

Vehicle Propulsion Systems

Lecture 7

Non Electric Hybrid Propulsion Systems

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Outline

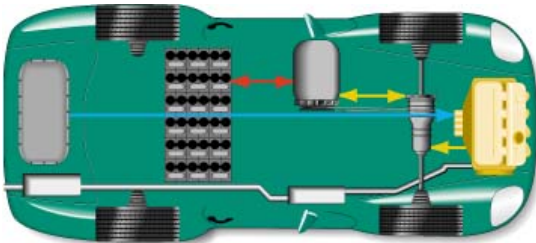
- Repetition
- Short Term Storage
- Hybrid-Inertial Propulsion Systems
 - Basic principles
 - Design principles
 - Modeling
 - Continuously Variable Transmission
- Hybrid-Hydraulic Propulsion Systems
 - Basics
 - Modeling
- Hydraulic Pumps and Motors
- Pneumatic Hybrid Engine Systems
- Case studies

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Hybrid Electrical Vehicles – Parallel

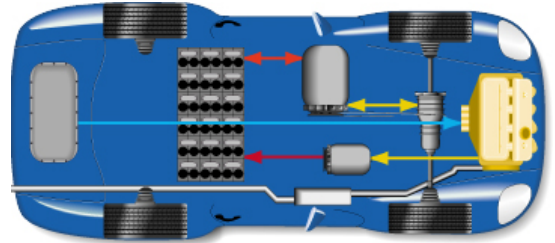
- ▶ Two parallel energy paths
- ▶ One state in QSS framework, state of charge



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Hybrid Electrical Vehicles – Serial

- ▶ Two paths working in parallel
- ▶ Decoupled through the battery
- ▶ Two states in QSS framework, state of charge & Engine speed

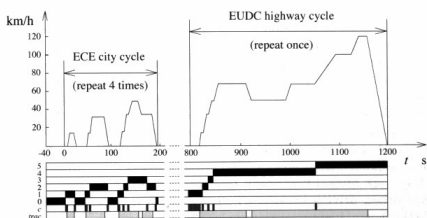


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Optimization, Optimal Control, Dynamic Programming

What gear ratios give the lowest fuel consumption for a given driving cycle?

– Problem presented in appendix 8.1



Problem characteristics

- ▶ Countable number of free variables, $i_{g,j}, j \in [1, 5]$
- ▶ A “computable” cost, $m_f(\dots)$
- ▶ A “computable” set of constraints, model and cycle
- ▶ The formulated problem

$$\begin{aligned} \min_{i_{g,j}, j \in [1,5]} & m_f(i_{g,1}, i_{g,2}, i_{g,3}, i_{g,4}, i_{g,5}) \\ \text{s.t.} & \text{model and cycle is fulfilled} \end{aligned}$$

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Optimal Control – Problem Motivation

Car with gas pedal $u(t)$ as control input:

How to drive from A to B on a given time with minimum fuel consumption?

- ▶ Infinite dimensional decision variable $u(t)$.
- ▶ Cost function $\int_0^t \dot{m}_f(t) dt$
- ▶ Constraints:
 - ▶ Model of the car (the vehicle motion equation)

$$\begin{aligned} m_v \frac{d}{dt} v(t) &= F_r(v(t), u(t)) - (F_a(v(t)) + F_r(v(t)) + F_g(x(t))) \\ \frac{d}{dt} x(t) &= v(t) \\ \dot{m}_f &= f(v(t), u(t)) \end{aligned}$$

- ▶ Starting point $x(0) = A$
- ▶ End point $x(t_f) = B$
- ▶ Speed limits $v(t) \leq g(x(t))$
- ▶ Limited control action $0 \leq u(t) \leq 1$

General problem formulation

- ▶ Performance index

$$J(u) = \phi(x(t_b), t_b) + \int_{t_a}^{t_b} L(x(t), u(t), t) dt$$

- ▶ System model (constraints)

$$\frac{d}{dt} x = f(x(t), u(t), t), x(t_a) = x_a$$

- ▶ State and control constraints

$$u(t) \in U(t)$$

$$x(t) \in X(t)$$

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Dynamic programming – Problem Formulation

- ▶ Optimal control problem

$$\min J(u) = \phi(x(t_b), t_b) + \int_{t_a}^{t_b} L(x(t), u(t), t) dt$$

$$\text{s.t. } \frac{d}{dt} x = f(x(t), u(t), t)$$

$$x(t_a) = x_a$$

$$u(t) \in U(t)$$

$$x(t) \in X(t)$$

- ▶ $x(t), u(t)$ functions on $t \in [t_a, t_b]$
- ▶ Search an approximation to the solution by discretizing
 - ▶ the state space $x(t)$
 - ▶ and maybe the control signal $u(t)$
 in both amplitude and time.
- ▶ The result is a combinatorial (network) problem

