Control Oriented Modeling of Internal Combustion Engines

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eProLab overview

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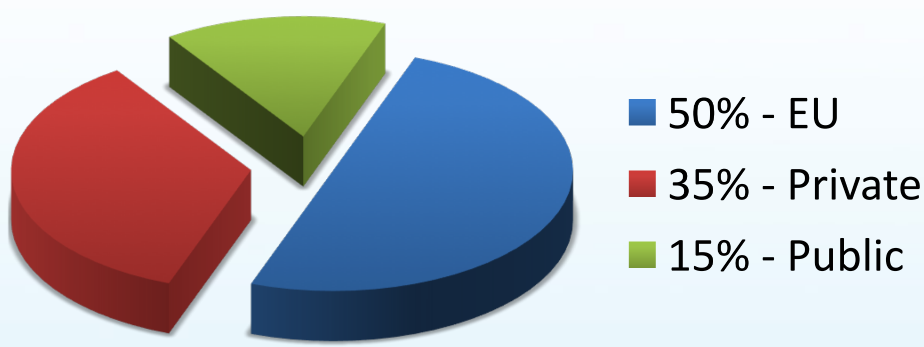
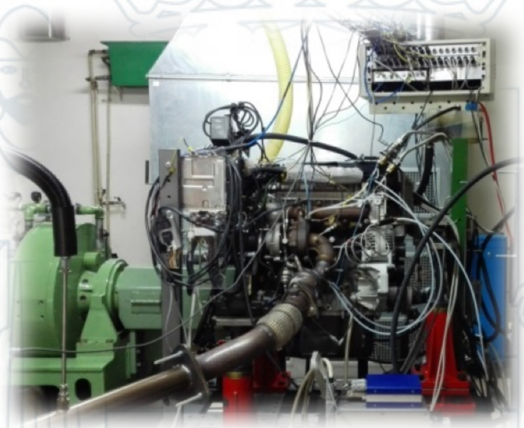
Main current partners…

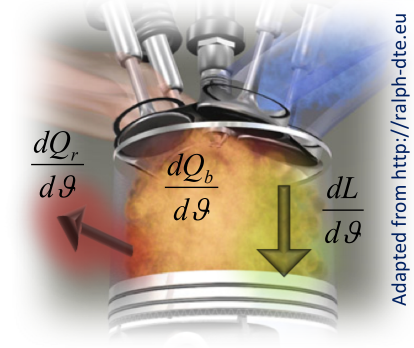


Research fields

Working Areas

- Engines, hybrid powertrains
- Non-conventional energy technologies (Fuel Cells)
- Simulation models for control, diagnosis, design and optimization





ICE Modeling & Control

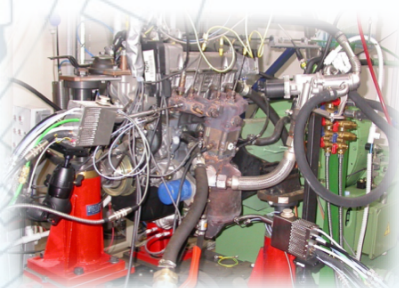
- CI/SI combustion/emissions
- Vehicle / powertrain
- After-treatment system
- Emissions' virtual sensors
- Pressure based control/diagnosis

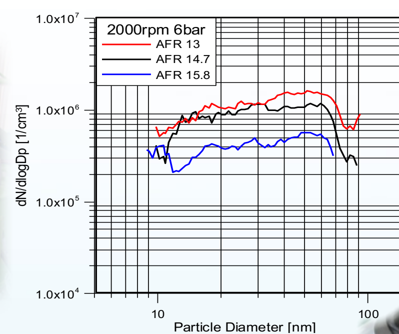
Eco-Innovation Technologies

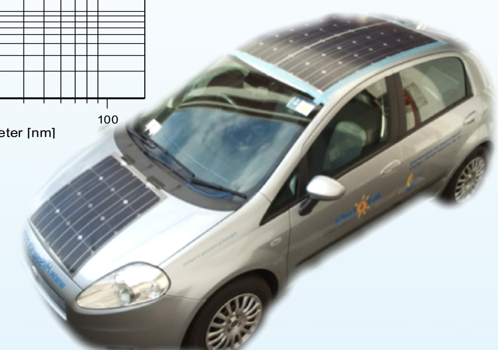
- Hybrid and hybrid solar vehicles
- WHR technologies (TEG, E-turbo, ORC)
- ADAS / Electronic Horizon

Facilities

- Fully equipped engine test bench
- Indicating equipment
- Emissions analyzers (HC, CO_x, NO_x)
- Cambustion fast NOx analyzer
- Smoke meter
- SMPS system for nano-particulate
- dSpace MicroAutobox & Etas INCA
- Two solar hybrid vehicle prototypes
- Two Fuel-Cells test benches







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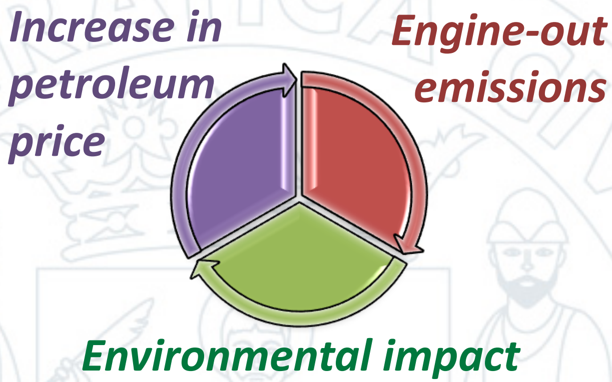
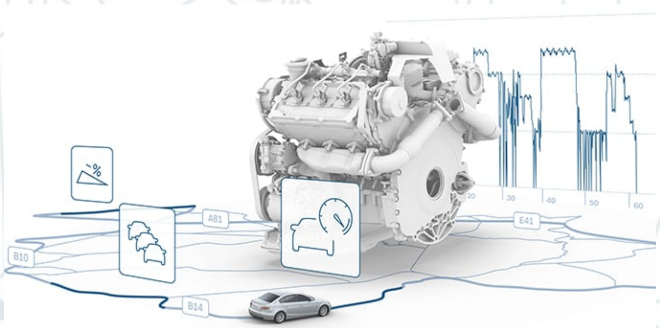
Modeling of SCR for Control Application

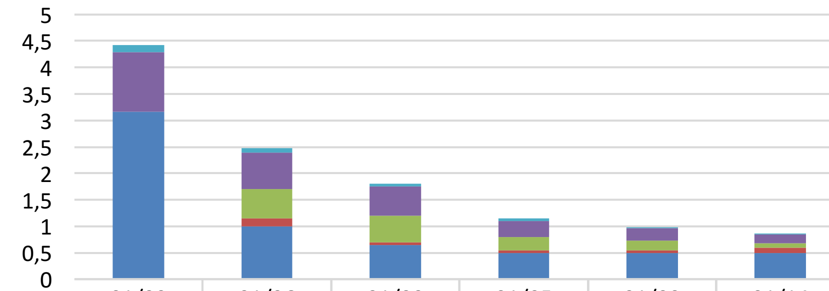
Enhancement of fuel economy by ADAS and Electronic Horizon

