Optimal Predictive Control for Connected HEV
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Optimal Predictive Control for cEM

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Internet of Everything (IoE) offers Enriching Possibilities

The Vehicle Becomes Part of the Internet of Everything

In the past, vehicles had no access to the Internet.

Today, more and more vehicles have Internet access.

Tomorrow, the vehicle will be part of the "Internet of Everything".
The Vehicle Becomes Part of the Internet of Everything
What are the Benefits?

“Visible” Services

→ Attractive Car

ITS Services

→ Better Traffic

“Invisible” Services

→ Better Car

What are the Benefits?
Tomorrow’s Situation: Sensors, Maps and Online Data

Dynamic eHorizon: The Vehicle Looks Around the Corner

1. Highly accurate map model provided and updated via the Backend

2. Extended preview information

3. Extension of limited in-vehicle resources

4. Fleet based data collection

Vehicle Sensor range
100-300m

Close preview: 10 minutes:
## Optimal Predictive Control for cEM

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Connected Energy Management
CO₂ Effective Features w/Comfort, Safety value for the Driver

„Smart Traffic Light Assist“
(CO₂ + Comfort)

„Slope & Curve Speed Assist“
(CO₂ + Safety)

„Intelligent Deceleration Assist“
(CO₂ + Comfort)

Close preview:
10 minutes:
# Optimal Predictive Control for cEM

1. Connectivity for Vehicles
2. Connected Energy Management
3. Functional approach
4. Optimization Technics & Algorithms
5. Demonstrations & Results
Connected Energy Management
A Global & Connected Optimization

Actions
› Selection of- and Application to-HYBRID Cars in current cEM project
› Optimization of EFFICIENCY of Energy onboard
  › Gear shift
  › Torque repartition (ICE/EMA)
  › Boost/ Coasting/ Recup.
  › CONNECTION to eHORIZON nice to have
› Optimization of USAGE of Mobility
  › Speed & Accel profiles
  › Boost/ Coasting/ Recup.
  › Eco-driving, Trip preparation…
  › CONNECTION to eHORIZON mandatory!

Energetic Paths
from Well to Tank
from Tank to Wheels
from Wheels to Miles

Global Optimization of Energy efficiency in Predicted Usages

Source: Dr. Mariano SANS
Predictive Energy Management for cEM
A Global & Connected Optimization

What Predictive Optimal control does is…

Normal Manual or Cruise driving control…

Optimal Torque Split (cycle relevant)  
< hybrid driving, from tank to wheels >  +  Optimal eco-speed (real driving)  
< smart driving, from wheels to miles >
# Predictive Optimal Control for CO₂
A Global & Connected Optimization

## For Pure ICE or HEV vehicles

› **ECO DRIVE:**
  - by Optimization of vehicle speed profiles (incl. accel & decel)
  - Based on **Criteria:** Fuel consumption
    - with standard gear shift / coasting phases
    - for eco-Driving purpose (HMI coaching)
    - or for eco ACC application

## For HEV vehicles

› **ACTIVE SOC MANAGEMENT** (in addition to ECO DRIVE)
  - by Optimization of electrical drive functions by providing the best Torque repartition (ratio of eTorque) & driving phases
  - Based on **Criteria:** Fuel consumption and delta battery State of Charge (SOC)
    - to get battery SOC sustain
    - or to reach a new SOC target (depletion or recharge)
Optimal Predictive Control for cEM

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**Connected Energy Management**

**Predictive Optimal Control**

**Optimal “Planning route” from A to B**

\[ J = \int_0^T \hat{g}(Tq)dt \]

**Solution**

› Use of Static & Dynamic eHorizon

› Use of Mathematical Functions with Maximum Principles (Lagrange, Pontryagin …)

for Predictive Optimal Control to calculate optimal Driving strategies on a trip,

› Acting on:
  - Eco-Driving / ACC
  - Hybrid Torque & SOC Management

› Predictive Optimal Control becomes possible with static & dynamic eHorizon

› Mathematical Optimization is now available for real-time Automotive applications

Source: Dr. Mariano SANS
Predictive Optimal Control for CO2

PMP History

› PMP = Pontryagin Maximum (Minimum) Principle
  › used in optimal control theory to find the best possible control for taking a dynamical system from one state to another, especially in the presence of constraints for the state or input controls.
  › formulated in 1956 by the Russian mathematician Lev Pontryagin and his students. (Euler–Lagrange equation of the calculus of variations is as a special case)

