Vehicle Propulsion Systems
Lecture 1
Course Introduction & Energy System Overview

Lars Eriksson
Associate Professor (Docent)

Vehicular Systems
Linköping University

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Outline

Vehicle Propulsion Systems

Vehicles as a hot topic is everlasting

- Brings freedom to the user
- Have a direct influence on the environment
- Consume resources that are limited
- Have different appeal to different persons

Vehicle Propulsion Systems

A diversity of powertrain configurations is appearing

- Conventional Internal Combustion Engine (ICE) powertrain. Diesel, Gasoline, New concepts
- Hybrid powertrains – Parallel/Series/Complex configurations
- Fuel cell electric vehicles
- Electric vehicles

Course goal:

- Introduction to powertrain configuration and optimization problems
- Mathematical models and ...
- ... methods for
  - Analyzing powertrain performance
  - Optimizing the powertrain energy consumption

Top Priorities in Vehicle Development

- Improve the fuel economy of vehicles
  (Better cars are our best oil-wells)
- Reduce costs
- Drivability
- Safety
- Emissions
  - Exhaust emissions
  - Road dust
  - Noise
  - Legislations

All issues are important but the first item is the main topic here.

Vehicle properties

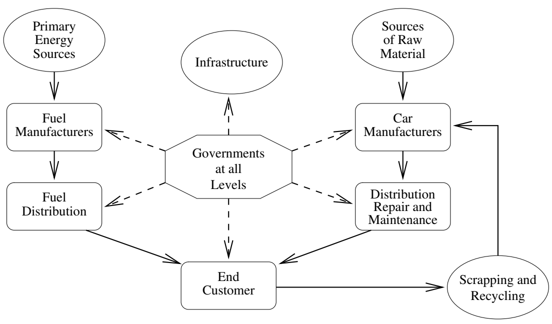
The vehicle in focus is passenger cars. (In the book.)
–What characterizes passenger cars?

- Autonomous and do not depend on fixed power grid.
- Have refueling time negligible compared to the driving time between two refuelings.
- Transport two to six persons and some payload.
- Accelerate from 0 to 100 km/h in 10-15 seconds, or drive uphill a 5% ramp at legal top speed.

Methods and tools are also applicable to trucks and other transportation systems.

- Numerical values differ
- Demands are different
- Principles are the same but solutions differ

Life Cycle of a Vehicle



Many things are important!
–Focus is on energy path and in-vehicle energy conversion

Outline

Examination – 4 Hand-In Assignments

Hand-In assignments done individually.
Compendium for Hand-In assignments.

1. Fuel consumption requirement of a driving mission.
   Methods and tools for estimating the fuel consumption.
   –Mandatory and optional tasks.
2. Optimal control of series and hybrid concepts.
   Tools for investigating the best possible driving schedule.
   –Mandatory and optional tasks.
3. Three concepts for short term energy storage.
   Very open ended problems.
   –Mandatory to investigate one concept.
4. Fuel cell vehicle.
   –Optional tasks.

Examination – Grading system

1. Pass – Grade 3.
   All mandatory tasks must be completed.
   Handed in, examined, returned (corrected, handed in again, until pass).
2. Higher grades.
   Handed in, graded by us (like an exam), returned.
   Point system connected to extra tasks.
   - Grade 3 – 0-13 p
   - Grade 4 – 14-? p
   - Grade 5 – 24-? p (+ demand on 2 points on truck or fuel cell)
3. More details are found in the compendium.
   Deadlines given on the home page.

Resources

- Computer tools are necessary, to be able to solve interesting problems.
  –Matlab and Simulink with extra packages.
- If you have your own computer, we encourage you to use it.
- 2 computer room booked on 2 occasions per week
  Mon 17–21, and (Wed 13-17 or Thursday 8-12).
- See it as support opportunity.
  – Lab room assistant, answers questions.
  – Collect your questions and come to us.

Preparations for hand-in – Refresh your knowledge

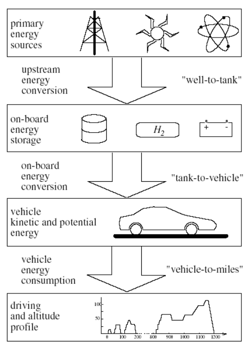
Matlab and Simulink programming experience.

Course Outline

Let's have a look on the course home page!

