Turbocharged Diesel Engine Modelling for Nonlinear Controller Design

Silvio Simani
Department of Engineering, University of Ferrara
Via Saragat, 1E - 44100 Ferrara (FE) ITALY
Ph: +39 0532 97 4844. Fax: +39 0532 97 4870
URL: **www.ing.unife.it/simani**
Email: **silvio.simani@unife.it**

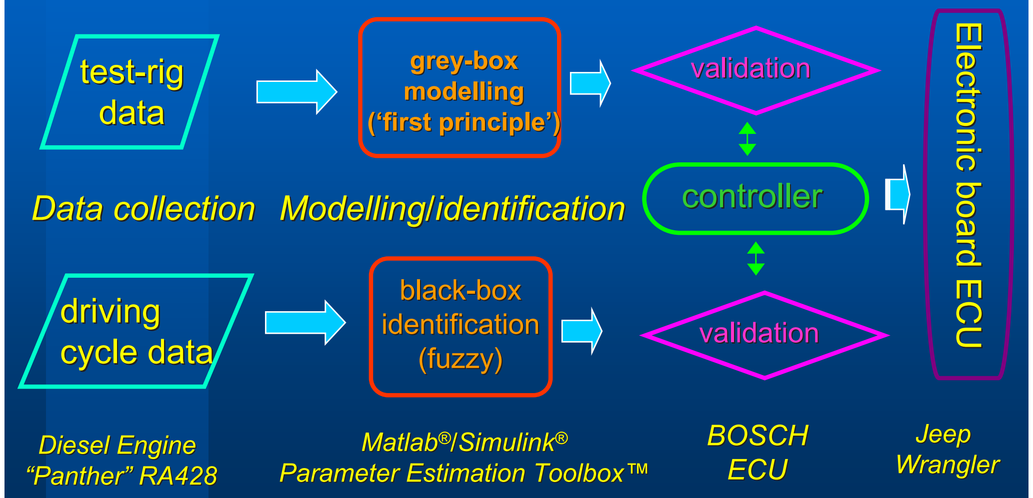
Projects and Research Topics

- ***Turbocharged Diesel Engine Modelling for Nonlinear Controller Design (2007-2009)***
- ✓ *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 (2004-2008, 2009-2011)
- ✓ Just started (2009 - 2011):
  - Mobile robots & SLAM - Simultanous Localization And Mapping
  - Image based visual servoing of robot manipulators - application to robotic surgery

Introduction

- ✓ **Control scheme calibration and tuning for commercial diesel engines (boats, ships, farm tractors, ...)**
  - **Diesel engine modelling and identification**
    - **grey-box**: analytical approach and identification
    - **black-box**: fuzzy modelling and identification
  - ***BOSCH* Electronic Control Unit (ECU)**
    - Controller parameter calibration and tuning
    - Automated software tool for 'diesel calibration engineers'

Project Logic Scheme



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 and parameter tuning

The Diesel Engine and its Emissions

Diesel Usage

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

Diesel Combustion

- ✓ Combustion: only two exhaust by-products?
  - CO_2 and H_2O
- ✓ Unfortunately...
  - Diesel is not pure carbon and hydrogen:
    - sulphur, nitrogen
  - Air is not pure oxygen
    - nitrogen
- ✓ Engine combustion at high temperature and high pressure: environment to form **many chemical compounds**

Diesel Emissions

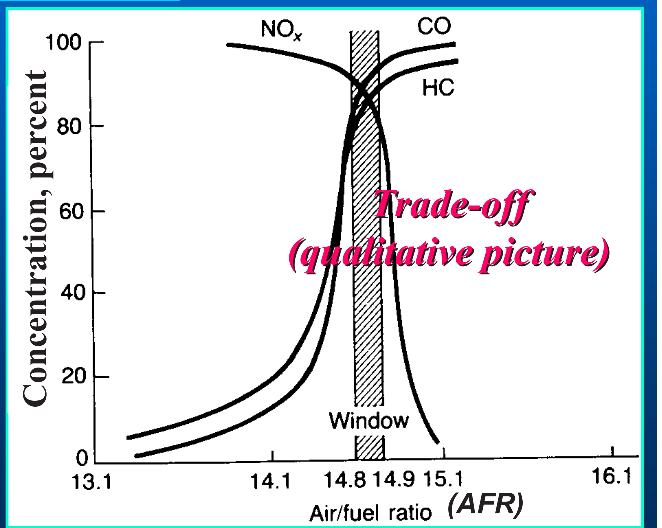
- ✓Particulate Matter (PM)
  - A product of incomplete combustion
- ✓Oxides of Nitrogen ($NO + NO_2 = NO_x$)
  - NO_x is a product of high temperature combustion
- ✓And other minor compounds...
  - Carbon monoxide, sulphur dioxide (SO_2)

Emission Reduction Strategies

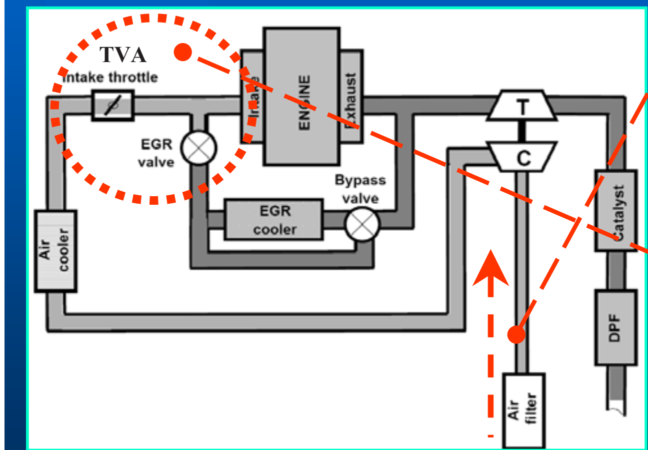
- ✓ Reducing PM
  - Improve combustion efficiency
  - Increase peak combustion temperature
- ✓ Reducing NO_x
  - Reduce peak combustion temperature
- ➢ **Air-to-Fuel (Mass) Ratio (AFR) Control**
  - **Computer-controlled fuel and air injection rates**
- ➢ **Exhaust Gas Recirculation (EGR)**
  - **Combustion temperature reduction**

Adjust AFR or *AMF*

- ➢ AFR adjustment
  - Depends on torque
  - Engine speed
- ➢ **AMF control**
  - exploited in this project!



