# Vehicle Propulsion Systems
# Lecture 3

## Conventional Powertrains with Transmission
## Performance, Tools and Optimization

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## About the hand-in tasks

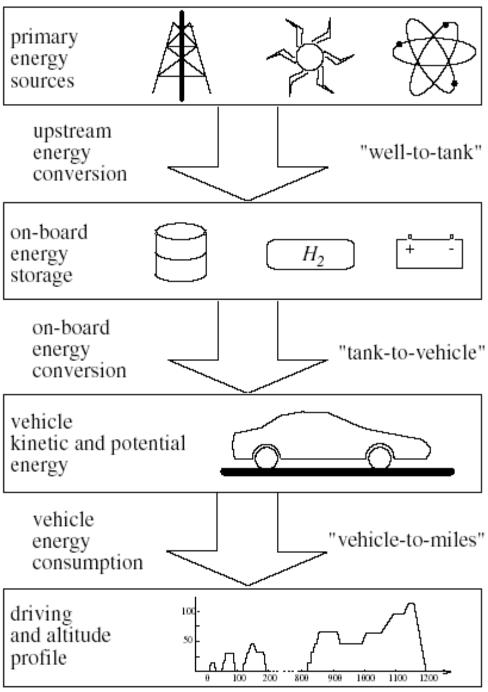
- General advice
  –Prepare yourselves before you go to the computer
  –Make a plan (list of tasks)
- Hand-in Format
  - Electronic hand-in
  - Report in PDF-format
  - Reasons:
    –Easy for us to comment
    –Will give you fast feedback

## Outline





## Energy System Overview




Primary sources

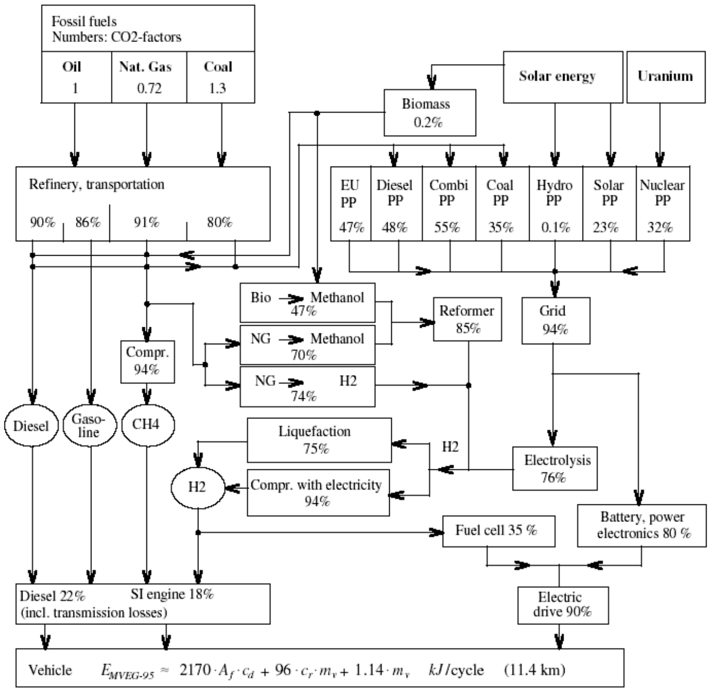
Different options for on-board energy storage

Powertrain energy conversion during driving

Cut at the wheel!

Driving mission has a minimum energy requirement.

## W2M – Energy Paths

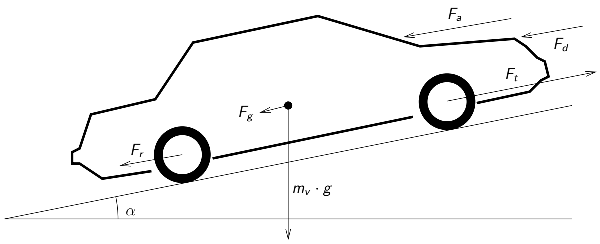





## The Vehicle Motion Equation

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*

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

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

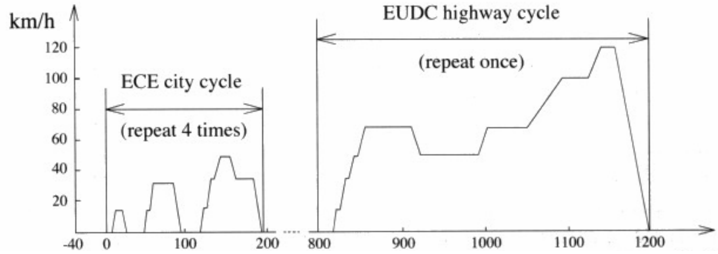
Resulting in these sums

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

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

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

# Values for cycles




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

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

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

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

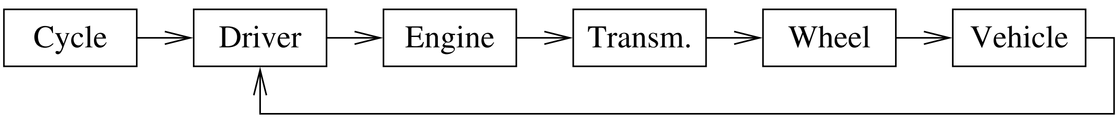
**Adopting appropriate units and packaging the results as an Equation**

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



# Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)



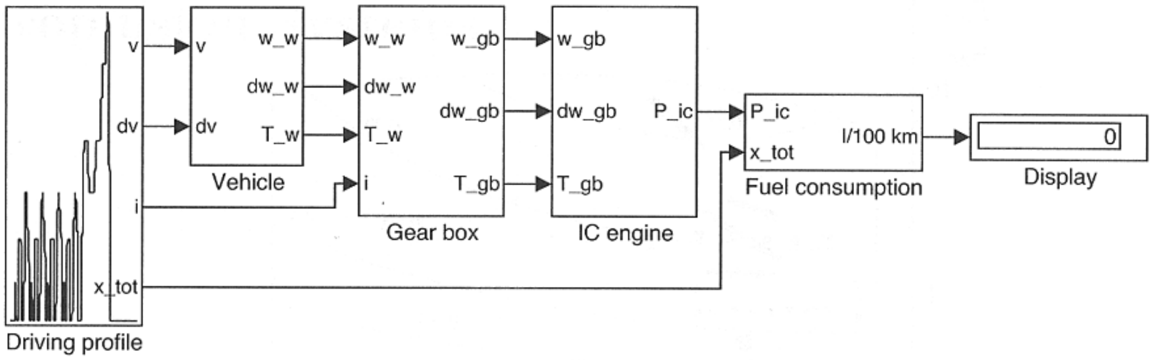

–“Normal” system modeling direction
–Requires driver model

- Quasistatic simulation (inverse simulation)


