

Vehicle Propulsion Systems

Lecture 3

Internal Combustion Engine Powertrains

Vehicle Energy System

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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

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Outline

Repetition

Energy System Overview

Different Links in the Energy Chain
Why liquid hydrocarbons?

A Well-to-Miles Analysis

Some Energy Paths
Conventional, Electric and Fuel Cell Vehicles
Pathways to Better Fuel Economy

Other Demands on Vehicles

Performance and Driveability

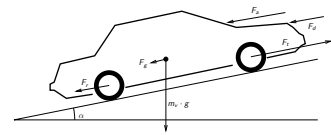
Optimization Problems

Gear ratio optimization

The Vehicle Motion Equation

Newtons second law for a vehicle

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

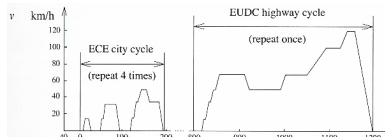


- ▶ F_t – tractive force
- ▶ F_a – aerodynamic drag force
- ▶ F_r – rolling resistance force
- ▶ F_g – gravitational force
- ▶ F_d – disturbance force

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Energy consumption for cycles



Numerical values for MVEG-95, ECE, EUDC

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

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

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

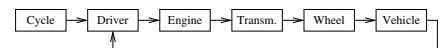
$$\bar{E}_{MVEG-95} \approx A_f C_d 1.9 \cdot 10^4 + m_v C_r 8.4 \cdot 10^2 + m_v 10 \quad \text{kJ/100km}$$

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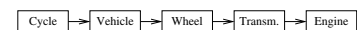
Two Approaches for Powertrain Simulation

Dynamic simulation (forward simulation)



- "Normal" system modeling direction
- Requires driver model

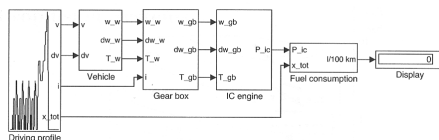
Quasistatic simulation (inverse simulation)



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

QSS Toolbox – Quasistatic Approach

▶ IC Engine Based Powertrain



▶ The Vehicle Motion Equation – With inertial forces:

$$\left[m_v + \frac{\gamma^2}{r_w^2} J_e + \frac{1}{r_w^2} J_w \right] \frac{d}{dt} v(t) = \frac{\gamma}{r_w} T_e - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$

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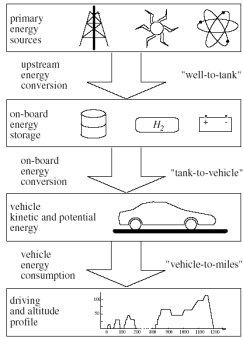
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Energy System Overview



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.

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Primary Energy Sources

Few sources – But many options

- ▶ Oil, Natural Gas, Coal
 - ▶ Oil wells as we know them will be depleted
 - ▶ Still much usable carbon in the ground
 - ▶ Cost will increase
- ▶ Nuclear power
 - ▶ Fission material available
 - ▶ Fusion material available
- ▶ Solar power
 - ▶ Hydro, wind, wave power
 - ▶ Solar cell electricity
 - ▶ Crop, forest, waste
 - ▶ Bacteria

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Energy Carriers for On-Board Storage

Energy carriers – Many possibilities

- ▶ Diesel, Gasoline, Naphtha, ...
- ▶ CH₄, Compressed Natural Gas (CNG), Liquefied Petr. Gas (LPG), ...
- ▶ CH₃OH, C₂H₅OH, C₄H₉OH, DME, ...
- ▶ H₂
- ▶ Batteries

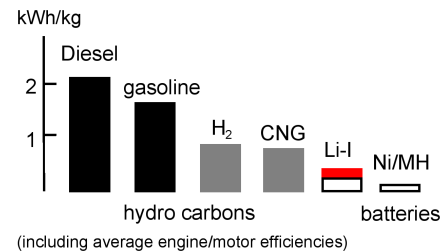
–What are the desirable properties?

- ▶ High energy density – Long range
- ▶ High refueling power – Fast refueling
- ▶ Simple refueling
- ▶ Low environmental impact (health aspects)
- ▶ Infrastructure

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Why (Liquid) Hydrocarbons?

- ▶ Excellent energy density
- ▶ High refueling power
- ▶ Good Well-to-Tank efficiency



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Why (Liquid) Hydrocarbons?

Think of the fuel molecules as a wire that pulls the vehicle forward.

