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UNIVERSITY

FACULTY OF ENGINEERING
AND ARCHITECTURE

**DEPARTMENT OF ELECTROMECHANICAL, SYSTEMS AND METAL ENGINEERING**
RESEARCH GROUP SUSTAINABLE THERMO-FLUID ENERGY SYSTEMS

# BEST

Fifth consortium meeting, 23/05/2022, Ward Suijs

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economie
FPS Economy, S.M.E.s, Self-employed and Energy

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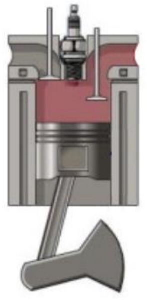
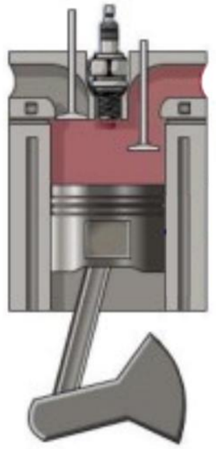
# THROWBACK

- Goal statement within the project:
  - Compute the <u>efficiency potential</u> of a methanol fueled SI ICE, as function of its <u>size</u>

Q: How to predict the performance of differently sized engines?

| | | |
|---|---|---|
|  B = 79mm |  B = 170mm |  B = 300mm |
| $V_d = 1.6l$ | $V_d = 50l$ | $V_d = 500l$ |
| $\eta_{max} = 42\%$ | $\eta_{max} = ?$ | $\eta_{max} = ?$ |
| $@\ P = 52\ kW$ | $@\ P = ?$ | $@\ P = ?$ |

# SCALING LAWS

- Intent: predict the important operating conditions (efficiency and power) based on the size requirement of the engine
- Literature review:
  - Curve fitted scaling laws
  - Willans Line method
  - Similitude
    - Review paper submitted to SAE PFL 2022

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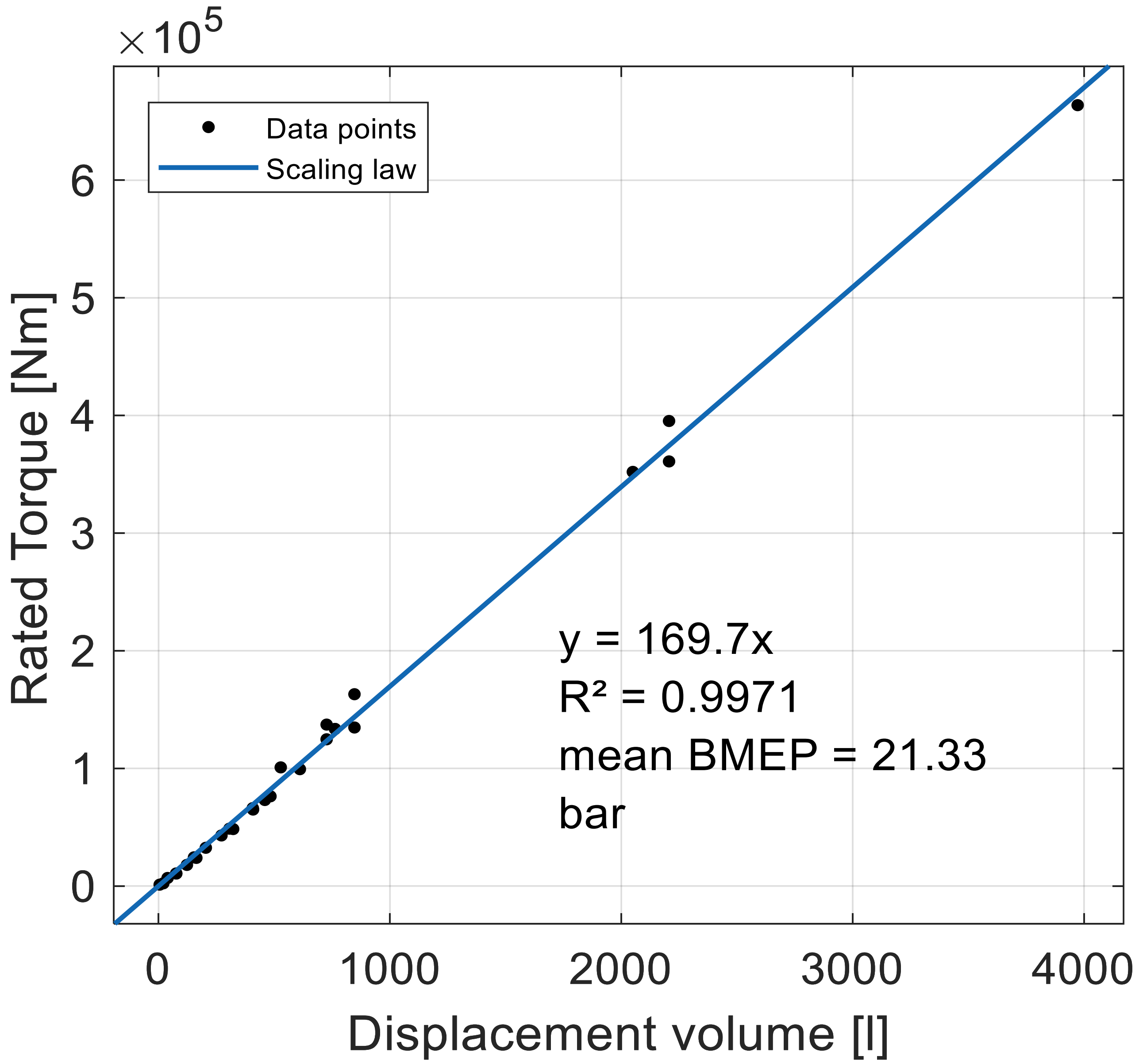
# CURVE FITTED EQUATIONS