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

# QSS Toolbox – Quasistatic Approach

- IC Engine Based Powertrain



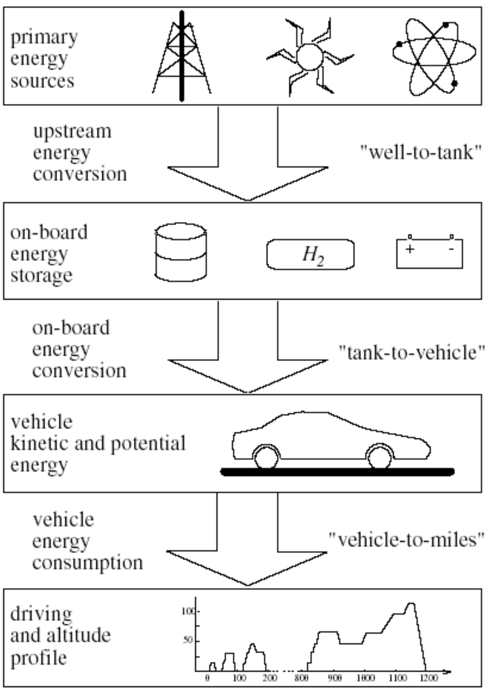

- The Vehicle Motion Equation – With inertial forces:

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

- Gives efficient simulation of vehicles in driving cycles



# Fuel Consumption and Range




Theoretical range calculations

- Driving cycles: E [kJ/km]
- Energy contents: $E[J] = \int F\, ds[Nm] = \int P\, dt[Ws]$
- Unit conversions: $1[kWh] = 1000 \cdot 3600[Ws] = 3.6MJ$
- Liqud Fuels: $q_{LHV}[J/kg]$, $E = m_f\, q_{LHV}$, $\rho[kh/l]$
- Gasoline: $q_{LHV} = 44[MJ/kg]$
- Batteries: Wh/kg
- Lithium Ion: 200-300 Wh/kg

**New Mindset**

- Conventional Vehicles [l/km], cost.
- Electric Vehicles [km], range.

## Outline





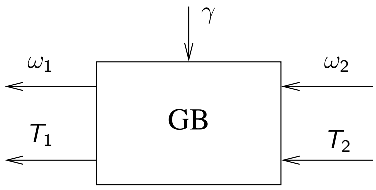
## Different Types of Gearboxes

- 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

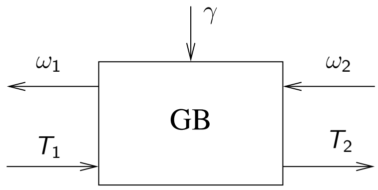
## Causality and Basic Equations

- Causalities for Gear-Box Models

Quasistatic Approach




Dynamic Approach




- Power balance – Loss free model

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



## Connections of Importance for Gear Ratio Selection

- Vehicle motion equation:

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

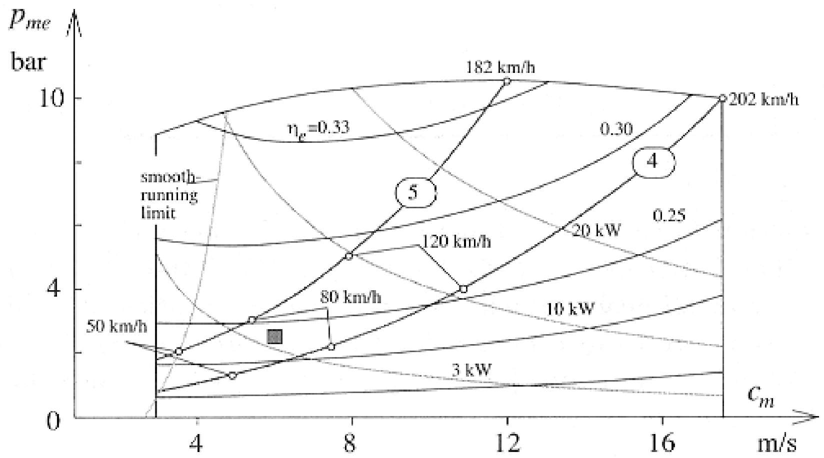
Constant speed $\frac{d}{dt} v(t) = 0$:

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

- 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 $\omega_e$ 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 – Engine Centric View

Gear ratio selection connected to the engine map.




The gear ratio, maps the road load into the engine map

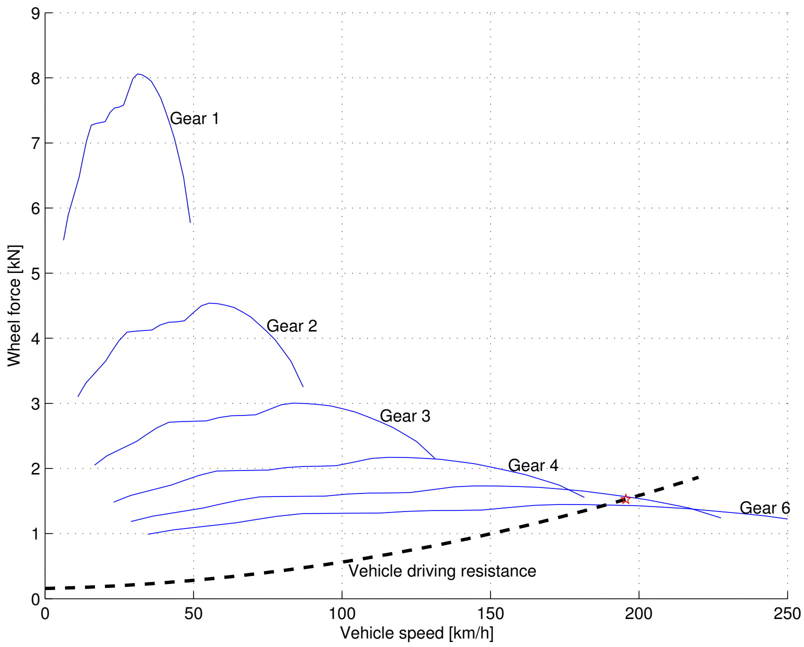
Selecting gear ratios helps achieve goals

- Top speed = Gear 4
- Overdrive = Gear 5 (F.E.)

