Development and Application of Design Techniques for Industrial Application

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Control of EGR/TVA of a Diesel Engine

A Process Model Identification for Controller Design Approach

Project Goals: Overview

- Design of a control scheme for commercial (HD) diesel engines (boats, ships, farm tractors, ...)
  - Diesel engine modelling
  - Control system strategy
- Diesel engine *analytical* description
  - Estimation of engine submodels, maps
  - Submodel parameter calibration
- Electronic Control Unit (ECU)
  - Control scheme implementation

Project Goals: Details

Theory

- System Identification
  - Modelling and Calibration
- Control theory

Application

- Diesel Engine

Automatic procedure for:

- Control-oriented model development
  - Component description, analysis and synthesis
- Performance optimisation
  - Static (*e.g.* map tuning)
  - Dynamic (*i.e.* dynamic control)

Related Documents

- *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:

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The Diesel Engine

Talk Topics

- **The Diesel Engine**
  - Diesel Engine Emissions
  - Diesel Engine Emissions and Pollution Control
  - Diesel Technologies
- **Diesel Engine Modelling for Control**
  - Diesel Engine Components: *Grey-Box Modelling*
  - Diesel Engine Black-Box Modelling - *Fuzzy Systems*
  - Control Scheme "Design"
  - BOSCH Controller Enhancement – Design Strategy
- **Concluding Remarks**

The Diesel Engine

- Ignites fuel without spark – instead uses the heat of compression to exceed the ignition temperature of a fuel
- Capable of using a wide variety of fuels
  - Diesel, Kerosene, Jet Fuel, Residual Oils
- Is the workhorse of the heavy-duty transportation industry
  - Current designs expected to last 1 – 1.5 million miles if properly maintained
- Fuel efficient, low-maintenance, dependable
- Flexible, dependable, durable, efficient, cost-effective

Diesel Combustion

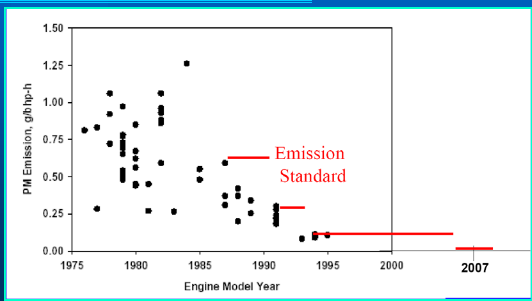
- Textbook combustion has only two exhaust by-products
  - CO_2 and H_2O
- Unfortunately, life is not like a textbook...
  - Diesel is not pure carbon and hydrogen:
    - sulphur, nitrogen
  - Air is not pure oxygen
    - nitrogen
- Engine combustion happens at high temperature and high pressure
  - A perfect environment to form many chemical compounds

Diesel Engine 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.

On-Road Heavy-Duty Engines



Diesel Emissions

Health Impact High to Low

- Particulate Matter (PM)
  - A product of incomplete combustion
  - Diesel PM is a Toxic Air Contaminant (TAC) and is the largest single carcinogen in ambient air
- Oxides of Nitrogen ($NO + NO_2 = NO_x$)
  - NO_x is a product of high temperature combustion: the higher the peak combustion temperature the more NO_x formed
    - Direct exposure to NO_2 is harmful
    - NO_x contributes to ozone formation and direct exposure to ozone is harmful

Emission Reduction Strategies

Health Impact High to Low

Engineering Challenge!!!

- Reducing PM
  - Improve combustion efficiency
    - increase peak combustion temperature
- Reducing NO_x
  - Reduce peak combustion temperature
- Reduce PM, VOC & CO
  - Precious metal catalyst

Diesel Emissions (Cont'd)

Health Impact High to Low

- Diesel engines also emit
  - Volatile Organic Compounds (VOC) which can be Toxic Air Contaminant and can also lead to ozone formation
  - Carbon Monoxide which is a poison
  - Sulphur dioxide (SO_2) which can form sulphuric acid

Emission Reduction Strategies (Cont'd)

- Engine design changes
  - Combustion chamber designs to maximize air/fuel mixture and minimize local hot spots
  - Air handling (*e.g.* turbo-charging, valve timing)
  - Cooled Exhaust Gas Recirculation (EGR)
  - Injection timing (retard/advance, rate shaping)
- Exhaust after-treatment
  - PM
    - % Control + Diesel Oxidation Catalyst + Filters
  - NO_x
    - % Control + Catalysis + EGR
  - VOC & CO
    - % Control + Catalysis

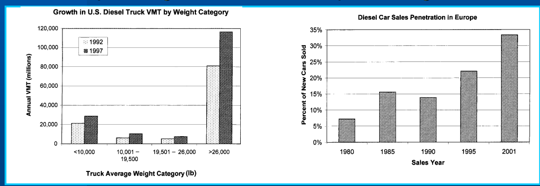
(Emission Reduction: Fuels)

- Additives
  - *e.g.* Precious and non-precious metals (platinum, cerium)
- Low sulphur diesel
- Water emulsions
- Alternative Fuels
  - Natural gas
  - Bio-diesel
  - Propane
  - Ethanol

Gasoline Engine *vs.* Diesel Engine

❖ Heavy Duty Vehicles

- For the same power output, only 70% mass compared to gasoline engines
- Lower CO_2 emission
- Lower operating cost, 2/3 of an equivalent gasoline truck



Gasoline Engine Pollutants (U.S.)

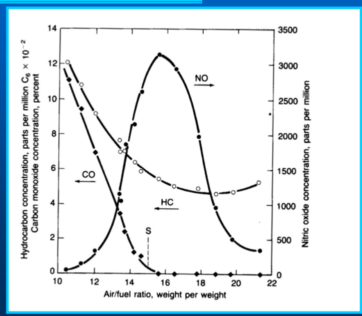
Pollutant	Metric Tons in 1990
CO	37.7
NO_x	7.5
VOC	6.4
Pb	2.2
PM	1.5
SO_x	1.0

Diesel Engines *vs.* Gasoline Engines

- ❖ Mostly on HDV (Heavy Duty Vehicles)
- ❖ Autoignition of diesel fuel at high compression (and temperature)
- ❖ Diesel fuel is heavier, less volatile than gasoline
- ❖ Engine operates lean
  - Low CO and VOC
  - High NO_x and PM

Diesel Engine Emissions and Pollution Control

Pollutant Formation *vs.* AFR



Air-to-Fuel (Mass) Ratio (AFR)

$C_8H_{16} + 12\ O_2 + 45.1\ N_2 \rightarrow 8\ CO_2 + 8\ H_20 + 45.1\ N_2$

- $(AFR)_{stoich}$ = 14.7 grams air/grams octane.
- Note: Air is 79 mol% N_2, 21 mol% O_2.
- Equivalence Ratio (ER) = $(AFR)_{actual}/(AFR)_{stoich}$.

Emission Controls

- Control AFR at ER of 0.98-0.99.
- Computer-controlled fuel and air injection rates

Exploited Here!

- Four-Stroke Engine Designs
  - *Chamber designs that induce swirl*
  - *Stratified-charge engine (two chambers per cylinder)*
  - *Extra-lean-burn engine (rich at plug, lean in cylinder*

Not investigated in this project

Emission Control Strategies

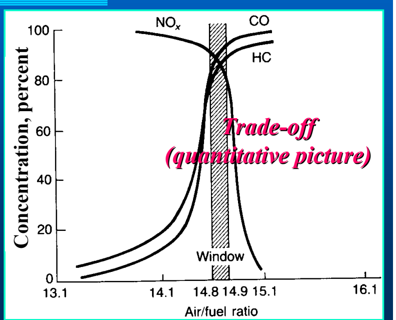
- Adjust AFR, i.e. AMF (Air Mass Flow)
- Exhaust Gas Recirculation (EGR)
- Note: diesel engines are currently being designed for emission control.
  - Adjust compression ratio
  - Adjust surface-to-volume ratio of chamber
  - Adjust spark timing

EGR Principle...

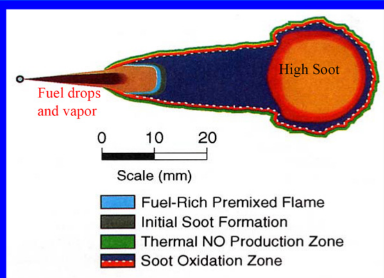
- Diesel engine is not clean
- Emissions of:
  - Particulate Matter (PM)
  - Nitrogen oxides
- Depend on combustion temperature
  - Diesel flame...

