Vehicle Propulsion Systems
Lecture 7
KERS & Non Electric Hybrid Propulsion Systems

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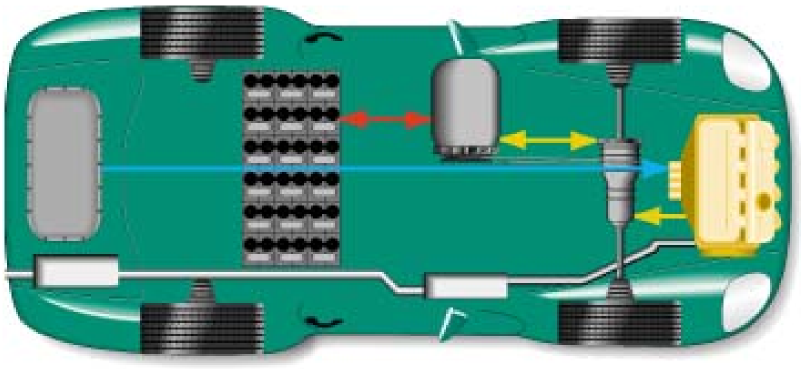
Outline

1. Repetition
2. Short Term Storage
3. Hybrid-Inertial Propulsion Systems
   - Basic principles
   - Design principles
   - Flywheel Model in Vehicle
   - Continuously Variable Transmission
4. Hybrid-Hydraulic Propulsion Systems
   - Basics
   - Modeling
5. Hydraulic Pumps and Motors
6. Pneumatic Hybrid Engine Systems
7. Case studies

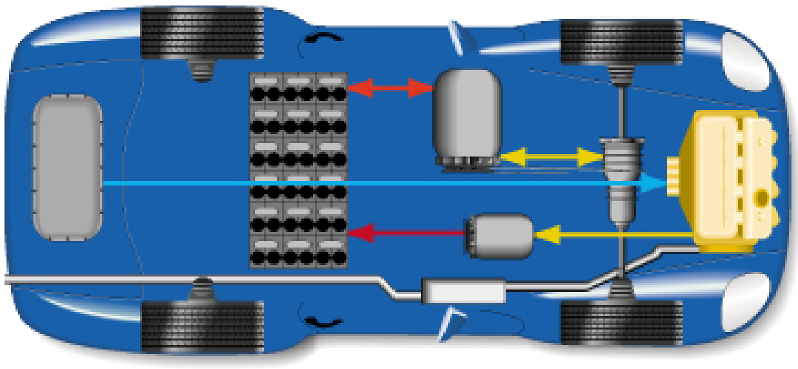
Hybrid Electrical Vehicles – Parallel

- Two parallel energy paths
- One state in QSS framework, state of charge



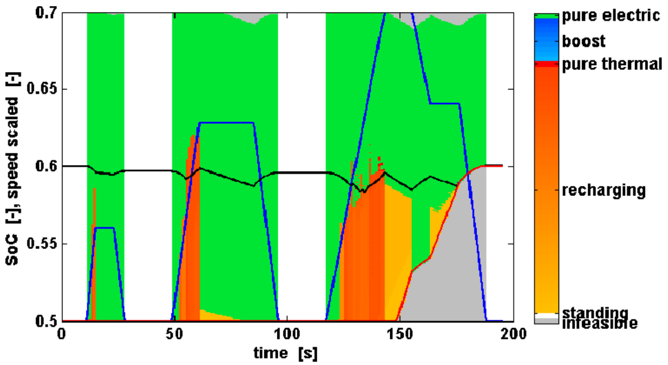
Hybrid Electrical Vehicles – Serial

- One path; Operation decoupled through the battery
- Two states in QSS framework, state of charge & Engine speed



Deterministic Dynamic Programming – Parallel Hybrid Example

- Fuel-optimal torque split factor $u(SOC, t) = \frac{T_{e-motor}}{T_{gearbox}}$
- ECE cycle
- Constraints $SOC(t = t_f) \geq 0.6$, $SOC \in [0.5, 0.7]$



Global optimum guaranteed within discretization.