Context & motivations



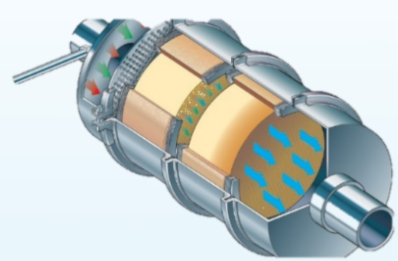


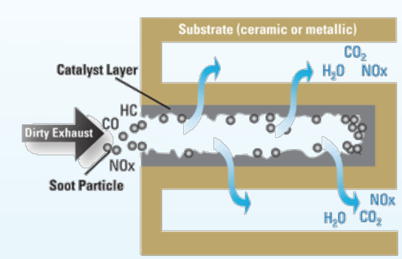
In order to comply with emission targets and RDE test procedure an optimized integration between combustion process and exhaust AT systems is mandatory.



	01/92 EURO I	01/96 EURO II	01/00 EURO III	01/05 EURO IV	01/09 EURO V	01/14 EURO VI
PM [g/Km]	0,14	0,08	0,05	0,05	0,005	0,005
HC+Nox [g/Km]	1,13	0,7	0,56	0,3	0,23	0,17
Nox [g/Km]		0,55	0,5	0,25	0,18	0,08
HC [g/Km]		0,15	0,06	0,05	0,05	0,09
CO [g/KM]	3,16	1	0,64	0,5	0,5	0,5

With current technologies, the most suitable after-treatment devices for the abatement of NO_X and PM emissions are the ***SCR and DPF systems.***





ATs layout

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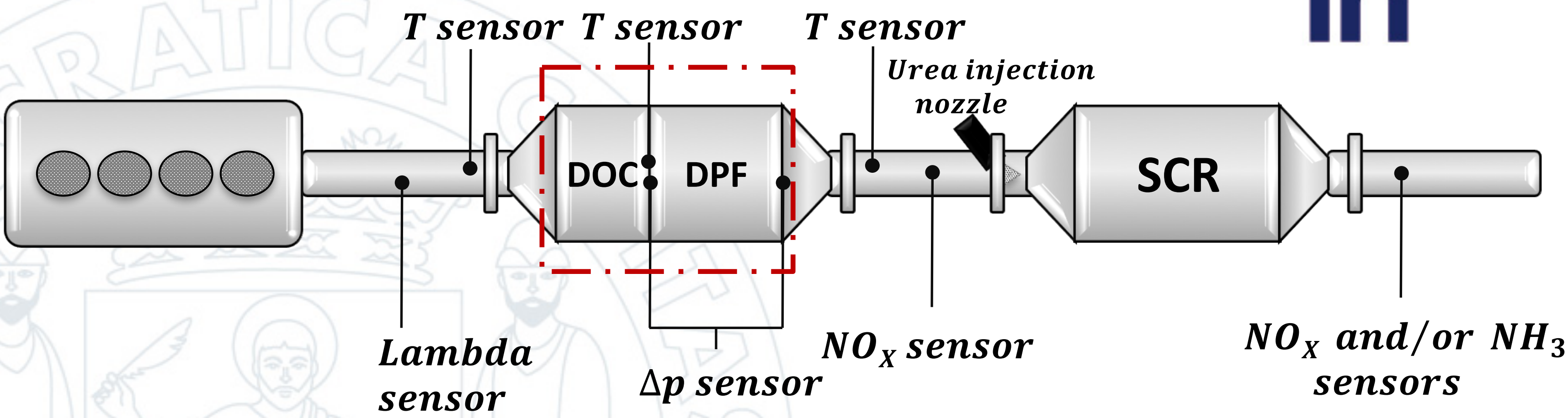

DOC – *Diesel Oxidation Catalyst*

- Oxidation of HC and CO
- Oxidation of NO to NO_2

DPF – *Diesel Particulate Filter*

✓ **Accumulation**

✓ **Depth filtration**

The particles fill the pores - High filter losses and moderate collection efficiency.

✓ **Cake deposition**

Soot layer builds up on the channel surface - Linear increase in pressure drop and high filtration efficiency.

✓ **Regeneration**

✓ **Active**

Enabled by an increase of gas temperature (suitable injection strategy / external source)

✓ **Passive**

Promoted at lower temperature by NO_2

SCR - main chemical phenomena

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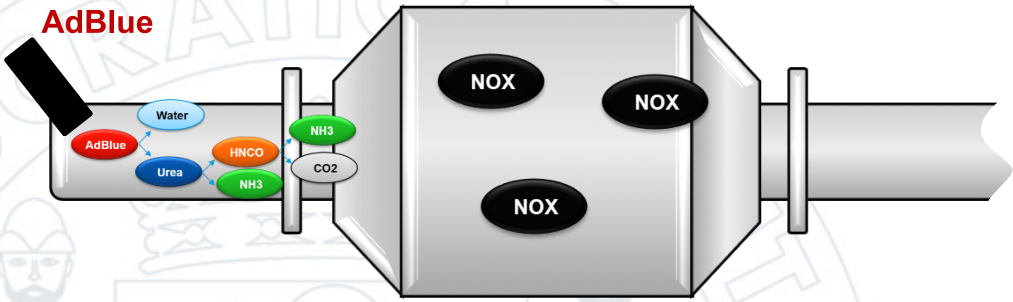
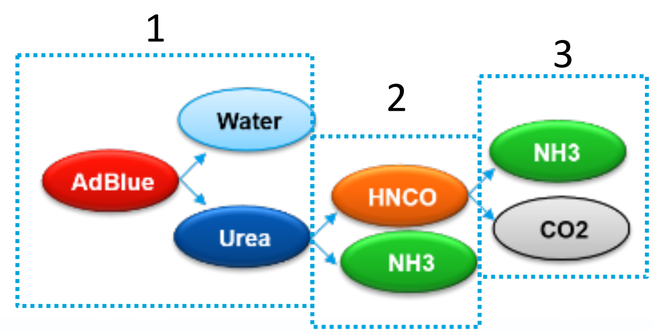


To supply the reducing agent (NH_3) required for SCR operation, a 32.5% aqueous urea solution (DEF - AdBlue) is injected for toxicity reasons.