Adjust (AFR) & AMF

- AFR adjustment
  - Depends on torque
  - Engine speed
- AMF control

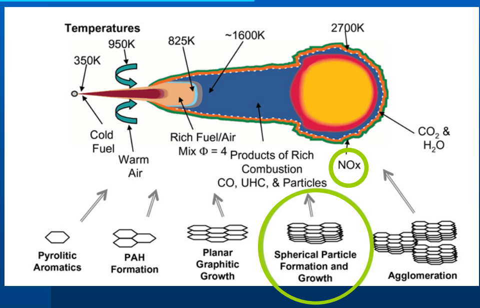


The Diesel Flame

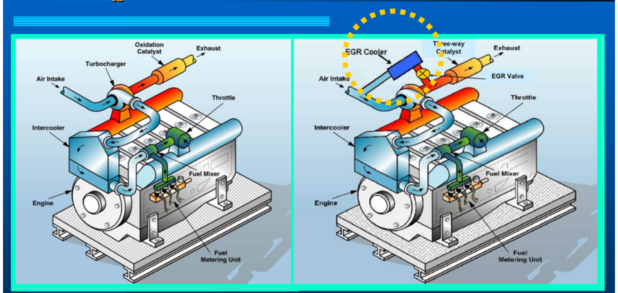


[1] "A Conceptual Model of DI Diesel Combustion Based on Laser-Sheet Imaging", John E. Dec, SAE 970873.

The Diesel Flame (Cont'd)



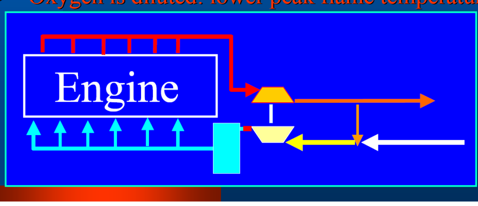
NO_x and PM Control (Cont'd)



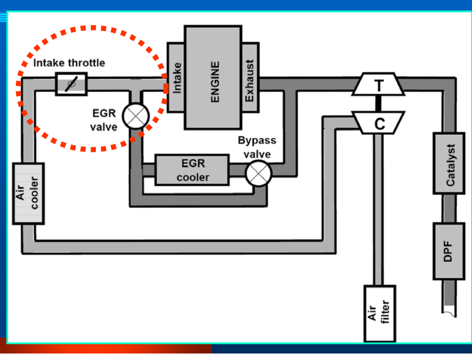
Diesel Engine w/o EGR *Diesel Engine with EGR*

NO_x and PM Control

1) AMF (Air Mass Flow) control
2) Reduce Flame Temperature
   - **EGR**
   - Oxygen is diluted: lower peak flame temperature



NO_x and PM Control (Cont'd)



Diesel Technologies

Diesel Technologies 2002- 2006

- **Exhaust Gas Recirculation (EGR)**
  - Plumbing
  - Cooler
  - Valve
  - Control and Sensors
- **Fuel and Combustion**
  - **Increased Fuel Pressure**
  - **Improved Injection Control**
  - **Combustion Bowl**

Diesel Technologies 2007- 2009

- Increased Exhaust Gas Recirculation Flow
  - **Additional cooling**
  - **Requires additional boost from turbocharger**
- Fuel and Combustion
  - **Injection system and bowl optimisation**
  - **Advanced combustion**
  - **Low sulphur fuel in place**
- Active Particulate Filter
  - **Post injection or secondary injector for regeneration - fuel penalty**
- Crankcase Ventilation System

Diesel Technologies 2010-???

- Fuel and Combustion
  - Possible improved strategies for reduced in-cylinder emissions
- NO_x Aftertreatment
  - Selective Catalytic Reduction (SCR)
    - SCR Catalyst
    - Urea Injection System
    - Diagnostics
    - On-Vehicle Urea Tank
    - Urea distribution
    - Vehicle operation limited with no urea
- Lean NO_x Absorber
  - Unlikely candidate for Heavy-Duty vehicles

Engineers will always make do…

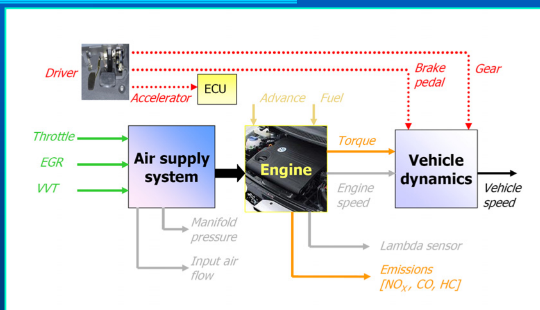
CONFIDENTIAL: Prototype 2007 HD truck – field test unit

Control-Oriented Diesel Engine Modelling

- System Description
- Engine Modelling and Validation
  - Grey-box approach
    - Engine Map Design
    - Engine Parameter Identification
  - Black-box approach
    - Fuzzy modelling and identification
- Control Scheme Design
- Open Problems
- Further Studies

Diesel Engine Modelling for Control

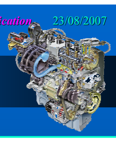
System Overview



System Characteristics

- Multivariable system
- Strongly non linear
- Heavily coupled
- Few measurements available on-board
- No measurements of performance variables (*e.g.*, torque, emissions)
  - Virtual sensors???

Diesel Engine Scheme



Main Inputs

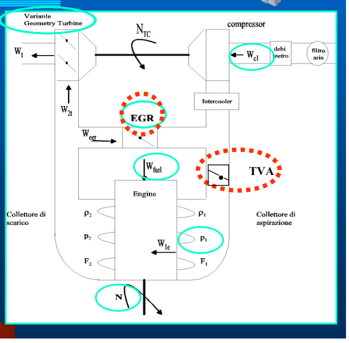
- Engine speed (N)
- Fuel flow rate (w_{fuel})
- Intake Temperature
- EGR
- VGT

Main Outputs

- Intake manifold pressure (p_1)
- Air Mass Flow AMF (w_{c1})

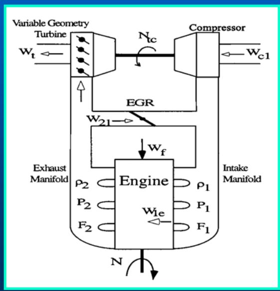
Control Variables

- EGR
- TVA
- VGT (not used here!)



EGR/TVA Control Objective

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



Dynamic Model and Assumptions

- ✓ Lumped-parameter, time-based, nonlinear equations, "gray-box" models, *parameter* and *map* estimation
- ✓ Uniform thermodynamic properties
- ✓ Homogeneous mixtures of air and combustion (ideal) gas
- ✓ Stoichiometric combustion of air and fuel
- ✓ Heat transfer effects neglected
- ✓ Flow through restrictions modelled as isentropic compressible flow
- **Diesel model interconnected subsystems**

Diesel Engine Components

Grey-Box Modelling

MATLAB ® /SIMULINK® Library

- ✓ Control-oriented simulation models
- ✓ MATLAB ® / SIMULINK® environments
- ✓ Easy to use
- ✓ Reduced simulation time
- ✓ Control design, test, performance assessment
- ✓ Final tuning and calibration
- ✓ Real-time applications
- ✓ Diesel engine test systems

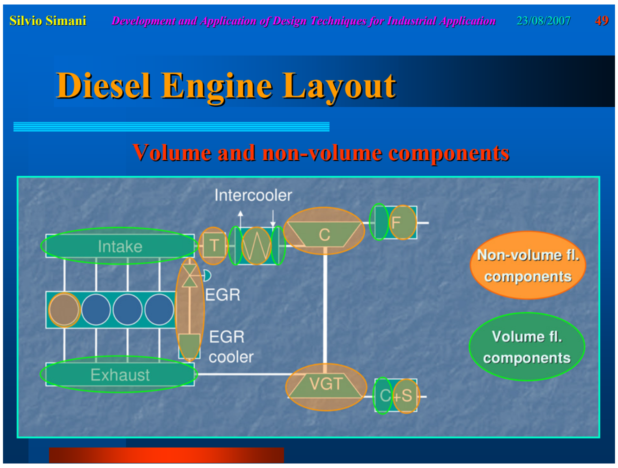
System Modelling

- **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-Dynamic Systems

- 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, $\Pi \neq 0$ & $\Phi \neq 0$)



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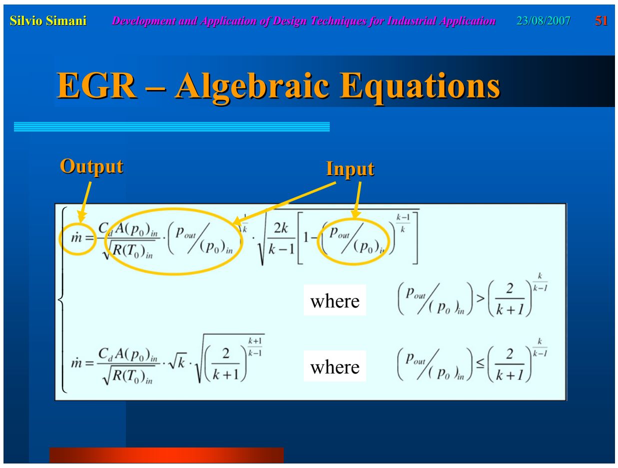
Diesel Engine Layout
Volume and non-volume components
Intercooler
Intake
T
C
F
EGR
EGR
cooler
Exhaust
VGT
C+S
Non-volume fl. components
Volume fl. components