› Tested on historical real cases
  › Brachistochrone problem (« minimum time » in Greek), Galileo, Bernouilli
  › Aeronautics, 1962: minimal time trajectory to reach 20km altitude by an F4 plane
  › Spatial, 1969: optimal change from one orbit to a maximum height orbit, rockets trajectory control,…
  › Optimization of air traffic…
  › Extensions to bio-medical,…
Predictive Optimal Control for CO2

PMP History

› Historical validation tests on real cases:
  › «Brachistochrone» problem («minimum time» in Greek), Galileo, Bernouilli

one of 1st trajectory optimisation
⇔ optimisation of a function vs time, not only a variable

Musée de la Science, Florence
Historical validation tests on real cases:

- **Aeronautics, 1962**: minimal time trajectory to reach 20km altitude by an F4 plane (→ actual applications to Drones)
Connected Energy Management
Predictive Optimal Control (Pontryagin’s “PMP” theory)

System State equations (pos, speed, SOC, $T^o_C$…
Linear, non-linear…)

\[ \dot{q} = f(q, tq_{ICE}, tq_{EMA}, t) \]

Target is $J = \text{global minimum}$

Criteria to minimized on a global time interval $[0…T]$ under constraints

\[ J = \int_0^T \hat{g}(q, tq_{ICE}, tq_{EMA}, ...) \, dt + \eta \int_0^T dt \]

PMP method

- calculates Lagrangian:
  \[ L(t) = \hat{g}(t) + \eta \]

- introduces additional co-states:
  \[ \lambda(t) \text{ and } \frac{d\lambda}{dt} \]

- calculates Hamiltonian to be minimized at each instant $t$:
  \[ H(t) = L + \lambda^T \dot{q} \text{ is a local minimum} \]

- Predictive Optimal Control becomes possible with static & dynamic eHorizon
  - Mathematical Optimization is now available for real-time Automotive applications

Source: Dr. Mariano SANS
**Connected Energy Management**

Predictive Optimal Control (Pontryagin’s “PMP” theory)

› Optimal Control Problem:

\[
\min J = \int_0^T P_{fuel}(Tq_{ice}(t), N_{ice}(t)) dt
\]

s.c \[SoC(T) = SoC_{targ}\]

\[SoC(t) = P_{elec}(Tq_{ema}(t), N_{ema}(t))\]

avec \[Tq_{request} = Tq_{ice} + \beta.Tq_{ema}\]

\[Tq_{request}, N_{ema}, N_{ice} \text{ sont données}\]

**We control the battery State of Charge in a way to minimize the Fuel Consumption**
Connected Energy Management
Predictive Optimal Control (Pontryagin’s “PMP” theory)

Torque split program:

Futur Torque request:
\[ T_{q, request} = T_{q, ice} + T_{q, ema} \]

\[ \lambda_{opt} \text{ must be found to assure } SoC_{t, arg} \]

Resolution:
\[ H_{\lambda_{opt}} (T_{q, ice}, t) = P_{ind} (T_{q, ice}, t) + \lambda_{opt} P_{elec} (T_{q, ice}, t) \]
\[ T_{q, ice}^{opt} = \arg \min_{T_{q, ice}} (H_{\lambda_{opt}} (T_{q, ice}, t)) \]

\[ \min J = \int_0^T P_{ind} (T_{q, ice}, t) dt \]
\[ s.c. \quad SoC (T) = SoC_{t, arg} \]
\[ . \quad SoC (t) = P_{elec} (T_{q, ice}, t) \]
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Connected Energy Management
CO₂ impacts g/km

Results of “PMP” (Pontryagin Max Principle) on Simulations:
- 3..4% reduction by SOC management
- 11% reduction by speed optimization
- Estimated Targets on cumulated results: 15% CO₂ reduction

High potential for CO₂ reduction
Active further developments and tests ongoing

Source: Dr. Mariano SANS
Predictive Energy Management for cEM
Application of “PMP” to Hybrid Torque optimization

Active SOC management: - 5% CO$_2$ @ NEDC, SOC maintain at 50%

Source: Hamza IDRISSI
Predictive Energy Management for cEM
Application of “PMP” to Speed optimization

Eco-Driving using “PMP” : -11% CO₂ @ RDE95, iso time & distance

Source: Dr. Mariano SANS
Connected Energy Management
Current Actions / Implementation of PMP

› Implementation of Eco drive & Optimum hybrid torque in GTC2 vehicle (48V P2)
› Real Time implementation (embedded) validation on vehicle
› Confirm concept flexibility (scalability to data availability)
› Enrichment of driving profile constraints: temperature, pollutants, drivability …

Gasoline Technology Car I
› CO₂ emission = 114 → 95 g/km (NEDC)

Gasoline Technology Car II
› CO₂ emission target < 85 g/km (NEDC)
Thank you for your attention!