Non-causal.

Full knowledge about the mission.

Curse of dimensionality $N_t N^{2d}$.

$d \in [1, 3]$

The reference tool used for development and comparisons.

Analytical Solutions to Optimal Control Problems

- Core of the problem

$$\min J(u) = \phi(q(t_f), t_f) + \int_0^{t_f} L(t, u(t))dt$$
$$s.t.\ \dot{q}(t) = f(t, q(t), u(t))$$

- Hamiltonian from optimal control theory

$$H(t, q(t), u(t), \mu(t)) = L(t, u(t)) + \mu(t)\, f(t, q(t), u(t))$$

- $\mu(t)$ is a Lagrange multiplier, it's a dear child with many names
  - Lagrange variable
  - Adjoint state
  - Co-state
  - Most often denoted $\lambda(t)$, but $\mu(t)$ is also used.

Analytical Solutions to Optimal Control Problems

- Hamiltonian

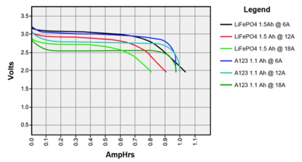
$$H(t, q(t), u(t), \mu(t)) = L(t, u(t)) + \mu(t)\, f(t, q(t), u(t))$$

- Solution Pontryagin's minimum principle (theory from Appendix B)

$$u(t) = \arg\min_u H(t, q(t), u(t), \mu(t))$$

with

$$\dot{\mu}(t) = -\frac{\partial}{\partial q} f(t, q(t), u(t))$$
$$\dot{q}(t) = f(t, q(t), u(t))$$



- If $\frac{\partial}{\partial q} f(t, q(t), u(t)) = 0$ the problem becomes simpler
  $\mu(t)$ becomes constant μ_0, update it while driving

ECMS

- Given the optimal $\lambda^* = \mu_0$ (cycle dependent exchange rate between fuel and electricity).
- Hamiltonian

$$H(t, q(t), u(t), \lambda^*) = P_f(t, u(t)) + \lambda^*\, P_{ech}(t, u(t))$$

- Optimal control action

$$u^*(t) = \arg\min_u H(t, q(t), u, \lambda^*)$$

- Guess λ^*, run one cycle see end SOC, update λ^*, and iterate until $SOC(t_f) \approx SOC(0)$.

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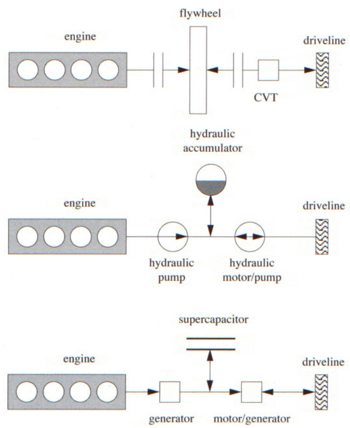
Examples of Short Term Storage Systems



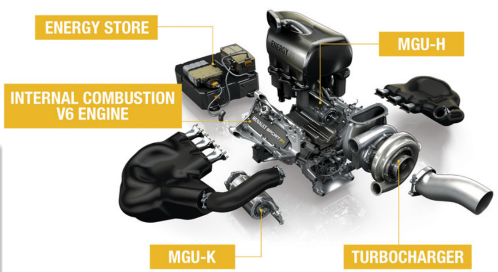
Short Term Storage – F1

2009 FIA allowed the usage of 60 kW, KERS (Kinetic Energy Recovery System) in F1. Technologies:

- Flywheel (Flybrid used @ Le Mans 2011)
- Super-Caps, Ultra-Caps
- Batteries

2014, FIA allowed KERS units with 120 kilowatts (160 bhp).
–To balance the sport's move from 2.4 l V8 engines to 1.6 l V6 engines.