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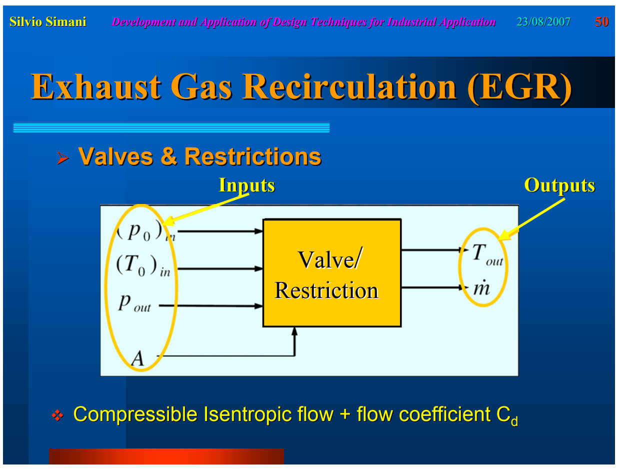
EGR – Algebraic Equations
Output
Input
$\dot m = \frac{C_d A (p_0)_{in}}{\sqrt{R (T_0)_{in}}} \cdot \left(p_{out} / (p_0)_{in} \right)^{\frac{1}{k}} \cdot \sqrt{\frac{2k}{k-1}\left[1-\left(p_{out} / (p_0)_{in} \right)^{\frac{k-1}{k}}\right]}$
where $\left(p_{out} / (p_0)_{in} \right) > \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}$
$\dot m = \frac{C_d A (p_0)_{in}}{\sqrt{R (T_0)_{in}}} \cdot \sqrt{k} \cdot \sqrt{\left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}$
where $\left(p_{out} / (p_0)_{in} \right) \le \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}$



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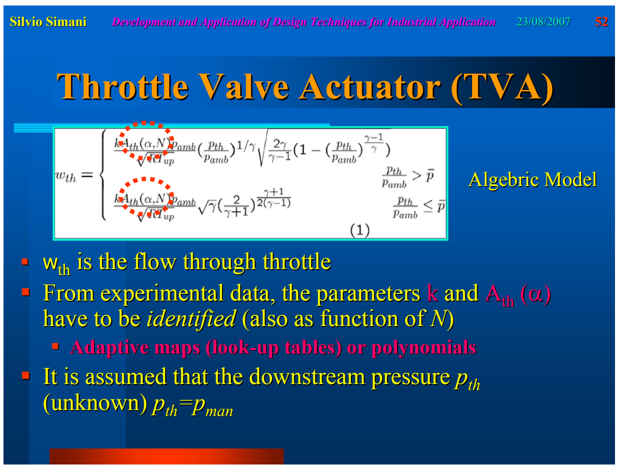
Exhaust Gas Recirculation (EGR)
Valves & Restrictions
Inputs
Outputs
$(p_0)_{in}$
$(T_0)_{in}$
p_{out}
A
Valve/ Restriction
T_{out}
$\dot m$
Compressible Isentropic flow + flow coefficient C_d



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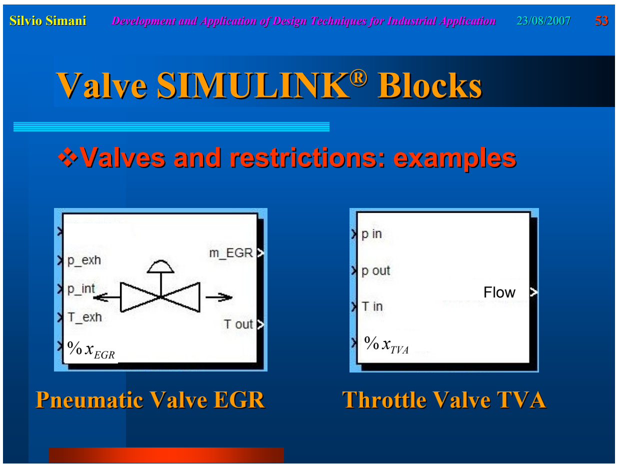
Throttle Valve Actuator (TVA)
$w_{th} =$
(1)
Algebric Model
w_{th} is the flow through throttle
From experimental data, the parameters k and A_{th} (α) have to be *identified* (also as function of *N*)
Adaptive maps (look-up tables) or polynomials
It is assumed that the downstream pressure p_{th} (unknown) $p_{th}=p_{man}$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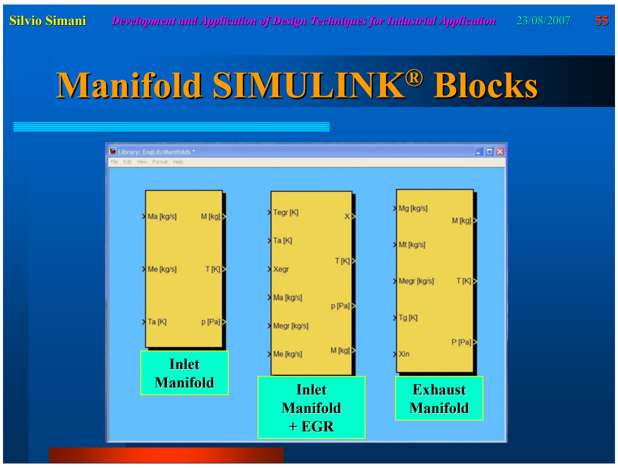
Valve SIMULINK® Blocks
❖Valves and restrictions: examples
p_exh
p_int
T_exh
% x_EGR
m_EGR
T out
p in
p out
T in
% x_TVA
Flow
Pneumatic Valve EGR
Throttle Valve TVA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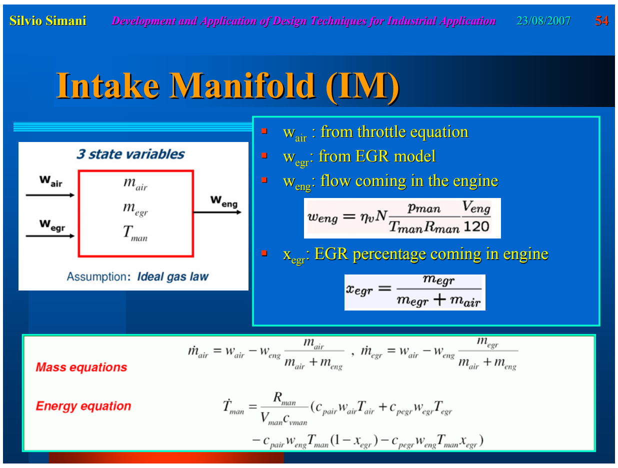
Manifold SIMULINK® Blocks
Inlet Manifold
Inlet Manifold + EGR
Exhaust Manifold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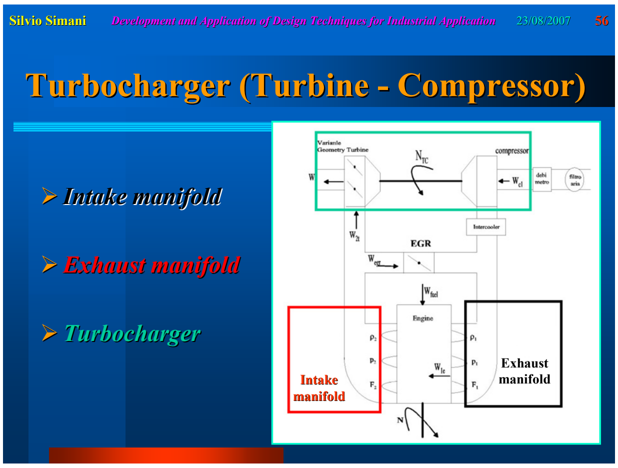
Intake Manifold (IM)
3 state variables
w_{air}
w_{egr}
m_{air}
m_{egr}
T_{man}
w_{eng}
Assumption: Ideal gas law
w_{air} : from throttle equation
w_{egr}: from EGR model
w_{eng}: flow coming in the engine
$w_{eng} = \eta_v N \frac{p_{man}}{T_{man} R_{man}} \frac{V_{eng}}{120}$
x_{egr}: EGR percentage coming in engine
$x_{egr} = \frac{m_{egr}}{m_{egr} + m_{air}}$
Mass equations
$\dot{m}_{air} = w_{air} - w_{eng} \frac{m_{air}}{m_{air} + m_{eng}}$, $\dot{m}_{egr} = w_{air} - w_{eng} \frac{m_{egr}}{m_{air} + m_{eng}}$
Energy equation
$\dot{T}_{man} = \frac{R_{man}}{V_{man} c_{vman}} (c_{pair} w_{air} T_{air} + c_{pegr} w_{egr} T_{egr} - c_{pair} w_{eng} T_{man} (1 - x_{egr}) - c_{pegr} w_{eng} T_{man} x_{egr})$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Turbocharger (Turbine - Compressor)
➢ Intake manifold
➢ Exhaust manifold
➢ Turbocharger
Varianle Geometry Turbine
compressor
N_{TC}
W
W_{c1}
debi metro
filtro aria
Intercooler
W_{2t}
EGR
W_{egr}
W_{fuel}
Engine
ρ_2
p_2
F_2
ρ_1
p_1
F_1
W_{1e}
Intake manifold
Exhaust manifold
N

