Optimal Predictive Control for Connected HEV

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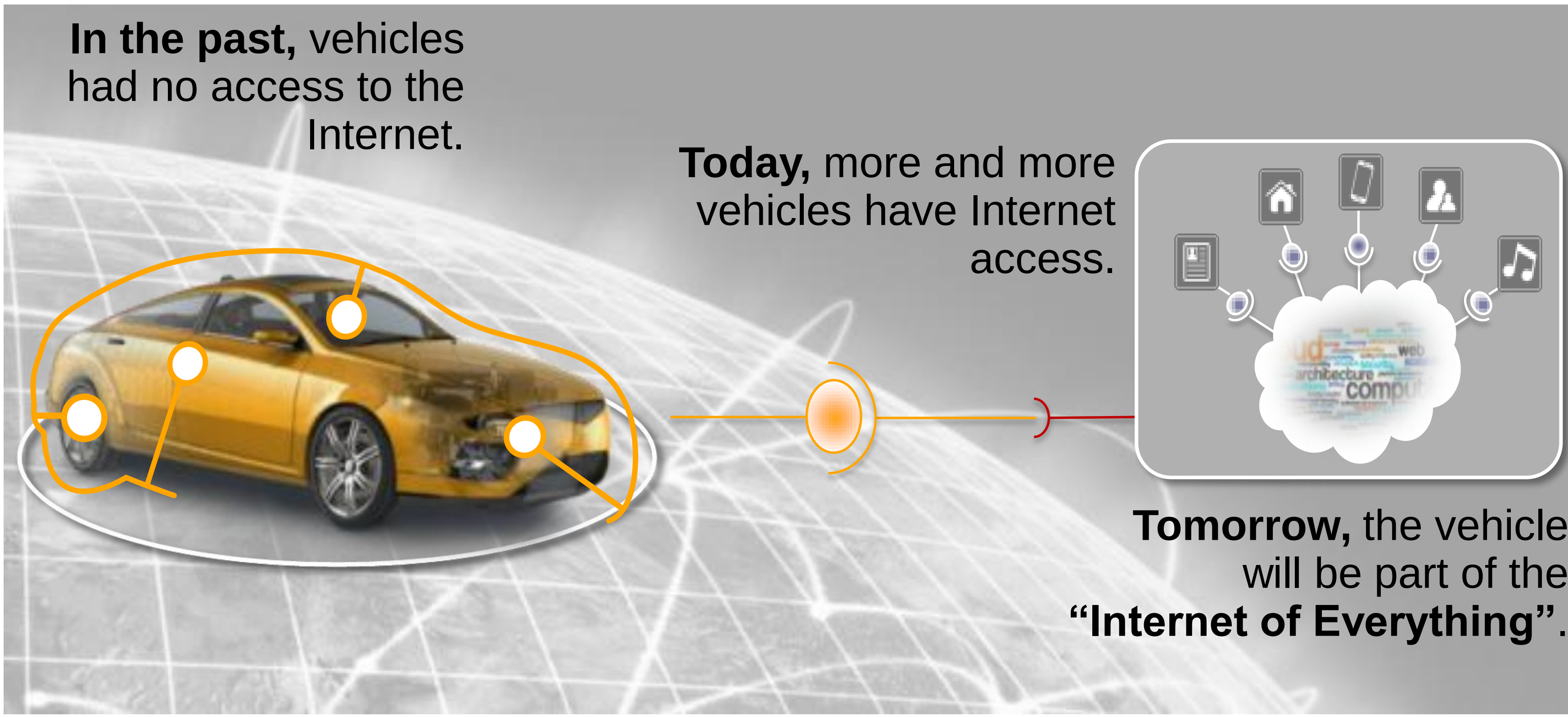
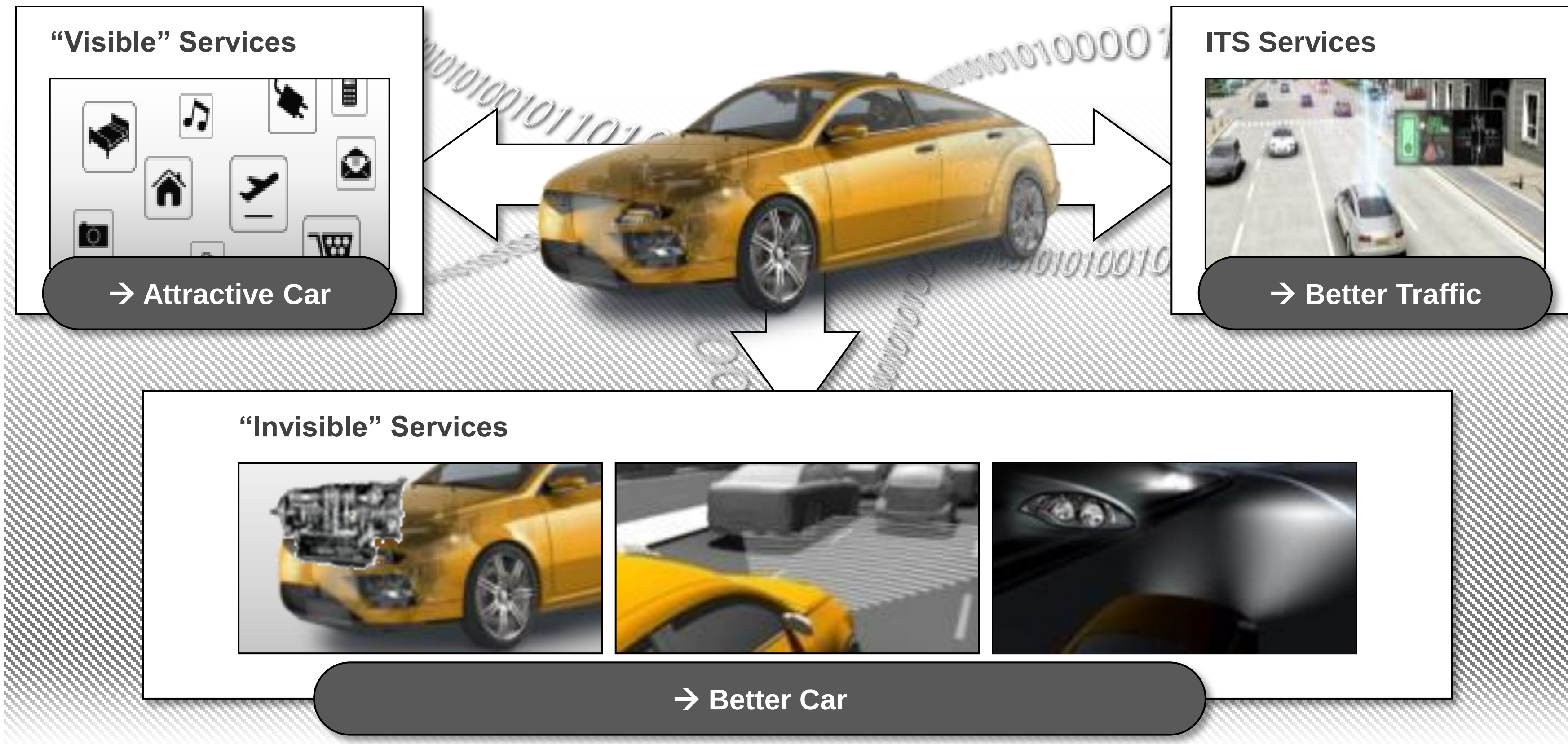
Optimal Predictive Control for cEM

