Vehicle Propulsion Systems
Lecture 2
Fuel Consumpmtion Estimation – The Basics

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October 27, 2010

Outline

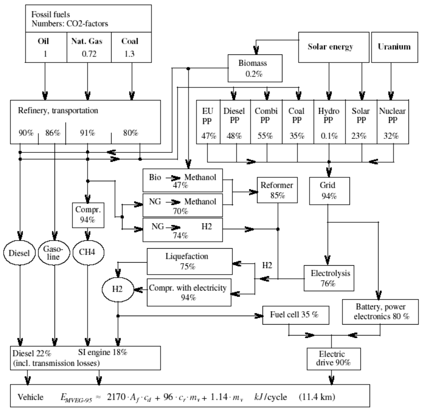
Repetition

Energy Consumption of a Driving Mission
The Vehicle Motion Equation
Losses in the vehicle motion
Energy Demand of Driving Missions

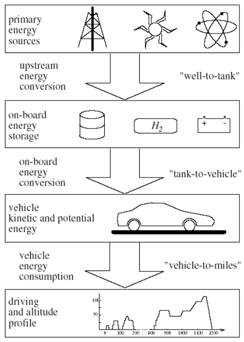
Other Demands on Vehicles
Performance and Driveability
Energy demand and recuperation

Methods and tools
Software tools

W2M – Energy Paths



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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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:

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

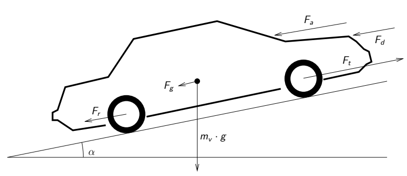
Newton's second law:

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

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 $v(t)$

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

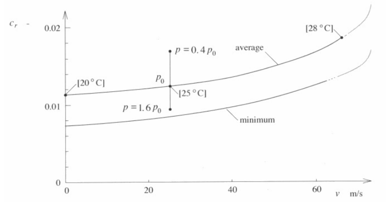
Approximate contributions to F_a

- 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

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

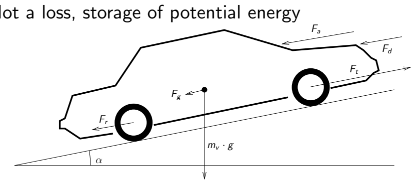


The velocity has small influence at low speeds.
Increases for high speeds where resonance phenomena start.
Assumption in book: c_r – constant

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

Gravitational Force

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

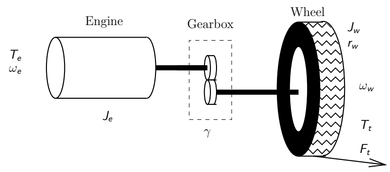


- Up- and down-hill driving produces forces.

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

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

Inertial forces – Reducing the Tractive Force



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

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:

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

- 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

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

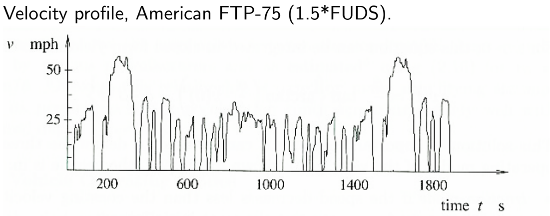
- Method 2: Solve (1) for F_t

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

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

Driving profiles

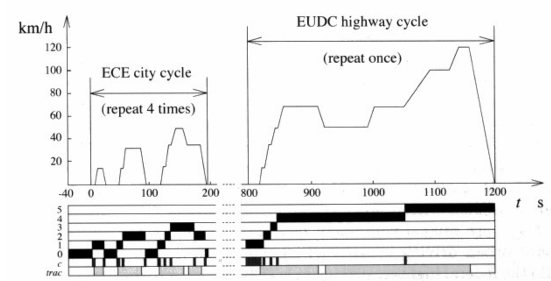
Velocity profile, American FTP-75 (1.5*FUDS).



Driving profiles in general

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

Driving profiles – Another example



Velocity profile, European MVEG-95 (ECE*4, EUDC)

No coasting in this driving profile.