Mercedes 2015 power unit was achieving more than 45 percent thermal efficiency – i.e. 45 percent of the fuel's energy is delivered to the crankshaft – and efficiency of more than 50 percent when the ERS is operating at full power. By comparison, the V8 engines pre-2014 achieved thermal efficiency of 29 percent and the first iteration of the Mercedes V6 turbo in 2014 managed 40 percent thermal efficiency.



Short Term Storage – F1

Energy Store (ES)

The ES is an integral part of an F1 car's powertrain and ERS, weights 20-25kg, usually lithium ion batteries. The ES can (deliver) 4MJ of energy per lap to the drivetrain, although MGU-K may only charge the ES 2MJ per lap.

Energy Recovery Systems (ERS)

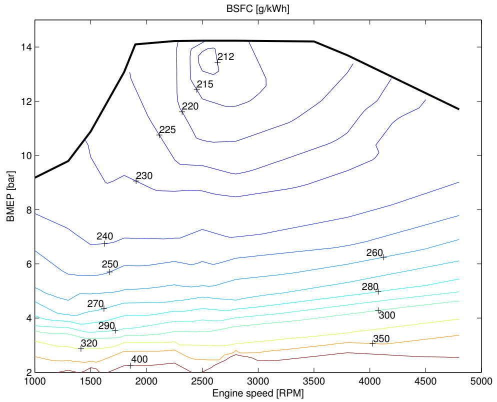
ERS consist of Motor Generator Units (MGU) that recuperates waste kinetic energy (from the braking system) and waste heat energy (from the turbocharger). An F1 car has two ERS: MGU-K (Kinetic) and MGU-H (Heat). ERS is capable of providing 120kw of power (approximately 160bhp) for approximately 33 seconds per lap.

MGU-H might be dropped for the 2021 season

Mercedes said that MGU-H provides 60% of the electric energy used to power the other part of the energy recovery system, the MGU-K, and contributes to a 5% increase of the engine's thermal efficiency.

Benefits with Hybrid Vehicle Systems

- Remove Engine Idle
- Kinetic energy recovery
- Load Shifting
  – Eliminate Low Efficiency
- Use “best” points – Duty cycle.
  - Run engine (fuel converter) at its optimal point.
  - Shut-off the engine.
- Pulse and glide (Pn’G)
  - Drive, jump to idle (lower friction)
  - Cylinder Deactivation
- Minimal powertrain energy demand
  - Constant speed, convex air-drag
  - Why Pn’G?
  - More gain in reduced engine losses



Remember global vs suboptimal solutions.

