# Virtual Sensors for Diesel Engine and After-treatment Management

Federico Covassin
Magneti Marelli S.p.A. - Powertrain

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# Company Overview

Magneti Marelli is an international company committed to the design and production of hi-tech systems and components for the automotive sector.

**AUTOMOTIVE LIGHTING**
(Headlamp, Rearlamp and Body Computer)

**POWERTRAIN**
(Gasoline and Diesel engine control, Electric Motor and Transmission)

**ELECTRONIC SYSTEMS**
(Instrument clusters, Infotainment & Telematics)

**SUSPENSION SYSTEMS**
(Suspension Systems, Shock Absorbers, Dynamic Systems)

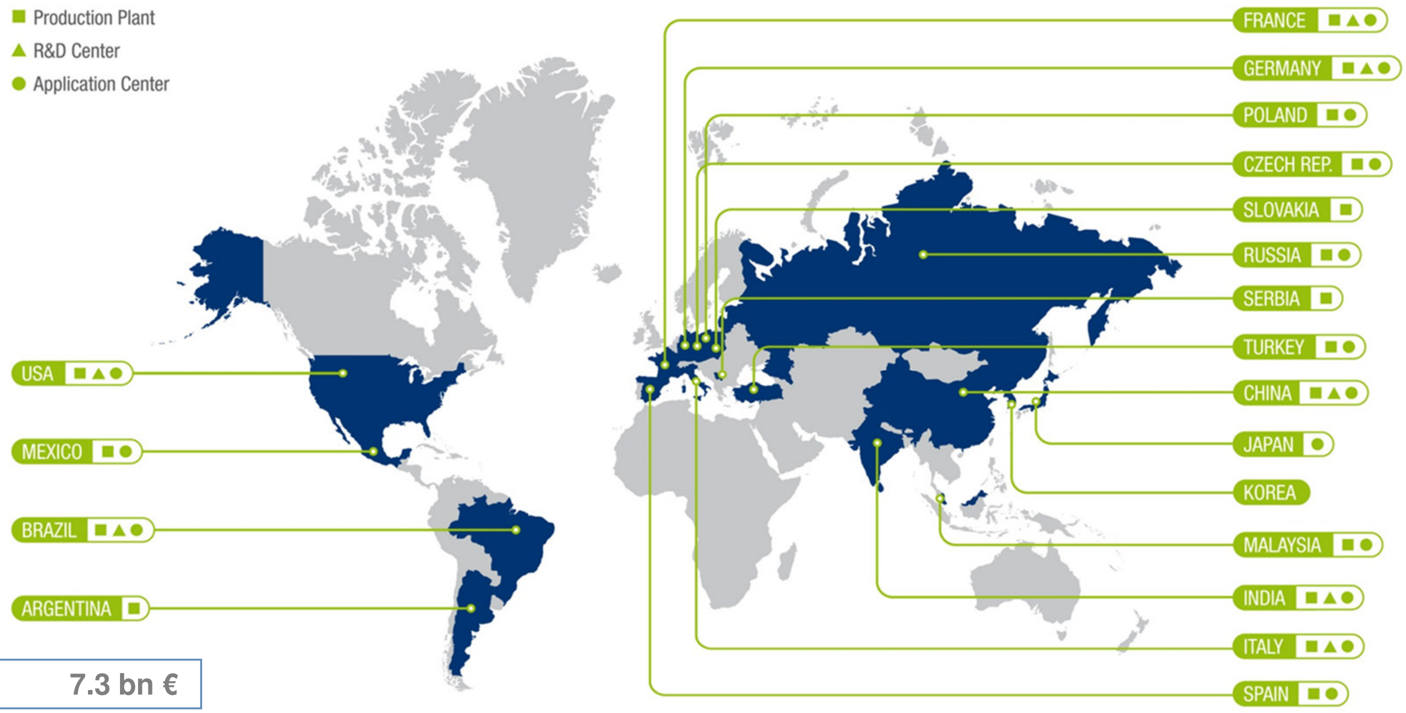

**EXHAUST SYSTEMS**
(Manifolds, Catalytic converter, DPF and Mufflers)

**PLASTIC COMPONENTS AND MODULES**
(Bumper, Dashboard, Central Consol, and Fuel system)

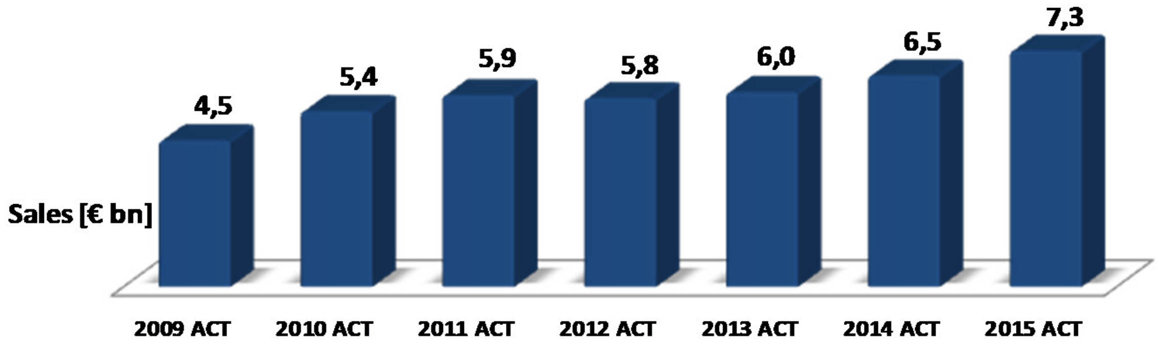
**AFTERMARKET PARTS & SERVICES**
(Mechanical, Body Work, Electrics and Electronic and consumables)