Internet of Everything (IoE) offers Enriching Possibilities
The Vehicle Becomes Part of the Internet of Everything

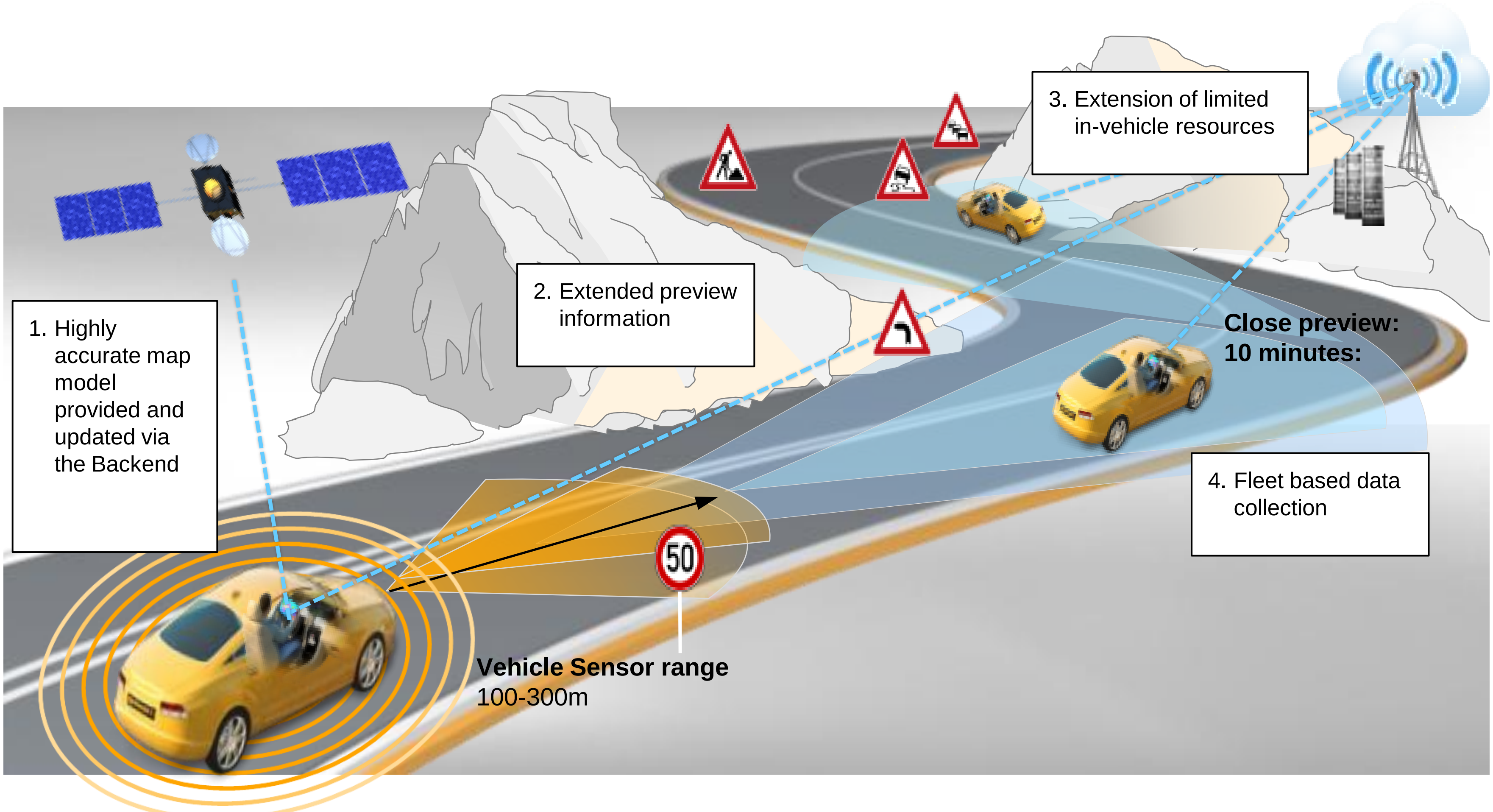


The Vehicle Becomes Part of the Internet of Everything
What are the Benefits?