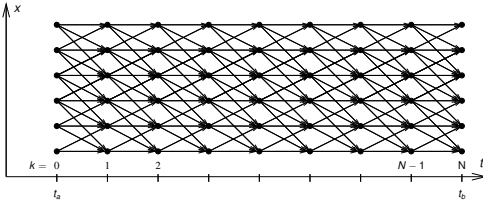
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$$J(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k)$$

$$x_{k+1} = f_k(x_k, u_k)$$

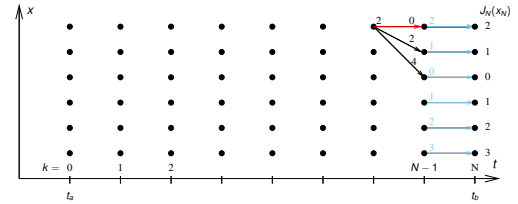
Algorithm idea:

Start at the end and proceed backwards in time to evaluate the optimal cost-to-go and the corresponding control signal.



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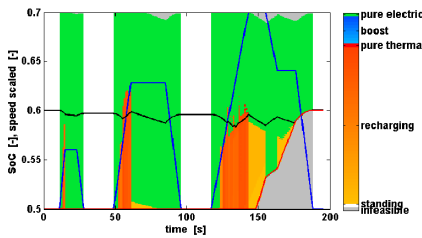
Graphical illustration of the solution procedure



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Parallel Hybrid Example

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



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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

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

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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 (theory from Appendix B)

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

with

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

$$\dot{q}(t) = f(t, q(t), u(t))$$

- ▶ If $\frac{\partial}{\partial q} H(t, q(t), u(t), \mu(t)) = 0$ the problem becomes simpler μ becomes a constant μ_0 , search for it when solving

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ECMS

- ▶ Given the optimal λ^* (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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Outline

Repetition

Short Term Storage

Hybrid-Inertial Propulsion Systems

- Basic principles
- Design principles
- Modeling
- Continuously Variable Transmission

Hybrid-Hydraulic Propulsion Systems

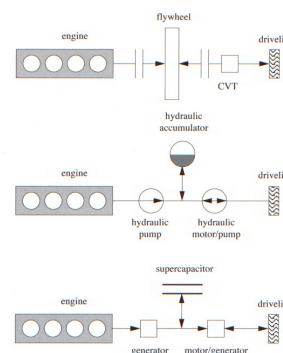
- Basics
- Modeling

Hydraulic Pumps and Motors

Pneumatic Hybrid Engine Systems

Case studies

Examples of Short Term Storage Systems



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Short Term Storage – F1

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

Technologies:

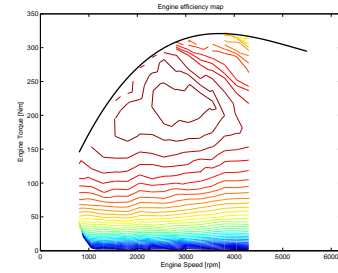
- ▶ Flywheel
- ▶ Super-Caps, Ultra-Caps
- ▶ Batteries

2014, will allow 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.

Basic Principles for Hybrid Systems

- ▶ Kinetic energy recovery
- ▶ Use "best" points – Duty cycle.
 - ▶ Run engine (fuel converter) at its optimal point.
 - ▶ Shut-off the engine.

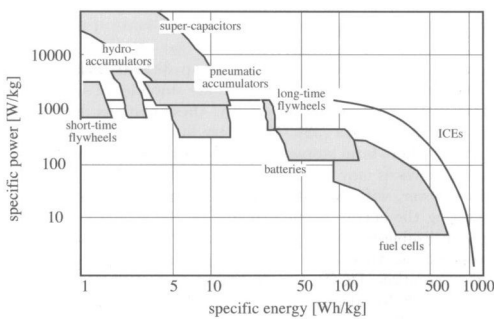


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Power and Energy Densities

Asymptotic power and energy density – The Principle



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Basics

Modeling

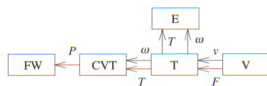
Hydraulic Pumps and Motors

Pneumatic Hybrid Engine Systems

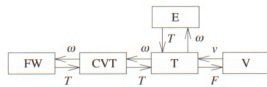
Case studies

Causality for a hybrid-inertial propulsion system

(a) quasistatic approach



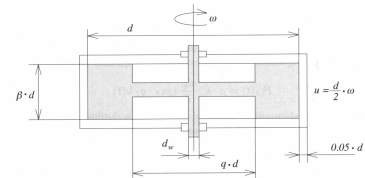
(b) dynamic approach



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Flywheel accumulator



- ▶ Energy stored ($\Theta_f = J_f$):

