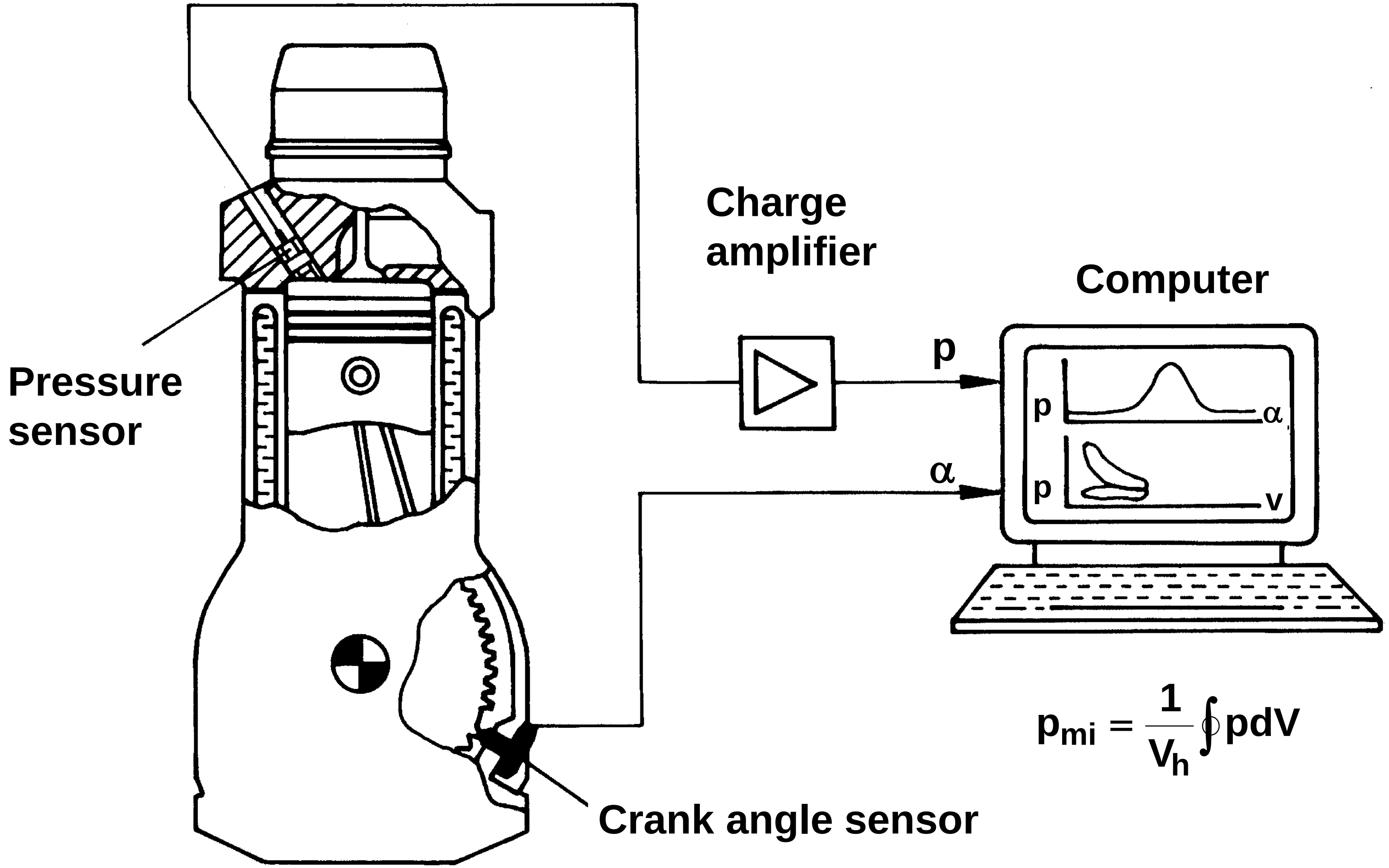
WP 2 - Establishing IMEP from p-V Diagram (2-stroke)





$W_{KA} = p_{mi} \cdot V_h$

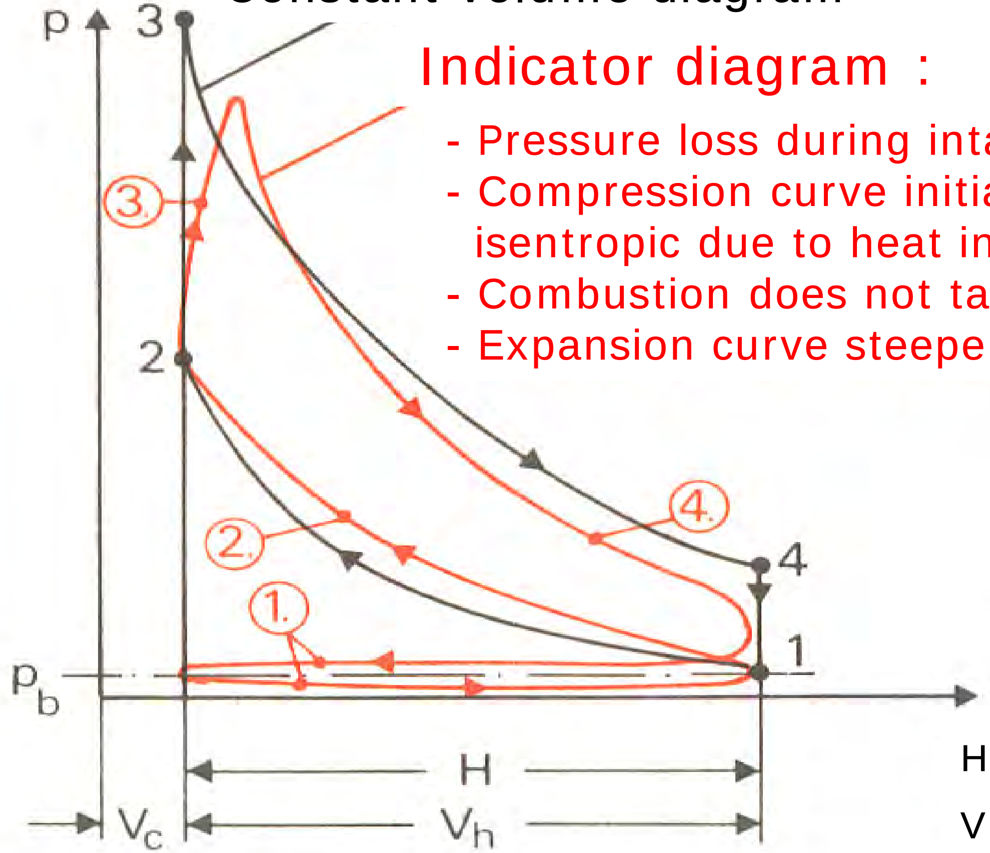
WP 2 - Set-up to Determine the p_{mi}



$$p_{mi} = \frac{1}{V_h} \oint p dV$$

WP 2 - Indicator Diagram of a 4-Stroke Petrol Engine

Constant volume diagram 1-2-3-4



Indicator diagram :

- Pressure loss during intake and exhaust flow
- Compression curve initially steeper and then gentler than isentropic due to heat intake and heat loss respectively
- Combustion does not take place at constant volume
- Expansion curve steeper due to heat loss

$$V = \frac{\pi D^2}{4} s$$

H (Piston displacement) and

V (Swept Volume) respectively

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WP 2 - Maximum Brake Mean Effective Pressure

	p_{me} [bar]
Motorcycle engines (four-stroke)	— 12
Racing engines (Naturally-aspirated)	— 16.6
Racing engines (turbocharged)	— 56
Passenger car gasoline engines (NA)	9 — 14.1
Passenger car gasoline engines (TC)	14 — 20
Passenger car diesel engines (TC)	12 — 21.2
Truck diesel engines (turbocharged)	11 — 23.5
Large high speed engines (Diesel)	15 — 29.4
Medium high speed engines (Diesel)	15 — 25
Crosshead engines (2-Stroke Diesel)	15 — 18.2

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WP 2 - Mean Piston Velocity

$$c_m = 2 \cdot s \cdot n$$

Major influences on:

- stresses due to mass forces: $\sigma_M \sim c_m^2$
- friction (wear)
- thermal loading
- volumetric efficiency and charging efficiency
- noise
- lifetime / wear

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WP 2 - Maximum Mean Piston Velocity Ranges

ENGINE TYPE	c_m		[m/s]
Motorcycle engines (four-stroke)		—	22
Racing engines (turbocharged)		—	21.7
Racing engines (naturally-aspirated)		—	27
Passenger car gasoline engines (NA)	9.5	—	24.7
Passenger car diesel engines (TC)	12.3	—	14.7
Truck diesel engines (turbocharged)	8.1	—	13.1
Large high speed engines (Diesel)	7.0	—	12
Medium high speed engines (Diesel)	5.3	—	9.5
Crosshead engines (2-stroke Diesel)	5.7	—	7.8

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WP 2 - Volumetric Efficiency und Charging Efficiency

$$\lambda_a = \frac{m_g}{V_h \, \rho_{th}}$$ Volumetric efficiency

$$\lambda_l = \frac{m_Z}{V_h \cdot \rho_{th}}$$ Charging efficiency

m_g: Mass of charge air (or mixture)

ρ_{th}: Theoretical charge density

m_Z: Mass of trapped cylinder charge per cycle

External mixture formation (conv. gasoline engine)	Internal mixture formation (diesel, DI-gasoline engine)	External mixture formation	Internal mixture formation
$m_g = m_B + m_L$ $\rho_{th} = \rho_G$ $m_g = V_G \cdot \rho_G$ $\lambda_a = \frac{V_G}{V_h}$	$m_g = m_L$ $\rho_{th} = \rho_L$ $m_g = V_L \cdot \rho_L$ $\lambda_a = \frac{V_L}{V_h}$	$m_Z = m_{ZB} + m_{ZL}$	$m_Z = m_{ZL}$

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WP 2 - Efficiency and Specific Fuel Consumption

$$\eta_e = \frac{P_e}{\dot{m}_B H_u}$$

Effective efficiency

H_u — **Heating value**

$\dot{m}_B$ — **Fuel mass flow**

Example:

$$\eta_e = 0.35 ; H_u = 42800 \frac{kJ}{kg}$$

$$b_e = \frac{1}{0.35 \cdot 42800} \frac{kg}{kJ} = \frac{1000}{0.35 \cdot 42800} \frac{g}{kWs}$$

Effective specific fuel consumption (BSFC)

$$= \frac{1000 \cdot 3600}{0.35 \cdot 42800} \frac{g}{kWh} = 240 \frac{g}{kWh}$$

$$\eta_i = \frac{P_i}{\dot{m}_B H_u}$$

Indicated efficiency

$$b_i = \frac{\dot{m}_B}{P_i} = \frac{1}{\eta_i H_u}$$

Indicated specific fuel consumption (ISFC)

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WP 2 - Mechanical Friction and Fuel Consumption

$$\eta_m = \frac{P_e}{P_i} = \frac{p_{me}}{p_{mi}}$$

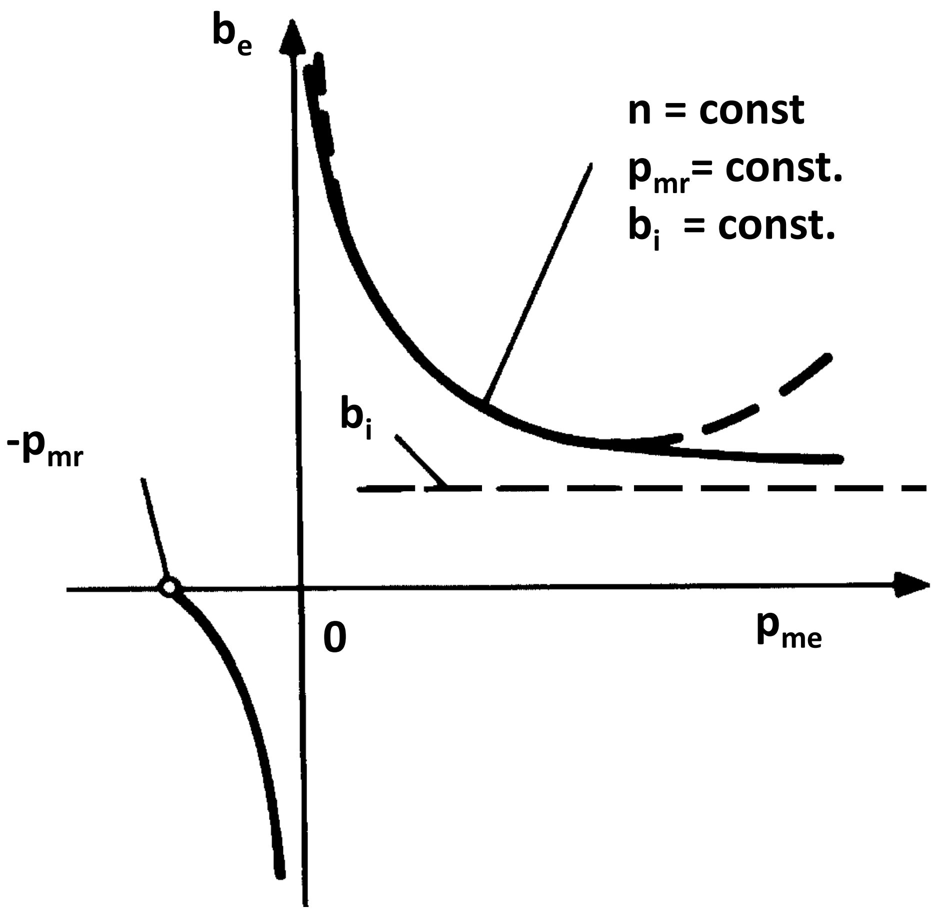
Mechanical efficiency

$$= \frac{\eta_e \cdot \dot{m}_B \cdot H_u}{\eta_i \cdot \dot{m}_B \cdot H_u} = \frac{\eta_e}{\eta_i} = \frac{b_i}{b_e}$$

$$\eta_m = \frac{p_{mi} - p_{mr}}{p_{mi}} = 1 - \frac{p_{mr}}{p_{mi}}$$

$$\frac{b_e}{b_i} = \frac{p_{mi}}{p_{me}} = \frac{p_{me} + p_{mr}}{p_{me}} = 1 + \frac{p_{mr}}{p_{me}}$$

$$b_e = (1 + \frac{p_{mr}}{p_{me}}) \cdot b_i$$



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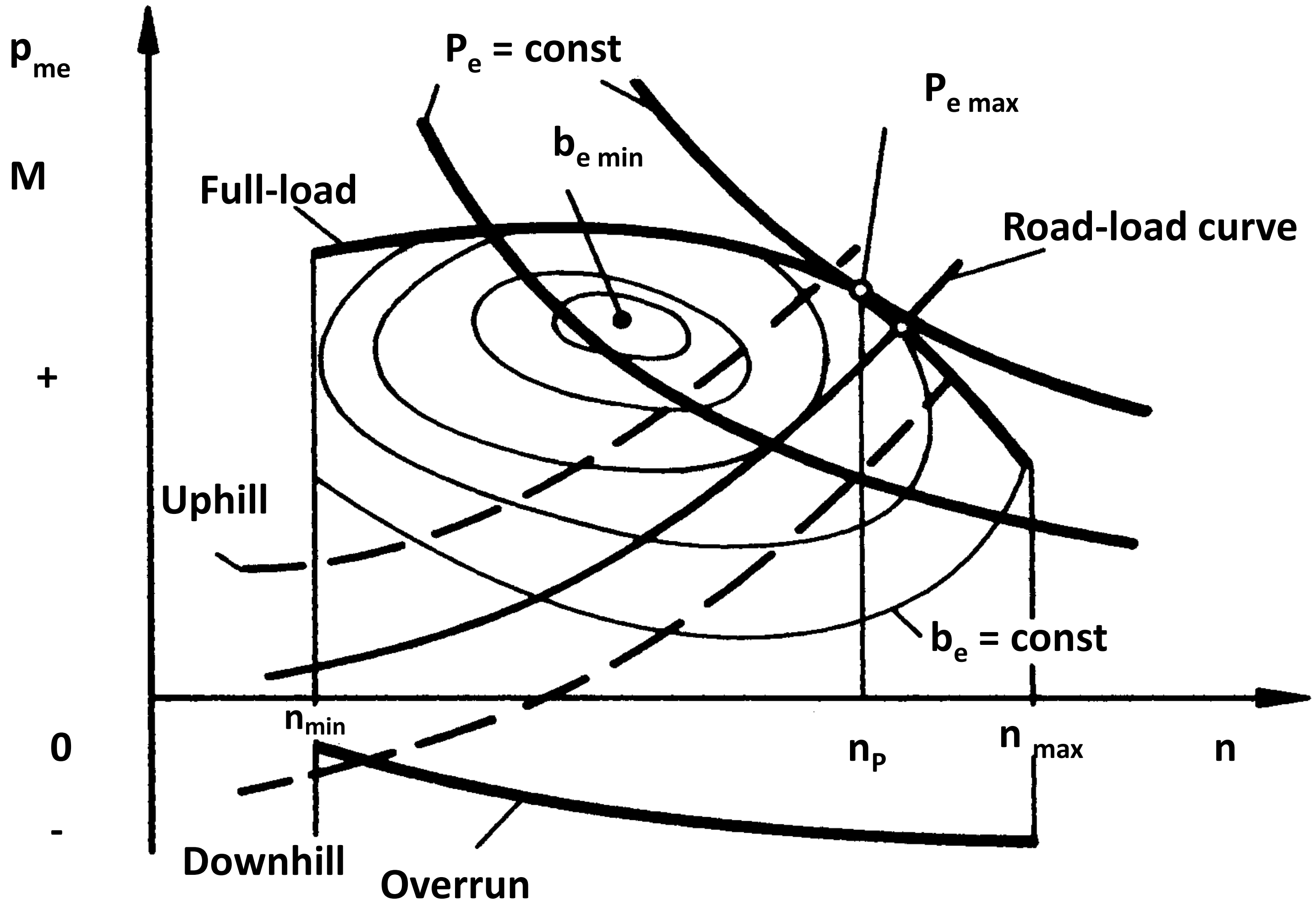
WP 2 - Fuel Consumption Map (schematic)



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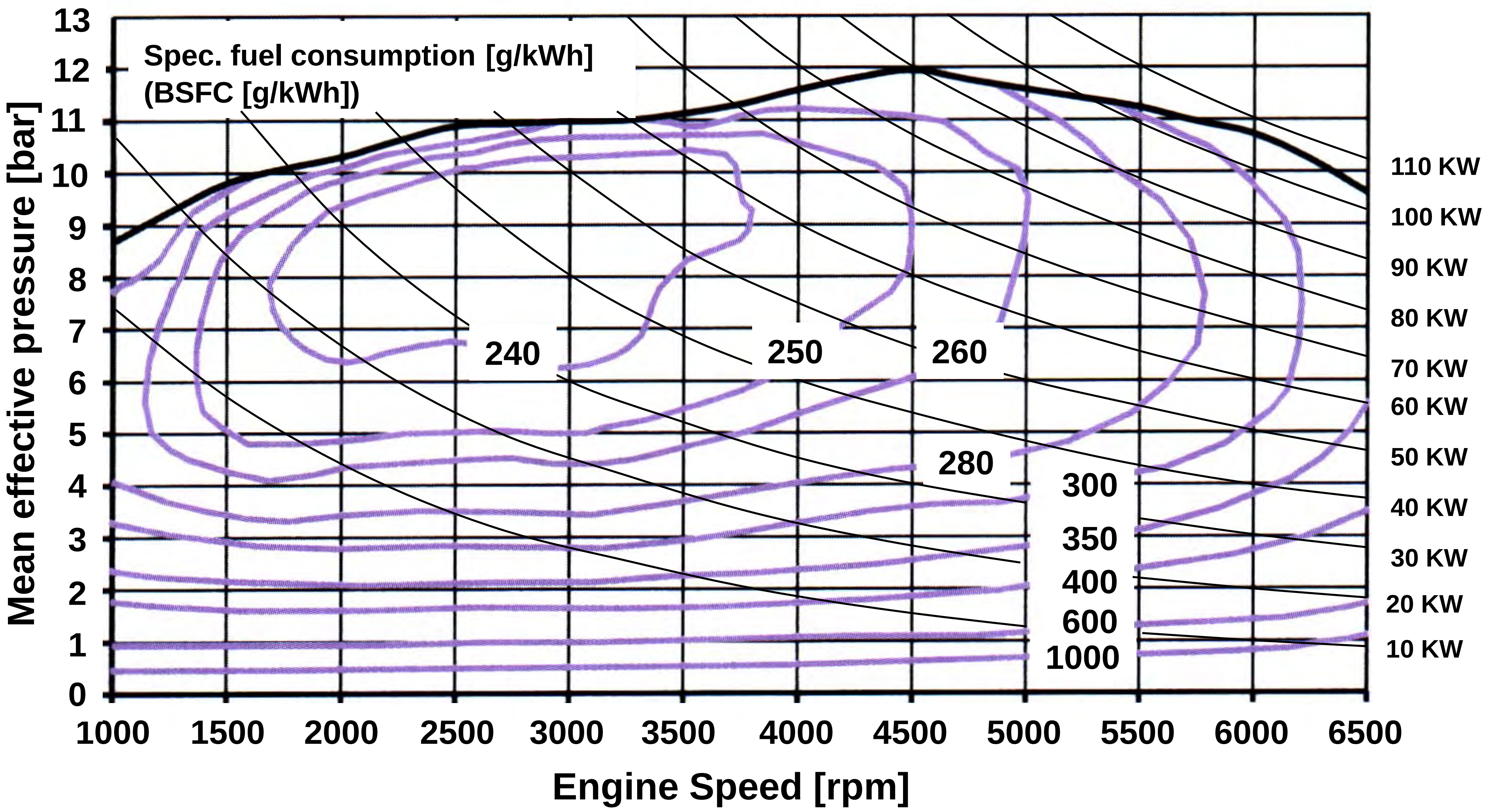
WP 2 - Fuel Consumption Map (2.0l Petrol Engine)



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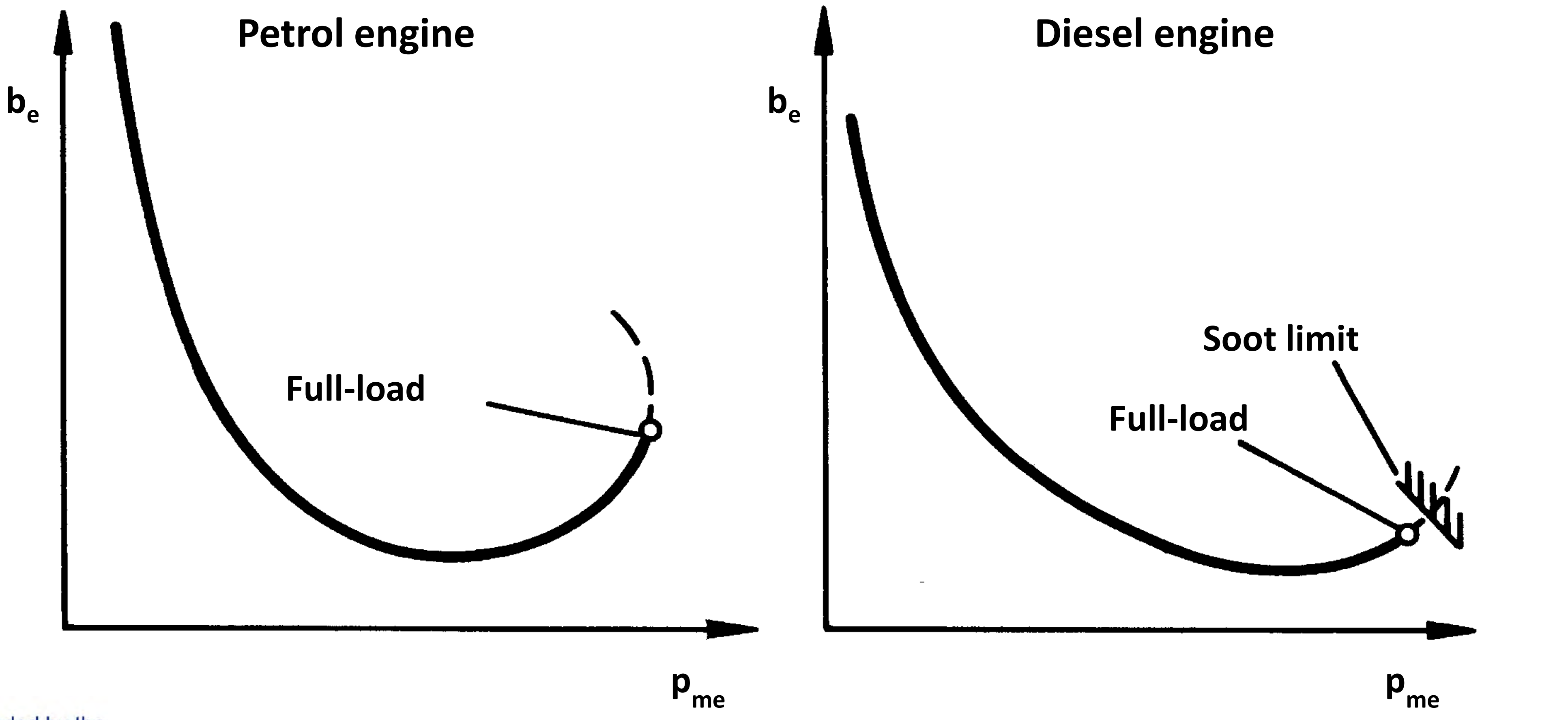
WP 2 - Partial - Load Fuel Consumption (n=const)



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WP 2 - Relative Air/Fuel Ratio

$$\lambda = \frac{\dot{m}_L}{\dot{m}_B} \cdot \frac{1}{L_{ST}}$$

$$L_{st} = \frac{1}{g_{O_2,fl}} \cdot \left[\frac{M_{O_2}}{M_C} \cdot c + \frac{M_{O_2}}{M_H} \cdot \frac{h}{4} + \frac{M_{O_2}}{M_S} \cdot s + \frac{M_{O_2}}{M_O} \cdot \frac{o}{2} \right]$$

$$L_{st} = \frac{1}{g_{O_2,fl}} \cdot \left[2,664 \cdot c + 7,937 \cdot h + 0,998 \cdot s - o \right]$$