Dynamic Equations

✓ **Manifold mass balance**

$$\dot{m}_1 = w_{c1} - w_{1e} + w_{egr} \qquad \dot{m}_2 = w_{1e} - w_{egr} - w_{2t} + w_{fuel}$$

✓ **Energy balance**

$$\dot{T}_1 = \frac{1}{m_1 c_{vair}} \left(w_{c1} (T_{c1} c_{pair} - T_1 c_{vair}) - w_{1e} T_1 R + w_{egr} (T_{egr} c_{pegr} - T_1 c_{vegr}) \right)$$

$$\dot{T}_2 = \frac{1}{m_2 c_{vair}} \left(w_{1e} (T_{eng} c_{pair} - T_2 c_{vair}) - w_{2t} T_2 R + w_{fuel} (T_{eng} c_{pegr} - T_2 c_{vegr}) - w_{egr} T_2 R - K_{conv} (T_2 - T_{amb}) \right)$$

✓ **Turbocharger**

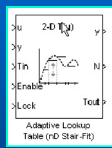
$$\dot{N}_{tc} = \frac{P_{turbine} - P_{compressor}}{N_{tc} I_{tc}}$$

$$P_{turbine} = w_{2t} c_{pegr} T_2 \eta_t \left(1 - \left(\frac{p_2}{p_0} \right)^{\frac{1-\gamma}{\gamma}} \right)$$

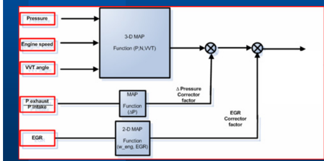
$$P_{compressor} = w_{c1} c_{pair} T_{amb} \left(\left(\frac{p_1}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \Big/ \eta_c$$

Static Maps (*i.e.* Look-up Tables)

- In MATLAB®/SIMULINK®
  - Adaptive, self tuning, self organising



Adaptive Lookup Table (nD Stair-Fit)



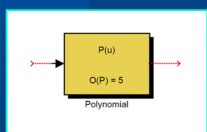
- Used for Modelling:
  - Volumetric efficiency
  - EGR valve
  - Engine temperature
  - ...

Engine Modelling Issues

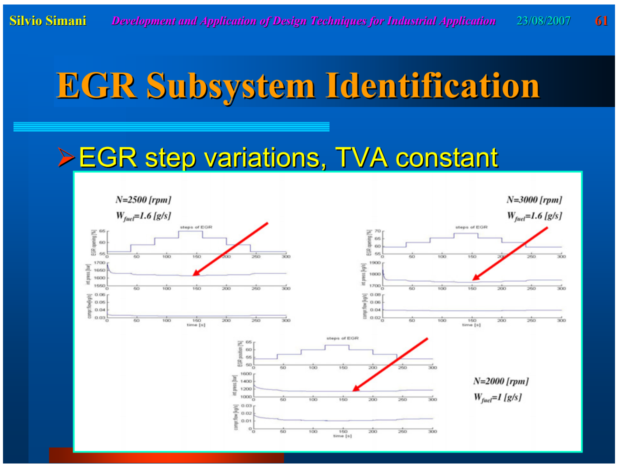
- **Engine subsystems contain unknown terms:**
  - Effective area (valves & restrictions, *i.e. EGR/TVA*): $A_{EGR}(x_{EGR})$, $A_{TVA}(x_{TVA})$
  - Volumetric efficiency (cylinder): $\eta_v(N_e, P_{im})$
  - Compressor/turbine isentropic efficiencies: $\eta_c(N_{tc}, T_{amb}, P_{im}/P_{amb})$, $\eta_t(x_{VGT}, N_{tc}, T_{em}, P_{out}/P_{em})$
  - Engine temperature: $f(N_e, W_f)$
- **Modelled with:**
  - Maps (1-D, 2-D, 3-D, …, N-D)
  - Polynomials (fixed order and coefficients to be estimated)

Polynomials (fixed order)

- In MATLAB®/SIMULINK®
  - The order is fixed *a priori*
  - Coefficients estimated via PEM strategy from input-output data



- Used for Modelling:
  - EGR/TVA effective area functions
  - VGT effective area
  - Turbine critical pressure ratio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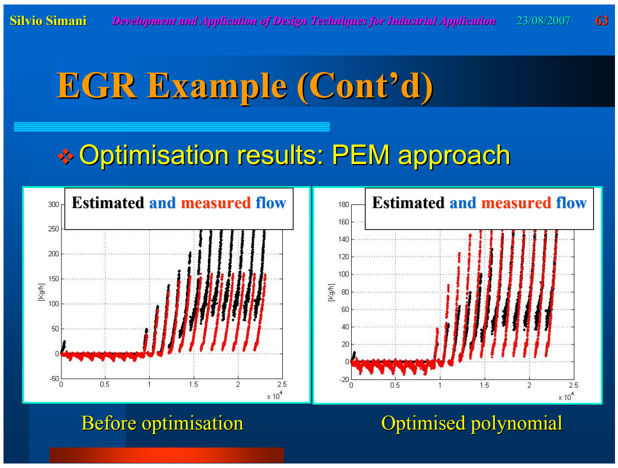
EGR Subsystem Identification
EGR step variations, TVA constant
N=2500 [rpm]
W_fuel=1.6 [g/s]
N=3000 [rpm]
W_fuel=1.6 [g/s]
N=2000 [rpm]
W_fuel=1 [g/s]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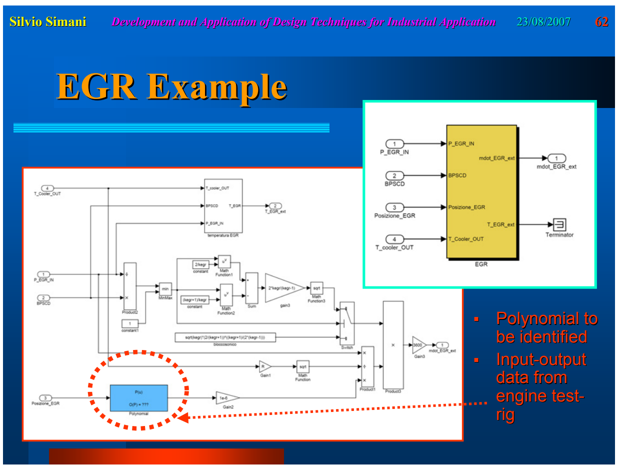
EGR Example (Cont'd)
Optimisation results: PEM approach
Estimated and measured flow
Estimated and measured flow
Before optimisation
Optimised polynomial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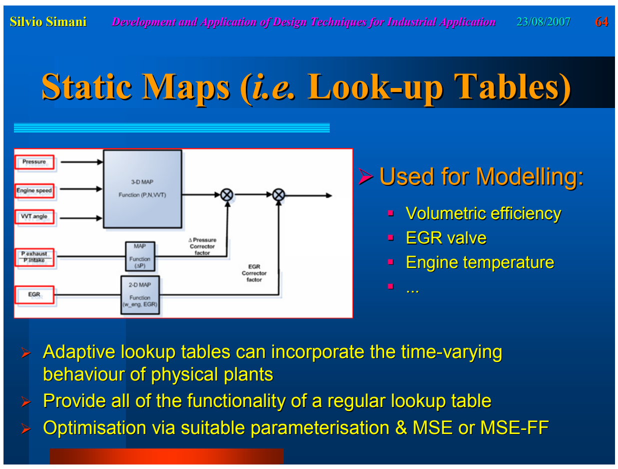
EGR Example
Polynomial to be identified
Input-output data from engine test-rig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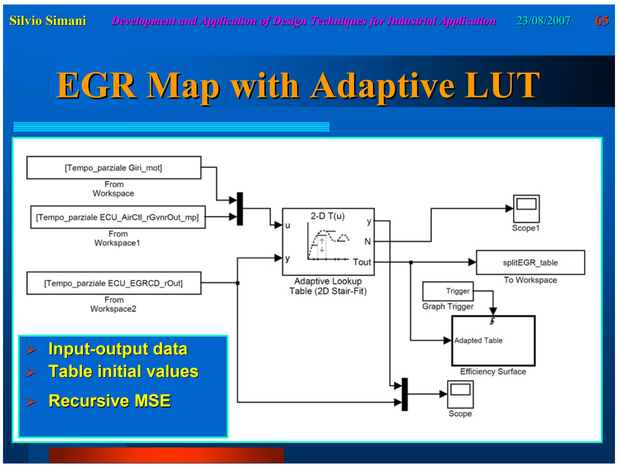
Static Maps (i.e. Look-up Tables)
Pressure
Engine speed
VVT angle
P exhaust
P intake
EGR
3-D MAP
Function (P,N,VVT)
MAP
Function
2-D MAP
Function
Pressure Corrector factor
EGR Corrector factor
Used for Modelling:
Volumetric efficiency
EGR valve
Engine temperature
...
Adaptive lookup tables can incorporate the time-varying behaviour of physical plants
Provide all of the functionality of a regular lookup table
Optimisation via suitable parameterisation & MSE or MSE-FF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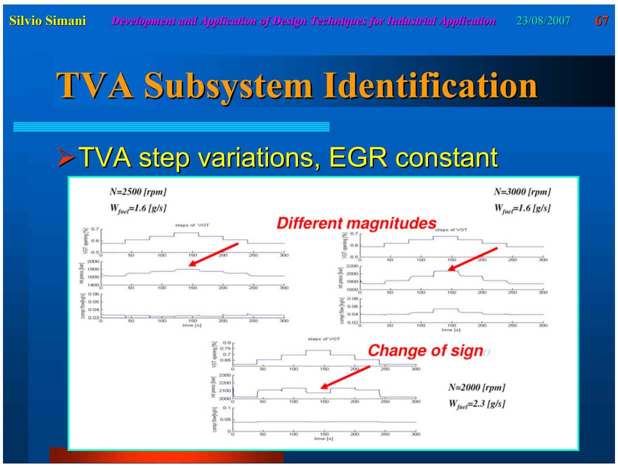
EGR Map with Adaptive LUT
[Tempo_parziale Giri_mot]
From Workspace
[Tempo_parziale ECU_AirCtl_rGvnrOut_mp]
From Workspace1
[Tempo_parziale ECU_EGRCD_rOut]
From Workspace2
2-D T(u)
Adaptive Lookup Table (2D Stair-Fit)
Scope1
splitEGR_table
To Workspace
Trigger
Graph Trigger
Adapted Table
Efficiency Surface
Scope
Input-output data
Table initial values
Recursive MSE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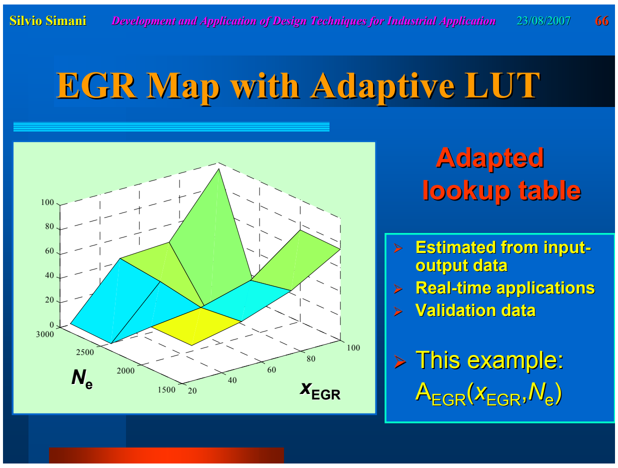
67
TVA Subsystem Identification
TVA step variations, EGR constant
N=2500 [rpm]
N=3000 [rpm]
Different magnitudes
Change of sign
N=2000 [rpm]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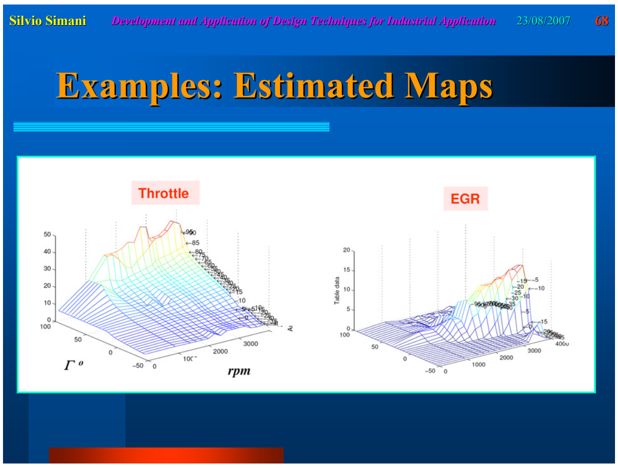
EGR Map with Adaptive LUT
Adapted lookup table
Estimated from input-output data
Real-time applications
Validation data
This example:
$A_{EGR}(x_{EGR},N_e)$
N_e
x_{EGR}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Examples: Estimated Maps
Throttle
EGR
rpm

