Vehicle Propulsion Systems
Lecture 3

Conventional Powertrains with Transmission
Performance, Tools and Optimization

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March 21, 2018

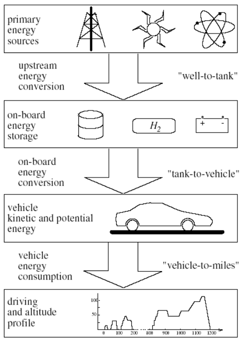
About the hand-in tasks

- General advice
  –Prepare yourselves before you go to the computer
  –Make a plan (list of tasks)
- Hand-in Format
  - Electronic hand-in
  - Report in PDF-format
  - Reasons:
    –Easy for us to comment
    –Will give you fast feedback

Outline

Repetition
Gear-Box and Clutch Models
  Selection of Gear Ratio
  Gear-Box Efficiency
  Clutches and Torque Converters
Analysis of IC Powertrains
  Average Operating Point
  Quasistatic Analysis
Other Demands on Vehicles
  Performance and Driveability
Optimization Problems
Gear ratio optimization
  Software tools

Energy System Overview



Primary sources

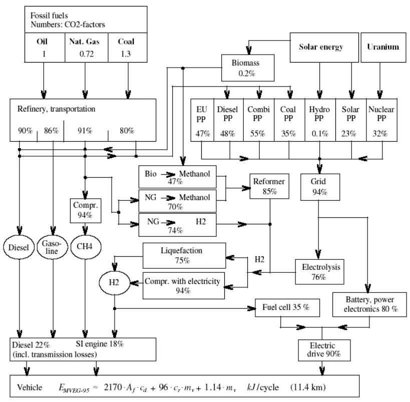
Different options for on-board energy storage

Powertrain energy conversion during driving

Cut at the wheel!

Driving mission has a minimum energy requirement.

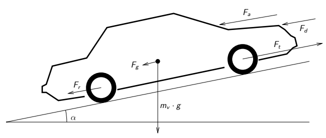
W2M – Energy Paths



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

Mechanical Energy Demand of a Cycle

Only the demand from the cycle

- The mean tractive force during a cycle

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_0^{x_{tot}} \max(F(x), 0)\, dx = \frac{1}{x_{tot}} \int_{t \in trac} F(t)v(t)dt$$

  where $x_{tot} = \int_0^{t_{max}} v(t)dt$.
- Note $t \in trac$ in definition.
- Only traction.
- Idling not a demand from the cycle.

Evaluating the integral

Tractive force from *The Vehicle Motion Equation*

$$F_{trac} = \frac{1}{2} \rho_a A_f c_d v^2(t) + m_v g c_r + m_v a(t)$$

$$\bar{F}_{trac} = \bar{F}_{trac,a} + \bar{F}_{trac,r} + \bar{F}_{trac,m}$$

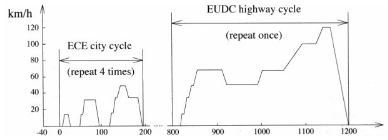
Resulting in these sums

$$\bar{F}_{trac,a} = \frac{1}{x_{tot}} \frac{1}{2} \rho_a A_f c_d \sum_{i \in trac} \bar{v}_i^3 h$$

$$\bar{F}_{trac,r} = \frac{1}{x_{tot}} m_v g c_r \sum_{i \in trac} \bar{v}_i h$$

$$\bar{F}_{trac,m} = \frac{1}{x_{tot}} m_v \sum_{i \in trac} \bar{a}_i \bar{v}_i h$$

Values for cycles



Numerical values for the cycles: {MVEG-95, ECE, EUDC}

$$\bar{X}_{trac,a} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i^3\, h = \quad \{319, 82.9, 455\}$$

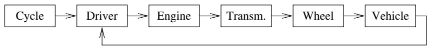
$$\bar{X}_{trac,r} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i\, h = \quad \{0.856, 0.81, 0.88\}$$

$$\bar{X}_{trac,m} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i\, \bar{v}_i\, h = \quad \{0.101, 0.126, 0.086\}$$