**MOTORSPORT**
(Injectors, ECU, KERS, DST, Hydraulic Gearbox Control Unit…)

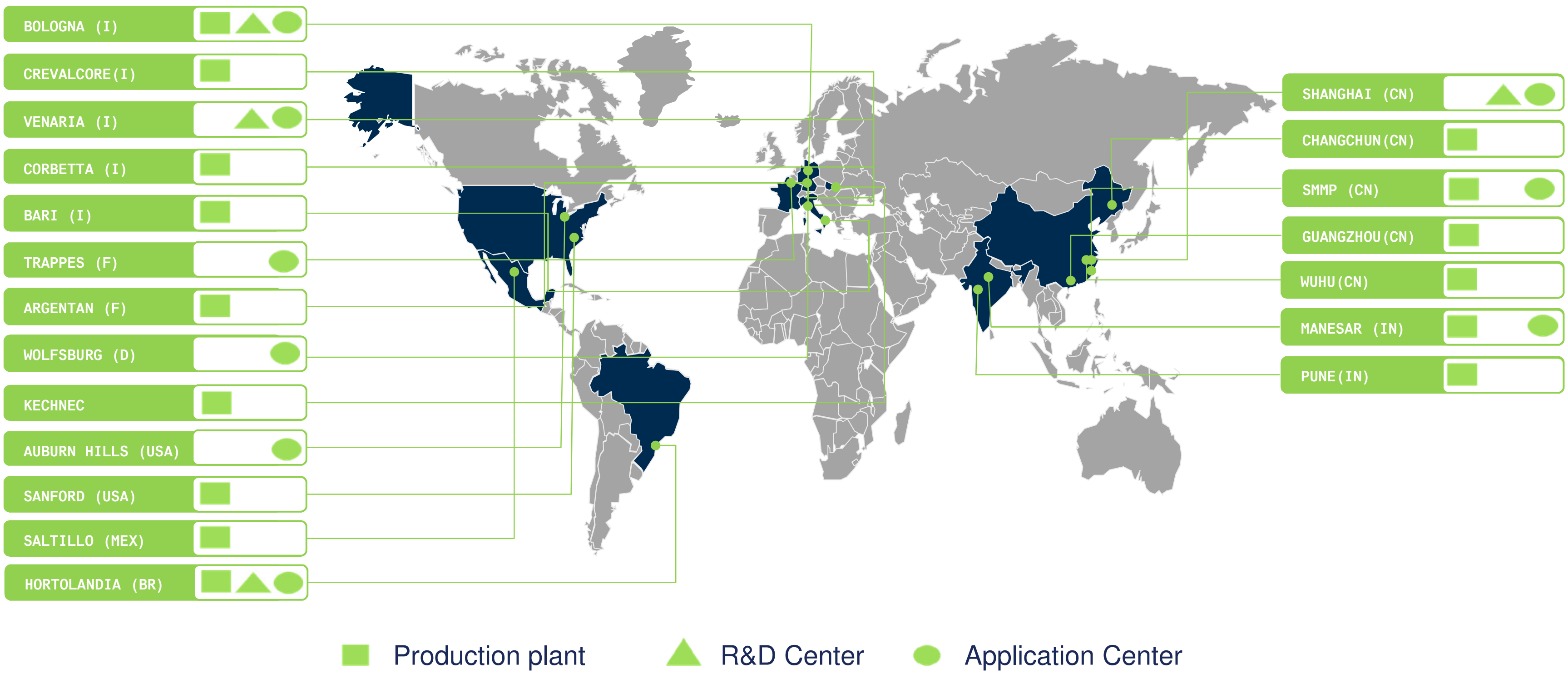
# Magneti Marelli Worldwide Presence




| | |
|---|---|
| Sales 2015 | 7.3 bn € |
| R&D Centers | 12 |
| R&D (of sales) | 4.6% |
| Production units | 89 |
| Application Centers | 30 |
| Investments (of sales) | 5.7% |
| Employees | 40,418 |



# Magneti Marelli Powertrain Worldwide Presence



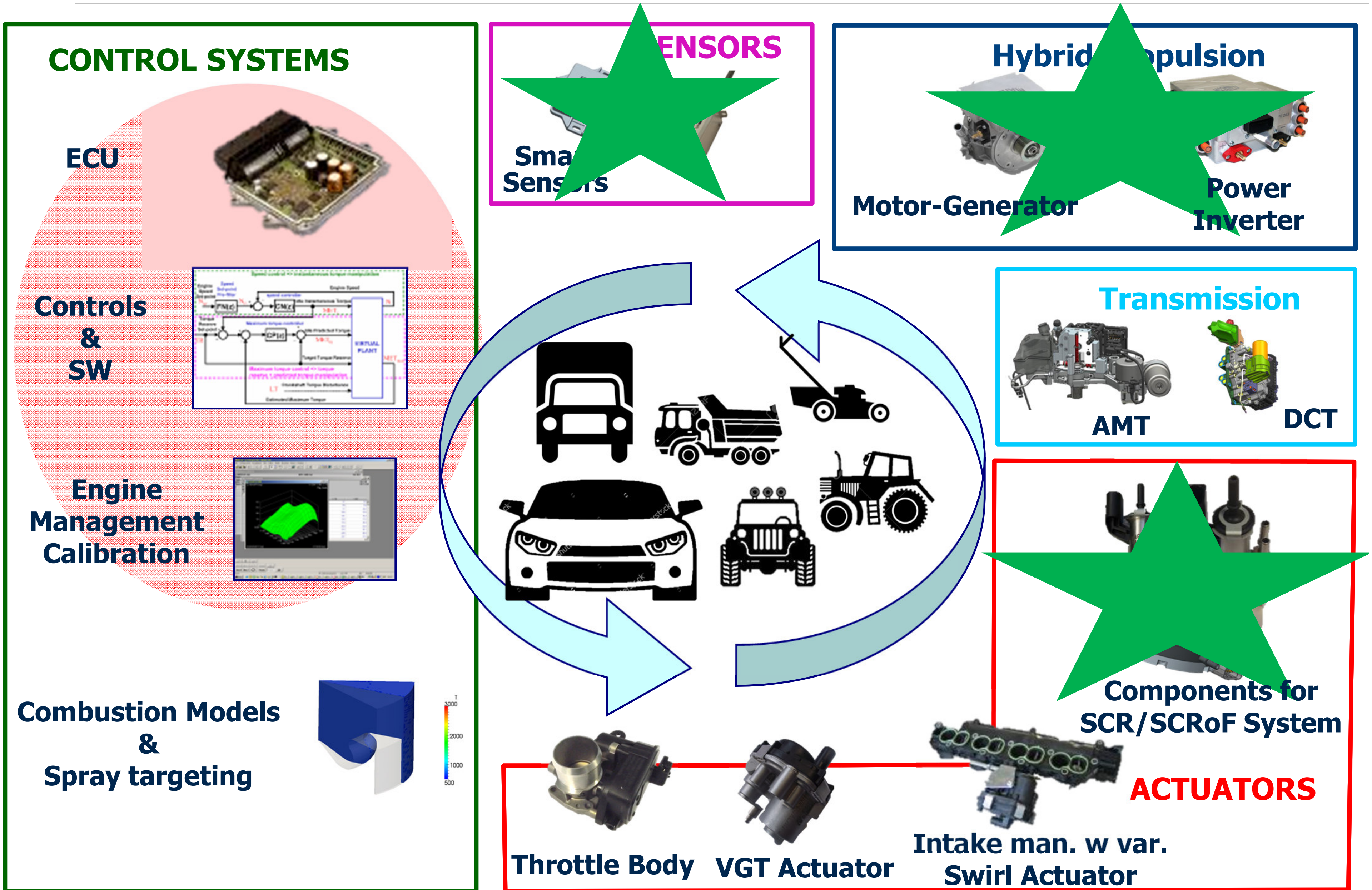

| | | | |
|---|---|---|---|
| Sales 2015 | **919 mio €** | Production units | **15** |
| R&D Centers | **4** | Application Centers | **9** |
| R&D* | **5.7%** | Investments* | **13.7%** |
| Employees worldwide | | | **5.293** |