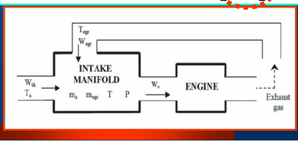
Mathematical Model

✓ The model, ignoring some additional dynamics and transport delays, takes the form:

$$\begin{cases}\dot{x} = f(x,u) \\ y = h(x,u)\end{cases} \quad \text{where}: x = \begin{bmatrix} T_{man} \\ m_{air} \\ m_{egr} \end{bmatrix},\ u = \begin{bmatrix} N \\ \alpha \\ T_{asp} \\ x_{egr} \\ x_{TVA} \end{bmatrix},\ y = \begin{bmatrix} AMF \\ P_{man} \end{bmatrix}$$

External inputs (N, α, T_{asp})

Control inputs (x_{egr}, x_{TVA})



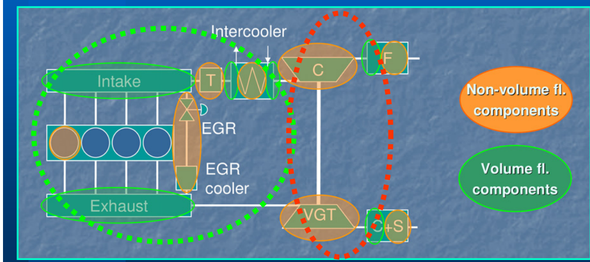
Problems

- Some state and output variables are not measured.
- Many static functions (maps, look-up tables) are derived from data and do not have an explicit mathematical form.

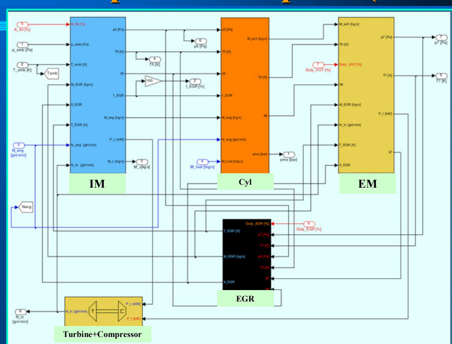
Engine Complete Description

- **Requirements**
  - ✓ EGR
  - ✓ TVA
  - ✓ IM/EM
    - ❖ Almost done!
  - ❑ Cylinders: Volumetric efficiency
  - ❑ Turbine + Compressor: flow & efficiency maps
  - ❑ Coolers: efficiency parameters
    - ❖ To be completed: lack of the test-rig

Engine Complete Description (Cont'd)



Engine Complete Description (Cont'd)



Diesel Engine Black-Box Modelling

Fuzzy Systems

Fuzzy Modelling - FMID

Brief Overview

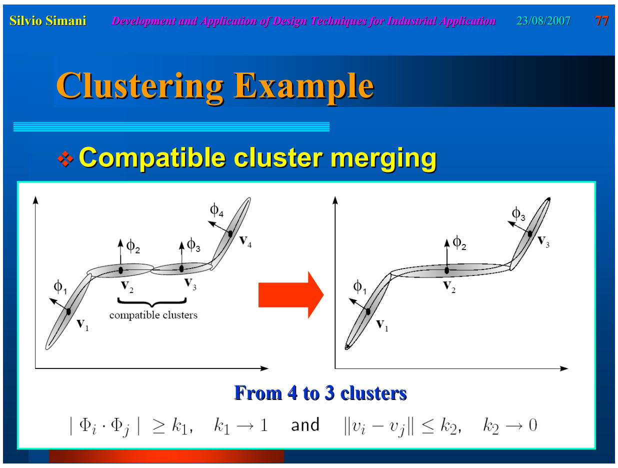
- A cluster is a set of objects that are more similar to each other than to objects from other clusters
- Applications of clustering techniques in pattern recognition and image processing
- Some machine-learning techniques are based on the notion of similarity (decision trees, case-based reasoning)
- Nonlinear regression and black-box modelling can be based on the partitioning data into clusters

FMID – Problem Formulation

- Given is a set of data in R^n and the (estimated) number of clusters to look for
- 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
- Usually, each cluster will have a prototype and the distance is measured from this prototype

FMID – Problem Formulation (Cont'd)

