Vehicle Propulsion Systems
Lecture 2
March 26, 2024

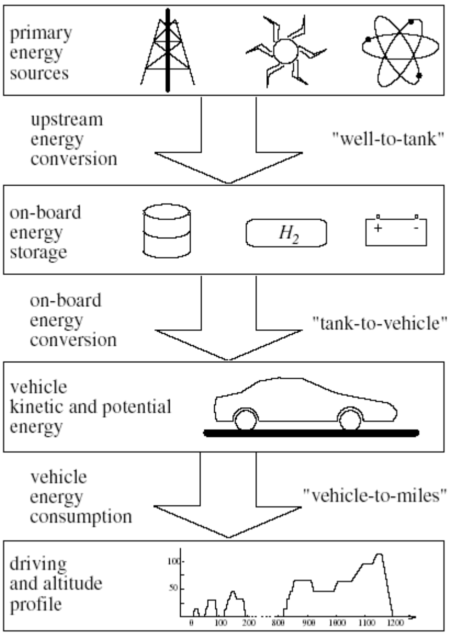
Lars Eriksson
Professor

Vehicular Systems
Linköping University

March 26, 2024

Outline

Energy System Overview



Primary sources

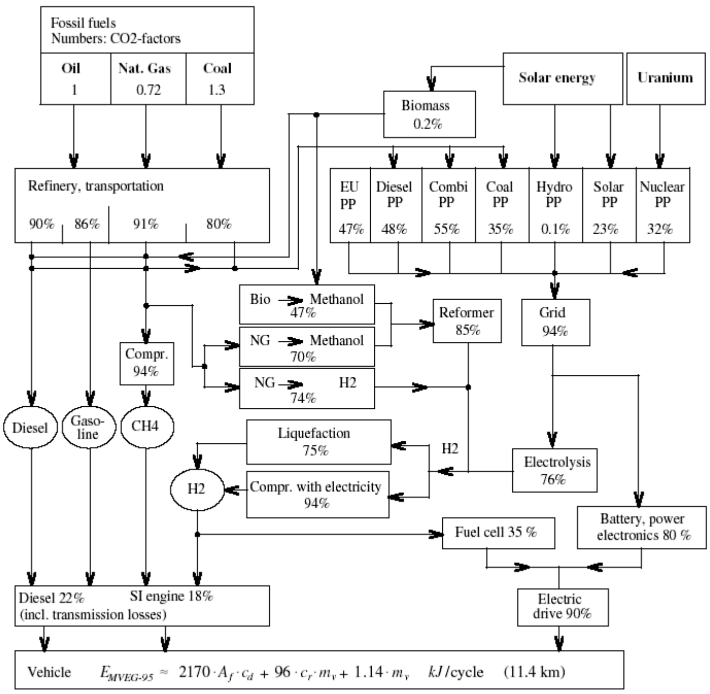
Different options for on-board energy storage

Powertrain energy conversion during driving

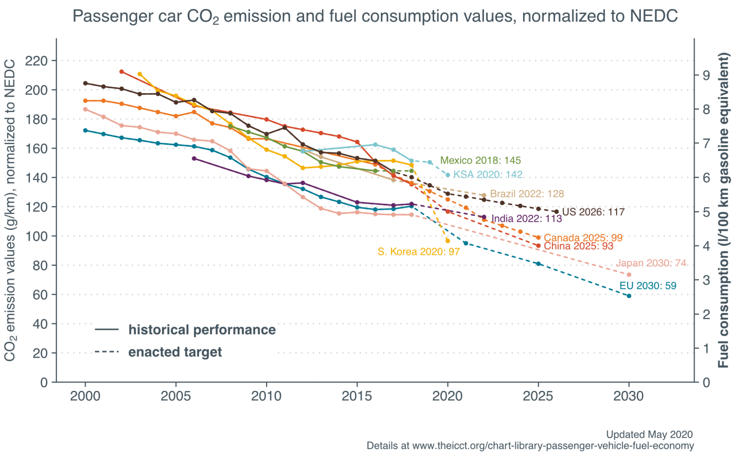
Cut at the wheel!

Driving mission has a minimum energy requirement.

W2M – Energy Paths



Environmental Concern – Tailpipe CO_2 as technology driver



CAFE

- Corporate Average Fuel Economy
- Tail-pipe CO_2
- Based on real sales
- Companies are responsible
- Must sell EV:s
- Advertising, media presence
- No incentive for bio-fuels among powerful companies
- Legislation is rigged for E-Mobility

Different cycles over the world, normalization to compare with NEDC cycle.

Results – The ICCT

BRIEFING

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AUGUST 2021

CO_2 emissions from new passenger cars in Europe: Car manufacturers' performance in 2020

Results

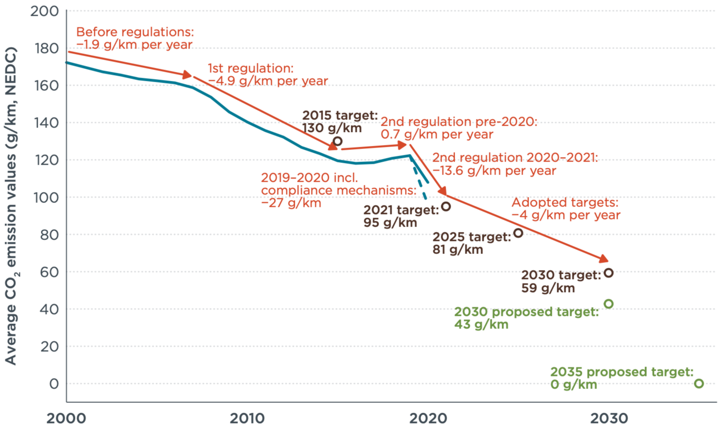


Figure 1. Historical average NEDC CO_2 emission values, targets, and annual reduction rates of new passenger cars.