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

Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)



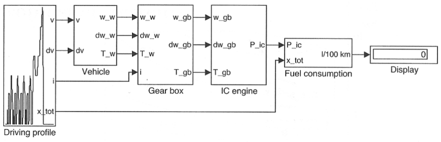
–"Normal" system modeling direction
–Requires driver model

- 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:
  $\left[m_v + \frac{1}{r_w^2} J_w + \frac{\gamma^2}{r_w^2} J_e\right] \frac{d}{dt} v(t) = \frac{\gamma}{r_w} T_e - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$
- Gives efficient simulation of vehicles in driving cycles

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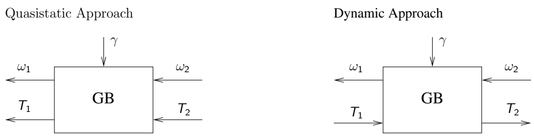
Causality and Basic Equations

- 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:

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

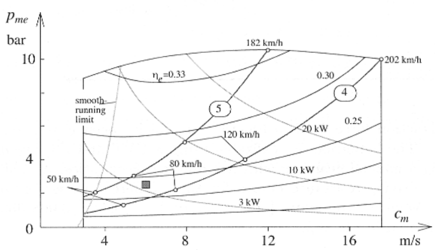
Constant speed $\frac{d}{dt} v(t) = 0$:

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

- 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.



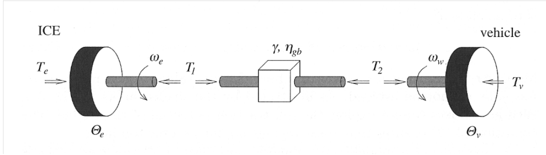
Additionally: Also geometric ratio between gears.
$\frac{i_{g,1}}{i_{g,2}} \approx \frac{i_{g,2}}{i_{g,3}} \approx \frac{i_{g,3}}{i_{g,4}} \approx \frac{i_{g,4}}{i_{g,5}}$

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



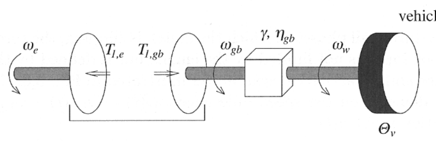
- In traction mode

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

- 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

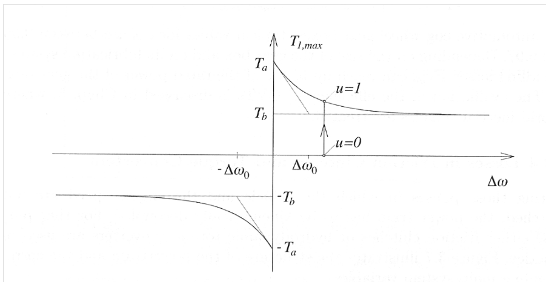


Friction clutch torque:

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

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

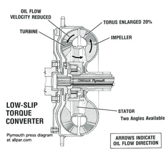
Input torque at the converter:

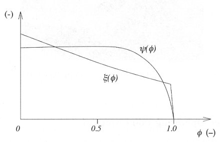
$$T_{1,e}(t) = \xi(\phi(t))\,\rho_h\,d_p^5\,\omega_e^2(t)$$

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

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

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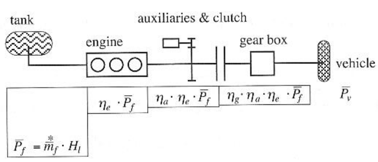
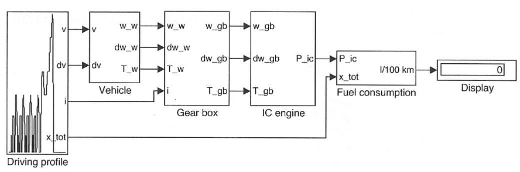
Average Operating Point Method