NO_x and PM Control

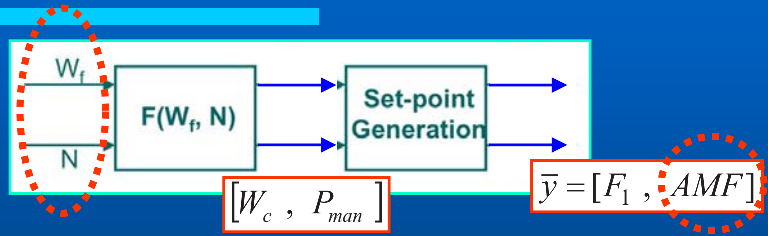


1) **AMF** (Air Mass Flow) control
   - ➢ *Reference, set point*
2) Reduce Flame Temperature
   - ➢ **EGR**
   - ➢ **TVA**

Control Objectives

- **The control objective is to operate the TVA and EGR valves in a way such that:**
  - the engine meets the driver's torque demand
  - NO_x and PM emissions are optimised
  - visible smoke generation is avoided
- **This can be achieved by regulating the Air Mass Flow (AMF) and the fraction of exhaust gases in the intake manifold to the corresponding set-points**

Set Point Generation

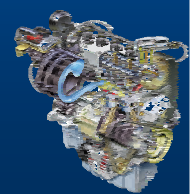


- Air Mass Flow (AMF) set-point is given as function of engine fuelling and speed
- It is computed to give minimum NO_x and PM emissions without any visible smoke
- In steady-state, AMF (and exhaust gas fraction) can be correlated to the engine outputs (*e.g.* compressor mass flow and exhaust manifold pressure) through thermodynamic relationships (maps)

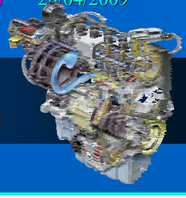
Control-Oriented Diesel Engine Modelling

Diesel Engine Modelling

- Process description and modelling
  1. **Grey-box approach**
     - Engine maps and look-up tables
     - Engine subsystems and components
  2. **Black-box approach**
     - Fuzzy modelling and identification
- Model Validation



Diesel Engine Scheme



Inputs

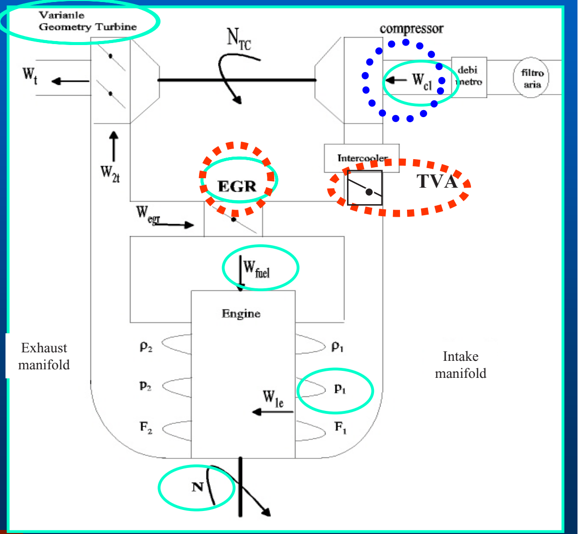
- Engine speed (*N*)
- Fuel flow rate (w_{fuel})
- Intake Temperature
- Engine Temperature

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 and final tuning
- Real-time applications

System Modelling

✓ **State parameters**
- P, T, ρ, c, W, …
- N (speed)
- X (chemical composition)
- …

✓ **Variables**
- …

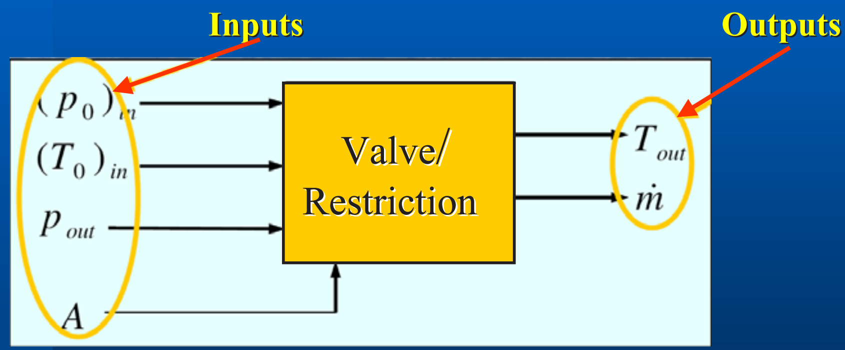
✓ **Equations**
- Mass conservation
- Energy conservation
- Momentum conservation
- Motion quantity conservation
- State equations
- Transformation equations

