Gestion de l'énergie des véhicules hybrides

avec prise en compte des dynamiques thermiques

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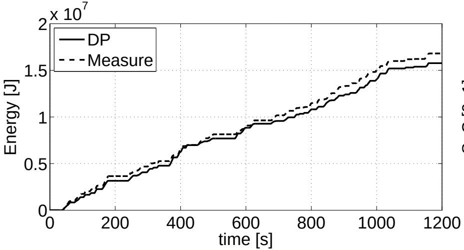
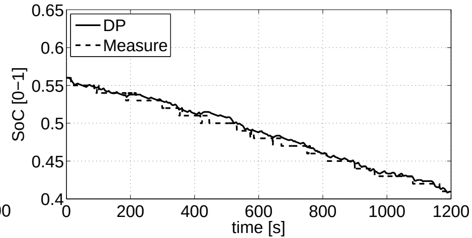
Context

- The calculation of an appropriate energy management system (EMS) for HEV can be formulated as an optimal control problem (OCP)
- Optimal online energy management has been proven for HEVs and PHEVs
- Example: IFPEN democar, ECMS implemented
- Experimental traces of fuel consumption and SOC can be very close to optimal
- In standard optimal EMS, only the SOC is considered as a dynamic variable in the OCP





Context

- However, thermal dynamics (of the power-train components, thermal accessories, heat recuperation, etc.) are comparably slow as that of SOC
- and they can be important to take into account because they affect fuel consumption
- but also other criteria (aging, pollutant emissions)
- Extended optimal EMS can be solved off line using either DP or PMP
- Include such dynamics in online optimization as it has been done in ECMS for the SOC costate is a new challenge
- $\Rightarrow$ general problem of online optimal control of multi-state systems (with unknown perturbations)

Engine temperature: Motivation

- Most EMS designs described in the literature assume that the engine is under thermal equilibrium (engine temperature is around $80°$C)
- In some situations, thermal transients are not negligible:
  - the engine is subject to stop-start phases
  - engine temperature impacts emission and fuel consumption rates
  - the efficiency of after-treatments systems is relatively poor at low temperatures

Objectives

- Quantify the benefit of including engine temperature in the EMS minimizing fuel consumption
- Find a sub-optimal, real-time capable approach

Engine temperature: OCP Formulation

- The cost function to be minimized is

$$J(u) = \int_0^T c(u, w) e(\theta_e) dt$$

  - $c(.)$ is the fuel consumption rate when engine is warm
  - $e(.)$ is the correction factor of fuel consumption
  - u is the engine torque
  - w is the uncontrolled disturbance (drive cycle, etc.)

- Two state variables, SOC (ξ) and a lumped engine temperature θ_e

$$\dot{\xi} = f(u, w), \quad \dot{\theta}_e = g(u, w, \theta_e)$$

- Global constraints: $\xi(0) = \xi_0, \quad \xi(T) = \xi_f, \quad \theta_e(0) = \theta_0, \quad \theta_e(T) = \text{free}$

Engine temperature: OCP Solution using PMP

- Hamiltonian definition

$$H_1(u, w, \theta_e, \lambda, \mu) = c(u, w)e(\theta_e) + \lambda \frac{d\xi}{dt} + \mu \frac{d\theta_e}{dt}$$

- Euler–Lagrange equations

$$\begin{aligned} \dot{\lambda}(t) &= -\frac{\partial H_1}{\partial \xi}(u^*(t), w, \theta_e, \lambda, \mu) = 0 \\ \dot{\mu}(t) &= -\frac{\partial H_1}{\partial \theta_e}(u^*(t), w, \theta_e, \lambda, \mu), \quad \mu(T) = 0 \end{aligned}$$

- Optimal control u^*

$$u^*(t) = \arg \min_{u \in U^{ad}} H_1(u, w, \theta_e, \lambda, \mu)$$

- Initial values $\lambda(0)$, $\mu(0)$ found by shooting methods

Engine temperature: OCP Results and Comparison

- Looking for a methodology to include engine temperature in real-time EMS
- **Proposed solution**: Control model (Hamiltonian) simplification
- Calculate the optimal controls solutions of

$$S \quad : \quad u^*(t) = \arg \min_{u \in U^{ad}} \underbrace{\left[c(u,w) e(\theta_e) + \lambda \frac{d\xi}{dt} + \mu \frac{d\theta_e}{dt} \right]}_{H_1(u,w,\theta_e,\lambda,\mu(t))}$$

$$S_1 \quad : \quad u_1^*(t) = \arg \min_{u \in U^{ad}} \underbrace{\left[c(u,w) + \lambda \frac{d\xi}{dt} \right]}_{H_1(u,w,\theta_e=\theta_w,\lambda,\mu(t)\equiv 0)}$$

$$S_2 \quad : \quad u_2^*(t) = \arg \min_{u \in U^{ad}} \underbrace{\left[c(u,w) e(\theta_e) + \lambda \frac{d\xi}{dt} \right]}_{H_1(u,w,\theta_e,\lambda,\mu(t)=0)}$$