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 – Road Centric View



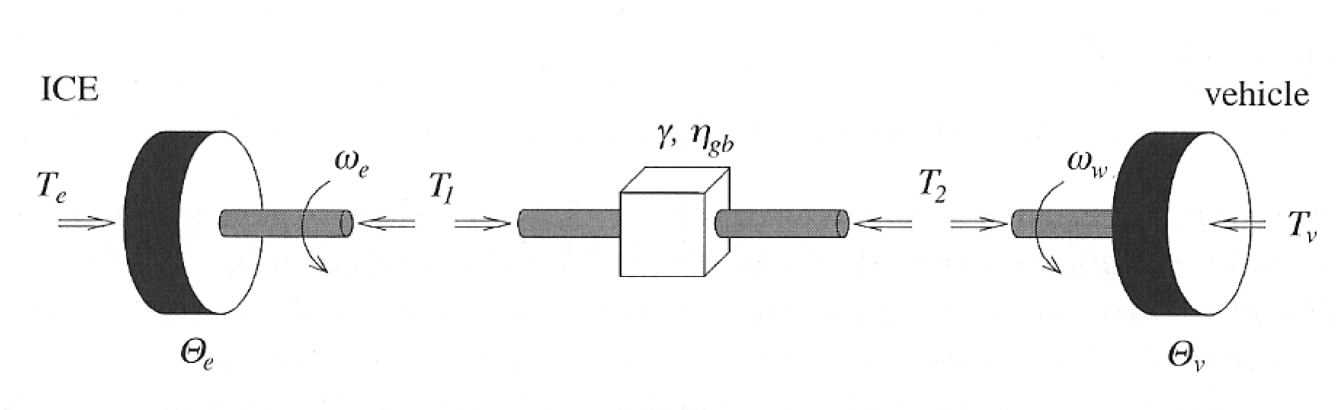
# Selection of Gear Ratio

Optimizing gear ratio for a certain cycle.

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

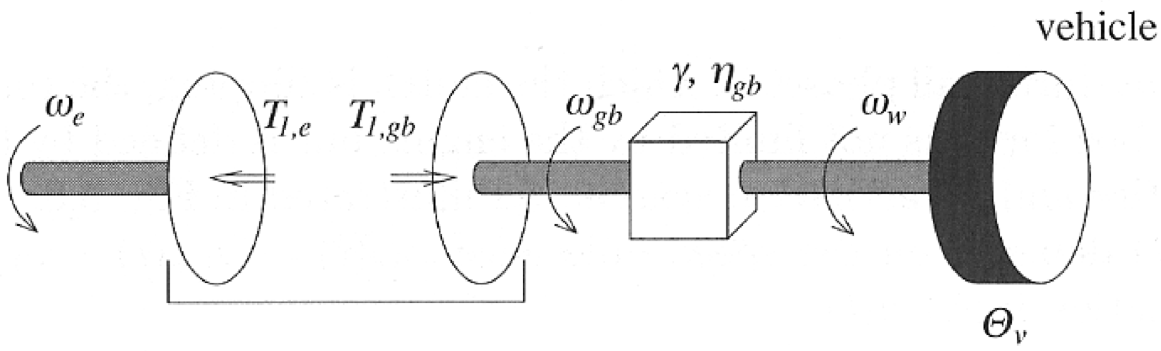


# Gear-box Efficiency




- 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



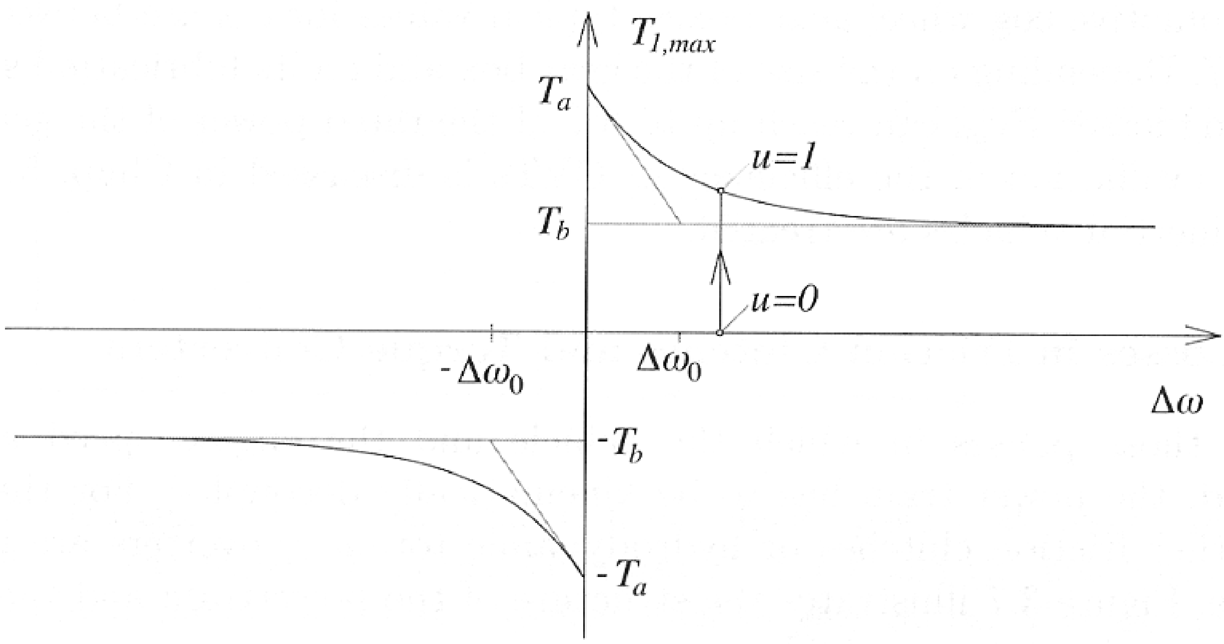

Friction clutch torque:

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

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

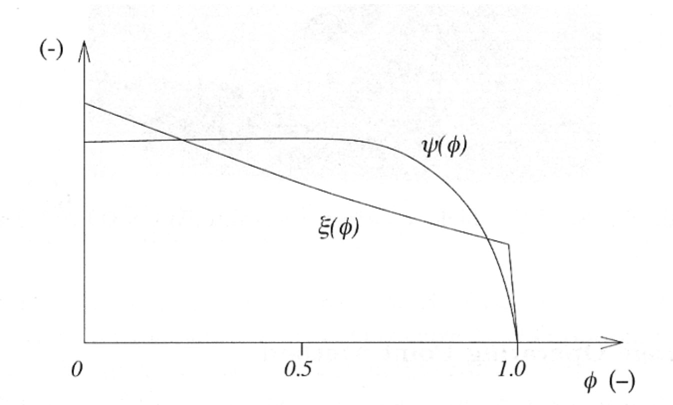
Input torque at the converter:

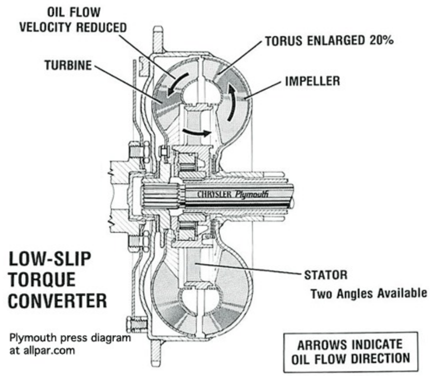
$$T_{1,e}(t) = \xi(\phi(t))\,\rho_h\,d_p^5\,\omega_e^2(t)$$