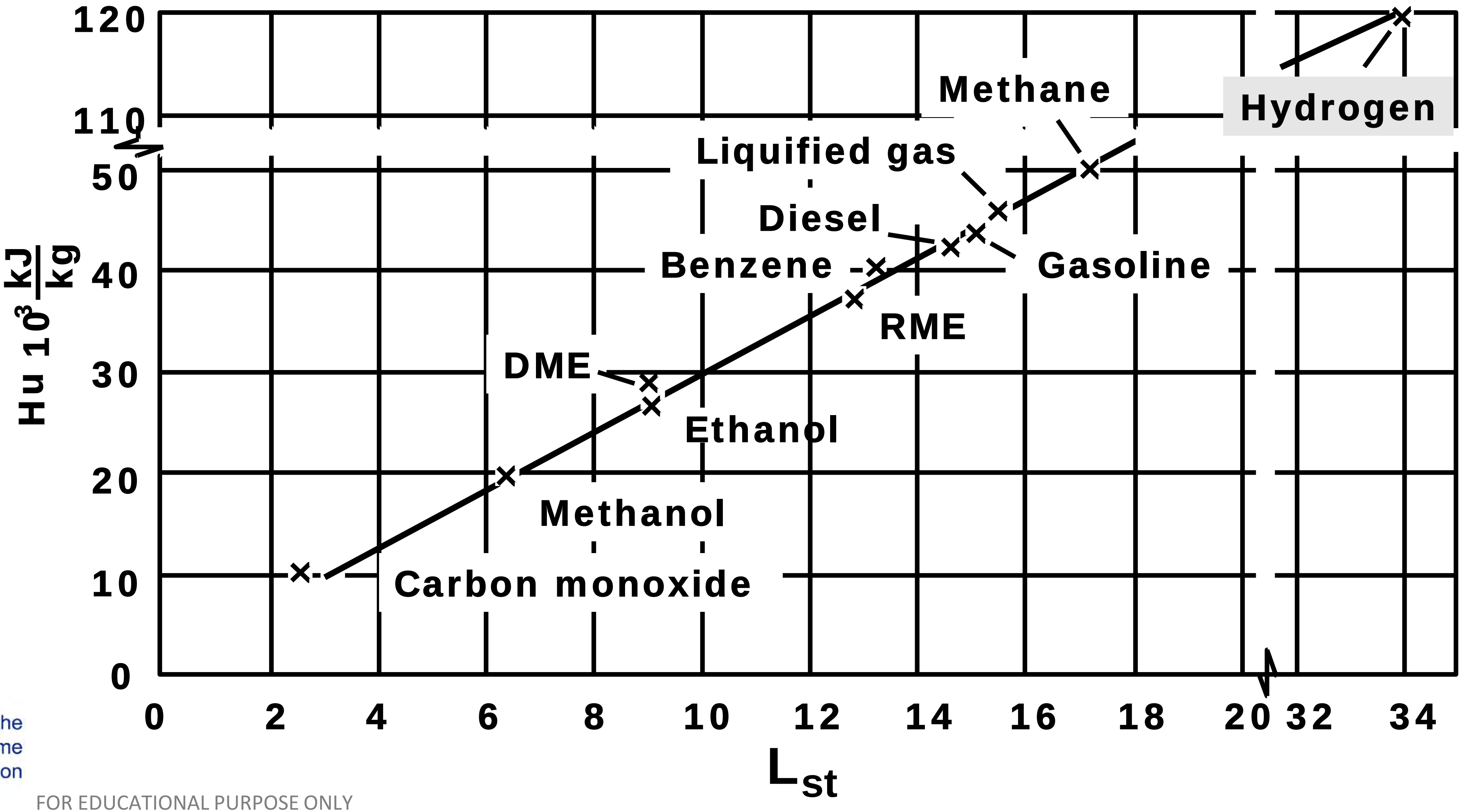
Petrol and Diesel fuel

$c \approx 0.87$

$h \approx 0.13$ $\quad L_{st} = 14.5$

$s \approx 0$

WP 2 - Another Important Equation



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WP 2 - Mixture Heating Value

$$H_G = \frac{m_B H_u}{V_G}$$

External mixture generation (conv. petrol engine)

$$V_G = \frac{m_G}{\rho_G} = \frac{m_L + m_B}{\rho_G} = \frac{m_B}{\rho_G} \cdot \left(\frac{m_L}{m_B} + 1 \right)$$

$$V_G = \frac{m_B}{\rho_G} (L_{st} \cdot \lambda + 1)$$

$$\boxed{H_G = \frac{H_u \cdot \rho_G}{L_{st}\lambda + 1}}$$

$$\overline{H}_G = \frac{m_B \cdot H_u}{V_L}$$

Internal mixture generation (Diesel, DI-petrol engine)

$$V_L = \frac{m_L}{\rho_L} = \frac{m_B}{\rho_L} \cdot \frac{m_L}{m_B} = \frac{m_B}{\rho_L} \cdot L_{st} \cdot \lambda$$

$$\boxed{\overline{H}_G = \frac{H_u \cdot \rho_L}{L_{st} \cdot \lambda}}$$

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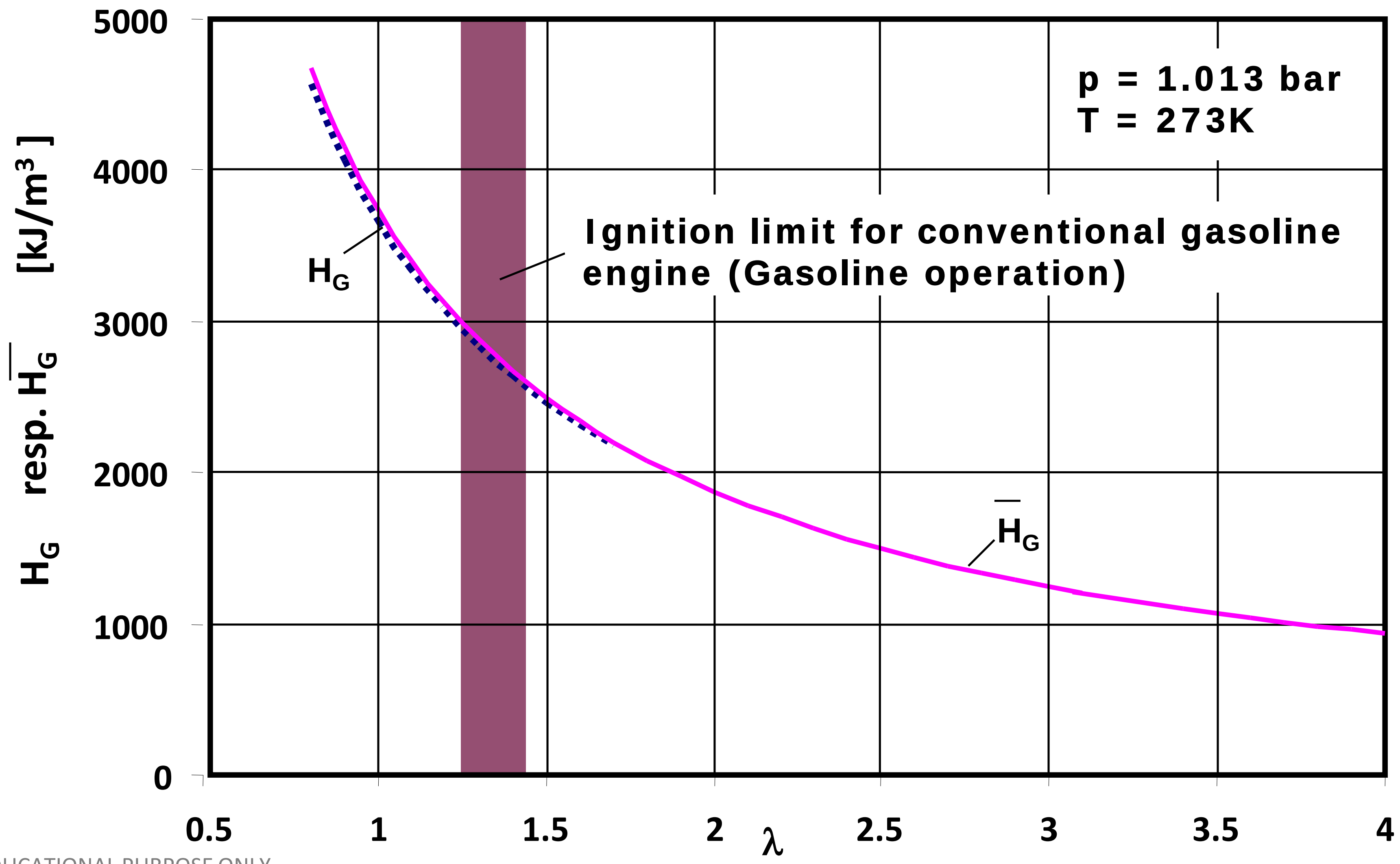
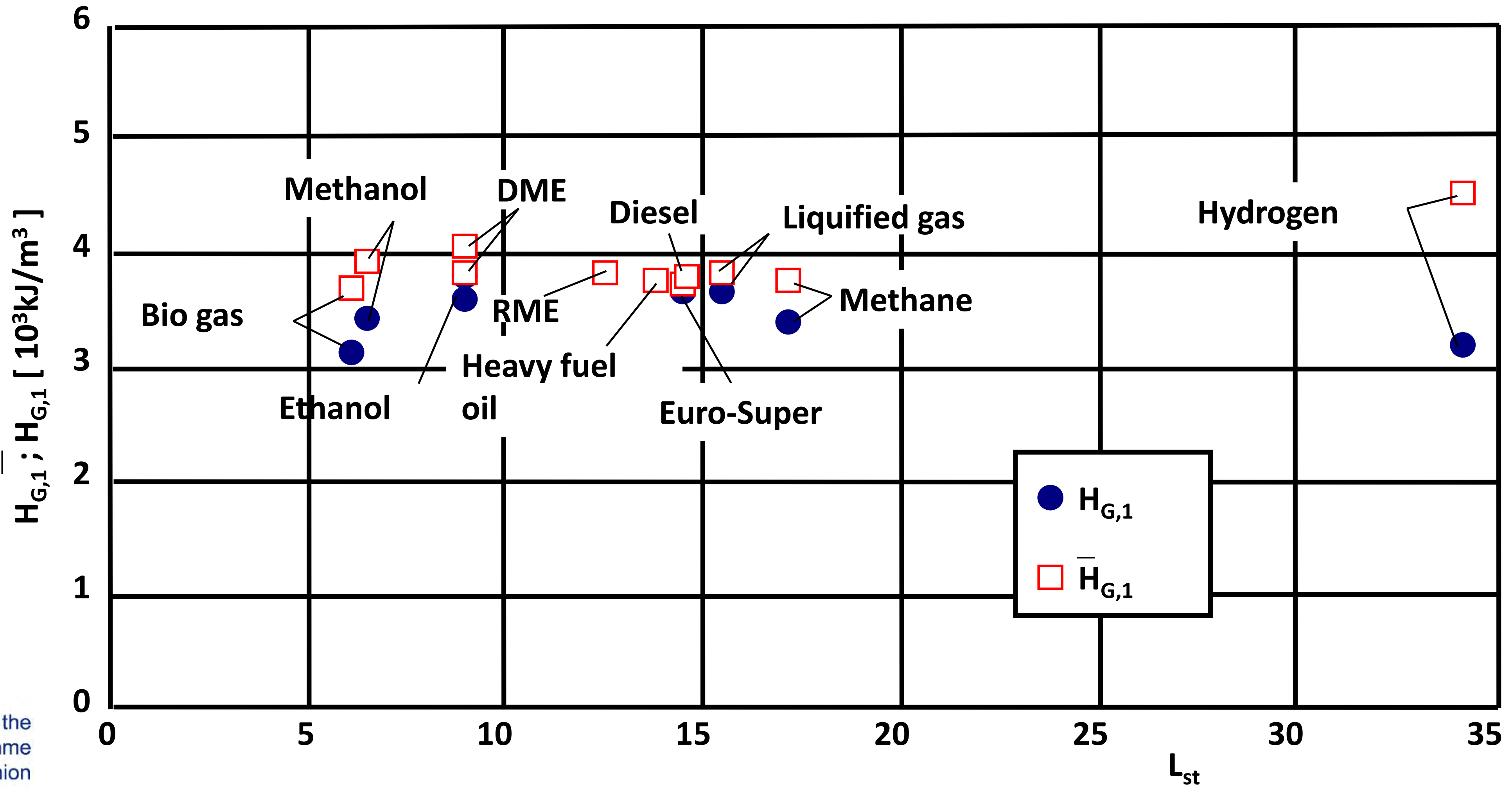
WP 2 - λ - Dependency on Mixture Heating Value



WP 2 - Air Requirement on Mixture Heating Value (λ =1)



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WP 2 - Charging Efficiency and p_{me}

	External mixture formation (conv. petrol engine)	Internal mixture formation (Diesel, DI petrol engine)
	$\eta_i = \frac{P_i}{\dot{m}_B H_u} = \frac{W_{KA}}{V_G \cdot H_G}$	$\eta_i = \frac{W_{KA}}{V_L \cdot \overline{H}_G}$
	$W_{KA} = \eta_i \cdot V_G \cdot H_G$	$W_{KA} = \eta_i \cdot V_L \cdot \overline{H}_G$
	$p_{mi} = \eta_i \frac{V_G}{V_H} \cdot H_G$	$p_{mi} = \eta_i \frac{V_L}{V_h} \cdot \overline{H}_G$
$p_{mi} = \frac{W_{KA}}{V_h}$	$p_{mi} = \eta_i \lambda_a H_G$	$p_{mi} = \eta_i \lambda_a \overline{H}_G$
	$p_{me} = \eta_e \lambda_a H_G$	$p_{me} = \eta_e \lambda_a \overline{H}_G$

Example: conv. gasoline engine, $\lambda_a = 0.9$ (full load), $\eta_e = 0.3$; $\lambda = 1$; 0 °C

$$H_{G,1} = 3750 \frac{kJ}{m^3} = 3750 \cdot 1000 \frac{Nm}{m^3} = 37.5\,bar$$

$$p_{me} = 0.3 \cdot 0.9 \cdot 37.5\,bar = 10.1\,bar$$

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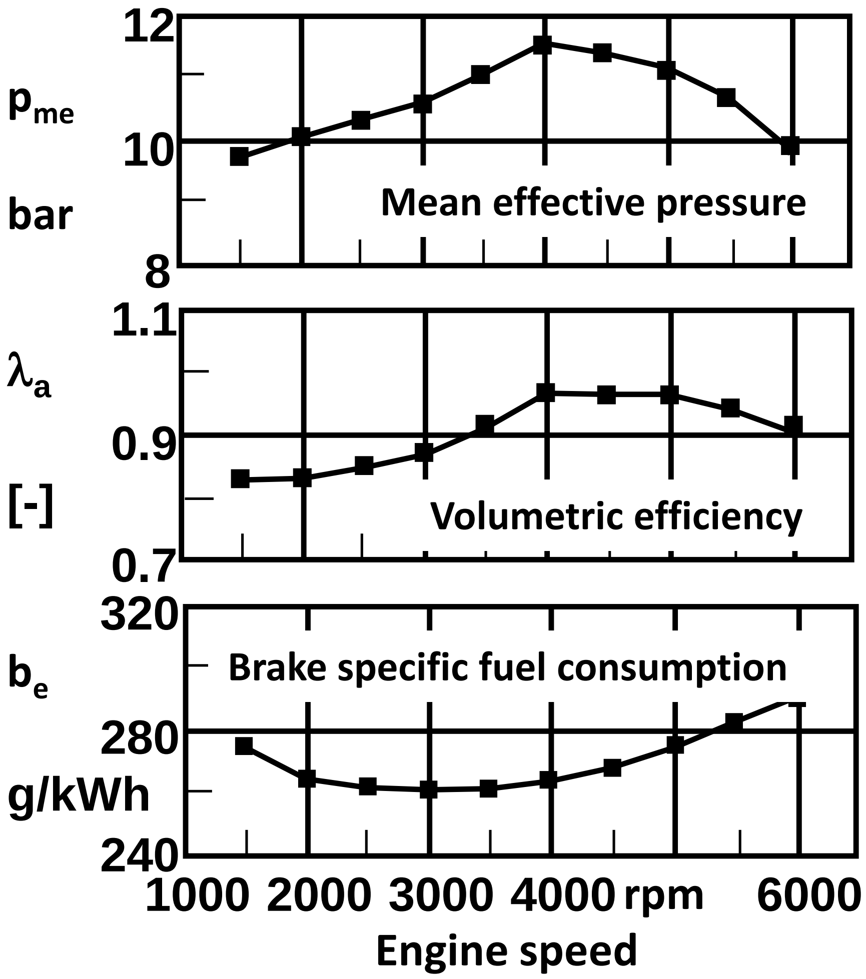
WP 2 - Full-Load Operation Behavior of a 4 Cylinder Petrol Engine

(λ = 0.9)



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WP 2 – Malaka SLOT 2

- ICE characteristics and **mixture formation** (20 minutes)

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WP 2 – In Cylinder Movement

- Efficient and emission free combustion at high λ needs intensive air/fuel movement within cylinder.
- This is a requirement for a homogeneous mixture dilution engine operation.

Classification of in-cylinder flow:

- Extension of in-cylinder flow
  - Global flow of cylinder charge (swirl, tumble)
  - Local flow of cylinder charge (turbulence)
- Creation of in-cylinder flow
  - Inlet induced charge motion
  - Compression induced charge motion

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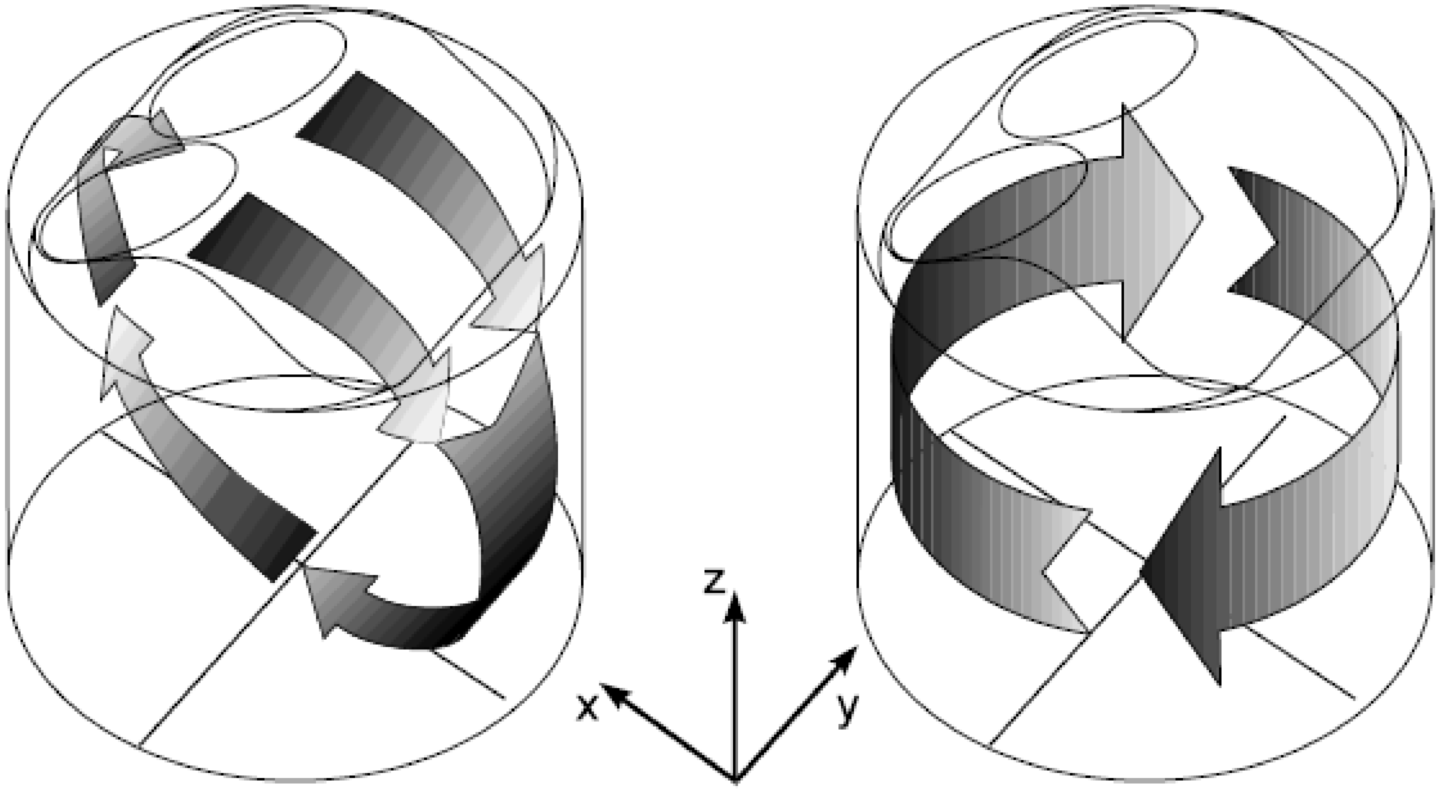
WP 2 – Global Formation of Charge Motion



Tumble Swirl

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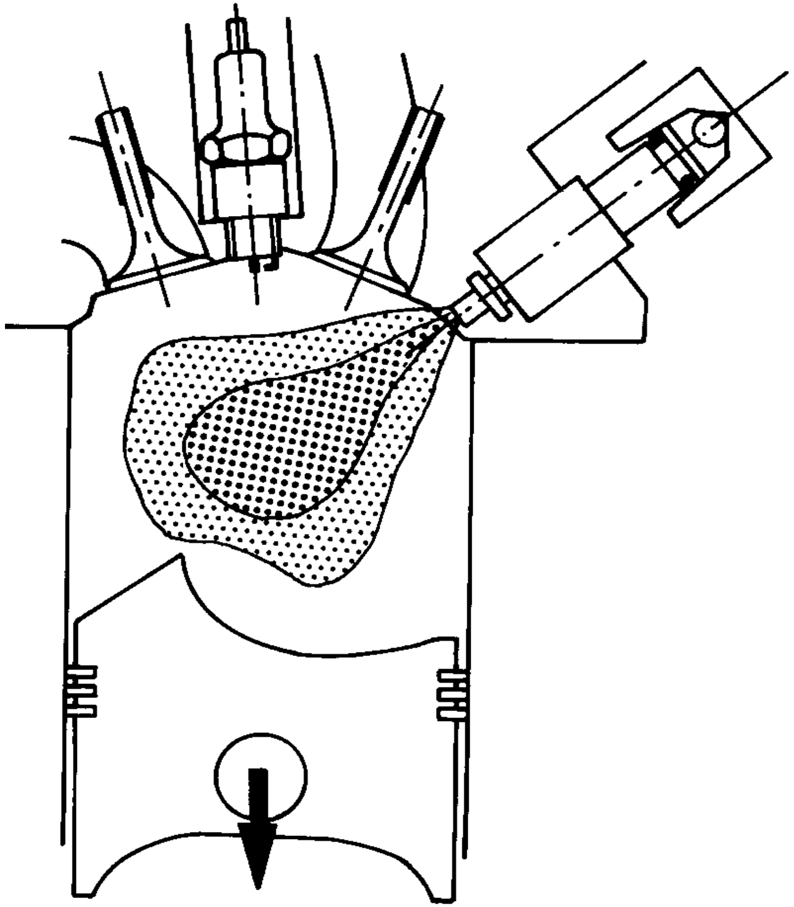
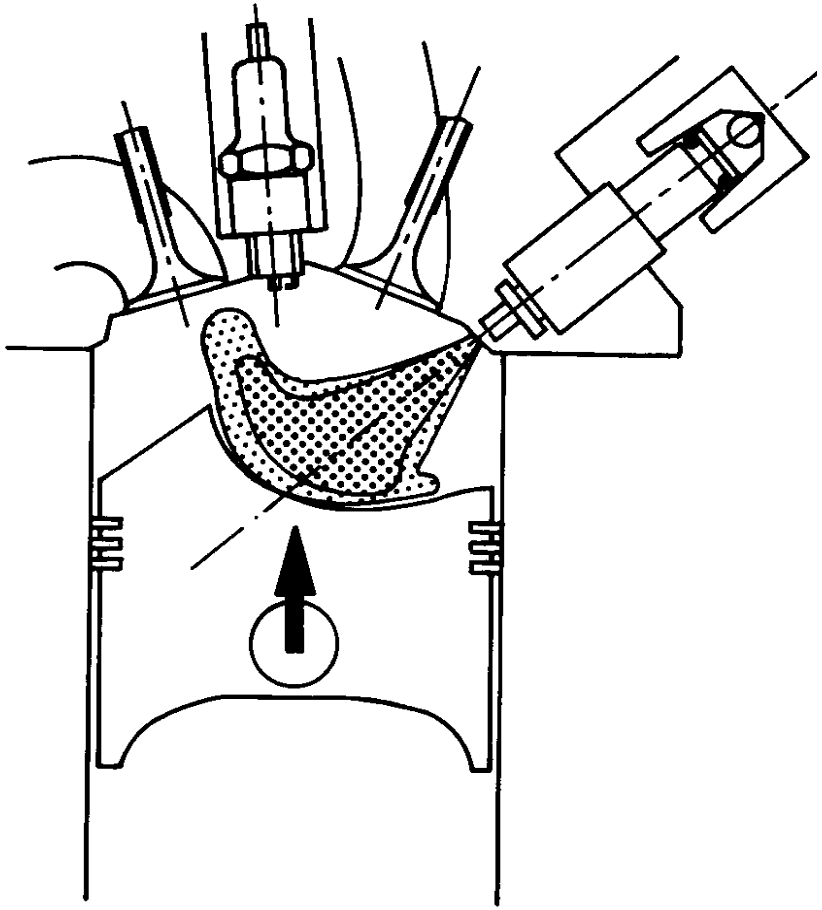
WP 2 – Direct Injection Base Concepts



Early Injection

Homogeneous operation



Late injection

Stratified load

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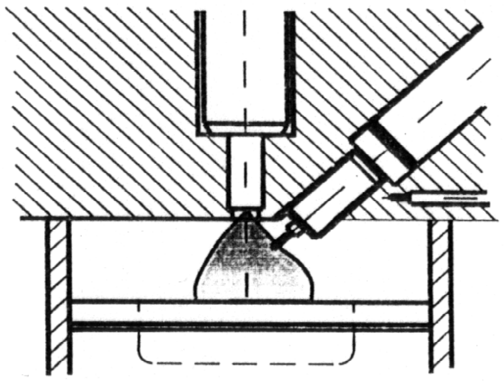
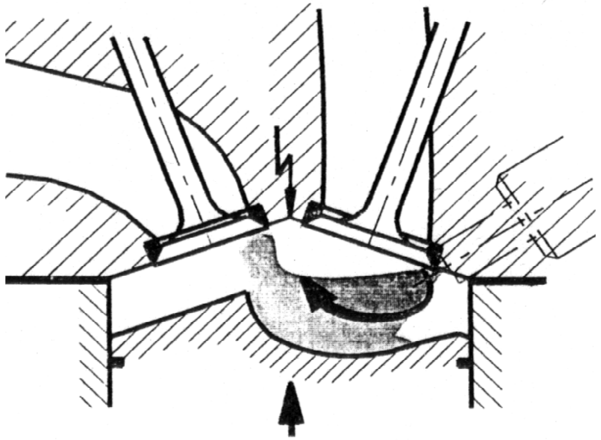
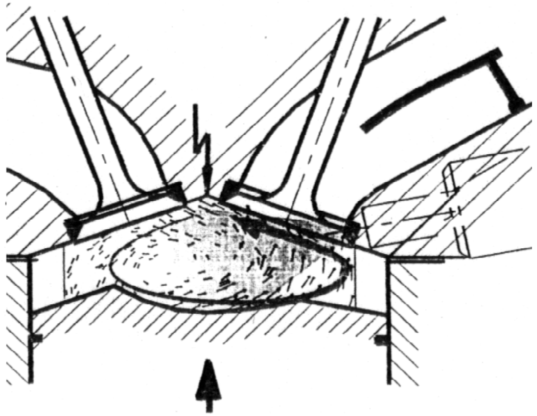
WP 2 – Classification of the DI-Process



Spray - guided



Wall – guided (Tumble)



Air – guided (Swirl)

- Charge movement of the wall and air controlled processes:

  Swirl around the cylinder axis

  Tumble around the cylinder longitudinal axis

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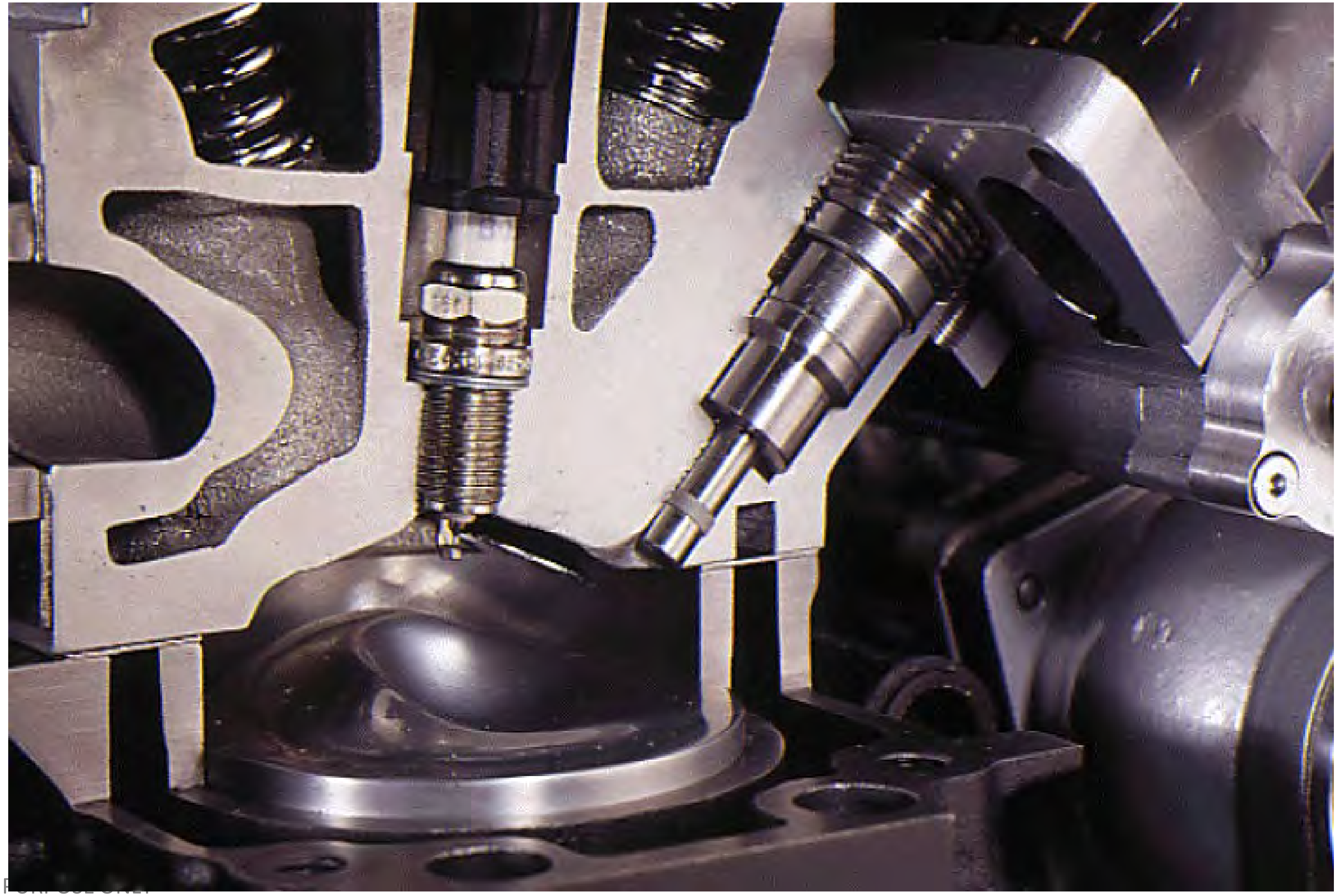
WP 2 – GDI Injection Nozzle, 1. Gen