* % of “make” sales

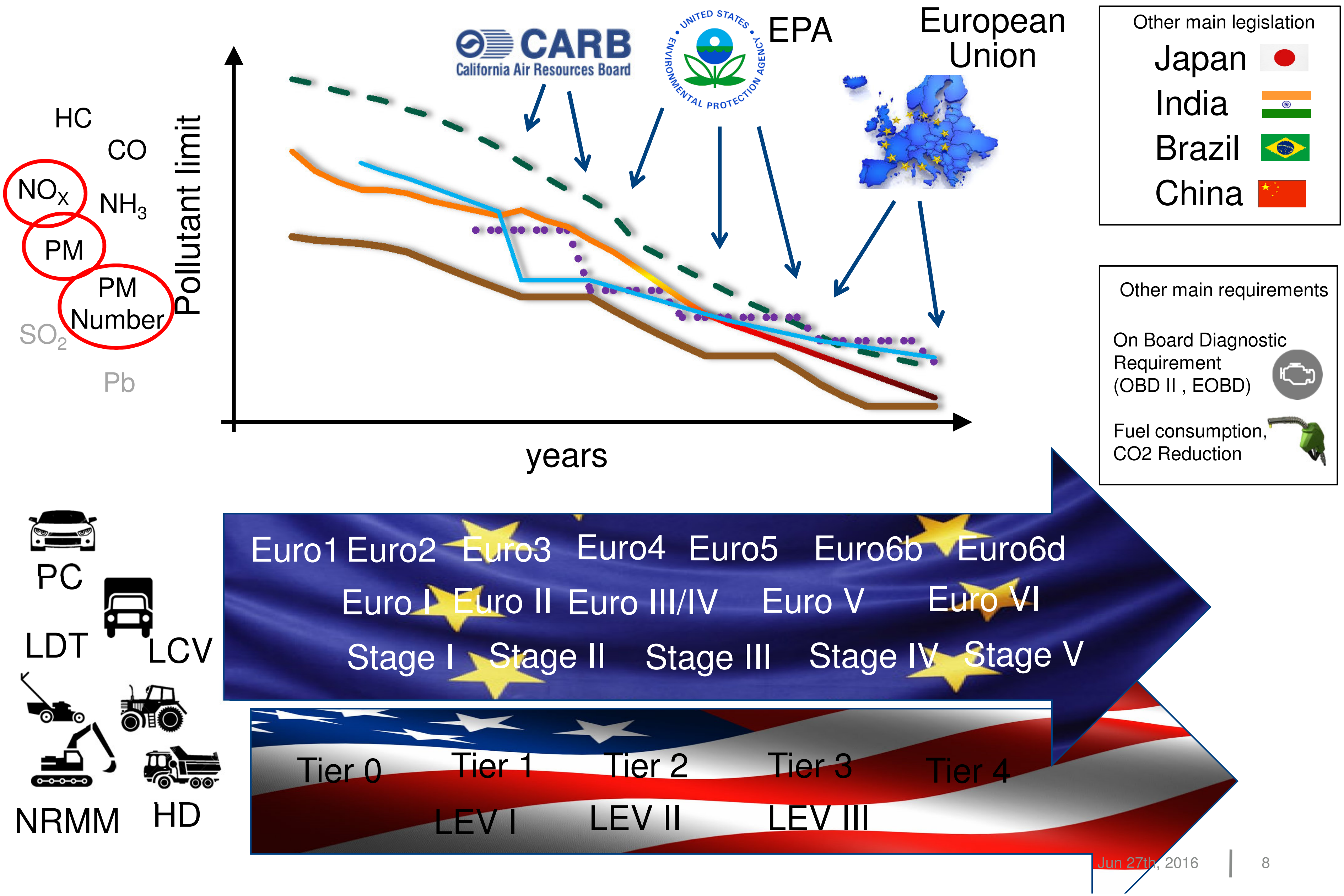
# Customer Brand Portfolio

MAGNETI MARELLI

# Magneti Marelli Powertrain – Diesel Systems



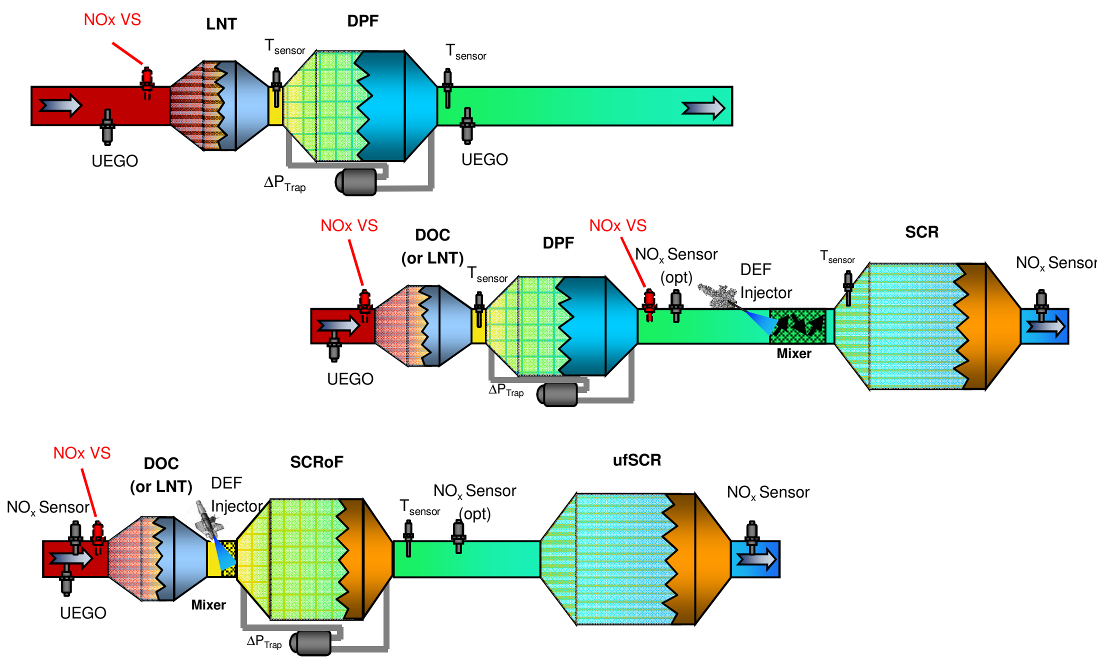
# Emission Standard trend



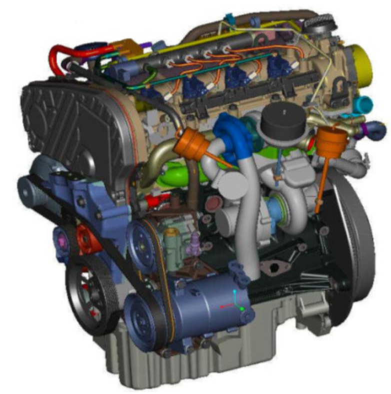
# Technologies for reaching the target

Two main ways for NOx reduction on Diesel Engine

- NOx Engine Out reduction → Combustion improvement (e.g. EGR HP, EGR LP)
- After-treatment technologies (e.g. LNT, SCR, SCRonF) could be combine for reach the target