Selecting Energy Storage Type – Ragone Plots

Asymptotic power and energy densities – The Principle

Weight is important

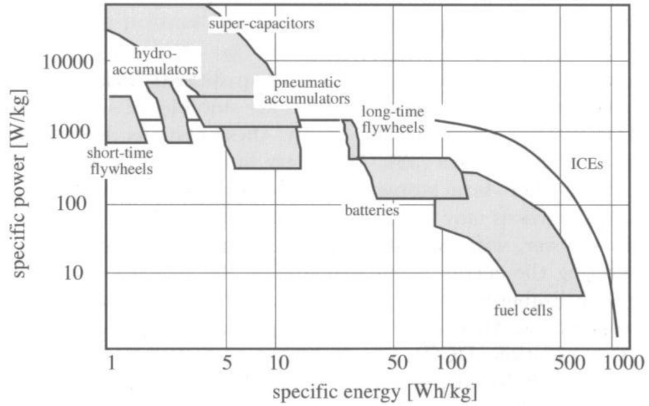
Energy is range

Power is performance

Braking, high power

Super caps

Peak shaving



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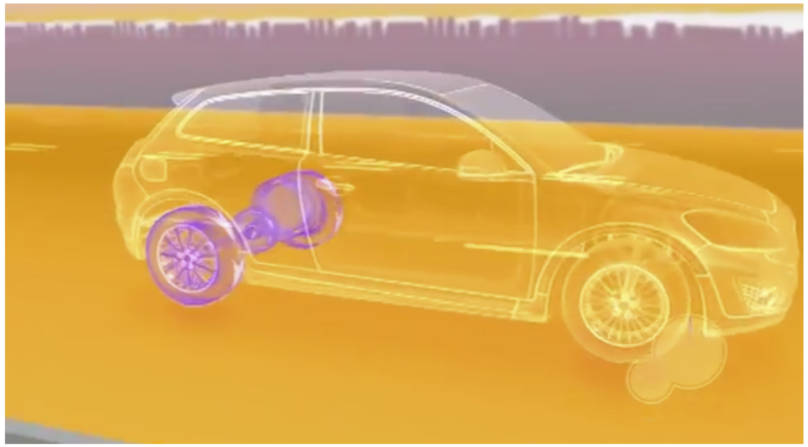
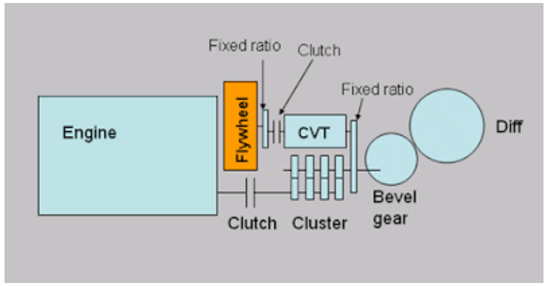
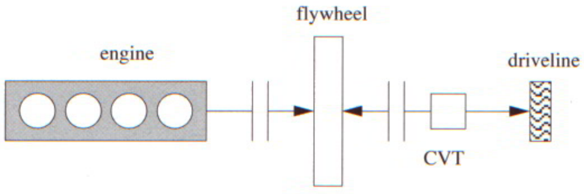
Example of a Hybrid-Inertial Propulsion System



Examples of Hybrid-Inertial Propulsion System

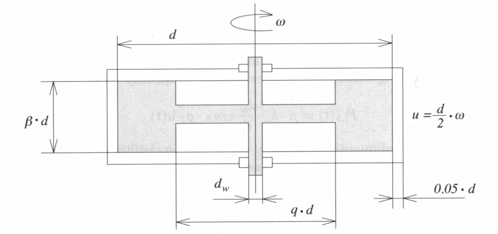




Essential Components

- Flywheel
- Clutches (free wheeling)
- CVT (Decouple speeds)
- Engine
- Vehicle

Flywheel as Accumulator



- Energy stored ($\Theta_f = J_f$):

$$E_f = \frac{1}{2}\,\Theta_f\,\omega_f^2$$

- Wheel inertia

$$\Theta_f = \rho\,b \int_{Area} r^2\,2\,\pi\,r\,dr = \ldots = \frac{\pi}{2}\,\rho\,b\,\frac{d^4}{16}\,(1 - q^4)$$

Flywheel Accumulator – Design principle

- Energy stored (SOC):

$$E_f = \frac{1}{2}\,\Theta_f\,\omega_f^2$$

- Wheel inertia

$$\Theta_f = \rho\,b \int_{Area} r^2\,2\,\pi\,r\,dr = \ldots = \frac{\pi}{2}\,\rho\,b\,\frac{d^4}{16}\,(1 - q^4)$$

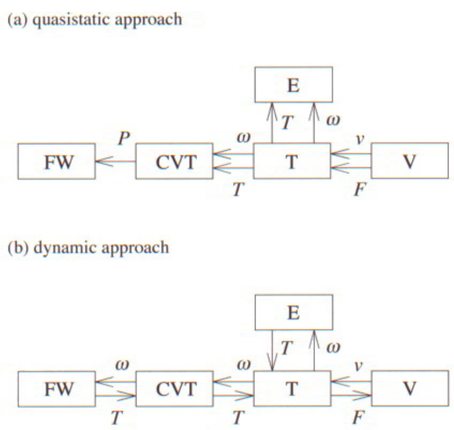
- Wheel Mass

$$m_f = \pi\,\rho\,b\,d^2\,(1 - q^2)$$

- Energy to mass ratio

$$\frac{E_f}{m_f} = \frac{d^2}{16}(1 + q^2)\omega_f^2 = \frac{u^2}{4}\,(1 + q^2)$$

