Vehicle Propulsion Systems
Lecture 3
Internal Combustion Engine Powertrains

Lars Eriksson
Associate Professor (Docent)

Vehicular Systems
Linköping University

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About the hand-in tasks

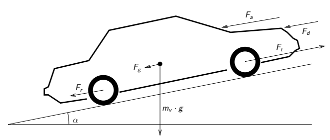
- General advice
  –Prepare yourselves before you go to the computer
  –Make a plan (list of tasks)
- Hand-in Format
  We would prefer (not a demand):
  - Electronic hand-in
  - Report in PDF-format
  - Reasons:
    –Easy for us to comment
    –Will give you fast feedback

Outline

The Vehicle Motion Equation

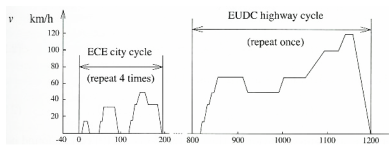
Newtons second law for a vehicle

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$



- F_t – tractive force
- F_a – aerodynamic drag force
- F_r – rolling resistance force
- F_g – gravitational force
- F_d – disturbance force

Energy consumption for cycles



Numerical values for MVEG-95, ECE, EUDC

$$\text{air drag} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i^3\, h = \{319, 82.9, 455\}$$

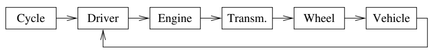
$$\text{rolling resistance} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i\, h = \{.856, 0.81, 0.88\}$$

$$\text{kinetic energy} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i\, \bar{v}_i\, h = \{0.101, 0.126, 0.086\}$$

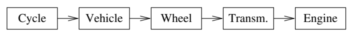
$$\bar{E}_{\text{MVEG-95}} \approx A_f\, c_d\, 1.9 \cdot 10^4 + m_v\, c_r\, 8.4 \cdot 10^2 + m_v\, 10 \qquad kJ/100km$$

Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)



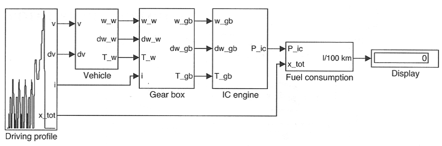
  –"Normal" system modeling direction
  –Requires driver model
- Quasistatic simulation (inverse simulation)



  –"Reverse" system modeling direction
  –Follows driving cycle exactly

QSS Toolbox – Quasistatic Approach

- IC Engine Based Powertrain



- The Vehicle Motion Equation – With inertial forces:
  $\left[m_v + \frac{\gamma^2}{r_w^2} J_e + \frac{1}{r_w^2} J_w\right] \frac{d}{dt} v(t) = \frac{\gamma}{r_w} T_e - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$

Acceleration Performance

- Starting point:
  Study the build up of kinetic energy

$$E_0 = \frac{1}{2}\, m_v\, v_0^2$$

- Assume that all engine power will build up kinetic energy (neglecting the resistance forces)
  Average power: $\bar{P} = E_0/t_0$
- Ad hoc relation, $\bar{P} = \frac{1}{2} P_{max}$
  Assumption about an ICE with approximately constant torque (also including some non accounted losses)

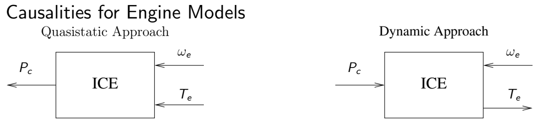
$$P_{max} = \frac{m_v\, v^2}{t_0}$$

Outline

Causality and Basic Equations

High level modeling – Inputs and outputs

- Causalities for Engine Models



- Engine efficiency

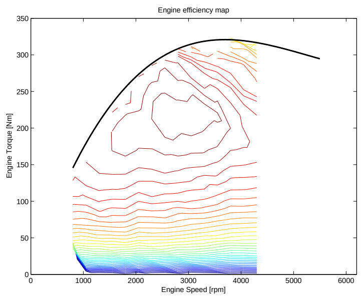
$$\eta_e = \frac{\omega_e\, T_e}{P_c}$$

- Enthalpy flow of fuel (Power $\dot{H}_{fuel} = P_c$)

$$P_c = \dot{m}_f\, q_{LHV}$$

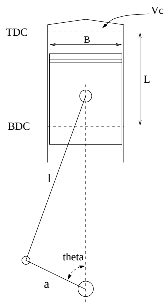
Engine Efficiency Maps

Measured engine efficiency map – Used very often



–What to do when map-data isn't available?