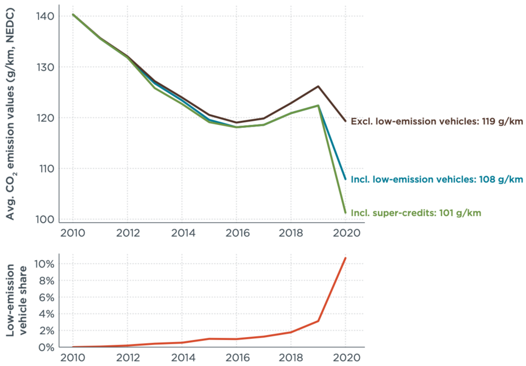
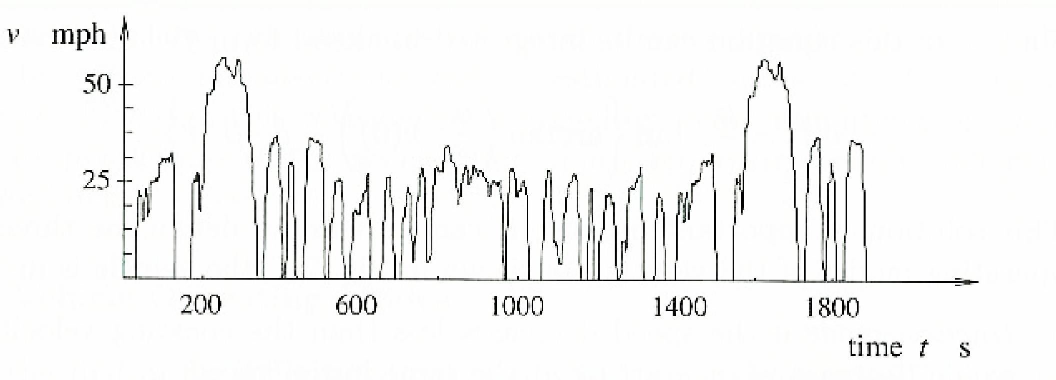


Figure 3. Top panel: Historical average CO_2 emissions (g/km, NEDC) excluding low-emission vehicles, including low-emission vehicles, and including the effect of super-credit multipliers. Bottom panel: Share of low-emission vehicles.

Outline

Driving profiles

Velocity profile, American FTP-75 (1.5*FUDS).

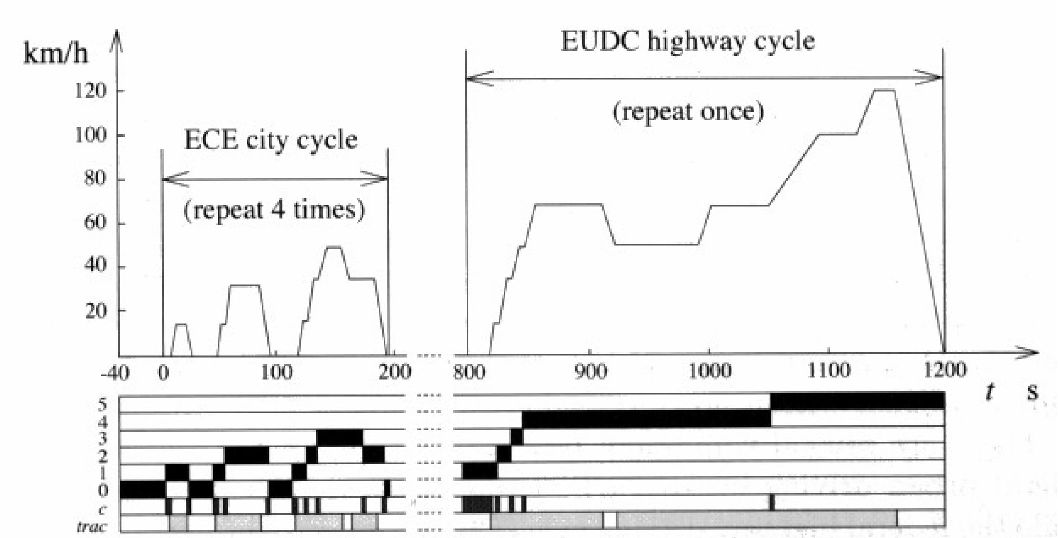


Driving profiles in general

- First used for pollutant control now also for fuel consumption.
- Important that all use the same cycle when comparing.
- Different cycles have different energy demands.

Driving profiles – Another example

Velocity profile, European MVEG-95

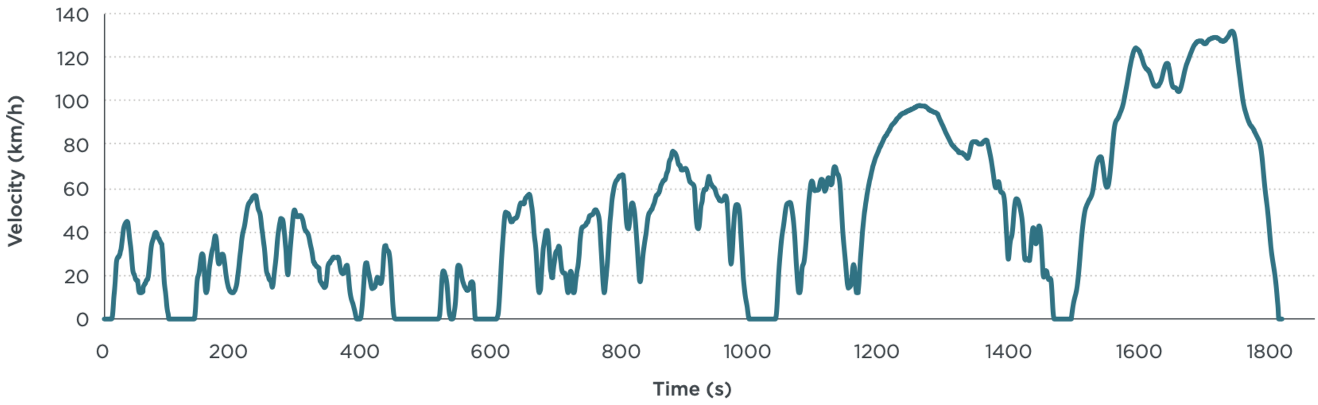


NEDC (ECE*4, EUDC)

No coasting in this driving profile.