- Evaluate the real fuel consumption $J(.)$ and calculate the state trajectories for each control: u^* and u_i^*, $i = 1, 2$

Engine temperature: OCP Results and Comparison

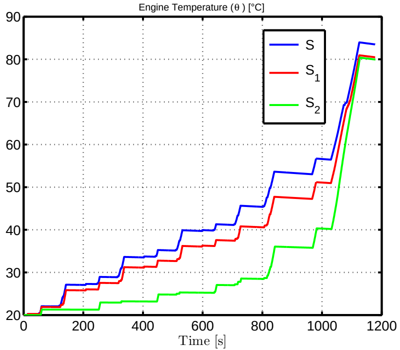


Figure: Optimal engine temperature trajectories for NEDC.

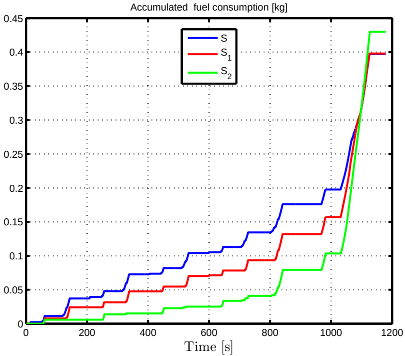


Figure: Accumulated fuel consumption trajectories for NEDC.

Engine temperature: OCP Results and Comparison

Table: Fuel consumption in **[L/100km]**.

Cycle	S_1	S_2	S
NEDC	4.80	5.20	4.79
Cycle 1	4.49	5.4	4.46
Cycle 2	5.34	5.71	5.32

- Error in fuel consumption between S and S_1 less than 0.5%
- Error in fuel consumption between S and S_2 higher $\Rightarrow$ importance of a correct simplification of the control model

Conclusion

Neglecting engine temperature changes in the EMS design leads to an acceptable sub-optimal solution (less than 0.5 $\%$) $\Rightarrow$ Simplify the numerical method used to solve the OCP.

Engine temperature: Toy Problem

- **Motivation:** Justify and understand the previous result of model simplification.
- Toy problem considered
  - Cost function:

$$J(u) = \int_0^T (\frac{1}{2} a u^2 - b\theta u) dt$$

  - Dynamics:

$$\frac{d\xi}{dt} = r_0(D - u)$$

$$\frac{d\theta}{dt} = cu$$

  - Boundary conditions:

$$\xi(0) = \xi_0 \quad \xi(T) = \xi_0$$

$$\theta(0) = \theta_0, \theta(T) = \text{free}$$

Engine temperature: Toy Problem

$$(S_1) \quad \begin{cases} H_1(u,\lambda) = \frac{1}{2}au^2 - b\theta_\infty u + \lambda\frac{d\xi}{dt} \\ \lambda = \dfrac{a}{T}E - b\theta_\infty \\ u_0^* = \dfrac{E}{T} \\ J(u_0^*) = \dfrac{a}{2T}E^2 - b(\theta_0 + \dfrac{c}{2}E)E \end{cases}$$

$$(S) \quad \begin{cases} H(u,\lambda,\theta,\mu) = \dfrac{1}{2}au^2 - b\theta u + \lambda\dfrac{d\xi}{dt} + \mu\dfrac{d\theta}{dt} \\ \lambda = \dfrac{a}{T}E - b(\theta_0 + cE), \quad \mu(t) = -bE + \dfrac{bE}{T}t \\ u^* = \dfrac{E}{T} \\ J(u^*) = \dfrac{a}{2T}E^2 - b(\theta_0 + \dfrac{c}{2}E)E \end{cases}$$

- Same controls, same state trajectories and **same cost** with different adjoint states.