Tomorrow's Situation: Sensors, Maps and Online Data

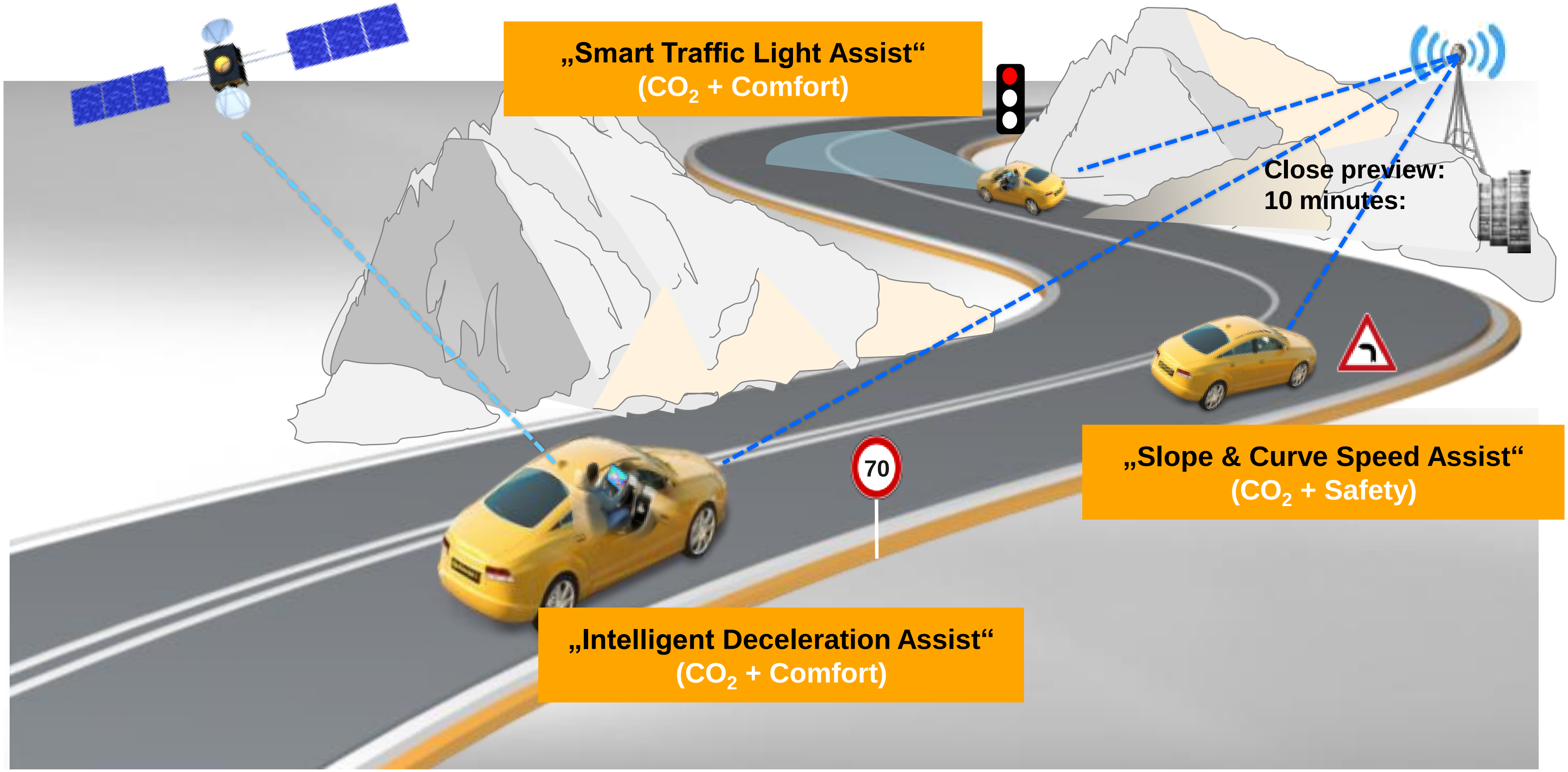
Dynamic eHorizon: The Vehicle Looks Around the Corner