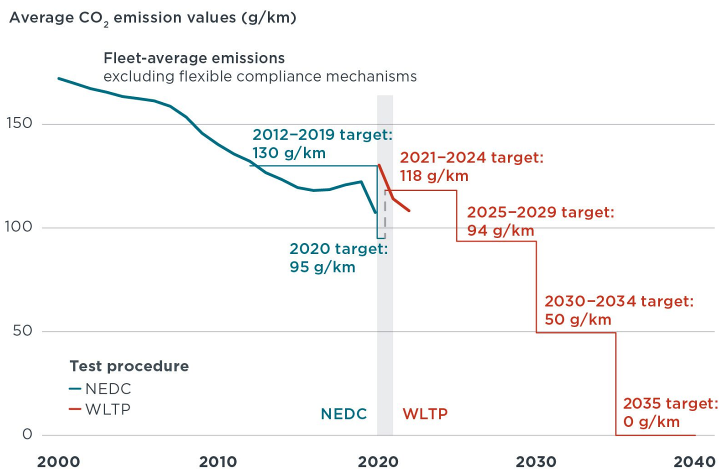
Driving profiles – A third example

Velocity profile, WLTP (Worldwide Harmonized Light Vehicles Test Procedure)



Adopted for new vehicles in 2017 in EU.
More demanding than NEDC.

Results due to change in cycle for CO_2



Changes in the cycle used
NEDC ➔WLTP

- 2017 Change for emission certification
- 2021 Change for CO_2
- More demanding cycle
- Adjusted 95g/km to 118g/km
- Different cycles have different energy demands
- Normalization performed for comparisons in the ICCT data.

Outline

Energy Consumption of a Driving Mission

- Remember the partitioning
  –Cut at the wheels.
- How large **force** is required at the wheels for driving the vehicle on a mission?

Repetition – Work, power and Newton's law

Translational system – Force, work and power:

$$W = \int F \, dx, \qquad P = \frac{d}{dt} W = F \, v$$

Rotating system – Torque ($T = F \, r$), work and power:

$$W = \int T \, d\theta, \qquad P = T \, \omega$$

Newton's second law:

Translational	Rotational
$m \frac{dv}{dt} = F_{driv} - F_{load}$	$J \frac{d\omega}{dt} = T_{driv} - T_{load}$

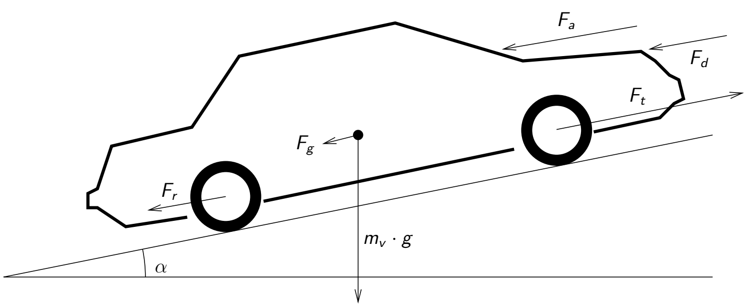
Warning

Nomenclature difference: Here J, in book Θ

The Vehicle Motion Equation

Newton's 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

Aerodynamic Drag Force – Loss

Aerodynamic drag force depends on:
Frontal area A_f, drag coefficient c_d, air density ρ_a and vehicle velocity $v(t)$

$$F_a(t) = \frac{1}{2} \cdot \rho_a \cdot A_f \cdot c_d \cdot v(t)^2$$

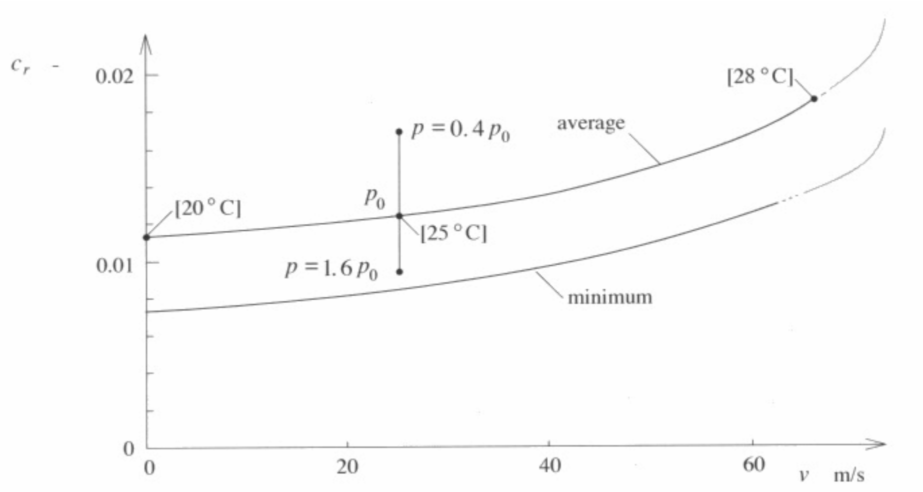
Approximate contributions to F_a

- 65% car body.
- 20% wheel housings.
- 10% exterior mirrors, eave gutters, window housings, antennas, etc.
- 5% engine ventilation.

Rolling Resistance Losses

Rolling resistance depends on: – load and tire/road conditions

$$F_r(v, p_t, \text{surface}, \ldots) = c_r(v, p_t, \ldots) \cdot m_v \cdot g \cdot \cos(\alpha), \qquad v > 0$$



The velocity has small influence at low speeds.

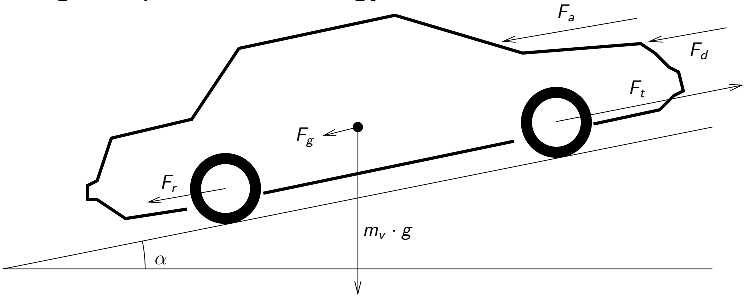
Increases sharply for high speeds where resonance phenomena occur.