- Fuzzy clustering: an optimisation approach subject to constraints
- Uses the Fuzzy c-Means Algorithm
  - Cluster prototype computation
  - Distance computation
  - Partition matrix update
- **Gustafson-Kessel Algorithm**
  - Number of cluster optimisation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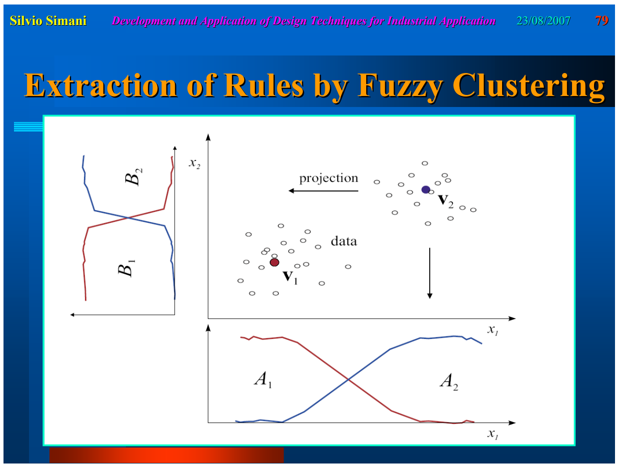
Clustering Example
Compatible cluster merging
compatible clusters
From 4 to 3 clusters
$|\Phi_i \cdot \Phi_j| \geq k_1, \quad k_1 \to 1$ and $\|v_i - v_j\| \leq k_2, \quad k_2 \to 0$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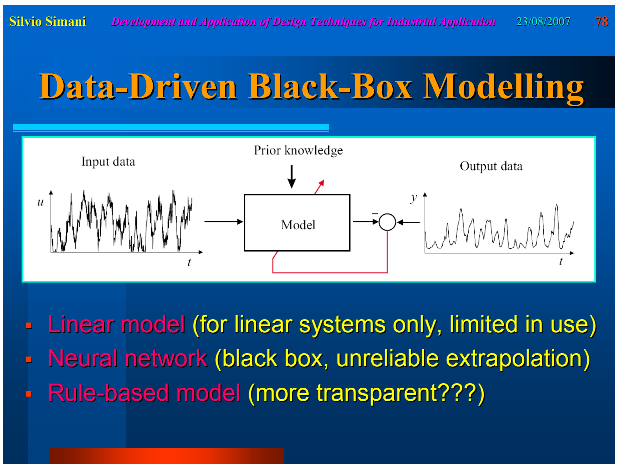
Extraction of Rules by Fuzzy Clustering
projection
data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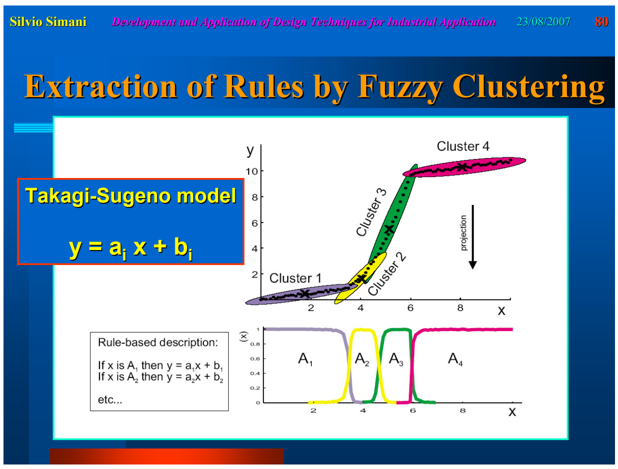
Data-Driven Black-Box Modelling
Input data
Prior knowledge
Output data
Model
Linear model (for linear systems only, limited in use)
Neural network (black box, unreliable extrapolation)
Rule-based model (more transparent???)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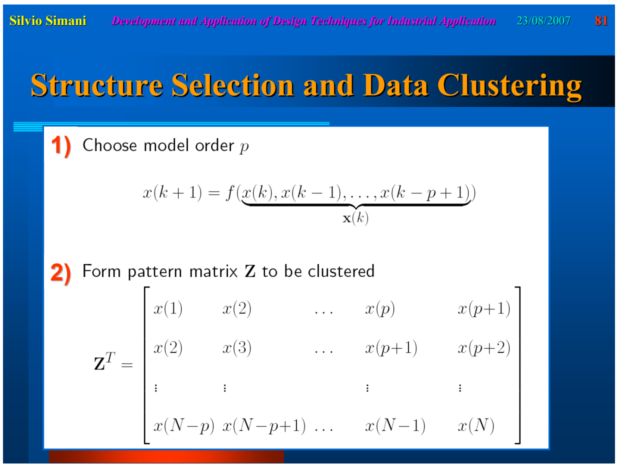
Extraction of Rules by Fuzzy Clustering
Takagi-Sugeno model
$y = a_i x + b_i$
Cluster 1
Cluster 2
Cluster 3
Cluster 4
projection
Rule-based description:
If x is A_1 then $y = a_1x + b_1$
If x is A_2 then $y = a_2x + b_2$
etc...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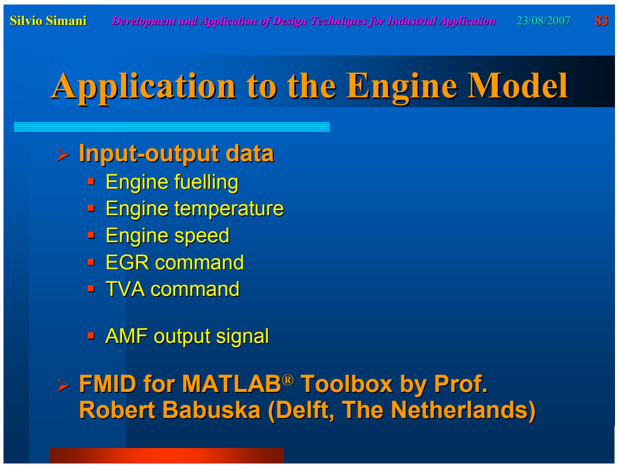
Structure Selection and Data Clustering
1) Choose model order p
x(k+1) = f(x(k), x(k−1), ..., x(k−p+1))
x(k)
2) Form pattern matrix Z to be clustered
Z^T =
x(1) x(2) ... x(p) x(p+1)
x(2) x(3) ... x(p+1) x(p+2)
x(N−p) x(N−p+1) ... x(N−1) x(N)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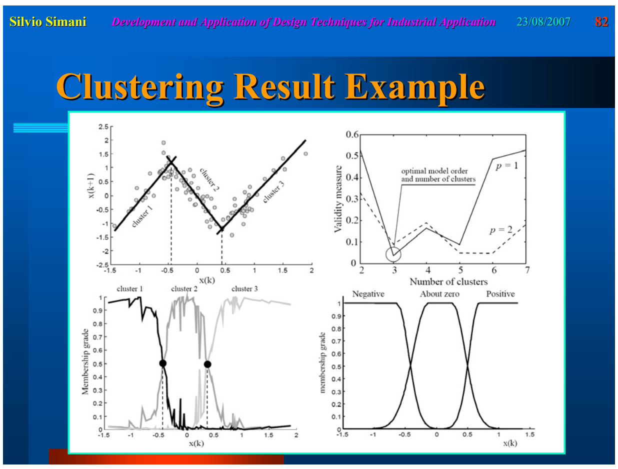
Application to the Engine Model
Input-output data
Engine fuelling
Engine temperature
Engine speed
EGR command
TVA command
AMF output signal
FMID for MATLAB® Toolbox by Prof. Robert Babuska (Delft, The Netherlands)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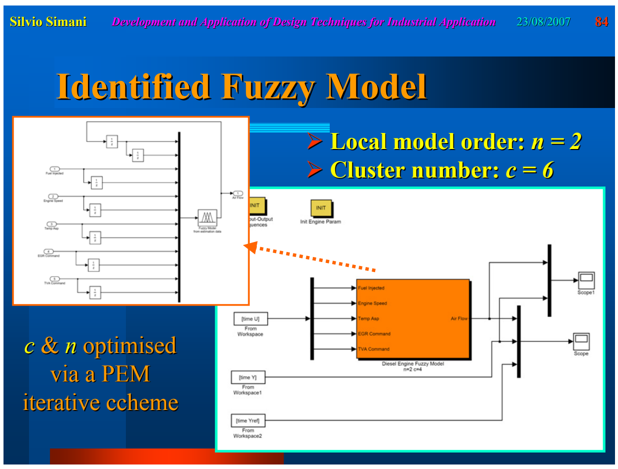
Clustering Result Example
x(k+1)
x(k)
cluster 1
cluster 2
cluster 3
Validity measure
optimal model order and number of clusters
p = 1
p = 2
Number of clusters
Membership grade
Negative
About zero
Positive
membership grade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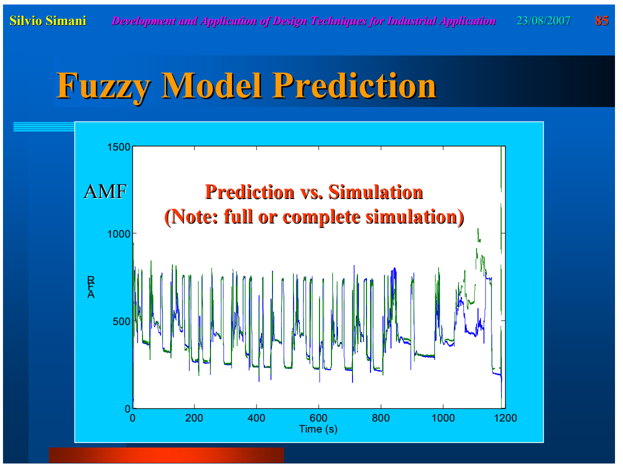
84
Identified Fuzzy Model
Local model order: n = 2
Cluster number: c = 6
c & n optimised via a PEM iterative ccheme
Diesel Engine Fuzzy Model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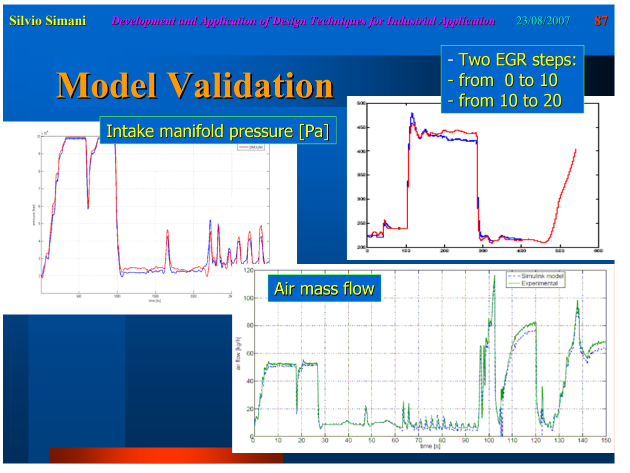
85
Fuzzy Model Prediction
AMF
Prediction vs. Simulation
(Note: full or complete simulation)
Time (s)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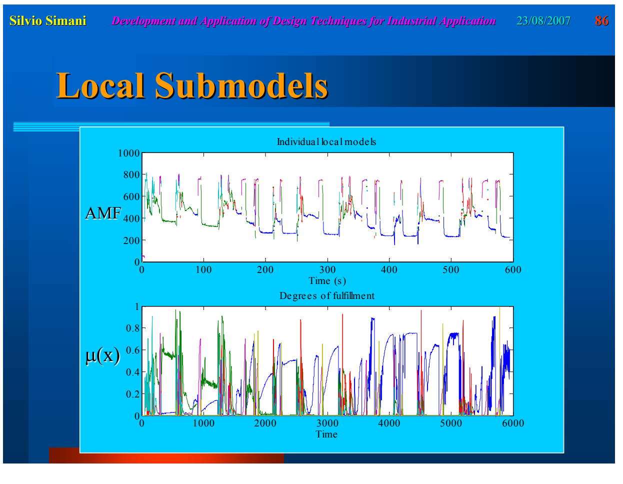
Model Validation
- Two EGR steps:
- from 0 to 10
- from 10 to 20
Intake manifold pressure [Pa]
Air mass flow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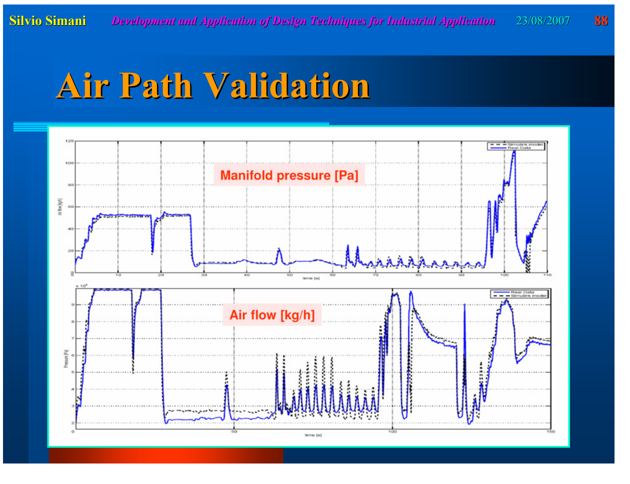
Local Submodels
Individual local models
AMF
Time (s)
Degrees of fulfillment
μ(x)
Time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Air Path Validation
Manifold pressure [Pa]
Air flow [kg/h]