Battery temperature: Motivation

- Standard formulation of ECMS, etc. minimizes only fuel consumption
- Battery temperature is a key factor (alongside to current) for battery aging:
  - capacity loss ⇒ replacement costs, operational costs
  - resistance increase ⇒ operational costs
- Multi-objective optimal control formulation with minimization of a mixed fuel–aging cost
- Thermal dynamics and a model of aging mechanisms to be considered in the optimal control

Objectives

- Quantify the benefit of including battery temperature in the EMS minimizing a trade off between fuel consumption and battery aging
- Find a sub-optimal, real-time capable approach

Battery temperature: OCP Formulation

- The combined cost function to be minimized is

$$J = (1-\alpha)\int_0^T c(u,w)\cdot LHV\,dt + \alpha\int_0^T \beta\cdot \dot{Y}(I(u,w),\xi,\theta_{bat})\,dt$$

  - $\dot{Y}$ is aging rate
  - α is a weighting factor to adjust the two criteria
  - β is an arbitrary transformation coefficient
- Two state variables, SOC ξ and a lumped battery temperature θ_{bat}

$$\dot{\xi} = f(I(u,w)), \quad \dot{\theta}_{bat} = f_\theta(I(u,w),\theta_{bat})$$

- Global constraints: $\xi(0) = \xi_0, \quad \xi(T) = \xi_f, \quad \theta_{bat}(0) = \theta_0, \quad \theta_{bat}(T) = \text{free}$

Battery temperature: OCP Solution using PMP

- Hamiltonian definition

$$H(u, w, \xi, \theta, \lambda_\xi, \lambda_\theta) = (1-\alpha) \cdot c(u, w) \cdot LHV + \alpha \cdot \beta \cdot \dot{Y}(u, w, \xi, \theta) + \\ + \lambda_\xi P_{ech}(u, w, \xi, \theta) + \lambda_\theta P_{th}(u, w, \xi, \theta)$$

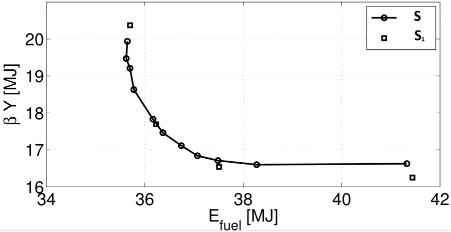
- Euler–Lagrange equations

$$\begin{aligned} C_{nom} U_0 \dot{\lambda}_\xi &= \frac{\partial H}{\partial \xi} = \alpha \cdot \beta \cdot \frac{\partial \dot{Y}}{\partial \xi} + \lambda_\xi \frac{\partial P_{ech}}{\partial \xi} + \lambda_\theta \frac{\partial P_{th}}{\partial \xi} \\ MC \dot{\lambda}_\theta &= \frac{\partial H}{\partial \theta} = \alpha \cdot \beta \cdot \frac{\partial \dot{Y}}{\partial \theta} + \lambda_\xi \frac{\partial P_{ech}}{\partial \theta} + \lambda_\theta \frac{\partial P_{th}}{\partial \theta} \end{aligned}$$

- Initial values $\lambda_\xi(0)$, $\lambda_\theta(0)$ found with shooting algorithms
- Control model simplification: compare
  - Two-states strategy (S)
  - SOC-state-only strategy (S_1), with $\lambda_\theta \equiv 0$ (θ_{bat} considered as a constant).

Battery temperature: OCP Results

- Increasing α reduces aging Y and increases FC
- Only small differences between S and S_1 ($< 2.5\%$)



Conclusions

Neglecting battery temperature changes in the EMS design leads to an acceptable sub-optimal solution except for extremely aging-biased cost functions

Battery temperature: Toy Problem

- **Motivation:** Justify and understand the previous result of model simplification.
- Toy problem considered
  - Cost function:

$$J(u) = \int_0^T \left[\frac{1}{2}(1-\alpha) a u^2 + \alpha b \theta_0 \theta \right] dt$$

  - Dynamics:

$$\dot{\xi} = D - u$$

$$\dot{\theta} = c(D_m - u) - k\theta$$

  - Boundary conditions:

$$\xi(0) = \xi_0 \quad \xi(T) = \Delta$$

$$\theta(0) = \theta_0, \theta(T) = \text{free}$$

Battery temperature: Toy Problem

$$(S_1) \quad \begin{cases} H_1 = \frac{1}{2}(1-\alpha)au^2 + \alpha b\theta_0^2 + \lambda(D-u) \\ \lambda = \frac{(1-\alpha)aE}{T}, \quad E = \int_0^T D dt - \delta, \quad u_0^* = \frac{E}{T} \end{cases}$$