Components and 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**



✓ Compressible Isentropic flow + flow coefficient C_d

EGR – Algebraic Equations

Output **Input**

$$\dot{m} = \begin{cases} \dfrac{C_d A (p_0)_{in}}{\sqrt{R (T_0)_{in}}} \cdot \left(\dfrac{p_{out}}{(p_0)_{in}}\right)^{\frac{1}{k}} \cdot \sqrt{\dfrac{2k}{k-1}\left[1-\left(\dfrac{p_{out}}{(p_0)_{in}}\right)^{\frac{k-1}{k}}\right]} & \text{where } \left(\dfrac{p_{out}}{(p_0)_{in}}\right) > \left(\dfrac{2}{k+1}\right)^{\frac{k}{k-1}} \\ \dfrac{C_d A (p_0)_{in}}{\sqrt{R (T_0)_{in}}} \cdot \sqrt{k} \cdot \sqrt{\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}} & \text{where } \left(\dfrac{p_{out}}{(p_0)_{in}}\right) \leq \left(\dfrac{2}{k+1}\right)^{\frac{k}{k-1}} \end{cases}$$

Note: grey-box approach

Throttle Valve Actuator (TVA)

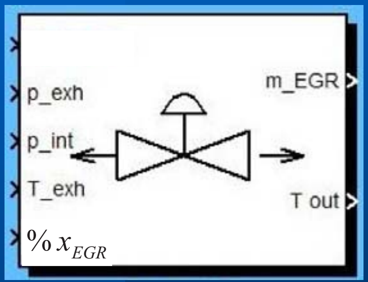
$$w_{th} = \begin{cases} \dfrac{k A_{th}(\alpha, N) p_{amb}}{\sqrt{R T_{up}}} \left(\dfrac{p_{th}}{p_{amb}}\right)^{1/\gamma} \sqrt{\dfrac{2\gamma}{\gamma-1}\left(1 - \left(\dfrac{p_{th}}{p_{amb}}\right)^{\frac{\gamma-1}{\gamma}}\right)} & \dfrac{p_{th}}{p_{amb}} > \bar{p} \\ \dfrac{k A_{th}(\alpha, N) p_{amb}}{\sqrt{R T_{up}}} \sqrt{\gamma} \left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} & \dfrac{p_{th}}{p_{amb}} \leq \bar{p} \end{cases} \quad (1)$$

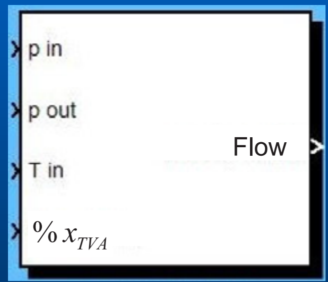
Algebric Model

- w_{th} is the flow through throttle
- From experimental data, the parameters k and $A_{th}(\alpha)$ 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 and restrictions: examples



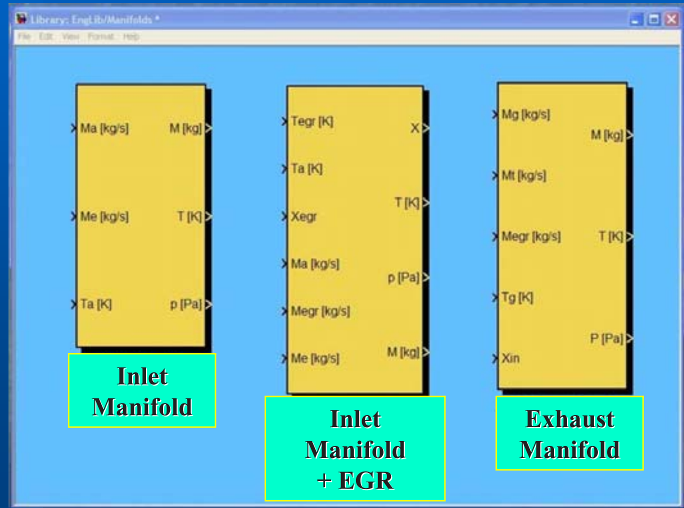


Pneumatic Valve EGR

Throttle Valve TVA

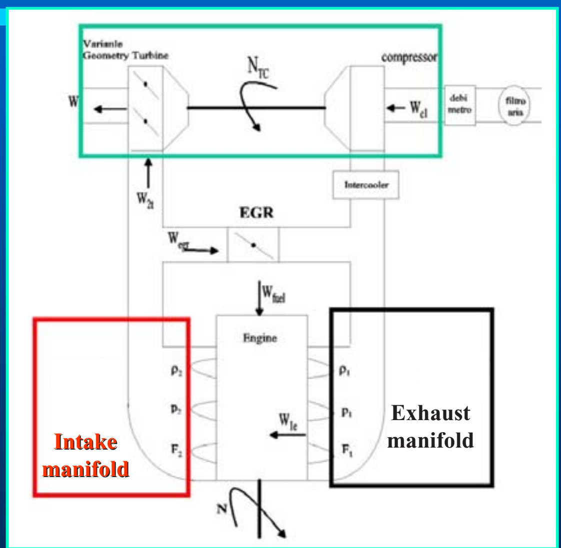
Control of the vacuum generator PWM and not the valve lift!