Assumption in book:
c_r – constant

$$F_r = c_r \cdot m_v \cdot g$$

Gravitational Force

- Gravitational load force
  –Not a loss, storage of potential energy

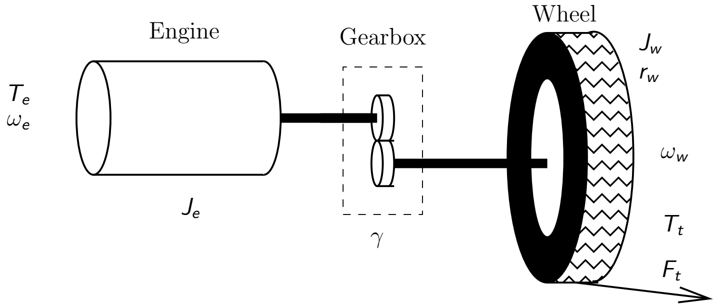


- Up- and down-hill driving produces forces.

$$F_g = m_v \, g \, \sin(\alpha)$$

- Flat road assumed $\alpha = 0$ if nothing else is stated (In the book).

Inertial forces – Reducing the Tractive Force



$$T_e - J_e \frac{d}{dt}\omega_e = T_{gb} \qquad\qquad T_{gb} \cdot \gamma - J_w \frac{d}{dt}\omega_w = T_t$$

Variable substitution: $T_w = \gamma \, T_e$, $\qquad \omega_w \, \gamma = \omega_e$, $\qquad v = \omega_w \, r_w$

Tractive force:

$$F_t = \frac{1}{r_w}\left[\left(T_e - J_e \frac{d}{dt}\frac{v(t)}{r_w}\gamma\right) \cdot \gamma - J_w \frac{d}{dt}\frac{v(t)}{r_w} \right] = \frac{\gamma}{r_w} T_e - \left(\frac{\gamma^2}{r_w^2} J_e + \frac{1}{r_w^2} J_w \right) \frac{d}{dt} v(t)$$

The Vehicle Motion Equation:

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

Vehicle Operating Modes

The Vehicle Motion Equation:

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

- $F_t > 0$ traction
- $F_t < 0$ braking
- $F_t = 0$ coasting

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

Coasting solution for $v > 0$

$$v(t) = \frac{\beta}{\alpha} \tan\left(\arctan\left(\frac{\alpha}{\beta}\, v(0)\right) - \alpha\, \beta\, t\right)$$

How to check a profile for traction?

The Vehicle Motion Equation:

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t)) \tag{1}$$

- Traction conditions:
  $F_t > 0$ traction, $F_t < 0$ braking, $F_t = 0$ coasting
- Method 1: Compare the profile with the coasting solution over a time step

$$v_{coast}(t_{i+1}) = \frac{\beta}{\alpha} \tan\left(\arctan\left(\frac{\alpha}{\beta}\, v(t_i)\right) - \alpha\, \beta\, (t_{i+1} - t_i)\right)$$

- Method 2: Solve (1) for F_t

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

Numerically differentiate the profile $v(t)$ to get $\frac{d}{dt} v(t)$.
Compare with Traction condition ($F_t > 0$).

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

Discretized velocity profile used to evaluate

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_{t \in trac} F(t)v(t)dt$$

here $v_i = v(t_i), \quad t_i = i \cdot h, \quad i = 1, \ldots, n$.
Approximating the quantites

$$\bar{v}_i(t) \approx \frac{v_i + v_{i-1}}{2}, \qquad t \in [t_{i-1}, t_i)$$

$$\bar{a}_i(t) \approx \frac{v_i - v_{i-1}}{h}, \qquad t \in [t_{i-1}, t_i)$$

Traction approximation

$$\bar{F}_{trac} \approx \frac{1}{x_{tot}} \sum_{i \in trac} \bar{F}_{trac,i}\, \bar{v}_i\, h$$

Evaluating the integral

Tractive force from *The Vehicle Motion Equation*

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

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

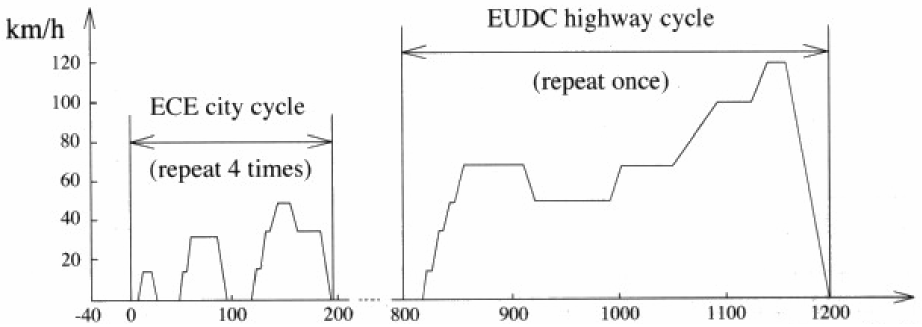
Resulting in these sums

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

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

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

Values for cycles



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

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

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

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

Values for cycles

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

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Adopting appropriate units and packaging the results as an Equation

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

Tasks in Hand-in assignment

Approximate car data

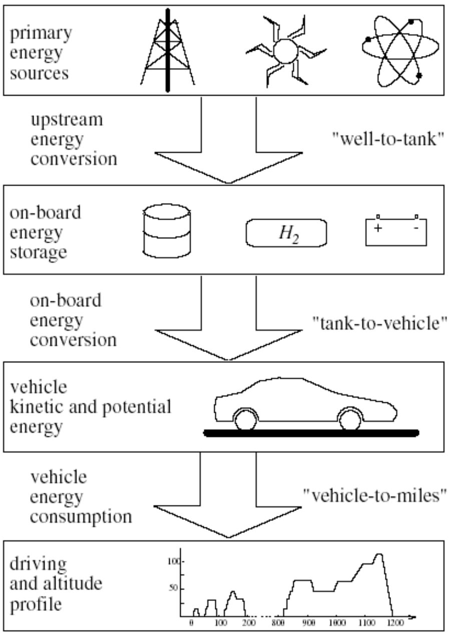
The energy need for the MVEG-95 cycle per 100 km.