– Constructing an empirical curve that best fits to a series of data points

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# CURVE FITTED EQUATIONS

- Standard form: $y = a \cdot x^b$
  - Menon et al[1].: $P\ [kW] = 37.919 \cdot V_d^{0.9543}$ & $\mathrm{BTE}\ [\%] = 15.322 \cdot V_d^{0.0688}$
  - Brown et al[2].: $P\ [kW] = 225.05 \cdot V_d^{0.74}$
- More pragmatic approach: start from fundamental engine performance parameters:
  - $\mathrm{BMEP}\ [bar] = \frac{4\pi \cdot T}{V_d}$

Chon and Heywood[3]:

$$P\ [kW] = \frac{N \cdot BMEP}{1200} \cdot V_d$$

$$P\ [kW] = \frac{c_m \cdot BMEP}{400} \cdot A_p$$

Heywood[4]:

$$P\ [kW] = 0.23 \cdot BMEP \cdot c_m \cdot V_d^{\frac{2}{3}} \cdot N_c^{\frac{1}{3}}$$

# CURVE FITTED EQUATIONS

- More pragmatic approach: start from fundamental engine performance parameters:
  - $\text{BMEP}\ [bar] = \frac{4\pi \cdot T}{V_d}$
  - ${}^{SA}/_{V_d}\ [cm^{-1}] = \frac{4}{\text{B}} + \frac{2}{\text{S}}$

Rowton[5]

$$P\ [kW] = \frac{\rho_{pwr} \cdot \pi}{4} \cdot \left(\frac{{}^{SA}/_{V_d}}{6}\right)^{-3}$$

$$BTE\ [\%] = 21 \cdot \left({}^{SA}/_{V_d}\right)^{-1.5}$$

$$BTE\ [\%] = 0.0125 \cdot V_d^{1.5} + 7$$

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# CURVE FITTED EQUATIONS: QUALITY OF FIT?

- Case study: set of 30 heavy duty SI gas engines
  - B > 100 mm
  - $V_d \in [5 - 4000]$ liter
  - Pre-chamber ignited

Mahle jet ignition system:
https://www.youtube.com/watch?v=n6Eutw0WU3U

# CURVE FITTED EQUATIONS: QUALITY OF FIT?

- Case study: set of 30 heavy duty SI gas engines
  - B > 100mm
  - Pre-chamber ignited
  - $V_d \in [5 - 4000]$ liter
- Quality of fit: $R^2$

| Power [kW] | | BTE [%] | |
|---|---|---|---|
| Scaling law | $R^2$ | Scaling law | $R^2$ |
| Menon[1] | 0.9664 | Menon[1] | 0.6495 |
| Chon & Heywood[3] | 0.9516 | Rowton[5] | 0.5168 |
| Chon & Heywood[3] | **0.9813** | Rowton[5] | **0.7369** |
| Heywood[4] | 0.9805 | | |
| | 0.8430 | | |

