

Vehicle Propulsion Systems

Lecture 3

Internal Combustion Engine Powertrains

Vehicle Energy System

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- ▶ 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

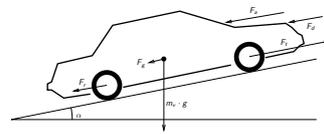
Gear ratio optimization

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The Vehicle Motion Equation

Newtons second law for a vehicle

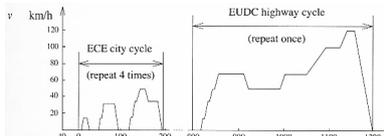
$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$



- ▶ 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

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

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

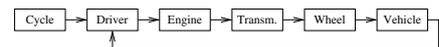
$$\text{kinetic energy} = \frac{1}{X_{tot}} \sum_{i \in \text{trac}} \bar{a}_i \bar{v}_i h = \{0.101, 0.126, 0.086\}$$

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

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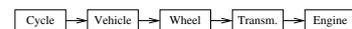
Two Approaches for Powertrain Simulation

▶ Dynamic simulation (forward simulation)



–“Normal” system modeling direction
–Requires driver model

▶ Quasistatic simulation (inverse simulation)

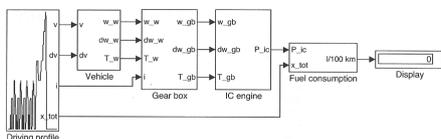


–“Reverse” system modeling direction
–Follows driving cycle exactly

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QSS Toolbox – Quasistatic Approach

▶ IC Engine Based Powertrain



▶ The Vehicle Motion Equation – With inertial forces:

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

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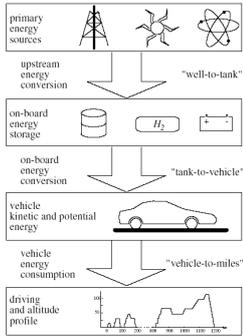
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Energy System Overview



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

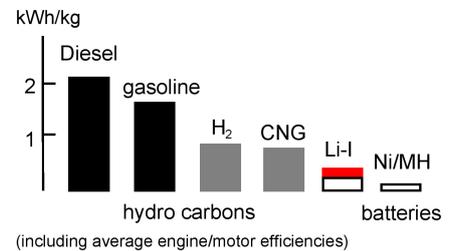
–What are the desirable properties?

- ▶ 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.
 $\text{Area} = 0.006 / 100000 = 6e-8 \text{ m}^2$
 $D = \sqrt{6e-8 * 4 / \pi} \approx 0.3 \text{ mm}$
- ▶ A 40000 kg truck needs 30 liters per 100 km.
 $\text{Area} = 0.03 / 100000 = 3e-7 \text{ m}^2$
 $D = \sqrt{3e-7 * 4 / \pi} \approx 0.6 \text{ mm}$

–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 $\rho = 0.69 \text{ [kg/dm}^3]$. 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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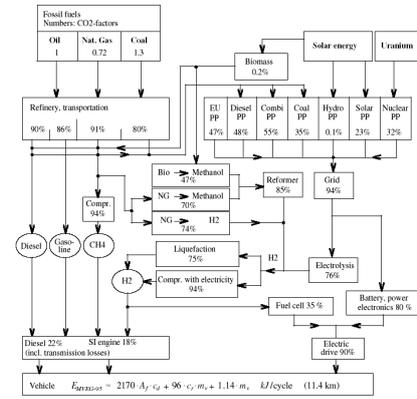
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Gear ratio optimization

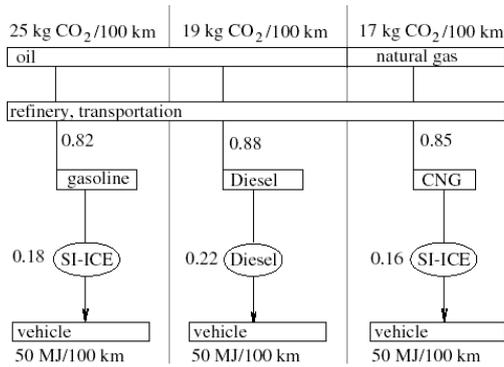
W2M – Energy Paths



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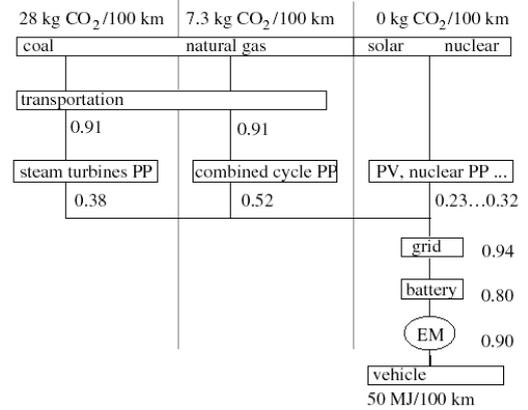
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W2M – Conventional Powertrains