Outline

Energy System Overview



Primary sources

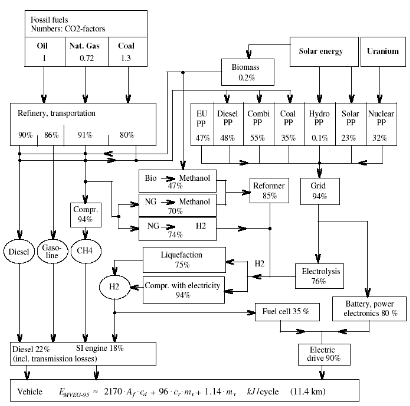
Different options for on-board energy storage

Powertrain energy conversion during driving

Cut at the wheel!

Driving mission has a minimum energy requirement.

Example of Some Energy Paths – W2M



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:

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

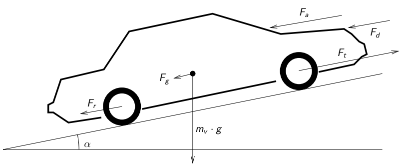
Newton's second law:

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

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 $v(t)$

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

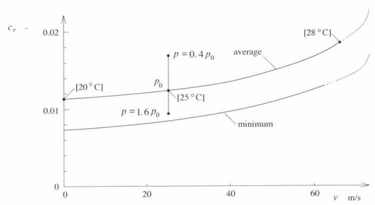
Approximate contributions to F_a

- 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

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

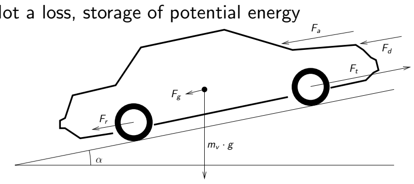


The velocity has small influence at low speeds.
Increases for high speeds where resonance phenomena start.
Assumption in book: c_r – constant

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

Gravitational Force

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

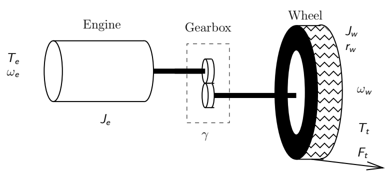


- Up- and down-hill driving produces forces.

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

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

Inertial forces – Reducing the Tractive Force



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

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

Tractive force:

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

The Vehicle Motion Equation:

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

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

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

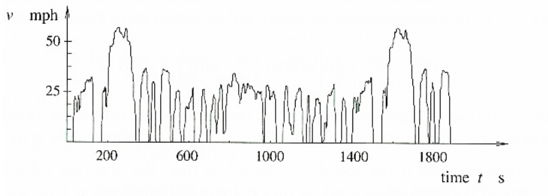
- Method 2: Solve (1) for F_t

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

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

Driving profiles

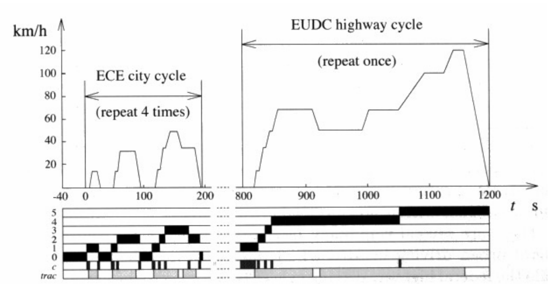
Velocity profile, American FTP-75 (1.5*FUDS).



Driving profiles in general

- First used for pollutant control now also for fuel 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 (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

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_0^{x_{tot}} \max(F(x), 0)\,dx = \frac{1}{x_{tot}} \int_{t \in trac} F(t)v(t)dt$$

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

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

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

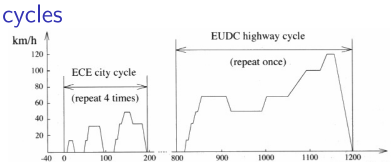
Resulting in these sums

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

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

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

Values for cycles



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

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

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

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

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

Tasks in Hand-in assignment

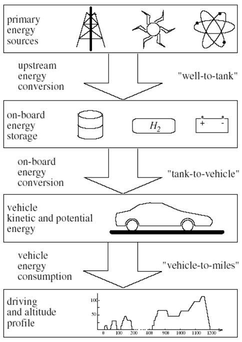
Approximate car data

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

	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	$.25 \cdot .07$ 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	
$\bar{P}_{\max}$	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.