1. Urea **evaporation**

$$NH_2 - CO - NH_{2_{liq}} \rightarrow NH_2 - CO - NH_2^* + xH_2O$$

2. Urea **decomposition**

$$NH_2 - CO - NH_2^* \rightarrow NH_3 + HNCO$$

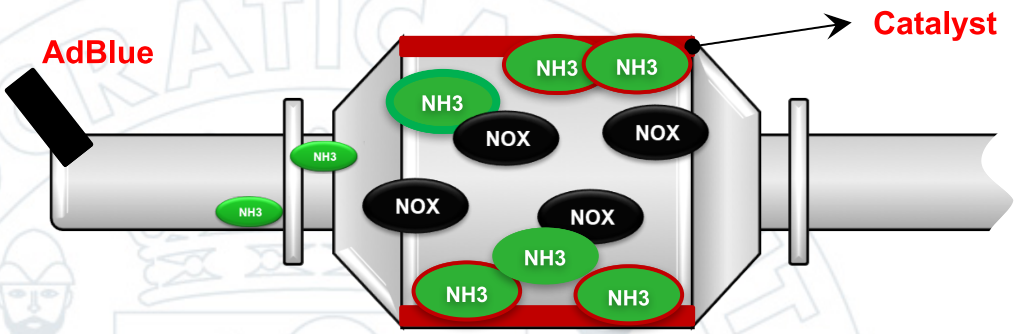
3. Isocyanic acid (HNCO) **hydrolyzation**

$$HNCO + H_2O \rightarrow NH_3 + CO_2$$

- Catalyst;
- High exhaust temperature;
- Optimal design of dosing unit.

Ideally, 100% urea to ammonia conversion can be expected at the very beginning part of the SCR catalyst.

SCR - main chemical phenomena



The key parameter in ammonia dynamics is the total NH_3 adsorption capacity Ω that is strongly dependent on temperature.

Adsorption & Desorption

$$NH_3 + S_{free} \rightarrow NH_3^*$$

$$NH_3^* \rightarrow NH_3 + S_{free}$$

Adsorbed NH_3 in the free active sites S_{free}

deNO$_x$ reactions

$$2NH_3^* + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$ ***Fast Reaction***

$$4NH_3^* + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$ ***Standard Reaction***

$$4NH_3^* + 3NO_2 \rightarrow 3.5N_2 + 6H_2O$$ ***Slow Reaction***

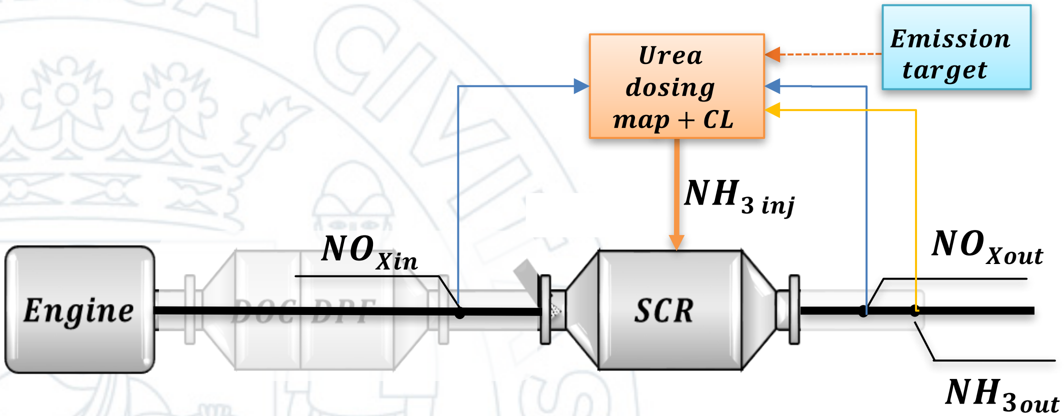
$$4NH_3^* + 3O_2 \rightarrow 2N_2 + 6H_2O$$ ***NH_3 Oxidation***

Slow Reaction and *NH_3 Oxidation*: *Negligible at Low Temperature*

The kinetic rates are strictly related to the free catalytic sites available on the catalytic substrate

SCR map based control

Objective: *optimization of Urea dosing strategies to reach balance between high NO_X reduction efficiency and low NH_3 slip*



Non linearities of the system

- Reaction kinetics
- Cross sentivity of NOx sensor to NH3

System dynamics

- Catalyst Temperature
- Ammonia storage

Transport delay

- From urea control signal to NH_3 in the catalyst

Uncertainties

- Engine out gas temperature, flow and composition (i.e. NO, NO2);
- Thermal state of the SCR;
- NH_3 injection accuracy, deposits.
- Sensor accuracy
- SCR actual NH_3 storage, formulation, aging

SCR model based control

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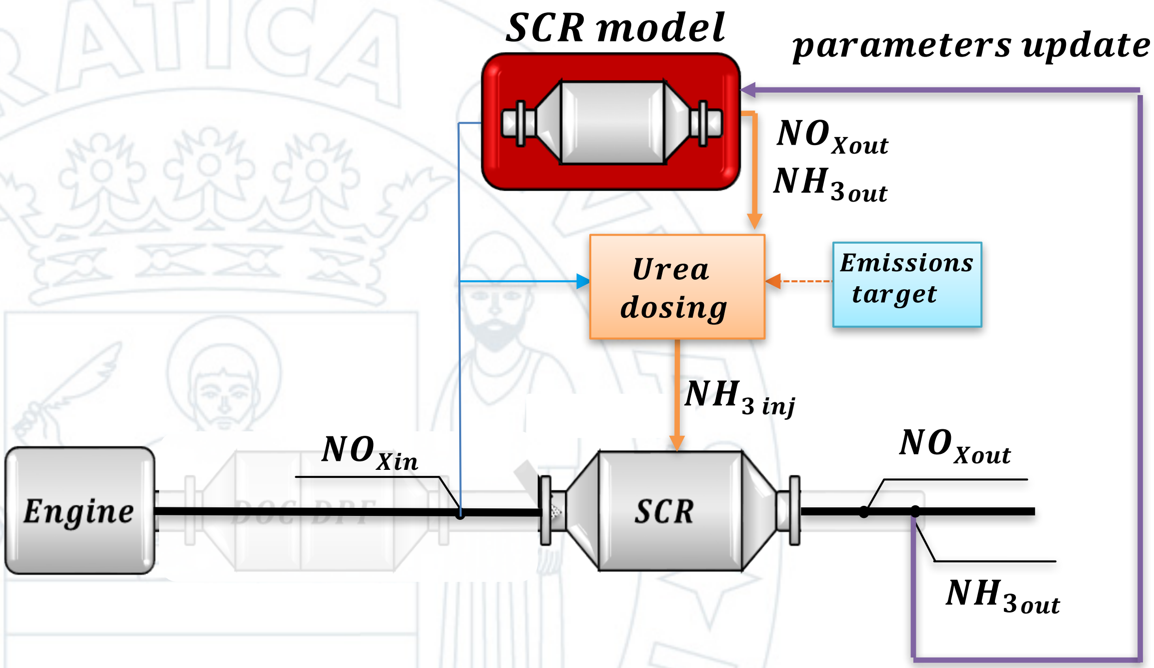