$$(S) \quad \begin{cases} H = \frac{1}{2}(1-\alpha)au^2 + \alpha b\theta_0\theta + \lambda(D-u) + \mu(c(D_m-u) - k\theta) \\ \lambda = \frac{(1-\alpha)aE}{T} - cp_1\left(1 - \frac{1-e^{-kT}}{kT}\right), \quad p_1 = \frac{\alpha b\theta_0}{k} \\ \mu(t) = p_1\left(1 - e^{-kT}e^{kt}\right) \\ u^* = u_0^* + \frac{cp_1}{(1-\alpha)a}\left(\frac{1-e^{-kT}}{kT} - e^{-kT}e^{kt}\right) \end{cases}$$

$$J(u_0^*) - J(u^*) = \frac{c^2\alpha^2b^2\theta_0^2}{(1-\alpha)ak^3}\left[\frac{(1-e^{-kT})^2}{2kT} - \frac{1}{4}(1-e^{-2kT})\right] \text{ (small)}$$

The toy model analysis shows that the difference is due to two partially compensating effects

Catalyst Temperature: Motivation

- Minimizing fuel consumption only without ad-hoc catalyst light-off strategies might not ensure satisfaction of EU regulations
- Catalyst temperature: a key factor to reduce pollutant emissions
- Multi-objective optimal control formulation with minimization of a mixed fuel–emission cost
- Thermal dynamics (engine and catalyst temperatures) considered in the optimal control

Objective

- Quantify the benefit of including engine and catalyst temperature in the EMS minimizing a trade off between fuel consumption and emissions
- Find a sub-optimal, real-time capable approach

Catalyst Temperature: OCP Formulation

- The combined cost function to be minimized is

$$J(u) = \int_0^T \left[(1-\alpha)e(\theta_e)c(u,w) + \alpha m_{CO}(u,w,\theta_e,\theta_c)\right] dt$$

  - α is a weighting factor to adjust the two criteria
  - $m_{CO}(.)$ is CO emission out of the catalyst

$$m_{CO}(u,w,\theta_e,\theta_c) = m_{CO,h}(u,w) f_{CO}(\theta_e)(1-\eta_{CO}(\theta_c))$$

  - $e(.)$ and $f_{CO}(.)$ are the correction factors of fuel consumption and CO emission with respect to θ_e
  - η_{CO} is the catalyst efficiency for CO
- Three state variables, SOC ξ, lumped engine and catalyst temperatures $\theta_e,\ \theta_c$:

$$\dot{\xi} = f(u,w), \quad \dot{\theta}_e = g(u,w,\theta_e), \quad \dot{\theta}_c = k(u,w,\theta_e,\theta_c)$$

- Global constraints:
  $\xi(0) = \xi_0, \quad \xi(T) = \xi_f, \quad \theta_e(0) = \theta_c(0) = \theta_0, \quad \theta_e(T) = \text{free}, \quad \theta_c(T) = \text{free}$

Catalyst Temperature: OCP Solution

- Offline solution using PMP

$$H(u, w, \theta_e, \theta_c, \lambda, \mu, \rho) = L(u, w, \theta_e, \theta_c) + \lambda f(.) + \mu g(.) + \rho k(.)$$

- Initial values $\lambda(0)$, $\mu(0)$ and $\rho(0)$ found by shooting methods
- Looking for a methodology to include catalyst temperature in real-time EMS
- **Proposed solution**: Control model (Hamiltonian) simplification

Catalyst Temperature: OCP Results and Comparison

- Calculation of the control using:

$$S \quad : \quad u^*(t) = \arg\min_{u \in U^{ad}} \left[L(u, w, \theta_e, \theta_c) + \lambda f(.) + \mu g(.) + \rho k(.) \right]$$

$$S_1 \quad : \quad u_1^*(t) = \arg\min_{u \in U^{ad}} \underbrace{\left[L(u, w, \theta_e = \theta_{e,h}, \theta_c) + \lambda f(.) + \rho k(.) \right]}_{H(u,w,\theta_e=\theta_{e,h},\theta_c,\lambda,\mu(t)=0,\rho)}$$