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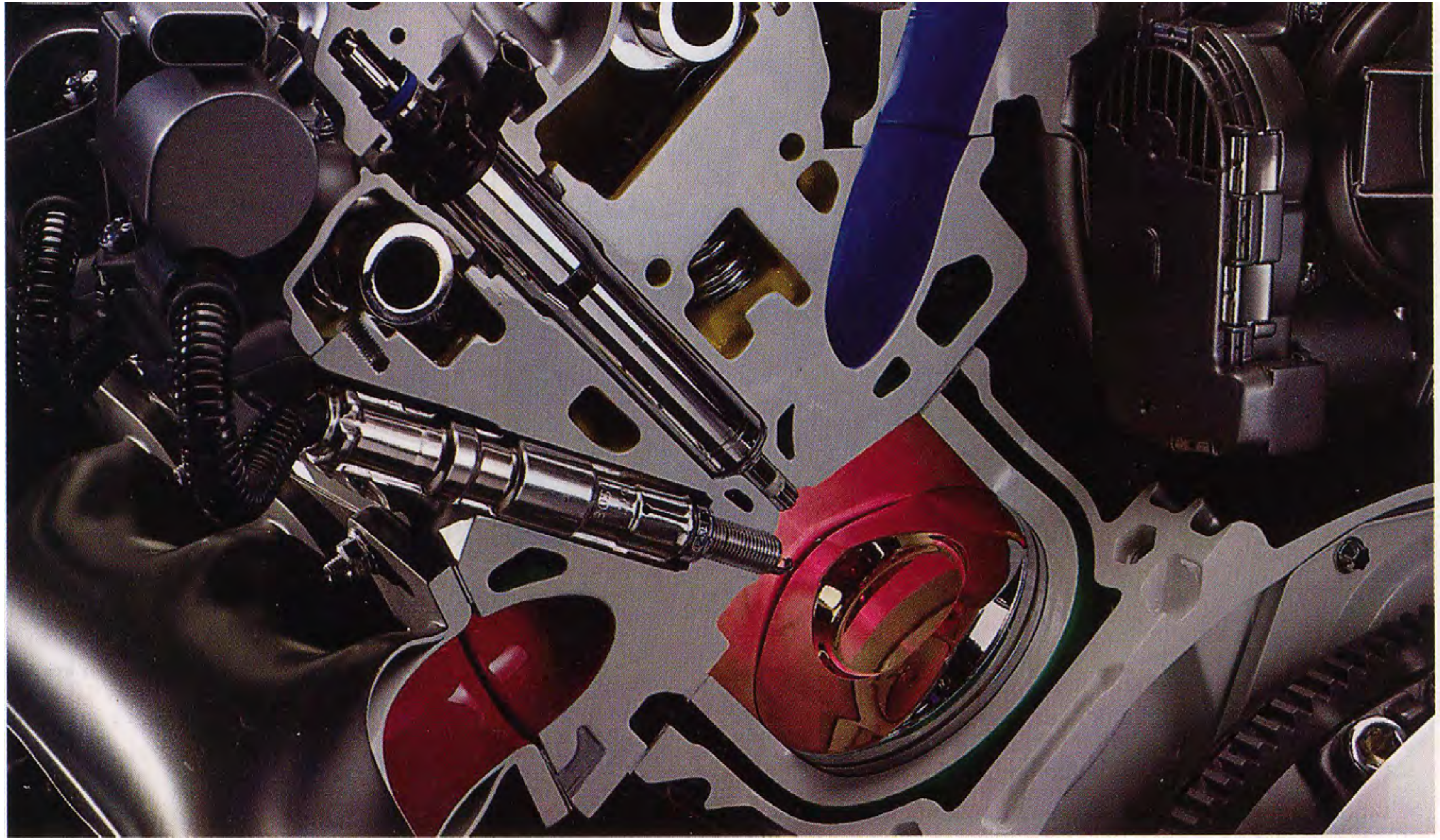
WP 2 – GDI Injection Nozzle, 2nd Gen



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WP 2 – GDI Injection Nozzle, 2nd Gen

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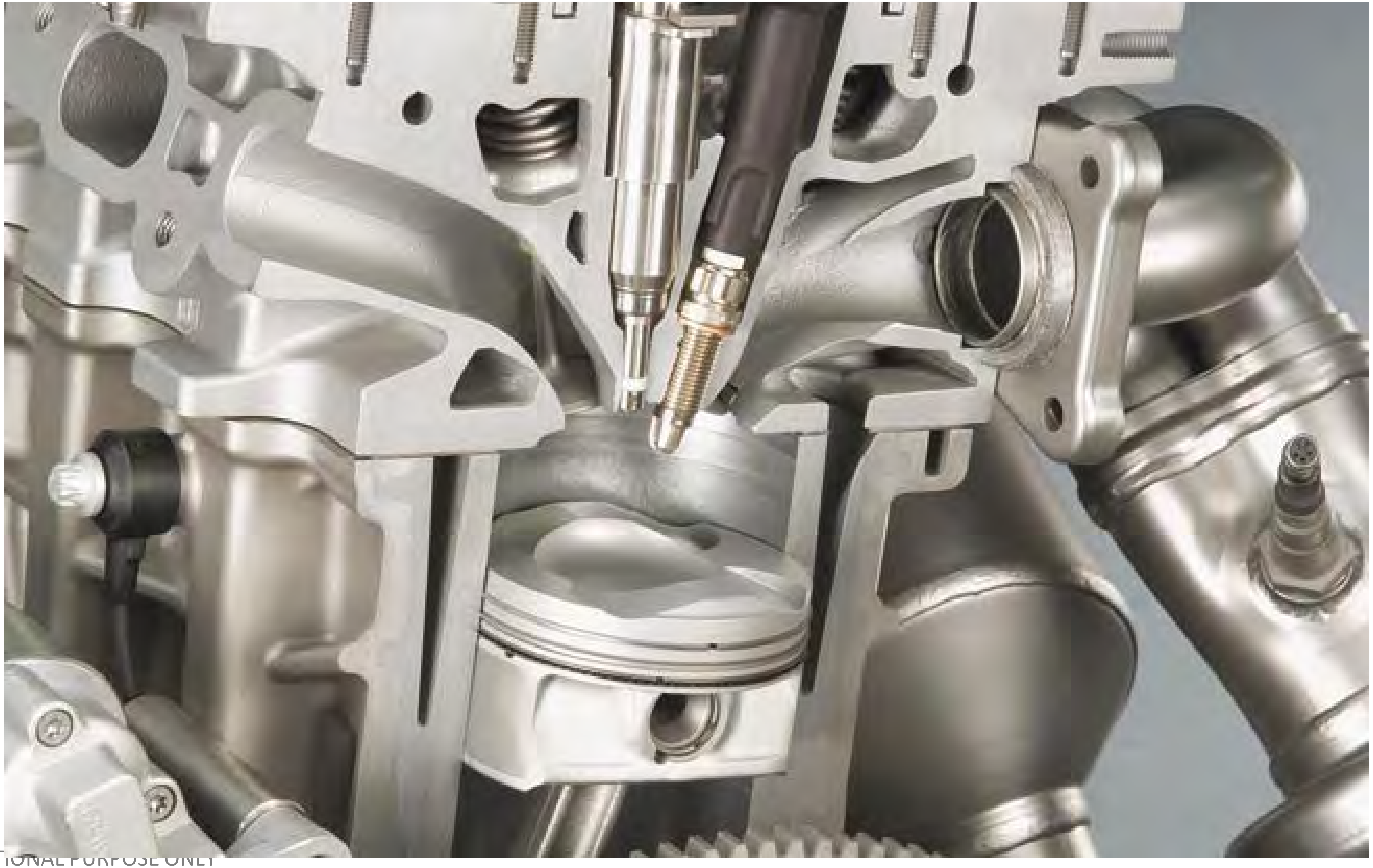

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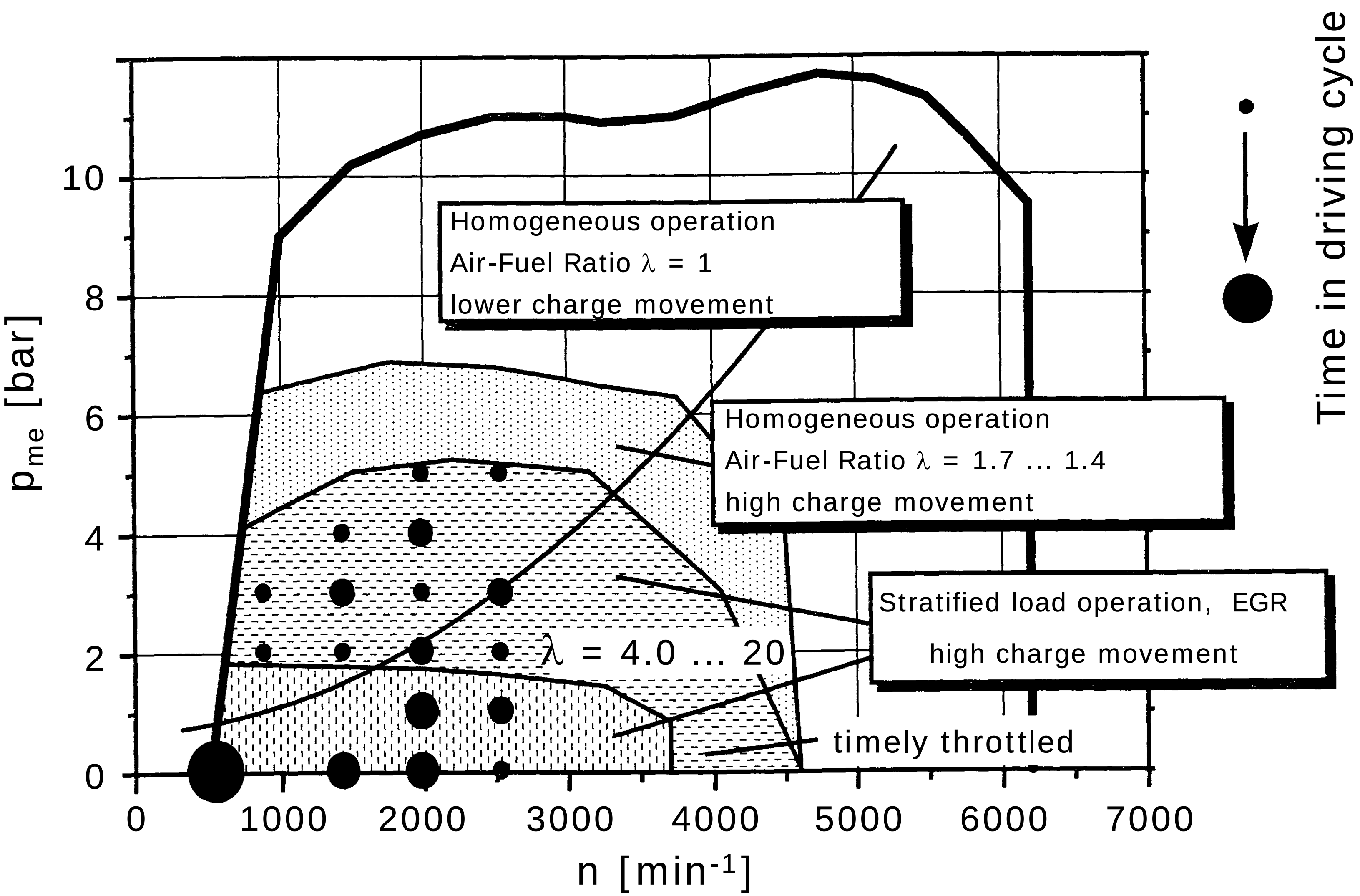
WP 2 – Operating Strategies for GDI



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WP 2 – GDI with Charge Stratification

- De-throttling of gas exchange
- Increase of compression ratio (equivalent anti-knocking properties) or higher full load torque due to internal cooling
- Thermodynamically more favorable gas composition
- Reduced heat loss through the wall in partial load operation through stratified combustion.
- Improved transient response due to the lack of wall-film problem
- Better qualitative control of the charge formation upto the beginning of combustion, using variation of injection beginning, injected quantity and ignition beginning
- Lowering of the idle speed and higher EGR rates possible

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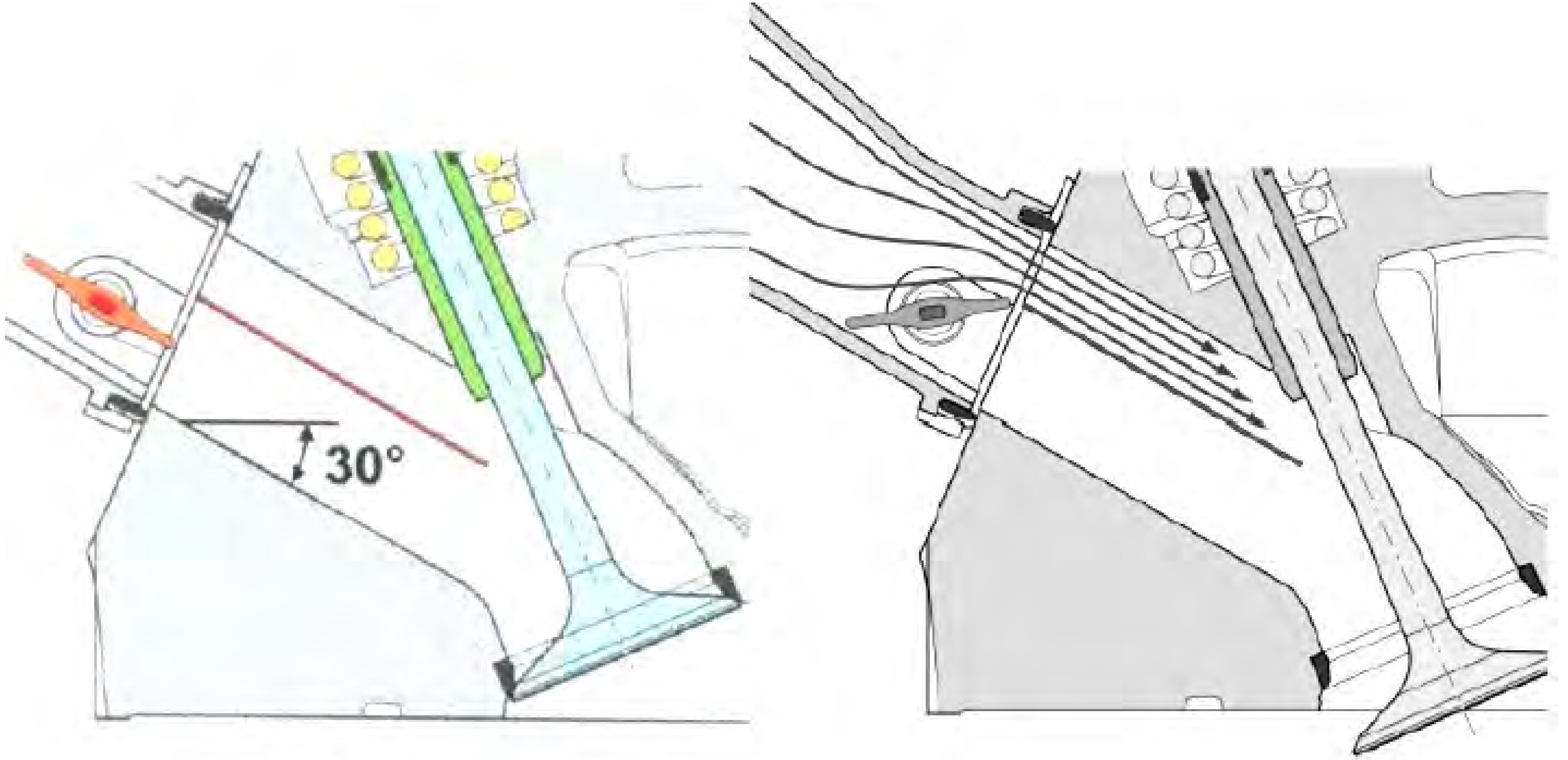
WP 2 – Control of Tumble



FSI Inlet port

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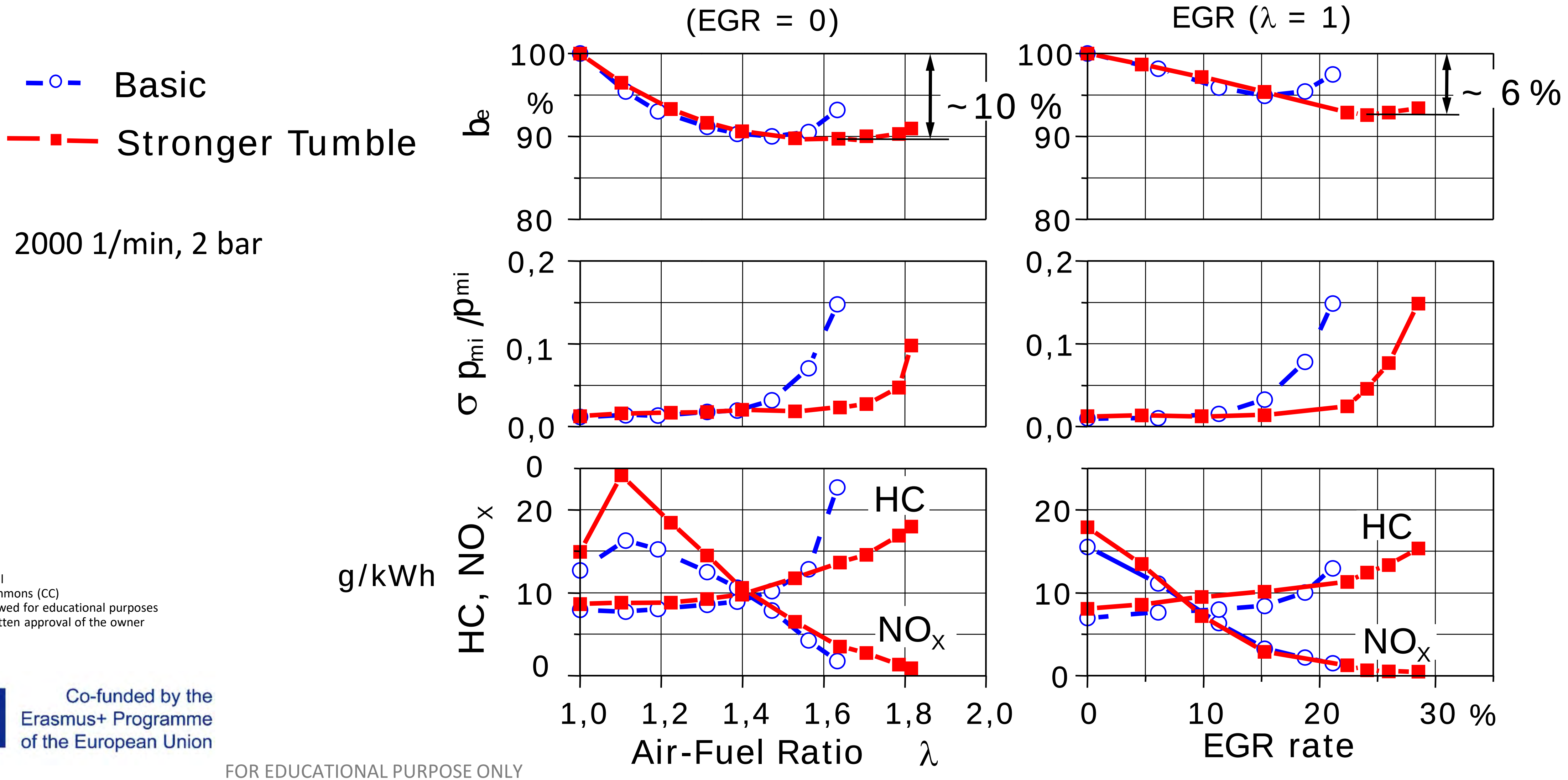
WP 2 – Effect of Increased Charge Motion (4V, be-opt)

2000 1/min, 2 bar



WP 2 – Training Overview

- Q&A, Discussion SLOT 2

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WP 2 – Malaka SLOT 2

- **ICE Gas Exchange** and future ICE technologies (15 minutes)

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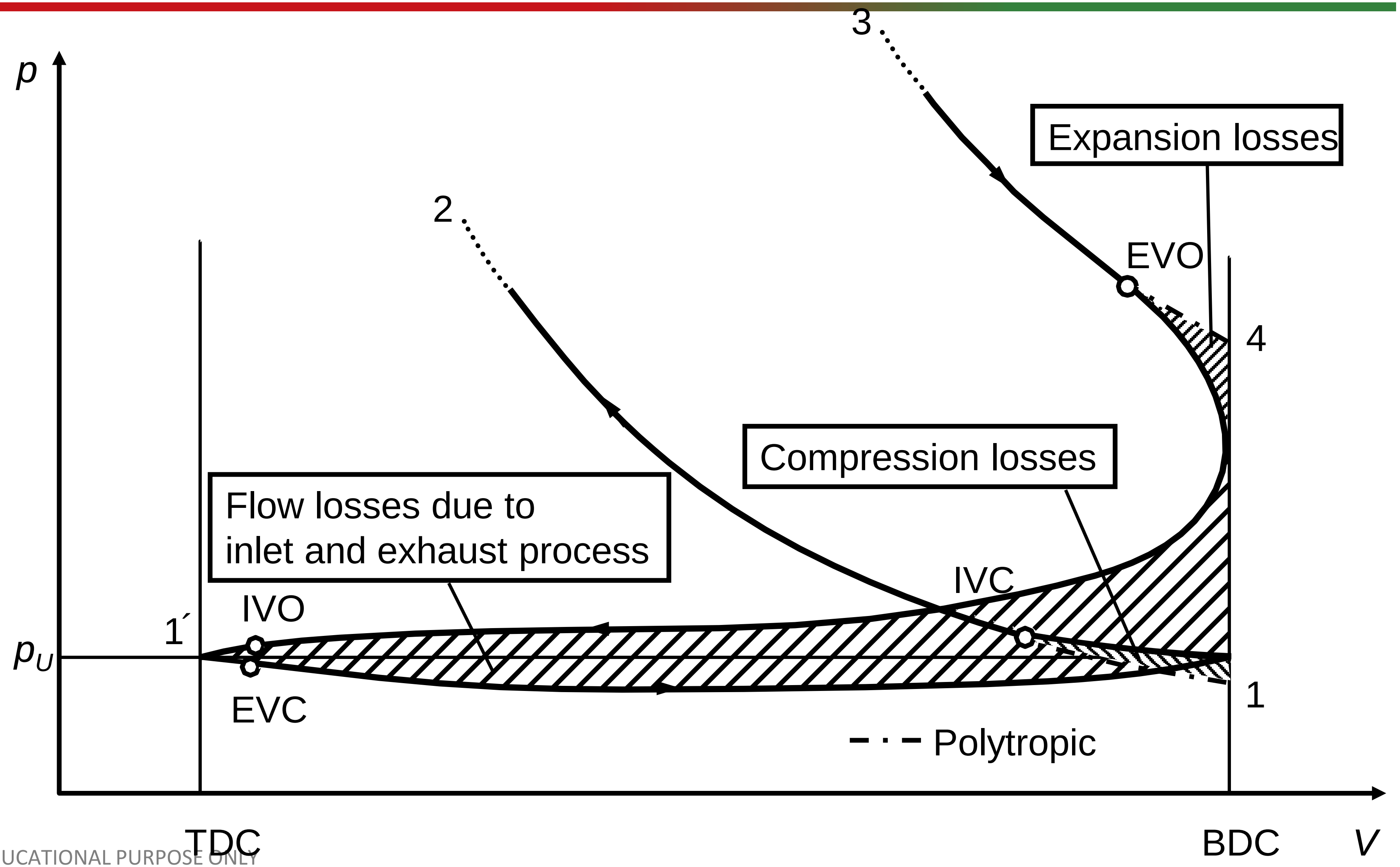
WP 2 – Gas Exchange Losses of 4-Stroke Engine



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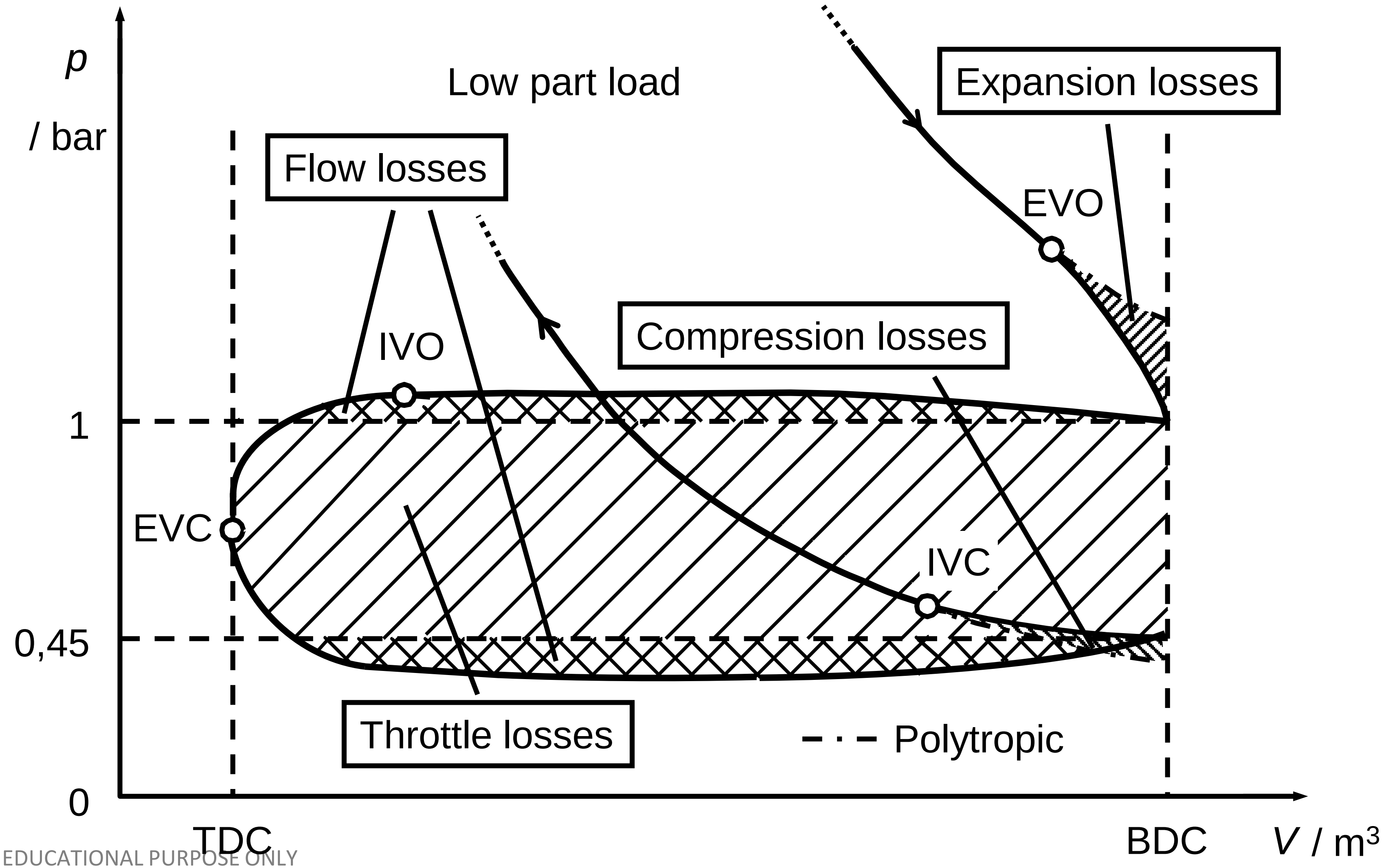
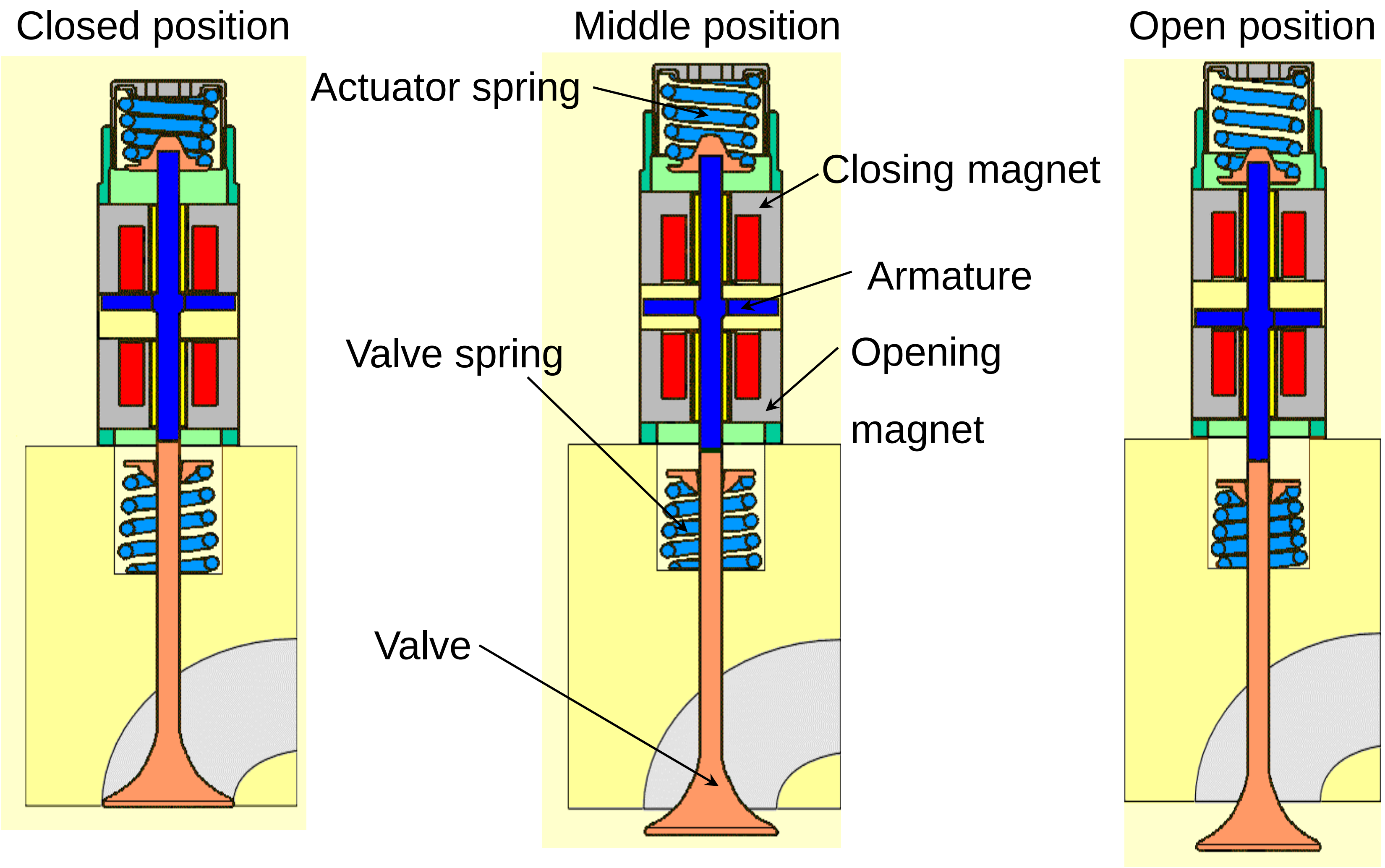
WP 2 – Gas Exchange Losses of 4-Stroke Engine