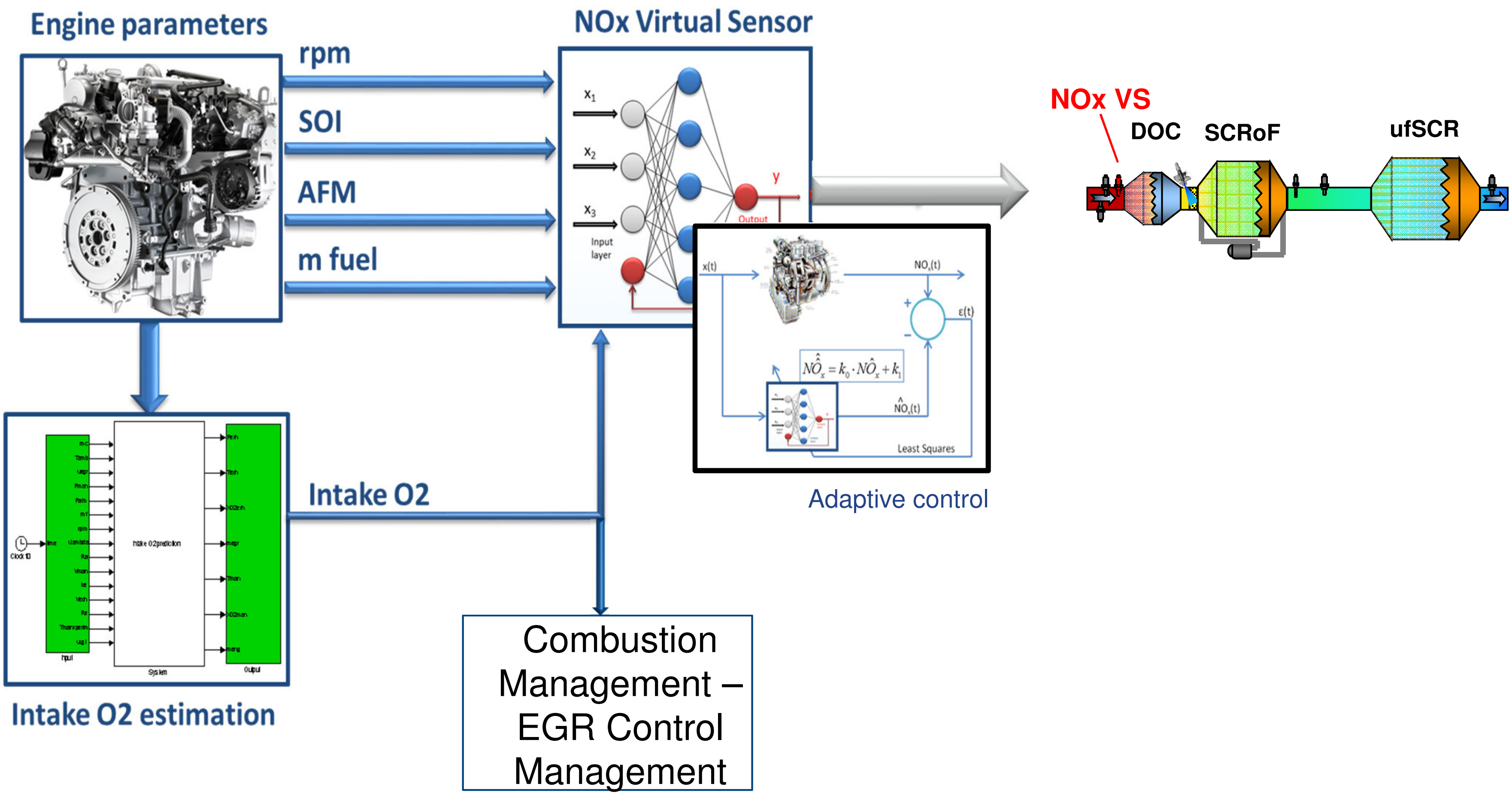



NOx Virtual Sensor



O2 Virtual Sensor

# Intake O2 and NOx Virtual Sensors

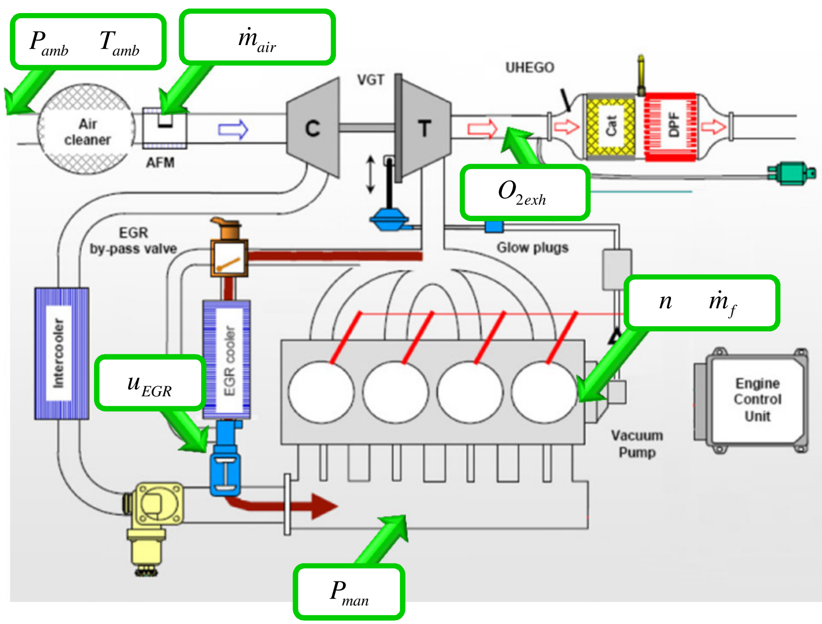


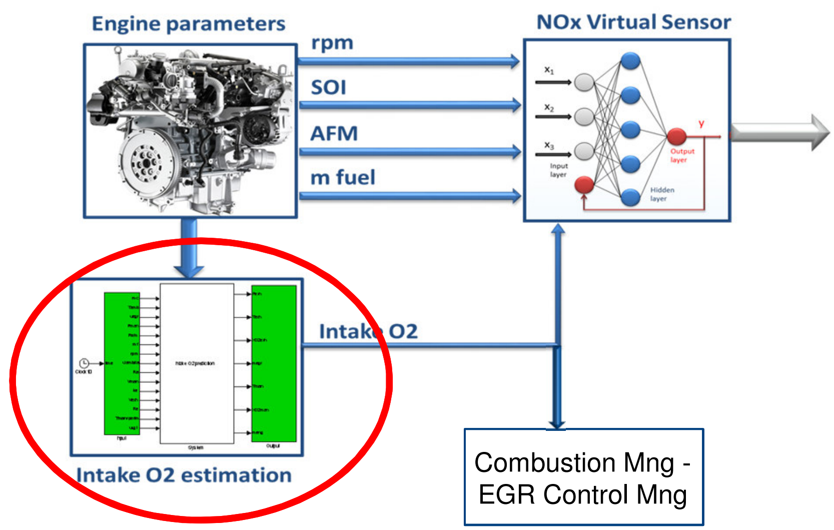

Partnership with University of Salerno

# Intake O2 Virtual Sensor

Purpose of intake O2 measure:

- Estimation of effective EGR ratio (e.g. EGR Valve Control Management)
- Enhancement of conventional and advanced combustion control (PCCI, HCCI,LTC)
- Improvement of NOx prediction during engine transients, suitable for both dynamic adjustments of EMS strategies and management of after-treatment devices.



# Intake O2 Virtual Sensor

## MEAN VALUE MODEL

- Filling and Emptying for intake/Exhaust manifolds
- Mass and energy conservation in any control volume
- Homogeneous pressure, temperature and chemical composition in the intake manifold
- Instantaneous and perfect mixing of incoming flows
- No heat transfer through manifold walls

→

- Low computational demand and identification issues
- Suitable for on-board implementation
- Model accuracy fully satisfactory

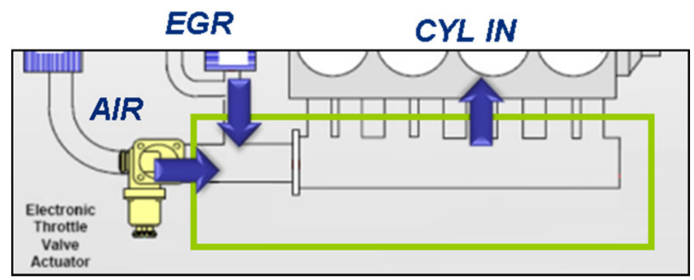
# Mean Value model Main equation

## Oxygen mass fraction in the intake manifold

$$\dot{O}_{2man} = \frac{R_{air}T_{man}}{P_{man}V_{man}}\left[\left(O_{2,exh} - O_{2,man}\right)\dot{m}_{egr} + \left(O_{2,amb} - O_{2,man}\right)\dot{m}_{air}\right]$$

## Intake manifold temperature

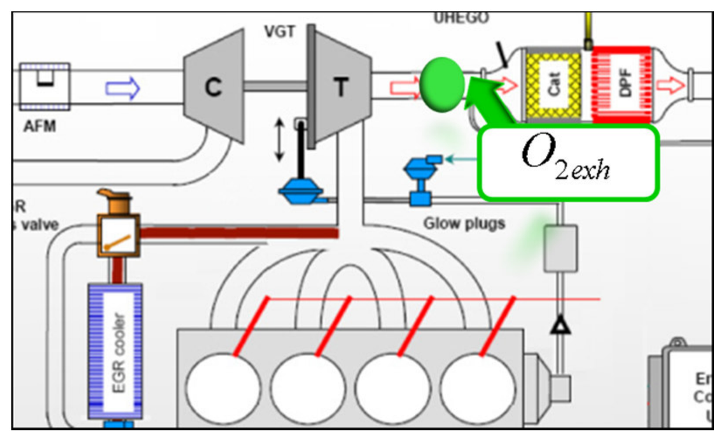
$$\dot{T}_{man} = \frac{R_{air}T_{amb}}{P_{man}V_{man}}\left[\left(k_{air}T_{egr} - T_{man}\right)\dot{m}_{egr} + \left(k_{air}T_{ic,out} - T_{man}\right)\dot{m}_{egr} - \left(k_{air} - 1\right)T_{man}\dot{m}_{cyl,in}\right]$$