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 $\psi(\phi(t))$



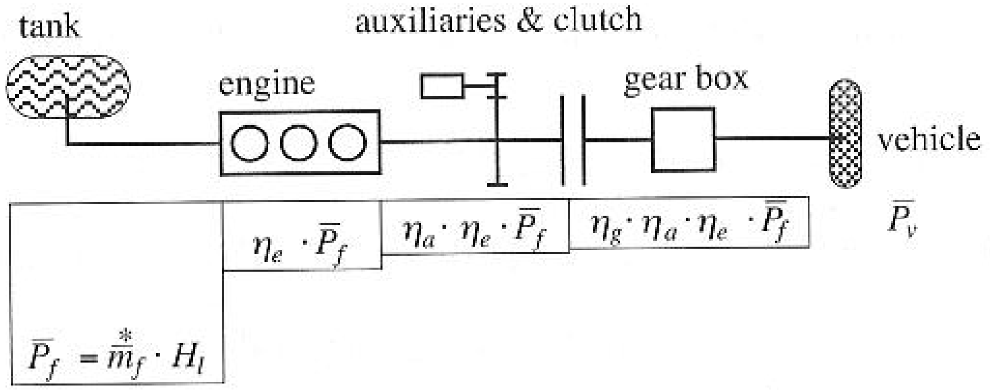

The efficiency in traction mode becomes

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



## Outline

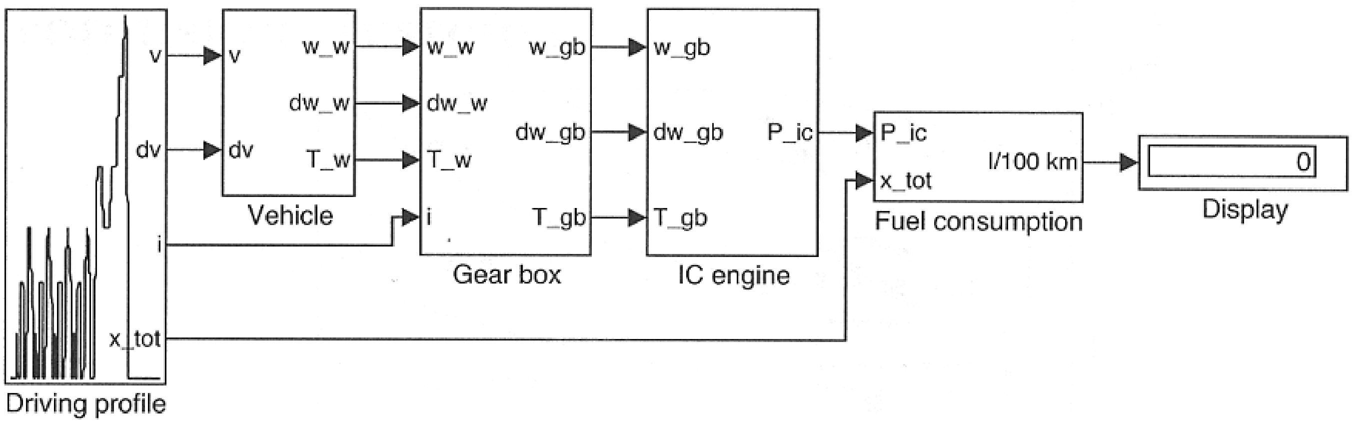
## Average Operating Point Method




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

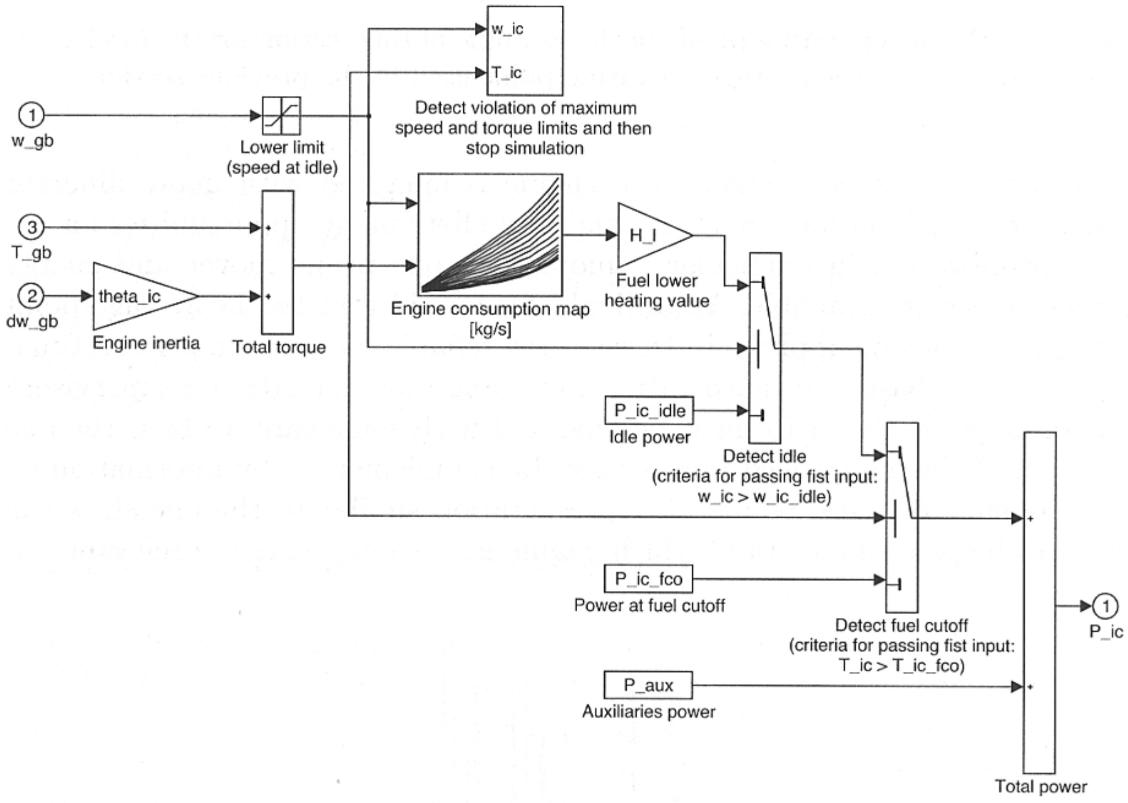


## Quasistatic analysis – Layout



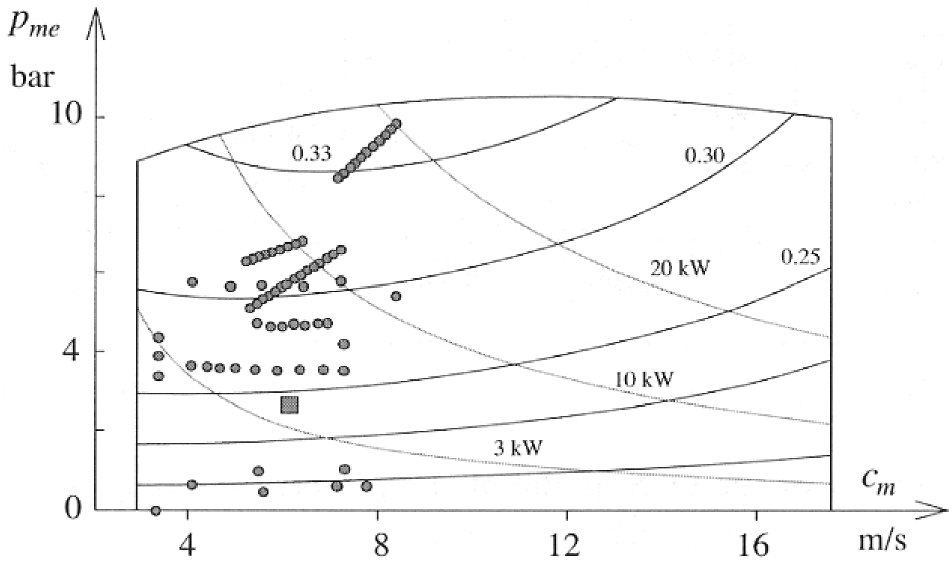

- More details and better agreement (depends on model quality)
  –Good agreement for general powertrains
- Hand-in assignment.

## Quasistatic analysis – IC Engine Structure



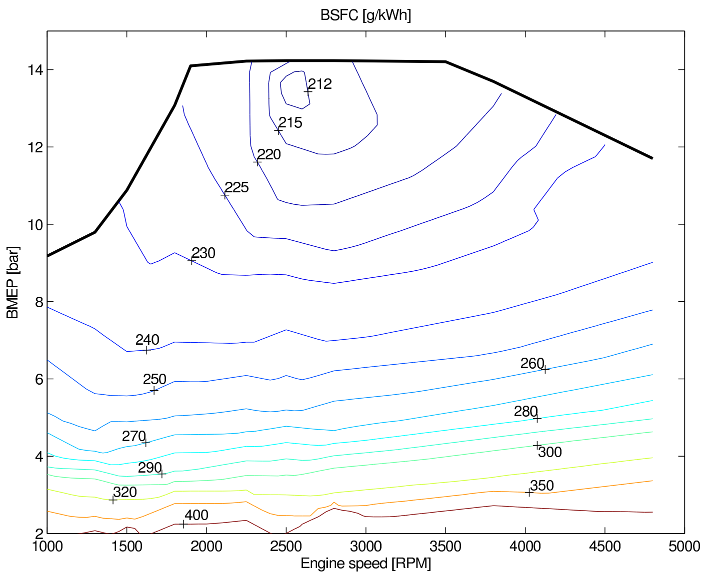



## Quasistatic analysis – Engine Operating Points

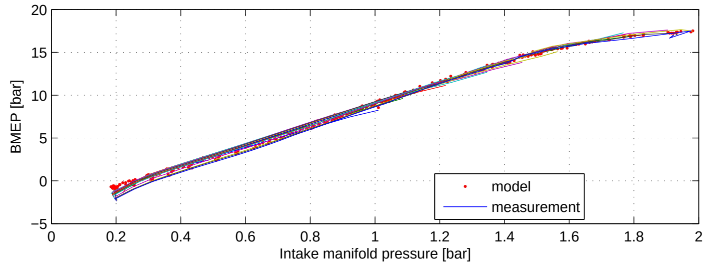


## Why is the average operating point surprisingly good?

The data is looks quite nonlinear...




