Vehicle Propulsion Systems
Lecture 3

Internal Combustion Engine Powertrains
Vehicle Energy System

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March 22, 2017

About the hand-in tasks

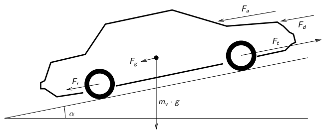
- General advice
  –Prepare yourselves before you go to the computer
  –Make a plan (list of tasks)
- Hand-in Format
  We would prefer (not a demand):
  - Electronic hand-in
  - Report in PDF-format
  - Reasons:
    –Easy for us to comment
    –Will give you fast feedback

Outline

The Vehicle Motion Equation

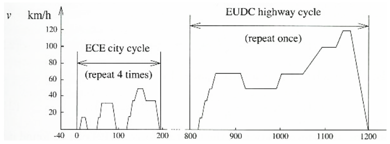
Newtons second law for a vehicle

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



- 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

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

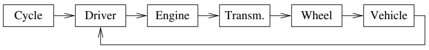
$$\text{rolling resistance} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i\, h = \quad \{.856, 0.81, 0.88\}$$

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

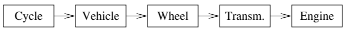
$$\bar{E}_{\text{MVEG-95}} \approx A_f\, c_d\, 1.9 \cdot 10^4 + m_v\, c_r\, 8.4 \cdot 10^2 + m_v\, 10 \qquad kJ/100km$$

Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)


Cycle → Driver → Engine → Transm. → Wheel → Vehicle

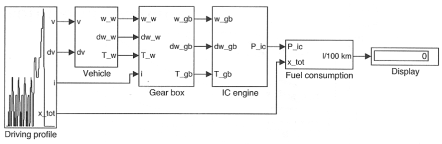
  –"Normal" system modeling direction
  –Requires driver model
- Quasistatic simulation (inverse simulation)


Cycle → Vehicle → Wheel → Transm. → Engine

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

QSS Toolbox – Quasistatic Approach

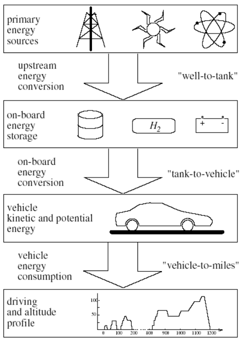
- IC Engine Based Powertrain



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

Outline

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.

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

Energy Carriers for On-Board Storage

Energy carriers – Many possibilities

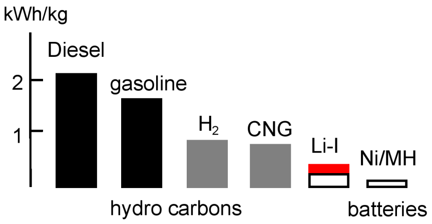
- Diesel, Gasoline, Naphtha, . . .
- CH4, Compressed Natural Gas (CNG), Liquefied Petr. Gas (LPG), . . .
- CH3OH, C2H5OH, C4H9OH, DME, . . .
- H2
- Batteries

–What are the desirable properties?

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

Why (Liquid) Hydrocarbons?

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



(including average engine/motor efficiencies)

Why (Liquid) Hydrocarbons?

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

- –How thick is the fuel wire?
- 1 500 kg car needs 6 liters per 100 km.
  Area $= 0.006/100000 =$ 6e-8 m^2
  $D = \sqrt{6e-8*4/pi} \approx 0.3$ mm
- A 40 000 kg truck needs 30 liters per 100 km.
  Area $= 0.03/100000 =$ 3e-7 m^2
  $D = \sqrt{3e-7*4/pi} \approx 0.6$ mm

–Chemical bonds are strong!

Why (Liquid) Hydrocarbons?

- Filling a car at the gas station.
  - filling the tank with 55 [dm^3] of gasoline
  - takes about 1 minute and 55 seconds
- What is the power?
  The heating value for isooctane is $q_{LHV} = 44.3$ [MJ/kg], and the density is $\rho = 0.69$ [kg/dm^3]. Gives the power

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

  (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 60 000 A!
  (Perspectives: 0.2 A kills a human.
  Residential house, 3*16 A.)