Quasistatic Modeling of FW Accumulators



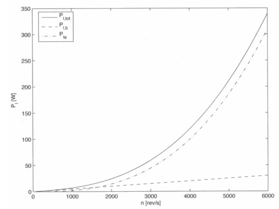
Flywheel speed (SOC)

$P_2(t)$ – power out

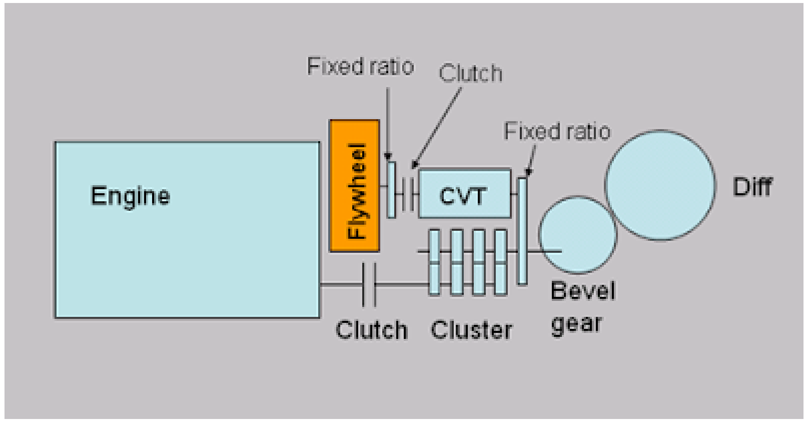
$P_l(t)$ – power loss

$$\Theta_f\,\omega_2(t)\,\frac{d}{dt}\omega_2(t) = -P_2(t) - P_l(t)$$

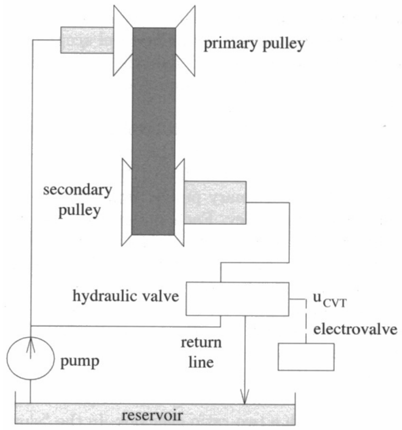
Air resistance and bearing losses



Next Component – Continuously Variable Transmission (CVT)



CVT Principle



CVT Modeling

- Transmission (gear) ratio ν, speeds and transmitted torques

$$\omega_1(t) = \nu(t)\,\omega_2(t)$$
$$T_{t1}(t) = \nu\,(T_{t2}(t) - T_l(t))$$

- Newtons second law for the two pulleys

$$\Theta_1 \frac{d}{dt}\omega_1(t) = T_1(t) - T_{t1}(t)$$
$$\Theta_2 \frac{d}{dt}\omega_2(t) = T_2(t) - T_{t2}(t)$$

- System of equations give

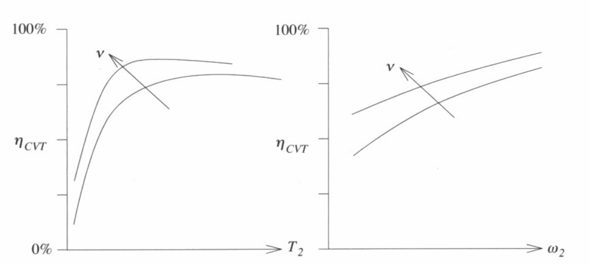
$$T_1(t) = T_l(t) + \frac{T_2(t)}{\nu(t)} + \frac{\Theta_{CVT}(t)}{\nu(t)}\frac{d}{dt}\omega_2(t) + \Theta_1 \frac{d}{dt}\nu(t)\,\omega_2(t)$$