WP 2 – Working Principle of EMVT



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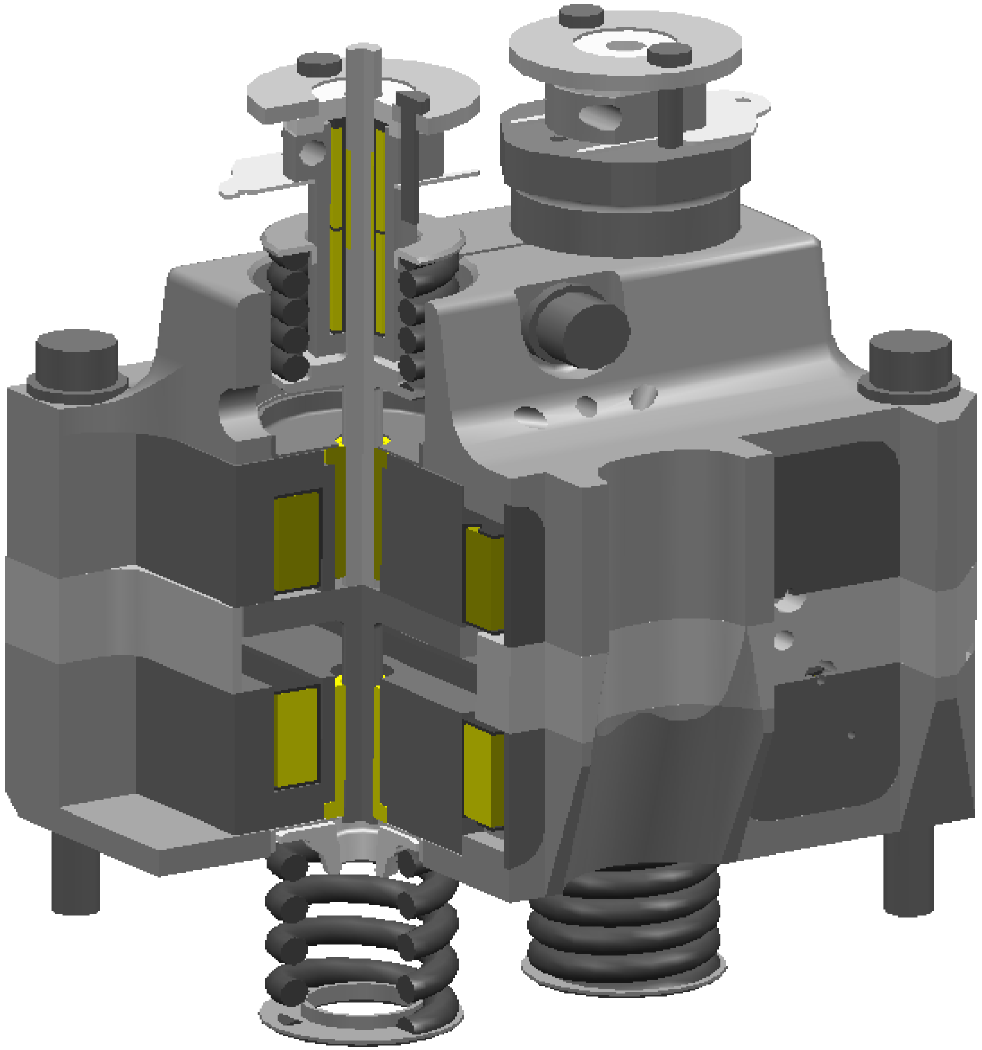
WP 2 – Design of EMVT Actuator



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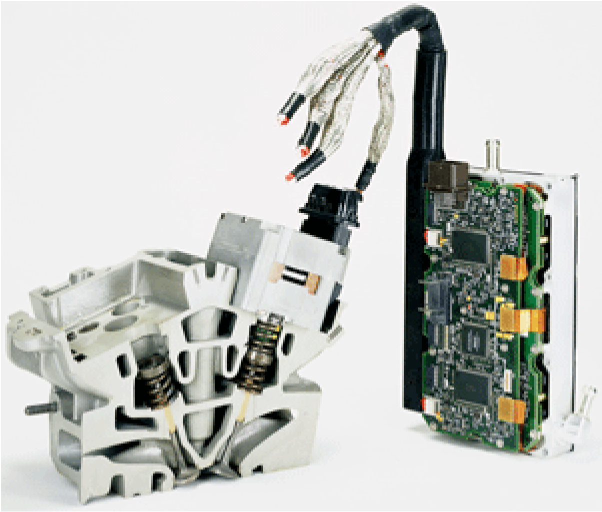
WP 2 – Design of EMVT Actuator with Sensor



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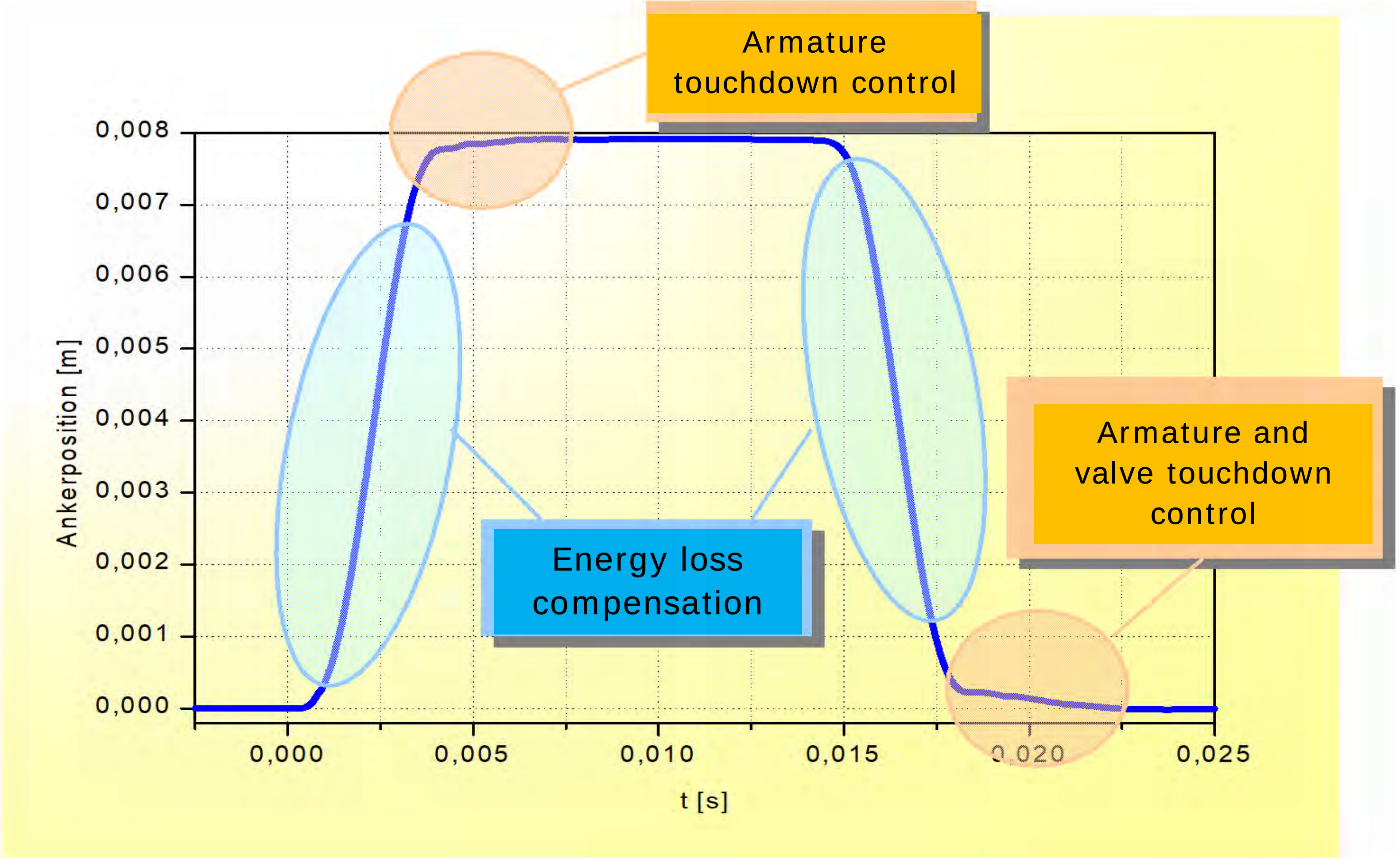
WP 2 – Valve Lift Curve of EMVT Actuator

Valve Open

Valve Closed



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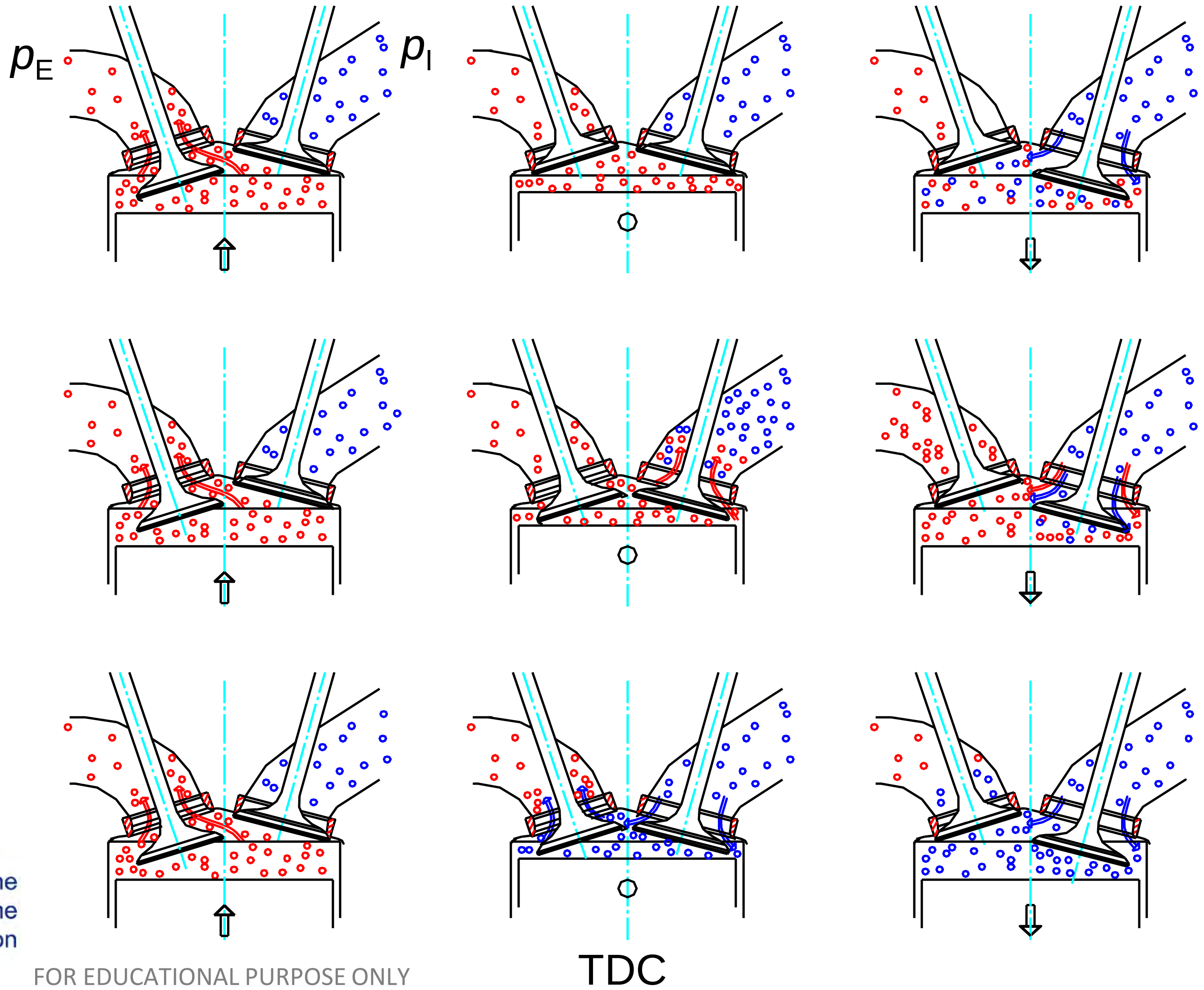
WP 2 – Residual Gas Control (Gas Exchange of 4-Stroke Petrol Engine)



Limit:
W/o valve overlap

With valve overlap
p_I < p_E (Part load)

With valve overlap
p_I > p_E or high speed
(Dynamic)

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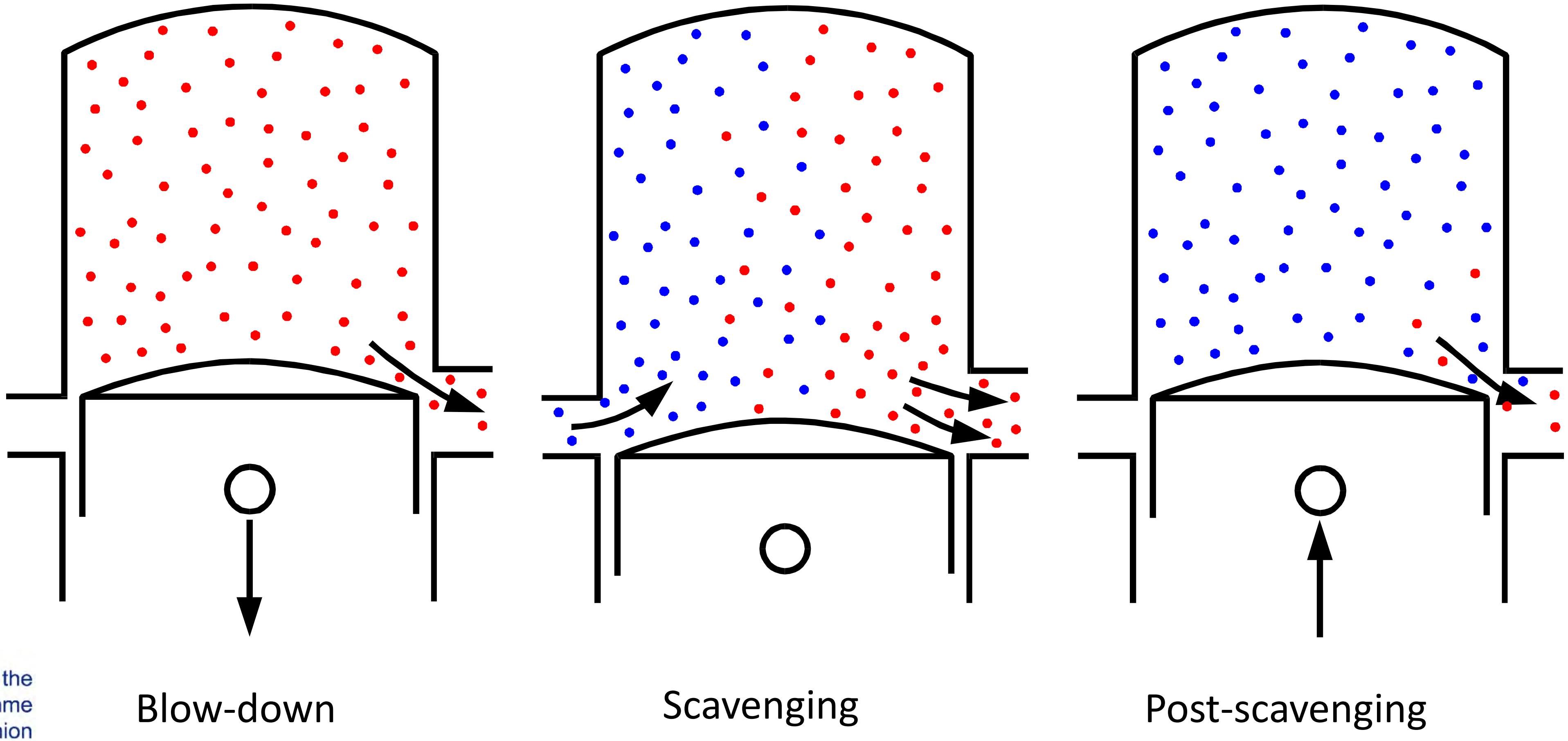
WP 2 – Gas Exchange for a 2-Stroke Engine



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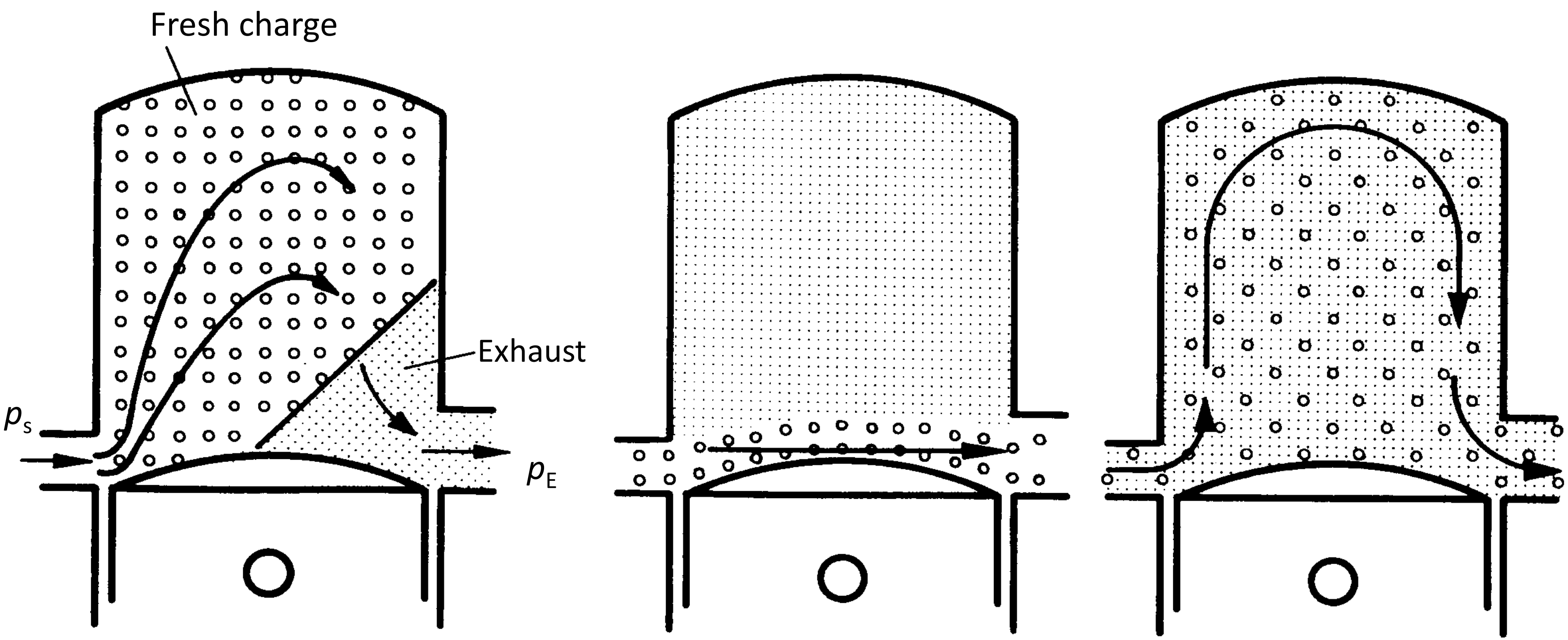
WP 2 – Scavenging Models (2-Stroke Engine)

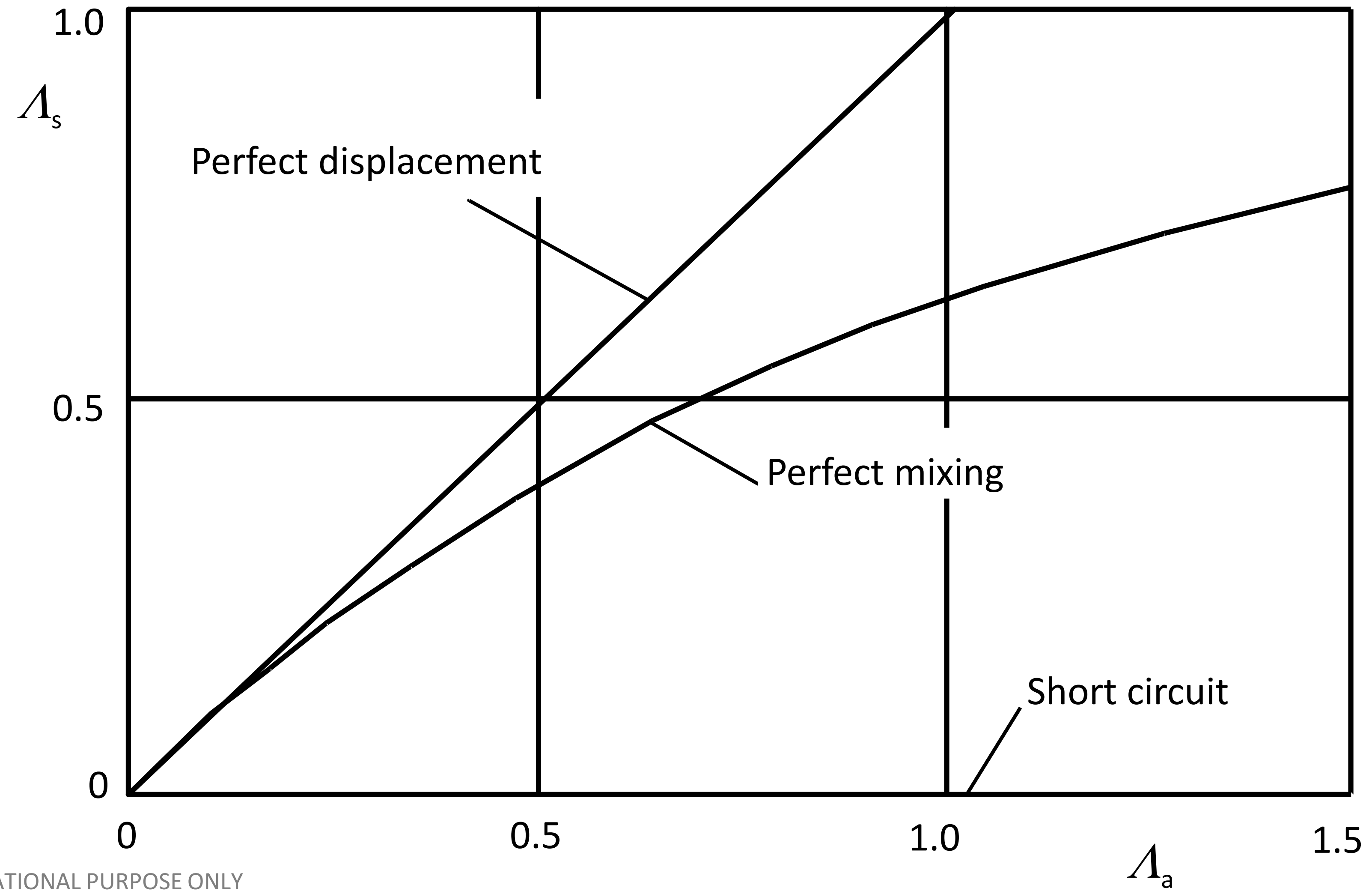


Perfect displacement scavenging

Short circuit scavenging

Perfect mixing scavenging

WP 2 – Scavenging Efficiency versus Volumetric Efficiency (Theoretical)



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WP 2 – Training Overview

- ICE Gas Exchange and **Future ICE Technologies for Higher Efficiencies** (15 minutes)

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WP 2 – Future ICE Technologies

- In gasoline engines, the combination of direct injection, downsizing and turbocharging has established itself in recent years as a technology that can be used worldwide to achieve the required reduction in fuel consumption.
- In addition to engine measures to reduce CO2 emissions, fuel is increasingly becoming the focus of development. Alternative biogenous fuels such as ethanol offer significant potential for reducing greenhouse gases as a blending component, provided they are provided by regenerative manufacturing processes. In addition, alcoholic fuels have a considerable efficiency potential in the combustion cycle due to their high resistance to knocking.

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WP 2 – Future ICE Technologies

- Approaches to increasing the efficiency of stoichiometric gasoline engines are external, cooled exhaust gas recirculation (EGR), variable valve train and extended expansion.
- Whereas in the past the focus of consumption measures was concentrated on the low load range (reduction of throttle losses), measures for extended expansion are increasingly targeting the high-load range.
- Miller or Atkinson cycles, where compression begins delayed from expansion due to a very early or very late intake close, are the most efficient approaches to extended expansion. Particularly in combination with correspondingly high geometric compression, the consumption potential of the Miller cycle in the upper load range can be significantly extended by external cooled EGR.

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WP 2 – Future ICE Technologies

- The progressive series introduction of "Rightsizing" and "Miller/Atkinson" concepts for gasoline engines, with effective efficiencies of 40-41% at their best, require the next logical development steps.
- Future development goals will focus on avoiding knocking combustion when increasing compression. With new ignition concepts (prechamber plug), combustion can be accelerated specifically in the direction of knock-critical areas, thus improving knock behaviour.
- However, the most efficient measure to avoid pre-ignition and knocking is to introduce the fuel only at the end of compression immediately before ignition. The local residence time of the fuel in knock-critical areas is too short to trigger pre-ignition or knocking.

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WP 2 – Future ICE Technologies

- However, the very late injection for the necessary preparation and distribution of the fuel requires extremely high injection pressures. With injection pressures > 800 bar (petrol engine) and very late (partial) injection (e.g. in OT) and corresponding system design, a sufficient treatment quality and homogenization can be achieved.
- Miller cycle: Early closing of the intake valve (FES, Miller) makes it possible to reduce peak temperatures and further dethrottling. In order to achieve high torque and performance data, however, higher demands are placed on the turbocharger, which is why exhaust gas turbochargers with variable turbine geometries have recently been used in series passenger car applications.

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WP 2 – Future ICE Technologies

- Supercharging concept (two-stage ATL, VTG-ATL): Two-stage compression with intercooling has the advantage of a lower final compression temperature, which means that a higher mean pressure can be achieved with the same control times or a stronger Miller design can be used with the same mean pressure. An exhaust gas turbocharger with variable turbine geometry (VTG-ATL) is a proven means of efficiently extending the power range of gasoline engines with Miller cycle.