- Prevent ammonia slip during transients;
- Optimize NOx conversion efficiency by maximizing NH3 availability, especially during fast changing operation.
- Provide adaptive features vs. systems aging and plant-model mismatch by on-board model parameters update

SCR model formulation

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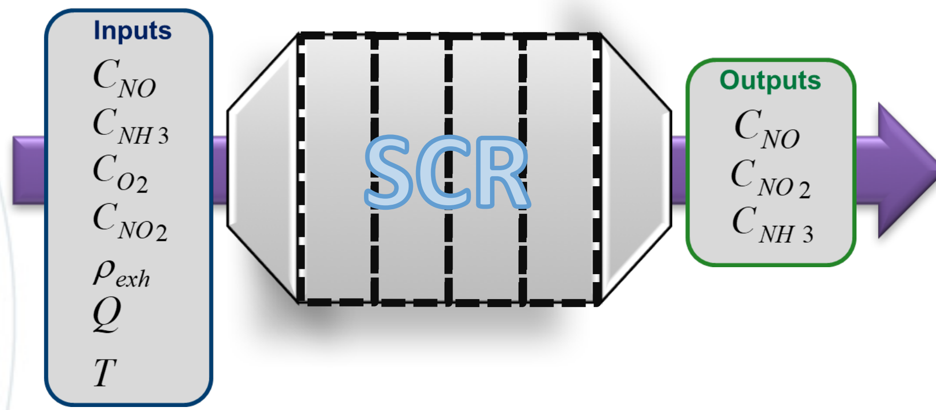
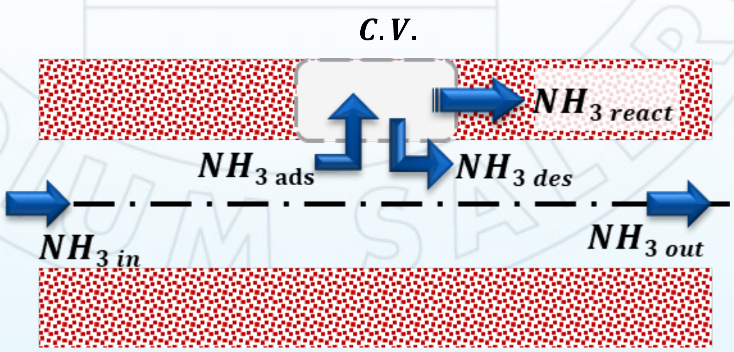
- Lumped approach: SCR catalyst is partitioned into **4 section** along the axial direction;
- Mass balance of chemical species involved;
- Mass transport neglected, **chemical kinetics** in the catalyst are reaction controlled;
- Reaction rates are defined as a function of **ammonia storage** $(\boldsymbol{\theta})$ and gas phase concentrations of NO and NO_2 by Arrhenius like formulation.





The interaction of ammonia with catalytic substrate is represented by **ammonia coverage ratio** $(\boldsymbol{\theta})$

$$\vartheta = \frac{C^*_{NH3}}{\Omega}$$

SCR model equations

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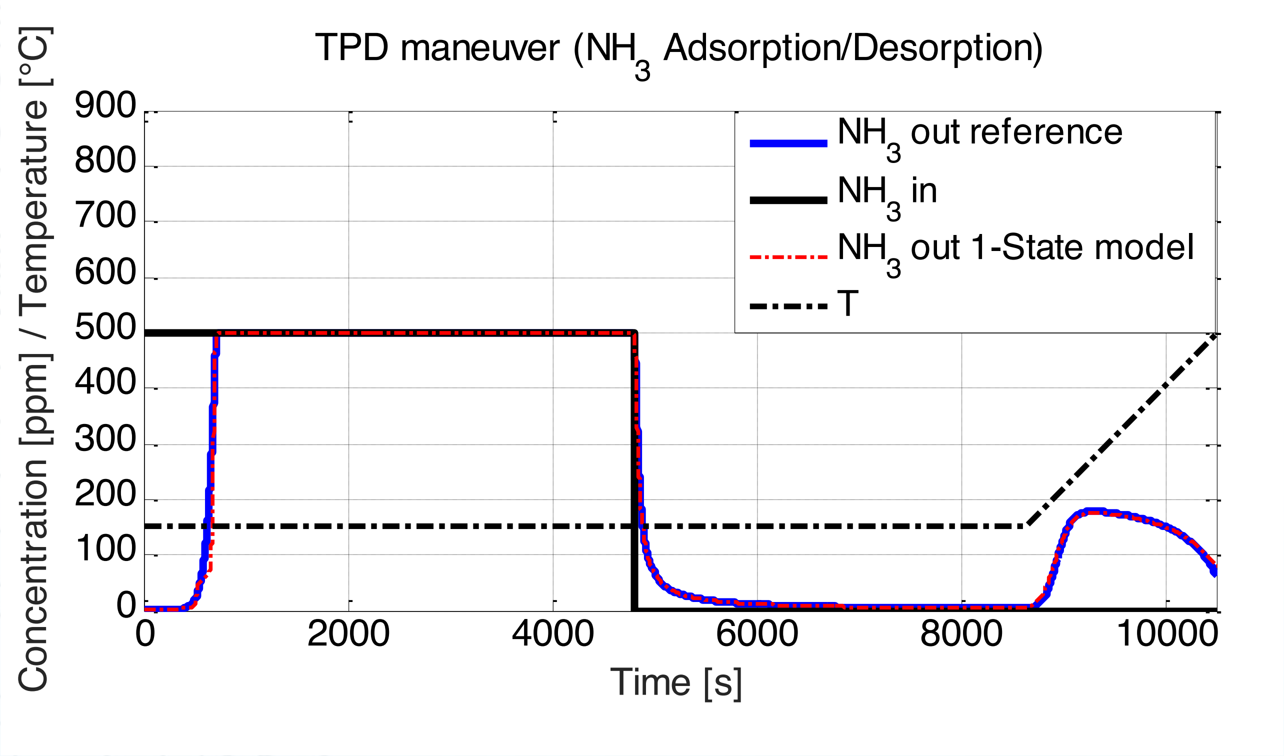
$$\begin{bmatrix} 0 \\ 0 \\ \dot{\vartheta} \\ 0 \end{bmatrix} = \begin{bmatrix} -\bar{Q}C_{NO} - K_{fast}\vartheta\Omega C_{NO}C_{NO_2} - K_{std}\vartheta\Omega C_{NO}C_{O_2} + \bar{Q}C_{NO_{in}} \\ -\bar{Q}C_{NO_2} - K_{fast}\vartheta\Omega C_{NO}C_{NO_2} - K_{slow}\vartheta\Omega C_{NO_2} + \bar{Q}C_{NO_{2in}} \\ -(K_{des}+K_{oxi})\vartheta + K_{ads}C_{NH_3}(1-\vartheta) - K_{fast}\vartheta C_{NO}C_{NO_2} - K_{std}\vartheta C_{NO}C_{O_2} - K_{slow}\vartheta C_{NO_2} \\ K_{des}\Omega\vartheta - [K_{ads}\Omega(1-\vartheta) + Q]C_{NH_3} + \bar{Q}C_{NH_{3in}} \end{bmatrix}$$

- The computational burden is not suitable for on-board control application.
- NO, NO_2 and NH_3 concentration dynamics are much faster than the ammonia storage.
- Reduction to one-state model with $\boldsymbol{\vartheta}$ as only dynamic process to be modelled.