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

	SUV	full-size	compact	light-weight	PAC-Car II
$A_f \cdot c_d$	1.2 m^2	0.7 m^2	0.6 m^2	0.4 m^2	$.25 \cdot .07$ m^2
c_r	0.017	0.017	0.017	0.017	0.0008
m_v	2000 kg	1500 kg	1000 kg	750 kg	39 kg
$\bar{P}_{\text{MVEG-95}}$	11.3 kW	7.1 kW	5.0 kW	3.2 kW	
$\bar{P}_{\text{max}}$	155 kW	115 kW	77 kW	57 kW	

Average and maximum power requirement for the cycle.

Energy System Overview



Primary sources

Different options for on-board energy storage

Powertrain energy conversion during driving

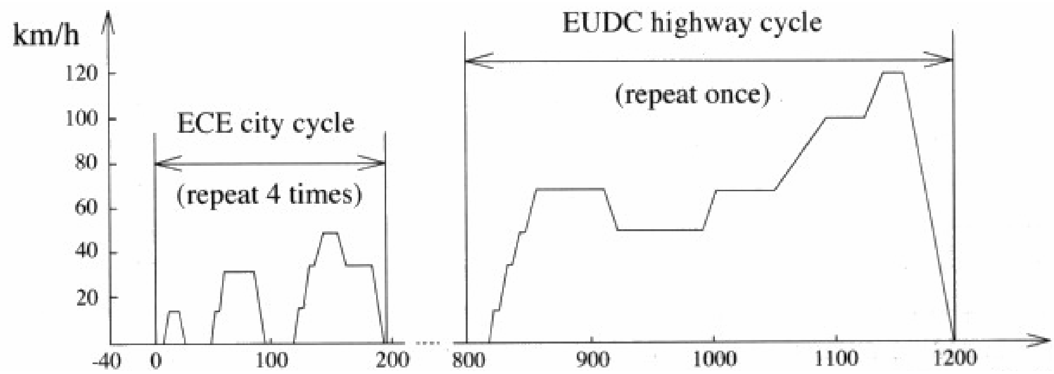
Cut at the wheel!

Driving mission has a minimum energy requirement.

Outline

Energy demand again – Recuperation

- Previously: Considered energy demand from the cycle.
- Now: The cycle can give energy to the vehicle.



Recover the vehicle's kinetic energy during driving.

Perfect recuperation

- Mean required force

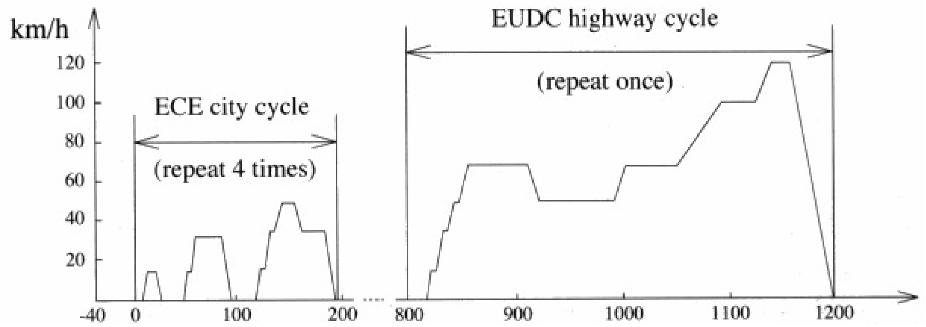
$$\bar{F} = \bar{F}_a + \bar{F}_r$$

- Sum over all points

$$\bar{F}_a = \frac{1}{x_{tot}} \frac{1}{2} \rho_a A_f c_d \sum_{i=1}^{N} \bar{v}_i^3 h$$

$$\bar{F}_r = \frac{1}{x_{tot}} m_v g c_r \sum_{i=1}^{N} \bar{v}_i h$$

Perfect recuperation – Numerical values for cycles



Numerical values for MVEG-95, ECE, EUDC

$$\bar{X}_a = \frac{1}{x_{tot}} \sum_i \bar{v}_i^3 \, h = \qquad \{363, 100, 515\}$$

$$\bar{X}_r = \frac{1}{x_{tot}} \sum_i \bar{v}_i \, h = \qquad \{1, 1, 1\}$$

$$\bar{E}_{\text{MVEG-95}} \approx A_f \, c_d \, 2.2 \cdot 10^4 + m_v \, c_r \, 9.81 \cdot 10^2 \qquad kJ/100km$$

Comparison of numerical values for cycles

- Without recuperation.

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

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

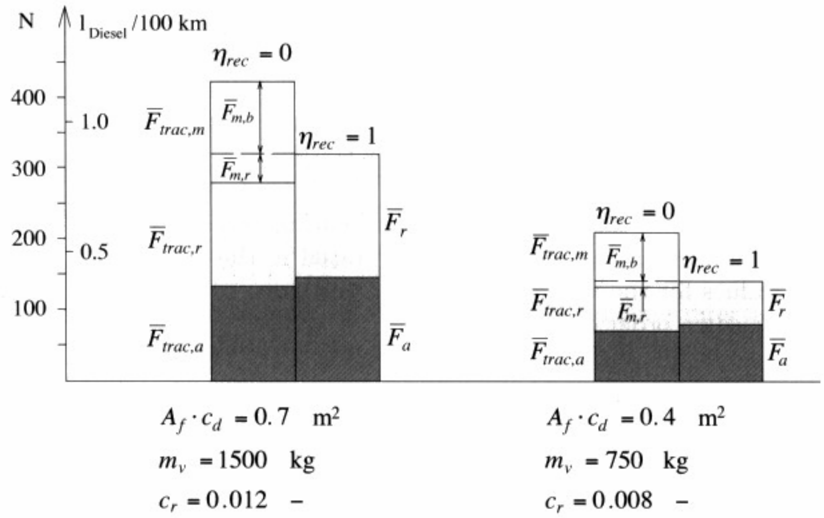
$$\bar{X}_{trac,m} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i \, \bar{v}_i \, h = \qquad \{0.101, 0.126, 0.086\}$$

- With perfect recuperation

$$\bar{X}_a = \frac{1}{x_{tot}} \sum_i \bar{v}_i^3 \, h = \qquad \{363, 100, 515\}$$

$$\bar{X}_r = \frac{1}{x_{tot}} \sum_i \bar{v}_i \, h = \qquad \{1, 1, 1\}$$

Perfect and no recuperation



Mean force represented as liter Diesel / 100 km.