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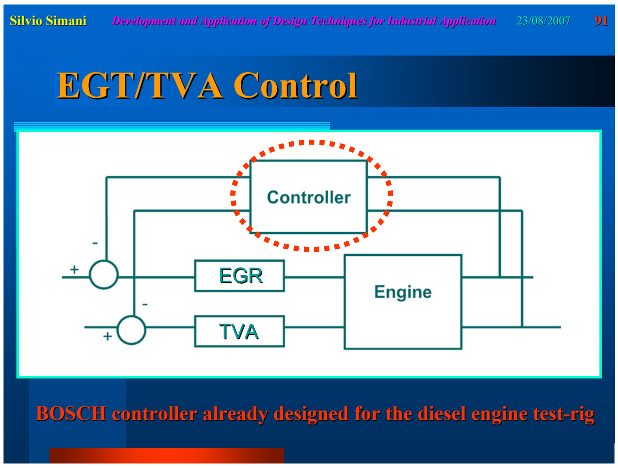
Control Scheme "Design"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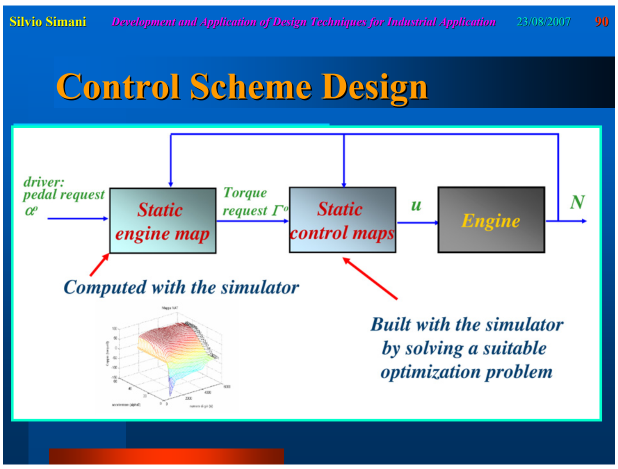
EGT/TVA Control
Controller
EGR
TVA
Engine
BOSCH controller already designed for the diesel engine test-rig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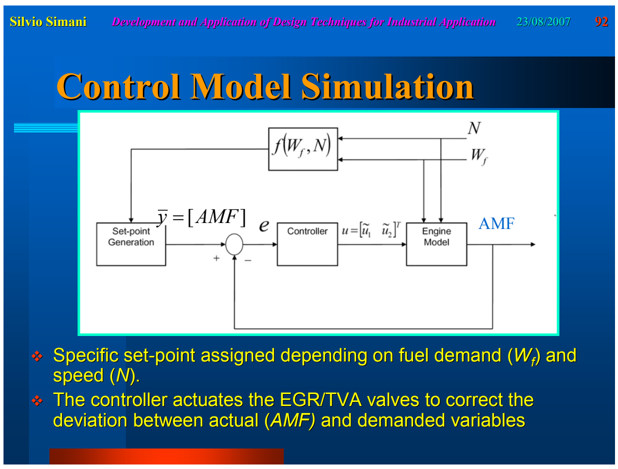
Control Scheme Design
driver:
pedal request
Static
engine map
Torque
request
Static
control maps
u
Engine
N
Computed with the simulator
Built with the simulator
by solving a suitable
optimization problem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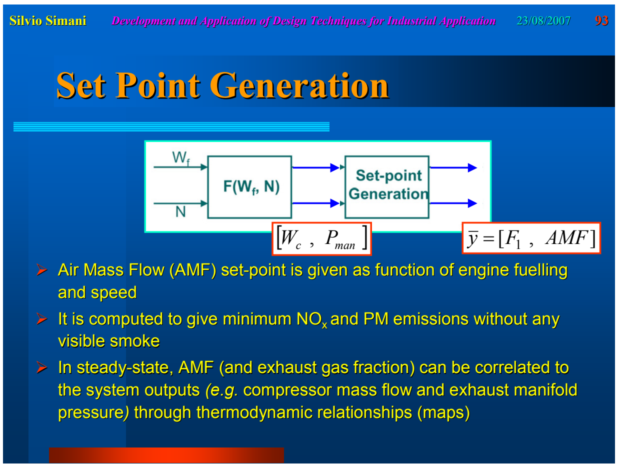
Control Model Simulation
N
W_f
$f(W_f, N)$
Set-point
Generation
$\bar{y} = [AMF]$
e
Controller
$u = [\tilde{u}_1 \quad \tilde{u}_2]^T$
Engine
Model
AMF
Specific set-point assigned depending on fuel demand (W_f) and speed (N).
The controller actuates the EGR/TVA valves to correct the deviation between actual (AMF) and demanded variables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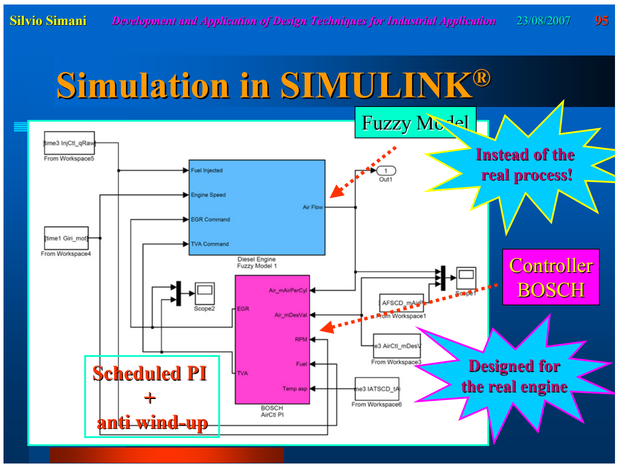
Set Point Generation
W_f
N
F(W_f, N)
Set-point Generation
[W_c , P_man]
y = [F_1 , AMF]
Air Mass Flow (AMF) set-point is given as function of engine fuelling and speed
It is computed to give minimum NO_x and PM emissions without any visible smoke
In steady-state, AMF (and exhaust gas fraction) can be correlated to the system outputs (e.g. compressor mass flow and exhaust manifold pressure) through thermodynamic relationships (maps)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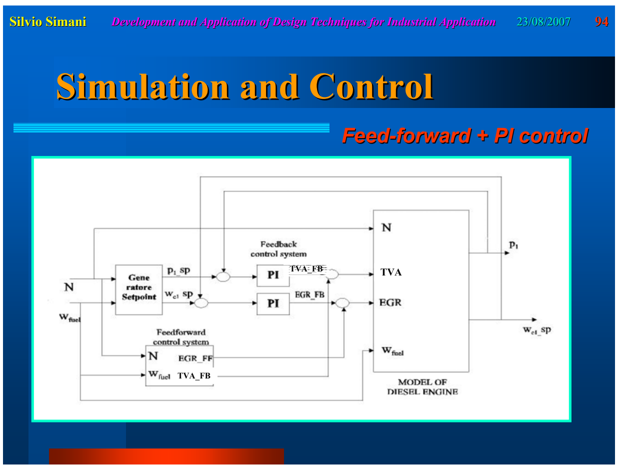
95
Simulation in SIMULINK®
Fuzzy Model
Instead of the real process!
Controller BOSCH
Designed for the real engine
Scheduled PI + anti wind-up
Diesel Engine Fuzzy Model 1
BOSCH AirCtl PI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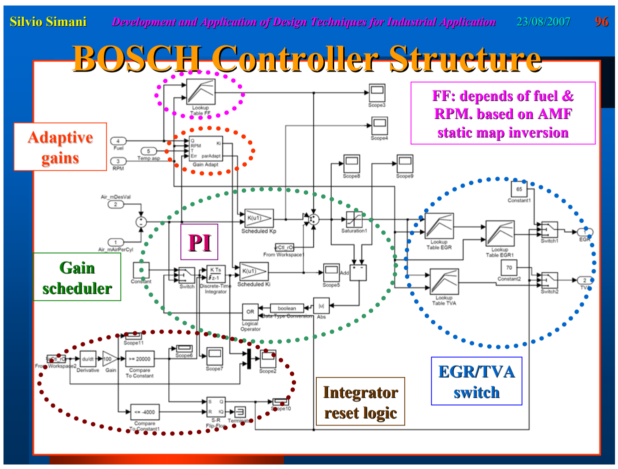
94
Simulation and Control
Feed-forward + PI control
N
W_fuel
Gene rator Setpoint
P_1_sp
W_c1_sp
Feedback control system
PI
PI
TVA_FB
EGR_FB
Feedforward control system
N
W_fuel
EGR_FF
TVA_FB
N
TVA
EGR
W_fuel
P_1
W_c1_sp
MODEL OF DIESEL ENGINE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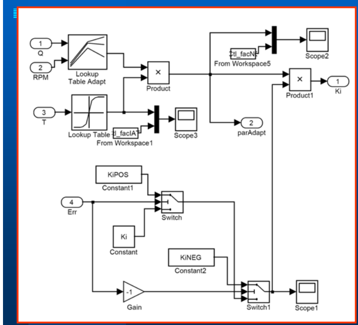
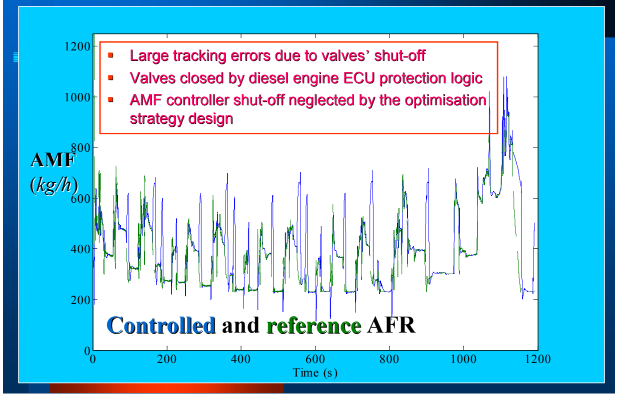
BOSCH Controller Structure
Adaptive gains
FF: depends of fuel & RPM. based on AMF static map inversion
PI
Gain scheduler
EGR/TVA switch
Integrator reset logic