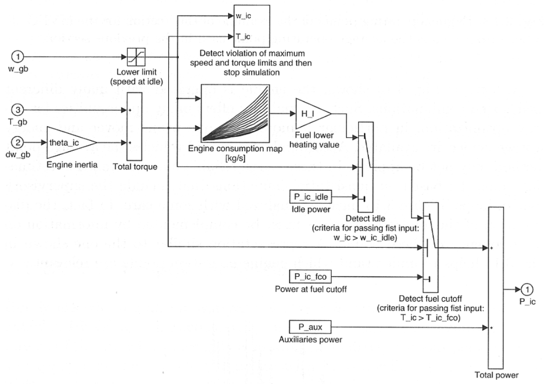
- Average operating point method
  –Good agreement for conventional powertrains.
- Hand-in assignment.

Quasistatic analysis – Layout

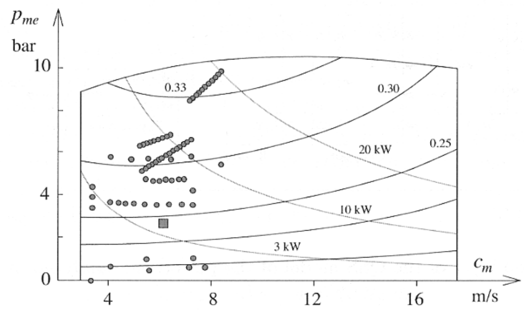


- More details and better agreement (depends on model quality)
  –Good agreement for general powertrains
- Hand-in assignment.

Quasistatic analysis – IC Engine Structure



Quasistatic analysis – Engine Operating Points



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Performance and driveability

- Important factors for customers
- Not easy to define and quantify
- For passenger cars:
  - Top speed
  - Maximum grade for which a fully loaded car reaches top speed
  - Acceleration time from standstill to a reference speed (100 km/h or 60 miles/h are often used)

Top Speed Performance

- Starting point – The vehicle motion equation.

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

- At top speed

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

  and the air drag is the dominating loss.
- power requirement ($F_t = \frac{P_{max}}{v}$):

$$P_{max} = \frac{1}{2} \rho_a A_f c_d v^3$$

  Doubling the power increases top speed with 26%.

Uphill Driving

- Starting point the vehicle motion equation.

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

- Assume that the dominating effect is the inclination ($F_t = \frac{P_{max}}{v}$), gives power requirement:

$$P_{max} = v \, m_v \, g \sin(\alpha)$$

- Improved numerical results require a more careful analysis concerning the gearbox and gear ratio selection.

Acceleration Performance

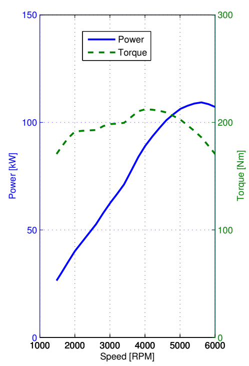
- Starting point:
  Study the build up of kinetic energy

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

- 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)

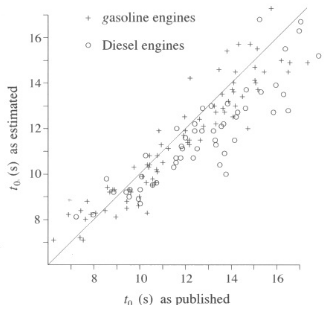
$$P_{max} = \frac{m_v v^2}{t_0}$$

Maximum Engine Torque and Power



Acceleration Performance – Validation

Published data and $P_{max} = \frac{m_v v^2}{t_0}$



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Optimization problems

Different problem types occur in vehicle optimization
- Structure optimization
- Parametric optimization
- Control system optimization

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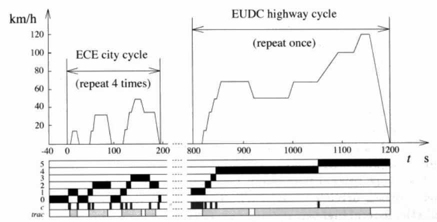
Driving cycle specification – Gear ratio



Gears specified but ratios free.
–How much can changed gear ratios improve the fuel economy?