Engine Geometry Definitions



Cylinder, Piston, Connecting rod, Crank shaft

- Bore, B
- Stroke, $S = 2\,a$
- Number of cylinders z
- Cylinder swept volume, $V_d = \frac{\pi\, B^2\, S}{4}$
- Engine swept volume, $V_d = z\, \frac{\pi\, B^2\, S}{4}$
- Compression ratio $r_c = \frac{V_{max}}{V_{min}} = \frac{V_d + V_c}{V_c}$

Definition of MEP

See whiteboard.

Normalized Engine Variables

- Mean Piston Speed ($S_p = mps = c_m$):

$$c_m = \frac{\omega_e\, S}{\pi}$$

- Mean Effective Pressure (MEP=p_{me} ($N = n_r \cdot 2$)):

$$p_{me} = \frac{N\, \pi\, T_e}{V_d}$$

- Used to:
  - Compare performance for engines of different size
  - Design rules for engine sizing.
    At max engine power: $c_m \approx 17$ m/s, $p_{me} \approx 1e6$ Pa (no turbo)
    $\Rightarrow$ engine size
  - Connection:

$$P_e = z\, \frac{\pi}{16}\, B^2\, p_{me}\, c_m$$

Simple Case Study – Engine Dimensioning

Design of an engine to a light weight vehicle:

- Specifications
  Mass: 750 kg + 100 kg payload
  Acceleration: 0 to 100 km/h in 15 seconds

  Simple relation (Le2) $\Rightarrow P_{max} = 45$ kW

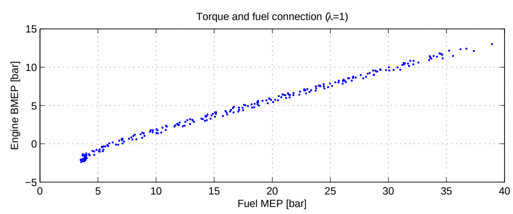
- Using the facts:
  At max engine power: $c_m \approx 17$ m/s, $p_{me} \approx 1e6$ Pa
  and the connection:

$$P_e = z\, \frac{\pi}{16}\, B^2\, p_{me}\, c_m$$

- Gives the engine size
  Selecting a three cylinder engine $z = 3$
  Gives bore $B = 6.7$ cm.

Torque modeling through – Willans Line

- Measurement data: x: p_{mf} y: $p_{me} = BMEP$

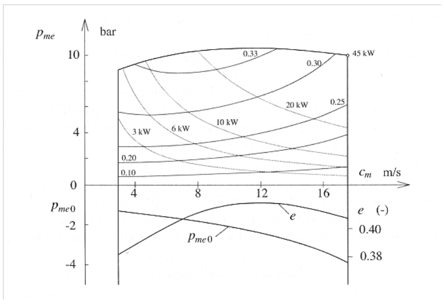


- Linear (affine) relationship – Willans line

$$p_{me} = e(\omega_e) \cdot p_{mf} - p_{me,0}(\omega_e)$$

- Engine efficiency: $\eta_e = \frac{p_{me}}{p_{mf}}$

Engine Efficiency – Map Representation



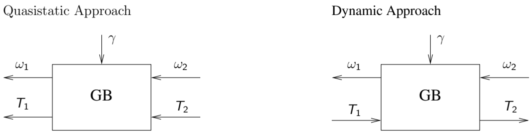
Willans line parameters: $e(\omega_e)$ $p_{me,0}(\omega_e)$

Outline

- Repetition
- IC Engine Models
  - Quasistatic and Dynamic Approach
  - Normalized Engine Variables
  - Engine Efficiency
- Gear-Box and Clutch Models
  - Quasistatic and Dynamic Approach
  - Selection of Gear Ratio
  - Gear-Box Efficiency
  - Clutches and Torque Converters
- Analysis of IC Powertrains
  - Average Operating Point
  - Quasistatic Analysis
- Gear ratio optimization

Causality and Basic Equations

- Causalities for Gear-Box Models



- Power balance – Loss free model

$$\omega_1 = \gamma \omega_2, \qquad T_1 = \frac{T_2}{\gamma}$$

Different Types of Gearboxes

- Manual Gear Box
- Automatic Gear Box, with torque converter
- Automatic Gear Box, with automated clutch
- Automatic Gear Box, with dual clutches (DCT)
- Continuously variable transmission

Connections of Importance for Gear Ratio Selection

- Vehicle motion equation:

$$m_v \frac{d}{dt} v(t) = F_t - \frac{1}{2} \rho_a A_f c_d v^2(t) - m_v g c_r - m_v g \sin(\alpha)$$

