Air Control in Turbocharged Diesel Engines: Modelling, Identification & Calibration

October 20th, 2025

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Projects & Research Topics

➢ ***Turbocharged Diesel Engine Modelling for Nonlinear Controller Design (2007-2014)***

✓ *Computerised Decision Support Systems* for Oral Anticoagulant Treatment (OAT) Dose Management (2005-2007)

✓ Development of *Fault Tolerant NGC (Navigation, Guidance & Control)* Algorithms for CUAV (Civil Unmanned Aerial Vehicle) Patrolling & Rescue Missions in Harsh Environment (2004-2025)

✓ Robotics & Medicine (2009 - 2011):

  ▪ Mobile robots & SLAM - Simultaneous Localization & Mapping

  ▪ Image-based visual servoing of robot manipulators - application to robotic surgery
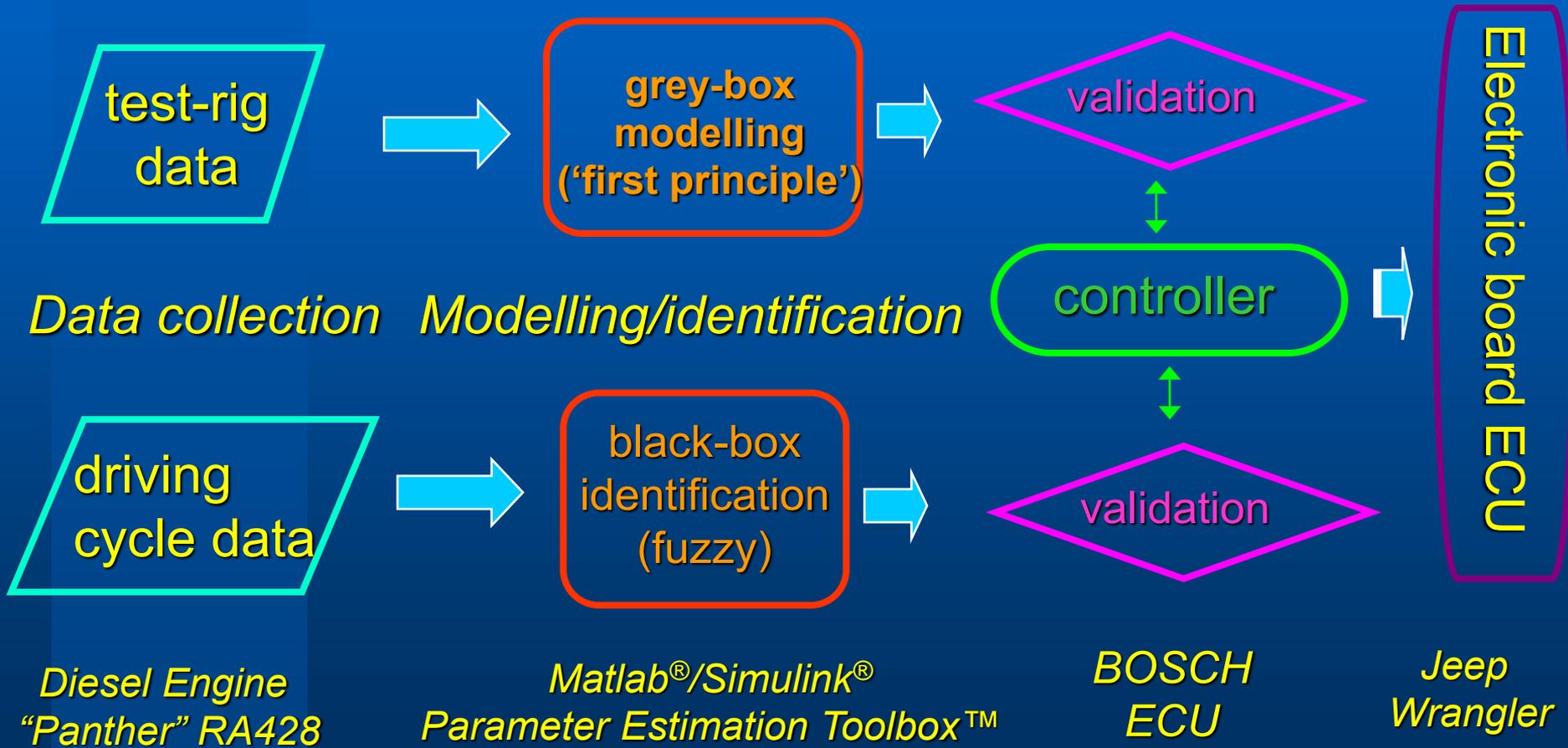
Main Points

- ➤ **Air-path control**

- ➤ **Turbocharged diesel engine**

- ➤ **Data-driven modelling**

- ➤ **Fuzzy modelling & system identification**

- ➤ **Controller calibration**

- ➤ **Simulation-based optimisation**

- ➤ **Emission reduction**

Introduction

✓ **Control scheme calibration & tuning for commercial diesel engines (boats, ships, farm tractors, ...)**

➢ **Diesel engine modelling & identification**

  ▪ **grey-box**: analytical approach & identification

  ▪ **black-box**: fuzzy modelling & identification

➢ *BOSCH* **Electronic Control Unit (ECU)**

  ▪ Controller parameter calibration & tuning

  ▪ Automated software tool for 'diesel calibration engineers'

Project Logic Scheme

test-rig data

→

grey-box modelling ('first principle')

→

validation

driving cycle data

→

black-box identification (fuzzy)

→

validation

controller

Electronic board ECU

Data collection   Modelling/identification

Diesel Engine "Panther" RA428

Matlab®/Simulink® Parameter Estimation Toolbox™

BOSCH ECU

Jeep Wrangler

Project Achievements

➢ Control-oriented simulation model

    ❑ Grey-box model from real data (test-rig engine system)

    ✓ Black-box engine model from real data (driving cycles)

➢ BOSCH controller implementation in Matlab/Simulink environments

➢ Automatic software (GUI) for controller calibration & parameter tuning

The Diesel Engine & Its Emissions

Diesel Usage

- ✓ Nearly all trucks, buses, trains, small ships
    - ▪ Good fuel efficiency
    - ▪ Lower greenhouse gas emissions
    - ▪ Reliability
    - ▪ Diesel price cheaper than gas (in Italy)
- ✓ Enormous size range:
    - ▪ 30 to 30,000 kW (40 to 40,000 hp)
- ✓ Usage has increased significantly in last 40 years

Diesel Combustion

✓ Combustion: only two exhaust by-products?

  ▪ CO_2 & H_2O

✓ Unfortunately...

  ▪ Diesel is not pure carbon & hydrogen:

    • Sulphur, nitrogen

  ▪ Air is not pure oxygen

    • Nitrogen

✓ Engine combustion at high temperature & high pressure: environment to form **many chemical compounds**

# Diesel Emissions

Health Impact High to Low

- ✓ Particulate Matter (PM)
  - ▪ A product of incomplete combustion
- ✓ Oxides of Nitrogen (NO + NO_2 = NO_x)
  - ▪ NO_x is a product of high temperature combustion
- ✓ & other minor compounds…
  - ▪ Carbon monoxide, sulphur dioxide (SO_2)

Emission Reduction Strategies

✓ Reducing PM

- Improve combustion efficiency
- Increase peak combustion temperature

✓ Reducing NO_x

- Reduce peak combustion temperature

➢ **Air-to-Fuel (Mass) Ratio (AFR) Control**

- **Computer-controlled fuel & air injection rates**

➢ **Exhaust Gas Recirculation (EGR)**

- **Combustion temperature reduction**

Adjust AFR or *AMF*

- ➢ AFR adjustment
  - ▪ Depends on torque
  - ▪ Engine speed

- ➢ **AMF control**
  - ▪ exploited in this project!

Trade-off (qualitative picture)
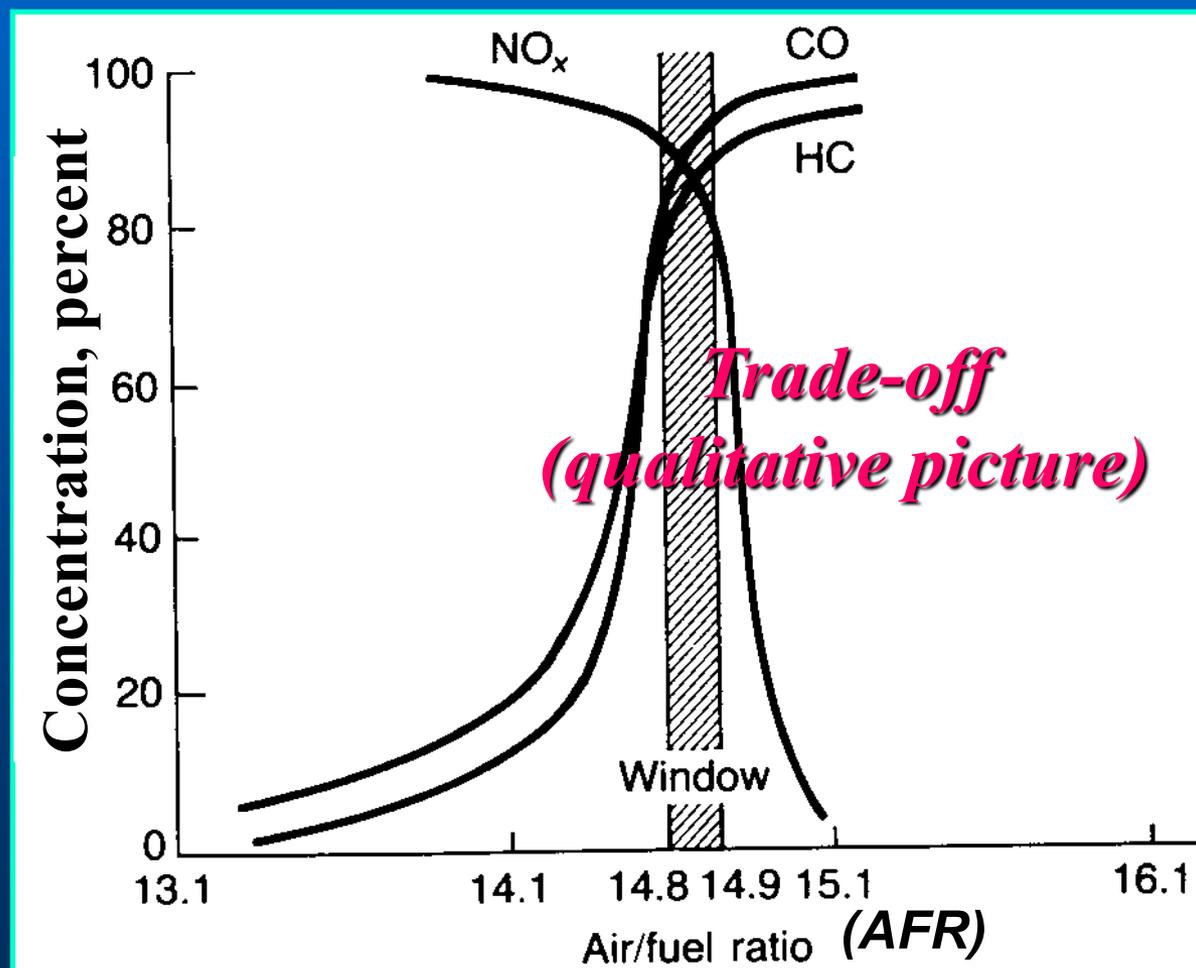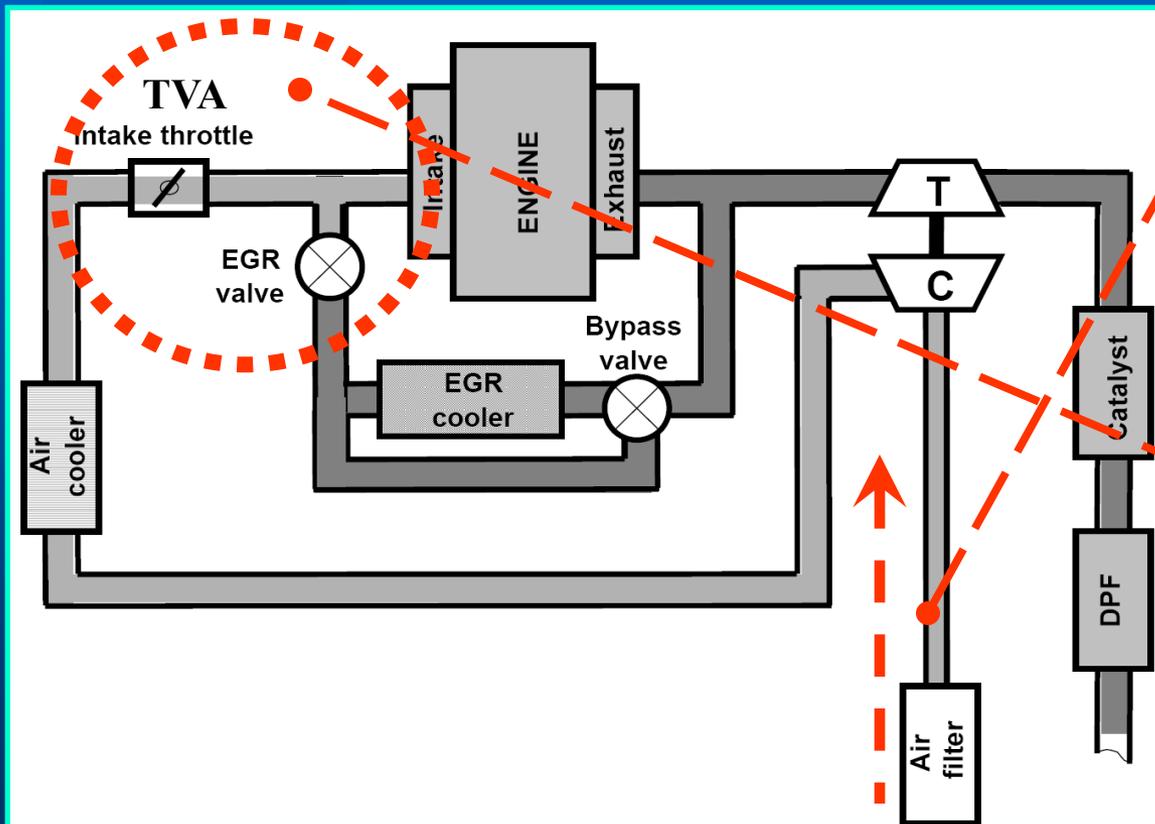
NO$_x$ & PM Control