SCR model parameters identification

Temperature Programmed Reaction at the Hot Flow Bench



SCR model validation - TPR tests

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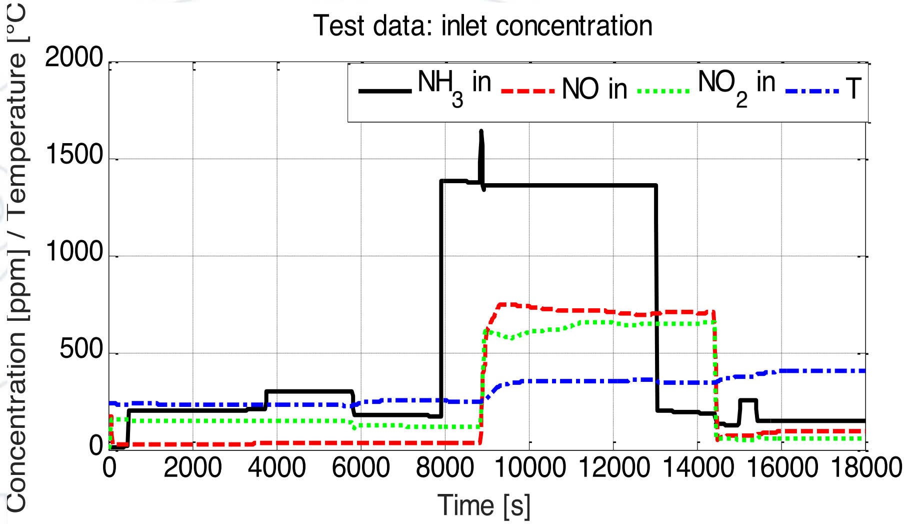
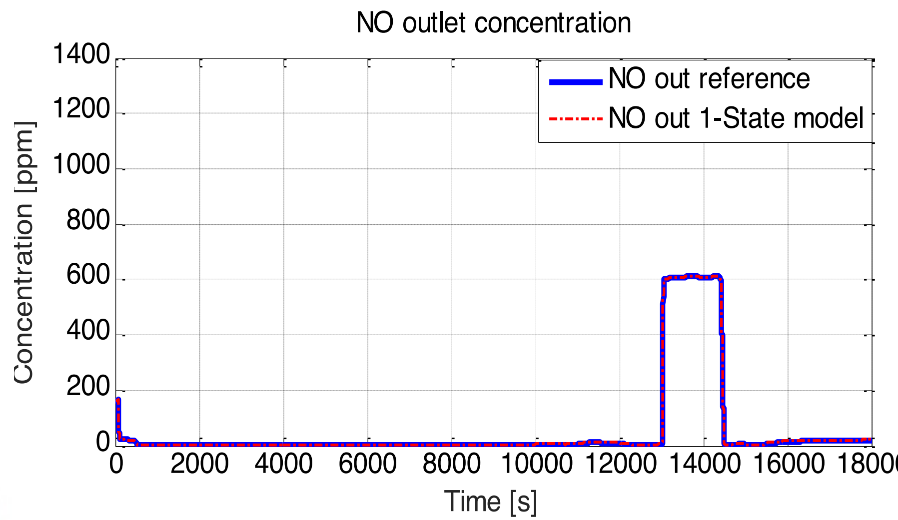
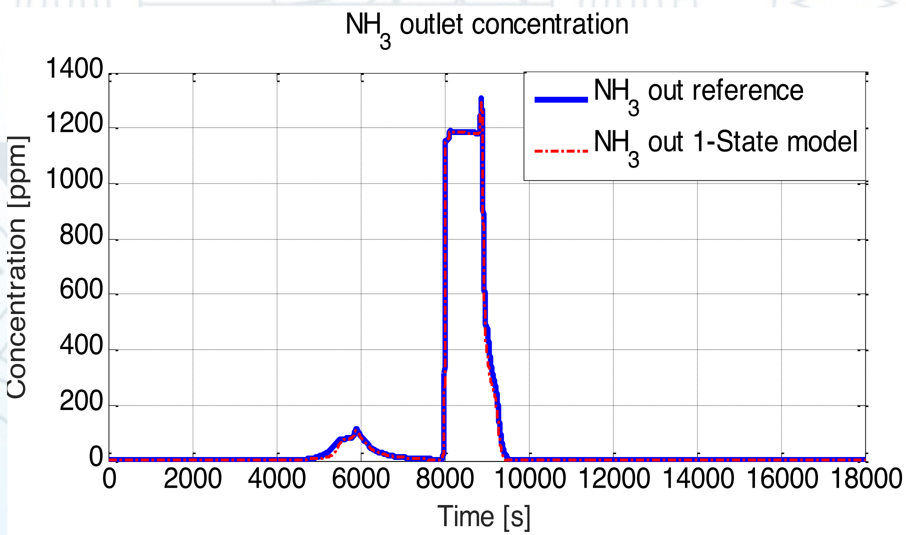
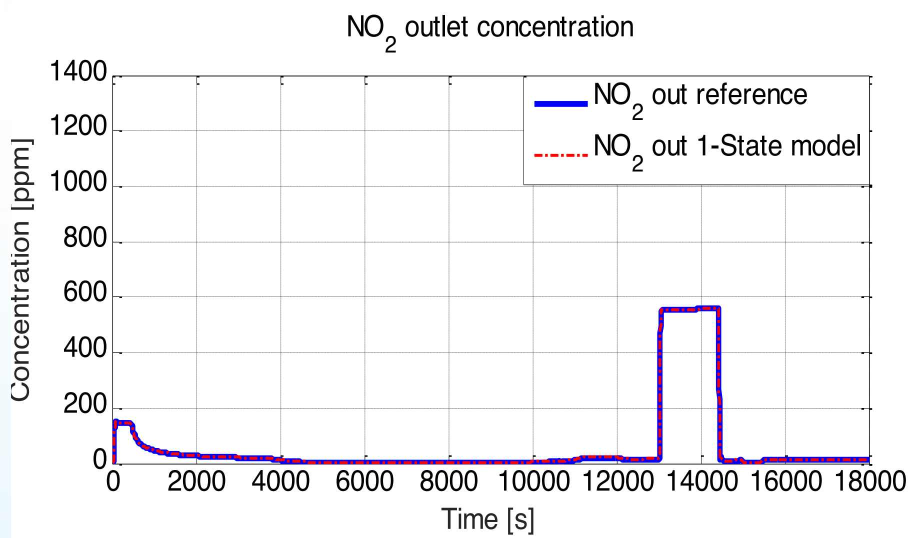