Manifold SIMULINK® Blocks



Turbocharger (Turbine - Compressor)

- ➢ *Intake manifold*
- ➢ *Exhaust manifold*
- ➢ *Turbocharger*



Engine Modelling Issues

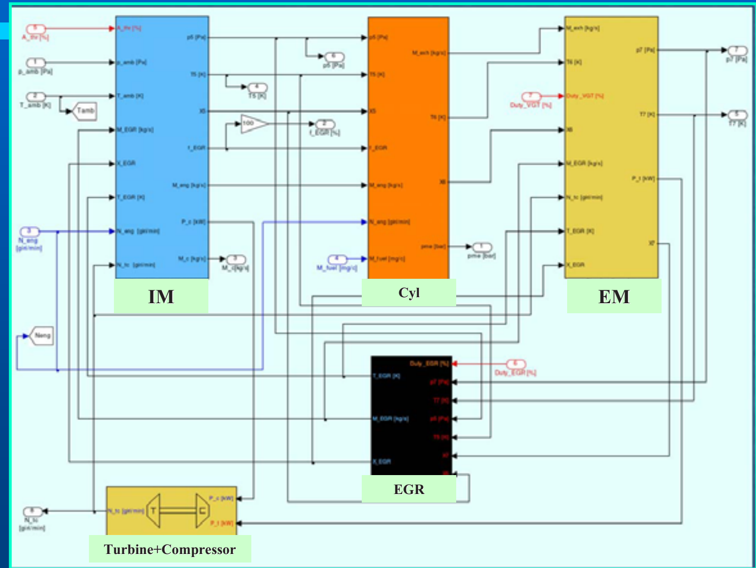
- ➢ Engine subsystems contain unknown terms:
  - Effective area (valves & restrictions, *i.e. EGR*/*TVA*): $A_{EGR}(x_{EGR})$, $A_{TVA}(x_{TVA})$
  - Volumetric efficiency (cylinder): $\eta_v(N_e, P_{im})$
  - Compressor/turbine isentropic efficiencies: $\eta_c(N_{tc}, T_{amb}, P_{im}/P_{amb})$, $\eta_t(x_{VGT}, N_{tc}, T_{em}, P_{out}/P_{em})$
  - 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**
  - ❑ To be completed

Engine Complete Description (Cont'd)



Diesel Engine *Black-Box Fuzzy Modelling*

Fuzzy Modelling - FMID™

- ➢ **Brief review**
  - Nonlinear regression and 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

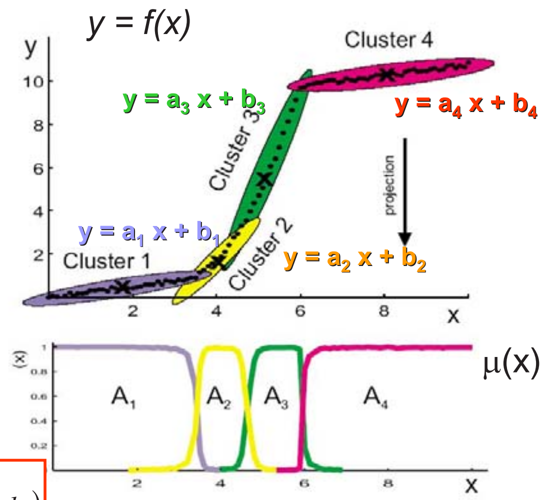
Fuzzy Clustering and Rules

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 $y = a_4\, x + b_4$



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

Diesel Engine Application

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

- **Input-output data**
  - Engine fuelling
  - Engine temperature
  - Intake temperature
  - Engine speed
  - EGR command
  - TVA command

  } **(4+2) Inputs (x)**

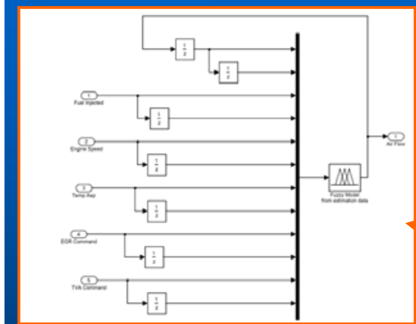
  - AMF output signal } **1 Output (y)**

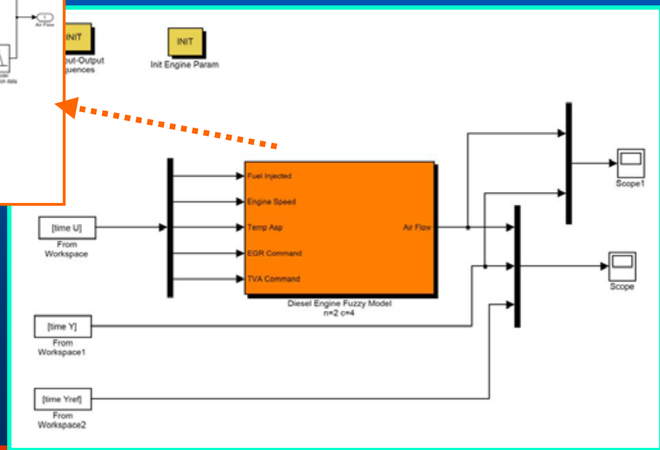
... few weeks

- **FMID™ for MATLAB® by Prof. Robert Babuska (Delft, The Netherlands). URL:** `http://www.dcsc.tudelft.nl/~babuska/`