1) **AMF** (Air Mass Flow) control
   - ➤ *Reference, set point*

2) Reduce Flame Temperature
   - ➤ **EGR**
   - ➤ **TVA**

Control Objectives

- ➢ **The control objective is to operate the TVA & EGR valves in a way such that:**
    - ▪ The engine meets the driver's *torque* demand
    - ▪ NO_x & PM emissions are optimised (minimised)
    - ▪ Visible smoke generation is avoided

- ➢ **This can be achieved by regulating the Air Mass Flow (AMF) & the fraction of exhaust gases (EGR) in the intake manifold to the corresponding set-points**

Set Point Generation

W_f

$F(W_f, N)$

N

Set-point Generation

$$[W_c \ , \ P_{man} \ ]$$

$$\bar{y} = [F_1 \ , \ AMF \ ]$$
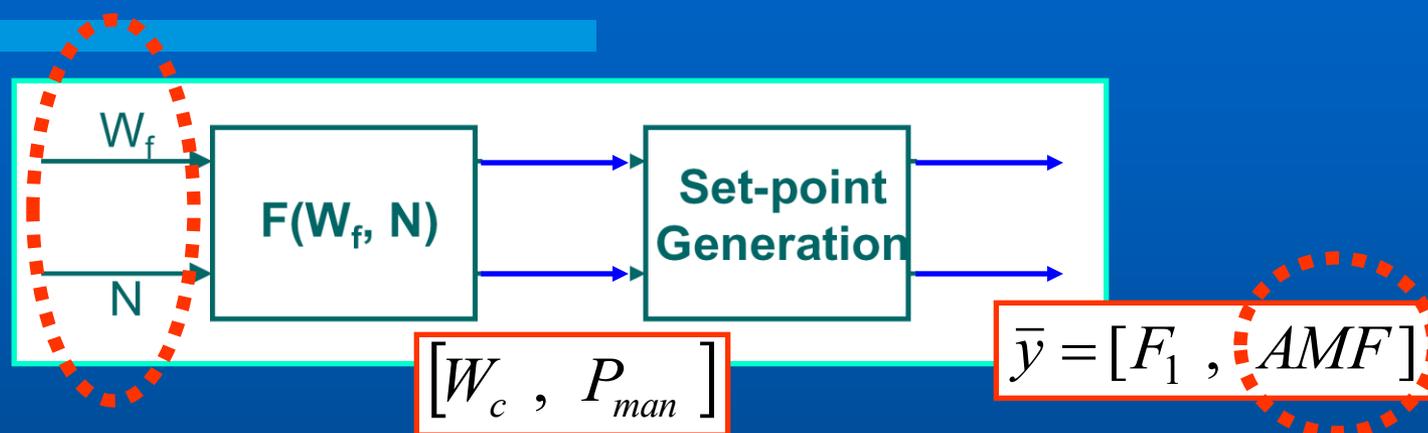
➢ Air Mass Flow (AMF) set-point is given as a function of engine fuelling (W_f) & speed (N)

➢ It is computed to give minimum NO_x & PM emissions without any visible smoke

➢ In steady-state, AMF (& exhaust gas fraction) can be correlated to the engine outputs *(e.g.* compressor mass flow W_c & exhaust manifold pressure P_{man}) through thermodynamic relationships (maps)
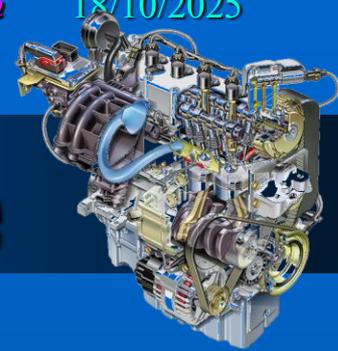
Control-Oriented Diesel Engine Modelling

Diesel Engine Modelling

➢ Process description & modelling

1. **Grey-box approach**

- Engine maps & look-up tables
- Engine subsystems & components

2. ***Black-box approach***

- Fuzzy modelling & identification

➢ Model Validation
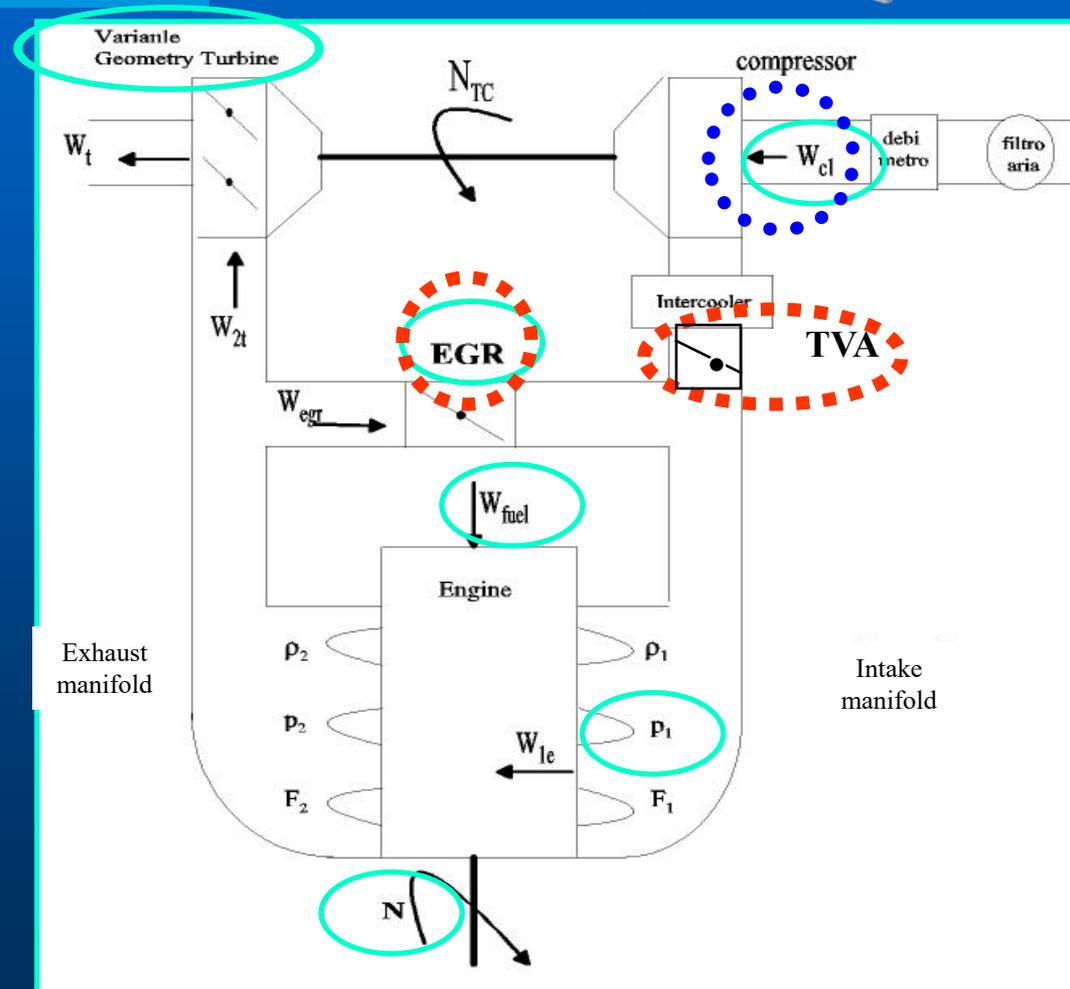
Diesel Engine Scheme

Inputs

- Engine speed (N)
- Fuel flow rate (W_{fuel})
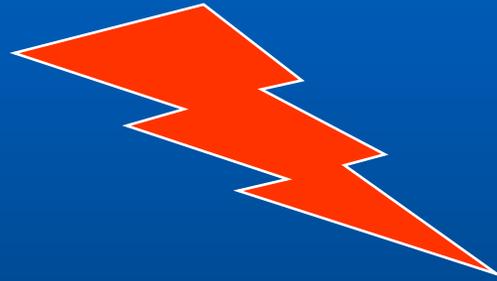- Intake Temperature
- Engine Temperature (oil)

Input Control Variables

- EGR command
- TVA command

Main Output

- Air Mass Flow AMF (w_{c1})

Diesel Engine
Grey-Box Modelling

MATLAB ® /SIMULINK® Library

- Control-oriented engine simulation model
- MATLAB ® / SIMULINK® environments
- Easy to use
- Reduced simulation time
- Control design, test, performance assessment
- Controller calibration & final tuning
- Real-time applications

System Modelling

✓ **State parameters**

- P, T, ρ, c, W, ...

- N (speed)

- X (chemical composition)
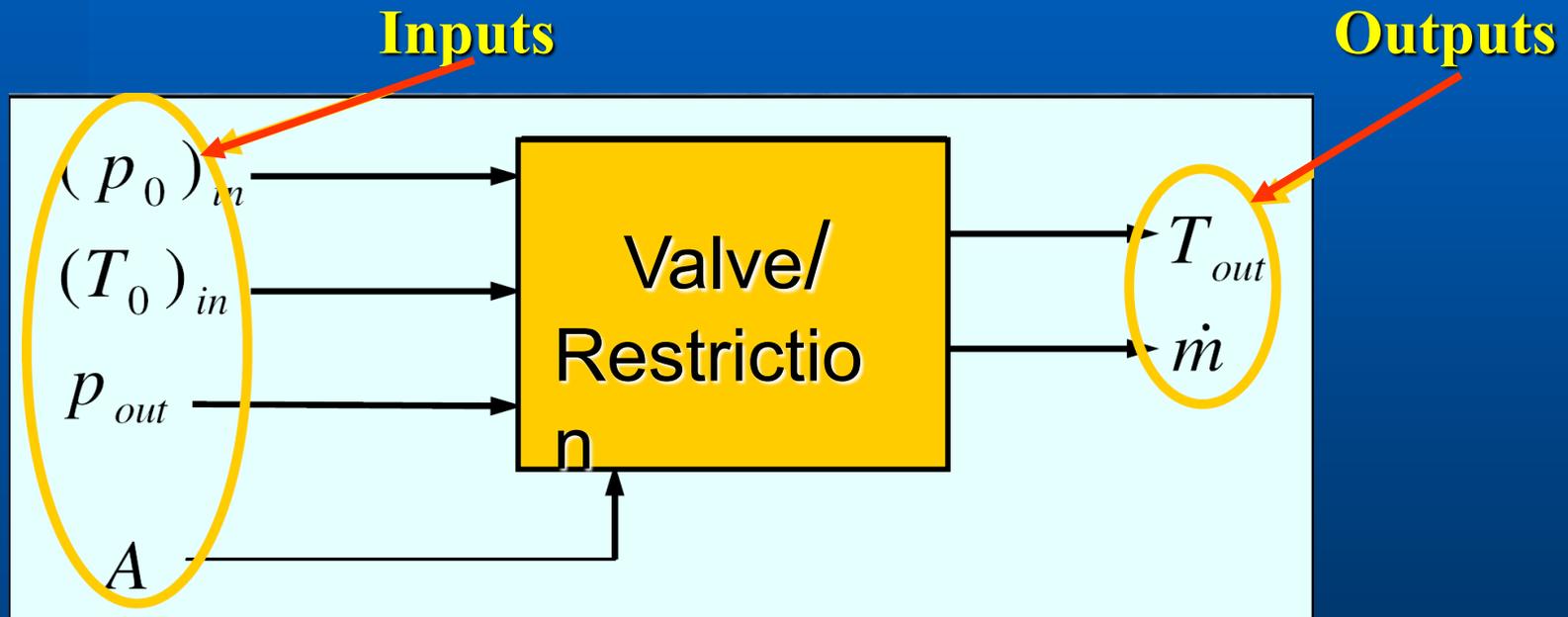
- ...

✓ **Variables**

- ...