- ▶ –How thick is the fuel wire?
- ▶ 1500 kg car needs 6 liters per 100 km.
 $\text{Area} = 0.006 / 100000 = 6 \times 10^{-8} \text{ m}^2$
 $D = \sqrt{6 \times 10^{-8} \times 4 / \pi} \approx 0.3 \text{ mm}$
- ▶ A 40000 kg truck needs 30 liters per 100 km.
 $\text{Area} = 0.03 / 100000 = 3 \times 10^{-7} \text{ m}^2$
 $D = \sqrt{3 \times 10^{-7} \times 4 / \pi} \approx 0.6 \text{ mm}$

–Chemical bonds are strong!

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Why (Liquid) Hydrocarbons?

- ▶ Filling a car at the gas station.
 - ▶ filling the tank with 55 [dm³] of gasoline
 - ▶ takes about 1 minute and 55 seconds
- ▶ What is the power?

The heating value for isooctane is $q_{LHV} = 44.3 \text{ [MJ/kg]}$, and the density is $\rho = 0.69 \text{ [kg/dm}^3\text{]}$. Gives the power

$$\dot{Q} = \frac{44.3 \cdot 0.69 \cdot 55 \text{ MJ}}{115 \text{ s}} = 14.6 \text{ [MW]}$$

(Perspective: Worlds biggest wind turbine is 7.58 MW. Enercon E-126, rated capacity 7.58 MW, height 198 m (650 ft), diameter 126 m.)
- ▶ What is the current?

For a single line 240 V system this would mean 60000 A!
 (Perspectives: 0.2 A kills a human.
 Residential house, 3*16 A.)

We have a challenge in finding a replacement for the fuel!

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Upstream Energy Conversion

- ▶ Manufacturing (pumping, crop, ...).
- ▶ Transport to refinery
- ▶ Refining
- ▶ Transport to filling station
- ▶ Filling of Vehicle

Ongoing intense research

–Investigating energy paths and improving all processes.

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Energy Conversion in Vehicles

Many paths in the vehicle

- ▶ Energy storage(s) (tank, battery, super caps)
- ▶ Energy refiner (reformer)
- ▶ Energy converter(s)
- ▶ Power (force) to/from transportation mission

This important topic will be covered later in the course

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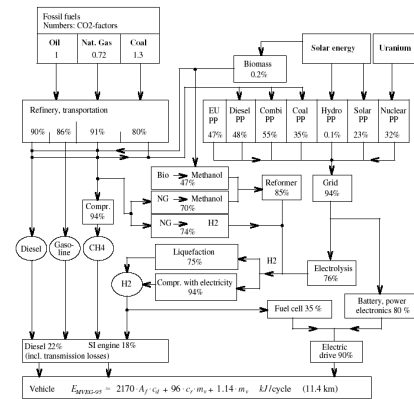
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Gear ratio optimization

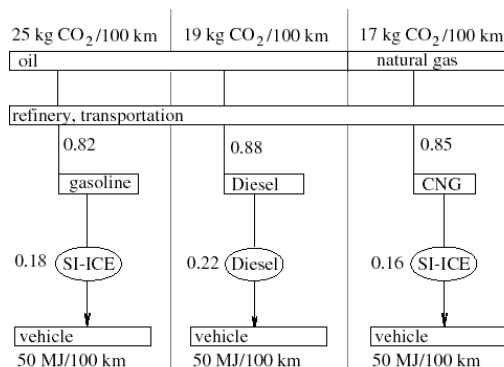
W2M – Energy Paths



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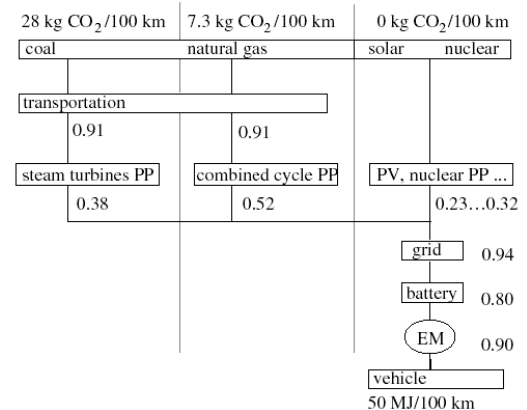
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W2M – Conventional Powertrains