Optimal Predictive Control for cEM

Connected Energy Management

CO_2 Effective Features w/Comfort, Safety value for the Driver

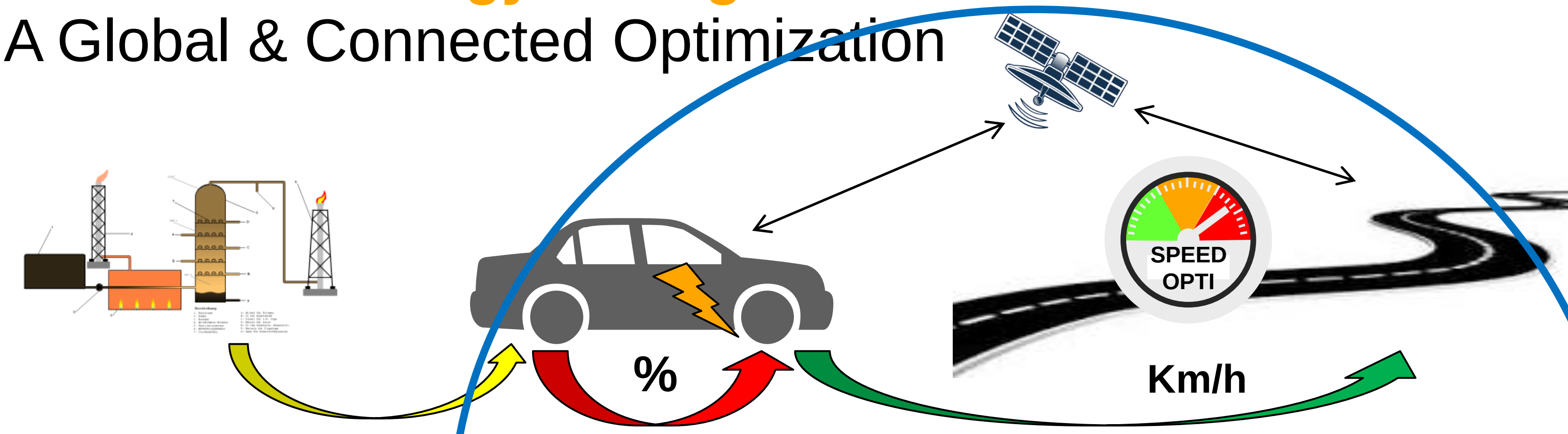


Optimal Predictive Control for cEM

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



from Well to Tank	from Tank to Wheels	from Wheels to Miles

Energetic Paths

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 *!*

› **Global Optimization of *Energy efficiency in Predicted Usages*** !

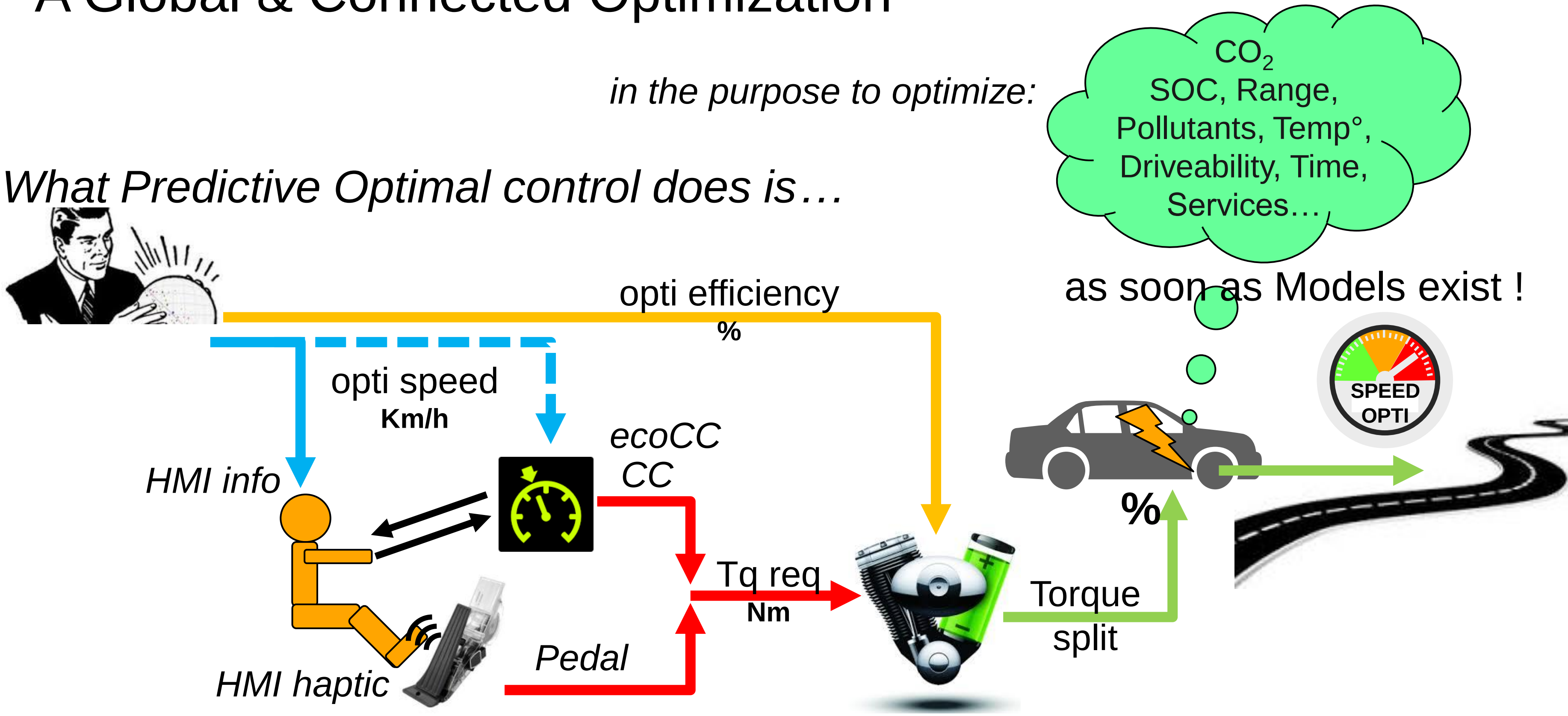
Source: Dr. Mariano SANS

Predictive Energy Management for cEM

A Global & Connected Optimization

in the purpose to optimize:

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 CO_2
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)**