CVT Modeling

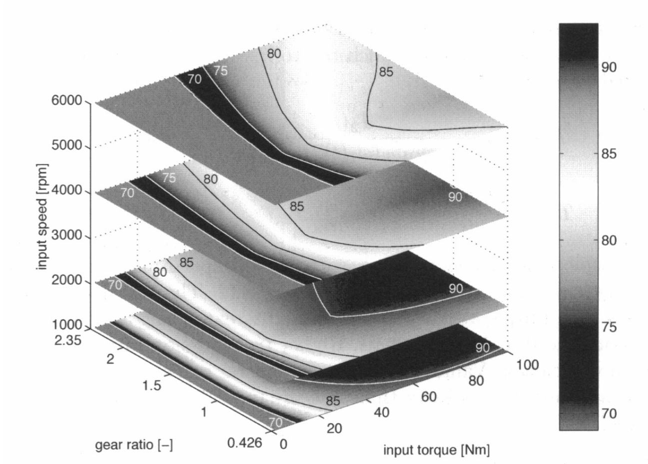
- Transmission (gear) ratio ν, speeds and transmitted torques

$$\omega_1(t) = \nu(t)\,\omega_2(t)$$
$$T_{t1}(t) = \nu\,(T_{t2}(t) - T_l(t))$$

- An alternative to model the losses, is to use an efficiency definition.



Efficiencies for a Push-Belt CVT



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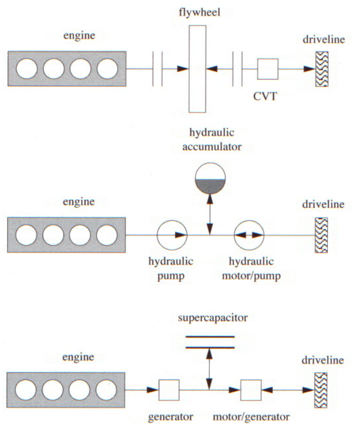
Examples of Short Term Storage Systems



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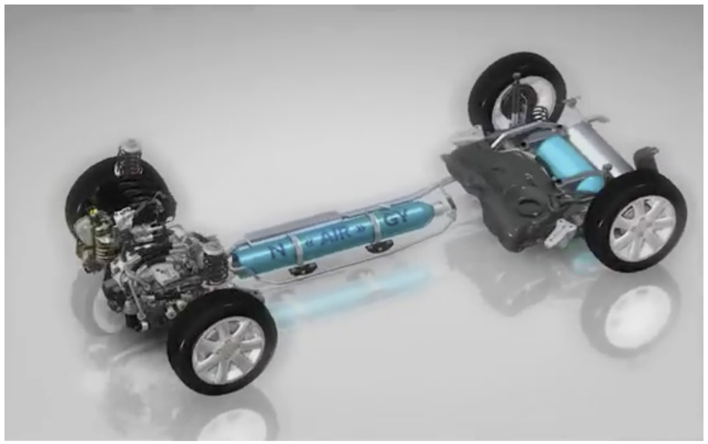
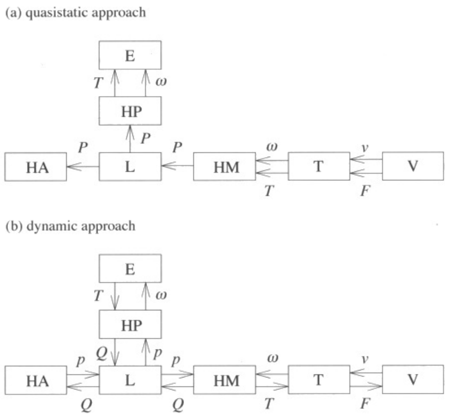


Causality for a hybrid-hydraulic propulsion system



Modeling of a Hydraulic Accumulator

Modeling principle
–Energy balance

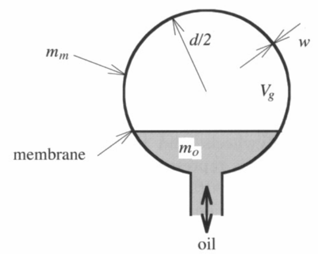
$$m_g\, c_v \frac{d}{dt}\theta_g(t) = -p \frac{d}{dt} V_g(t) - h\, A_w\, (\theta_g(t) - \theta_w)$$

