# Actuator fault diagnosis with application to a diesel engine test bed

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SCODECE
Smart COntrol & Diagnosis for Economical & Clean Engine

# SCODECE

**Smart COntrol & Diagnosis for Economical & Clean Engine**

VERS UN MOTEUR DIESEL NOUVELLE GENERATION

A NEW GENERATION OF DIESEL ENGINES

HEI INGÉNIEURS POUR LE MONDE

US University of Sussex

UNIVERSITÉ de Picardie Jules Verne

2 Mers Seas Zeeën INTERREG IV A

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RÉGION Nord-Pas de Calais

# INTERREG IVA : 05 025 FR SCODECE

## Smart Control and Diagnosis for Economic and Clean Engine

- **Début:** **Juin 2010** **Fin:** **Decembre 2013**
- **Partenaires académiques :** **HEI Lille (Leader), UPJV-MIS Amiens, UoS (Brighton)**
- **Partenaire industriel :** **TECHNORD Tournai (Belgique)**
- **Personnel Technique impliqué: HEI (5), UPJV (6), UoS (5)**
- **Objectifs :** **Réduction de 20% de particules polluantes**
  **Réduction de 10% consommation de carburant**
- **Site Web:** **http://www.scodece.org**
- http://www.youtube.com/watch?v=Ya3aRduOCR4

SCODECE
Smart COntrol & Diagnosis for Economical & Clean Engine

# INTERREG IVA : 05 025 FR SCODECE

## Problematic

Driver

NOx, CO,…

**Reduce pollutant emissions whatever the engine load**

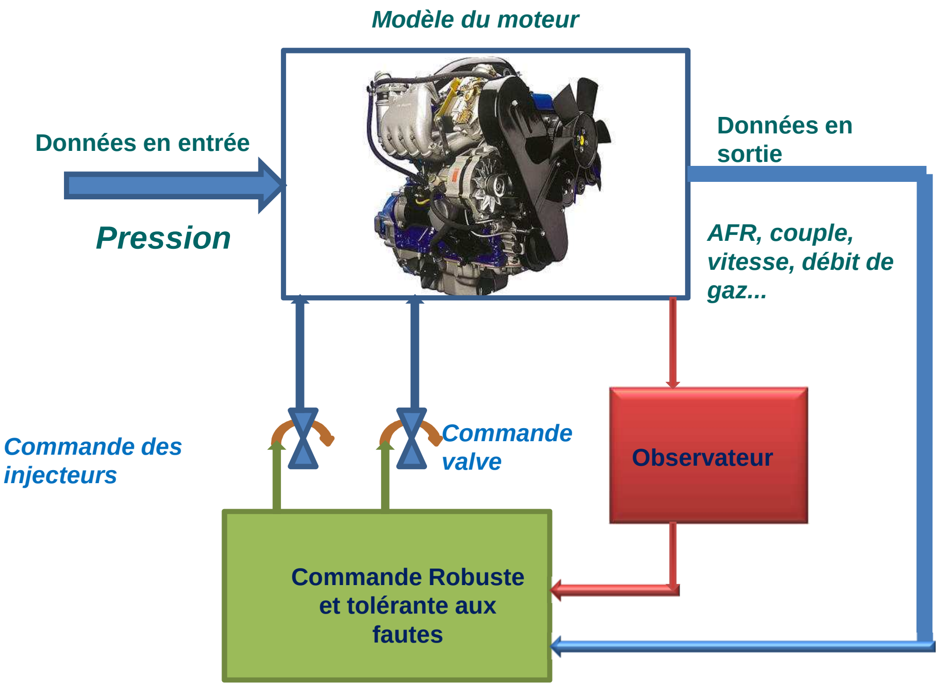
**<u>Reduce the fuel consumption</u>**

# ACTIVITES

## Activité 1

- Travaux d'identification du modèle du moteur
- CFD Simulation du facteur d'homogénéité comme

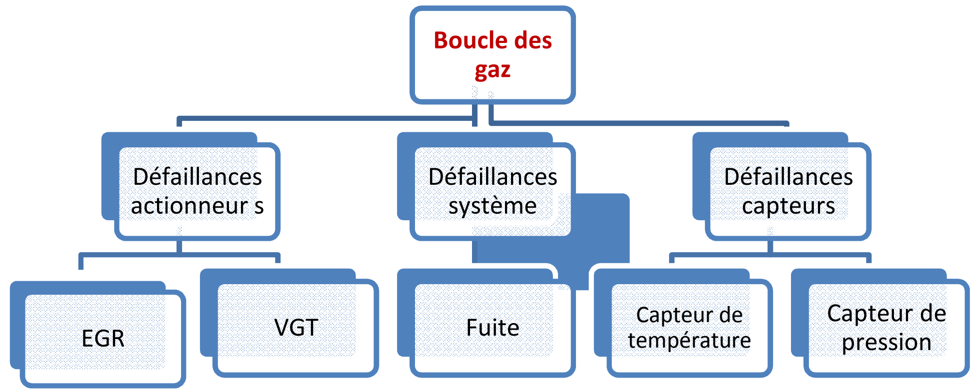
  un contrôleur basé sur un modèle moyen
- Simulation de commande du moteur à combustion
- Développement de commande avancée (LPV, TS, Hinf, etc..)