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

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.

Energy Conversion in Vehicles

Many paths in the vehicle

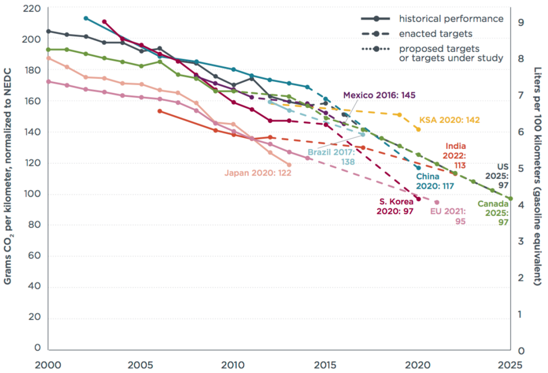
- Energy storage(s) (tank, battery, super caps)
- Energy refiner (reformer)
- Energy converter(s)
- Power (force) to/from transportation mission

This important topic will be covered later in the course

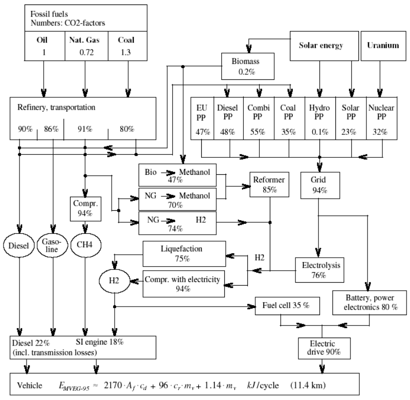
Outline

- 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

Environmental Concern – CO_2 as technology driver



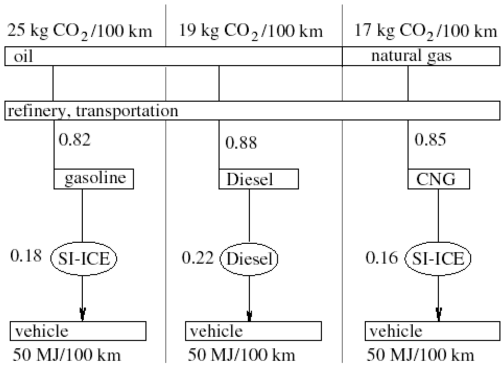
W2M – Energy Paths



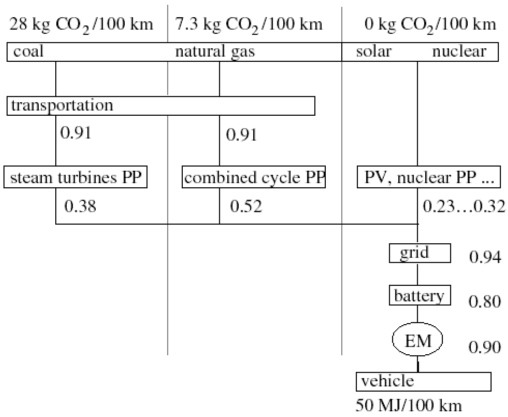
$E_{MVEG\text{-}95} \approx 2170 \cdot A_f \cdot c_d + 96 \cdot c_r \cdot m_v + 1.14 \cdot m_v$ kJ/cycle (11.4 km)