✓ **Equations**

- Mass conservation

- Energy conservation

- Momentum conservation

- Motion quantity conservation

- State equations

- Transformation equations

Components & Fluid-Dynamics

✓ Fluid machines (work exchange, $\Pi \neq 0$ & $\Phi = 0$)

✓ Restrictions (no energy exchange, $\Pi = 0$ & $\Phi = 0$)

✓ Heat exchangers & combustion chambers (thermal exchange, $\Pi = 0$ & $\Phi \neq 0$)

✓ In-Cylinder Processes (thermal & work exchange, $\Pi \neq 0$ & $\Phi \neq 0$)

Exhaust Gas Recirculation (EGR)

➤ **Valves & Restrictions**

Inputs

Outputs

$(p_0)_{in}$

$(T_0)_{in}$

p_{out}

A

Valve/
Restrictio
n

T_{out}

$\dot{m}$

✓ Compressible Isentropic flow + flow coefficient C_d

EGR – Algebraic Equations

Output   **Input**

$$\dot{m} = \frac{C_d A(p_0)_{in}}{\sqrt{R(T_0)_{in}}} \cdot \left(\frac{p_{out}}{(p_0)_{in}} \right)^{\frac{1}{k}} \cdot \sqrt{\frac{2k}{k-1}\left[1 - \left(\frac{p_{out}}{(p_0)_{in}} \right)^{\frac{k-1}{k}} \right]}$$

where $\left(\frac{p_{out}}{(p_0)_{in}} \right) > \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}$

$$\dot{m} = \frac{C_d A(p_0)_{in}}{\sqrt{R(T_0)_{in}}} \cdot \sqrt{k} \cdot \sqrt{\left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}$$

where $\left(\frac{p_{out}}{(p_0)_{in}} \right) \le \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}$

Note: grey-box approach

Throttle Valve Actuator (TVA)

$$w_{th} = \begin{cases} \dfrac{kA_{th}(\alpha,N)p_{amb}}{\sqrt{RT_{up}}}\left(\dfrac{p_{th}}{p_{amb}}\right)^{1/\gamma}\sqrt{\dfrac{2\gamma}{\gamma-1}\left(1-\left(\dfrac{p_{th}}{p_{amb}}\right)^{\frac{\gamma-1}{\gamma}}\right)} & \dfrac{p_{th}}{p_{amb}} > \bar{p} \\[3ex] \dfrac{kA_{th}(\alpha,N)p_{amb}}{\sqrt{RT_{up}}}\sqrt{\gamma}\left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} & \dfrac{p_{th}}{p_{amb}} \le \bar{p} \end{cases} \quad (1)$$
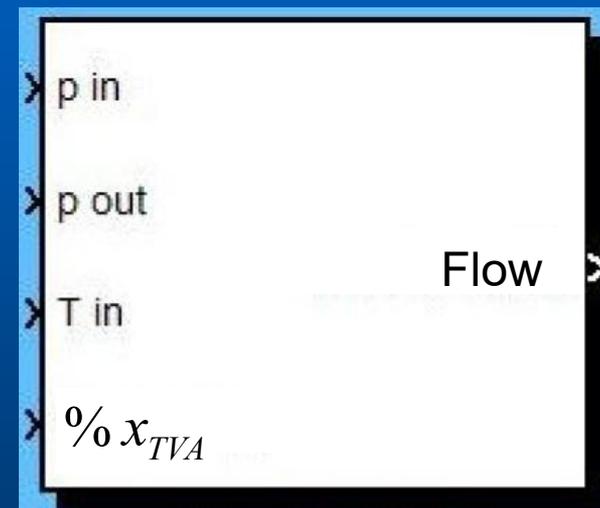
Algebric Model

- w_{th} is the flow through throttle
- From experimental data, the parameters k & A_{th} (α) have to be *identified* (also as function of *N*)
  - **Maps (look-up tables) or polynomials**
- It is assumed that the downstream pressure p_{th} (unknown) $p_{th}=p_{man}$

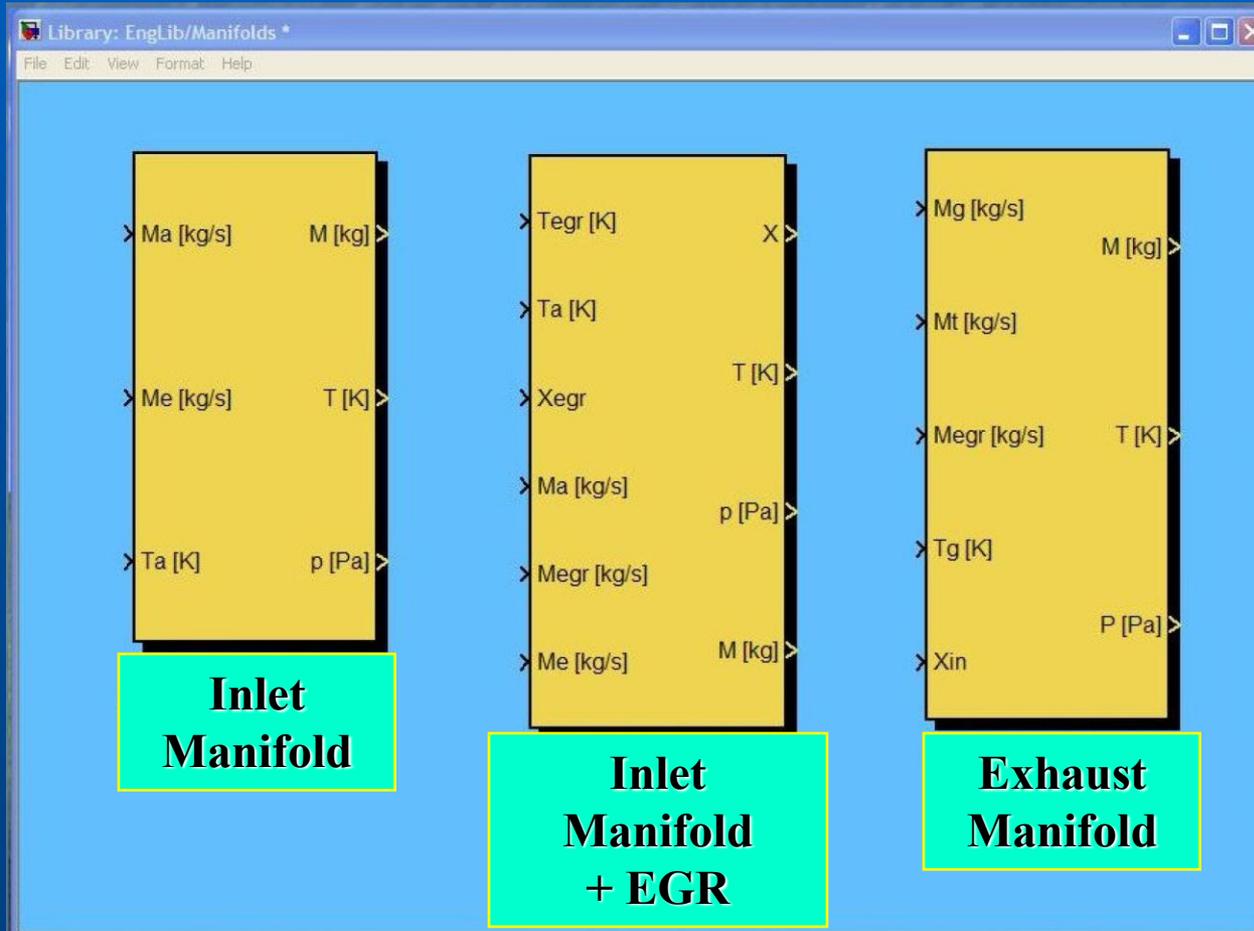# Valve SIMULINK® Blocks

▪ Valves & restrictions: examples
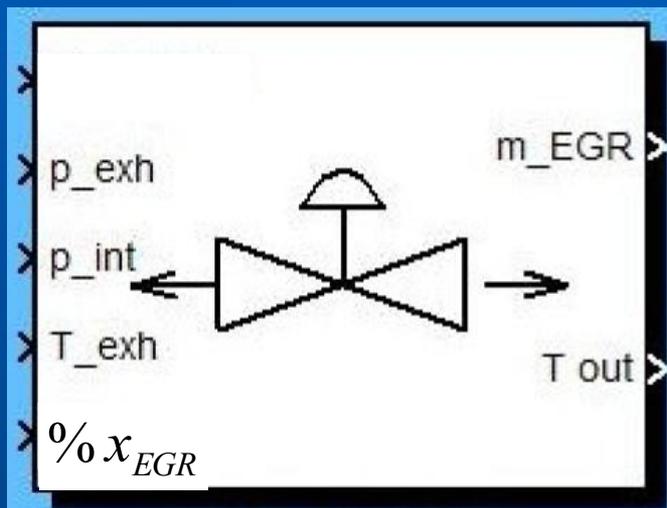
Pneumatic Valve EGR

Throttle Valve TVA

Control of the vacuum generator PWM & not the valve lift!

Manifold SIMULINK® Blocks
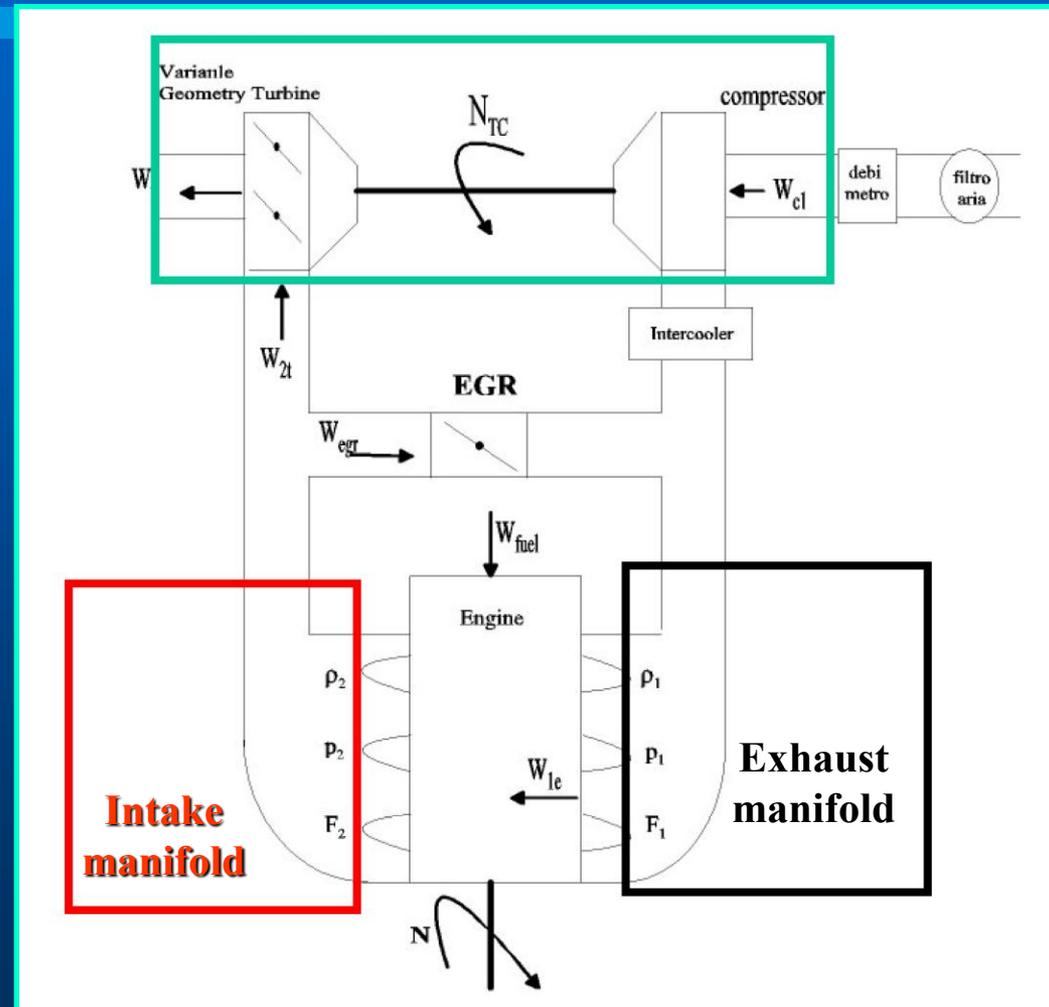
Turbocharger (Turbine - Compressor)

➢ *Intake manifold*

➢ *Exhaust manifold*

➢ *Turbocharger*

Engine Modelling Issues

- ➤ **Engine subsystems contain unknown terms:**
  - Effective area (valves & restrictions, *i.e. EGR/TVA*): $A_{EGR}(x_{EGR})$, $A_{TVA}(x_{TVA})$
  - Volumetric efficiency (cylinder): $\eta_v(N_e, P_{im})$
  - Compressor/turbine isentropic efficiencies:

    $\eta_c(N_{tc}, T_{amb}, P_{im}/P_{amb})$, $\eta_t(x_{VGT}, N_{tc}, T_{em}, P_{out}/P_{em})$
  - Engine temperature: $f(N_e, W_f)$
- ➤ **Modelled by:**
  - Maps (1-D & 2-D) or polynomials

... about 1 year
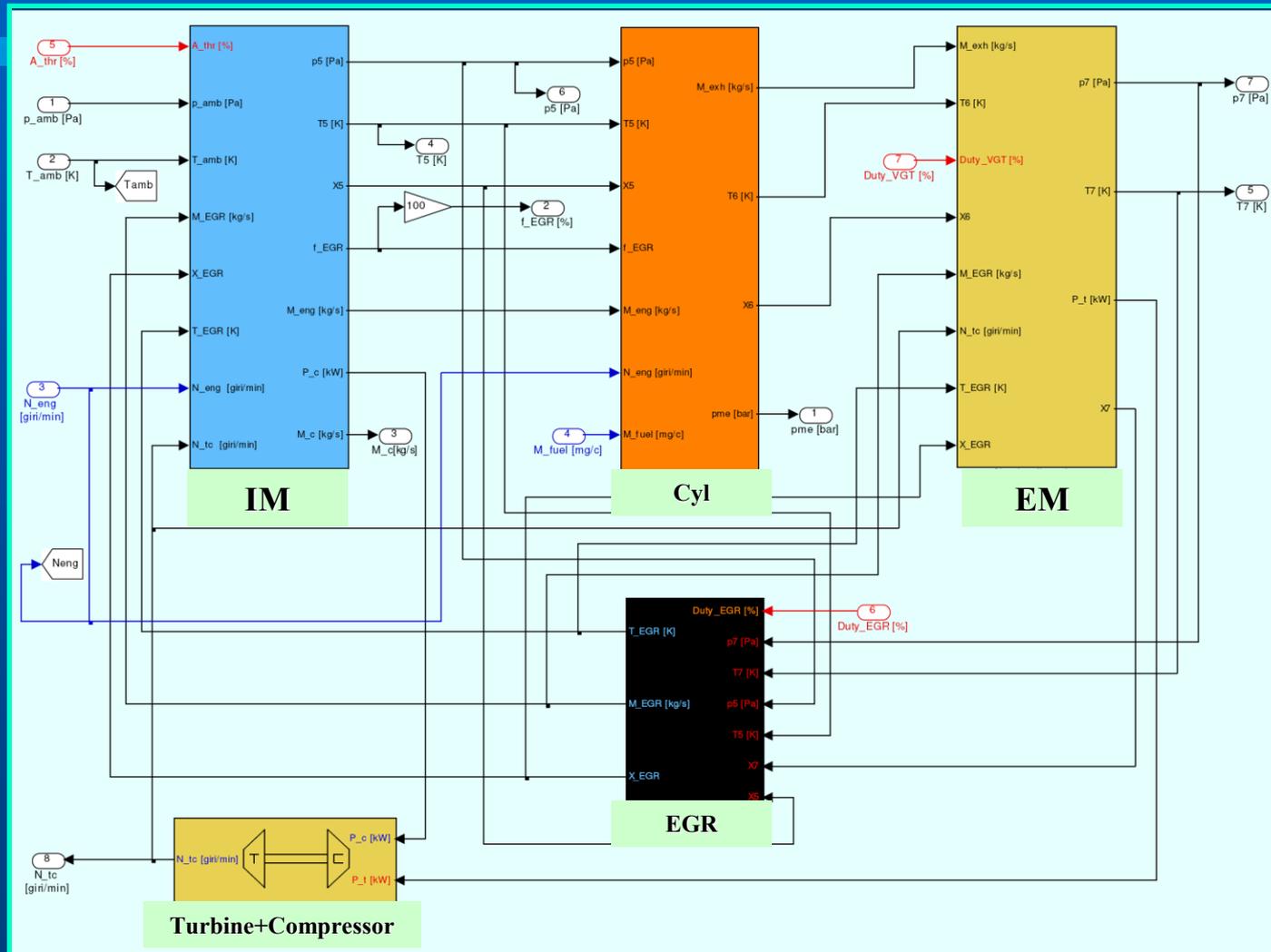
Engine Complete Description

➢ **Engine Sub-models**

- ✓ EGR
- ✓ TVA
- ✓ IM/EM
- ✓ Cylinders: Volumetric efficiency
- ❑ Turbine + Compressor: flow & efficiency maps
- ✓ Coolers: efficiency parameters

❑ **Model Validation**

- ❑ Completed but failed!