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WP 2 – Future ICE Technologies

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- Increasing the geometric compression ratio (ε): By increasing the geometric compression ratio, the thermal efficiency ηth is increased, but this increases the knock and pre-flame tendency as well as the thermal load of the unit. This problem can be mitigated by the use of variable compression ratios. For example, the Multi-Link system enables a high ε=14 in the lower load ranges and a low ε=8 in the high load ranges.
- Increasing the geometric compression ratio (ε): By increasing the geometric compression ratio, the thermal efficiency ηth is increased, but this increases the knock and pre-flame tendency as well as the thermal load of the unit. This problem can be mitigated by the use of variable compression ratios. For example, the Multi-Link system enables a high ε=14 in the lower load ranges and a low ε=8 in the high load ranges.

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WP 2 – Future ICE Technologies

- Water injection: By using water injection, either thermal stress can be reduced, thereby improving the knock tendency, or the stoichiometric operating range can be extended further. It is also possible to further increase the geometric compression ratio. This is made possible by the high latent evaporation heat of the water, which lowers the temperatures in the combustion chamber.
- Charge dilution (exhaust gas recirculation): Advantages of cooled exhaust gas recirculation can be expected in terms of efficiency, reduction of throttle losses, increase in specific heat capacity and reduction of the tendency to knock. Thus a maximum approx. 42-43% effective efficiency is achieved at the best point.

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WP 2 – Future ICE Technologies

- By combining the Miller combustion process with cooled exhaust gas recirculation, a specific fuel consumption of 200 g/kWh can be achieved for a turbocharged, direct-injection petrol engine. This corresponds to an effective efficiency of 42.3% (assumption: lower calorific value Hu 42.5 MJ/kg).
- Combustion process, reduction of burning time: A further reduction in consumption can be achieved by increasing the intensity of charge movement within the engine. In gasoline engines, this is achieved by increasing the tumble intensity, which reduces the burning time and thus brings the combustion process closer to the ideal process.

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WP 2 – Future ICE Technologies

- Exhaust gas heat recovery (reforming): By recovering the exhaust gas heat, it is possible to further increase the thermal efficiency of gasoline engines. By integrating a reformer into the exhaust gas recirculation section and by means of an endothermically controlled process, fuel is split up and the calorific value of the synthesis gas produced increased.

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WP 2 – Training Overview

- Q&A, Discussion SLOT 2

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WP 2 – Training Overview

- **Mobility engineer 2030 (academia)** (20 minutes)

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WP 2 – Mobility Engineer for 2030

- How Automotive is changing?
- The four disruptions in Automotive industry!
- Redefinition of automobiles
- Attributes of a modern automotive mobility device
- Fundamantal questions from Automotive industry!
- The three demands from Automotive industry!

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WP 2 – Statement

With

connectivity, autonomy, propulsion, safety and security

now as important to the next phase of our industry development as the traditional mechanical and electrical engineering disciplines have been to previous generations,

it is clear

that how industry and academia engage is critical to the process of creating and sustaining sufficiently capable and ‘workplace ready’ engineers.

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WP 2 – How Automotive is Changing?

UNITED

- Current developments in mobility engineering are increasingly very volatile.
- Many things happen simultaneously and it is crucial to maintain the overview.
- In this section I would like to offer three independent inputs that might be able to provide some insight.
  - ✓ Four disruptions
  - ✓ Redefinition of automobiles
  - ✓ Attributes of a modern mobility device
- There is no aim to provide a complete picture, however, a discussion about future education of engineers does require a vision about the future technology demand.

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WP 2 – The 4 Disruptions in Automotive

The four disruptions are:

1. Electric traction: eco-system including non-automotive infrastructure. This includes renewable energies and smart grids.
2. Automated driving: robotization with high level of safety/security. This includes artificial intelligence, machine learning and formal methods to provide the required level of safety.
3. Connected cars: eco-system with telco technologies and business model. This includes standardization of protocols, bandwidth, cybersecurity, etc.
4. Mobility on demand: new services with partnership with public authorities (city, etc...). Access versus ownership, new business models, diverse partnerships.

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WP 2 – Redefinition of Automobiles

UNITED

Automotive Industrial Pattern in the Future:

- Multipartite participation and cooperative competition.
- In case of such changes, the automotive industry has transformed from the original vertical industrial chain composed of OEMs, suppliers and dealers into an ecosystem without border with multipartite participation, bringing huge opportunities.

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WP 2 – Attributes of a Modern Mobility Device

- Mechanics: Highly optimized construction, weight and cost-effective. Complexity management to cover various demands, e.g. powertrain, body style or level of equipment. Mix of high- and low-volume manufacturing techniques, including personalization (Industry 4.0).
- Electrics and Electronics (including automated driving): Increasing proportion in the value chain. Short development cycles and x-industry innovations. Increasing number of interfaces and industrial standards. New players entering the automotive domain.
- Software (including V2X and automated driving): Increasing proportion in the value chain. Many interfaces and strategic alliances. Sophisticated algorithms, e.g. AI, machine learning, sensor fusion, model-based controls. Substantial effort on quality engineering.
- Device and Environment (including business models): Mixed modal transportation. Access vs. ownership. Total customer experience vs. vehicle performance. Smart vehicles for a smart world.

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WP 2 – Fundamental Questions from Industry

Two fundamental questions from industry:

1. What type of engineers will your organization need in the future?
2. What are the future industry requirements in terms of engineering expertise, skills and abilities?

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WP 2 – Fundamental Questions from Industry

Their collated response can be summarized as:

1. The engineering landscape in the automotive industry will broaden in scope – in addition to mechanical engineers, companies will be in significantly greater need of engineers from IT and associated 'new technology' disciplines.
2. Besides specialists, the industry will require generalists with capability across different engineering disciplines that link the various engineering fields, and engineering collaboration across multiple disciplines will become critical success factors for engineering in the future.
3. In parallel, the skillset of engineers will expand from predominantly technical requirements to more process-related skills, such as agile project management, communication skills, operating in virtual environments, and flexible organizations will become important competencies in the engineering role profile.

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WP 2 – The Demands from Industry

The demands of industry:

- Technical and interdisciplinary skill requirements
- Project, process management and soft skills requirements
- New paradigms

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WP 2 – Technical and Interdisciplinary Skill Requirements (1)

- Feedback from industry shows that traditional science, technology, engineering and mathematics (STEM) skills will remain an important part of the skills mix.
- Respondents unanimously confirmed that the ‘classical’ automotive engineer with profound knowledge in mechanical engineering, mechatronics and materials will still be necessary.
- However, in the context of electrified, connected, autonomous and shared mobility, the qualification profile of a ‘universal’ engineer with a deeper understanding of other engineering disciplines will gain increasing importance.

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WP 2 – Technical and Interdisciplinary Skill Requirements (2)

- Several respondents prioritized systems engineering and the increasing complexity of vehicles as crucial in engineering discipline terms, and already becoming a significantly important area.
- Industry experts see simulation, virtual testing, virtual prototyping and virtual reality as areas with disruptive potential in the automotive engineering process.
- A rapid increase in model-based development, hand-in-hand with the ability to transfer simulation results into reality, is seen as essential to developing advanced products rapidly.

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WP 2 – Technical and Interdisciplinary Skill Requirements (3)

- The evolution of Industry 4.0 (automation and data exchange in manufacturing technologies) and the growing availability of big data, enabling the development of predictive models, are challenging the automotive engineering community to establish competencies in gathering, analysing and working with the large volumes of data being generated by machines and processes.
- Engineers who understand and think in process-terms, rather than silo specialists, are required to meet this challenge.
- It is therefore suggested that a new engineering species of 'data scientists' who are experts in analyzing complex data, will collaborate with process experts to quickly make reliable predictions.

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WP 2 – Technical and Interdisciplinary Skill Requirements (4)

- In view of the increasing role of simulation and the trend towards remote engineering, industry contributors also highlight a growing need for expertise in ‘manufacturability’.
- The ability to recognize key factors that impact the manufacturing process very early in the design process is and will continue to be an important asset for engineers, as development cycles get shorter and products become increasingly complex.
- In this context, detailed knowledge of the appropriate manufacturing processes, techniques and tools will be crucial.

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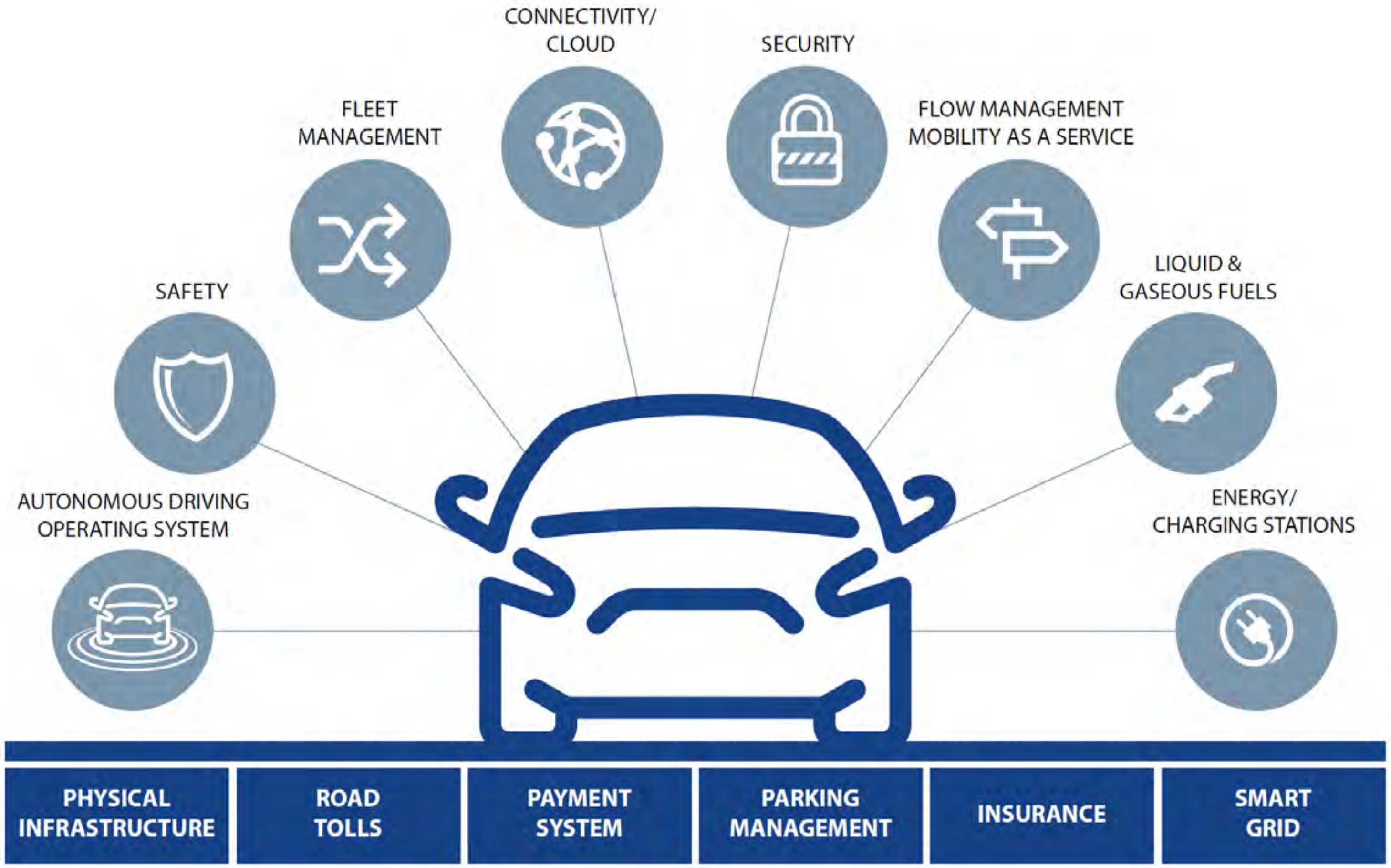
WP 2 – Technical and Interdisciplinary Skill Requirements (5)

The surrounding environment of the future automotive/mobility industry



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WP 2 – Project, Process Management and Soft Skill Requirements (1)

UNITED

- As the car evolves and incorporates more consumer electronics devices with a development emphasis on in-car experiences, traditional engineers must actually also deliver other ‘non-engineering’ capabilities, such as knowledge in market and societal trends, in user experience and human factors.
- With technology evolving faster and faster, companies stress the need for visionary thinking and an out-of-the-box attitude to find innovative and creative solutions quickly.
- In the evermore connected global environment, work-sharing within worldwide R&D networks is required, with companies expecting engineers to have strong project management skills and the flexibility to work in different locations on different projects.

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WP 2 – Project, Process Management and Soft Skill Requirements (2)

UNITED

- In this context, communication skills are considered an increasingly important requirement.
- For example, engineers require presentation skills in virtual environments for collaborative team-working, project reviews, reporting and other virtual and actual team-based activities.
- Engineers also require an increasing capability of co-designing in virtual team environments, while collaborating with colleagues in remote locations.
- Soft skills, such as social/cultural competences, an appreciation of diversity, and language skills, will all support a successful engineer of the future.

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WP 2 – Project, Process Management and Soft Skill Requirements (3)

- In the future, engineers will work in even more agile and cross-functional environments than today, meaning companies will increasingly value open-mindedness and a curiosity for new ways of collaborating in new organizational structures and new team-based working models.
- Working in so-called ‘swarm organizations’ is likely to become part of the daily routine, a new style of work discipline which is considered to be an important and progressive management skill.

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WP 2 – Project, Process Management and Soft Skill Requirements (4)

- Broader, interdisciplinary knowhow and flexibility are seen as key ingredients of the future engineers’ skill set.
- The ‘ideal’ engineer will be able to adopt new knowledge and understand new technologies quickly and be able to develop non-standard solutions.
- In the context of fast changes in technology, legal and regulatory requirements, emission laws, differing customers and needs, combined with international social trends and complexities, engineers need to be capable of collaborating with multiple groups of colleagues of differing engineering disciplines, and working in cross-functional teams, while applying virtual tools across different working locations.

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WP 2 – New Paradigms

- Mobility engineering, more than many other professions, exists in a state of flux between traditional and understood forms of engineering and those that are yet to be fully established in a changing environment.
- Specialist versus generalist, mechanics versus electronics, hardware versus software, disruption versus refinement, complexity versus simplicity, exclusivity versus mass production, manual versus automated, to reference just a few factors.
- As a result, potential students could experience a complex and challenging environment.
- This is understandable and therefore short-term delivery of clarity and an achievable and attractive curriculum is important. However, the academic community should consider two paradigm shifts to prepare students for a career in mobility engineering:

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WP 2 – Paradigm 1

Paradigm 1:

It becomes questionable whether it is achievable to attempt to teach the most important subjects associated with ‘mobility’ in one single curriculum.

While there may be opportunity to educate a generalist with shallow knowledge in the relevant areas, it would be challenging to reach the levels of knowledge required for competitive R&D experts in mechanical, electrical and software engineering in one single education, as experts will be needed to operate to high standards of competency in many different disciplines.

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WP 2 – Paradigm 2

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Paradigm 2:

The concept of university education preparing engineers for many years of success in their profession is becoming challenged. Engineers who were educated in the 1980s and 1990s will not have the knowledgebase to deliver against future mobility engineering requirements, without some form of further personal development. Therefore, the same will be true of today's engineers in 2030 and beyond.

There is no reason to believe that any education can last long enough to carry someone through their entire professional life, **continued professional development** is key to the continued technical relevance of a career-long engineer. An investment in 'career learning' would be a positive approach for all engineering foundations that need to be laid at university.

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WP 2 – The Amsterdam Approach

The Amsterdam community has now definitively put the Action Plan for Clean Air, which was presented in May 2019. The aim is that, by 2030, there will no longer be any transport in the city area based on fossil fuels.

Regulatory procedure for the city area:
2020 driving ban for all vehicles worse Euro 4
2022 local buses and travel buses must have local emissions free drivetrains
2022 driving ban for all heavy duty vehicles worse Euro 6
2025 driving ban for commercial traffic (taxes, delivery traffic, craftsmen, freight) with fossil energy carriers
2025 driving ban of two-wheelers with combustion engines
2025 urban ferries must be free of emissions
2025 prohibition of round trip boats and leisure boats with fossil energy sources
2030 prohibition of private vehicles with fossil energy sources

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WP 2 – Training Overview

- Q&A, Discussion SLOT 2

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WP 2 - Combustion Remains an Essential Part of Mobility

UNITED

- Combustion engines will continue to be used in the future. There is still a very high potential in efficiency increase for e.g. VCR, CAI, VVT, HPI
- The extent to which synthetic fuels and e-fuels can contribute to emission-free propulsion will be discussed along the trainings.
- Even if parallel developments take place, I see no synthetic fuels on the market for the next five years.
- Compared to the pure battery vehicle, these synthetic fuels are actually clearly disadvantaged in terms of efficiency and costs.
- There has been no alternative to internal combustion engines in commercial vehicles, shipping or the aircraft sector, for example. A sustainable mobility of the future must rely on life cycle analysis for an integrated, joint solution.

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WP 2 - Combustion Remains an Essential Part of Mobility

- The main aim is to present cost-benefit calculations for different drive types in an electricity-based energy world in 2050 on the basis of various scenarios.
- Compared to fuel cell vehicles and vehicles powered by synthetic fuels with combustion engines, the BEV is very efficient.
- However, there is also a disadvantage: on the one hand, a very expensive infrastructure required to buffer the energy (hydrogen), and on the other hand, very high vehicle costs (battery).
- "The cost risk for BEV and Fuel Cell is extremely high“.
- The fixation on electric cars is therefore not a panacea
- **“Combustion remains an essential part of mobility."**

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WP 2 – Training Overview

- **Southeast Asia Discovers Electro Mobility** (20 minutes)

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WP 2 – Southeast Asia Discovers Electro Mobility

- Electromobility is now also an issue in the countries of Southeast Asia (ASEAN).
- While the focus in the past was primarily on China in the area of e-mobility, the up-and-coming ASEAN states are now increasingly moving into the focus of the German automotive industry.

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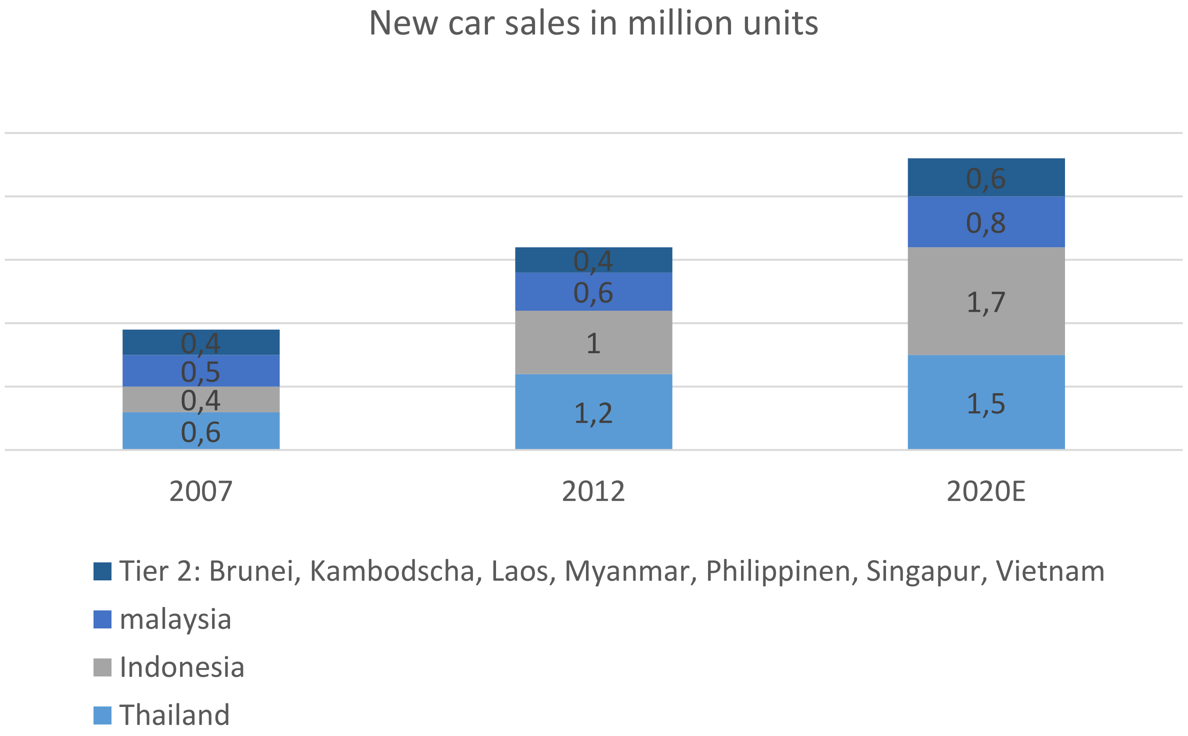
WP 2 – Southeast Asia Discovers Electro Mobility

The global automotive market is growing and will shift from the BRICS (Brasil, Russia, India, China and South Africa) countries, the USA and Europe, to the so-called "Beyond BRICS" countries, which include the ASEAN countries (Thailand, Indonesia, Malaysia, etc.).



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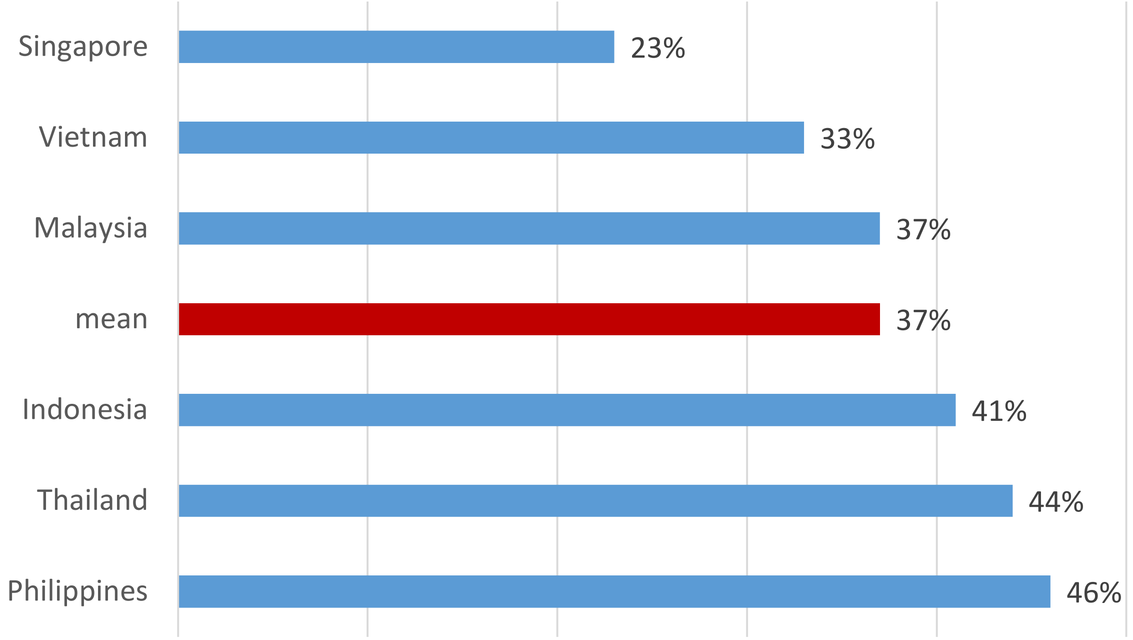
WP 2 – Southeast Asia Discovers Electro Mobility

More than one in three people in the Asean region would be willing to buy a battery-powered car, as the graph from the report The Asean states dare to use electric mobility. The respondents in the Philippines, Thailand and Indonesia show the greatest interest.



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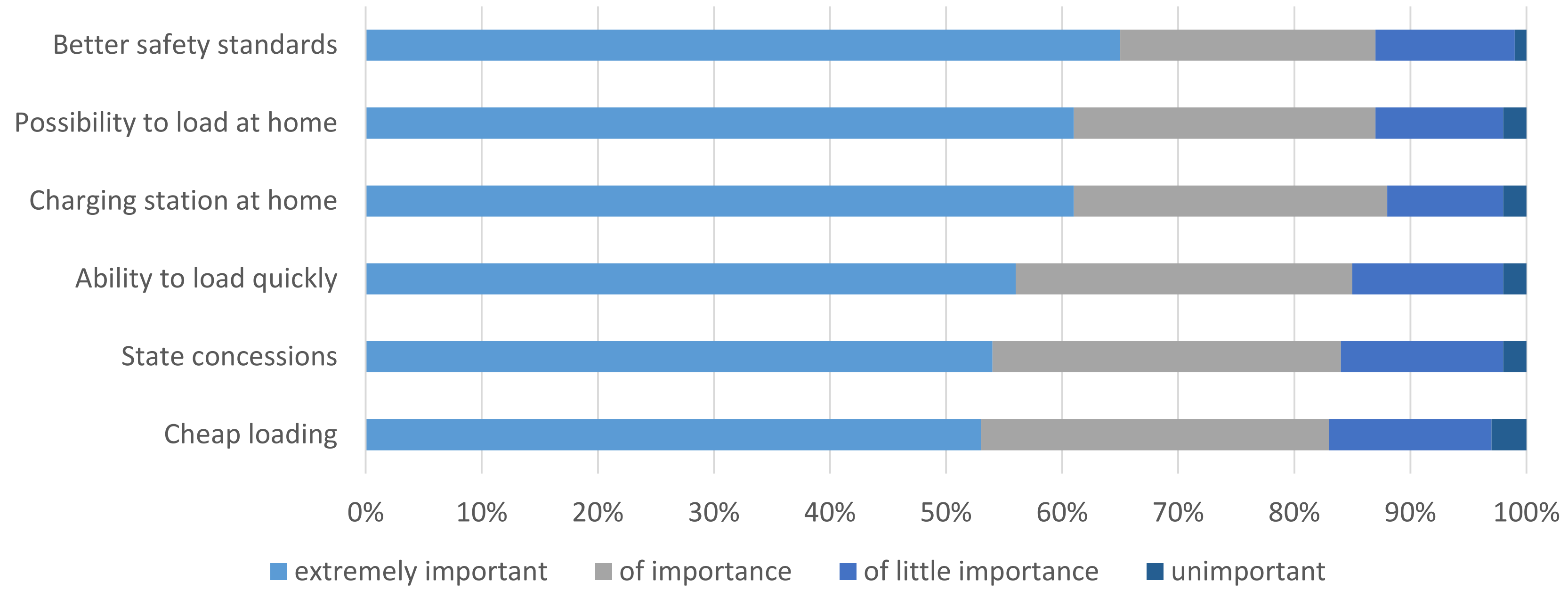
WP 2 - Southeast Asia Discovers Electro Mobility

Contrary to popular belief that the high cost of buying an electric car is an obstacle, the chart shows that safety and charging concerns are highly valued by customers. In fact, ASEAN customers are willing to pay up to 50 percent more for an electric vehicle than for a conventional car.