## Prediction of Exhaust $O_2$ concentration in place of UEGO measurement

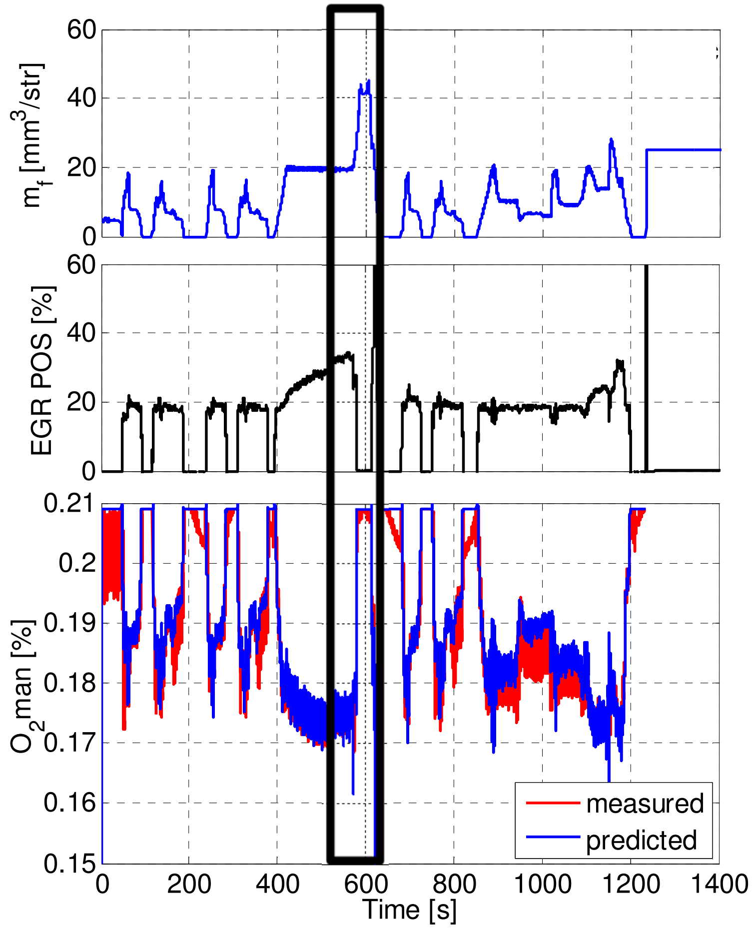
$$\dot{O}_{2,exh} = \frac{R_{exh}T_{exh}}{P_{exh}V_{exh}}\left[\left(O_{2,cyl,out} - O_{2,exh}\right)\dot{m}_{cyl,out}\right]$$

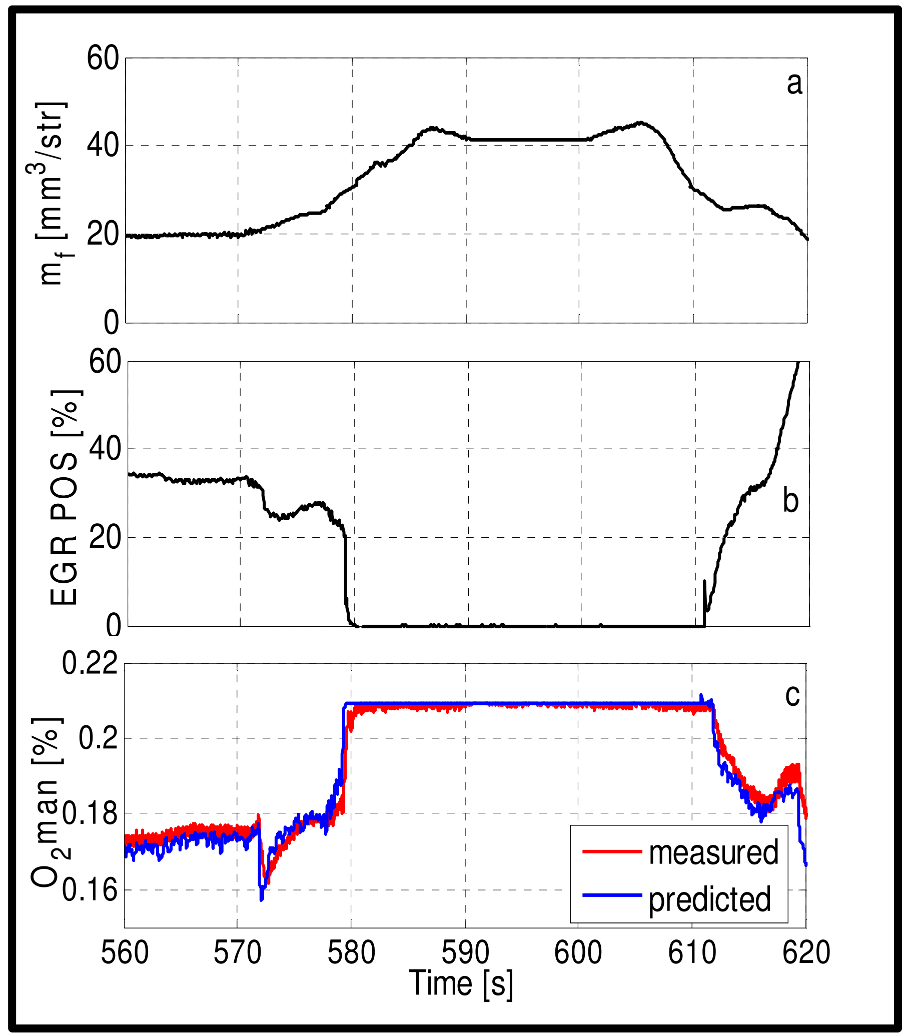
$$O_{2,cyl,out} = \frac{\dot{m}_{cyl,in}O_{2,man} - \alpha_{st}\dot{m}_f O_{2,man}}{\dot{m}_{cyl,in} + \dot{m}_f}$$