The Willans line approximation
–is surprisingly good for normal driving.




The average value from a process that has variations that follow a line will end up on the line.

If we avoid the extremes it becomes a good approximation.



## Outline

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

## 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

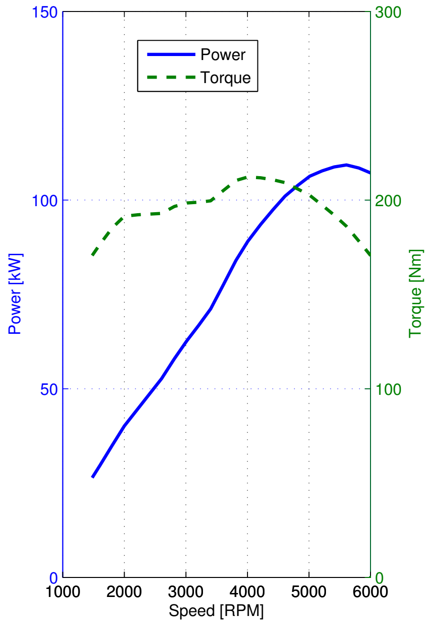
$$E_0 = \frac{1}{2} m_v v_0^2$$

- Assume that all engine power will build up kinetic energy (neglecting the resistance forces)
  Average power during acceleration: $\bar{P} = E_0 / t_0$
- Ad hoc relation,

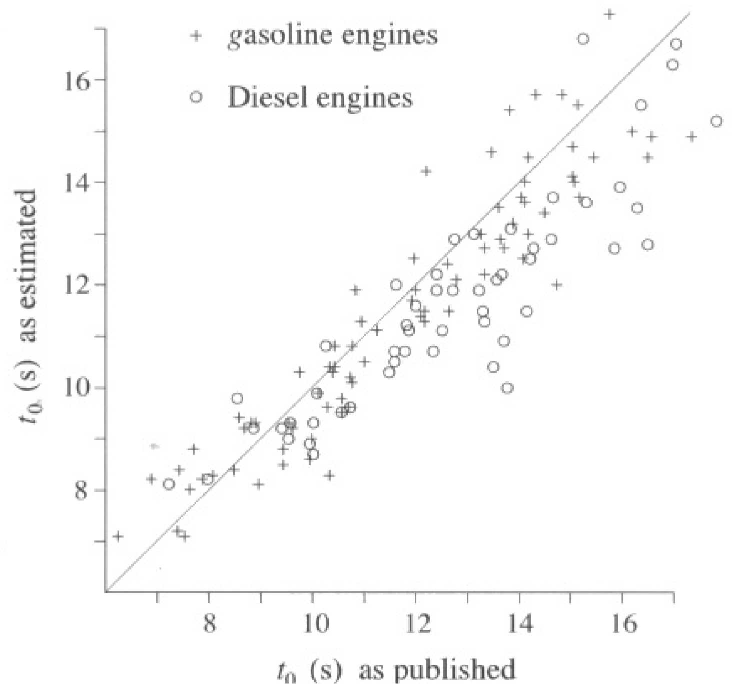
$$\bar{P} = \frac{1}{2} P_{max}$$

  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 acceleration data**

Compared to

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

Surprisingly good agreement

Encourages us to make simplified models and analyses



## Outline

## Optimization problems

Different problem types occur in vehicle optimization

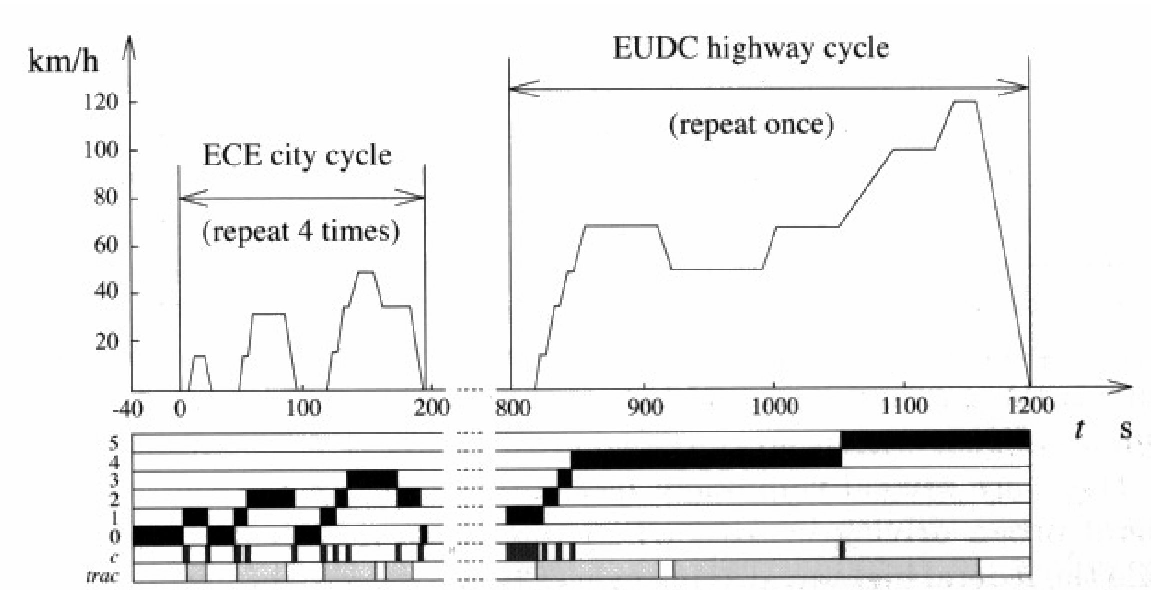
- Structure optimization
  –What components to select and use?
- Parametric optimization
  –What are the optimal design parameters?
- Control system optimization
  –How shall the system be controlled?

**Next up**

Parametric optimization of the gear ratios in a conventional vehicle.