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UNITED

Engineering Knowledge Transfer Units to Increase Student´s Employability and Regional Development

https://www.facebook.com/unitederasmus/

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Engineering Knowledge Transfer Units to Increase Student´s Employability and Regional Development

Module 2: From ICE to Alternative Powertrain

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About city of Turin

- Located in North Italy, Near the Alps, Region of Piedmont
- 880 000 inhabitants
- Turin based automotive companies:
  - Abarth
  - **FCA**
  - Gruppo Bertone
  - GM Global Propulsion Systems
  - Italdesign Giugiaro
  - Iveco
  - New Holland Agriculture
  - Pininfarina

Mole Antonelliana

Source: Wikipedia

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About Politecnico di Torino

The Regio Politecnico di Torino (Royal Turin Polytechnic) was founded as institution in 1906, but its origins go back further. It was preceded by the Scuola di Applicazione per gli Ingegneri (Technical School for Engineers) founded in 1859

Students (A.Y. 2017/2018)

35,000 students enrolled in Bachelor's and Master's degree programmes

684 PhD candidates - A.Y. 2018/2019

68% students from outside Piedmont (52% italians from outside Piedmont, 16% foreigners)

Graduates 2018

6,691 graduates

3,495 Bachelor's degree graduates - *Average age: 23.7*

3,196 Master's degree graduates - *Average age: 26.2*

Employment rate of Master's graduates one year after graduation (Almalaurea 2019): 88,6% (Italian average 73%)

Course catalogue (A.Y. 2018/2019)

22 Bachelor's degree programmes (3 in Architecture and 19 in Engineering)

28 Master's degree programmes (5 in Architecture and 23 in Engineering)

16 PhD programmes

Automotive engineering only:

567 BS students

434 MS students

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Discovering the University

Mirafiori

Turin Polytechnic University in Tashkent

Main campus

Verres campus

Castello di Valentino
UNESCO World Heritage

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About Politecnico: Departments

- **11 Departments:**
  - DAD - Department of Architecture and Design
  - DAUIN - Department of Control and Computer Engineering
  - **DENERG - Department of Energy**
  - DET - Department of Electronics and Telecommunications
  - DIATI - Department of Environment, Land and Infrastructure Engineering
  - DIGEP - Department of Management and Production Engineering
  - **DIMEAS - Department of Mechanical and Aerospace Engineering**
  - DISAT - Department of Applied Science and Technology
  - DISEG - Department of Structural, Geotechnical and Building Engineering
  - DISMA - Department of Mathematical Sciences
  - DIST - Interuniversity Department of Regional and Urban Studies and Planning

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About Politecnico Interdepartmental Centers

- **CARS@PoliTO - Center for Automotive Research and Sustainable Mobility**
- CWC - CleanWaterCenter@PoliTo
- Ec-L - Energy Center Lab
- FULL - Future Urban Legacy Lab
- IAM@PoliTo - Integrated Addtive Manufacturing
- J-Tech@PoliTo
- **PEIC - Power Electronics Innovation Center**
- PhotoNext - PoliTO Interdepartmental Centre for Applied Photonics
- **PIC4SeR - PoliTO Interdepartmental Centre for Service Robotics**
- PolitoBIOMed Lab - Biomedical Engineering Lab
- R3C - Responsible Risk Resilience Centre
- SISCON - Safety of Infrastructures and Constructions
- SmartData@PoliTO - Big Data and Data Science Laboratory

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LIM - Mechatronics Lab

- LIM - Laboratorio Interdisciplinare di Meccatronica
- Established in 1993 as a "joint-venture" by a number of people of the Departments of Control and Computer Sciences (**DAUIN**), Electronics and Telecomunications (**DET**) and Department of Mechanical and Aerospace Engineering (**DIMEAS**) of Politecnico di Torino.
- http://www.lim.polito.it/
- Research areas:

Automotive	Mobile Robotics and Unmanned Vehicles
Control Units for Mechatronic Applications	Power Actuation
Energy	Rotodynamics
Magnetic Suspension	Vibration Control
Mechatronic Systems for Mountain Safety	

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Short CV

- 1998-2004, MS degree in AE from Tashkent Automotive&Road Construction Institute
- 2004-2007, PhD degree, Tashkent Automotive&Road Construction Institute
- 2007-2010, Researcher, Tashkent Automotive&Road Construction Institute
- 2010-2013, PhD degree in Mechatronics from Politecnico di Torino
- 2013 – present, Researcher in DIMEAS, Politecnico di Torino
- 2018 – present, Associate professor, Turin Polytechnic University in Tashkent

- Courses: Machine design, Motor Vehicle Design, Modelling and Simulation for Vehicle Component Design

- Research: Hybrid Electric Vehicles, Automotive Mechatronic Systems for Energy consumption reduction, Vehicle Dynamics

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Agenda

- **'Well-to-wheel' analysis**
  - Control of polluting emissions and greenhouse gases
  - Main types of emissions, their sources and formation processes
  - Environmental impact of exhaust emissions from IC engines
  - The regulation to limit the pollutant and CO2 emissions
- **Combustion simulation**
  - Combustion diagnostics
  - Simulation models of speed of combustion in diesel/SI engines

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Course material

- Course material based on the following courses:
- Combustion engines and their application to vehicle, D'AMBROSIO STEFANO
- Thermal Machines, BARATTA MIRKO
- Fundamentals of thermal and hydraulic machines and fluid, FINESSO ROBERTO
- Sustainable transport systems: energy and environmental issues, SPESSA EZIO

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'Well-to-wheel' analysis

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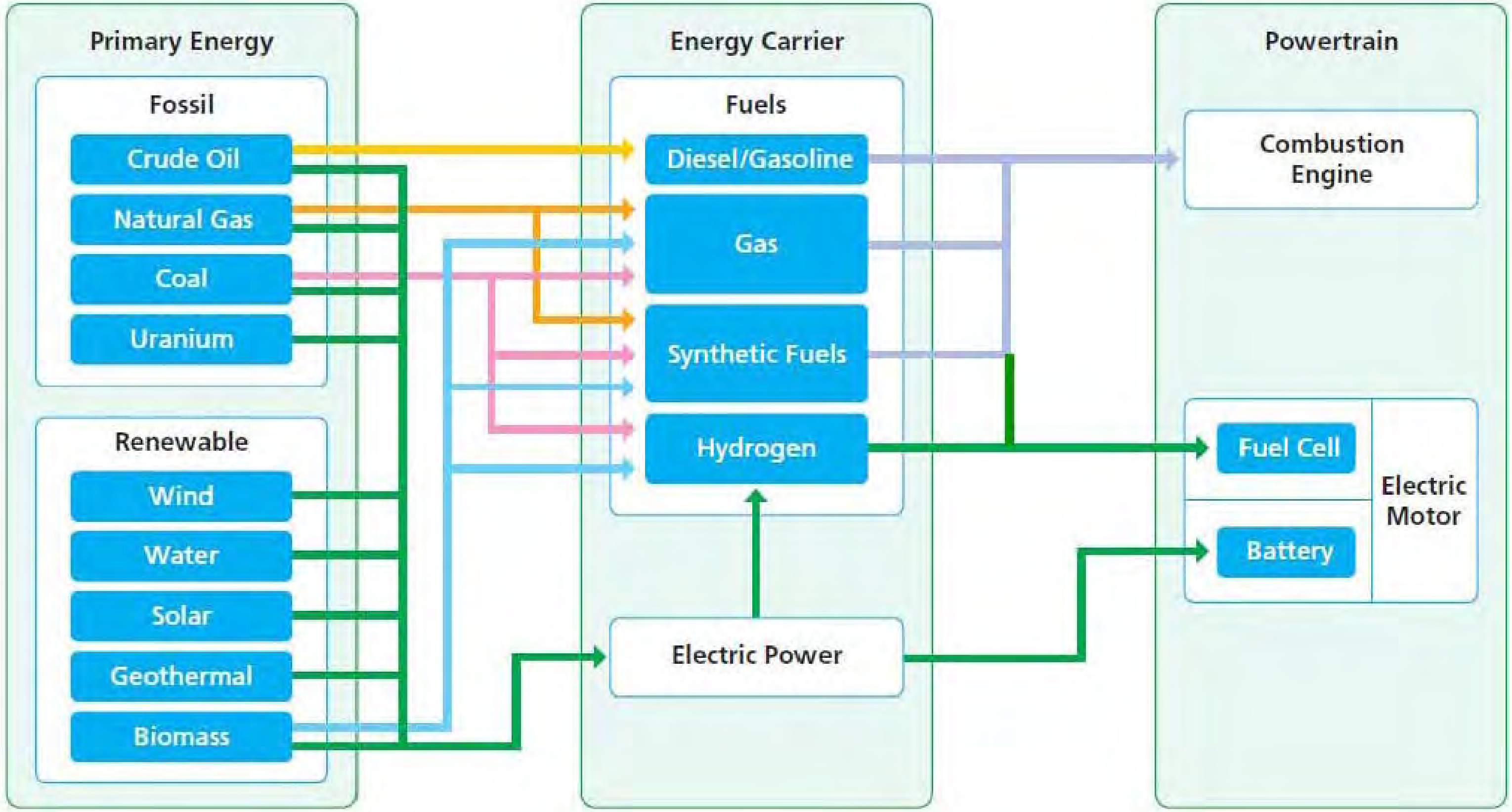
Energy Pathways for fuels



Source: https://www.ertrac.org/

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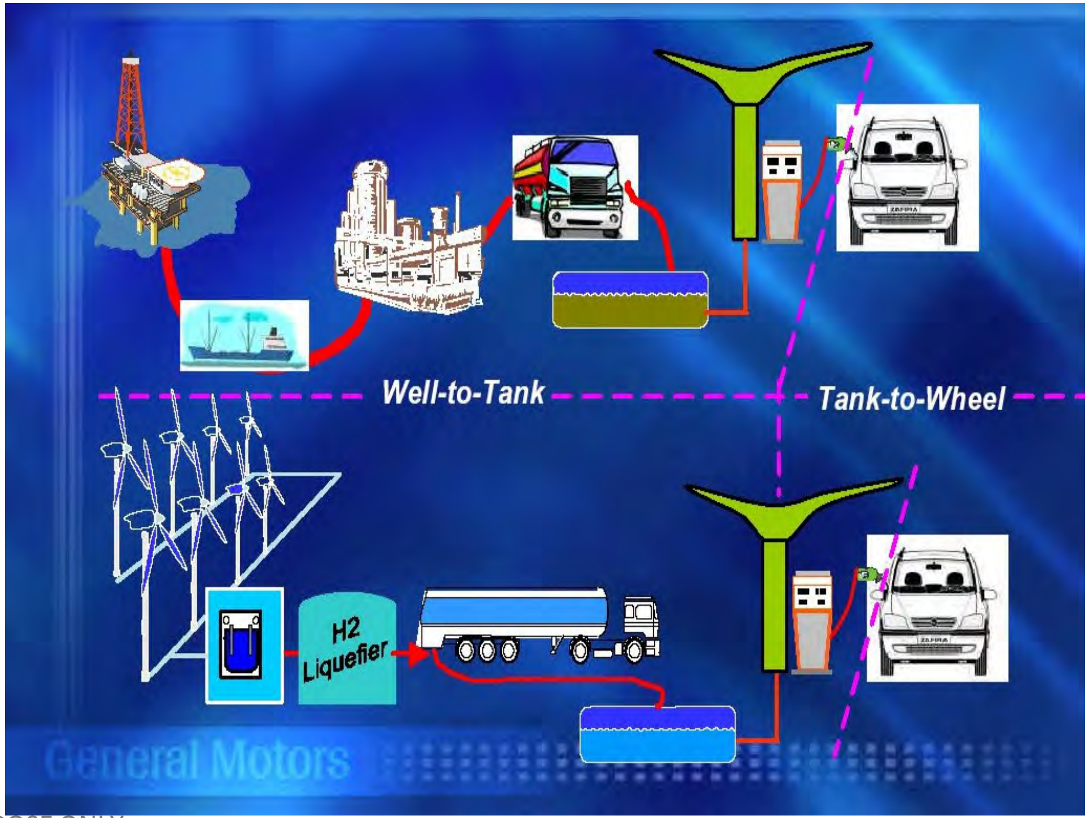
Well-to-Tank analysis (WTT)

Energy source → Production and conditioning at source → Transformation at source → Transportation to EU markets → Processing in EU → Conditioning and distribution



Source: General Motors

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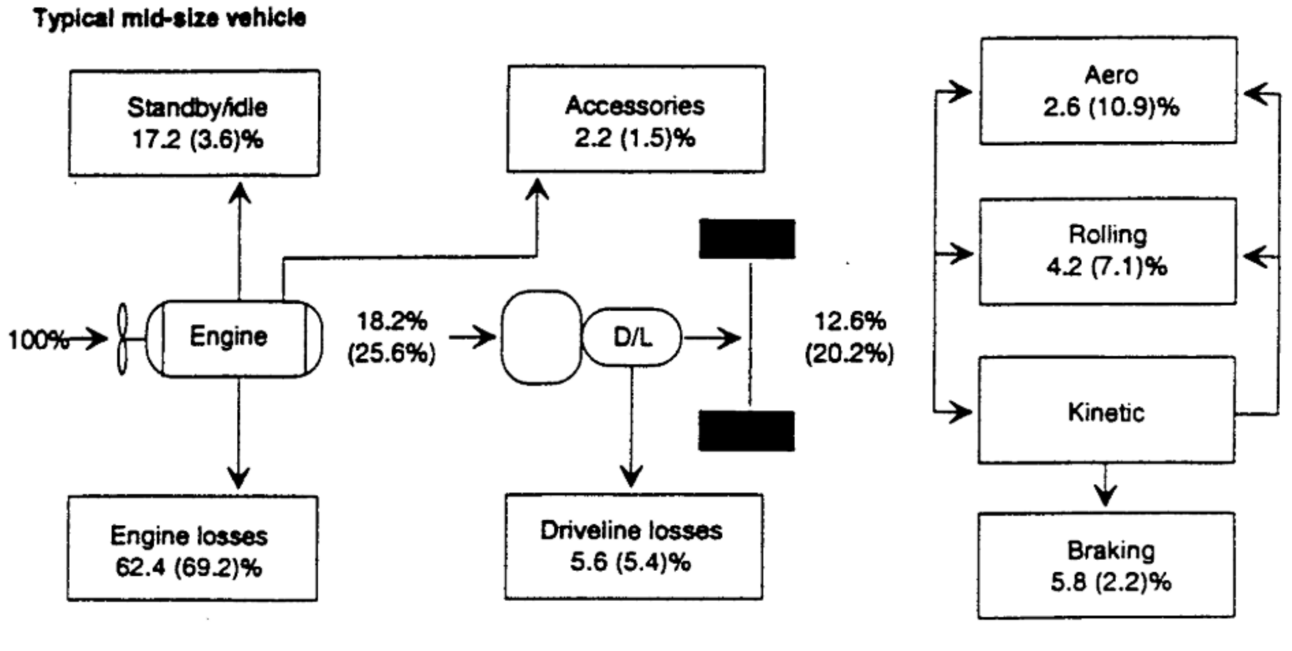
Tank-To-Wheel analysis TTW



NOTE: Numbers indicate urban energy distribution. Numbers in paretheses indicate highway energy distribution.
SOURCE: Partnership for a New Generation of Vehicles.

Source: Plotkin

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Tank-To-Wheel analysis TTW

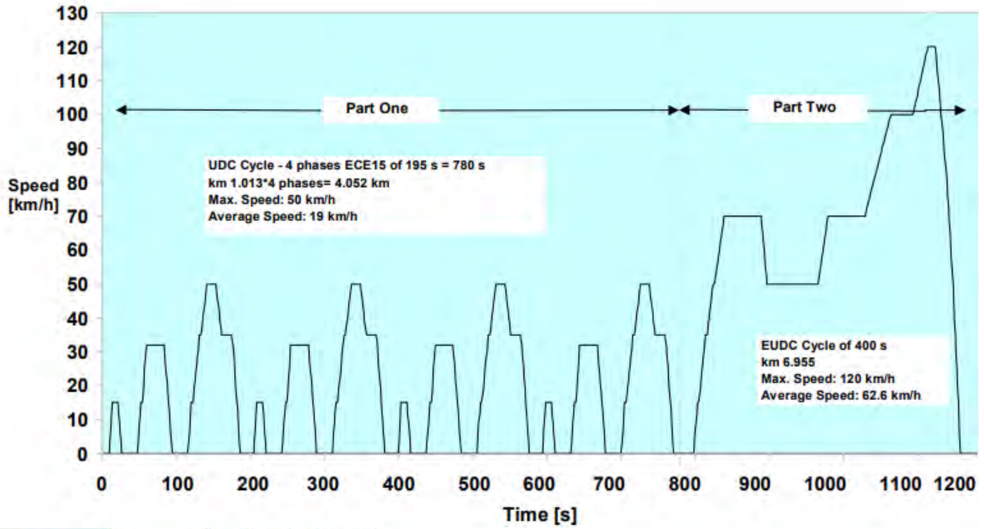
UNITED

Time lag for 0-50 km/h	s	<4
Time lag for 0-100 km/h	s	<13
Time lag for 80-120 km/h in 4th gear	s	<13
Time lag for 80-120 km/h in 5th gear	s	-
Gradability at 1 km/h	%	>30
Top speed	km/h	>180
Acceleration	m/s^2	>4.5
Range(1)	km	>600

(1) Where applicable 20 km ZEV range

VW Golf

Curb weight	kg	1181
Weight class	kg	1250
Drag coefficient	-	0.321
Vehicle front area	m^2	2.1
Tyre radius	m^2	0.309
Tyre inertia	$kg.m^2$	0.7
Engine displacement	l	1.6
Engine inertia	$kg.m^2$	0.125
Efficiency differential + gear		0.9
Transmission ratio of differential gear		4.25
Transmission ratio 1st to 5th gear		3.455/1.944/1.370/1.032/0.850



Simulation results with **AVL ADVISOR**

Tank → **Internal Combustion Engine** → **Powertrain + Auxiliary** → **Wheel**

Source: Edwards

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Well-To-Wheel (WTW)

WTW energy [MJ/100km] = (1+WTT energy [MJ_{ex}/MJ_f]) x TTW energy [MJ_f/100km]

Total energy required to drive (WTT + TTW) the vehicle over 100 km on the NEDC cycle (regardless of fuel origin)

MJ_f – Energy contained in the fuel
MJ_{ex} – External energy spent to produce 1MJ

WTW GHG [gCO_2eq/km] = TTW GHG [gCO_2eq/km] +
+ TTW energy [MJ_f /100 km]/100 x WTT GHG [gCO_2eq/ MJ_f]

CO_2 equivalent = CO_2 emissions + $21 \cdot CH_4 + 310 \cdot N_2O$

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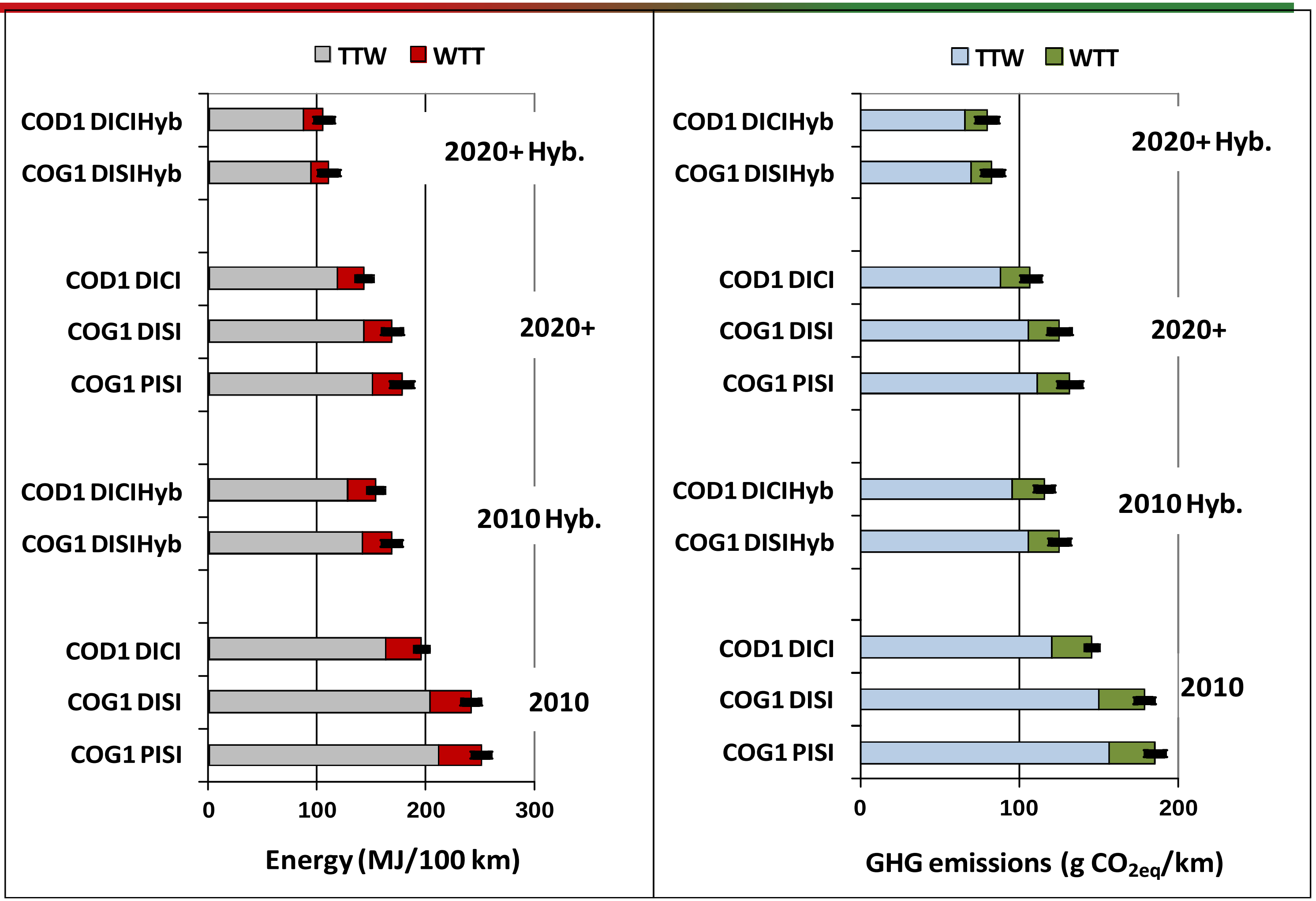
Source: Edwards

Conventional fuel WTW = TTW+WTT

PISI – Port Injection Spark Ignition
DISI – Direct Injection Spark Ignition
DICI – Direct Injection Compression Ignition
Hybr. – Hybrid

COG1 – Conventional Gasoline
COD1 – Conventional Diesel



Source: Edwards

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Fuel combustion and air pollution

- The combustion of hydrocarbon fuels removes O_2 from the atmosphere and releases equivalent amount of H_2O and CO_2 always with trace amounts of numerous other compounds including hydrocarbons (CH_4, C_2H_2, C_2H_6, C_2H_8, C_6H_6, CH_2, CHO, etc.), carbon monoxide (CO), nitrogen oxides (NO, N_2O) and reduced nitrogen (NH_3 and HCN), sulfur gases (SO_2, OCS, CS_2), halocarbons (CHCI and CH_3Br), and particles.
- Combustion is clearly responsible for most of the enhanced greenhouse effect (through CO_2, stratospheric O_3, soot).
- The definition of **pollution** is "the introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological system, damage to structures or amenity, or interference with legitimate uses of the environment". Air pollutants are either gaseous or particulate in form.
- All pollution events have certain characteristics in common, and all involve:
  - **the pollutant (emission)**,
  - **the source** of the pollutant (such as combustion),
  - the transport medium (air, water or soil),
  - the target (the organisms), ecosystems or items of property affected by the pollutant.

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Main types of emissions, their sources and formation processes (1)

Primary pollutants are those emitted directly as a result of human activity or natural processes, while **secondary pollutants** are created from primary pollutants, sunlight and components in the atmosphere reacting with one another.

Primary air pollutants from combustion systems are:

- generated by incomplete and non-ideal combustion process: carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM)
- derived by additives or other chemical species present in the fuel: sulfur gases (SO_x), metal compounds (such as salt of Pb in old gasoline fuel)
- derived from lubricant oil (aerosol of lubricant oil) or material coming from wear of machine components.

Non-combustion emissions are also relevant. They consist of process emissions in industry and nonexhaust emissions in transport.

Non-exhaust emissions are very significant in transport, relating to emissions from the abrasion and corrosion of vehicle parts (e.g. tyres, brakes) and road surfaces, and are (in many cases) still relevant for those vehicles that have no exhaust emissions

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Main types of emissions, their sources and formation processes (2)

Main **secondary air pollutants** are:

- ground-level ozone O_3
- photochemical smog
- Acid rains (acid deposition)

Manmade industrial chemicals (CFC) and pollutants (NO_x) can also deplete the ozone layer in the stratospheric ozone (“ozone hole”).

Source: IEA, WEO 2016, Special report on Energy and Air Pollution

Examples of sources of energy-related air pollution

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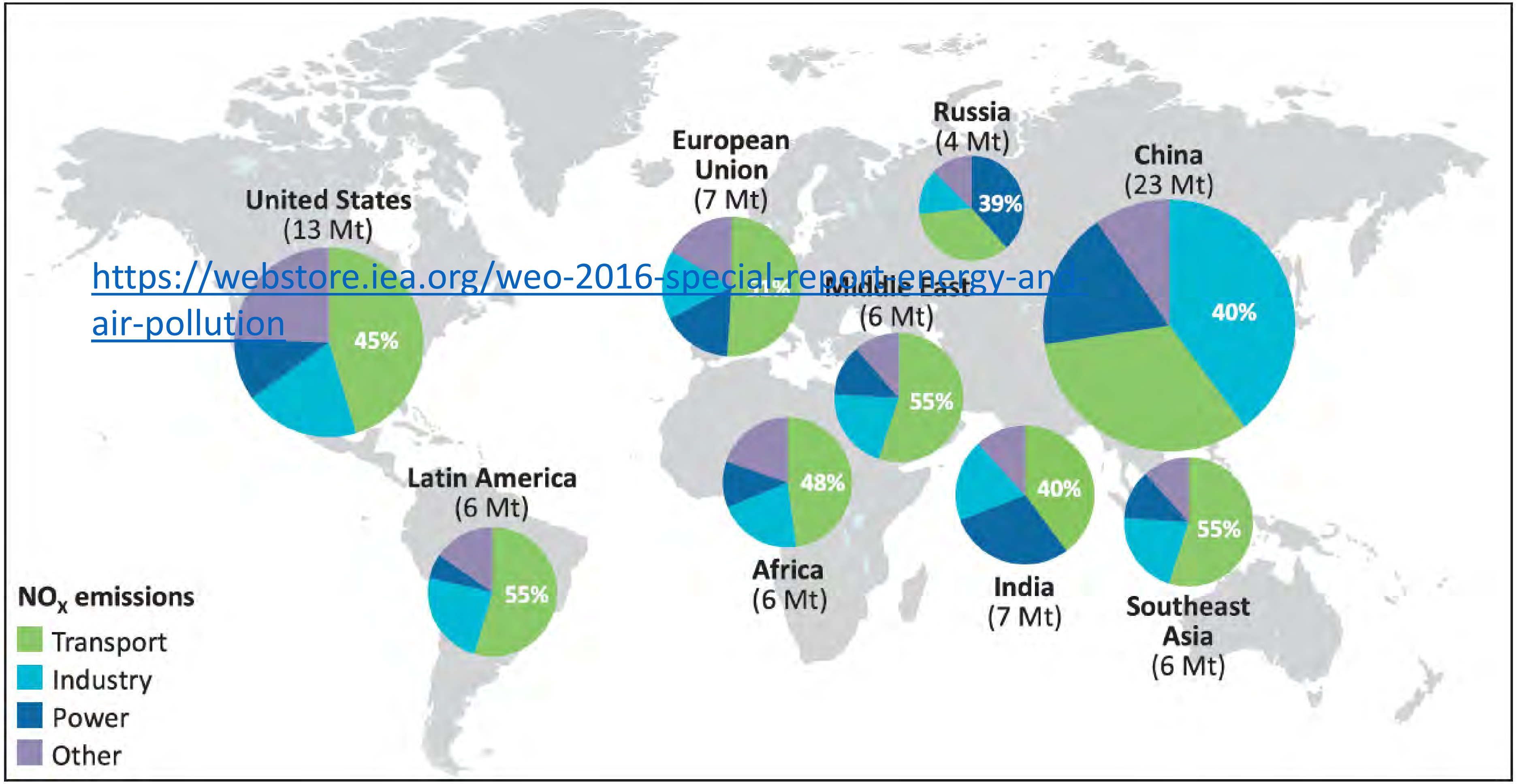
Energy-related NOx emissions (2015)

UNITED



https://webstore.iea.org/weo-2016-special-report-energy-and-air-pollution

Source: IEA, WEO 2016, Special report on Energy and Air Pollution

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Pollutant formation in conventional SI engines

The processes by which these pollutants are formed within the cylinder of a ***conventional spark-ignition engine*** are illustrated qualitatively in the next figure.

The schematic shows the combustion chamber during four different phases of the engine operating cycle: compression, combustion, expansion and exhaust.

Source: Heywood 1988

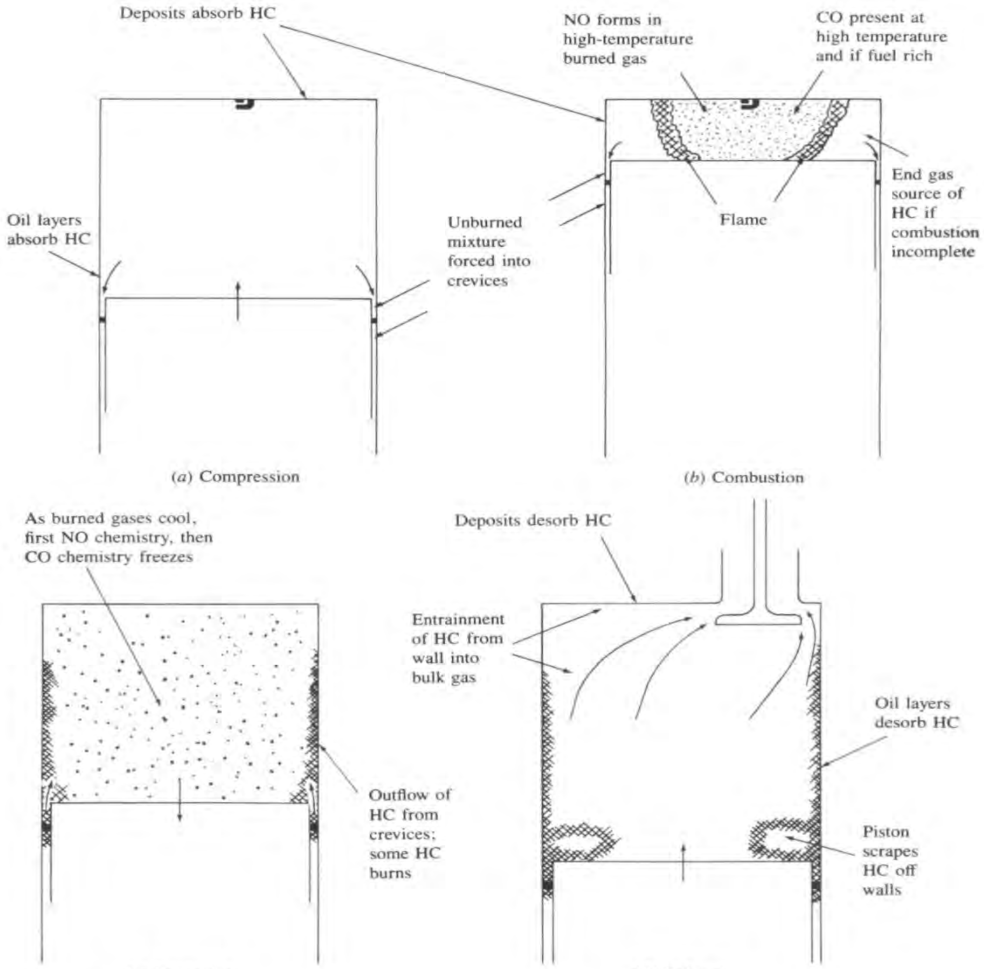

FIGURE 11-1
Summary of HC, CO, and NO pollutant formation mechanisms in a spark-ignition engine.