Engine Complete Description (Cont'd)

Diesel Engine *Black-Box Fuzzy Modelling*

Fuzzy Modelling – FMID™

- ➢ **Brief review**

  - ▪ Nonlinear regression & black-box modelling can be based on the partitioning data into *clusters*

  - ▪ A cluster is a set of objects that are more similar to each other than to objects from other clusters

FMID – Problem Formulation

➢ Given is a set of data

➢ Find the partitioning of the data into subsets (clusters), such that samples within a subset are more 'similar' to each other than to samples from other subsets

➢ Similarity is mathematically formulated by using a distance measure

Fuzzy Clustering & Rules

Takagi-Sugeno system (one model for each cluster *i*)
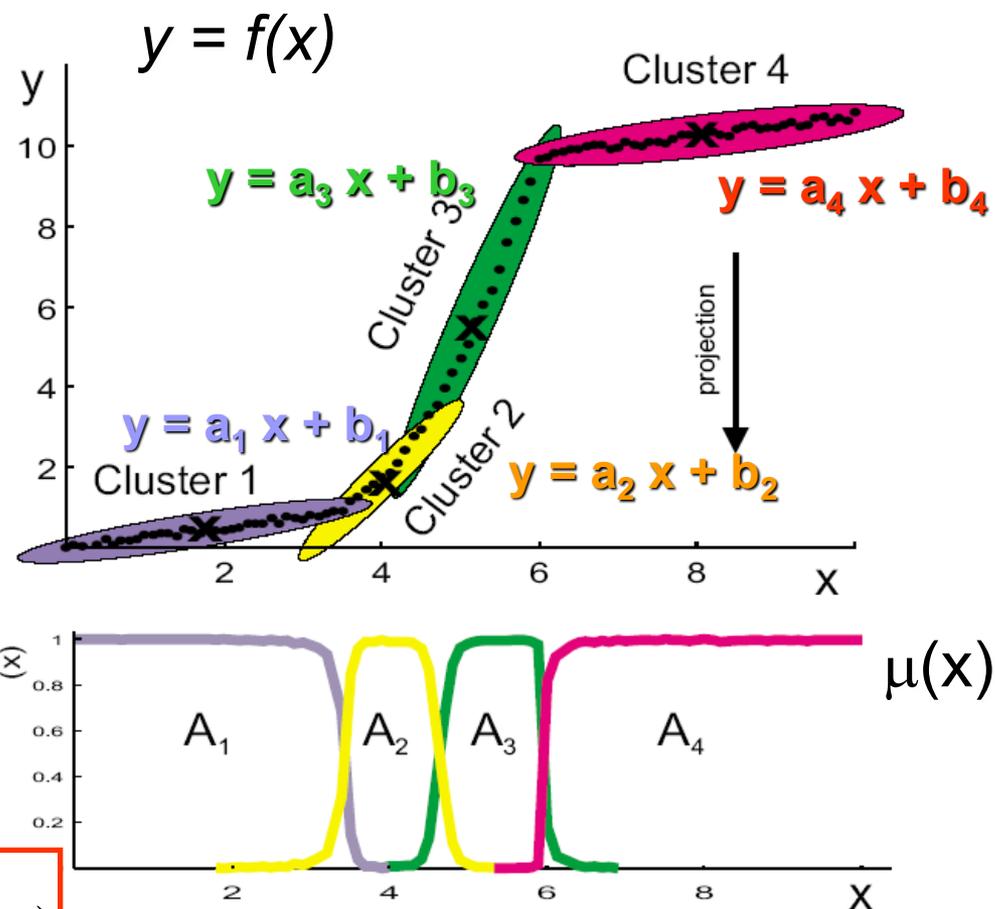
$$y = a_i \, x + b_i$$

Rule-based description

If x is A_1 then $y = a_1 \, x + b_1$
If x is A_2 then $y = a_2 \, x + b_2$
If x is A_3 then $y = a_3 \, x + b_3$
If x is A_4 then $y = a_4 \, x + b_4$

$$\text{Global } \textit{fuzzy} \text{ model} : \sum_{i=1}^{c} \mu(x)\big(a_i \, x + b_i\big)$$

$y = f(x)$

Cluster 4

$y = a_3 \, x + b_3$

$y = a_4 \, x + b_4$

Cluster 3

$y = a_1 \, x + b_1$

Cluster 1

Cluster 2

$y = a_2 \, x + b_2$

projection

$\mu(x)$

A_1 A_2 A_3 A_4

Diesel Engine Application

$$Fuzzy \; \text{model} : y(t) = \sum_{i=1}^{c} \mu\big(x(t)\big)\big(a_i\, x(t) + b_i\big)$$

➤ **Input-output data**

- Engine fuelling
- Engine temperature
- Intake temperature
- Engine speed
- EGR command
- TVA command

(4+2) Inputs – x(t)

- AMF output signal

1 Output – y(t)

... few weeks

➤ **FMID™ for MATLAB® by Prof. Robert Babuska (Delft, The Netherlands). URL: `http://www.robertbabuska.com/`**