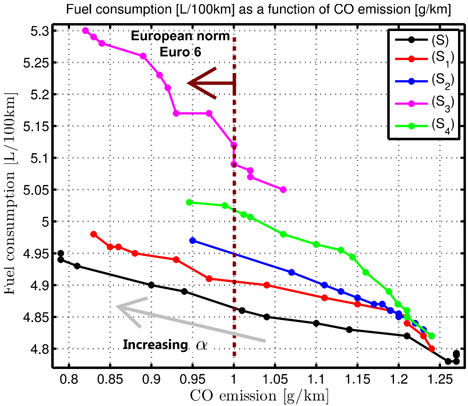
$$S_2 \quad : \quad u_2^*(t) = \arg\min_{u \in U^{ad}} \underbrace{L(u, w, \theta_e = \theta_{e,h}, \theta_c = \theta_c(0)) + \lambda f(.)}_{H(u,w,\theta_e=\theta_{e,h},\theta_c=\theta_c(0),\lambda,\mu(t)=0,\rho(t)=0)}$$

- Two additional heuristic strategies, neglecting the adjoint states:

$$S_3 \quad : \quad u_3^*(t) = \arg\min_{u \in U^{ad}} \underbrace{\left[L(u, w, \theta_e, \theta_c) + \lambda f(.) \right]}_{H(u,w,\theta_e,\theta_c,\lambda,\mu(t)=0,\rho(t)=0)}$$

$$S_4 \quad : \quad u_4^*(t) = \arg\min_{u \in U^{ad}} \underbrace{\left[L(u, w, \theta_e = \theta_{e,h}, \theta_c) + \lambda f(.) \right]}_{H(u,w,\theta_e=\theta_{e,h},\theta_c,\lambda,\mu(t)=0,\rho(t)=0)}$$

Catalyst Temperature: OCP Results and Comparison



Conclusions

- Neglecting temperatures changes in the EMS design leads to a acceptable sub-optimal solutions except for extremely emission-biased cost functions

Theoretical Justification: Approach

Next step

- Justify from theoretical viewpoint (general case) the model simplifications presented (engine, battery and catalyst temperatures).

- We want to solve the following optimal control problem:

$$(P_\varepsilon)\begin{cases} \min\limits_{u\in U^{ad}} J_\varepsilon(u) = \int_0^T l_\varepsilon(x_\varepsilon, u)\,dt, \\ \dot{x}_\varepsilon = f_\varepsilon(x_\varepsilon, u), \\ x_\varepsilon(0) = x_0, \end{cases}$$

$$\boxed{l_\varepsilon(x_\varepsilon, u) = c(u, w)e(\theta_e)}$$

$$\boxed{x = [\xi,\ \theta_e]}$$

- By solving the following simplified (nominal) problem:

$$(P_0)\begin{cases} \min\limits_{u\in U^{ad}} J_0(u) = \int_0^T l_0(x_0, u)\,dt, \\ \dot{x}_0 = f_0(x_0, u), \\ x_0(0) = x_0, \end{cases}$$

$$\boxed{l_0(x, u) = c(u, w)}$$

$$\boxed{x = \xi}$$

Theoretical Justification: Result

Main result

Under some assumptions, we prove that $\exists\ K > 0$ st:

$$J_\varepsilon(u_0) - J_\varepsilon(u_\varepsilon) \leq K\varepsilon^2$$

- How can we determine if K is small? **Counter example**

Table: Estimation of K based on nominal solution

	Thermal management	Eco-driving
K_{est}/K_{num}	11	26
$\Delta J/J_\varepsilon(u_0)$	1 %	90 %
$K_{est}/J_\varepsilon(u_0)$	0.105	19.62
Sub-optimality	Acceptable	Not Acceptable

Conclusions and perspectives

- **Conclusions:**
  - Hamiltonian simplification leads to acceptable sub-optimality for thermal-management problems
  - A priori calculation of K can be used to predict the sub-optimality induced by control model (Hamiltonian) simplification
- **Current work:**
  - Find a solution to adapt the adjoint states as a function of the temperature measurements in real-time
  - Experimental validation of the results concerning catalyst temperature (Diesel hybrid)
- **Papers:**

1. D. Maamria, F. Chaplais, N. Petit and A. Sciarretta. **Numerical Optimal Control As a Method to Evaluate the Benefit of Thermal Management in Hybrid Electric Vehicles** . in Proc. of the 2014 IFAC World Congress.
2. D. Maamria, F. Chaplais, N. Petit and A. Sciarretta. **On the impact of model simplification in input constrained optimal control: application to HEV energy-thermal management**. IEEE-CDC 2014 (**To appear**).
3. D. Maamria, F. Chaplais, N. Petit and A. Sciarretta. **Comparison of several strategies for HEV energy management system including engine and catalyst temperatures**. ACC 2015 (**Submitted**).