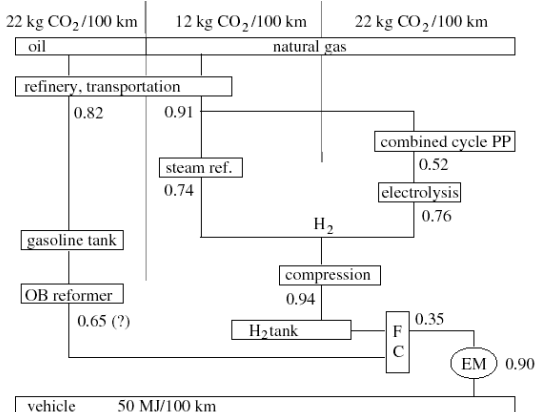
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W2M – Electric Vehicle



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W2M – Fuel Cell Electric Vehicle



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Pathways to Better Fuel Economy

Improvements on the big scale

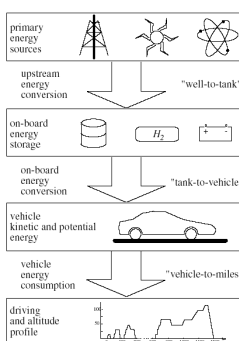
- ▶ Well-to-tank (Upstream)
- ▶ Wheel-to-miles (Car parameters: mass, rolling, aerodynamics)
- ▶ Tank-to-wheel

Improvements in Tank-to-wheel efficiencies

- ▶ Peak efficiency of the components
- ▶ Part load efficiency
- ▶ Recuperate energy
- ▶ Optimize structure
- ▶ Realize supervisory control algorithms that utilize the advantages offered in the complex systems

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- ▶ 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)

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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:

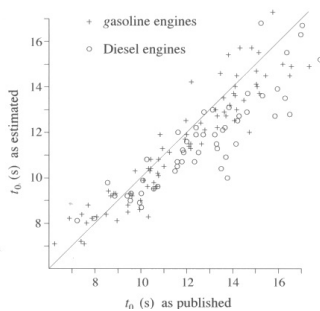
$$P_{max} = v m_v g \sin(\alpha)$$

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

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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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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%.

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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)

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

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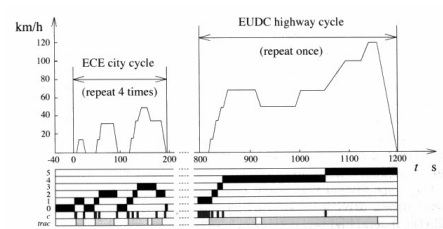
Optimization Problems

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Driving cycle specification – Gear ratio

Path to the solution



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

- ▶ 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

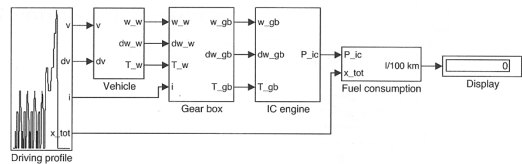
$$\begin{aligned} \min \quad & m_f(i_{g,1}, i_{g,2}, i_{g,3}, i_{g,4}, i_{g,5}) \\ \text{s.t.} \quad & \text{model and cycle is fulfilled} \end{aligned} \tag{1}$$

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

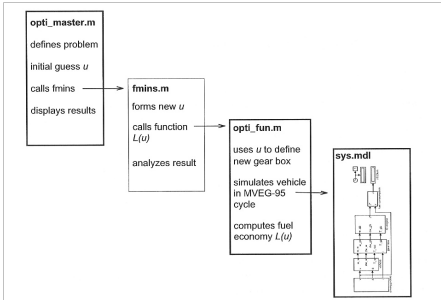
Model implemented in QSS

Structure of the code

Conventional powertrain.



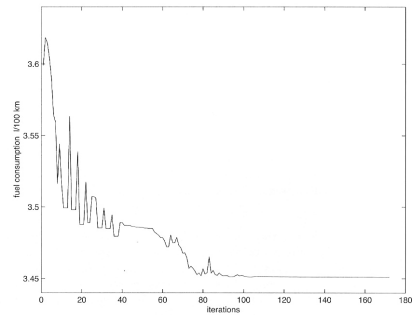
Efficient computations are important.



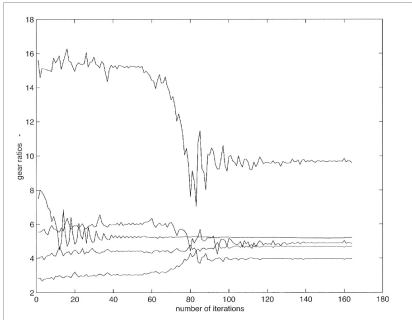
Will use a similar setup in hand-in assignment 2.

Running the solver

Running the solver



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



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