Path to the solution

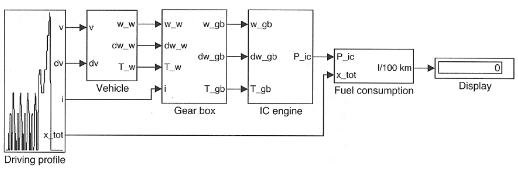
- Implement a simulation model that calculates m_f for the cycle.
- Set up the decision variables $i_{g,j}$, $j \in [1, 5]$.
- Set up problem

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

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

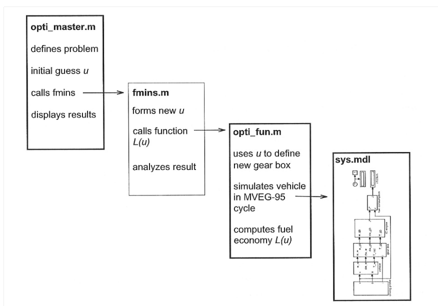
Model implemented in QSS

Conventional powertrain.



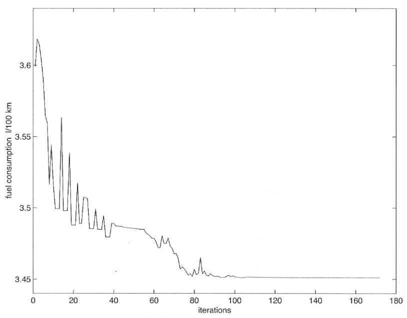
Efficient computations are important.

Structure of the code



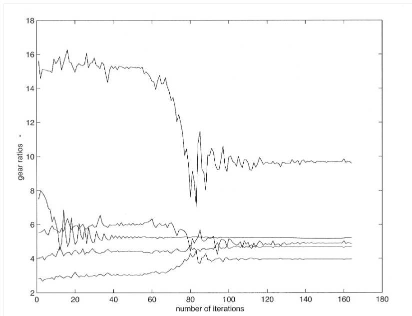
Will use a similar setup in hand-in assignment 2.

Running the solver



Improves the fuel consumption with 5%.
–Improvements of 0.5% are worth pursuing.

Running the solver



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

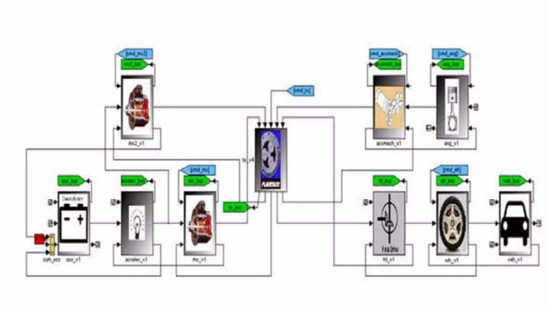
Software tools

Different tools for studying energy consumption in vehicle propulsion systems

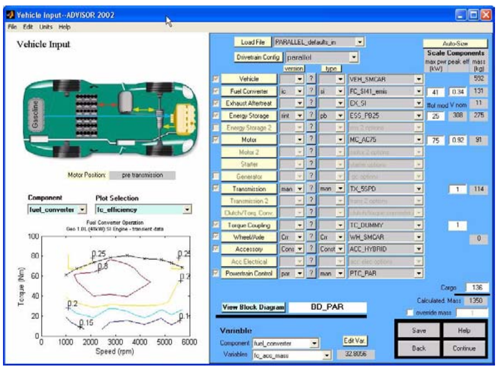
	Quasi static	Dynamic
QSS (ETH)	X	
Advisor, AVL	X	(X)
PSAT		X
CAPSim (VSim)		X
Inhouse tools	(X)	(X)

PSAT

Argonne national laboratory



Advisor



Advisor

Information from AVL:

- The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) first developed ADVISOR in 1994.
- Between 1998 and 2003 it was downloaded by more than 7,000 individuals, corporations, and universities world-wide.
- In early 2003 NREL initiated the commercialisation of ADVISOR through a public solicitation.
- AVL responded and was awarded the exclusive rights to license and distribute ADVISOR world-wide.