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

- ▶ Wheel inertia

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

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Flywheel accumulator – Design principle

- ▶ Energy stored (SOC):

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

- ▶ Wheel inertia

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

- ▶ Wheel Mass

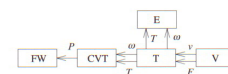
$$m_f = \pi \rho b d^2 (1 - q^2)$$

- ▶ Energy to mass ratio

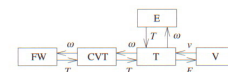
$$\frac{E_f}{m_f} = \frac{d^2}{16} (1 + q^2) \omega_f^2 = \frac{u^2}{4} (1 + q^2)$$

Quasistatic Modeling of FW Accumulators

(a) quasistatic approach



(b) dynamic approach



Flywheel speed (SOC) $P_2(t)$ – power out, $P_1(t)$ – power loss

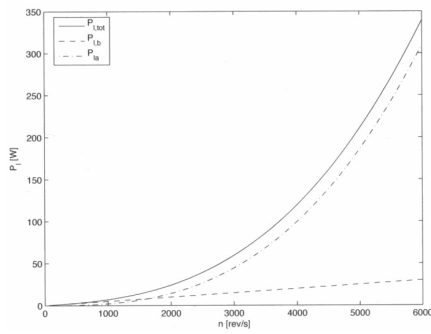
$$\Theta_f \omega_2(t) \frac{d}{dt} \omega_2(t) = -P_2(t) - P_1(t)$$

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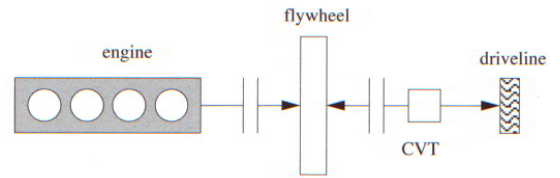
Power losses as a function of speed

Air resistance and bearing losses



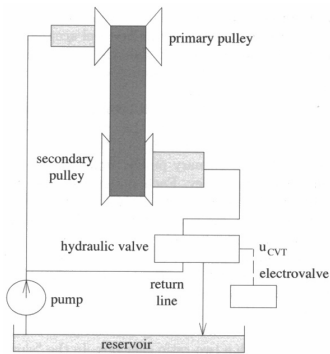
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Continuously Variable Transmission (CVT)



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CVT Principle



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CVT Modeling

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

$$\omega_1(t) = \nu(t) \omega_2(t)$$

$$T_{H1}(t) = \nu(T_{I2}(t) - T_I(t))$$

- Newtons second law for the two pulleys

$$\Theta_1 \frac{d}{dt} \omega_1(t) = T_1(t) - T_{H1}(t)$$

$$\Theta_2 \frac{d}{dt} \omega_2(t) = T_2(t) - T_{I2}(t)$$

- System of equations give

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

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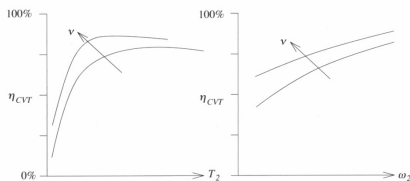
CVT Modeling

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

$$\omega_1(t) = \nu(t) \omega_2(t)$$

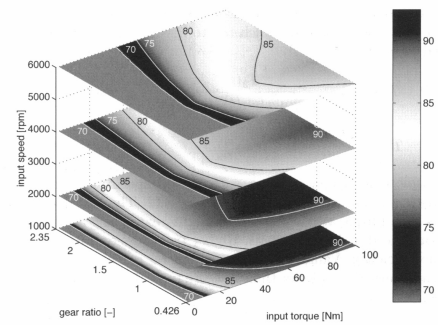
$$T_{H1}(t) = \nu(T_{I2}(t) - T_I(t))$$

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



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Efficiencies for a Push-Belt CVT



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Repetition

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Hybrid-Hydraulic Propulsion Systems