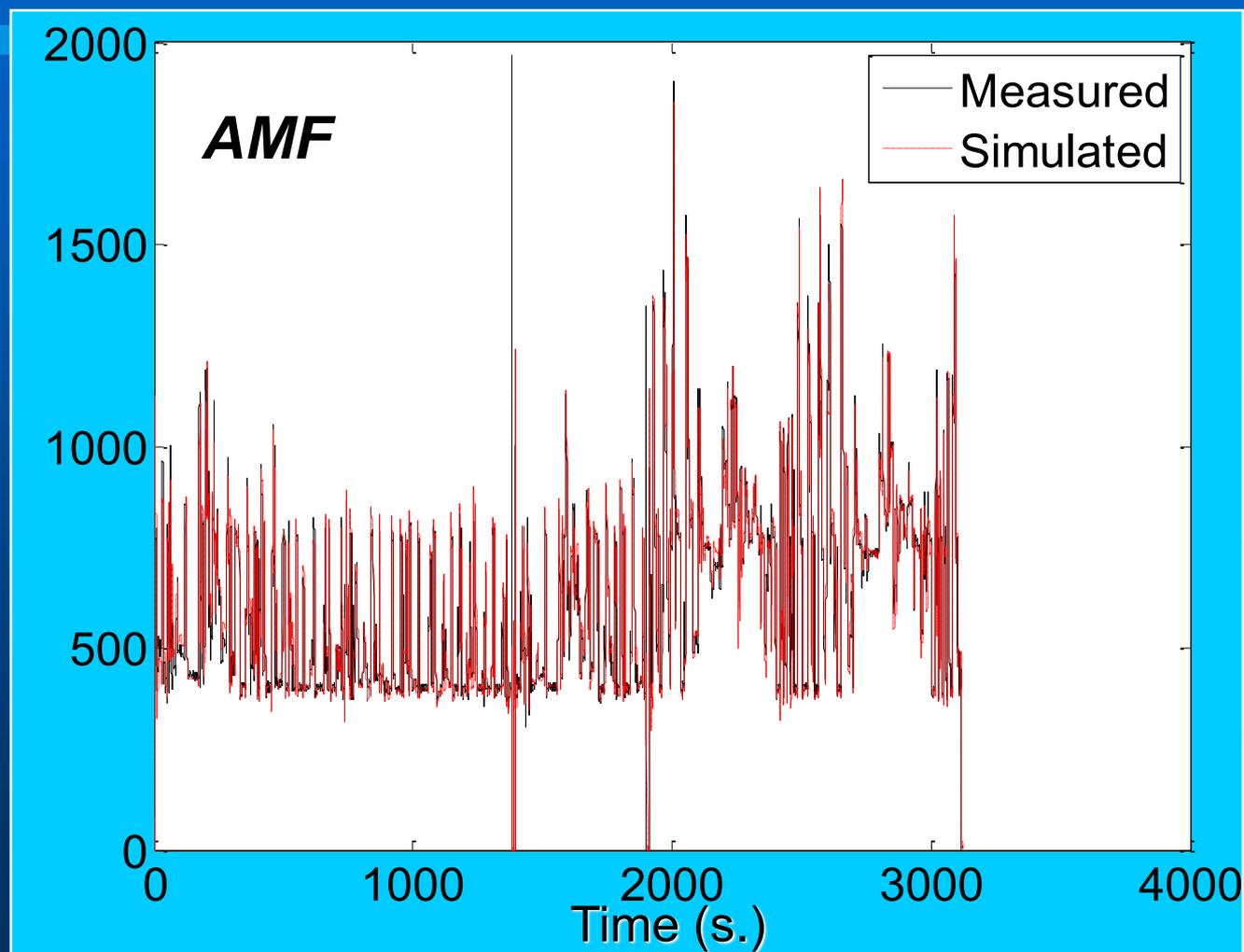# Identified Fuzzy Model FMID™

> ➢ **Local models' order: *n* = 2**
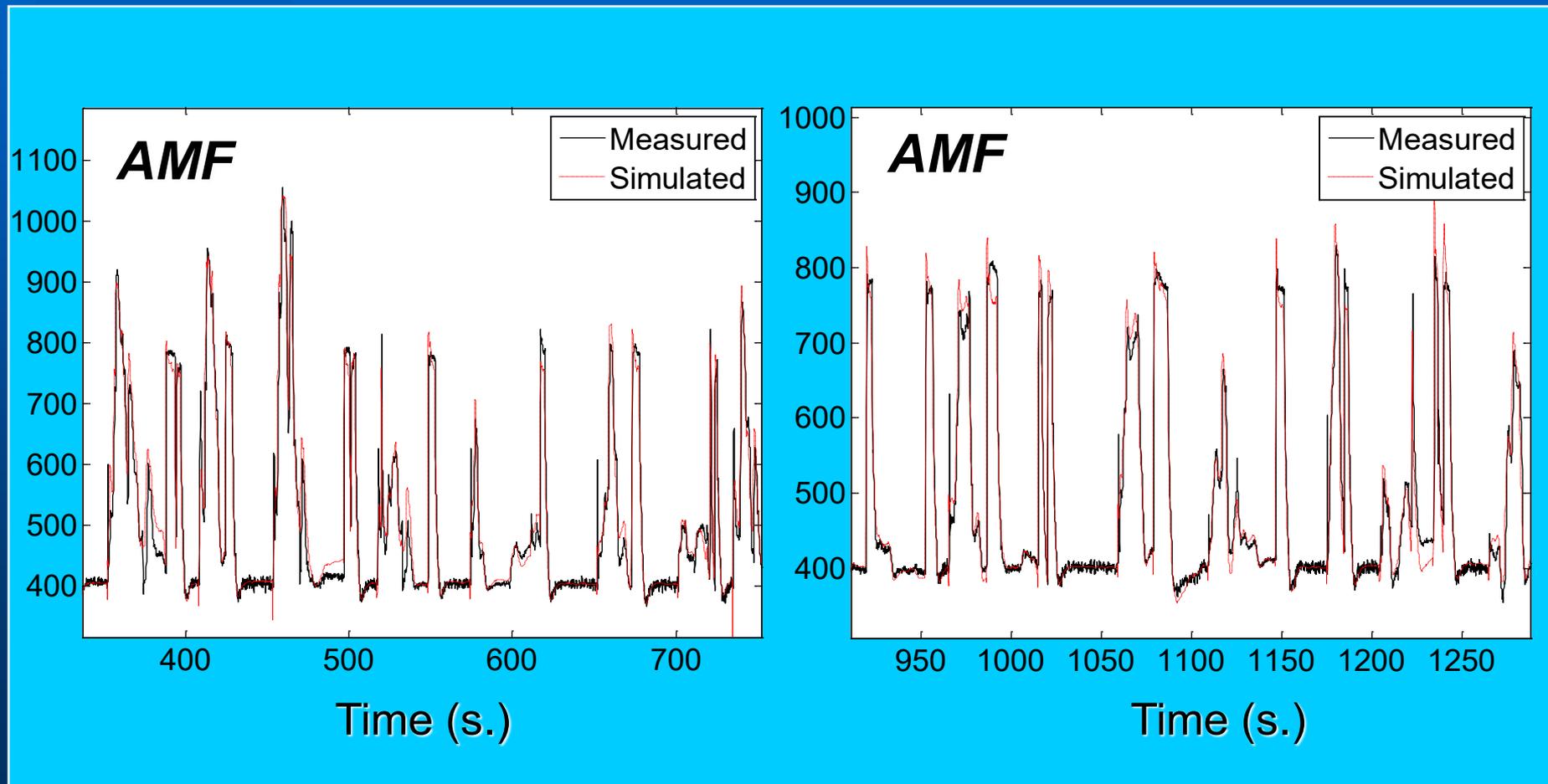> ➢ **Cluster number: *c* = 9**
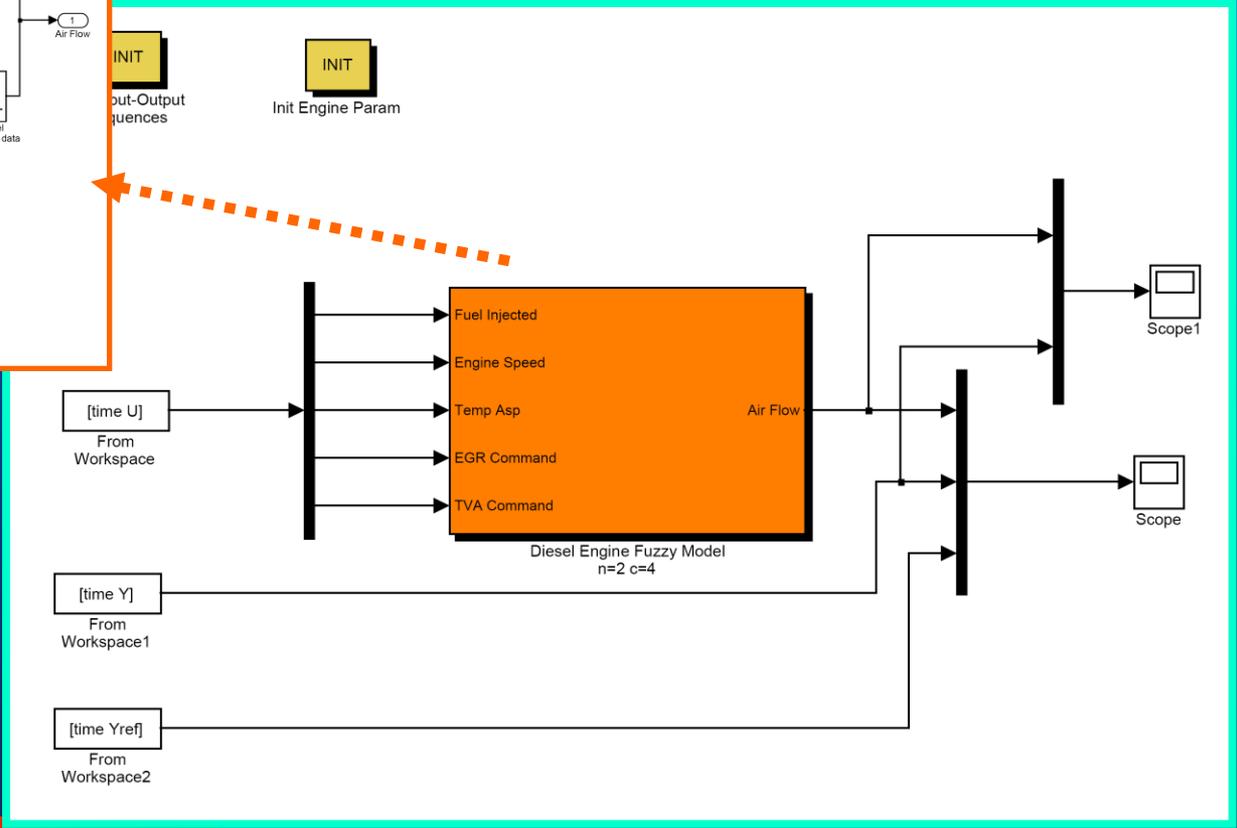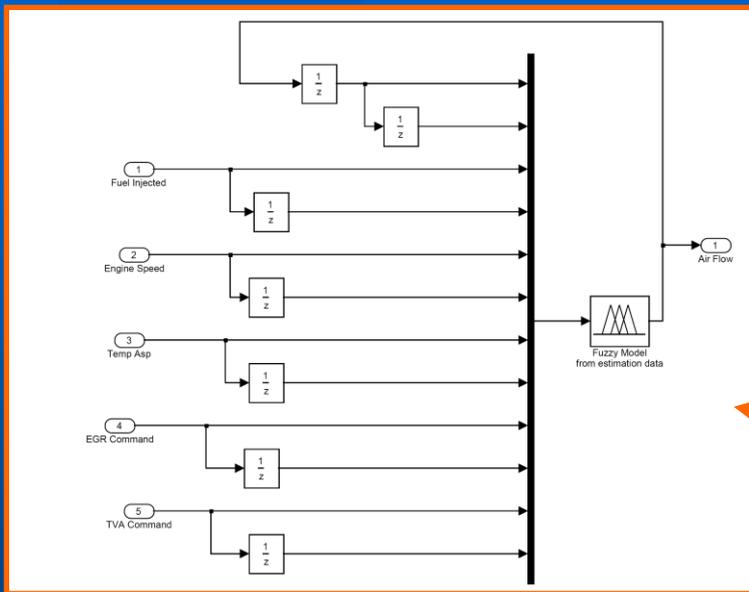
Note:
c & *n* optimised
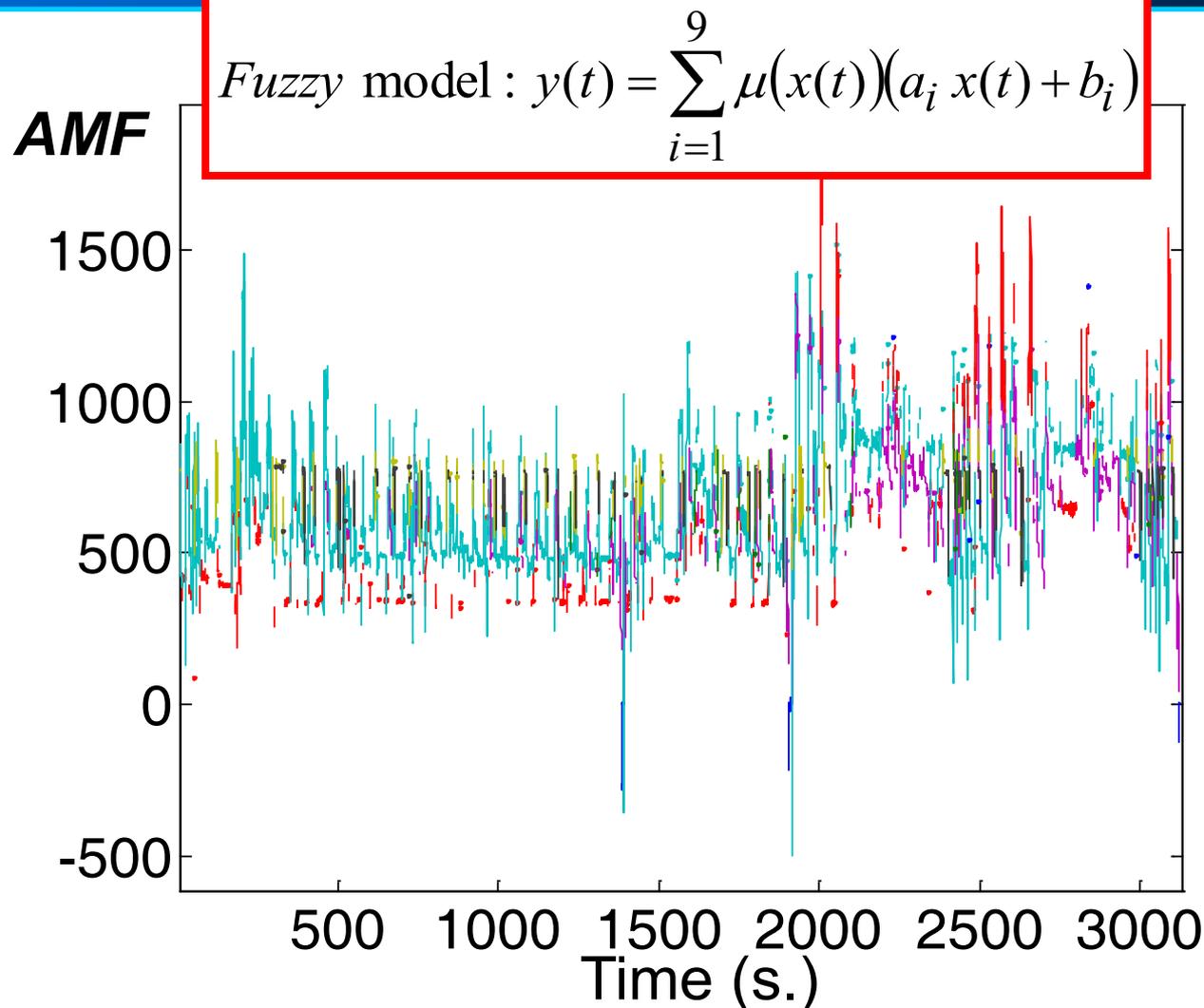via a PEM
iterative scheme

Fuzzy Model Simulation

- *Fuzzy model simulation*

- *Good performances for validation & several test data sequences*

- *Best Fit > 75% (in simulation & validation)*

Fuzzy Model Simulation (zoom)

Local Submodels *(9 ARX models)*

$$Fuzzy \text{ model}: y(t) = \sum_{i=1}^{9} \mu(x(t))(a_i\, x(t) + b_i)$$

BOSCH Controller 'Strategy' & Parameter Tuning
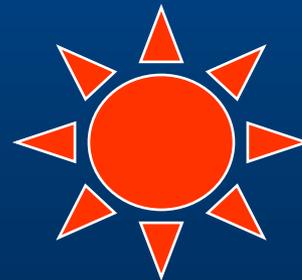
Control Model Simulation
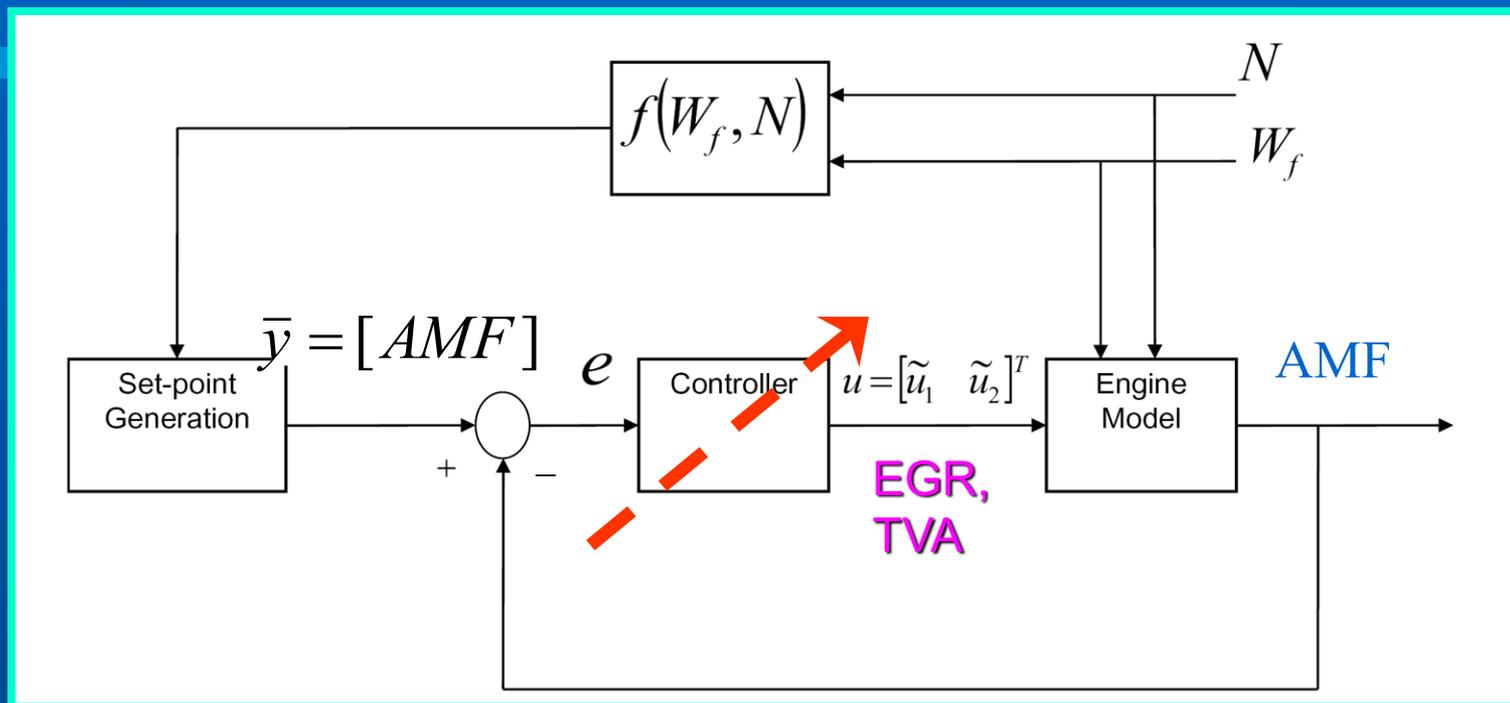
- ✓ Specific set-point assigned depending on fuel demand (W_f) & speed (N)
- ✓ The controller actuates the EGR & TVA valves to correct the deviation between the actual (*AMF)* & demanded variable

Calibration in SIMULINK®

Fuzzy Model

Instead of the real process!