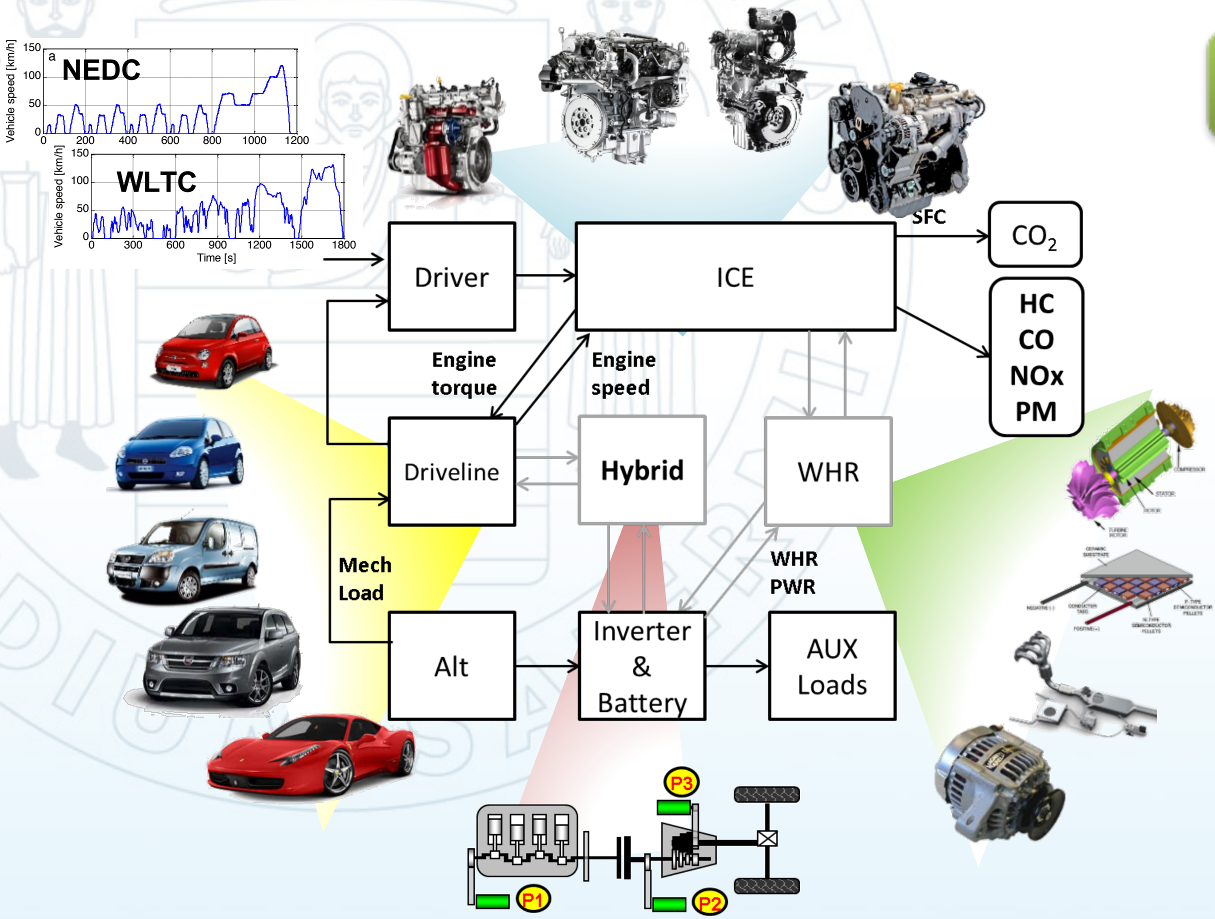




Enhancement of fuel economy by EH/ADAS

Need to fullfil European CO_2 targets from innovative technologies: ‘eco-innovations’.

Model Based Computational Framework to simulate different vehicles with different powertrain configurations along standard (NEDC, WLTC) or arbitrary driving cycles and evaluate the benefits achievable in reducing CO_2 emissions, depending on WHR/Hybrid technology, components sizing and system management.



- WHR
  - ETC
  - TEG
  - ORC
- Hybrid
  - P1/P2/P3
  - Fuel Cell
- EH-ADAS
  - Advanced CC
  - HEVs Energy Management

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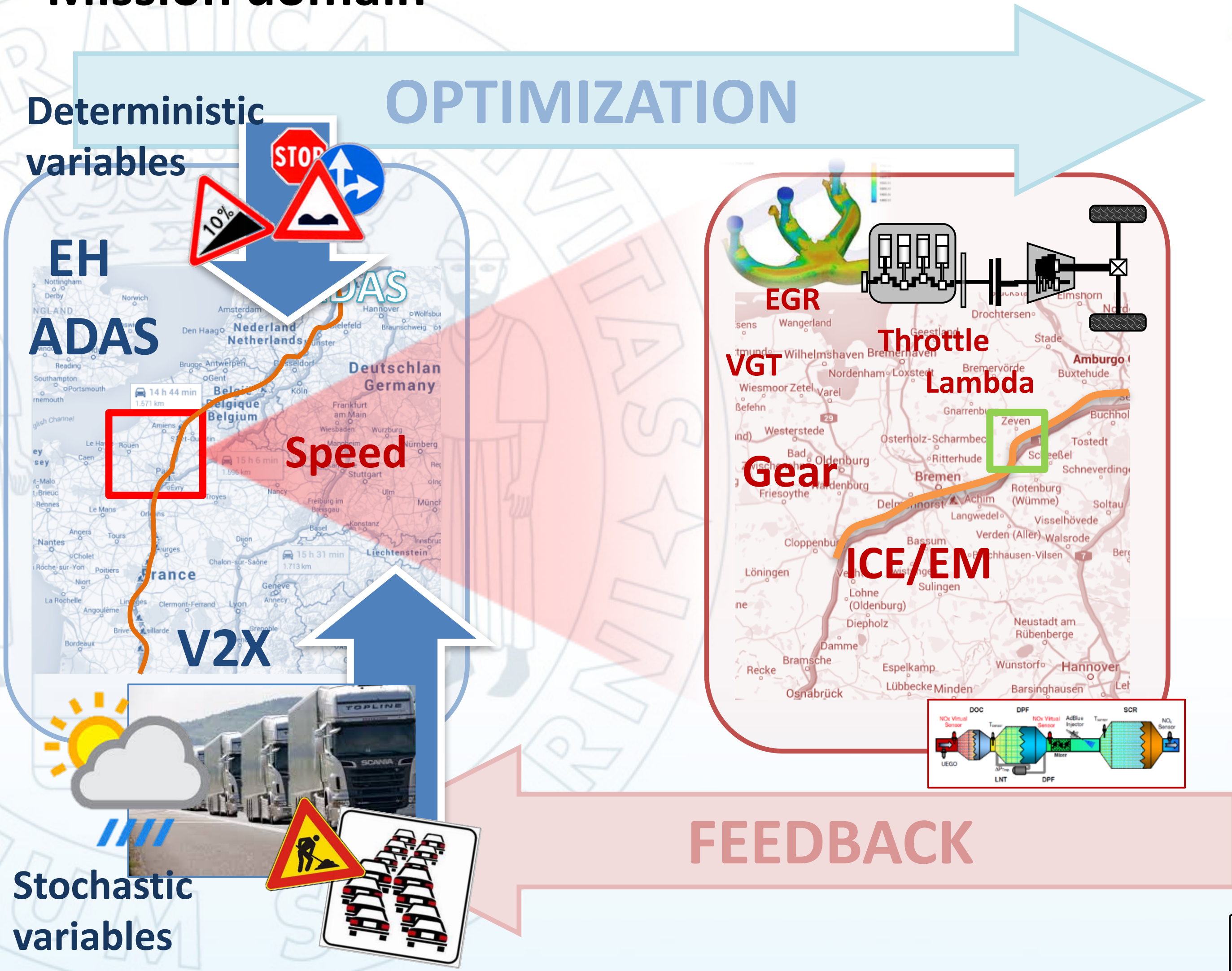
From EH to Engine