Identified Fuzzy Model FMID™

- **Local models' order: *n* = 2**
- **Cluster number: *c* = 9**

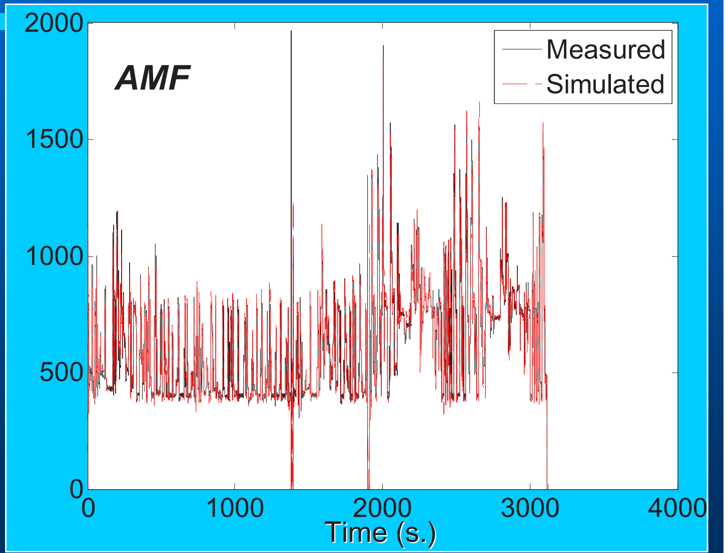




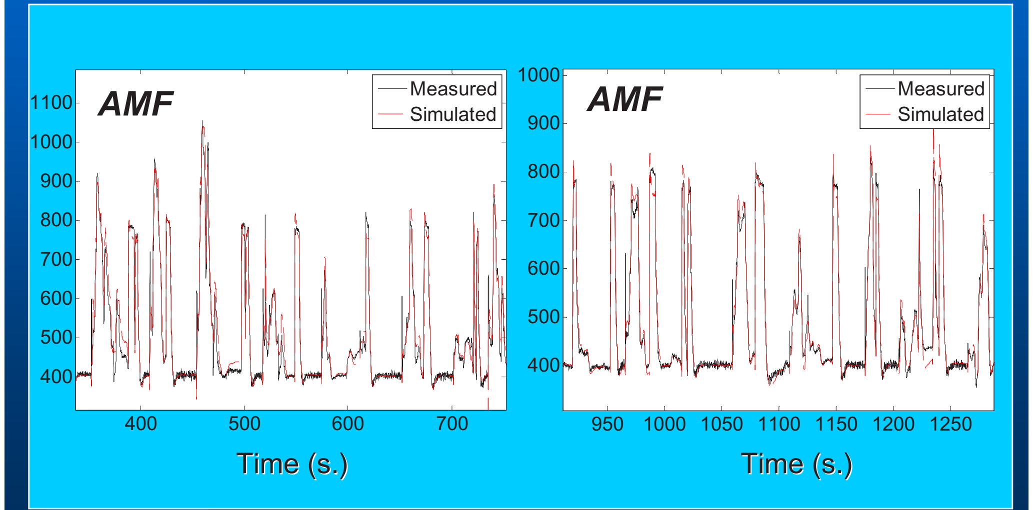
Note:
c & *n* optimised via a PEM iterative scheme

Fuzzy Model Simulation

- *Fuzzy model simulation*
- *Good performances for validation and several test data sequences*
- *Best fit > 75% (in simulation & validation)*

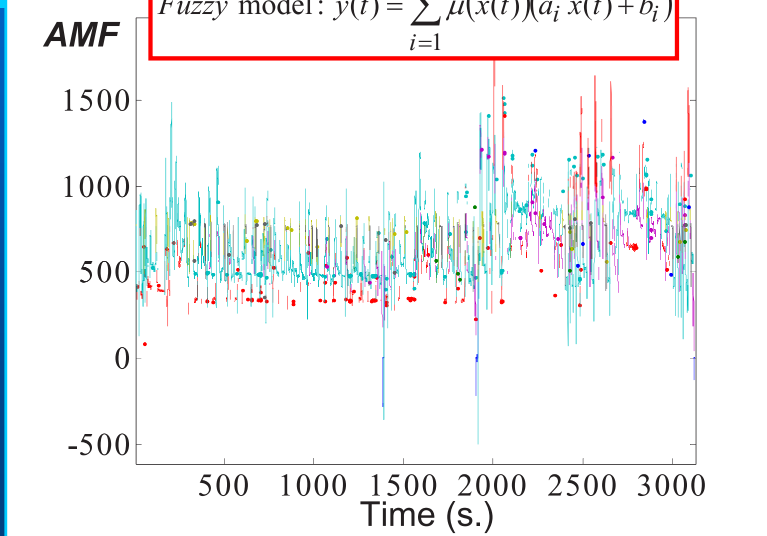


Fuzzy Model Simulation (zoom)