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Pollutant formation in conventional SI engines

Nitric oxide (NO) forms throughout the high-temperature burned gases behind the flame through chemical reactions involving nitrogen and oxygen atoms and molecules, which do not attain chemical equilibrium.

The higher the burned gas temperature, the higher the rate of formation of NO.

As the burned gases cool during the expansion stroke the reactions involving NO freeze, and leave NO concentrations far in excess of levels corresponding to equilibrium at exhaust conditions.

Carbon monoxide also forms during the combustion process.

With rich fuel-air mixtures, there is insufficient oxygen to burn fully all the carbon in the fuel to CO2; also, in the high-temperature products, even with lean mixtures, dissociation ensures there are significant CO levels. Later, in the expansion stroke, the CO oxidation process also freezes as the burned gas temperature falls.

Source: Heywood 1988

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Pollutant formation in conventional SI engines

- The *unburned hydrocarbon* (HC) emissions have several different sources:

a) filling of crevice volumes

  - During compression and combustion, the increasing cylinder pressure forces some of the gas in the cylinder into crevices (i.e. narrow volumes, connected to the combustion chamber): the volumes between the piston rings, and cylinder wall are the largest of these.
  - Most of this gas is unburned fuel-air mixture; much of it escapes the primary combustion process because the entrance to these crevices is too narrow for the flame to enter. This gas, which leaves these crevices later in the expansion and exhaust processes, is one source of unburned hydrocarbon emissions.

Source: Heywood 1988

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Pollutant formation in conventional SI engines

b) flame quenching at the combustion chamber walls

- Another possible source is the combustion chamber walls. A quench layer containing unburned and partially burned fuel-air mixture is left at the wall when the flame is extinguished as it approaches the wall.
- However, the HC in these thin (≤ 0.1 mm) layers burn up rapidly after flame quenching so this is not a large source. It has been shown that the porous deposits on the walls of engines in actual operation do increase engine HC emissions, due to a flame quenching process.

c) absorption of fuel vapor into oil layers on the cylinder

- A third source of unburned hydrocarbons is believed to be any engine oil left in a thin film on the cylinder liner. This oil layer absorbs and desorbs fuel hydrocarbon components, before and after combustion, respectively, thus permitting a fraction of the fuel to escape the primary combustion process unburned.

Source: Heywood 1988

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Pollutant formation in conventional SI engines

d)incomplete combustion

A final source of HC in engines is incomplete combustion due to bulk quenching of the flame in that fraction of the engine cycles where combustion is especially slow. Such conditions are most likely to occur during transient engine operation when the air fuel ratio, spark timing, and the fraction of the exhaust recycled for emission control may not be properly matched.

The unburned hydrocarbons exit the cylinder by being entrained in the bulk-gas flow during blowdown and at the end of the exhaust stroke as the piston pushes gas scraped off the wall out of the exhaust valve.

Oxidation of the hydrocarbons which escape the primary combustion process by any of the above processes can occur during expansion and exhaust.

The amount of oxidation depends on the temperature and oxygen concentration time histories of these HC as they mix with the bulk gases.

Source: Heywood 1988

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Pollutant formation in conventional SI engines

One of the most important variables in determining spark-ignition engine emissions is the relative air/fuel ratio, λ.

The spark-ignition engine has historically been operated close to stoichiometric, or slightly fuel-rich, to ensure smooth and reliable operation.

Leaner mixtures give lower CO and HC emissions until the combustion quality becomes poor (and eventually misfire occurs), when HC emissions rise sharply and engine operation becomes erratic. However, NO emissions peak about 10% lean of stoichiometric. The shapes of these curves indicate the complexities of emission control.

In a cold engine, when fuel vaporization is slow, the fuel flow is increased to provide an easily combustible fuel-rich -mixture in the cylinder. Thus, until the engine warms up and this enrichment is removed, CO and HC emissions are high.

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Environmental impact of exhaust emissions from IC engines

Air pollutant	Main characteristic	Principal sources	Principal health effects
Carbon monoxide (CO) 0.7%	Colorless, odorless gas with strong affinity to hemoglobin in blood	Incomplete combustion of fuels and other carbonaceous materials	Absorbed by lungs; impairs physical and mental capacities; affects fetal development
Hydrocarbons (HC) 0.2%	Organic compounds in gaseous or particulate form (such as methane, ethylene, acetylene); component in forming photochemical smog	Incomplete combustion of fuels and other carbon containing substances	Acute exposure causes eye, nose, and throat irritation; chronic exposure suspected to cause cancer
Lead (P_b)	Heavy, soft, malleable, gray metallic chemical element; often occurs as lead oxide aerosol or dust	Occupational exposure in nonferrous metal smelting, metal fabrication, battery making and from automobiles.	Enters primarily through respiratory tract and wall of digestive system; accumulates in body organs causing serious physical and mental impairment
Nitrogen oxides (NO_X) 0.1%	Mixture of gases ranging from colorless to reddish brown	Stationary combustion (power plants), mobile sources and atmospheric reactions	Major role as component in creating photochemical smog; evidence linking respiratory problems and cardiovascular illnesses
Particulate matter	Any solid or liquid particles dispersed in the atmosphere, such as dust, ash, soot, metals, and various chemicals; often classified by diameter size-particles in microns, (>50 µm),aerosols <50 µm, particulate,<3 µm	Stationary combustion of solid fuels; industrial process such as cement and steel manufacturing	Toxic effects or aggravation of the effects of gaseous pollutants; aggravation of respiratory or cardio respiratory symptoms
Sulfur dioxide (SO_2)	Colorless gas with pungent odor; oxidizes to form sulfur trioxide (SO_3) and sulfuric acid with water	Combustion of sulfur containing fossil fuels, smelting of sulfur-hearing metal ores, certain industrial processes	Classes as mild respiratory irritant; major cause of acid rain

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The regulation to limit the pollutant and CO2 emissions

- The US state of California has assumed a pioneering role in efforts to restrict by law pollutant emissions emanating from motor vehicles.
- California introduced the first emission-control legislation for gasoline engines in the mid-1960s. These regulations became progressively more stringent in the ensuing years. In the meantime, all industrialized countries have introduced emission-control laws which define limits for gasoline and diesel engines, as well as the test procedures employed to confirm compliance. In some countries, regulations governing exhaust emissions are supplemented by limits on evaporative losses from the fuel system.

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The regulation to limit the pollutant and CO2 emissions

- The most important legal restrictions on exhaust emissions are :
  - CARB regulations,
  - EPA regulations,
  - EU regulations,
  - Japanese regulations.
- Japan and the European Union have followed the lead of the United States by defining test procedures for certifying compliance with emissions limits. These procedures have been adopted in modified or unrevised form by other countries.

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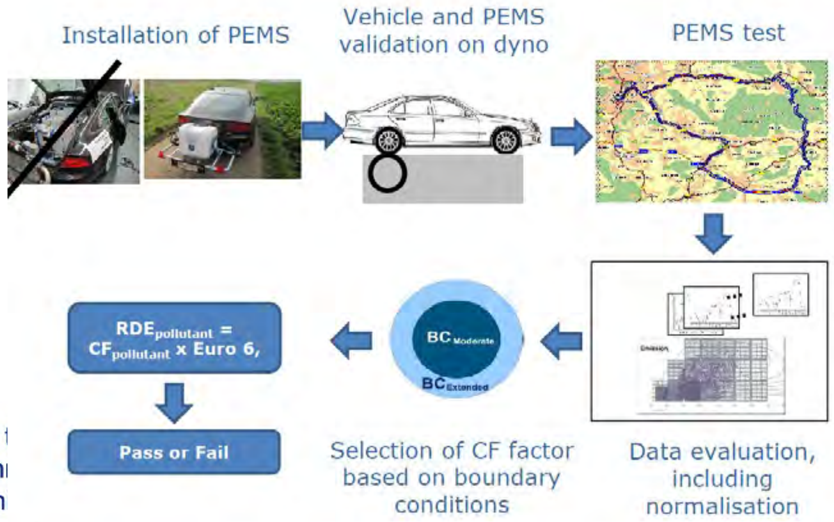
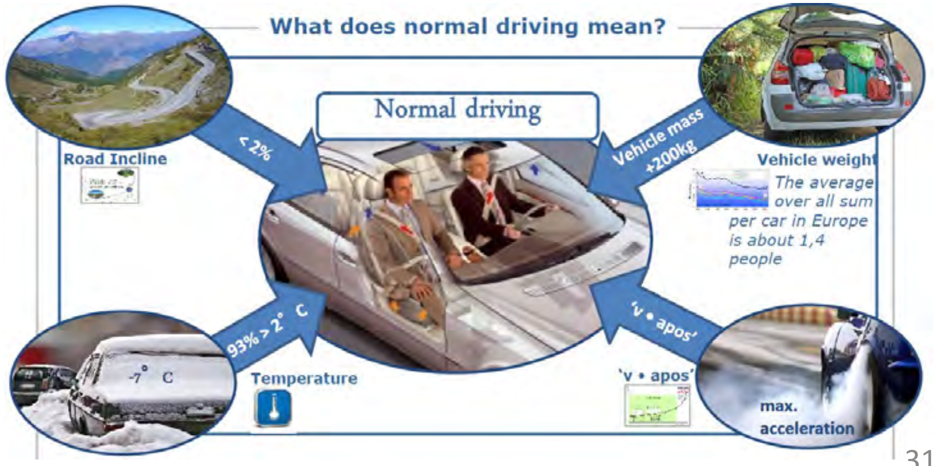
Emission control regulations for passenger cars in EU

No. 715/2007 : pollutant emission limits for passenger cars (CO, HC, NOx, PM, PN)

Euro 1	Euro 2	Euro 3	Euro 4	Euro 5a	Euro 5b	Euro 6
1992	1996	2000	2005	2009	2011	2014

- Set emission standards for vehicle type-approval
- Different emission targets for vehicle running on SI/CI ICEs
- Real Driving Emissions (RDE) testing requirements are being phased-in between 2017 and 2021 to control vehicle emissions in real operation, outside of the laboratory emission test.





Source: Klaus Land

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Emission control regulations for passenger cars in EU

Table 1
EU emission standards for passenger cars (Category M_1*)

Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					#/km
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-	-
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]
Compression Ignition (Diesel)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

Source: www.dieselnet.com

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Emission control regulations for passenger cars in EU

Durability. Useful vehicle life for the purpose of emission regulations is:

Euro 3 stage: 80’000 km or 5 years (whichever occurs first); instead of an actual deterioration run, manufacturers may use the following deterioration factors: 1.2 for CO, HC, NO_x (gasoline) or 1.1 for CO, 1.0 for NO_x, HC+NO_x and 1.2 for PM (diesel).

Euro 4 stage: 100’000 km or 5 years, whichever occurs first.

Euro 5/6 stage: durability testing of pollution control devices for type approval: 160,000 km or 5 years (whichever occurs first). Instead of an actual deterioration run, manufacturers may use the following Euro 5 deterioration factors: 1.5 for CO, 1.3 for HC, 1.6 for NO_x (gasoline), 1.0 for PM and PN or 1.5 for CO, 1.1 for NO_x, HC+NO_x and 1.0 for PM and PN (diesel).

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European Union – Emission Test Cycles: WLTC

- the WLTP (World-wide harmonized Light duty Test Procedure) and the corresponding Cycles (World-wide harmonized Light duty Test Cycle) replaced the NEDC procedure in order to:
  - design a new legislative driving cycle to predict more accurately the exhaust emissions and fuel consumption under **real-world driving conditions**;
  - develop a gearshift procedure which simulates **representative gearshift operation for light duty vehicle**.

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European Union – Emission Test Cycles: WLTC

- The WLTC was derived from "real world" driving data from five different regions: EU + Switzerland, USA, India, Korea and Japan covering a wide range of vehicle categories.
- WLTC considers different road types (urban, rural, motorway) and driving conditions (peak, off-peak, weekend) for three vehicle categories of different power-to-mass (PMR) ratio. The PMR parameter is defined as the ratio of rated power (W) / curb mass (kg). The cycle definitions may also depend on the maximum speed (v_max) declared by the vehicle manufacturer.

WLTP Test Cycles

Category	PMR	Speed Phases	Comments
Class 3	PMR > 34	Low, Middle, High, Extra-High	If v_max < 135 km/h, phase 'extra-high' is replaced by a repetition of phase 'low'.
Class 2	34 ≥ PMR > 22	Low, Middle, High	If v_max < 90 km/h, phase 'high' is replaced by a repetition of phase 'low'.
Class 1	PMR ≤ 22	Low, Middle	If v_max ≥ 70 km/h, phase 'low' is repeated after phase 'middle'. If v_max < 70 km/h, phase 'middle' is replaced by a repetition of phase 'low'.

Source: www.dieselnet.com

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Transition steps from NEDC procedure to WLTC

- The transition from NEDC to WLTC occurs over the following schedule:
- September 2017: WLTP type approval testing is introduced for new car types. Cars approved using the old NEDC test can still be sold.
- September 2018: All new vehicles must be certified according to the WLTP test procedure.
- January 2019: All cars at dealerships should have WLTP-CO_2 values only (with some exceptions for a limited number of vehicles in stock). National governments should adjust vehicle taxation and fiscal incentives to WLTP values.

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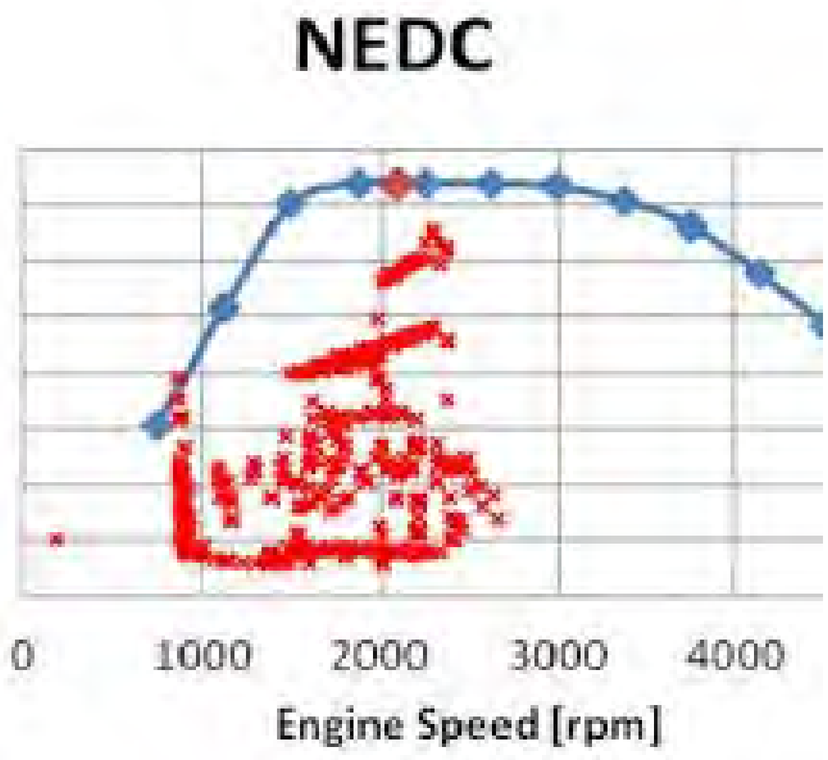
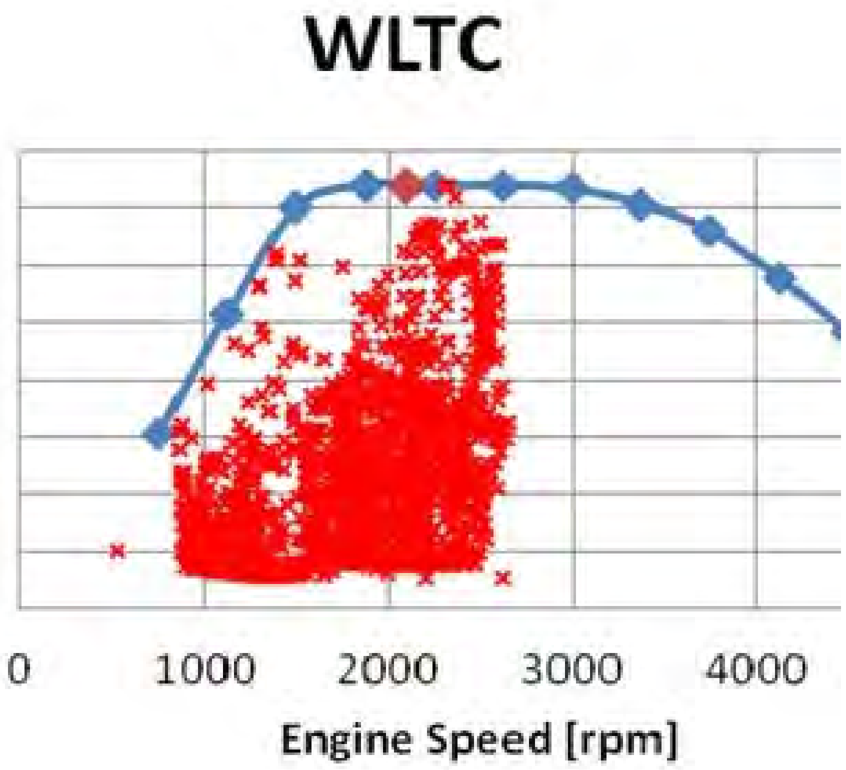
NEDC vs WLTC: ICE working points





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OBD Requirements

Starting from the Euro 3 stage, vehicles must be equipped with an *onboard diagnostic* system for emission control.

Driver must be notified in case of a malfunction or deterioration of the emission system that would cause emissions to exceed mandatory thresholds (a malfunction indicator lamp is switched on the vehicle dashboard).

To distinguish from the US OBD, the European limits are also referred to as the EOBD (European OBD).

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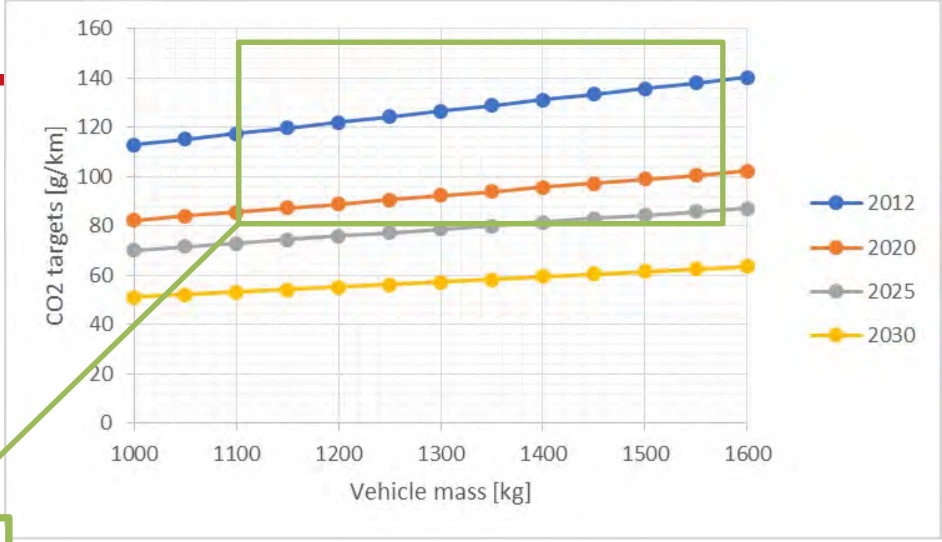
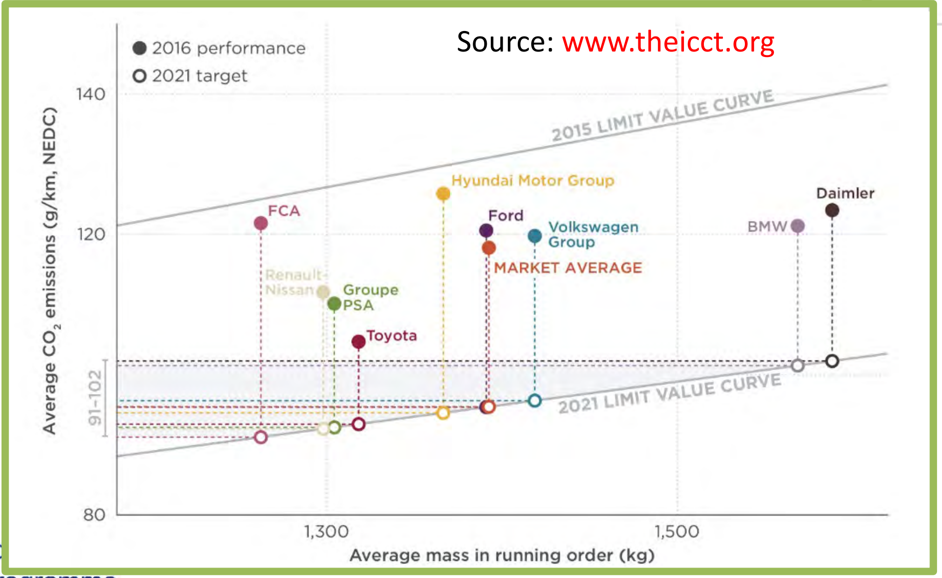
Emission control regulations for passenger cars in EU

- The fleet average to be achieved by all cars registered in the EU is 130 g CO2/km
- From 2020: CO_2 fleet average = 95 gCO2/km.
- 2025: CO_2 fleet average = -15% wrt 2021
- 2030: CO_2 fleet average = -37.5% wrt 2021
- **excess emissions fees**: 95 Euro per each exceeding gCO_2/km for each vehicle sold (from 2019)





Average CO_2 emission values and vehicle mass of major manufacturer groups in 2016. Hypothetical 2021 targets are based on 2016 vehicle mass.

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No. 443/2009: to reduce CO2 from passenger cars (2012-2018 phase-in)

GHG emissions from passenger cars

- The regulation established that a fleet-average CO_2 emission target of 130 g/km must be reached by each vehicle manufacturer by 2015 using vehicle technology. To meet the EU CO_2 emission target of 120 g/km, a further emission reduction of 10 g/km is to be provided by additional measures, such as the use of biofuels. The regulation is applicable to passenger cars (M1). CO_2 emissions are measured over the NEDC test cycle.
- The specific emissions target for each manufacturer in a calendar year is based on the vehicle mass. It is calculated as the average of the specific emissions of CO_2 (g/km) of each new passenger car registered in that calendar year, where:
  - Specific Emissions of CO_2 = $130 + 0.0457 \times (M - M0)$
- In the above formula, M is the mass of the vehicle (kg), and M0 is 1372 kg for calendar years 2012-2015. From 2016, the value of M0 will be adjusted annually to reflect the average mass of passenger cars in the previous three calendar years. Thus, the target of 130 g/km is directly applicable to vehicles of an average mass, while lighter cars have lower CO_2 targets and heavier vehicles have higher CO_2 targets.

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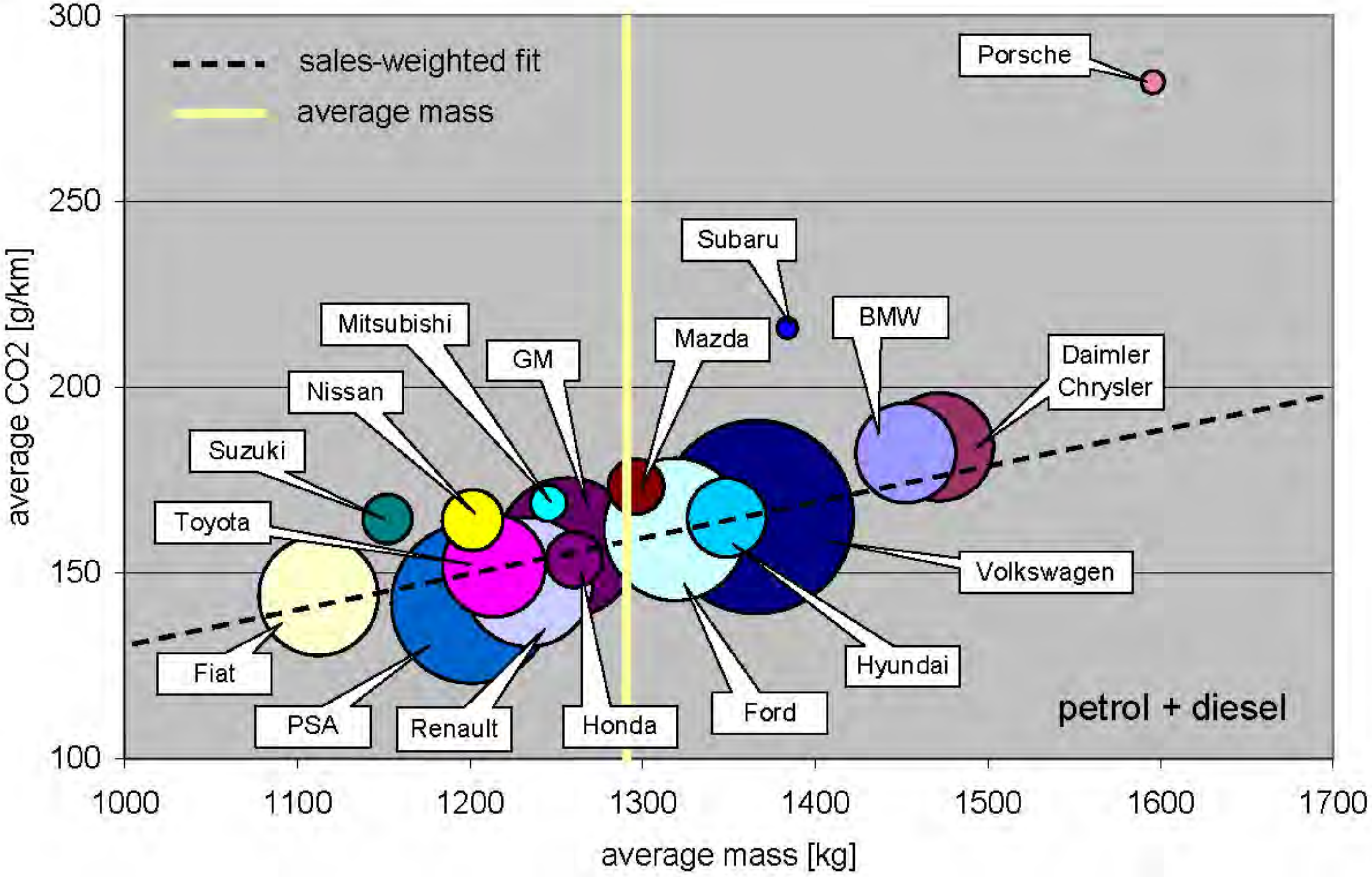
GHG emissions from passenger cars

Average vehicle mass and CO_2 emissions (2007)



Source: https://ec.europa.eu/clima/policies/transport/vehicles/cars_el

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GHG emissions from passenger cars and LDV

- On December 17, 2018, representatives of the European Commission, the European Parliament, and the European Council agreed on a compromise for the European Union (EU) regulation setting binding carbon dioxide (CO_2) emission targets for new passenger cars and light-commercial vehicles for 2025 and 2030.
- The agreed-upon targets aim to reduce the average CO2 emissions from new cars by 15% in 2025 and by 37.5% in 2030, both relative to a 2021 baseline.
- For light-commercial vehicles, a 15% target for 2025 and a 31% target for 2030 were agreed upon.