## Driving cycle specification – Gear ratio




Number of gears and their usage is 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

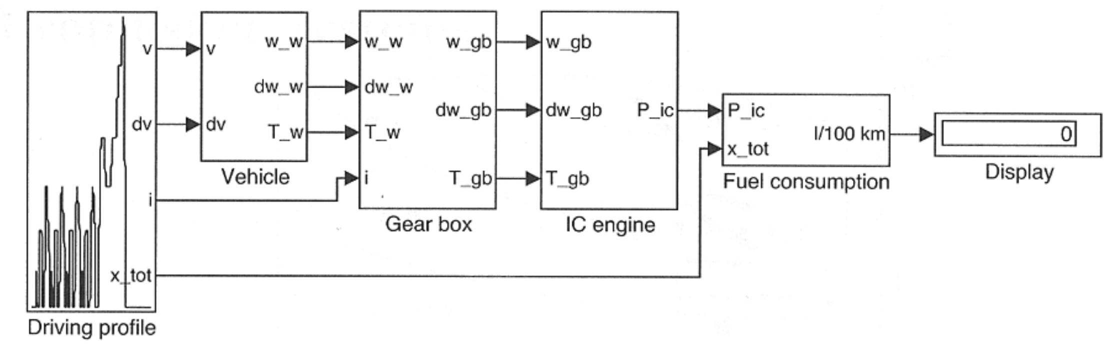
$$\begin{array}{ll} \min & m_f(i_{g,1}, i_{g,2}, i_{g,3}, i_{g,4}, i_{g,5}) \\ \text{s.t.} & \text{model and cycle is fulfilled} \end{array} \tag{1}$$

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



## Model implemented in QSS

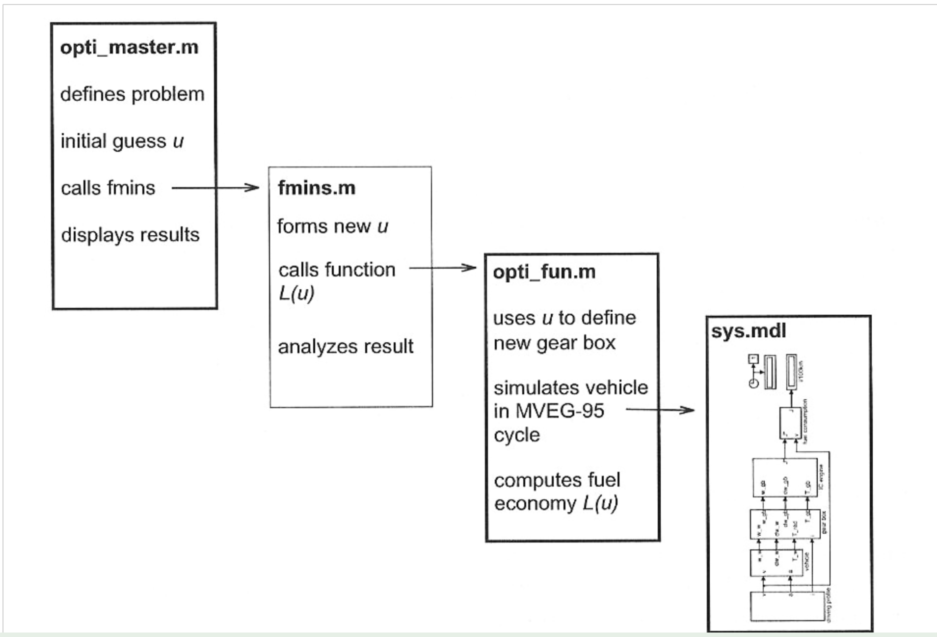
Conventional powertrain.




**Efficient computations are important**

The simulation model is evaluated many times while we search.

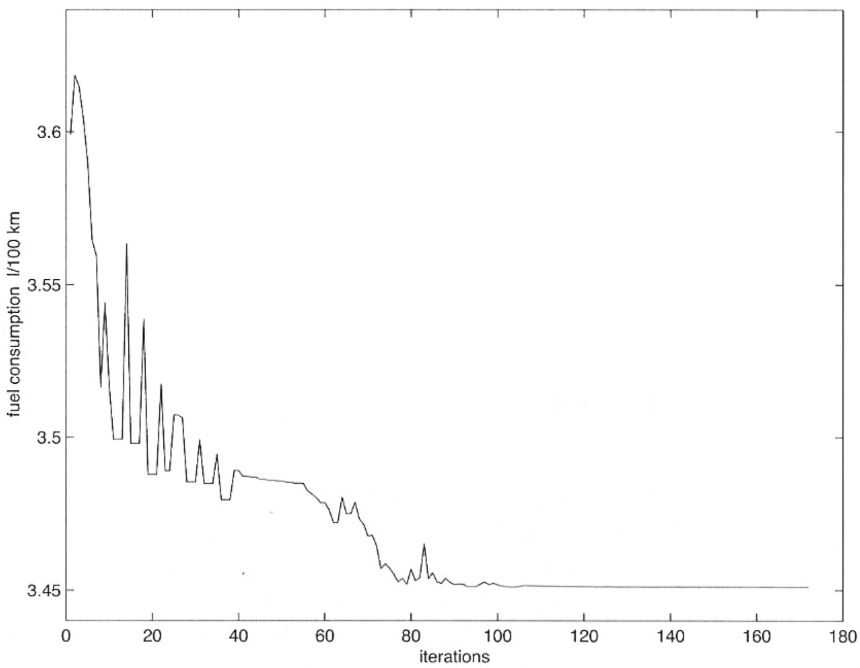
## Structure of the code




Will use a similar setup, for a different problem, in hand-in assignment 2.