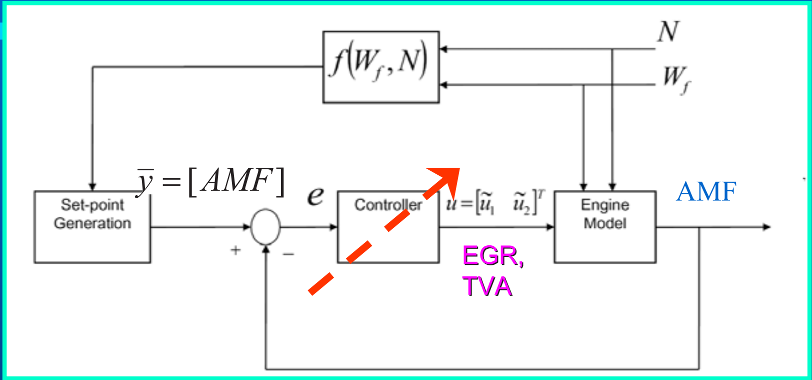
Local Submodels *(9 ARX models)*

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



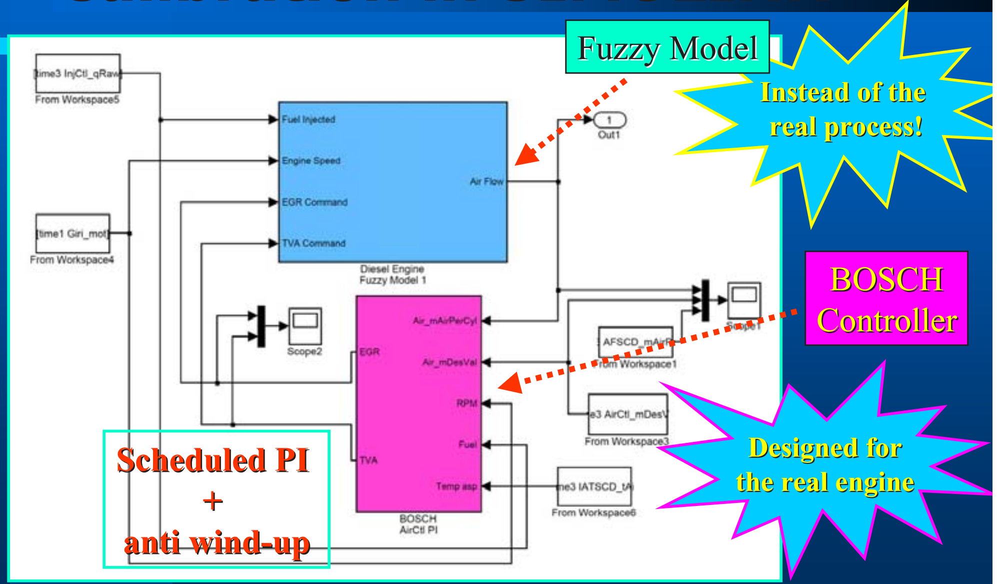
BOSCH Controller 'Strategy' and Parameter Tuning

Control Model Simulation

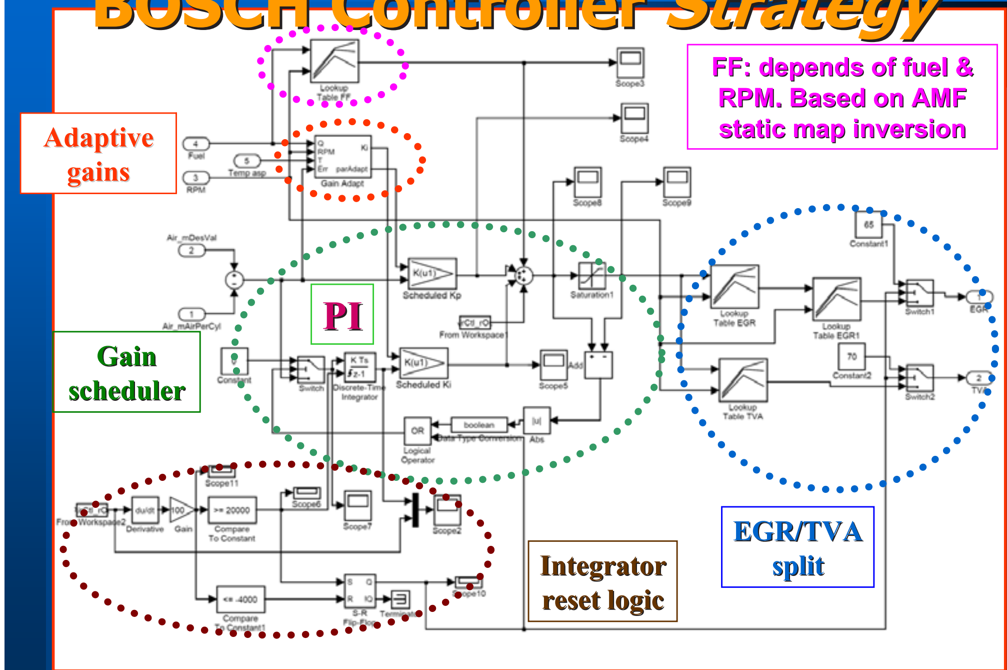


- ✓ Specific set-point assigned depending on fuel demand (W_f) and speed (N).
- ✓ The controller actuates the EGR and TVA valves to correct the deviation between actual (*AMF*) and demanded variable

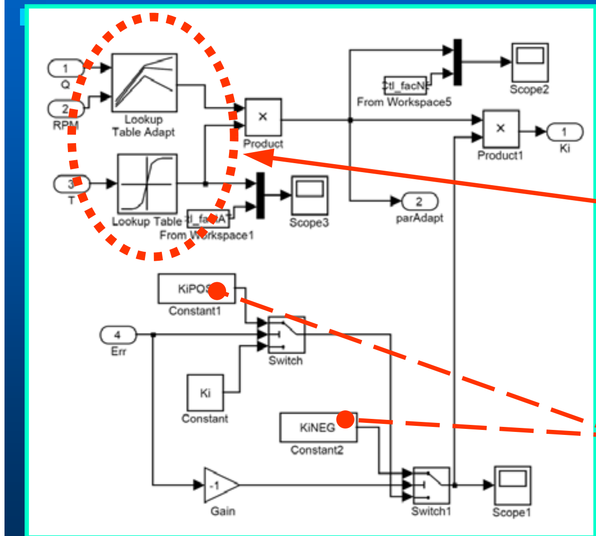
Calibration in SIMULINK®



BOSCH Controller *Strategy*

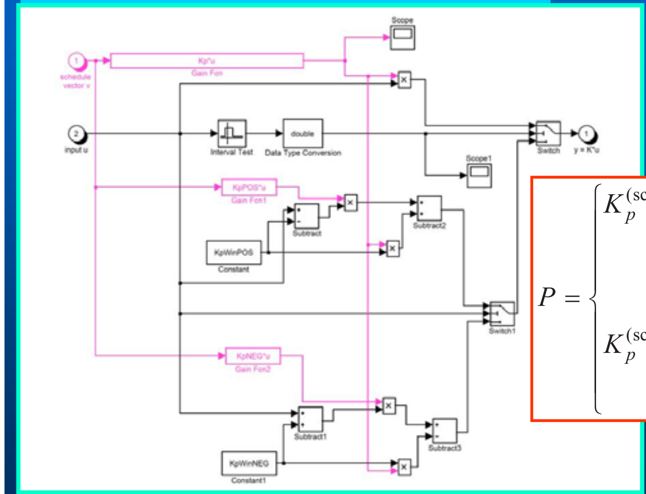


Parameter Adaptation *(Gain Adapt)*



- ➢ BOSCH controller's main main idea is to correct the PI gains (Ki & Kp) on the basis of the error value and precompiled static maps
- ➢ Depends on engine fuelling, RPM, asp. temp and tracking error (actual and desired MAF)
- ➢ Fixed thresholds (KiPOS & KiNEG)