BOSCH Controller

Designed for the real engine
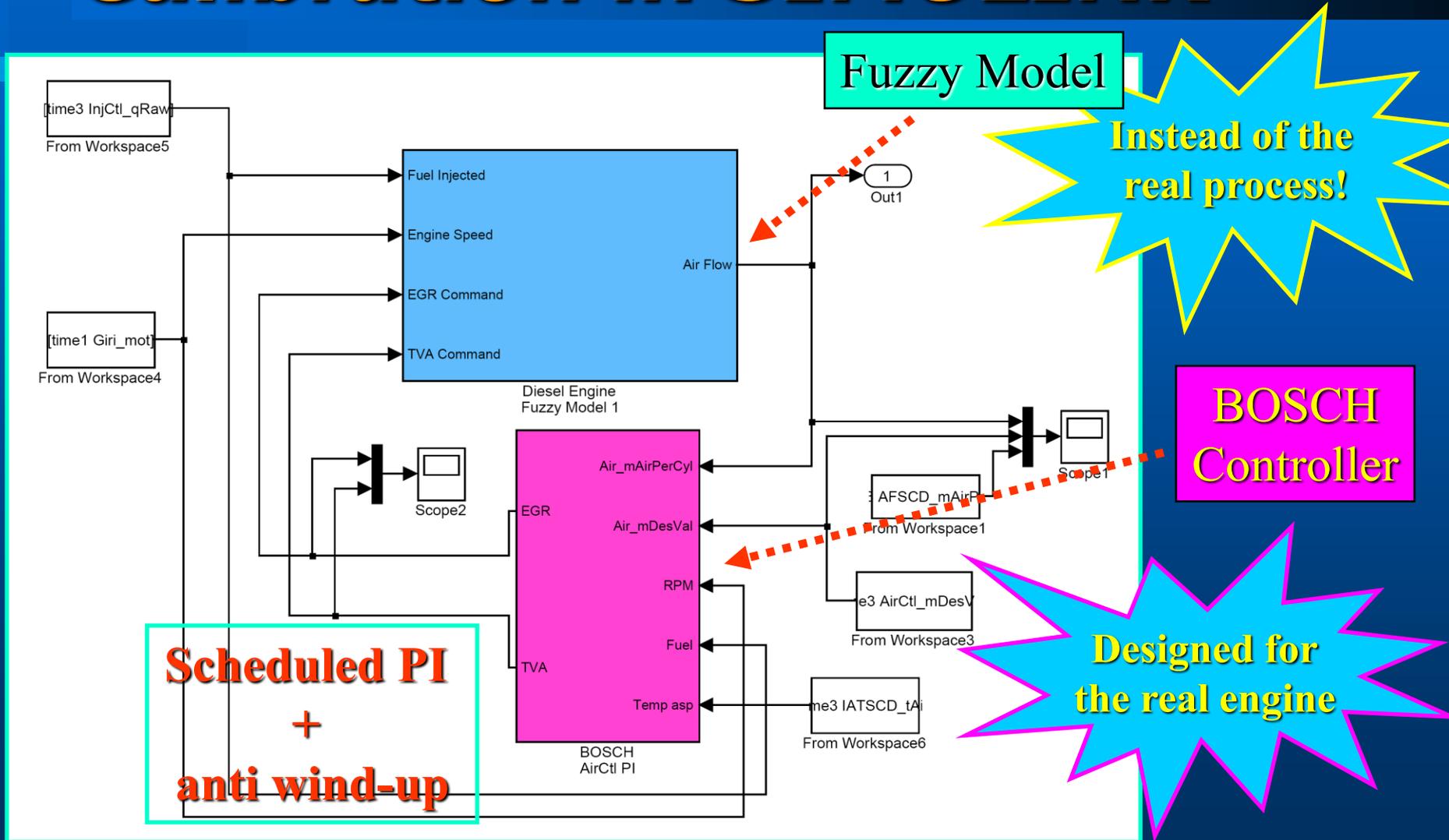
Scheduled PI
+
anti wind-up

BOSCH Controller *Strategy*

FF: depends of fuel & RPM. Based on AMF static map inversion

Adaptive gains

Gain scheduler

PI

Integrator reset logic

EGR/TVA split
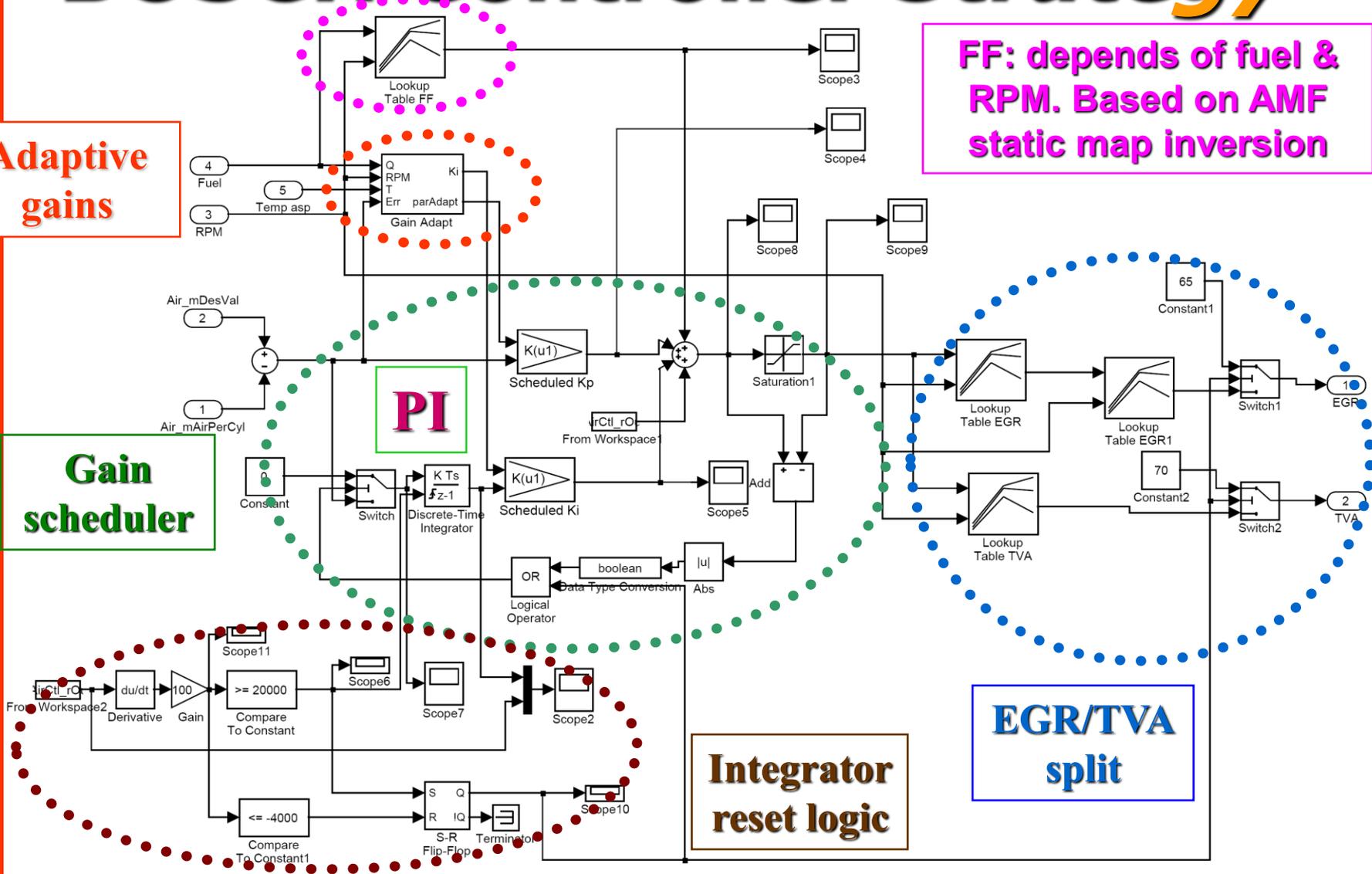
Parameter Adaptation *(Gain Adapt)*
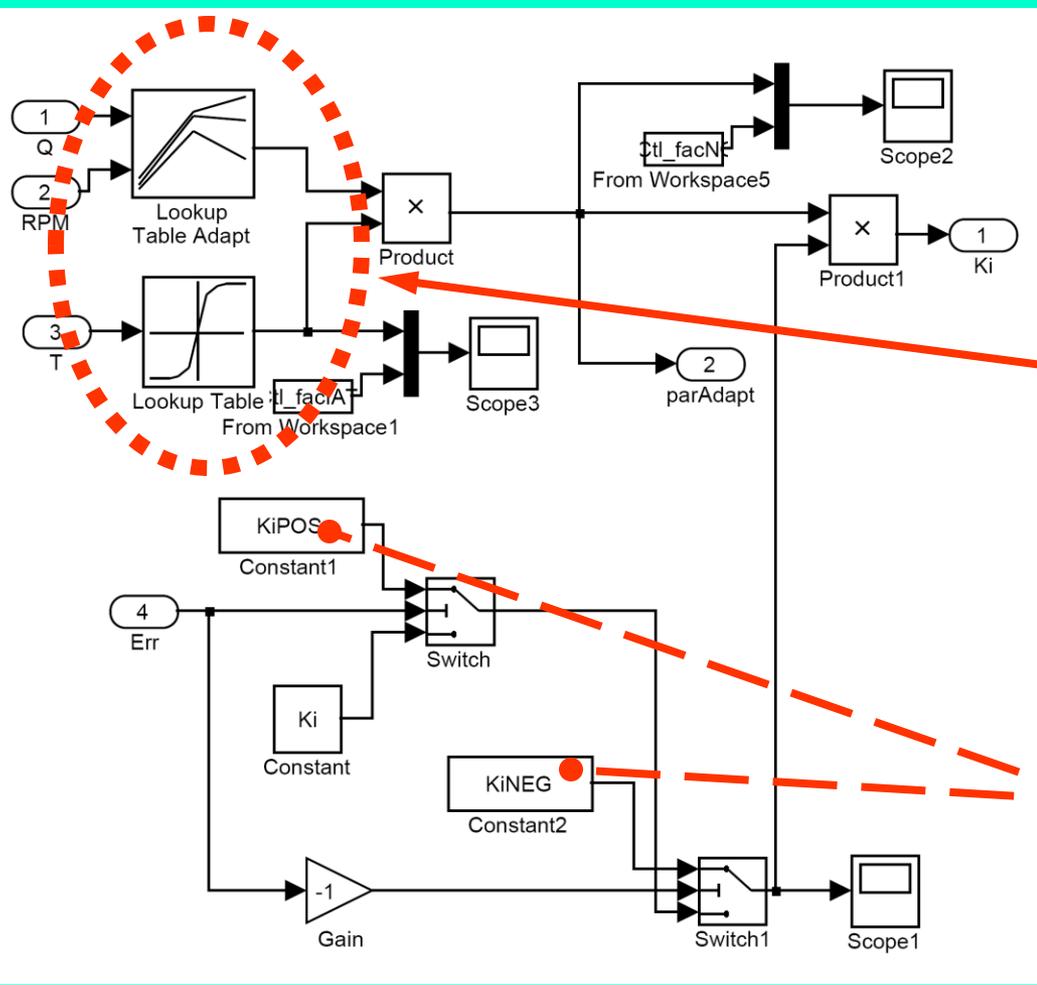
- ➢ **BOSCH controller's main main idea is to correct the PI gains (Ki & Kp) based on the error value & precompiled static maps**

- ➢ **Depends on engine fuelling, RPM, asp. temp & tracking error (actual & desired MAF)**

- ➢ **Fixed thresholds (KiPOS & KiNEG)**

Gain Scheduler: '*PI*' Params
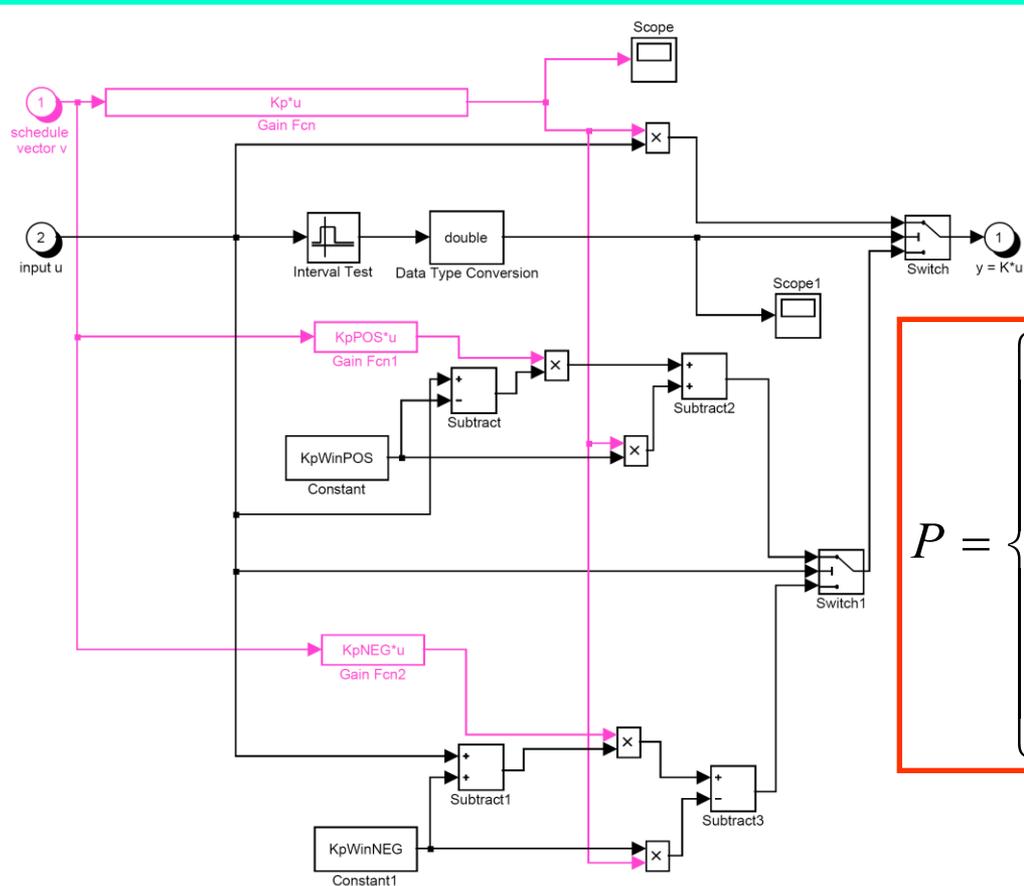
➢ It multiplies P & I gains & parameters