Parameter Adaptation *(Gain Adapt)*

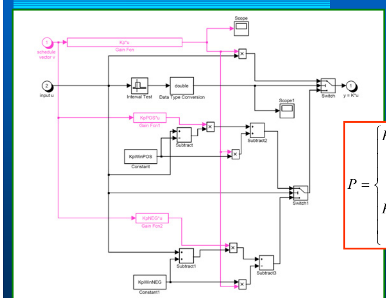


- The main idea is to correct the PI gains (Ki & Kp) on the basis of the error value and precompiled static maps
- Depends on engine fuelling, RPM, asp. temp & tracking error (actual and desired MAF)
- Fixed thresholds (KiPOS & KiNEG)
- Values in [1 – 1.5]

Simulation Results *(EU Driving Cycle)*



Gain Scheduler



- 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 Enhancement

Design Strategy

Controller Enhancement

- **Some ideas and suggestions**
  - Gain-scheduling – attractive, conceptually simple method
  - Local model → local controller, interpolation
  - Stable design example (mainstream literature):

$$\dot{x}(t) = \sum_{i=1}^{c} w_i(x)\left(A_i - B_i K_i\right)x(t)$$

  - Important issue: design of weighting functions
  - Significant gain in performance possible

Possible Controller Design

Local controller parameters:

C = *D*(G;*H*)

- *D* design method (pole placement, optimisation, etc.)
- *H* performance specification (closed-loop reference model)

✓ Model G weighting functions are usually shared by the controller C weighting functions

✓ ⇒ Sub-optimal closed-loop behaviour

Controller Enhancement

- **Schedule model parameters**, design controller on-line:

  C(**z**) = *D*(**g**(**z**); *H*), ∀**z**

- Can be infeasible for computationally demanding design methods, or for methods requiring interaction of the designer
- **Design optimal weighting functions** (off-line)

Technology

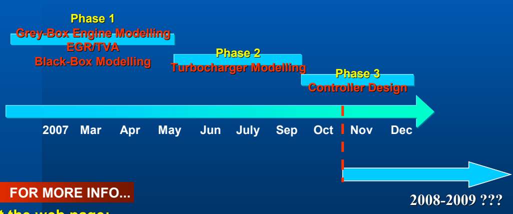
- Diesel engine test-rig
  - Engine model type???
- MATLAB®/SIMULINK®
  - Calibration, optimisation; model, controller analysis, simulation and design
- ATI VISION™
  - Integrated calibration measurement solution for accessing ECUs
  - Table calibration
  - Memory emulation (microcontrollers)
  - On target rapid prototyping
  - MATLAB®/SIMULINK® interface

Team/Resources

- Resources allocated to this project
  - ✓ 2 academics
  - ✓ 1 Ph.D.
  - ✓ 1 graduated student
  - ✓ 3 employees of
  - ✓ VM Motors (Cento, Italy)
  - ✓ PCs, software, engine test-rig

Suggested Schedule

- Scheduled milestones



FOR MORE INFO...

Visit the web page:

`www.ing.unife.it/simani/nlw2007.html`

Alternative Procedures

- Related HD diesel engine control literature:
  - Model-based predictive controller
  - H_∞ robust controller
  - Fuzzy controller
  - Neural networks
  - Adaptive observer & controller
  - Sliding mode controller
  - Gain scheduling state-feedback + LMI

Current Status

- Progress against schedule
  - EGR/TVA description and modelling
  - Turbocharger modelling
  - Controller design
- Delays or difficult issues
  - Maps and lookup tables
  - GUI and ECU interface (“by-pass” software)
  - Engine test-rig

Conclusion

- TVA/EGR controller design
- Diesel engine modelling
  - Subsystems estimation and calibration
  - TVA, EGR, IM and EM (grey-box) modelling
- Application of the existent control law to the identified engine model
  - Black-box modelling
- Preliminary modelling and simulation results
- Future actions

Further Studies and Open Problems

- Built up the complete model of a multi-cylinder HD diesel engine with VGT
  - Turbocharger and related maps
- Design the control law and its implementation scheme for the complete dynamic model
  - Control law with the real engine
    - Closing the loop by *virtual sensors*???
    - Comparison with different control strategies???
- Perform response and parametric uncertainty analysis