Mission domain **Powertrain domain**



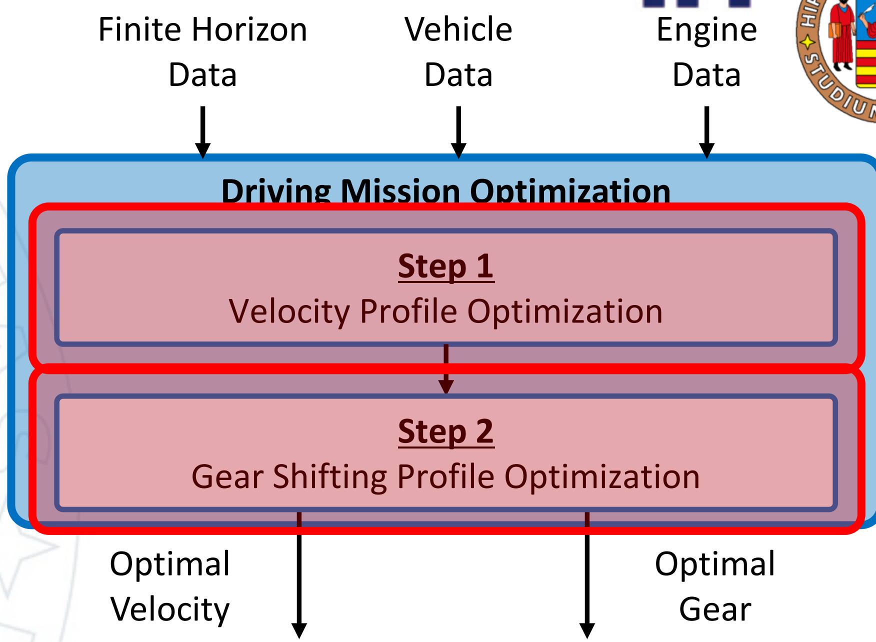
Max fuel economy with constraints on

- V_{avg} , V_{max}
- NOx, PM
- SOC

Proposed Approach

The proposed approach splits the optimization problem:

1. compute a velocity profile that minimizes the energy spent to move the vehicle along the route;
2. choose the gear or the ICE/EM torque demand entailing the minimum fuel consumed to follow the velocity reference computed in the first step.



Step 1

$$J_k(\bar{u}_k, \bar{x}_k) = J_k(u_F, K_k) = \Delta x \left(F_{drv,k}^2 + \mu \ \max\left(0, \left(v_{avg} - v_k\right)\right)\right)$$

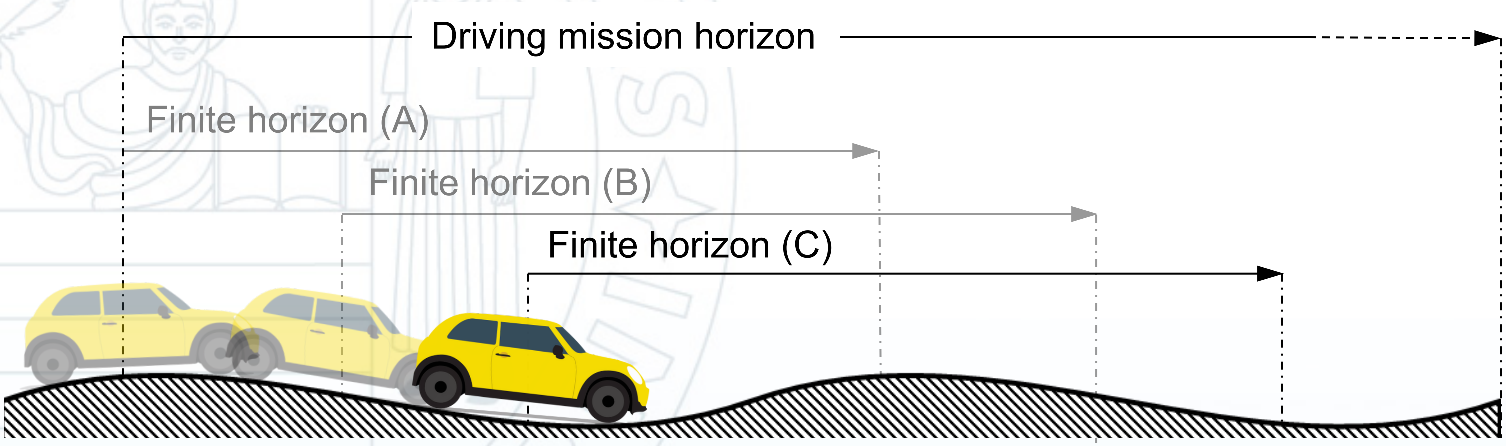
Step 2

$$J_k(\bar{u}_k, \bar{x}_k) = J_k\left(u_{sh,k}, \gamma_k\right) = \frac{\dot{m}_{f,k} v_k}{\Delta x} + \Phi K_{loss,k} u_{sh,k}$$

Rolling Horizon Approach

Real driving scenarios are characterized by
- **traffic flows**
- interactions with **surrounding vehicles**
- **traffic lights**…

which can prevent the calculated optimal velocity from being tracked.
The optimal control problem is solved for a **finite rolling horizon**.