Sensitivity Analysis – Design changes

- Cycle energy reqirement (no recuperation)

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

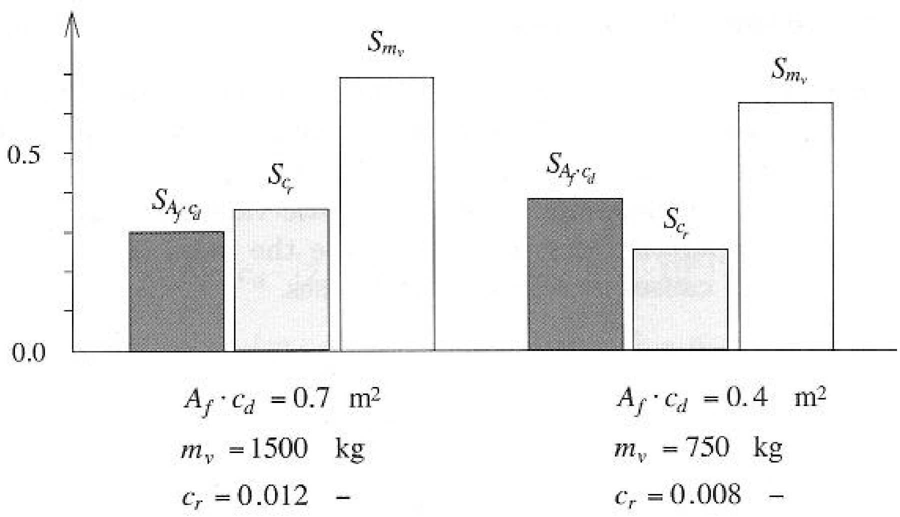
- Sensitivity analysis

$$S_p = \lim_{\delta p \to 0} \frac{\left[\bar{E}_{\text{MVEG-95}}(p+\delta p) - \bar{E}_{\text{MVEG-95}}(p)\right] / \bar{E}_{\text{MVEG-95}}(p)}{\delta p / p}$$

$$S_p = \lim_{\delta p \to 0} \frac{\left[\bar{E}_{\text{MVEG-95}}(p+\delta p) - \bar{E}_{\text{MVEG-95}}(p)\right]}{\delta p} \frac{p}{\bar{E}_{\text{MVEG-95}}(p)}$$

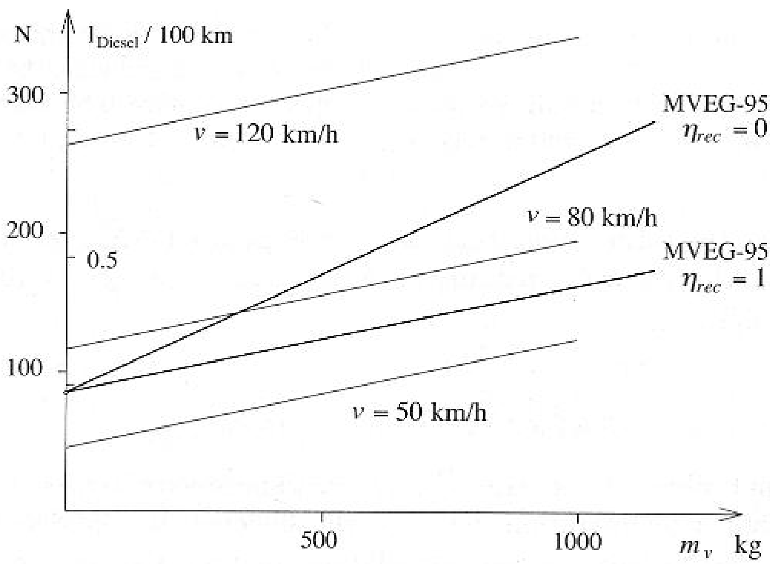
- Consider the vehicle design parameters:
  - $A_f\, c_d$
  - c_r
  - m_v

Sensitivity Analysis

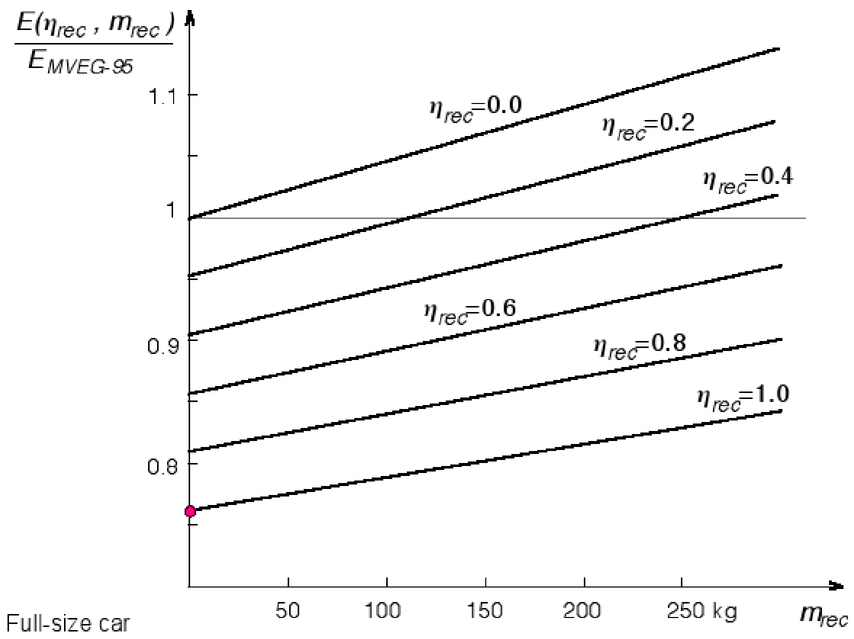


Vehicle mass is the most important parameter.