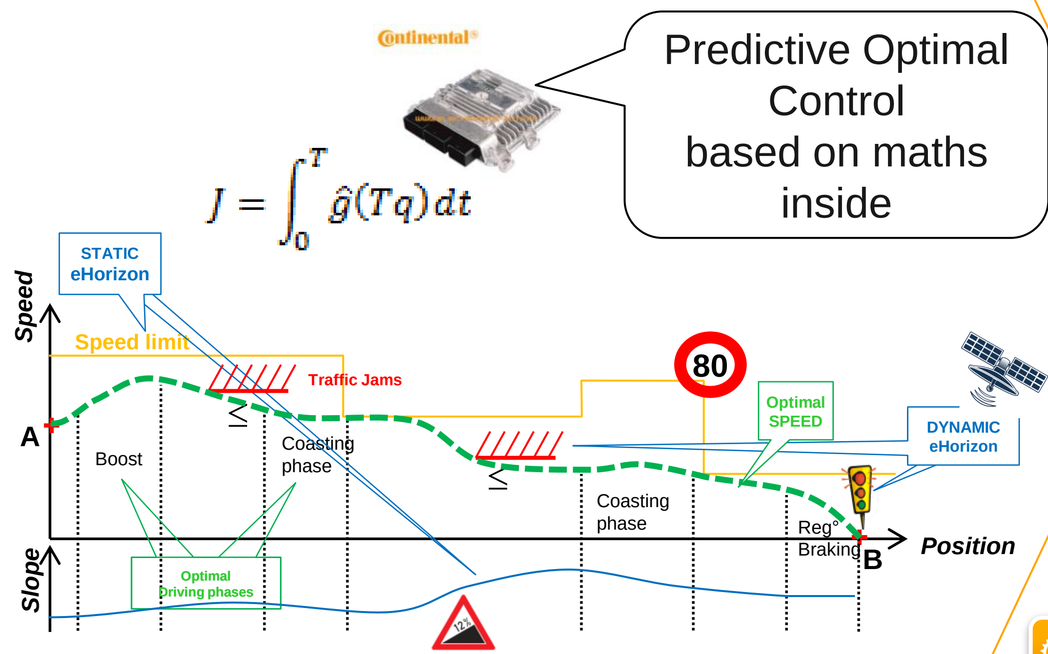
    - to get battery SOC sustain
    - or to reach a new SOC target (depletion or recharge)

Optimal Predictive Control for cEM

Connected Energy Management

Predictive Optimal Control

Optimal "Planning route" from A to B



Solution

- Use of **Static & Dynamic eHorizon**
- Use of **Mathematical Functions with Maximum Principles (Lagrange, Pontryagin …)**

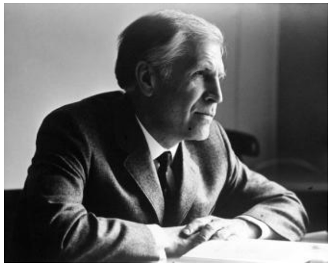
  for **Predictive Optimal Control** to calculate optimal Driving strategies on a trip,
- Acting on :
  - **Eco-Driving / ACC**
  - **Hybrid Torque & SOC Management**