$$P\ [kW] = \frac{c_m \cdot BMEP}{400} \cdot A_p$$

$$BTE\ [\%] = 0.0125 \cdot V_d^{1.5} + 7$$

# WILLANS LINE METHOD

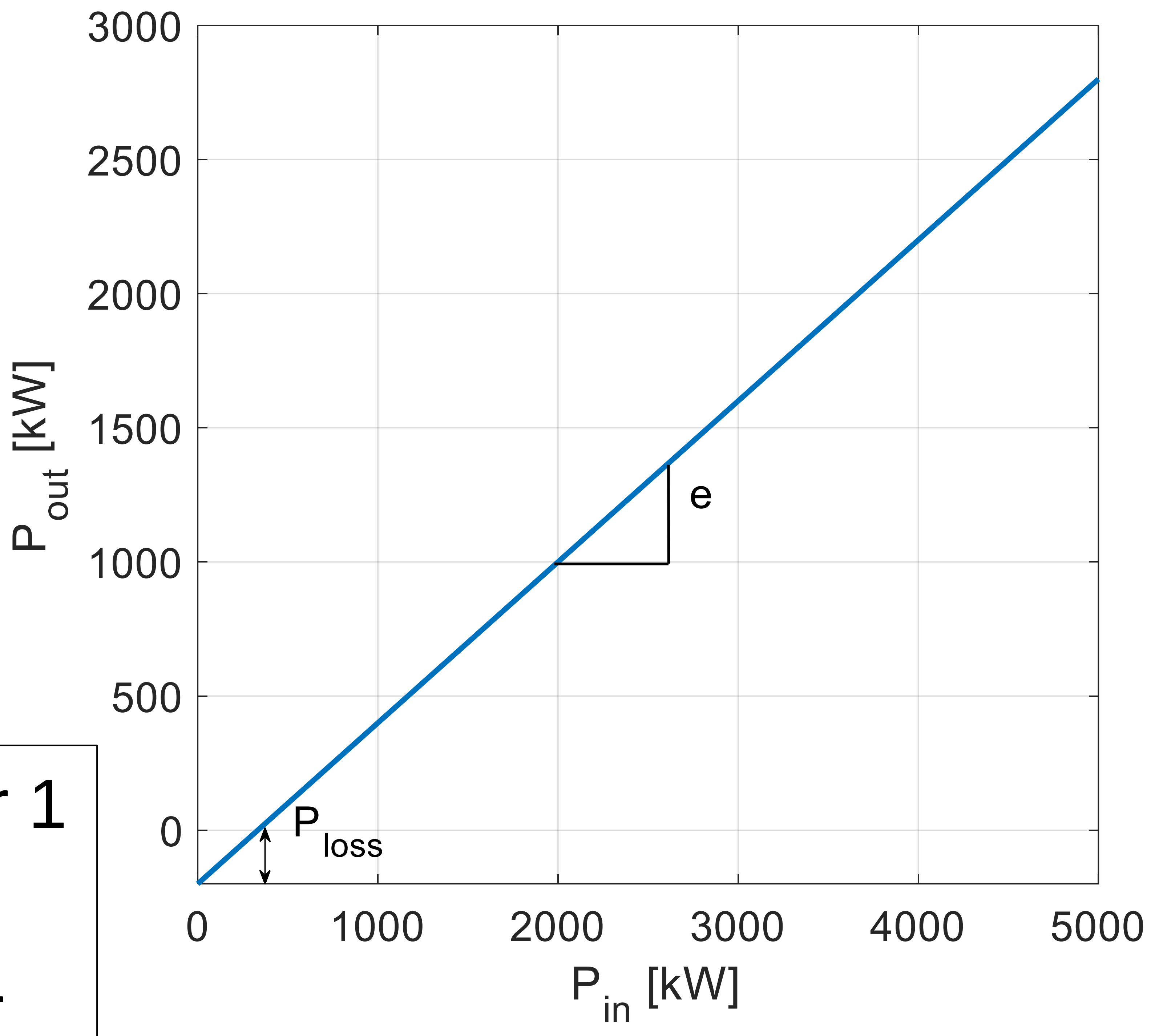
- Scaling law for fuel consumption
- Assumes that:
  - At constant N [rpm]: bsfc ~ load

    → $P\ [kW] = e \cdot P_{in} - P_{loss}$
  - Writing it independently of $V_d$:

    → $BMEP\ [Pa] = e \cdot AMEP - p_{m_{loss}}$

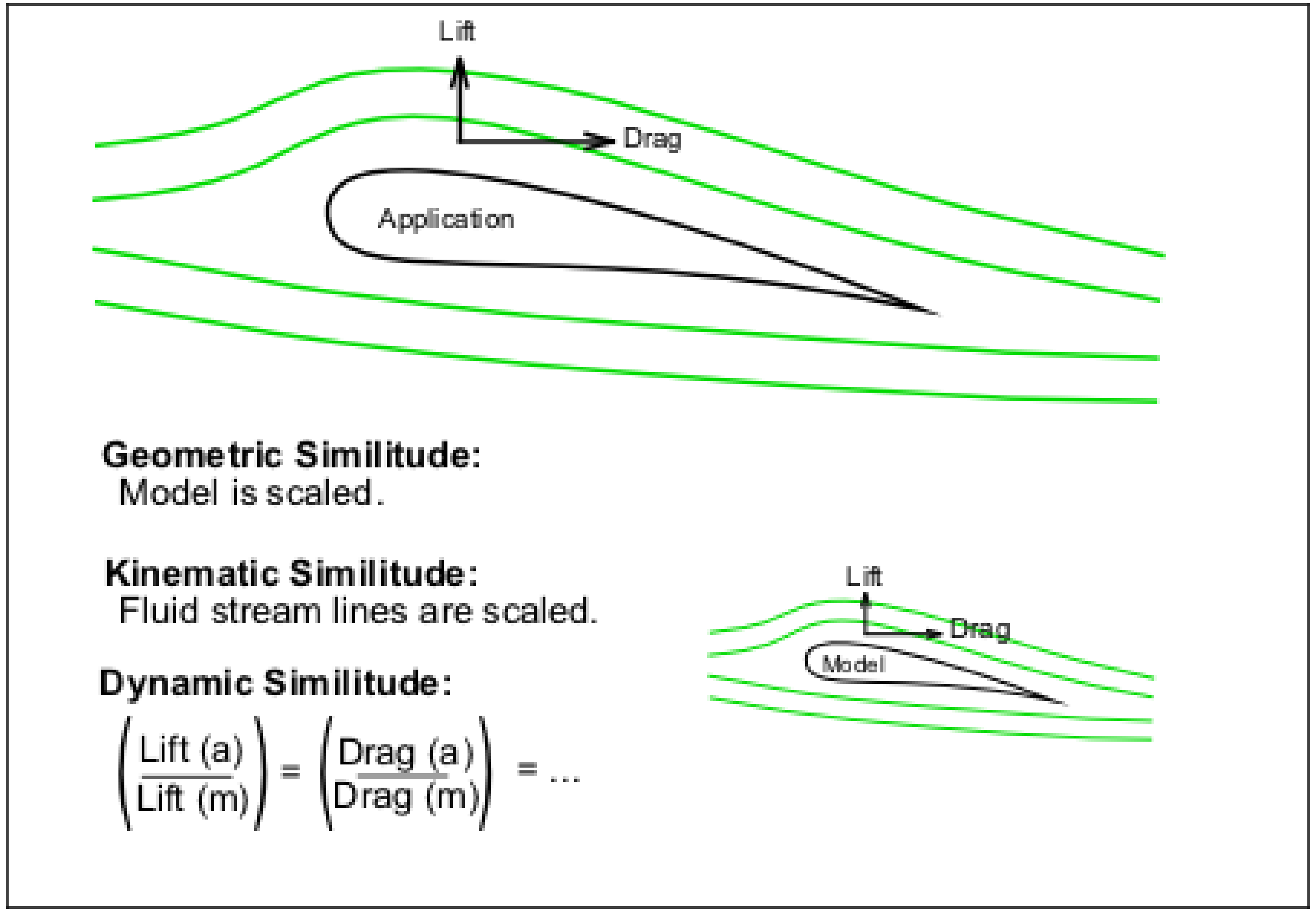
Rizzoni et al[6].: If BMEP and AMEP known for 1 optimized engine

→ $e\ \&\ p_{m_{loss}}$ can be calculated and used for other sized engines



# SIMILITUDE/SIMILARITY

– Concept originating from fluid mechanics




If similarity achieved → All dimensionless performance parameters equal to each other