Gain Scheduler: '*PI*' Params

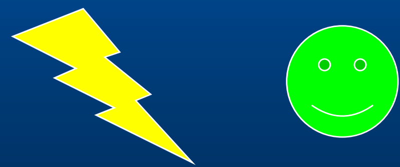


- It multiplies P & I gains and parameters
- Example:

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

- 'Bumpless' strategy

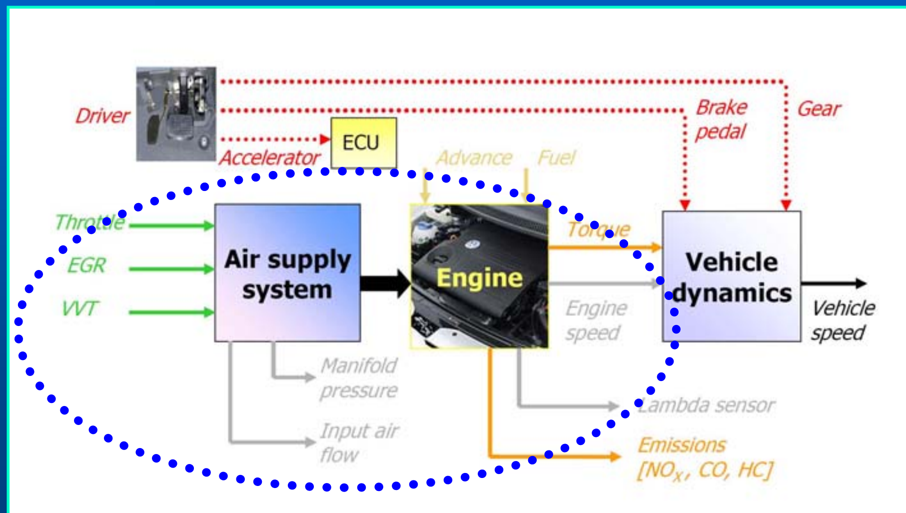
BOSCH Controller *Calibration Strategy*



Driving Cicle Prototype...

CONFIDENTIAL: Prototype 2009 HD truck – field test unit

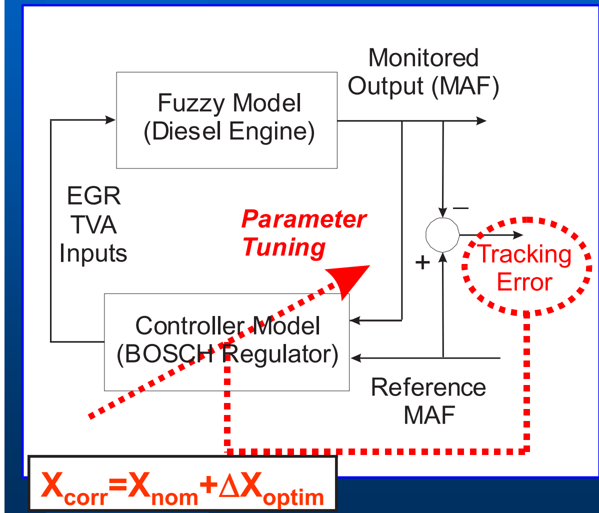
Complete System *(EU Driving Cycle)*



Technology

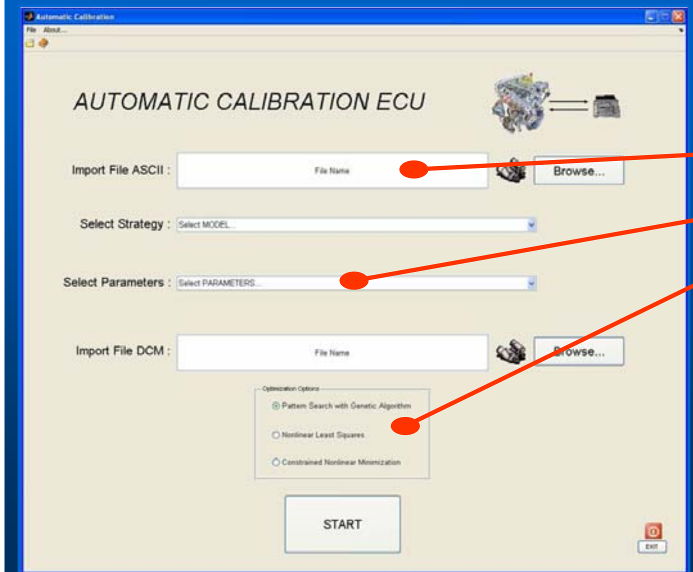
- Diesel engine driving cycle data
- MATLAB®/SIMULINK® interface
  - Calibration, optimisation; model, controller analysis, simulation and design
- ATI VISION™
  - Integrated calibration measurement solution for accessing ECUs
  - Table calibration
  - Memory emulation (μ–controller)
  - On target rapid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

Parameter Correction



- **Matlab/Simulink**
  - Parameter Estimation Toolbox
  - Optimisation Toolbox
  - Pattern Search and Genetic Algorithm
- **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

Giri [rpm] \ Portata [mm^3 / cyc]	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