–Mass balance
(=volume for an incompressible fluid)

$$\frac{d}{dt} V_g(t) = Q_2(t)$$

–Ideal gas law

$$p_g(t) = \frac{m_g\, R_g\, \theta_g(t)}{V_g(t)}$$



Power generation

$$P_2(t) = p_2(t)\, Q_2(t)$$

Model Simplification

Simplifications made in thermodynamic equations to get a simple state equation.

- Assuming steady state conditions.
  –Eliminating θ_g and the volume change gives

$$p_2(t) = \frac{h\, A_w\, \theta_w\, m_g\, R_g}{V_g(t)\, h\, A_w + m_g\, R_g\, Q_2(t)}$$

- Combining this with the power output gives

$$Q_2(t) = \frac{V_g(t)}{m_g} \frac{h\, A_w\, P_2(t)}{R_g\, \theta_w\, h\, A_w - R_g\, P_2(t)}$$

- Integrating $Q_2(t)$ gives V_g as the state in the model.
- Modeling of the hydraulic systems efficiency, see the book.
- A detail for the assignment
  –This simplification can give problems in the simulation if parameter values are off.
  (Division by zero.)

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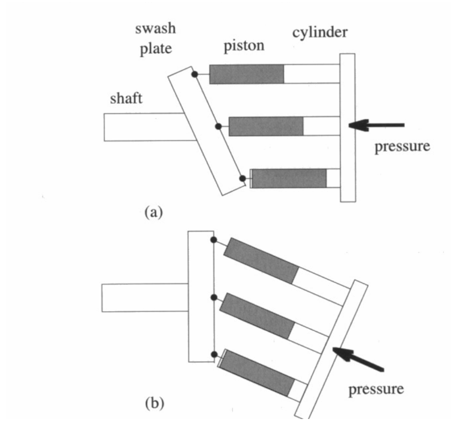
Hydraulic Pumps



There are separate courses on hydraulic systems.

We're interested in power transfers and losses.

Modeling of Hydraulic Motors

- Efficiency modeling

$$P_1(t) = \frac{P_2(t)}{\eta_{hm}(\omega_2(t), T_2(t))}, \qquad P_2(t) > 0$$
$$P_1(t) = P_2(t)\,\eta_{hm}(\omega_2(t), -|T_2|(t)), \qquad P_2(t) < 0$$

- Willans line modeling, describing the loss

$$P_1(t) = \frac{P_2(t) + P_0}{e}$$

- Physical modeling
  Wilson's approach provided in the book.

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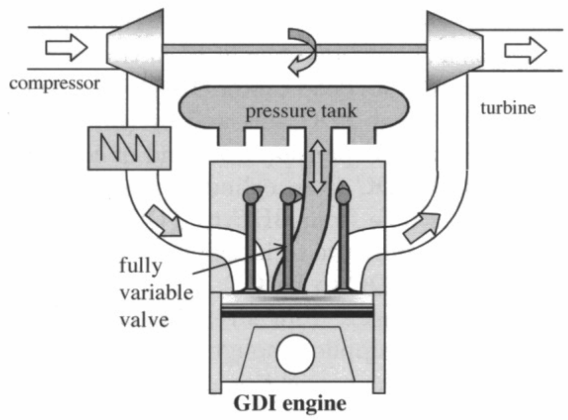
Pneumatic Hybrid Engine System