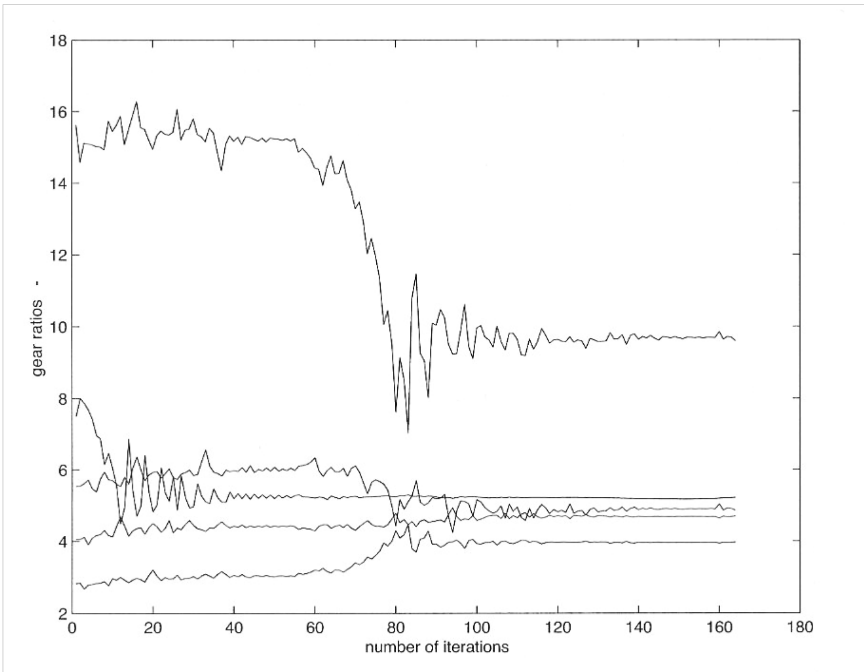
## Running the solver




Improves the fuel consumption with 5%.

–Improvements of 0.5% are worth pursuing.

## Running the solver




Complex problem
–Global optimum not guaranteed.

Make sure you're not stuck in a bad local minimum.

Several runs with different initial guesses.

The optimizer shamelessly exploits all means it has.
–The solution is always an extreme point.
–Not necessarily good...



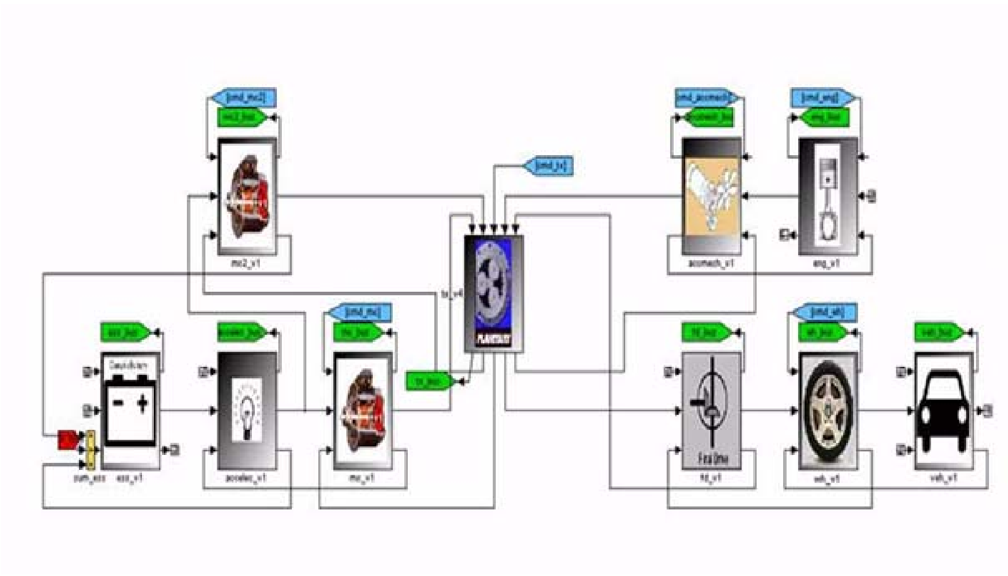
## Software tools

There are many tools for studying energy consumption of different vehicle propulsion systems

| | Quasi static | Dynamic |
|---|---|---|
| QSS (ETH) | X | |
| Advisor, NREL→AVL | X | (X) |
| PSAT | | X |
| ALPHA | | X |
| VECTO | | X |
| VSim (Volvo) | | X |
| VTAB (Scania) | | X |
| Inhouse tools | (x) | (X) |

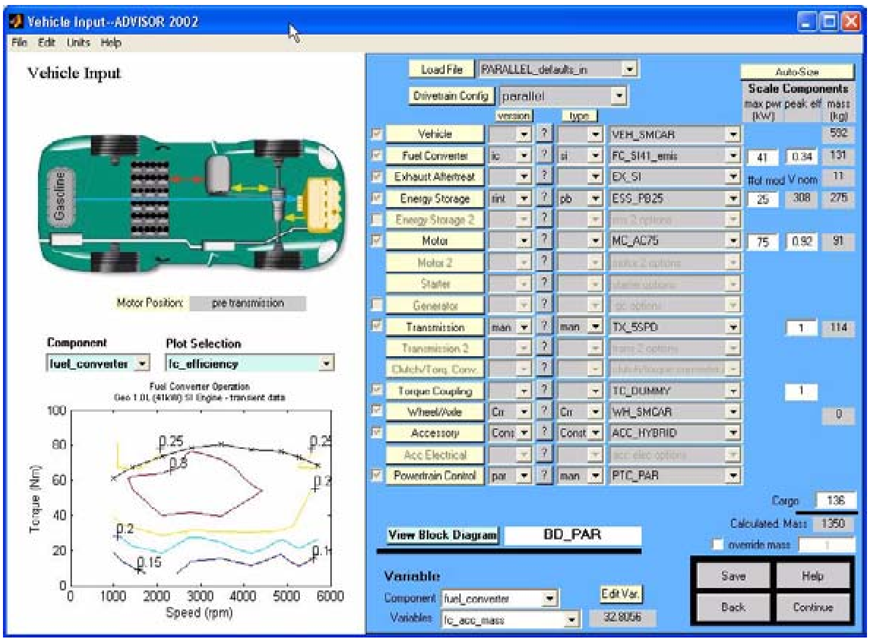
ALPHA – Advanced Light-Duty Powertrain and Hybrid Analysis. (EPA)
VECTO – Vehicle Energy Consumption calculation TOol. (EU, HD)

# PSAT – Argonne national laboratory





# Advisor – AVL



## 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.