Scaling Functions for the Simulation of Different SI-Engine Concepts in Conventional and Electrified Power Trains

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Agenda

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- Scaling of SI-engines
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  - engine definition
  - scaling procedure
  - database of parameter variations
  - scaling functions
- Scaling examples and applications
- Conclusion
Motivation

- **Rising pressure on carmakers to reduce fuel consumption and emissions:** Climate change, finiteness of oil, policy, customer demands

- **Promising technologies for SI-engines:**
  - small, turbocharged engines
  - highly variable engines
  - lowering mechanical losses
  - thermal management
  - lean burn concepts
  - electric hybridisation

- **What is the right size and concept of ICE and EM in a HEV?**
Approach

- Engine maps
  - Flexibility
  - Accuracy

- Engine data
  - Efficiency
  - Friction losses
  - Exhaust energy
  - Heat losses

- Scaling Functions

- Engine cycle simulation

- Full vehicle simulation system
  - Fuel consumption
  - Performance
  - Thermal behavior

- Computing time
- Expertise
Engine definition

Parameters of a SI-engine:

**Geometry**
- cylinder z
- single cyl. volume $V_h$
- stroke-bore-ratio $s/d$
- compression ratio $\varepsilon$

**Charging**
- naturally aspirated
- turbocharged

**Mixture Formation**
- port fuel injection
- direct injection

**Load Control**
- throttled
- unthrottled

**Combustion**
- air/fuel ratio $\lambda$
- exhaust gas fraction $y_r$

![Diagram showing fuel energy distribution between exhaust, cooling, work, and friction.](image)
Scaling procedure

Reference data

Normalization: ideal combustion phasing

Normalization: \( \lambda = 1.00 \)

Multiple scaling

\( V_h, s/d, \varepsilon, \lambda, x_r \)

Scaled data

Re-normalization: real combustion phasing

Scaling

\( f_{Skal}(n, \lambda, x_{Skal}) \)
Sources of data and information:

- **References**: Over 100 years of engine development
- **Experimental data**: BMW engines
  - burn rate calculation (BRC)
  - three pressure analysis (TPA)
- **Gas exchange and cycle simulation**: GT-Power
  - completely scalable engine geometry (bore as scaling factor)
  - various engine concepts: NA – Turbo, PFI – DI, VVT, ext. EGR, etc.
  - geometry based sub-models:
    - predictive combustion model ("SI-Turbulent")
    - turbulence ("In-Cylinder Flow")
    - heat transfer ("Flow")
  - empirical knock model ("SI Knock", extended for diluted operation)

- Calibration by experimental and reference data
- Huge parameter variations in the entire operation map
Parameter variation

**Variation of s/d-ratio at part-load:** $n = 1500 \text{ 1/min, } \lambda_l = 0,4$

- Long-stroke engines show higher efficiency: fast combustion, low heat losses
- Only predictive and geometry based sub-models can describe all relevant phenomena accurately
Parameter variation

Variation of EGR and $\lambda$ at high load: $n = 4000 \text{ 1/min, } p_{\text{me}} = 19 \text{ bar}$

$\tau = 0.01809 \cdot P \cdot (\text{ON/100})^{3.402} \cdot P^{-1.7} \cdot e^{(3800/T_u)}$

$P(\lambda, y_R) = 2.89 \cdot \lambda^2 - 4.85 \cdot \lambda + 2.50 \cdot y_R + 3.63$

extension for diluted operation

![Graphs showing variations in efficiency and other performance metrics with EGR rate and air/fuel ratio.](image)
Parameter variation

Combustion retard at borderline knock limit: Influence on the energy balance

- Satisfying accordance with measurements and references
- Stable correlations for various scaling parameters and operating points
Scaling functions

Requirements:
- flexible
- modular
- handy
- transparent
- comprehensible
- accurate

Type of functions:

**basic function**

\[ f_{\text{Skal}} = \frac{a + b \cdot x^c}{a + b \cdot x_0^c} \]

\[ \eta_i = \eta_{i,0} \cdot f_{\text{Skal},\eta}(x, x_0) \]

**speed & load:** polynomial type

\[ f_{\text{Skal}} = \frac{a + f(n, \lambda_1, \ldots) \cdot x^c}{a + f(n, \lambda_1, \ldots) \cdot x_0^c} \]

**interaction:** linear type

\[ f_{\text{Skal}} = \left( \frac{a + f(n, \lambda_1, \ldots) \cdot x^c}{a + f(n, \lambda_1, \ldots) \cdot x_0^c} \right) \sum_{i}^{n} (x_{q,i} - x_{q,0,i})d_i + 1 \]
Scaling example

Scaling a Turbocharged DI-engine from fixed to variable compression ratio:

**Procedure:** Finding the ideal compression ratio for every operation point by scaling function.

Further examples: Downsizing (w/ and w/o cylinder change), high load EGR, lean burn concepts, etc.
Fuel savings by downsizing and var. compression ratio:

- full vehicle simulation system: NEDC
- premium sedan: 1700 kg, 225 kW, automatic gearbox (8 gears), automatic engine stop
- scaled engine maps: friction, fuel consumption, exhaust energy, heat losses

![Graph showing fuel savings for different engine sizes.]

- 3.4 L 6 cyl. $\varepsilon_{ref} = 10.5$, -3.8%
- 3.0 L 6 cyl. $\varepsilon_{ref} = 11.0$, -4.0%
- 2.5 L 6 cyl. $\varepsilon_{ref} = 10.2$, -6.8%
- 2.0 L 4 cyl. $\varepsilon_{ref} = 9.1$, -6.8%

Sigma >20%
Interaction of engine technologies and electrification:

> fuel savings by electrification strongly depend on the the base efficiency of the conventional power train

> **but:** the extent depends on the effectiveness and the characteristic of a certain engine concept

> the operational strategy must be adapted for every HEV-architecture
Conclusion

- GT-Power was essential for deriving thermodynamic dependencies:
  - predictive and geometry based sub-models
  - extensive libraries to model and control diverse engine configurations
  - limited interfaces to sub-models
  - modeling of unburnt fuel (HC-Emissions)

- Scaling approach is suitable for investigating various SI-engine concepts and technologies in an early stage of development:
  - **not** for detailed engine optimization
  - **but** energetic evaluations

- Modular and stepwise procedure is open to further extensions:
  - more scaling parameters
  - distinguishing different engine concepts
  - detailed thermodynamics: further simulations, measurements
Thank you for your attention!