Source: https://theicct.org/sites/default/files/publications/EU-LCV-CO2-2030_ICCTupdate_201901.pdf
https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en

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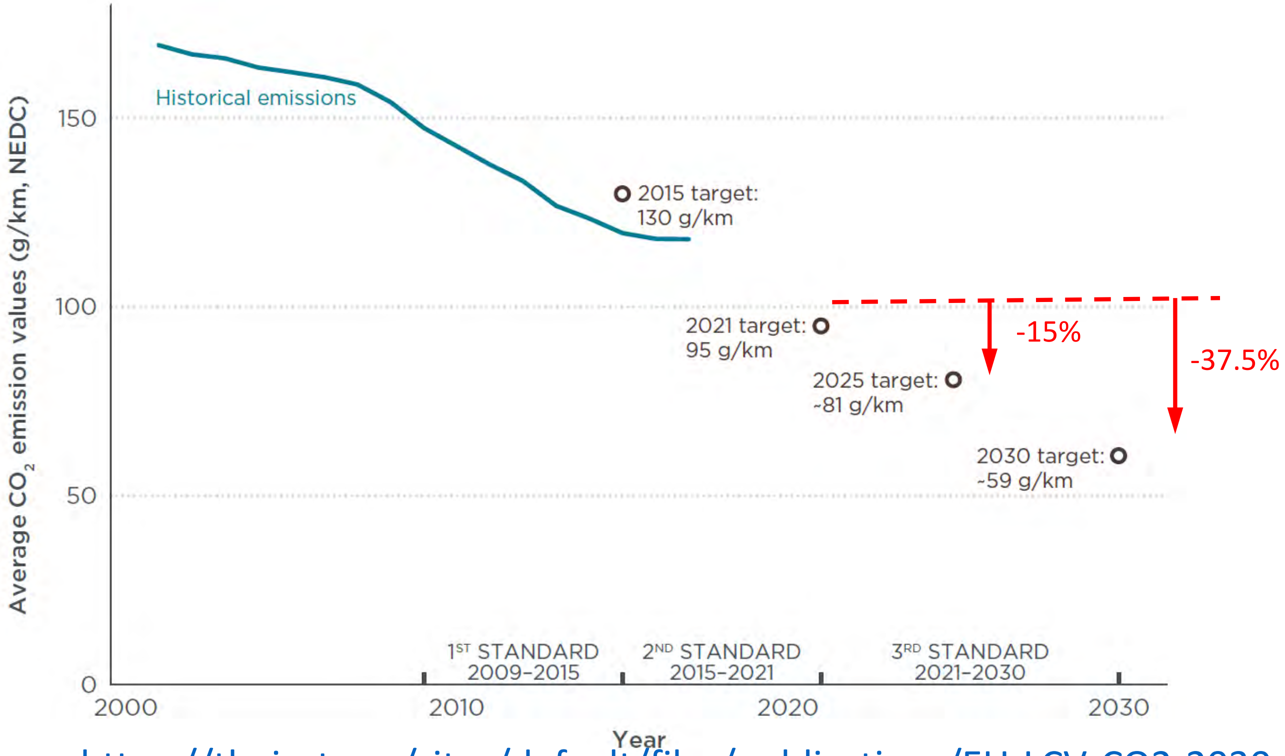
GHG emissions from passenger cars

The figure shows the average historical CO_2 emission values and the adopted and proposed CO_2 standards for new passenger cars in the EU. All CO_2 values refer to New European Driving Cycle (NEDC) measurements.



Source: https://theicct.org/sites/default/files/publications/EU-LCV-CO2-2030_ICCTupdate_201901.pdf
https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en

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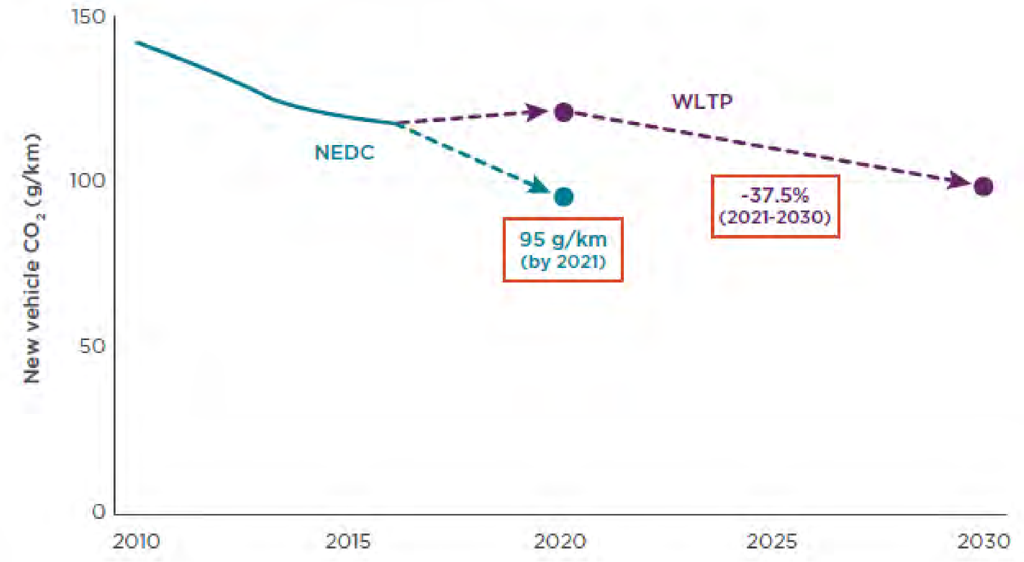
CO_2 reduction scenarios

From 2021 on, the WLTP will be the only procedure used for testing and all future regulations will refer to WLTP results for compliance monitoring.

As of the latest agreement upon the EU regulation for CO2 emissions target of new passenger car (December 17, 2018), it has been decided that, relative to a 2021 baseline, the target will be:

- Reduced by 15% for 2025
- Reduced by 37.5% for 2030



Source: https://theicct.org/sites/default/files/publications/EU-LCV-CO2-2030_ICCTupdate_201901.pdf
https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en

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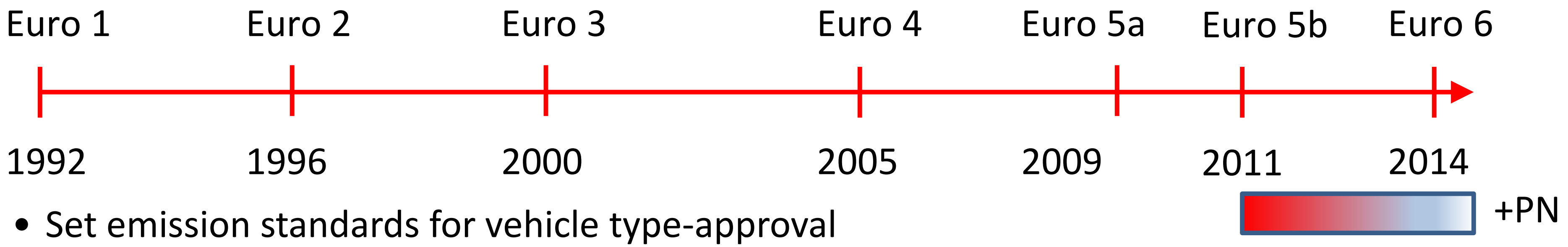
Emission control regulations for LD commercial vehicles in EU

No. 715/2007 : pollutant emission standards for LDVs (CO, HC, NO_x, PM, PN)



- Set emission standards for vehicle type-approval
- Different emission targets for vehicle running on SI/CI ICEs
- Real Driving Emissions (RDE) testing requirements are being phased-in between 2017 and 2021 to control vehicle emissions in real operation, outside of the laboratory emission test.

No. 510/2011: to reduce CO_2 from light-duty vehicles

- The fleet average to be achieved by all LDVs registered in the EU is 175 g CO_2/km
- From 2020: CO_2 fleet average = 147 gCO_2/km.
- 2025: CO_2 fleet average = -15% wrt 2021
- 2030: CO_2 fleet average = -31% wrt 2021
- **excess emissions fees**

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Source: https://theicct.org/sites/default/files/publications/EU-LCV-CO2-2030_ICCTupdate_201901.pdf
https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en

Combustion simulation

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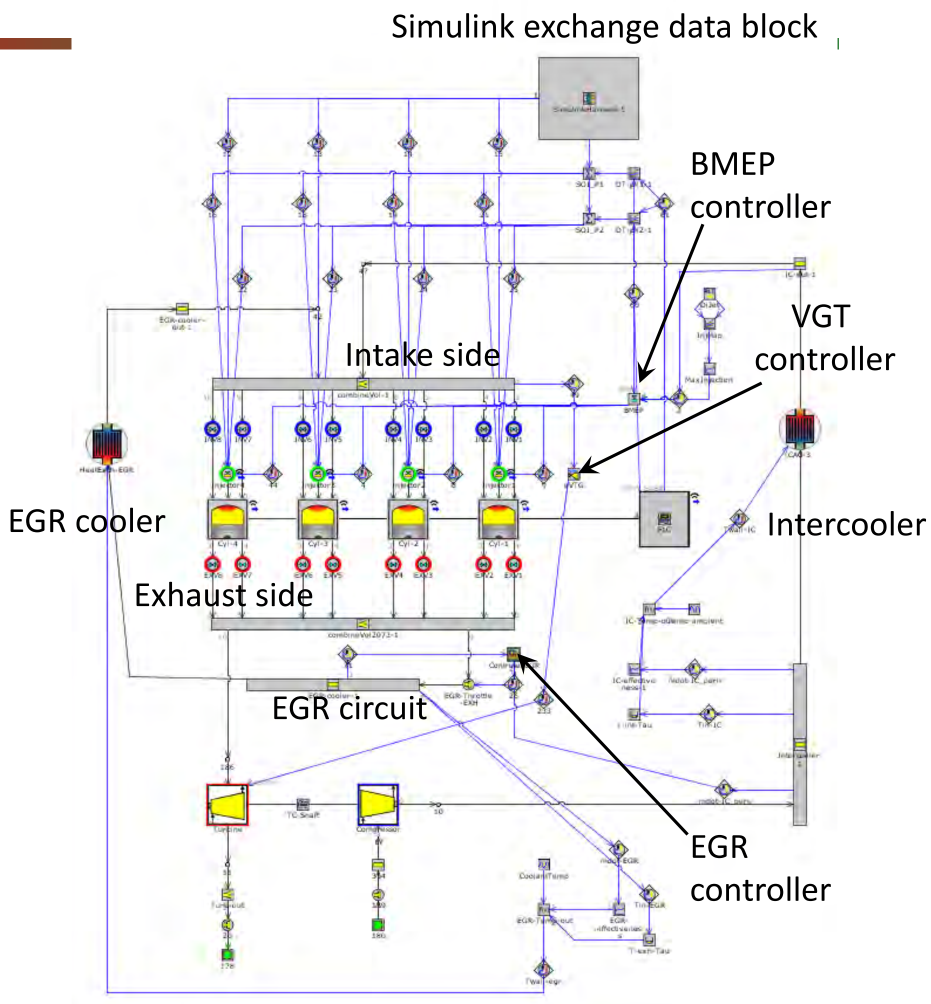
1D-CFD modeling

The complete simulation of the engine is usually carried out with 1D-CFD models (to model the thermo-fluid-dynamics in the pipes and intake/exhaust manifolds of the engine system), which are coupled with a zero-dimensional modeling of the cylinders, injectors, valves, turbocharging system and cranktrain.

The 1D approach is based on the application of the Navier-Stokes equations (mass, momentum and energy) for the unsteady compressible flows in the pipes, considering only 1 coordinate (axial direction of the pipe), and it allows the wave propagation phenomena, as well as the inertial effects, to be captured at steady-state and transient conditions.



FIC 3.0L diesel engine

Source: SAE 2017-01-0794

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1D-CFD modeling

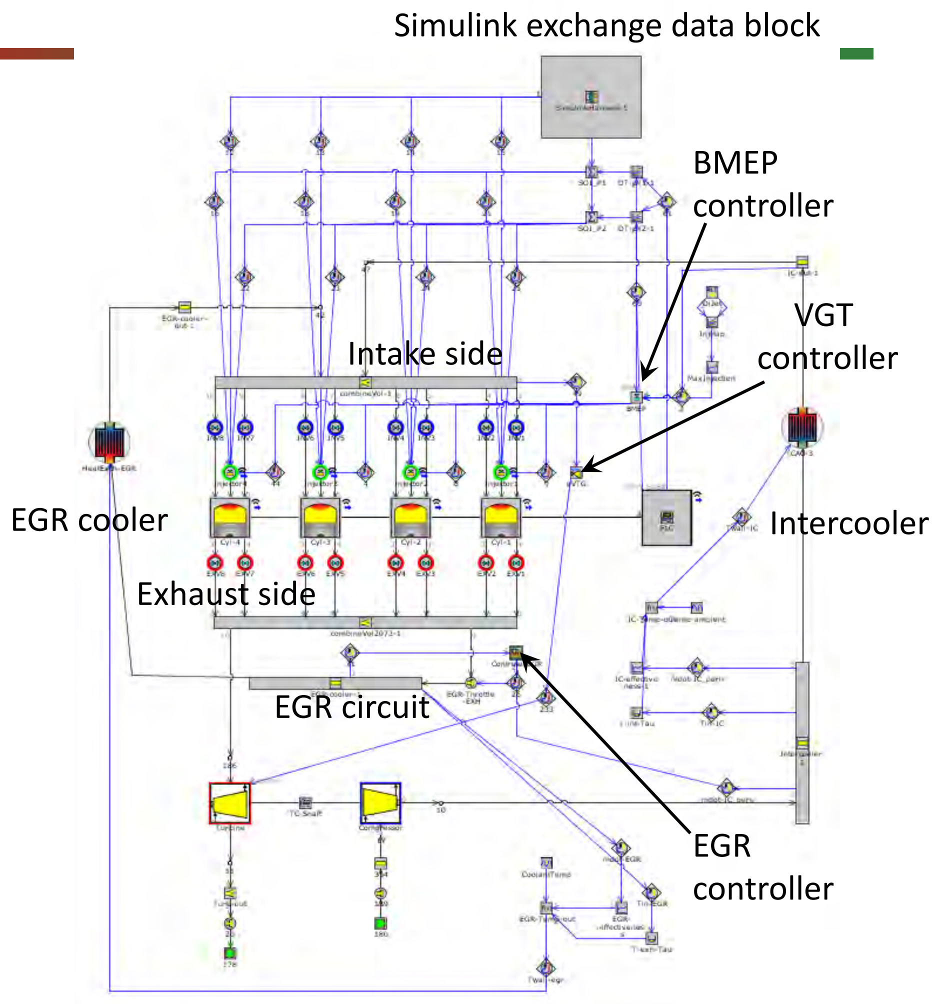
The most widely used commercial codes which implement the previous approach for the complete engine simulation are

GT-power

Ricardo Wave

AVL Boost

In this presentation, some model examples using GT-power software will be shown.



Source: SAE 2017-01-0794

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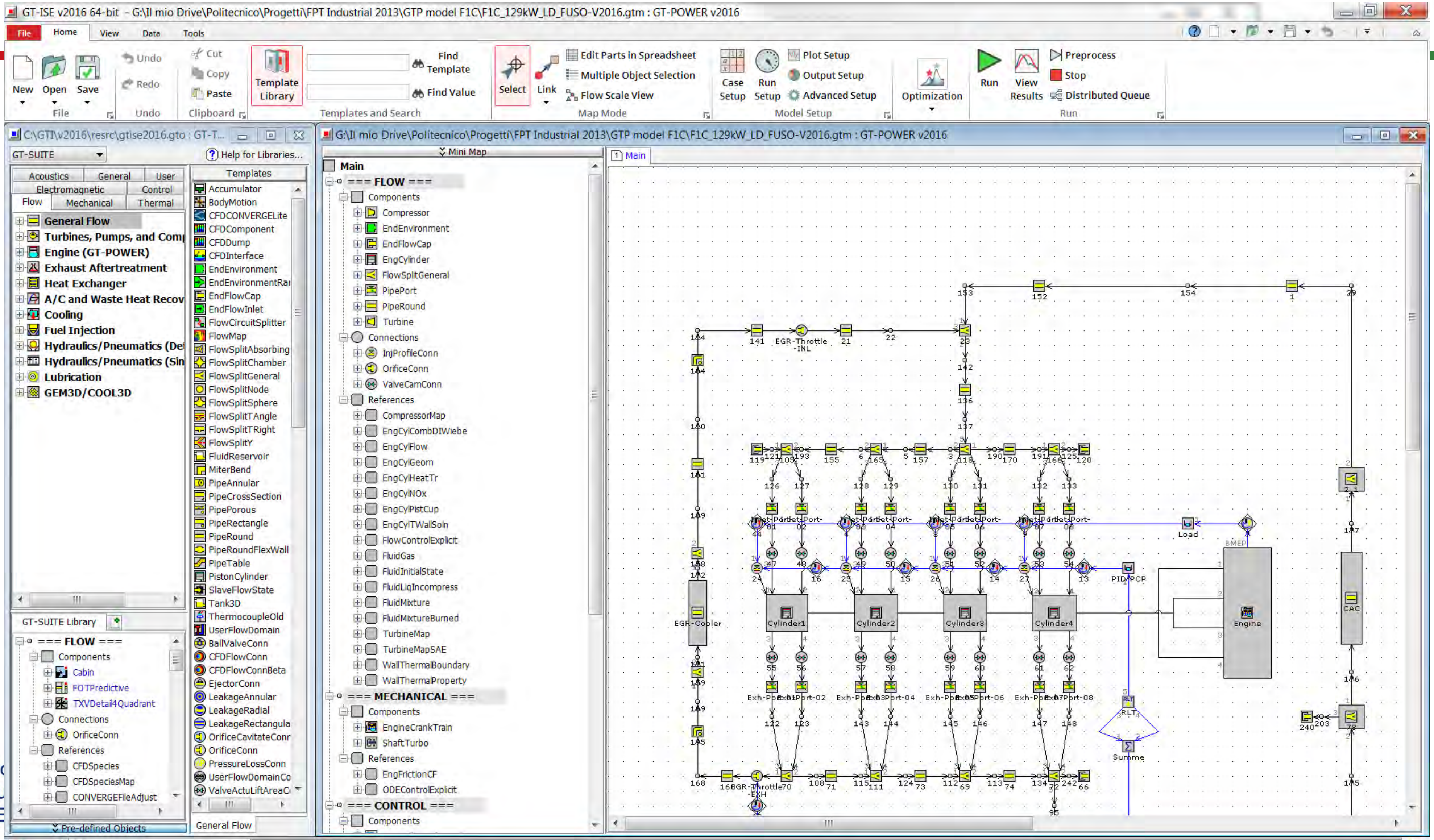
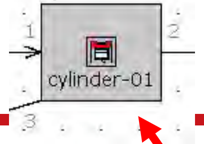
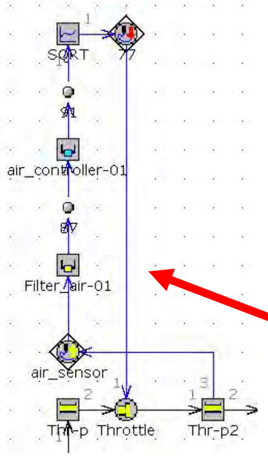
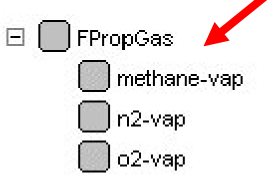
Typical GT-power interface

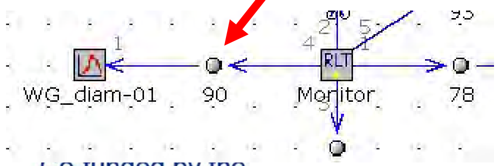


GT-power









Components

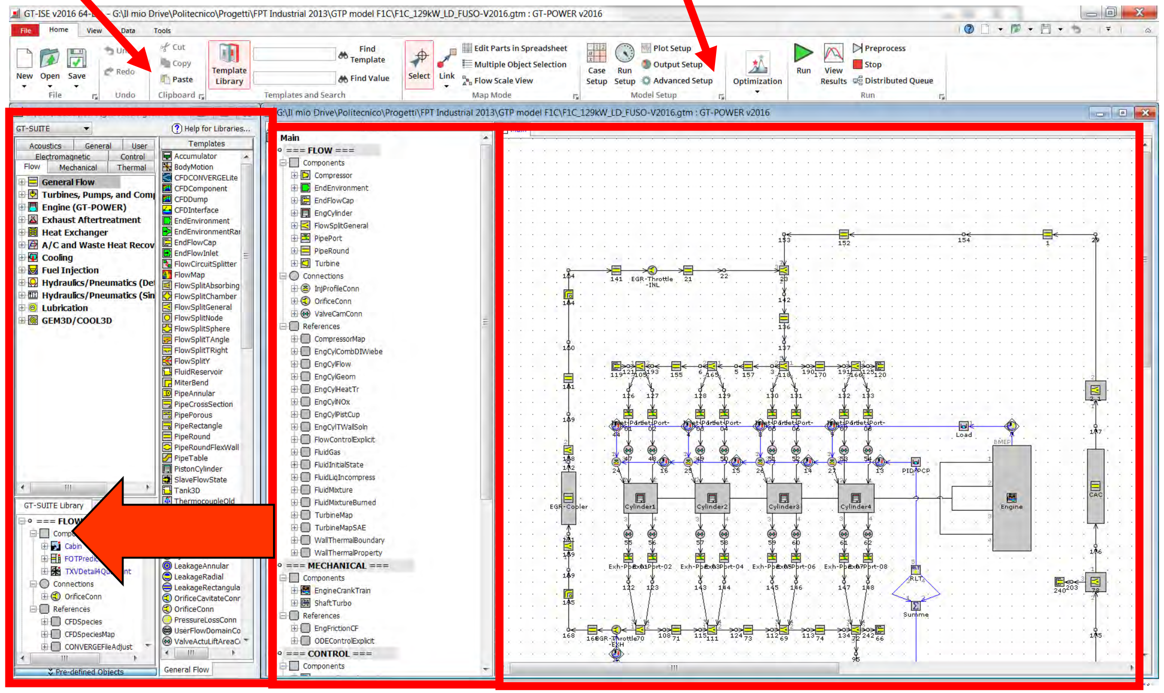
Compounds

Reference objects

Connections

Template archive

Engine layout with “Parts”



Objects with defined properties

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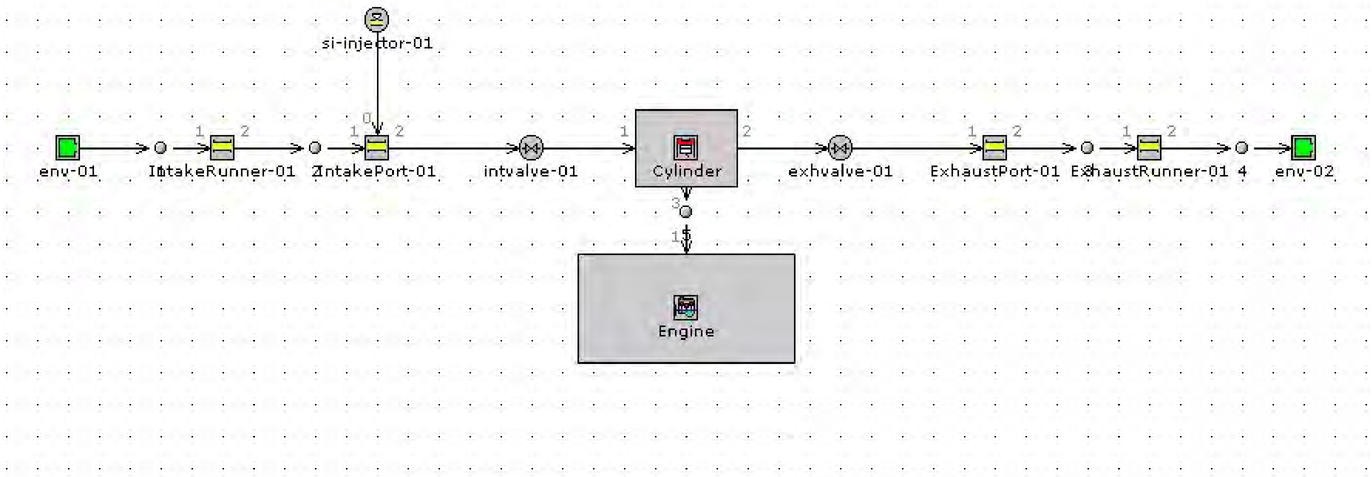
GT-power

Intake and exhaust manifolds are represented by means of pipes and connections.



Single-cylinder engine

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GT-power

1D CFD tools allow the designer to:

- ✓ numerically investigate and predict the engine performance and emissions (λv, imep, bmep, BSFC, NOx…);
- ✓ evaluate the effect of engine geometric parameters or valve timings on performance, so as to reduce the number of required experimental tests;
- ✓ estimate some quantities which are difficult to be measured, for example, the instantaneous mass-flow rate past the valves.

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GT-power: Main modeling assumptions

- Transient flow in the whole domain;
- 1-D flow in pipes, 0-D evolution within the cylinders;
- Compressible flow;
- Pipes with variable cross-section are allowed;
- Heat exchange and flow losses are taken into account (Generalized Euler equations in a quasi-1D form are implemented and solved).

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GT-power: main features

- Geometric and kinematic data of the engine;
- Valve lift time history and flow coefficient;
- In-cylinder heat transfer model;
- Injection model;
- Combustion model;
- Friction and accessory model.

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Combustion diagnostics

Single-zone real-time approach

- The in-cylinder content is considered as an homogeneous zone
- Based on the application of the energy conservation principle to the in-cylinder content
- Capable of estimating Q_{ch} (released chemical energy of the fuel as a function of the crank angle) and its derivative with respect to crank angle, i.e., HRR (heat release rate) on the basis of the measured in-cylinder pressure

Multizone approach

- Based on the **integration** of a predictive non-stationary variable-profile **1D spray model** with a **MULTIZONE thermodynamic model of the in-cylinder combustion** and **submodels of pollutant emission formation (NOx, PM, CO, HC)**
- Input required:
  - in-cylinder pressure time histories
  - Estimate of the injection rate
- Main outputs:
  - temperature and mass time-histories of the zones
  - time-histories of pollutant emissions (NOx, PM, CO, HC) in the combustion chamber.

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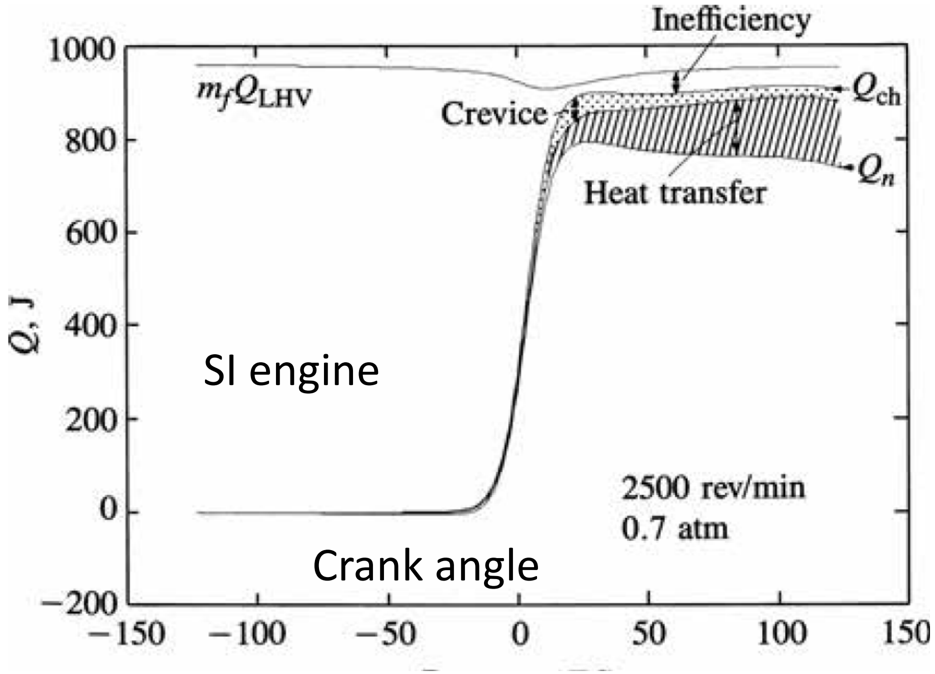
Source: Heywood, 1988
Finesso, 2012

Single-zone real-time approach

$$\frac{dQ_{ch}}{d\theta} = \underbrace{\frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta}}_{Q_n} + \underbrace{\frac{dQ_{cr}}{d\theta}}_{\text{Losses due to crevices}} + \underbrace{\frac{dQ_{ht}}{d\theta}}_{\text{Heat losses}}$$

Q_{ch}: released (or gross) chemical energy
Q_n: net energy of the charge
θ: crank angle
V: in-cylinder volume
p: measured in-cylinder pressure
Q_{ht}: heat exchanged by the charge with the walls
m_f: mass of fuel
Q_{LHV}: lower heating value of the fuel
$\gamma = c_p/c_v$ (ratio of specific heats)



Source: Heywood, 1988

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