› 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 CO_2

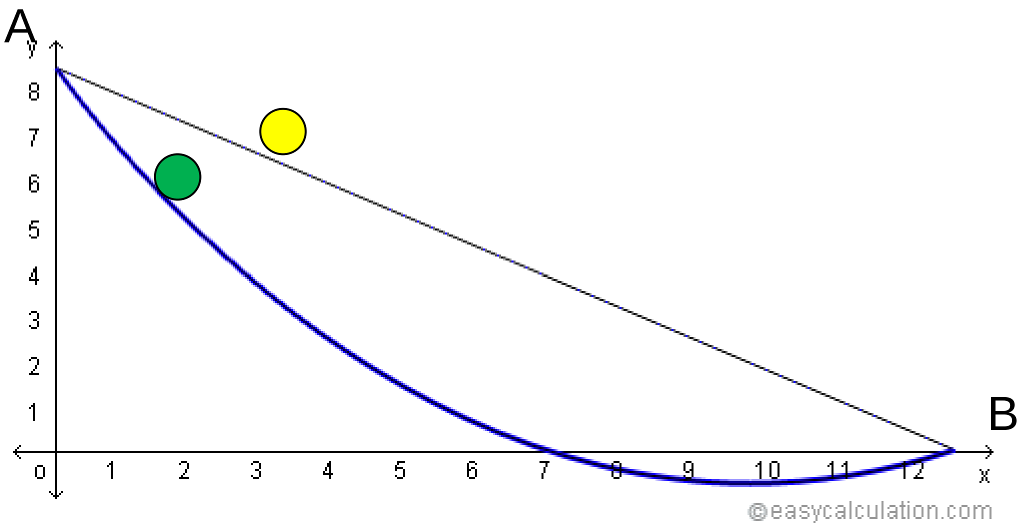
PMP History



- **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 CO_2
PMP History

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

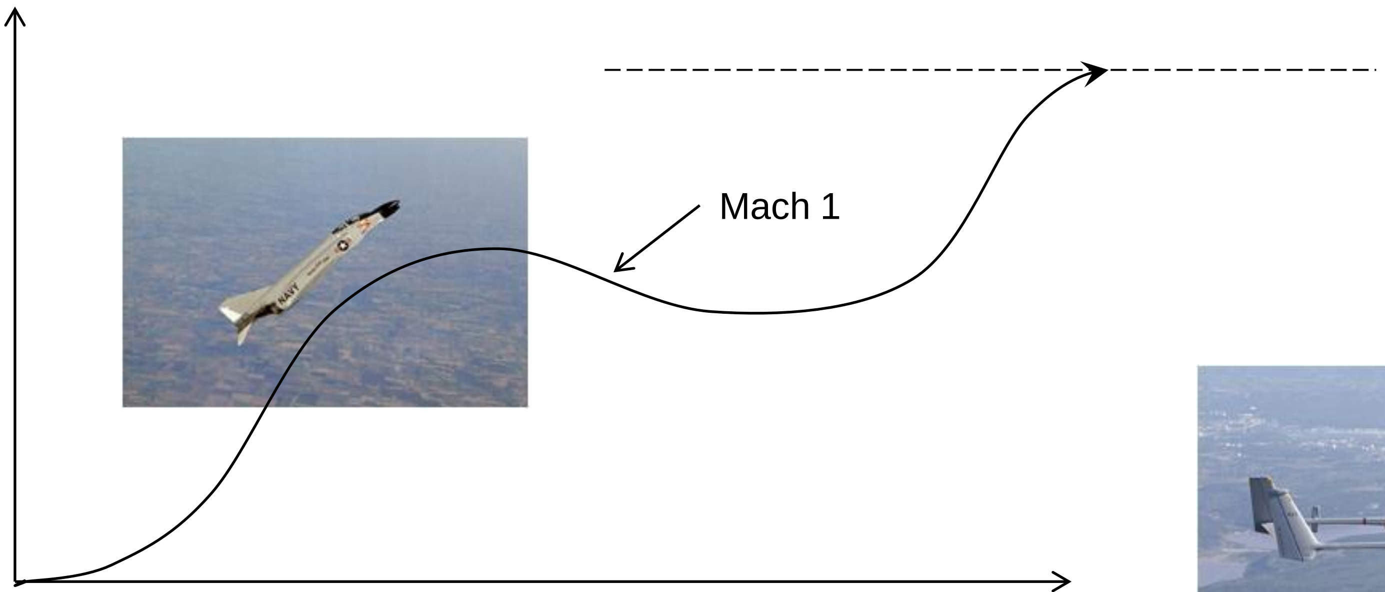


Musée de la Science, Florence

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

Predictive Optimal Control for CO_2
PMP History

- 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°C…
Linear, non-linear…)

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

*Target is **J** = global minimum*

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

$$J = \int_0^T \hat{g}(q, tq_{ICE}, tq_{EMA}, \ldots)dt \quad + \quad \eta \int_0^T dt$$

PMP method

- calculates Lagrangian: $L(t) = \hat{g}(t) + \eta$
- introduces additional co-states: $\lambda(t) \text{ and } d\lambda / dt$
- calculates Hamiltonian to be minimized at each instant t :

$? \; tq_{ICE}, tq_{EMA} \;\; as$

$H(t) = L + \lambda^T . \dot{q} \quad is \; a \; local \; minimum$

- 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:

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

$$s.c \qquad SoC(T) = SoC_{t\arg}$$

$$\dot{SoC}(t) = P_{elec}(Tq_{ema}(t), N_{ema}(t))$$

$$avec \qquad Tq_{request} = Tq_{ice} + \beta . Tq_{ema}$$

$$Tq_{reques}, N_{ema}, N_{ice} \quad sont\ données$$

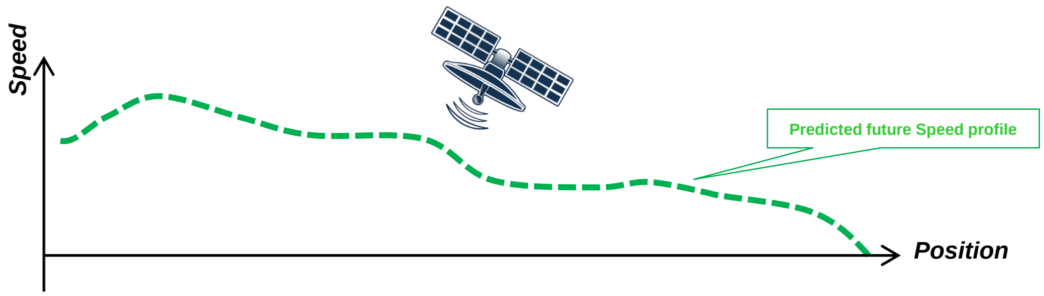
Minimise
ICE fuel

Control
Battery SoC

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 :