Vehicle mass and fuel consumption

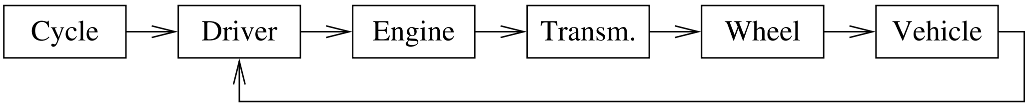


Realistic Recuperation Devices



Outline

Dynamic approach



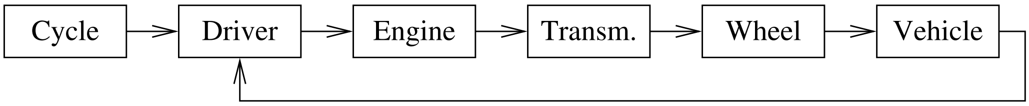
- Forward simulation.
- Drivers input u propagates to the vehicle and the cycle
- Drivers input ⇒ . . . ⇒ Driving force ⇒ Losses ⇒ Vehicle velocity ⇒ Feedback to driver model
- Available tools (= Standard simulation) can deal with arbitrary powertrain complexity.

Quasistatic approach

- Backward simulation
- Driving cycle ⇒ Losses ⇒ Driving force ⇒ Wheel torque ⇒ Engine (powertrain) torque ⇒ . . . ⇒ Fuel consumtion.
- Available tools are limited with respect to the powertrain components that they can handle.
  – The models need to be prepared for inverse simulation.
- Considering new acausal tools such as Modelica opens up possibilities.
- See also: *Efficient Drive Cycle Simulation*, Anders Fröberg and Lars Nielsen (2008) . . .

Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)



–“Normal” system modeling direction
–Requires driver model

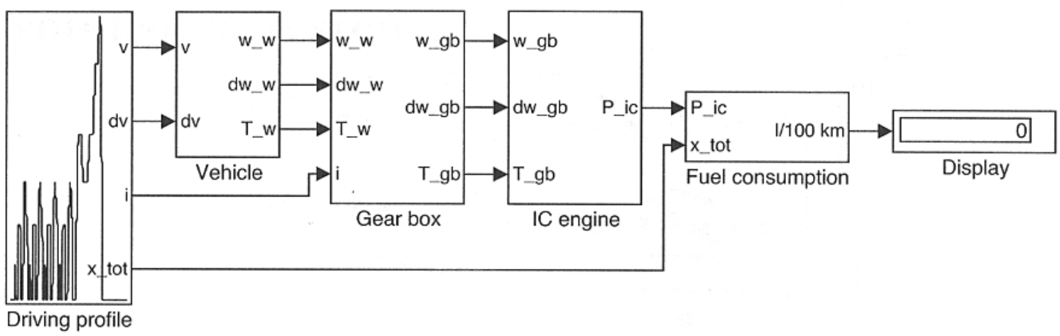
- Quasistatic simulation (inverse simulation)

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

- Model (or calculation) causality

QSS Toolbox – Quasistatic Approach

- IC Engine Based Powertrain



- The Vehicle Motion Equation – With inertial forces:

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

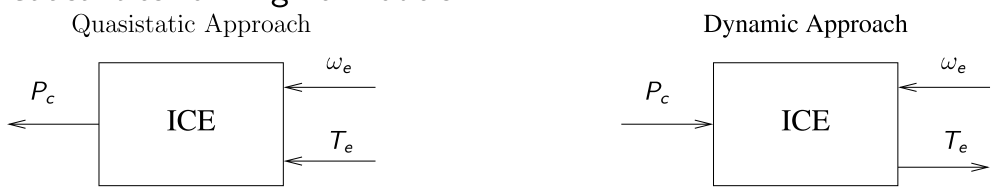
- Gives efficient simulation of vehicles in driving cycles

Outline

Causality and Basic Equations

High level modeling – Inputs and outputs

- Causalities for Engine Models



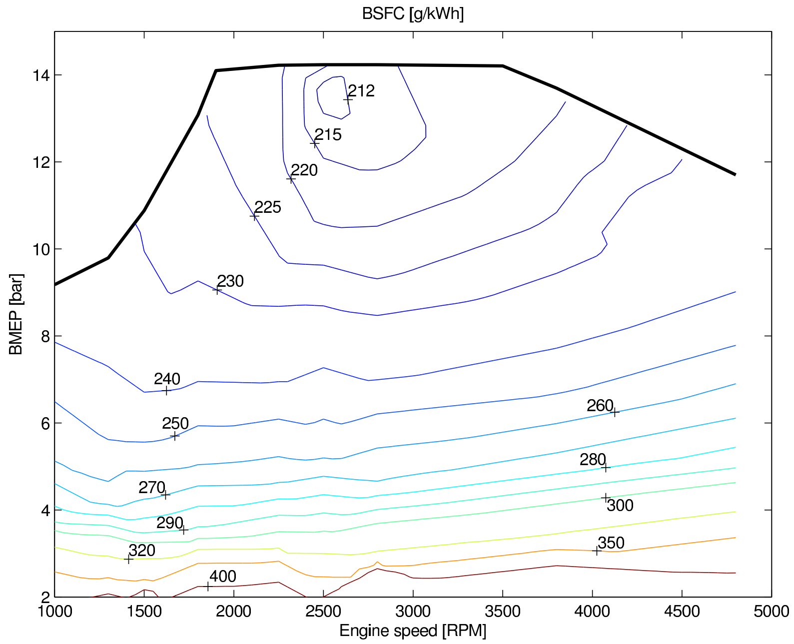
- Engine efficiency

$$\eta_e = \frac{\omega_e \, T_e}{P_c}$$

- Enthalpy flow of fuel (Power $\dot{H}_{fuel} = P_c$)

$$P_c = \dot{m}_f \, q_{LHV}$$

Engine Efficiency Maps



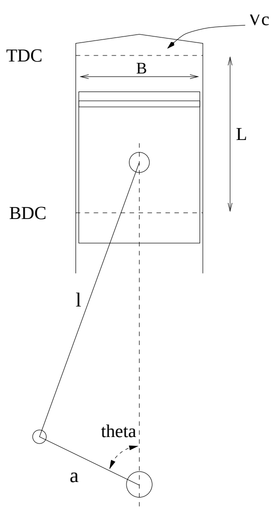
Measured engine efficiency map.