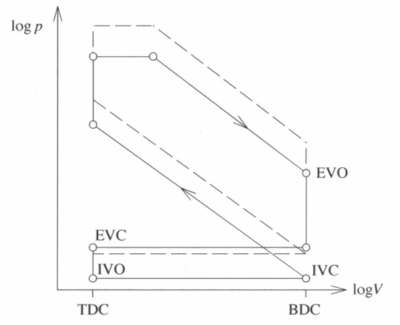


Conventional SI Engine

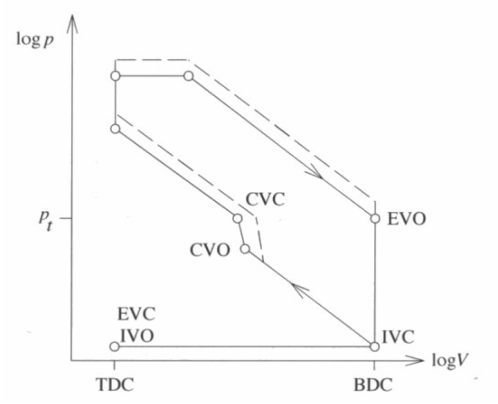
Compression and expansion model

$$p(t) = c\, v(t)^{-\gamma} \qquad \Rightarrow \qquad \log(p(t)) = \log(c) - \gamma \log(v(t))$$

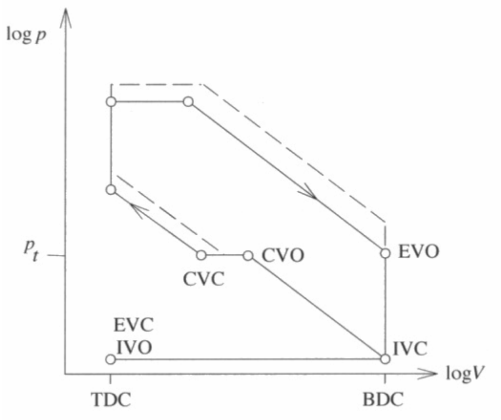
gives lines in the log-log diagram version of the pV-diagram



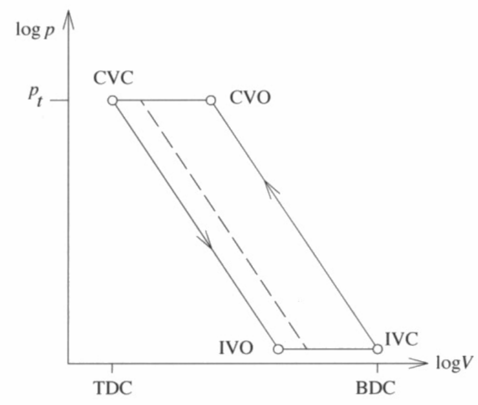
Super Charged Mode



Under Charged Mode



Pneumatic Brake System



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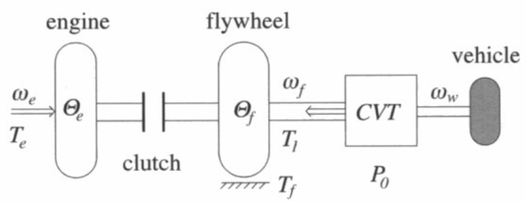
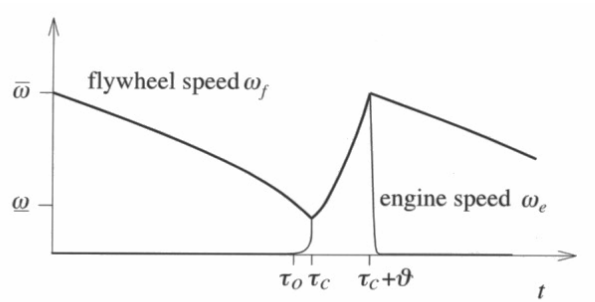
Case Study 3: ICE and Flywheel Powertrain

- Control of a ICE and Flywheel Powertrain
- Switching on and off engine



Problem description

For each constant vehicle speed find the optimal limits for starting and stopping the engine
–Minimize fuel consumption



–Solved through parameter optimization ⇒ Map used for control

Case Study 8: Hybrid Pneumatic Engine

- Local optimization of the engine thermodynamic cycle
- Different modes to select between
- Dynamic programming of the mode selection