Mechanical Energy Demand of a Cycle

Only the demand from the cycle

- The mean tractive force during a cycle

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_0^{x_{tot}} F(x)dx = \frac{1}{x_{tot}} \int_{t \in trac} F(t)v(t)dt$$

  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 $v_i = v(t_i)$, $t = i \cdot h$, $i = 1, \dots, n$.
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

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

Evaluating the integral

Tractive force from *The Vehicle Motion Equation*

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

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

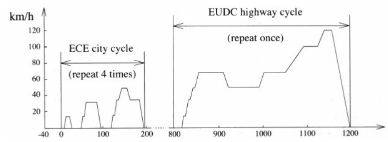
Resulting in these sums

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

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

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

Values for cycles



Numerical values for MVEG-95, ECE, EUDC

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

$$\bar{X}_{trac,r} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i h = \qquad \{.856, 0.81, 0.88\}$$

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

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

Tasks in Hand-in assignment

Approximate car data

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

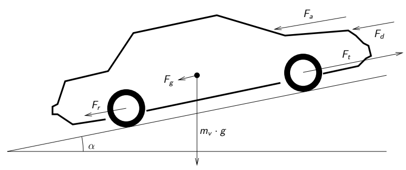
	SUV	full-size	compact	light-weight	PAC-Car II
$A_f \cdot c_d$	1.2 m^2	0.7 m^2	0.6 m^2	0.4 m^2	.25 · .07 m^2
c_r	0.017	0.017	0.017	0.017	0.0008
m_v	2000 kg	1500 kg	1000 kg	750 kg	39 kg
$\bar{P}_{\text{MVEG-95}}$	11.3 kW	7.1 kW	5.0 kW	3.2 kW	
$\bar{P}_{\max}$	155 kW	115 kW	77 kW	57 kW	

Average and maximum power requirement for the cycle.

The Vehicle Motion Equation

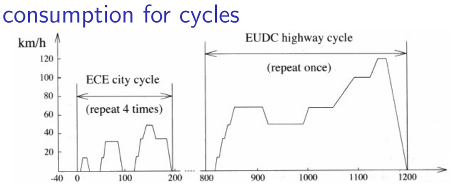
Newton's second law for a vehicle

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



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

Energy consumption for cycles



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

Outline

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

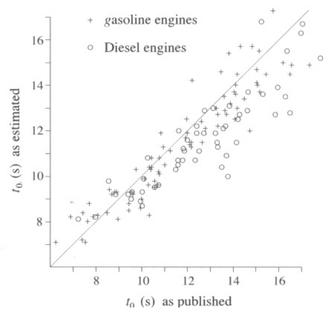
$$E_0 = \frac{1}{2} m_v v_0^2$$

- 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)

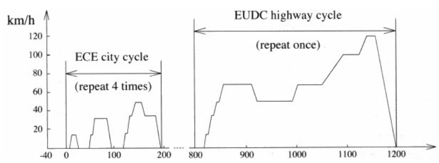
$$P_{max} = \frac{m_v v^2}{t_0}$$

Acceleration Performance – Validation

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



Energy demand again – Recuperation



Recover the vehicle's kinetic energy during driving

Perfect recuperation

- Mean required force

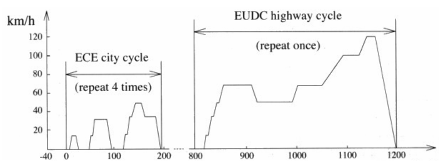
$$\bar{F} = \bar{F}_a + \bar{F}_r$$

- 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



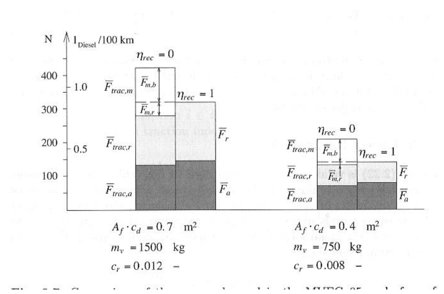
Numerical values for MVEG-95, ECE, EUDC

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

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

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

Perfect and no recuperation



Mean force represented as liter Diesel / 100 km.