Used very often for fuel consumption assessment.

The engineering perspective, design/evaluation.

–What to do when map-data isn't available?

Engine Geometry Definitions



Cylinder, Piston, Connecting rod, Crank shaft

- Bore, B
- Stroke, $S = 2\,a$
- Number of cylinders z
- Cylinder swept volume, $V_d = \frac{\pi\,B^2\,S}{4}$
- Engine swept volume, $V_D = z\,\frac{\pi\,B^2\,S}{4}$
- Compression ratio $r_c = \frac{V_{max}}{V_{min}} = \frac{V_d+V_c}{V_c}$

Definition of MEP

- Mean Effective Pressure (MEP) $= \frac{\text{Work}}{\text{Displacement Volume}} = \frac{4\,\pi\,T_e}{V_D}$
- MEP – normalizes the work output with the size of the engine.

The engineering perspective

If we can build a good model in the MEP domain,
then we can scale it with V_D and get a generic engine model,
with which we can evaluate the design impact of different engine sizes.

Opens up possibilities for selecting engines for optimal fuel economy for a vehicle, etc.

Warning

Nomenclature: MEP here, p_{me} in the book.

Normalized Engine Variables

- Mean Piston Speed ($S_p = mps = c_m$):

$$c_m = \frac{\omega_e\,S}{\pi}$$

- Mean Effective Pressure (MEP=p_{me} ($N = n_r \cdot 2$)):

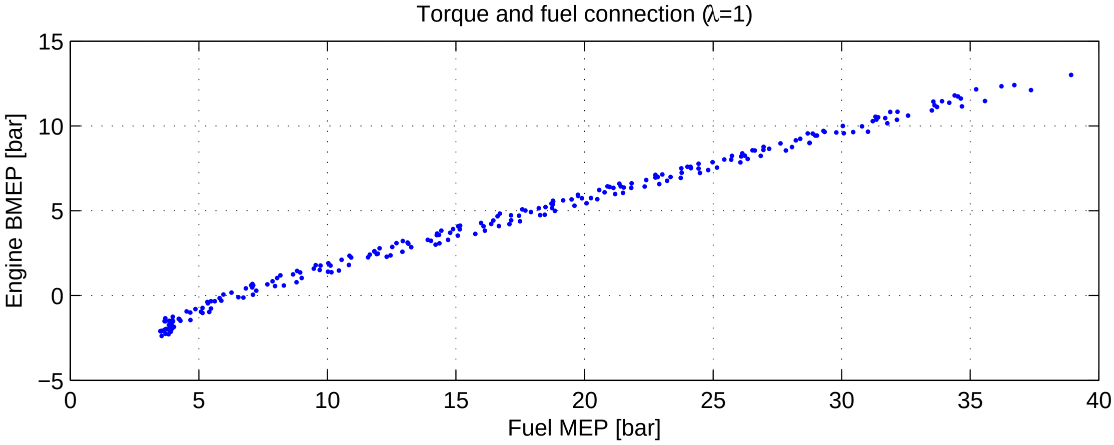
$$p_{me} = \frac{N\,\pi\,T_e}{V_d}$$

- Used to:
  - Compare performance for engines of different size
  - Design rules for engine sizing.
    At max engine power: $c_m \approx 17$ m/s, $p_{me} \approx$ 1e6 Pa (no turbo)
    $\Rightarrow$ engine size
  - Connection:

$$P_e = z\,\frac{\pi}{16}\,B^2\,p_{me}\,c_m$$

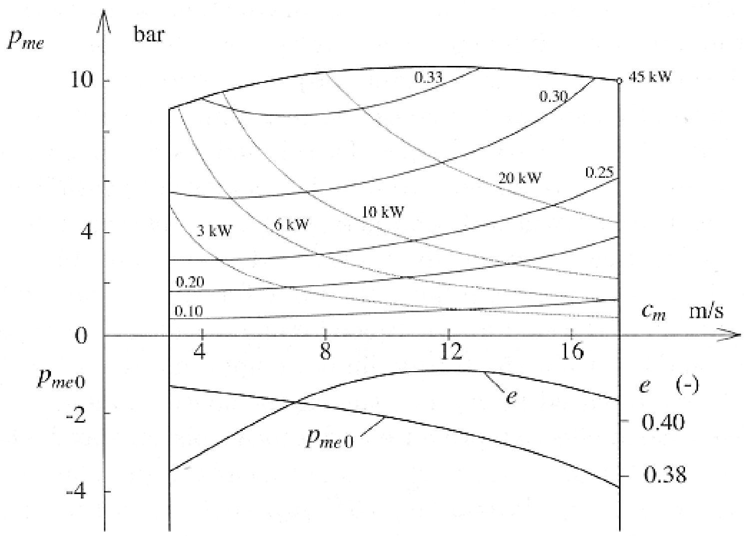
Torque modeling through – Willans Line

- Measurement data: x: p_{mf} y: $p_{me} = BMEP$



- Linear (affine) relationship – Willans line $p_{me} = e(\omega_e) \cdot p_{mf} - p_{me,0}(\omega_e)$
- Engine efficiency: $\eta_e = \frac{p_{me}}{p_{mf}}$

Engine Efficiency – Map Representation



Willans line parameters

Engine speed dependent

- $e(\omega_e)$
- $p_{me,0}(\omega_e)$