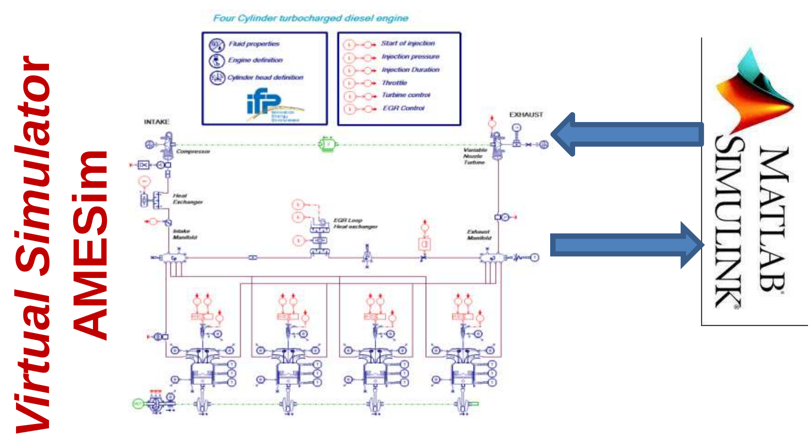


# ACTIVITES

## Activité 2

- **Analyse structurelle et par arbre de défaillances**
- **Surveillance de la boucle d'air et de fuel**
- **Commande Tolérante aux fautes active**



# Engine Faults

- **Malfunction causes:**

  **Design errors, implementation errors, human operator errors, wear, aging, environmental aggressions.**

- **Type of faults:**

  - **Actuator faults : EGR-valve position and VGT vane position**
  - **Sensor faults : exhaust gas pressure, inlet manifold gas pressure, etc..**
  - **System Dysfunction : fuel leakage, air leakage**