$$Tq_{request} = Tq_{ice} + Tq_{ema}$$

λ_{opt} *must be found to assure* $SoC_{t\arg}$

$$\min \quad J = \int_0^T P_{ind}(Tq_{ice}, t)dt$$

$$s.c \qquad SoC(T) = SoC_{t\arg}$$

$$\dot{SoC}(t) = P_{elec}(Tq_{ice}, t)$$

Resolution

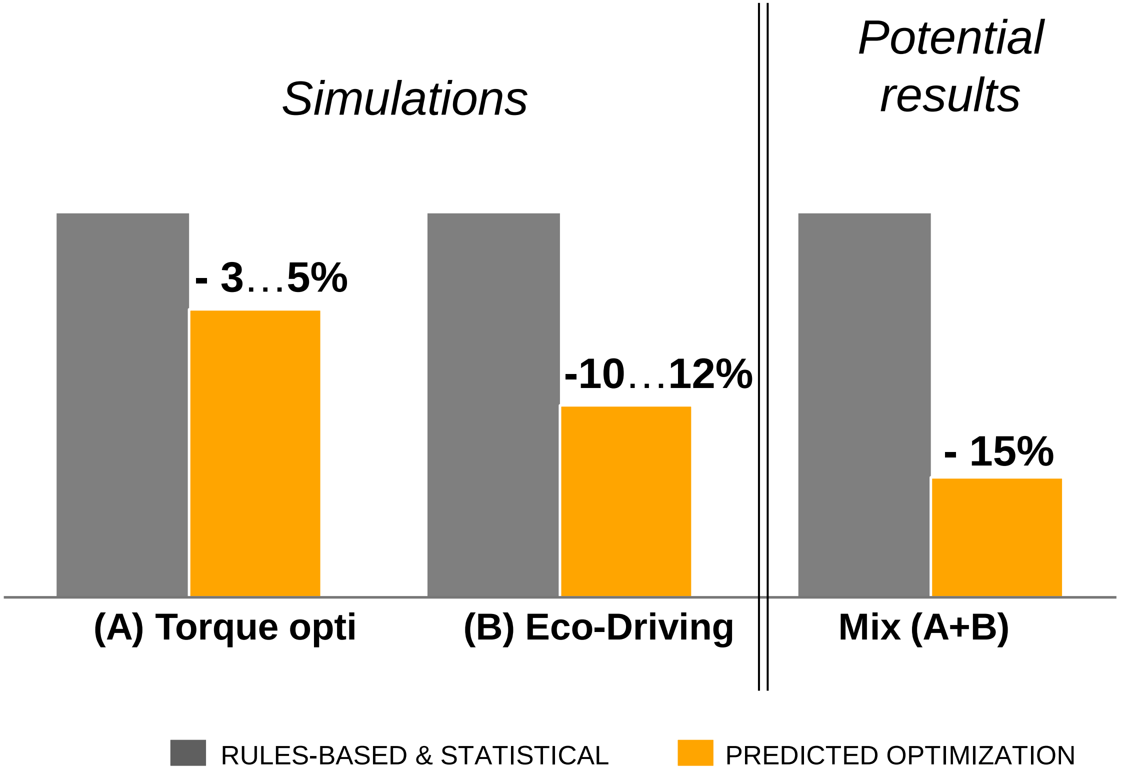
$$H_{\lambda_{opt}}(Tq_{ice}, t) = P_{ind}(Tq_{ice}, t) + \lambda_{opt}.P_{elec}(Tq_{ice}, t)$$

$$Tq_{ice}^{\ opt} = \arg\min_{Tq_{ice}}(H_{\lambda_{opt}}(Tq_{ice}, t))$$

Optimal Predictive Control for cEM

Connected Energy Management

CO_2 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

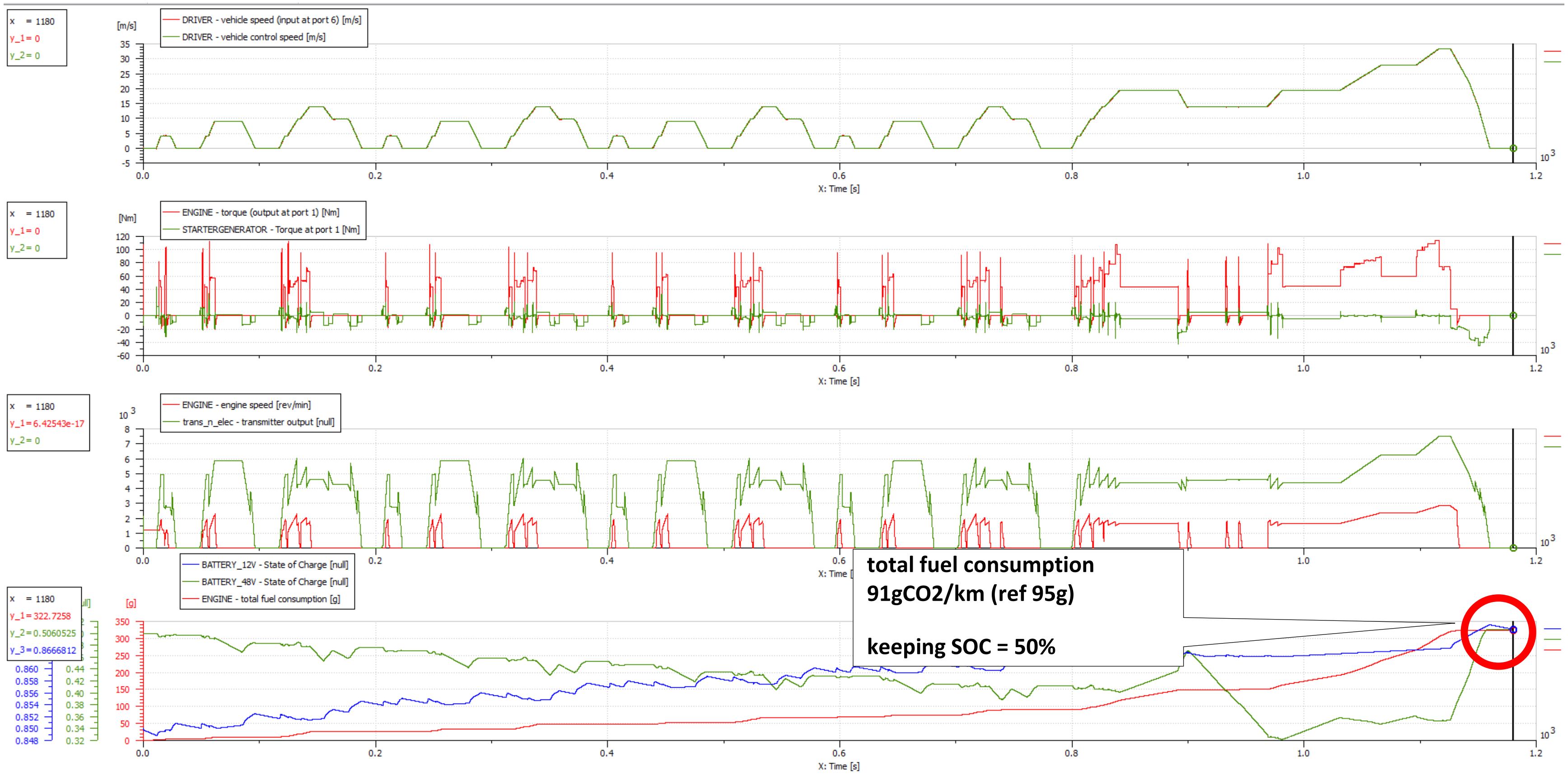
› **High potential for CO_2 reduction**
› **Active further developments and tests ongoing**