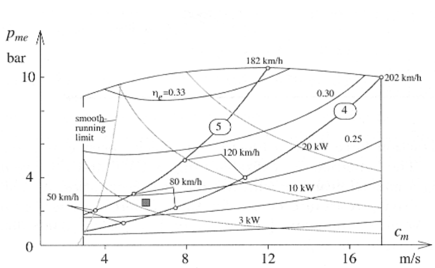
Constant speed $\frac{d}{dt} v(t) = 0$:

$$F_t = \frac{1}{2} \rho_a A_f c_d v^2(t) + m_v g c_r + m_v g \sin(\alpha)$$

- A given speed v will require power $F_t v$ from the powertrain.
- This translates to power at the engine $T_e \omega_e$. Changing/selecting gears decouples ω_e and v.
- Required tractive force increases with speed. For a fixed gear ratio there is also an increase in required engine torque.

Selection of Gear Ratio

Gear ratio selection connected to the engine map.



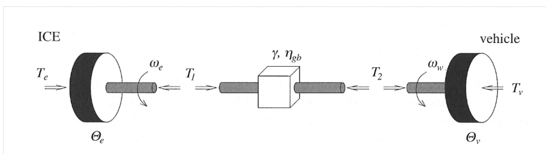
Additionally: Also geometric ratio between gears.
$\frac{i_{g,1}}{i_{g,2}} \approx \frac{i_{g,2}}{i_{g,3}} \approx \frac{i_{g,3}}{i_{g,4}} \approx \frac{i_{g,4}}{i_{g,5}}$

Selection of Gear Ratio

Optimizing gear ratio for a certain cycle.

- Potential to save fuel.
- Case study 8.1 (we'll look at it later).

Gear-box Efficiency



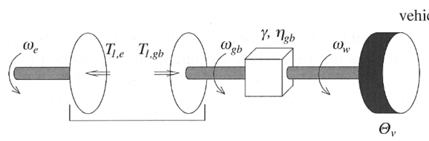
- In traction mode

$$T_2 \omega_w = e_{gb} T_1 \omega_e - P_{0,gb}(\omega_e), \qquad T_1 \omega_e > 0$$

- In engine braking mode (fuel cut)

$$T_1 \omega_e = e_{gb} T_2 \omega_w - P_{0,gb}(\omega_e), , \qquad T_1 \omega_e < 0$$

Clutch and Torque Converter Efficiency

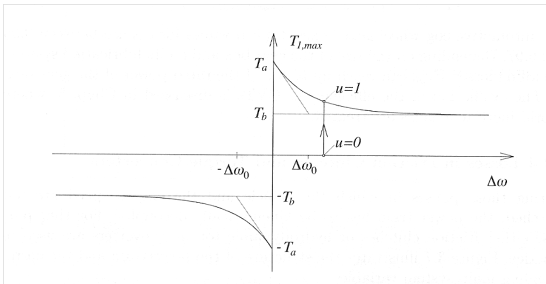


Friction clutch torque:

$$T_{1,e}(t) = T_{1,gb}(t) = T_1(t) \; \forall t$$

Action and reaction torque in the clutch, no mass.

Torque Characteristics of a Friction Clutch



Approximation of the maximum torque in a friction clutch

$$T_{1,max} = \text{sign}(\Delta\omega)\left(T_b - (T_b - T_a)\cdot e^{-|\Delta\omega|/\Delta\omega_0}\right)$$

Main parameters in a Torque Converter

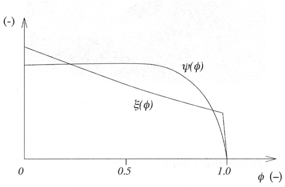
Input torque at the converter:

$$T_{1,e}(t) = \xi(\phi(t))\, rho_h\, d_p^5\, \omega_e^2(t)$$

Converter output torque

$$T_{1,gb}(t) = \psi(\phi(t)) \cdot T_{1,e}(t)$$

Graph for the speed ratio $\phi(t) = \frac{\omega_{gb}}{\omega_e}$, and the experimentally determined $\psi(\phi(t))$

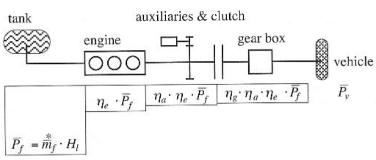


The efficiency in traction mode becomes

$$\eta_{tc} = \frac{\omega_{gb}\, T_{1,gb}}{\omega_e\, T_{1,e}} = \psi(\phi)\,\phi$$