# O2 Experimental results

## Common-Rail Diesel 1.3 – EGR/HP - VGT



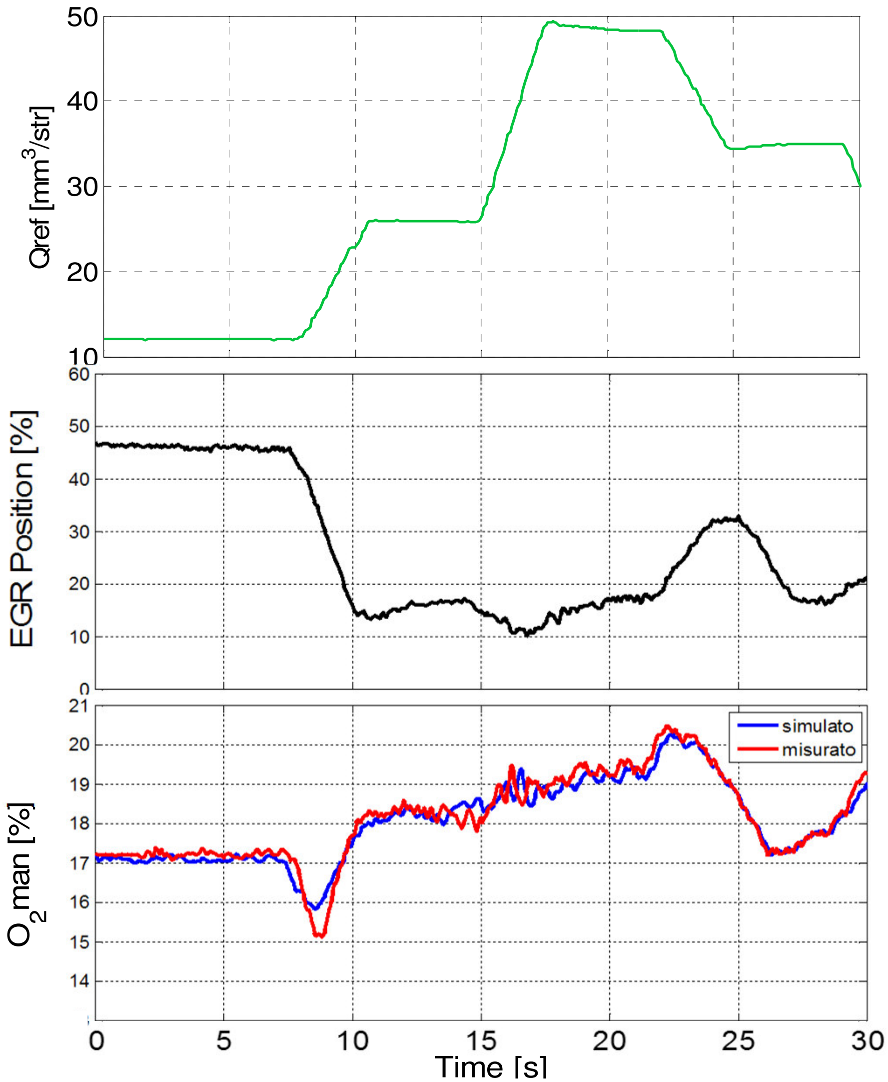




*O2 intake measured with O2 sensor

# O2 Experimental results

## Common-Rail Diesel 2.3 – EGR/HP - VGT

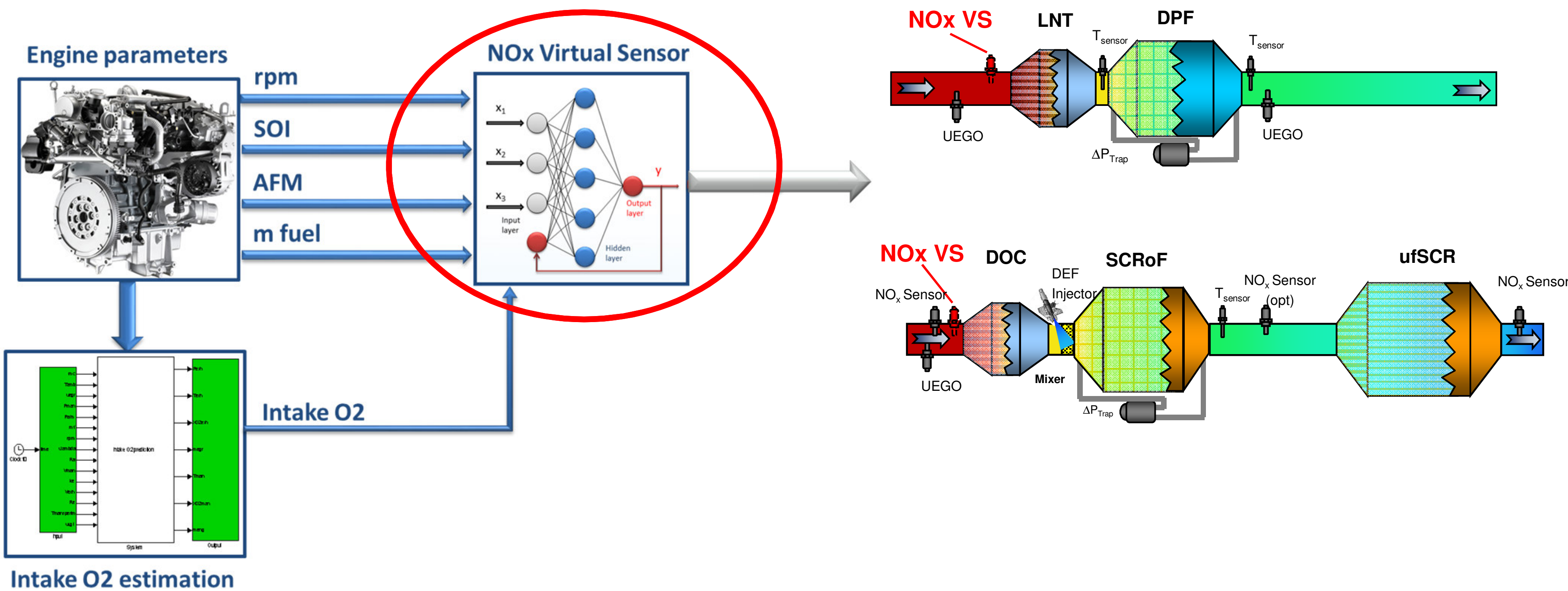
| Engine Key characteristics | |
|---|---|
| Rated Power and Max. Torque | 150Hp and 320Nm |
| Cylinders | 4 in line |
| Displacement | 2286 $cm^3$ |
| Valves per cylinder | 4 (DOHC) |
| Combustion System | Diesel Direct Injection |
| Compression Ratio | 19:1 |
| Synchronisation system | • Crankshaft position sensor<br>• Camshaft position sensor |
| Fuel Injection System | Common Rail Solenoid Injectors (160 MPa) |
| Intake Air System | • Electrical Throttle Body actuator<br>• Intake manifold pressure and temperature sensor |
| Turbo charging System | VGT turbocharger, vacuum controlled with vacuum electro-modulator with VGT position sensor |
| EGR System | • DC-Motor EGR valve + position feedback<br>• Air Flow Meter, before Turbo-Compressor |
| Exhaust Gas System | • 1 linear oxygen sensor (UHEGO) in the exhaust pipe, downstream of turbine just before catalyst |
| After-treatment System | • Oxidant Catalyst + Diesel Particulate Filter (coated soot filter, without additive), close-coupled<br>• DPF Differential pressure sensor<br>• DPF inlet temperature sensor |



# NOx Virtual Sensor

Purpose:

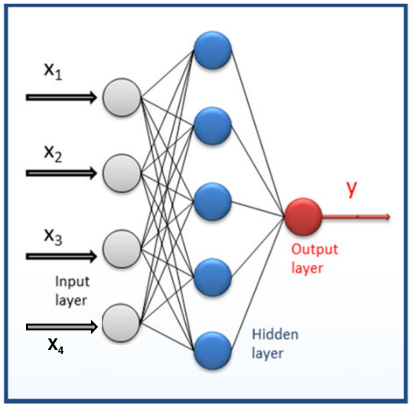
- After-Treatment Device Management (LNT, SCR, SCRoF, etc.)
- Diagnosis After-treatment system:
  - NOx Sensor diagnosis: plausibility check & functional diagnosis



# Recurrent Neural Network in one slide

**Neural Network:**

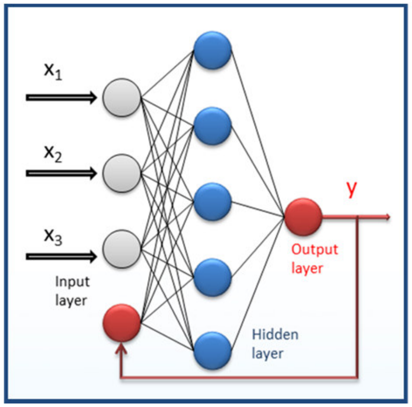
- Black Box Model
- Basic elements (neurons) are combine together with connections and are placed in different layers depending on the architecture
- Right inputs are fundamental for good result
- The training and validation phases are important to make more or less strong  connections
- A lot of NN parameters impact the final result: number of neuros, number of layers, NN architecture, training algorithm, epoch of training, initial conditions, etc.