➢ Example:

$$
P = \begin{cases}
K_p^{(\text{scheduled})} \times e \\
\quad \text{if} \quad |e| < e_{\max} \\
\\
K_p^{(\text{scheduled})} \times e_{\max} + K_{p,\max} \times (e - e_{\max}) \\
\quad \text{otherwise}
\end{cases}
$$

➢ 'Bumpless' strategy

BOSCH Controller *Calibration Strategy*

Complete System *(EU Driving Cycle)*
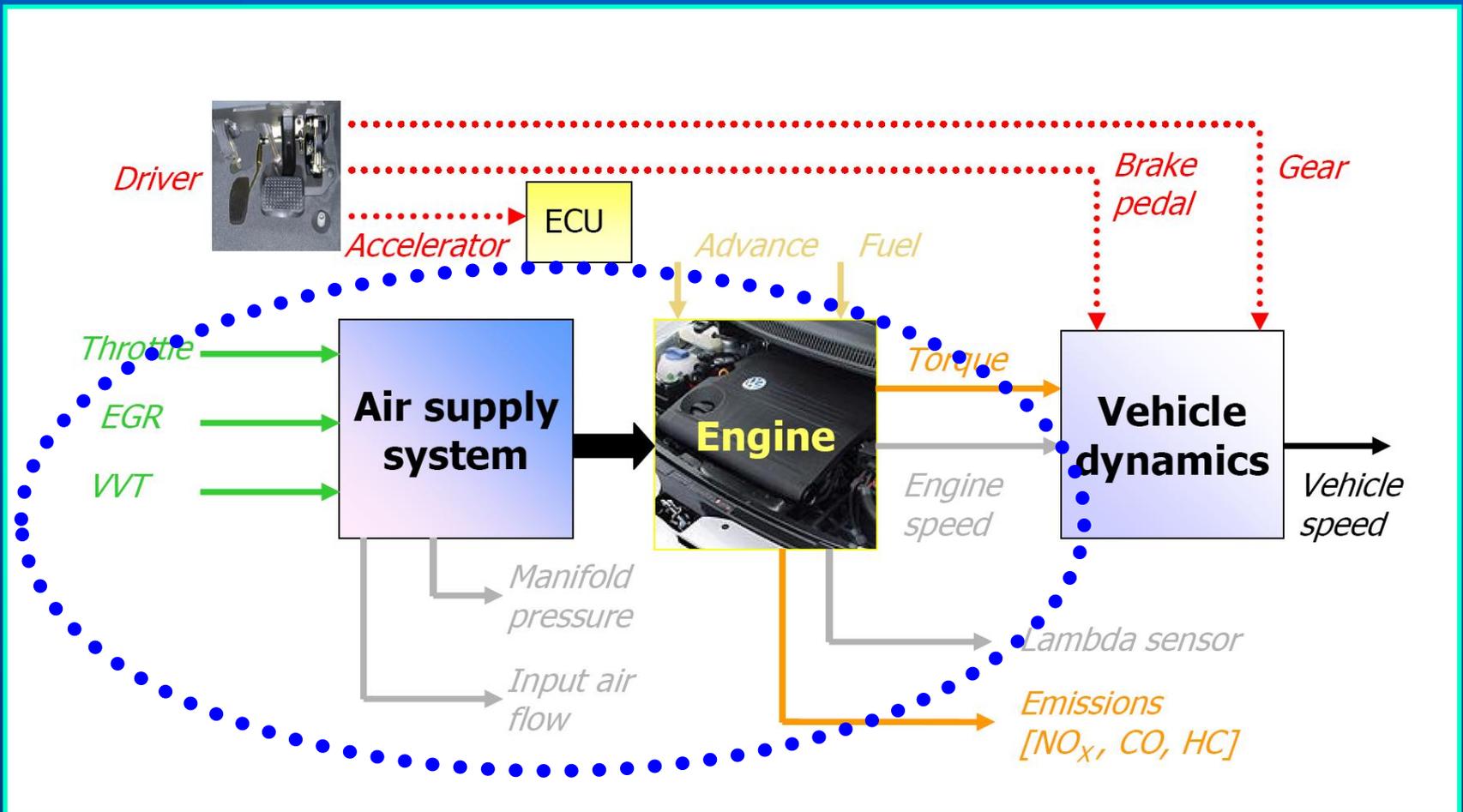
Technology

- ➢ Diesel engine driving cycle data
- ➢ MATLAB®/SIMULINK® interface
  - ▪ Calibration, optimisation; model, controller analysis, simulation & design
- ➢ ATI VISION™
  - ▪ Integrated calibration measurement solution for accessing ECUs
  - ▪ Table calibration
  - ▪ Memory emulation (μ–controller)
  - ▪ On target rapid prototyping

Parameter Correction

Monitored Output (MAF)

Fuzzy Model (Diesel Engine)

EGR TVA Inputs

Parameter Tuning

−

+

Tracking Error

Controller Model (BOSCH Regulator)

Reference MAF

$$X_{corr} = X_{nom} + \Delta X_{optim}$$
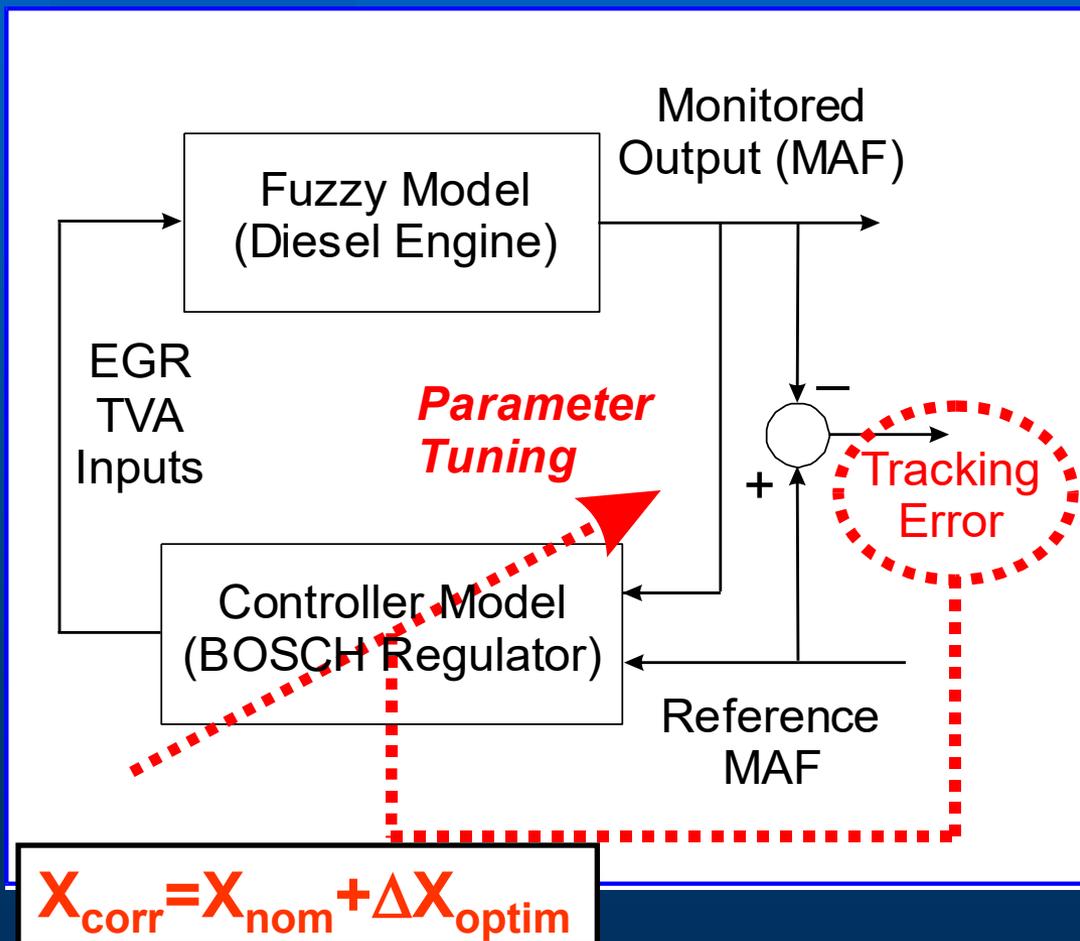
- ➤ **Matlab/Simulink**
  - ❖ Parameter Estimation Toolbox
  - ▪ Optimisation Toolbox
- ➤ **PEM algorithm**
- ➤ **MAF tracking optimisation**
- ➤ Final validation

GUI: The Final Interface
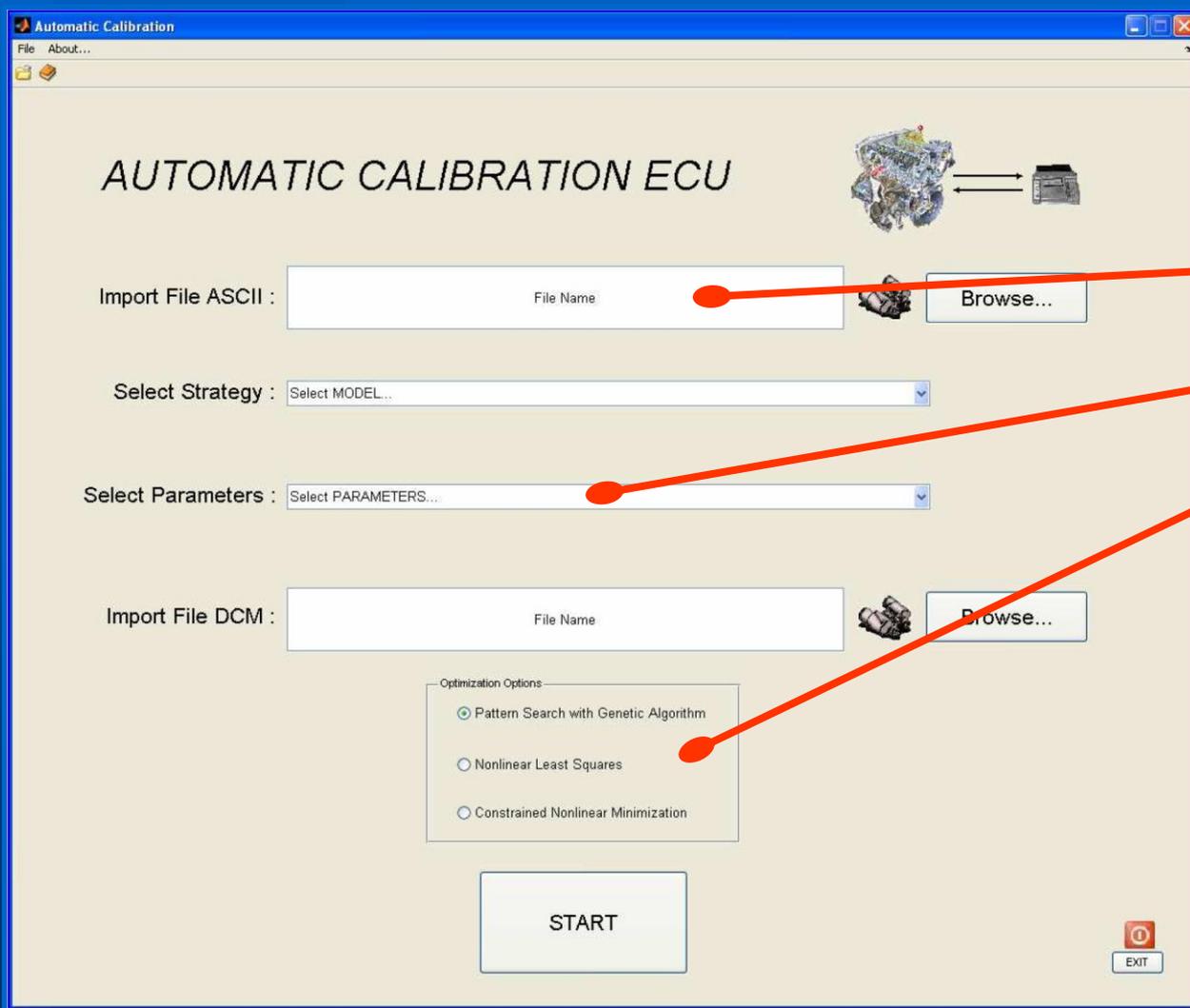
➢ The user can select:
- Data
- Parameters
- Optimisation agorithms

➢ The GUI tool 'suggests' the controller params & maps

Parameter Correction (Example)

AirCtl_facNQPar_MAP

Portata [mm^3 / cyc]

Giri [rpm]

	0	3	6	9	12	15	18	21	24	27	30	35	45	50	55	60
600	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
800	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1200	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1400	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1600	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1800	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2000	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2200	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2400	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2600	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2800	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

(Correction Map, i.e. the tuned parameter)

+

AirCtl_facNQPar_MAP_Correzioni

Portata [mm^3 / cyc]

Giri [rpm]

	0	3	6	9	12	15	18	21	24	27	30	35	45	50	55	60
600	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209	3,9209
800	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961	4,4961
1000	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713	5,0713
1200	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465	5,6465
1400	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217	6,2217
1600	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969	6,7969
1800	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721	7,3721
2000	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473	7,9473
2200	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225	8,5225
2400	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977	9,0977
2600	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729	9,6729
2800	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481	10,2481

(Nominal Map, IC)

=

AirCtl_facNQPar_MAP_Corretta

Portata [mm^3 / cyc]

Giri [rpm]

	0	3	6	9	12	15	18	21	24	27	30	35	45	50	55	60
600	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209
800	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961
1000	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713	6,0713
1200	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465	6,6465
1400	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217	7,2217
1600	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969	7,7969
1800	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721	8,3721
2000	8,9473	8,9473	8,9473	8,9473	8,9473	8,9473	8,9473	8,9473	8,9473	89,2473	8,9473	8,9473	8,9473	8,9473	8,9473	8,9473
2200	9,5225	9,5225	9,5225	9,5225	9,5225	9,5225	9,5225	9,5225	9,5225	95,2250	9,5225	9,5225	9,5225	9,5225	9,5225	9,5225
2400	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977	10,0977
2600	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729	10,6729
2800	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481	11,2481

(Controller Tuned Final Map)

Map Correction (Example)