!

Source: Dr. Mariano SANS

Predictive Energy Management for cEM

Application of “PMP” to Hybrid Torque optimization

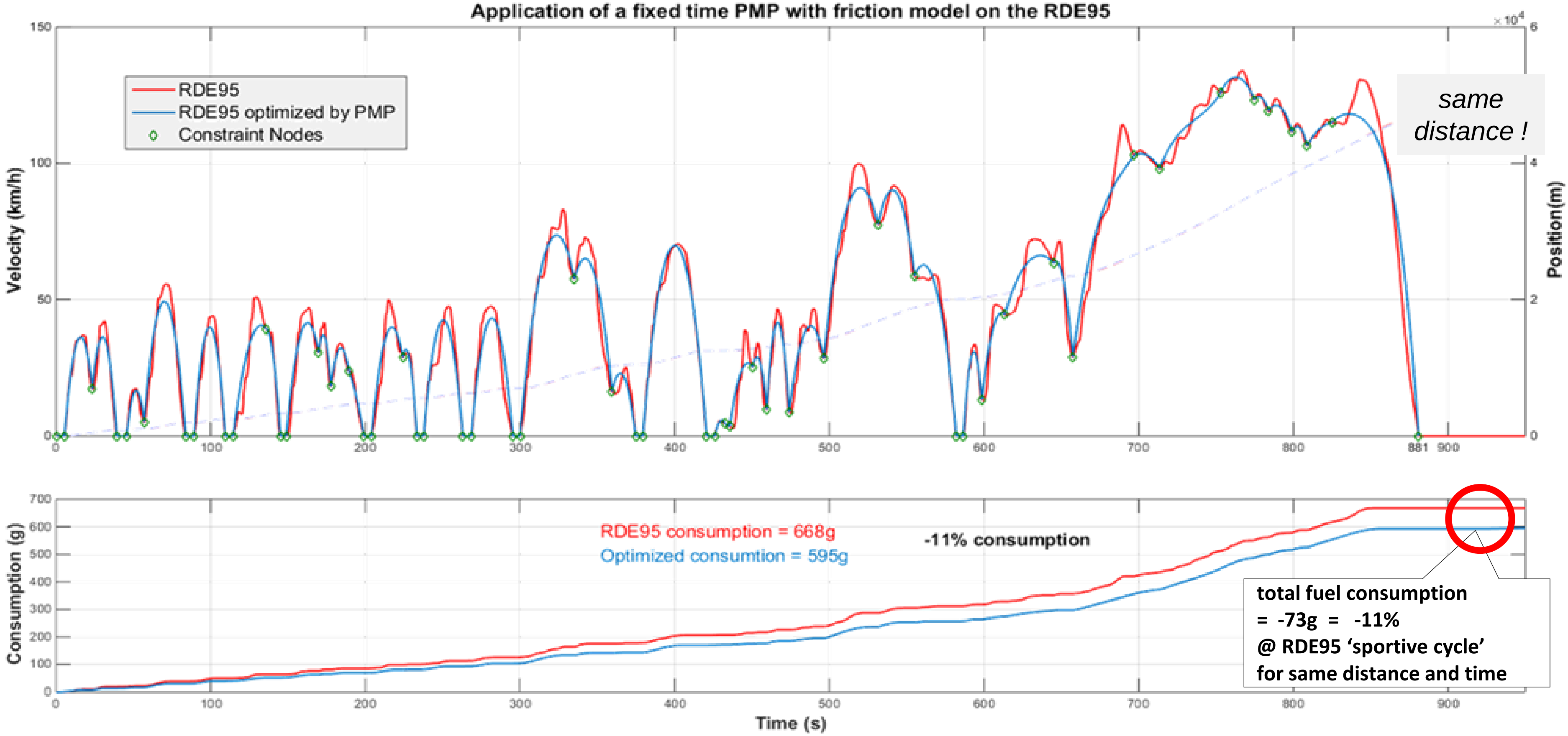


› **Active SOC management : - 5% CO_2 @ NEDC, SOC maintain at 50%**

Source: Hamza IDRISSI

Predictive Energy Management for cEM

Application of “PMP” to Speed optimization



› **Eco-Driving using “PMP” : -11% CO_2 @ 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

- **CO_2 emission = 114 → 95 g/km (NEDC)**

Gasoline Technology Car II

- **CO_2 emission target < 85 g/km (NEDC)**

Thank you

for your attention !