Environmental Concern – Coal+Sulphur, Beijing 2013

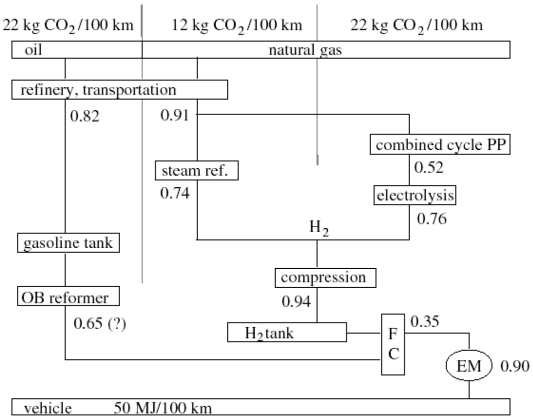
W2M – Conventional Powertrains



W2M – Electric Vehicle



W2M – Fuel Cell Electric Vehicle



Pathways to Better Fuel Economy

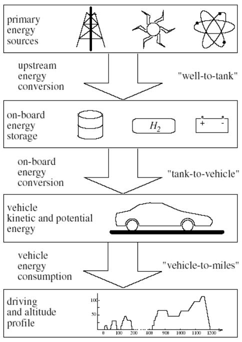
Improvements on the big scale

- 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

Energy System Overview



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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

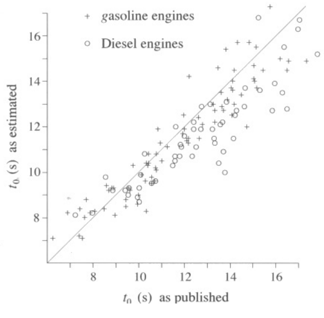
$$E_0 = \frac{1}{2} m_v \, v_0^2$$

- 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)

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

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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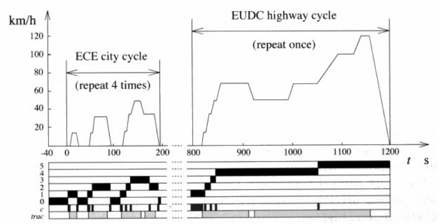
Optimization Problems

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

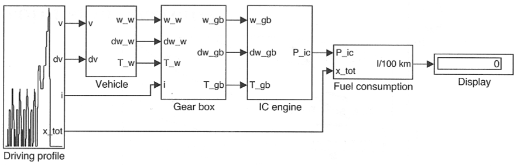
- Implement a simulation model that calculates m_f for the cycle.
- Set up the decision variables $i_{g,j}$, $j \in [1,5]$.
- Set up problem

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

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

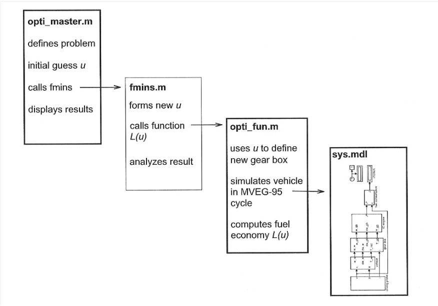
Model implemented in QSS

Conventional powertrain.



Efficient computations are important.

Structure of the code



opti_master.m
defines problem
initial guess *u*
calls fmins
displays results

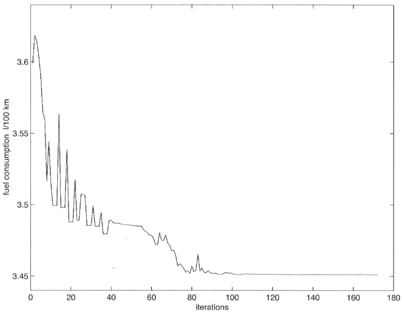
fmins.m
forms new *u*
calls function *L(u)*
analyzes result

opti_fun.m
uses *u* to define new gear box
simulates vehicle in MVEG-95 cycle
computes fuel economy *L(u)*

sys.mdl

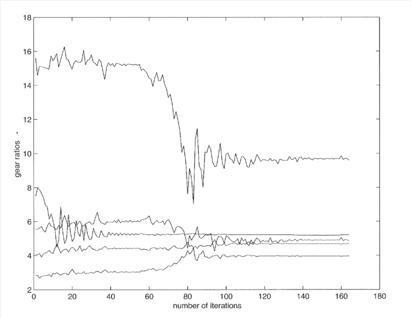
Will use a similar setup in hand-in assignment 2.

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.