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# SIMILITUDE/SIMILARITY

- Applied to ICEs: If small engine and large engine achieve similarity → BTE [%] and specific power [kW/l] identical
- For CI engines, 3 different approaches were established to reach similarity: S-law, P-law and L-law

| Parameters | Speed rule | Pressure rule | Lift-off rule |
|---|---|---|---|
| Bore ratio ($B_{scaled}/B_{ref}$) | r | r | r |
| Lift-off length ratio ($H_{scaled}/H_{ref}$) | $r^{4/3}$ | $r^{1/3}$ | r |
| Ratio of swirl ratio's ($SR_{scaled}/SR_{ref}$) | 1 | 1 | 1 |
| Fuel mass flow rate ratio ($\dot{m}_{f,scaled}/\dot{m}_{f,ref}$) | $r^3$ | $r^3$ | $r^3$ |
| Engine speed ratio ($N_{scaled}/N_{ref}$) | 1 | $r^{-1}$ | $r^{-1/3}$ |
| Injection rate ratio ($u_{0,scaled}/u_{0,ref}$) | r | 1 | $r^{2/3}$ |
| Injection duration ratio ($\tau_{scaled}/\tau_{ref}$) [s] | 1 | r | $r^{1/3}$ |
| Injection pressure ratio ($\Delta P_{scaled}/\Delta P_{ref}$) | $r^2$ | 1 | $r^{4/3}$ |

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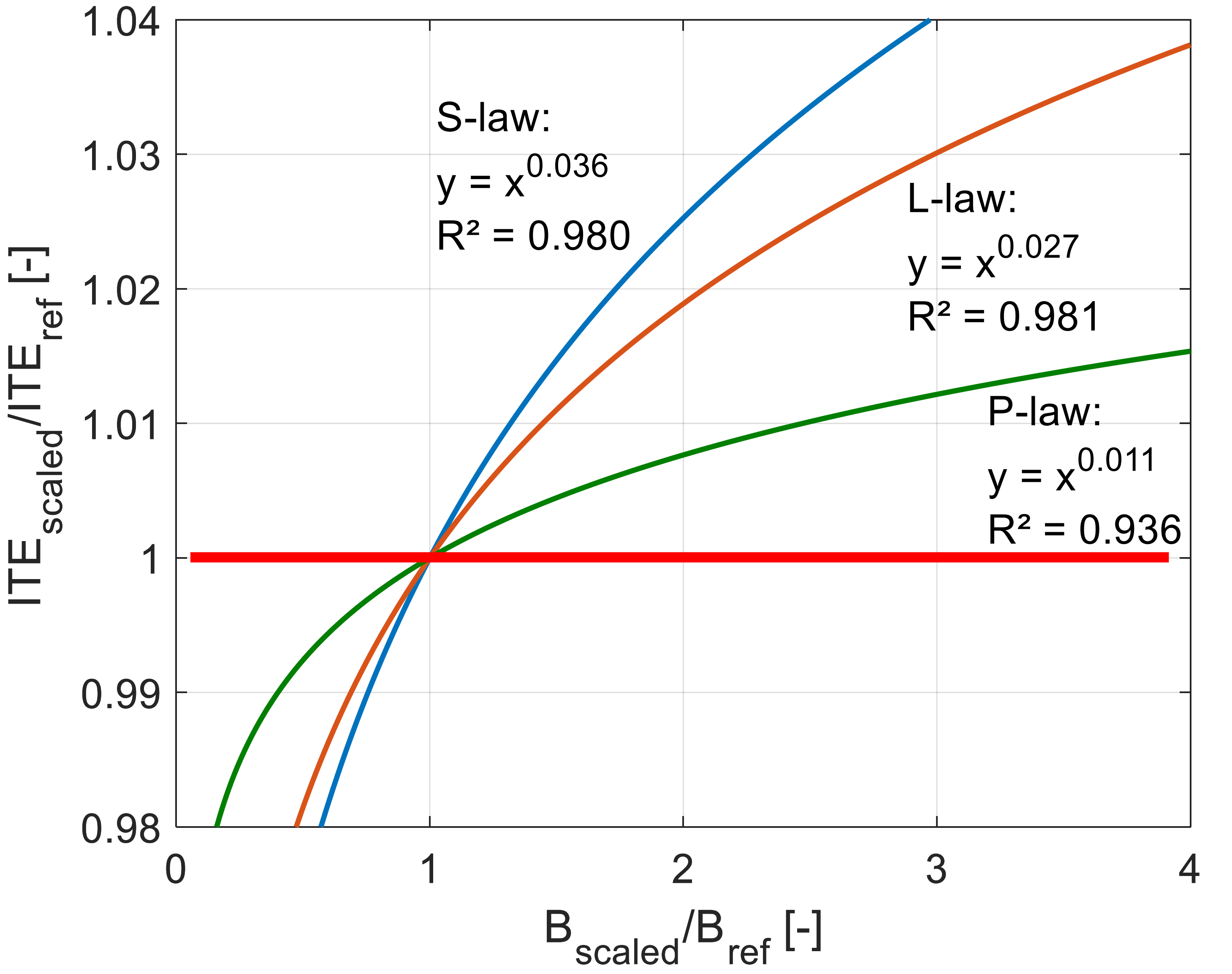
# SIMILITUDE/SIMILARITY