Nominal Map
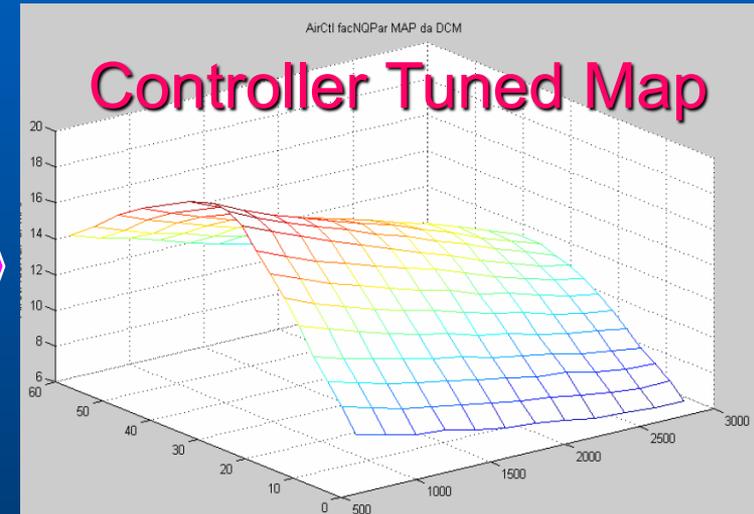
Correction Map
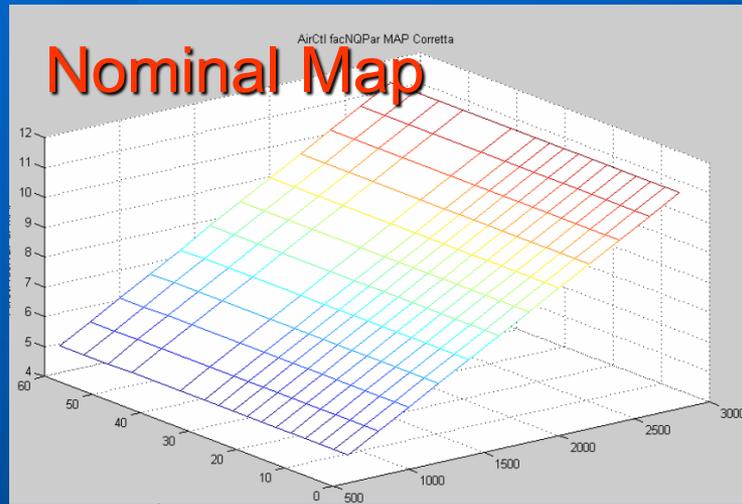
(provided by BOSCH)

(the map to be tuned)
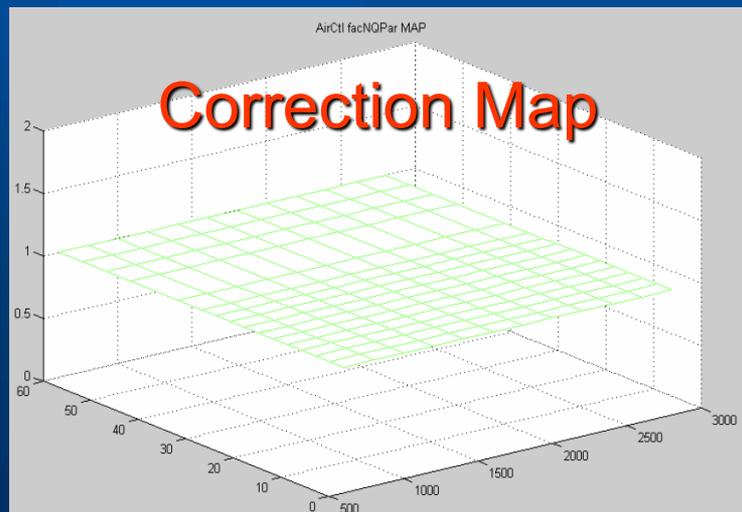
Controller Tuned Map
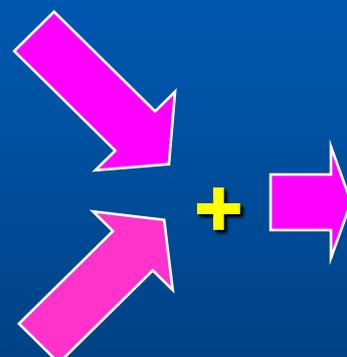
Final controller map

Parameter Estimation Toolbox
& Genetic Algoritm

Controller Structure & Params

$$X_{corr} = X_{nom} + \Delta X_{optim}$$
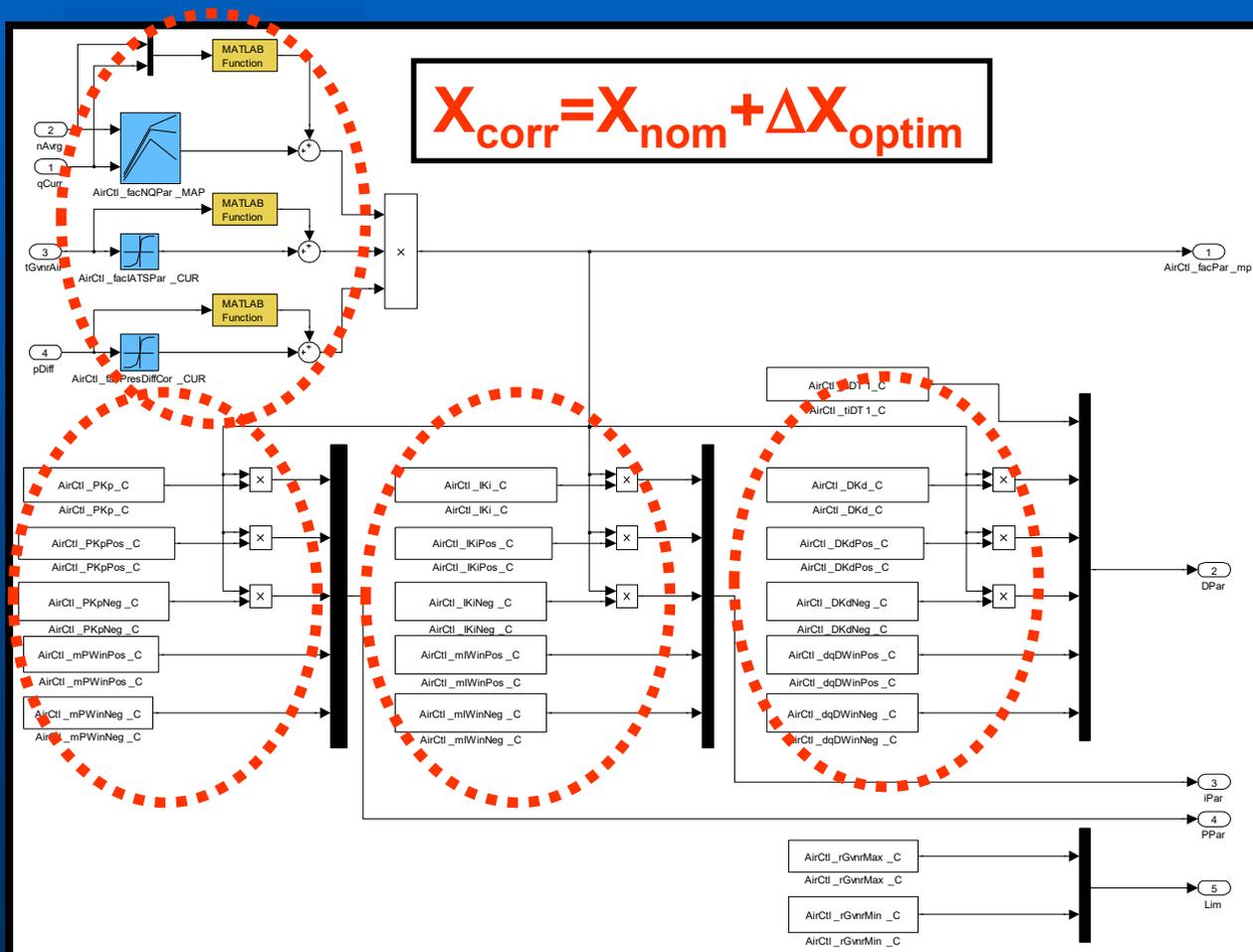
- ✓ **Pre-control**: 1 map

- ✓ **Gain adapt**: 2 maps

- ✓ *P*: 5 real variables

- ✓ *I*: 5 real variables

Simulation Results *(EU Driving Cycle)*

Reference AMF (set point)

Initial AMF (w/o optimisation)

Tuned AMF (final, after the calibration)

AMF

Time [s]
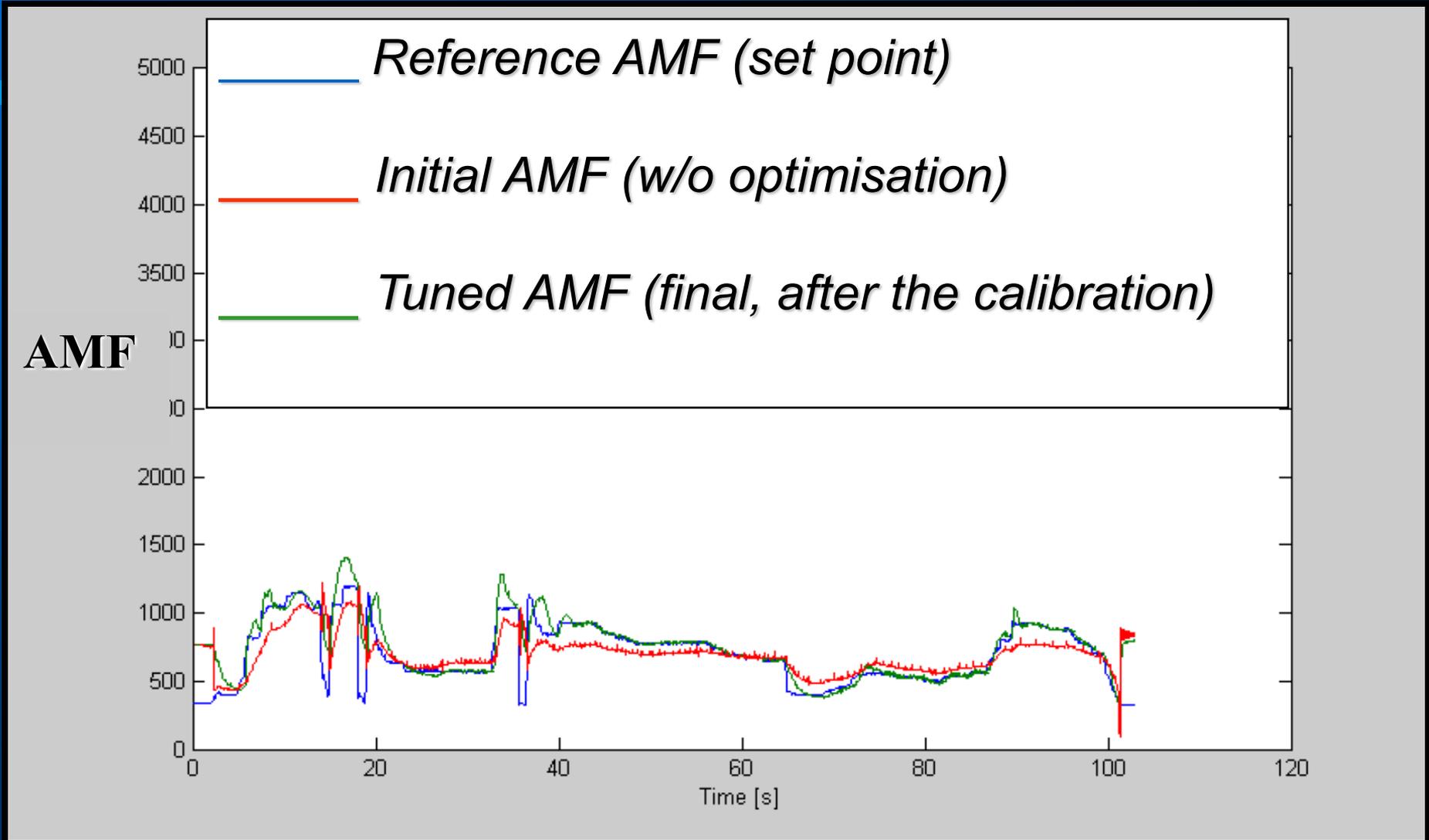
Alternative Procedures

➢ **Related HD diesel engine control literature:**

❑ Model-based predictive controller

❑ Fuzzy controller

❑ Neural networks

✓ **Adaptive controllers**

Conclusions

- ✓ **TVA/EGR control design**
- ✓ **Application of the existent control law (BOSCH) to the identified engine model**
  - ▪ Black-box modelling (fuzzy system)
- ✓ Identified system & controller integration
  - ▪ EU Driving cycle data
  - ▪ Controller parameter tuning/optimisation
- ➢ Matlab/Simulink GUI interface
  - ▪ **Automated calibration software tool for 'diesel calibration engineers'**
  - ▪ **ECU calibration & final tuning enhancement**

Further Investigations

- Validation of the complete model of a multi-cylinder diesel engine
  - Turbocharger & related maps (grey-box)
- Control law implementation for the complete dynamic model
  - Control law with the real engine
  - Comparison with different control strategies (*e.g.* adaptive schemes)

References

- *Introduction to Modeling and Control of Internal Combustion Engine Systems* by Lino Guzzella and Christopher H. Onder. Springer, August 2004. ISBN-10: 354022274X. ISBN-13: 978-3540222743.

- Control of diesel engines, by Guzzella, L.; Amstutz, A., *IEEE Control Systems Magazine*, Volume 18, Issue 5, Oct. 1998 Pages: 53 – 71.

- Modeling and Control of Turbocharged SI and DI Engines, by L. Eriksson. In: *Oil & Gas Science and Technology* - Rev. IFP. DOI: 10.2516/ogst:2007042

FOR MORE INFO...

Visit Silvio Simani's personal web page:

`http://www.silviosimani.it/talks.html`

Thank you for your attention!