**Recurrent Neural Network:**

- The current output also depends on the previous outputs

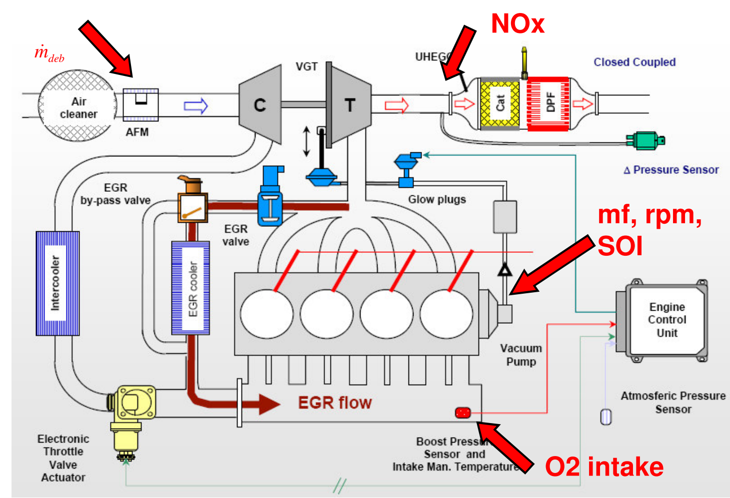
$$y(t,\theta) = F\begin{bmatrix} y(t-1,\theta),\dots, & y(t-i,\theta), \\ x_1(t),\dots, & x_1(t-j+1), \\ x_2(t),\dots, & x_2(t-j+1), \\ x_3(t),\dots, & x_3(t-j+1) \end{bmatrix}$$

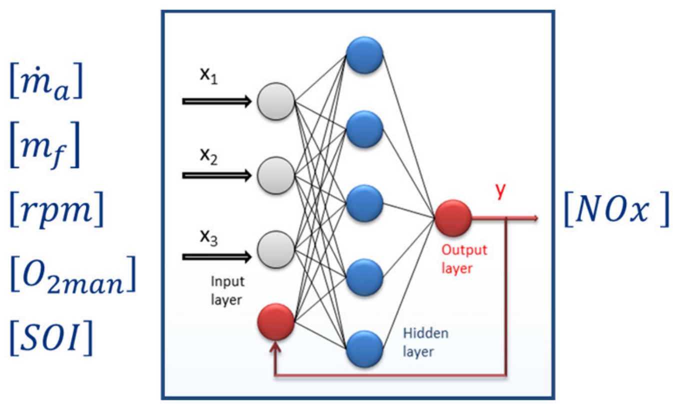


# Recurrent Neural Network training

## Recurrent Neural Network

- Delay compensation from measured data
- RNN identification/ training:
  - Parametric analysis and selection of the most suitable neural network structure;
  - Deterministic analysis to set RNN weights initial conditions;
  - RNN Pruning by means of the Optimal Brain Surgeon (OBS) algorithm.



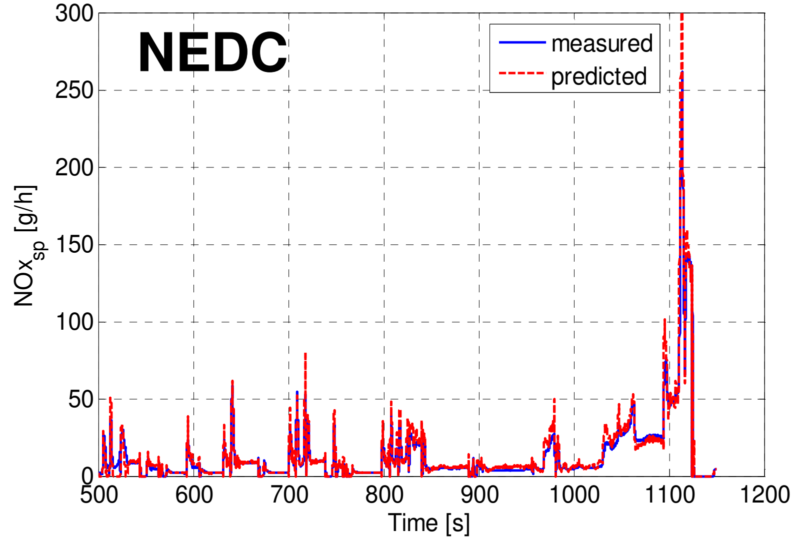



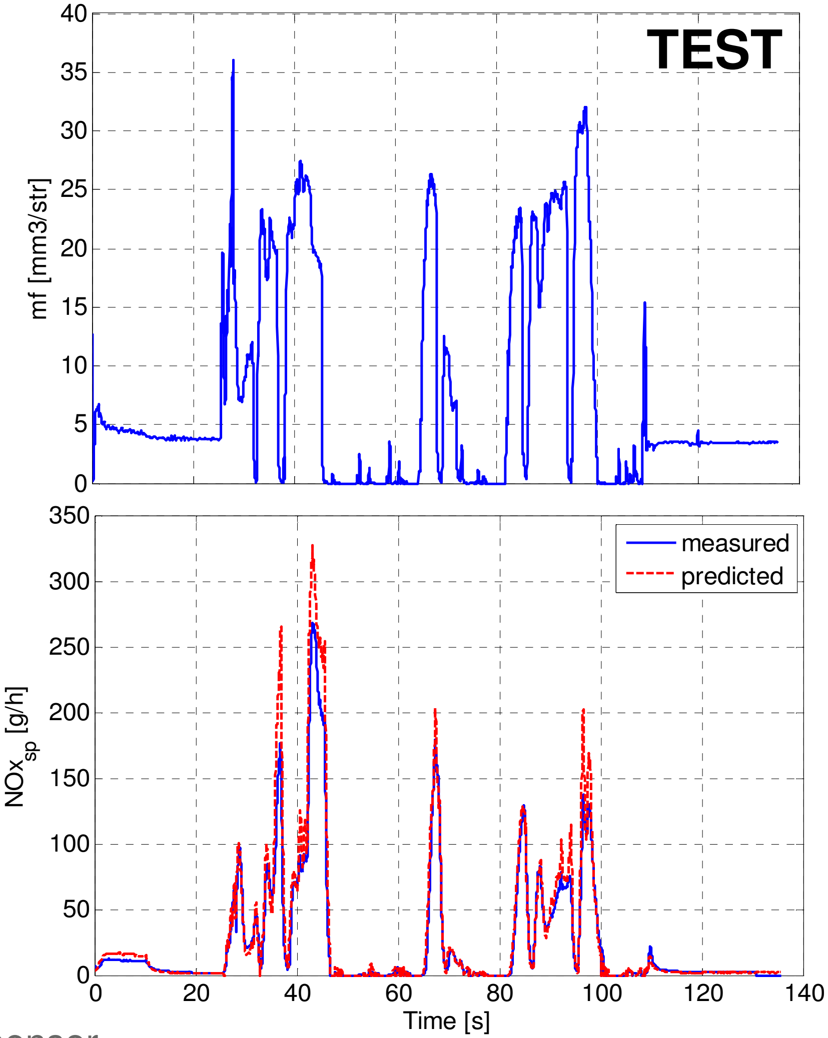

RNN main parameters:

- N. of Layers: 3
- N. of neurons in hidden layer: 18
- N. of epoch: 80
- Lag input space: 2
- Lag output space: 2