- Theory ↔ Reality
  - Example: ≠ heat losses
- Solution:




→ e.g.: P-law: $ITE_{scaled}\ [\%] = 50.63 \cdot V_{d,scaled}^{0.004}$

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# PROS AND CONS

## Curve fitted equations

- Ease of implementation
- Rapid result

- Large set of data is needed
- No boundary conditions or constraints defined
- No scaling laws with respect to emissions found

## Willans line method

- Ease of implementation
- Rapid result
- Only 1 reference engine needed

- No boundary conditions or constraints defined
- Designed for small changes in $V_d$
- Limited to scaling fuel consumption

## Similitude

- Already defines some design parameters
- Only 1 reference engine needed
- Constraints implemented

- Complex
- Yet unproven for SI operation

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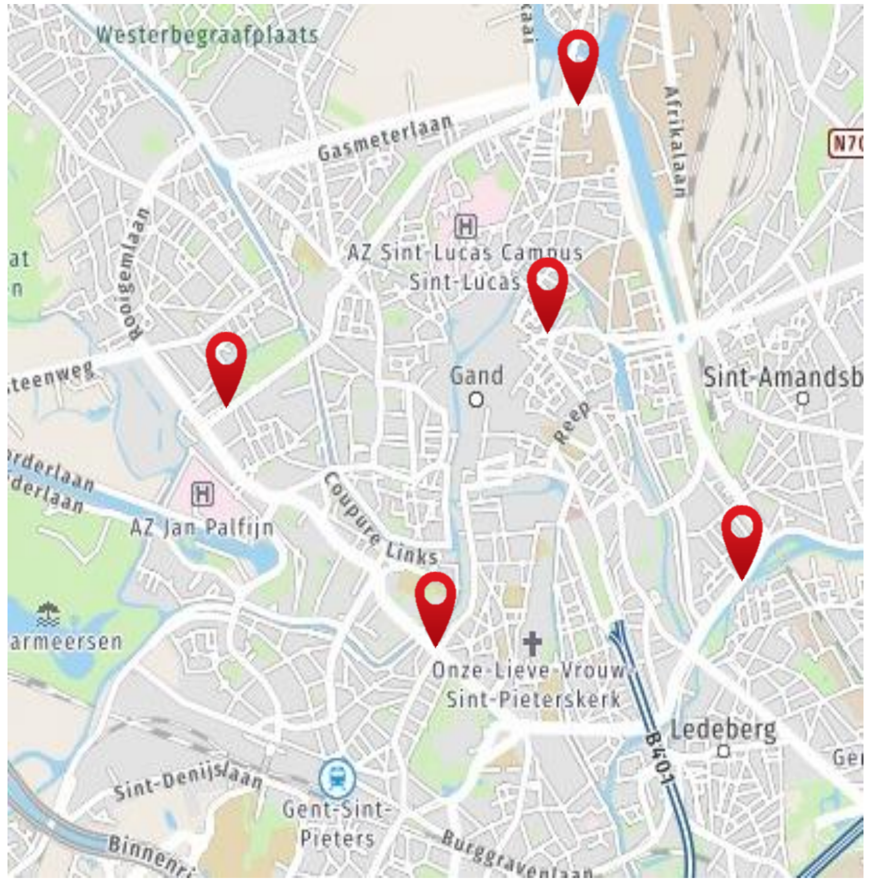
# FUTURE PERSPECTIVES

- In the short term: curve fitted equations show the highest potential
  - →Next requirement: gather/create as much engine data as possible
  - →Example: Thesis 2022-2023: conversion of 7.15l CI diesel engine to SI methanol operation
- If we then know, both <u>cost</u> and the <u>efficiency</u> of a large range of engines, we can make the following exercise:

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– 6) Rizzoni, G., Guzzella, L. and Baumann, B. M. “Unified modeling of hybrid electric vehicle drivetrains,” *IEEE/ASME Trans. Mechatronics*, vol. 4, no. 3, pp. 246–257, 1999, doi: 10.1109/3516.789683