Basics

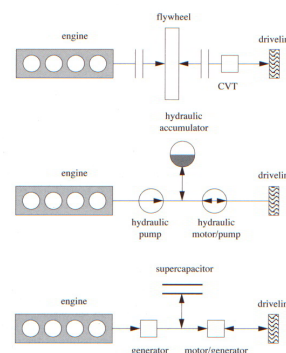
Modeling

Hydraulic Pumps and Motors

Pneumatic Hybrid Engine Systems

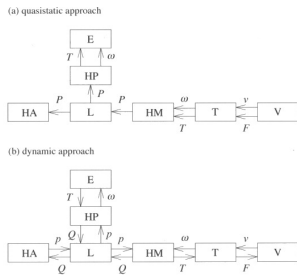
Case studies

Examples of Short Term Storage Systems



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Modeling principle
 -Energy balance

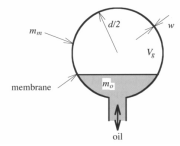
$$m_g c_v \frac{d}{dt} \theta_g(t) = -p \frac{d}{dt} V_g(t) - h A_w (\theta_g(t) - t)$$

-Mass balance
 (=volume for 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

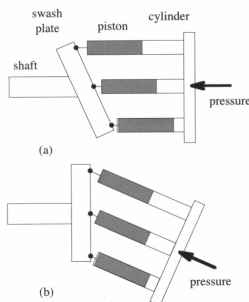
$$Q_2(t) = \frac{V_g(t)}{m_g} \frac{h A_w P_2(t)}{R_g \theta_w h A_w - R_g P_2(t)}$$

- ▶ 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



Modeling of Hydraulic Motors

- ▶ Efficiency modeling

$$P_1(t) = \frac{P_2(t)}{\eta_{hm}(\omega_2(t), T_2(t))}, \quad P_2(t) > 0$$

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

- ▶ Willans line modeling, describing the loss

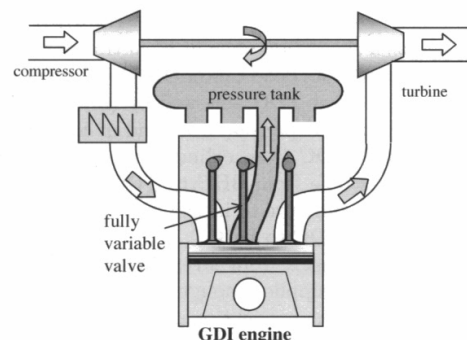
$$P_1(t) = \frac{P_2(t) + P_0}{e}$$

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

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Pneumatic Hybrid Engine System

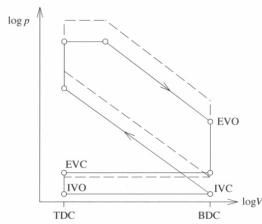


Conventional SI Engine

Compression and expansion model

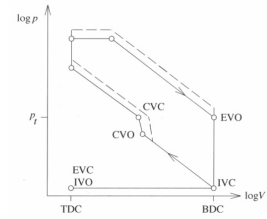
$$p(t) = c v(t)^{-\gamma} \Rightarrow \log(p(t)) = \log(c) - \gamma \log(v(t))$$

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



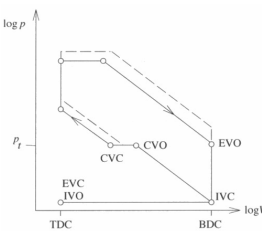
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Super Charged Mode



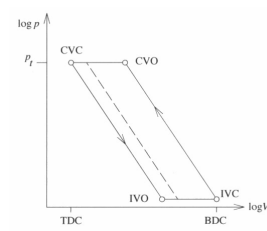
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Under Charged Mode



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Pneumatic Brake System



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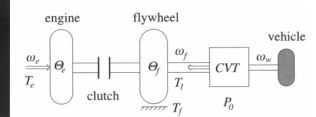
Pneumatic Hybrid Engine Systems

Case studies

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Case Study 3: ICE and Flywheel Powertrain

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

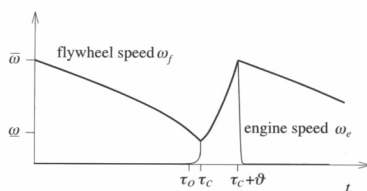


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Problem description

For each constant vehicle speed find the optimal limits for starting and stopping the engine

–Minimize fuel consumption

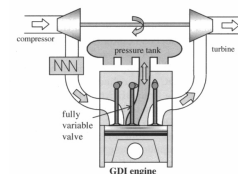


–Solved through parameter optimization \Rightarrow Map used for control

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Case Study 8: Hybrid Pneumatic Engine

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



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