# NOx Experimental Result

## Common-Rail Diesel 1.3 – EGR/HP - VGT

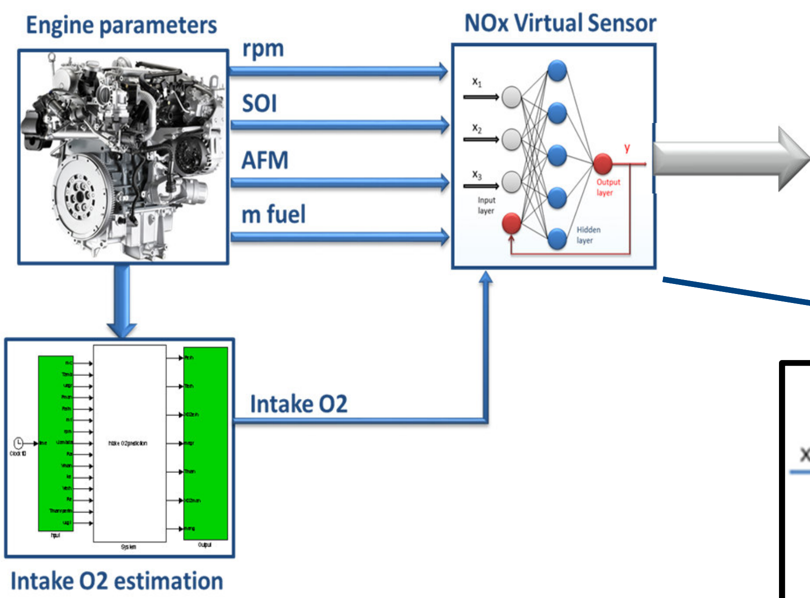



| | MSE | R2 | ERR.INT |
|---|---|---|---|
| NEDC | 16,14 | 0,9746 | 0,0909 |
| TEST | 90,21 | 0,9756 | 0,1707 |

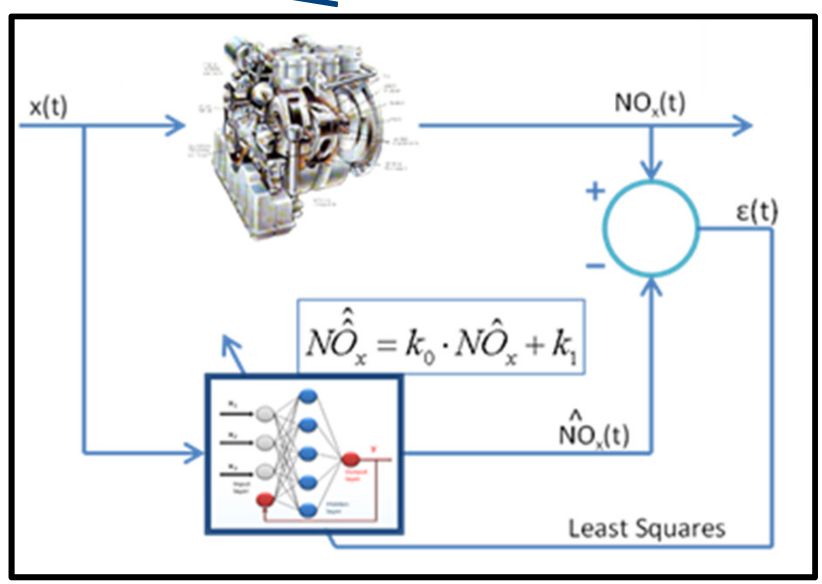
*NOx Engine Out measured with NOx production sensor

# Recursive Least Square based Adaptation




Off/On-line parameters update (adaptivity)

- Implementation of RLS methods.
- Development of methods for neural network.

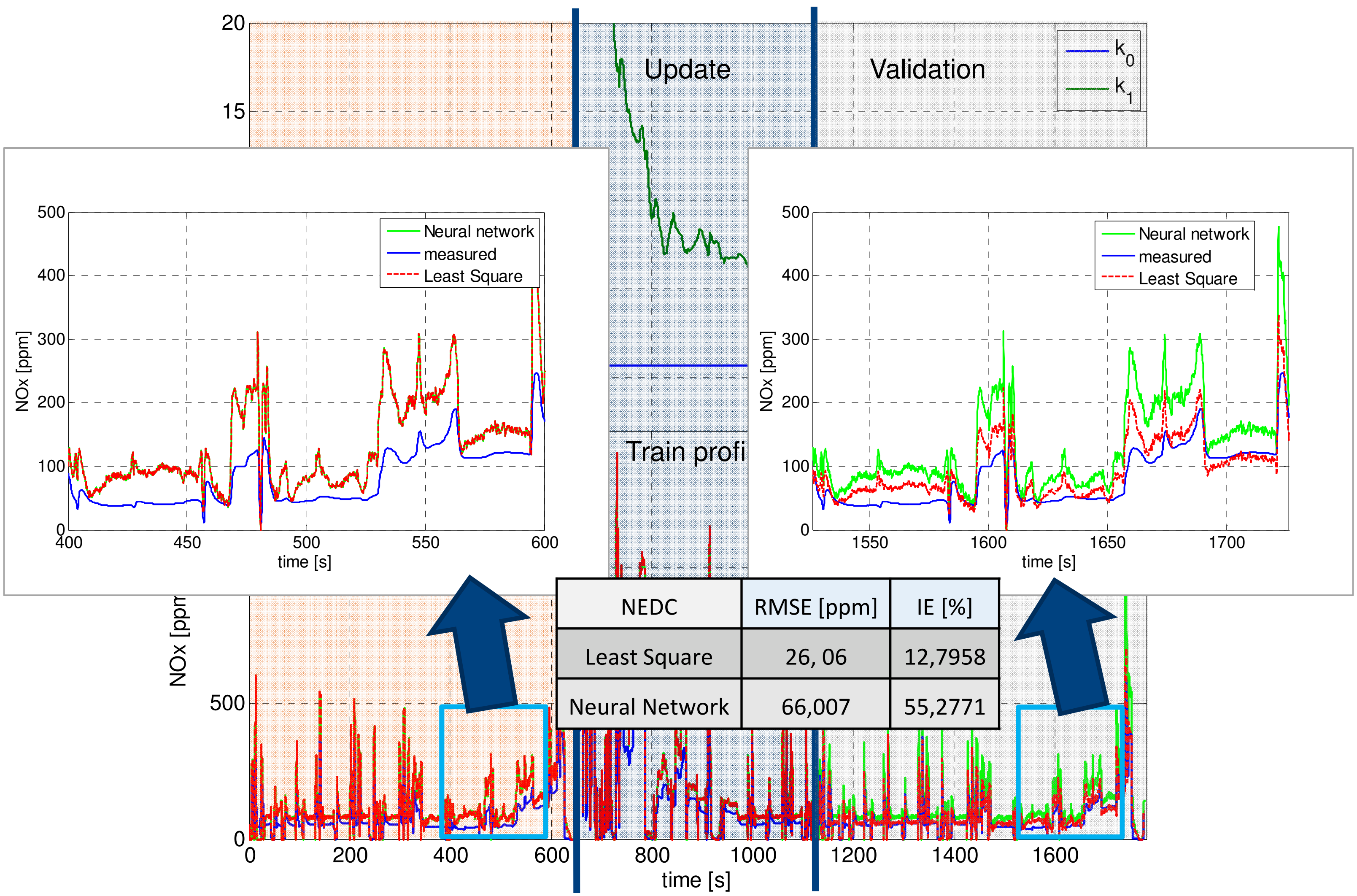



Adaptive Control

- Adaptivity based on gain/offset parameter already implemented. → Low CPU load
- RNN re-training procedure → more powerful but high CPU load

# Recursive Least Square based Adaptation

NOx measured, plus imposed drift of -30%.




| NEDC | RMSE [ppm] | IE [%] |
|---|---|---|
| Least Square | 26, 06 | 12,7958 |
| Neural Network | 66,007 | 55,2771 |

# Conclusion

- Emissions standard trend requests strict pollutant limit
- Engine Management System and after-treatment will be more complex and more expensive and Virtual Sensors represent a good opportunity
- O2 intake estimation with model based approach gives good result and could be implemented on ECU for real-time estimation
- NOx engine out estimation with Recurrent Neural Network also present good results with benefits on calibration effort
- Parameters update (adaptivity) is implemented with good result recovering the system dispersion

# Thank You

# Backup