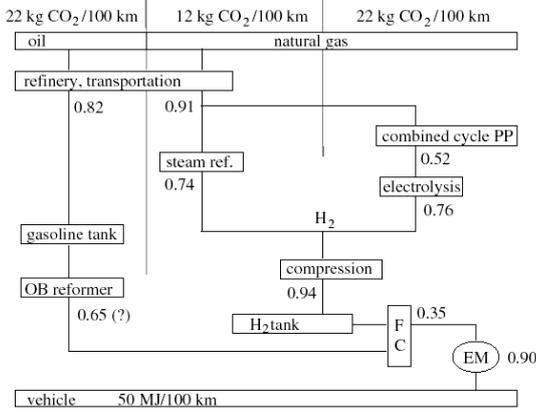
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W2M – Electric Vehicle



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W2M – Fuel Cell Electric Vehicle



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Pathways to Better Fuel Economy

Improvements on the big scale

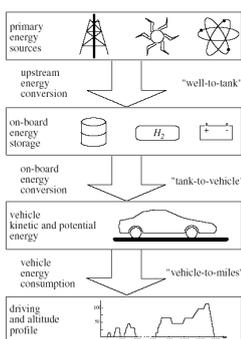
- ▶ Well-to-tank (Upstream)
- ▶ Wheel-to-miles (Car parameters: mass, rolling, aerodynamics)
- ▶ Tank-to-wheel

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)

Uphill Driving

- ▶ Starting point the vehicle motion equation.

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

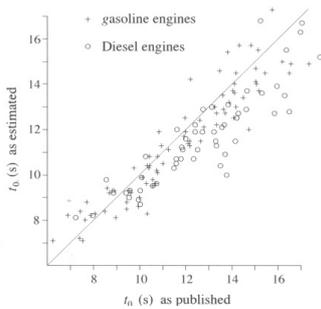
- ▶ Assume that the dominating effect is the inclination ($F_t = \frac{P_{max}}{v}$), gives power requirement:

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

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

Acceleration Performance – Validation

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



Optimization problems

Different problem types occur in vehicle optimization

- ▶ Structure optimization
- ▶ Parametric optimization
- ▶ Control system optimization

- ▶ 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%.

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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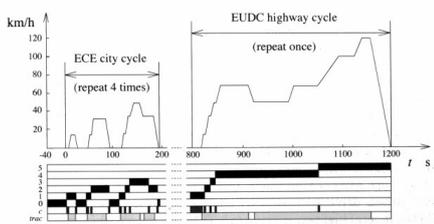
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Optimization Problems

Gear ratio optimization

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

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

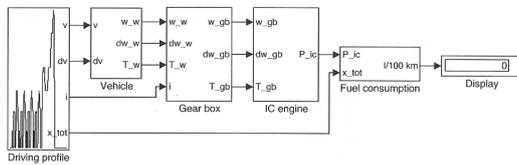
- ▶ Use an optimization package to solve (1)
- ▶ Analyze the solution.

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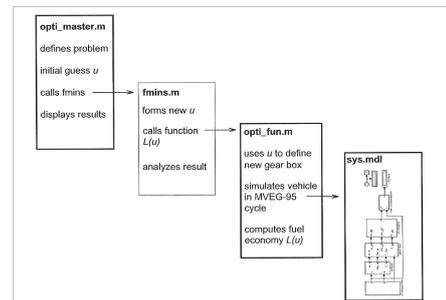
Model implemented in QSS

Conventional powertrain.



Efficient computations are important.

Structure of the code

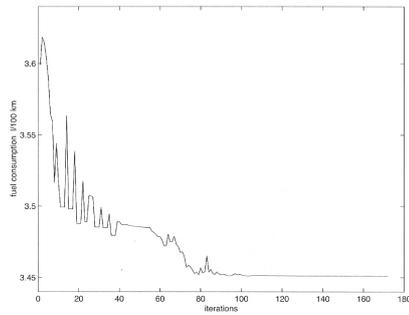


Will use a similar setup in hand-in assignment 2.

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Running the solver

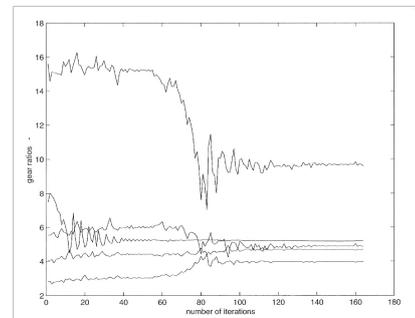


Improves the fuel consumption with 5%.

–Improvements of 0.5% are worth pursuing.

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Running the solver



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

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