- Sub-optimality of the solution
- Updates the optimal control law each 500 m
- Reduces the calculation time and memory usage (that are fixed)
- Dynamic adaptability to the environmental changes
- … optimization can be triggered if the vehicle drifts from the optimal reference

Approaches Comparison

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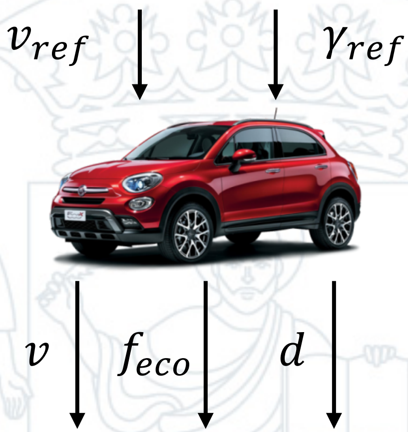
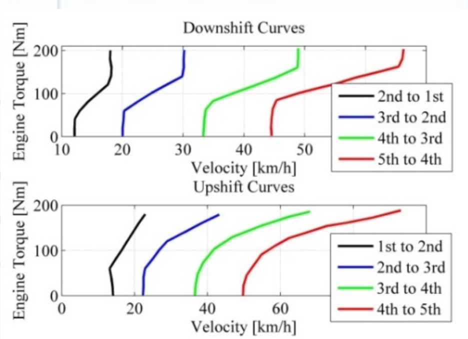
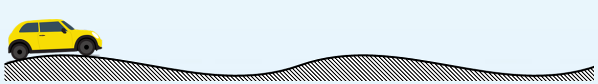
Classic Cruise Controller - **CC**

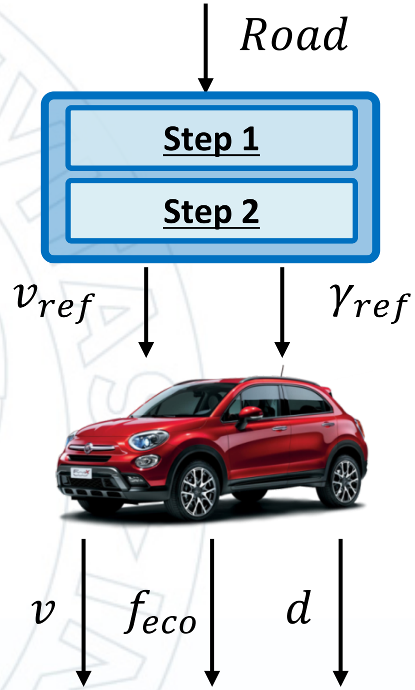


Fixed velocity set-point and shifting maps

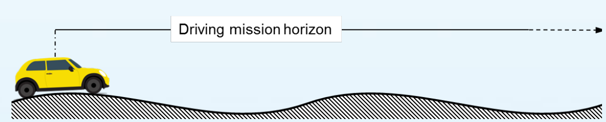




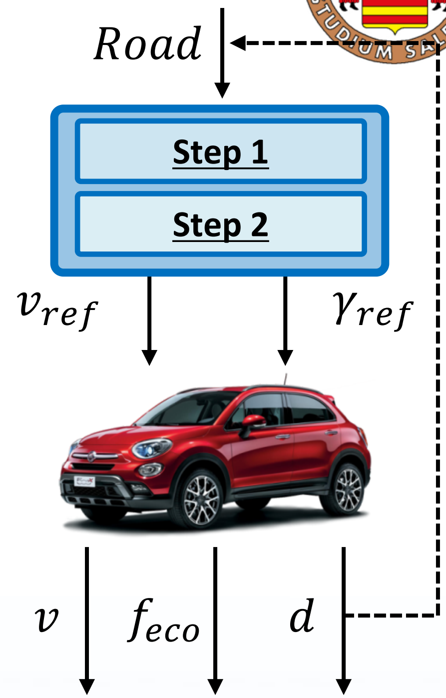
Entire Horizon - **EH**



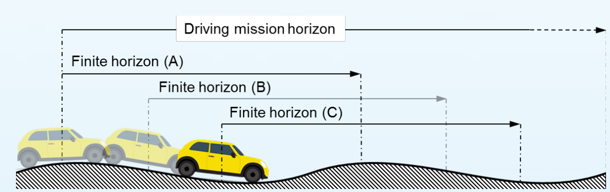
DP Optimizion over the entire mission horizon



Finite Horizon - **FH**



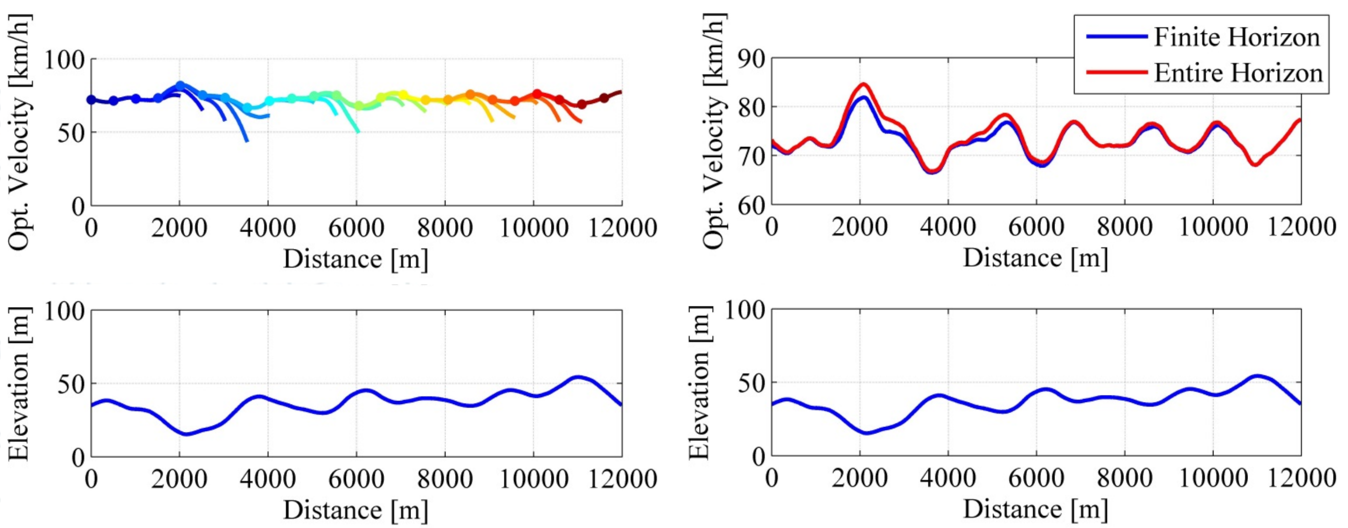
DP Optimized over a finite rolling horizon approach



Simulation Results

Scenario #1

- Three-lanes highway
- $12\ km$
- $\alpha \in [-2.7\%, +3.1\%]$
- $v_{max} = 90\ km/h$



	Time [s]	$\Delta time$ [%]	Fuel Eco [km/l]	$\Delta fuel$ [%]
CC	584.8	-	26.82	-
FH	579.3	**-0.94**	27.85	**-3.84**
EH	575.1	**-1.66**	28.12	**-4.85**

Thank You

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