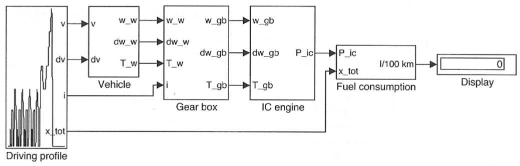
Outline

Average Operating Point Method



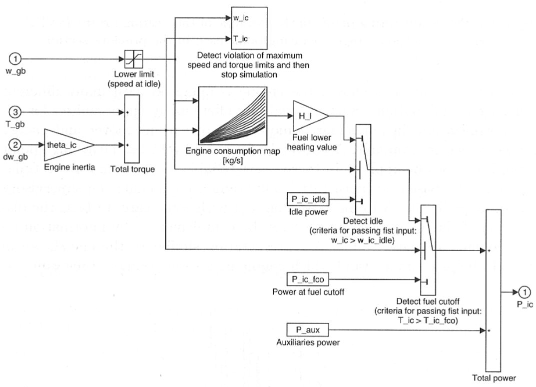
- Average operating point method
  –Good agreement for conventional powertrains.
- Hand-in assignment.

Quasistatic analysis – Layout

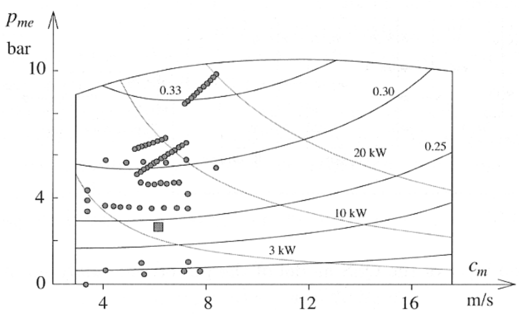


- More details and better agreement (depends on model quality)
  –Good agreement for general powertrains
- Hand-in assignment.

Quasistatic analysis – IC Engine Structure



Quasistatic analysis – Engine Operating Points



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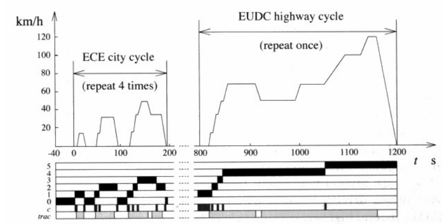
Driving cycle specification – Gear ratio



Gears specified but ratios free.
–How much can the gear ratio be improved?

Path to the solution

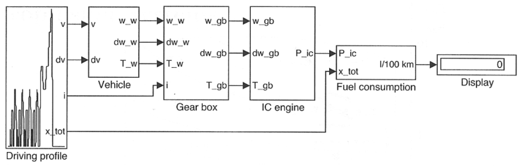
- Implement a simulation model that calculates m_f for the cycle.
- Set up the decision variables $i_{g,j}$, $j \in [1,5]$.
- Set up problem

$$\begin{aligned} \min \quad & m_f(i_{g,1}, i_{g,2}, i_{g,3}, i_{g,4}, i_{g,5}) \\ \text{s.t.} \quad & \text{model and cycle is fulfilled} \end{aligned} \qquad (1)$$

- Use an optimization package to solve (1)
- Analyze the solution.

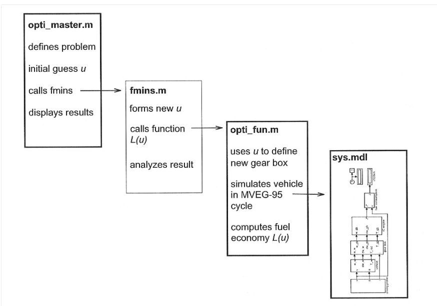
Model implemented in QSS

Conventional powertrain.



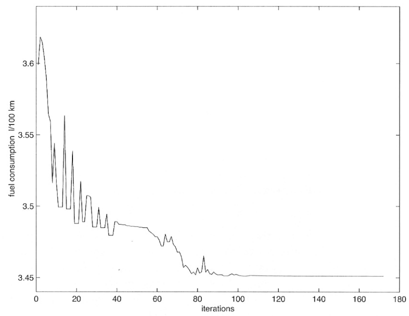
Efficient computations are important.

Structure of the code



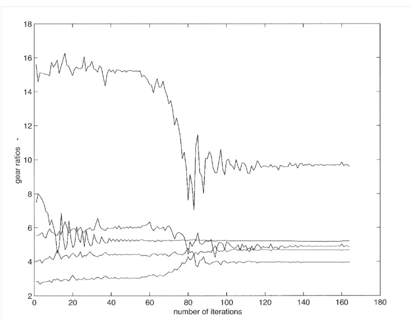
Will use a similar setup in hand-in assignment 2.

Running the solver



Improves the fuel consumption with 5%.

Running the solver



Complex problem, global optimum not guaranteed.
Several runs with different initial guesses.