Giri [rpm] \ Portata [mm^3 / cyc]	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	8,5228	8,5228	8,5228	8,5228	8,5228
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)

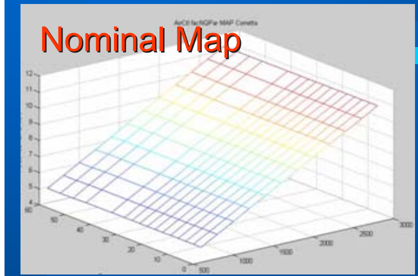
=

AirCtl_facNQPar_MAP_Corretta

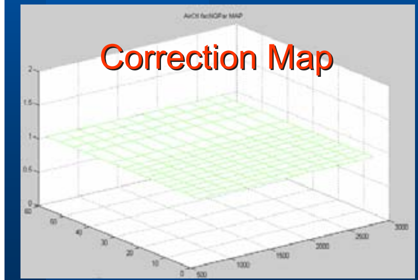
Giri [rpm] \ Portata [mm^3 / cyc]	0	3	6	9	12	15	18	21	24	27	30	35	45	50	55	60
600	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209	4,9209
800	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	5,4961	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	89,4720	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)

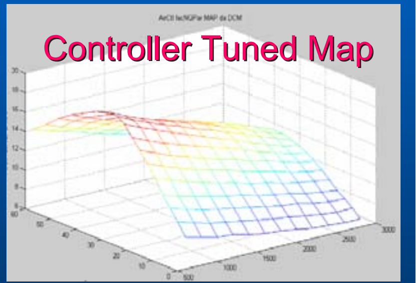


(provided by BOSCH)



(the map to be tuned)

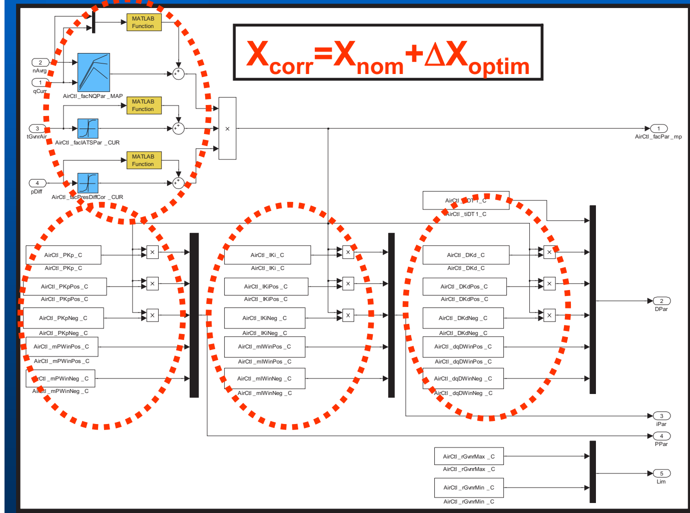
\+



Final controller map

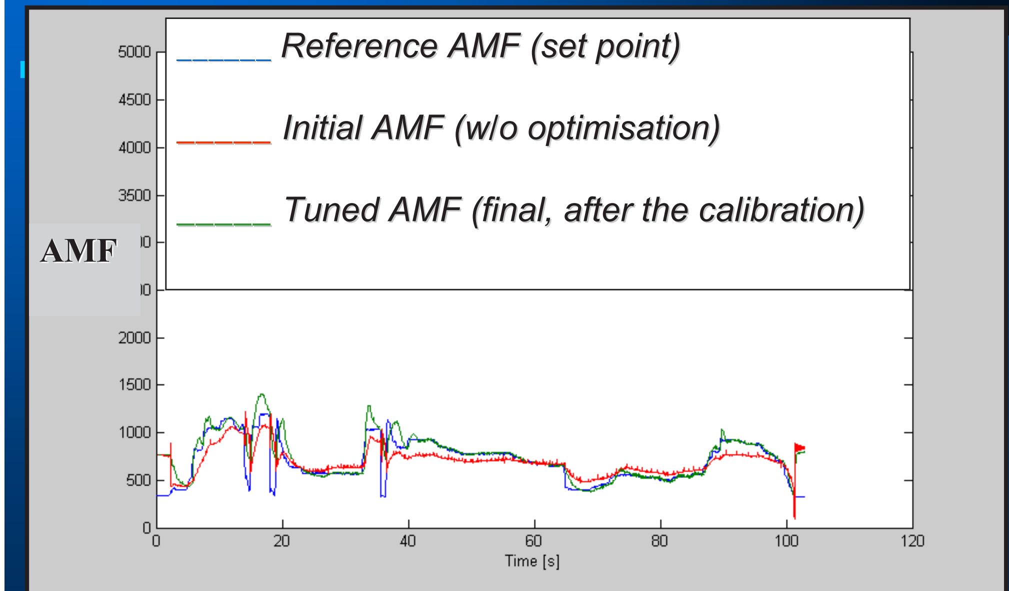
Parameter Estimation Toolbox and Genetic Algoritm

Controller Structure & Params



- ✓ **Pre-control:** 1 map
- ✓ **Gain adapt:** 2 maps
- ✓ ***P***: 5 real variables
- ✓ ***I***: 5 real variables

Simulation Results *(EU Driving Cycle)*



Alternative Procedures

- **Related HD diesel engine control literature:**
  - ❑ Model-based predictive controller
  - ❑ Fuzzy controller
  - ❑ Neural networks
  - ✓ **Adaptive controllers**

Conclusion

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

Further Investigations

- ❑ Validation of the complete model of a multi-cylinder diesel engine
  - Turbocharger and 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 the web page:

www.ing.unife.it/simani/nlw2009.html

Thank you for your attention!

We are well behind and still have a long way to go...