Sensitivity Analysis

- Cycle energy reqirement (no recuperation)

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

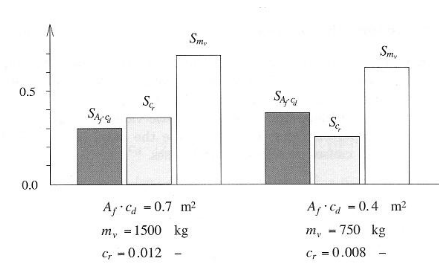
- Sensitivity analysis

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

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

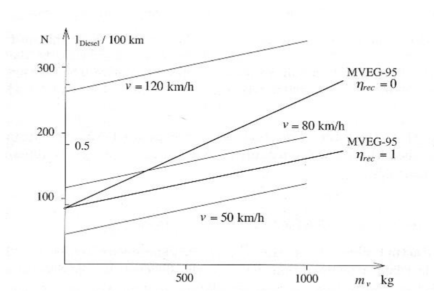
- Vehicle parameters:
  - $A_f\, c_d$
  - c_r
  - m_v

Sensitivity Analysis

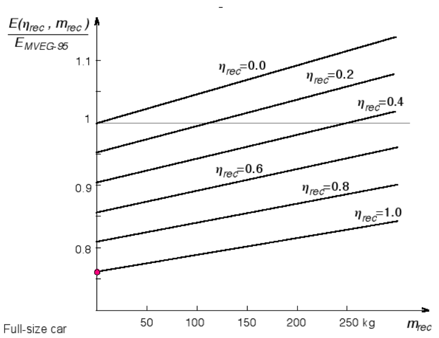


Vehicle mass is the most important parameter.

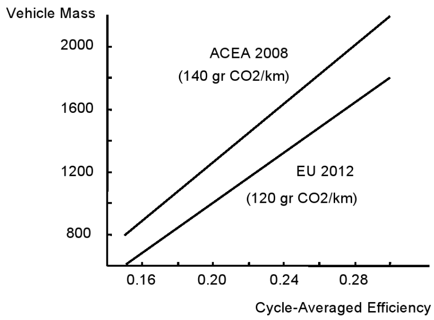
Vehicle mass and fuel consumption



Realistic Recuperation Devices



Vehicle Mass and Cycle-Averaged Efficiency



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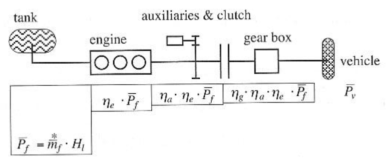
Methods and tools

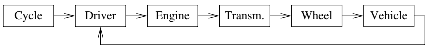
Average operating point method.



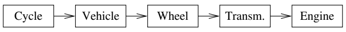
One task among in the Hand-in assignments.

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 causality

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, considering Modelica opens up new possibilities.
- See also: *Efficient Drive Cycle Simulation*, Anders Fröberg and Lars Nielsen (2008) . . .

Dynamic approach

- 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.

Optimization problems

- Structure optimization
- Parametric optimization
- Control system optimization

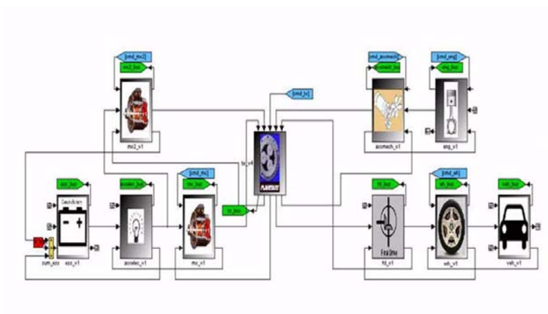
Software tools

Different tools for studying energy consumption in vehicle propulsion systems

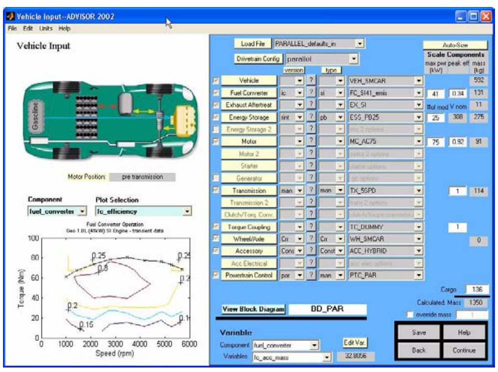
	Quasi static	Dynamic
QSS (ETH)	X	
Advisor, AVL	X	(X)
PSAT		X
CAPSim (VSim)		X
Inhouse tools	(X)	(X)

PSAT

Argonne national laboratory



Advisor



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.