# Activité 3: Testbed
# Caterpillar 3126 Midrange Truck Engine

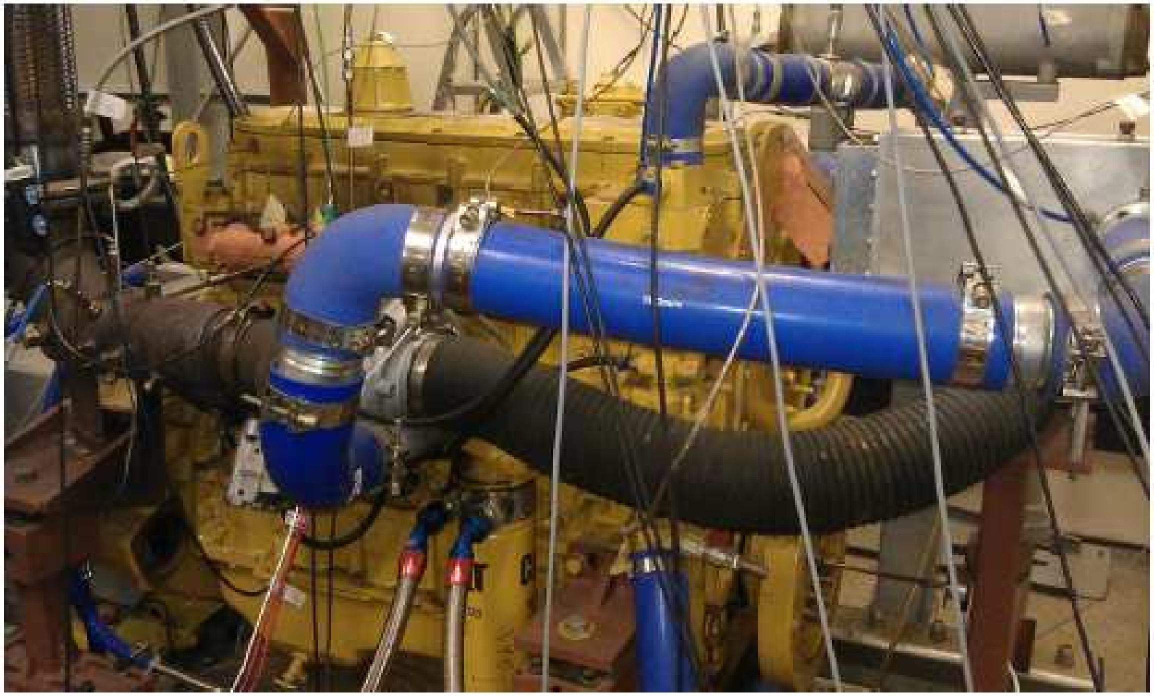
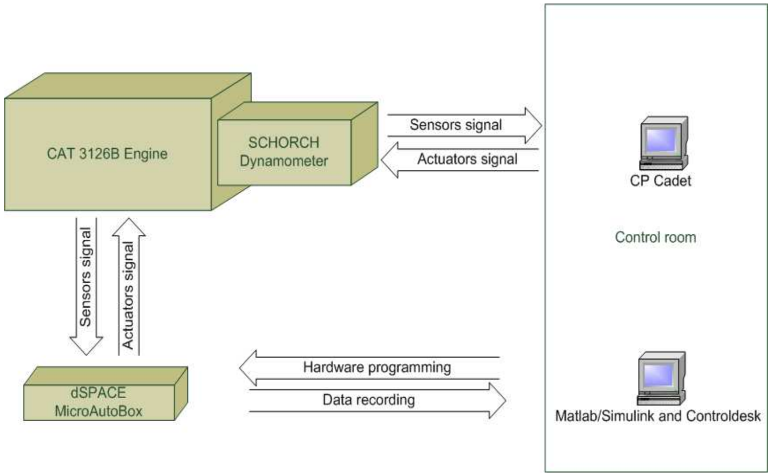
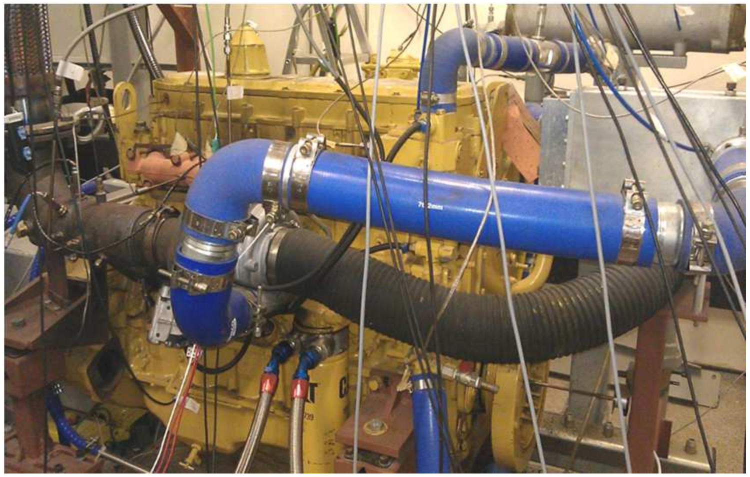


Fig. 1. Caterpillar testbed 3126, Sussex university

# Caterpillar 3126B test bed

| | |
|---|---|
| **Model** | CAT3126B |
| **Stroke** | 127mm |
| **Bore** | 110mm |
| **Displacement** | 7.25L |
| **Number of cylinders** | 6 |
| **Cylinder arrangement** | In-line |
| **Connecting Rod** | 199.9mm |
| **Crank throw radius** | 63.5mm |
| **Compression ratio** | 14.5:1 |
| **Number of Inlet valves** | 2 |
| **Number of Exhaust valves** | 1 |
| **Type of combustion** | Direct Injection |
| **Firing order** | 1-5-3-6-2-4 |
| **Dry weight** | 588Kg |

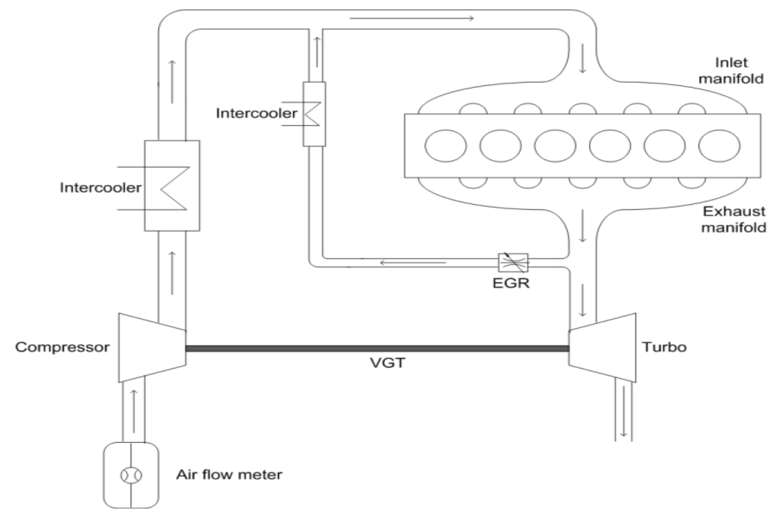


# Considered Air-Path system

Function of VGT:

1. Primarily used to reduce turbo lag at low engine speed;
2. Help to introduce the EGR technology.

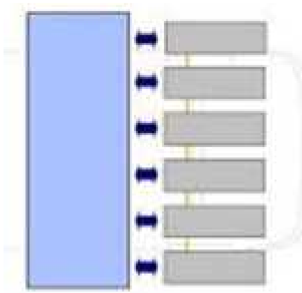



Function of EGR:

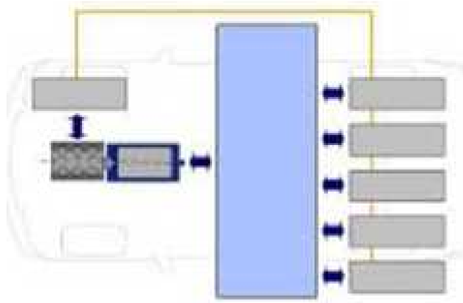
1. To reduce NOx emission for diesel engines. (Oxygen and nitrogen tend to combine and form NOx when the immediate surrounding temperature exceed 1370 ℃.
2. During the normal combustion process, the temperature in the cylinder will go well above this[1])

1. Instability at low engine speed
2. Torque suffered at high load demand

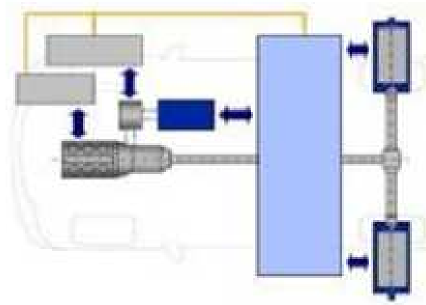
# Different stages of the Validation process (V-diagram)



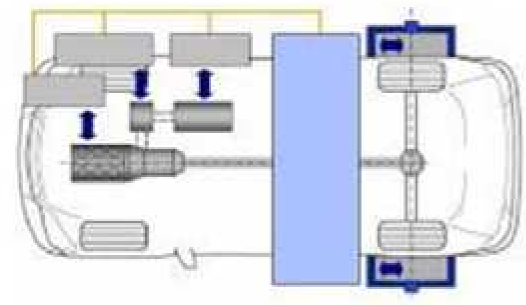
**HIL**



**Engine in the Loop**



**Power train in the Loop**

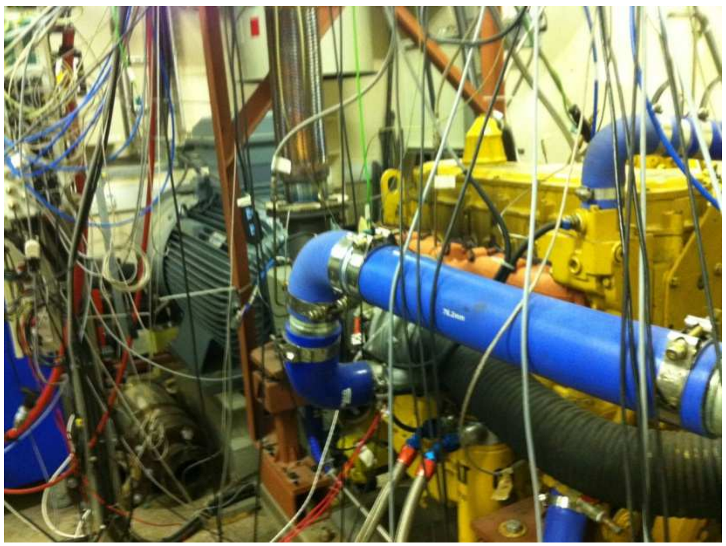


**Vehicule in the Loop**

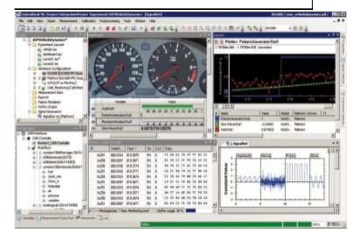
Optimization and validation of :

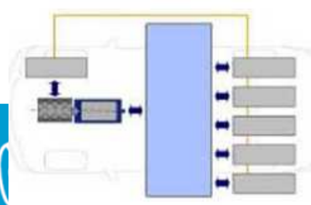
- Emission,
- Fuel consumption
- Drivability

# *Engine in the Loop?*



MATLAB SIMULINK

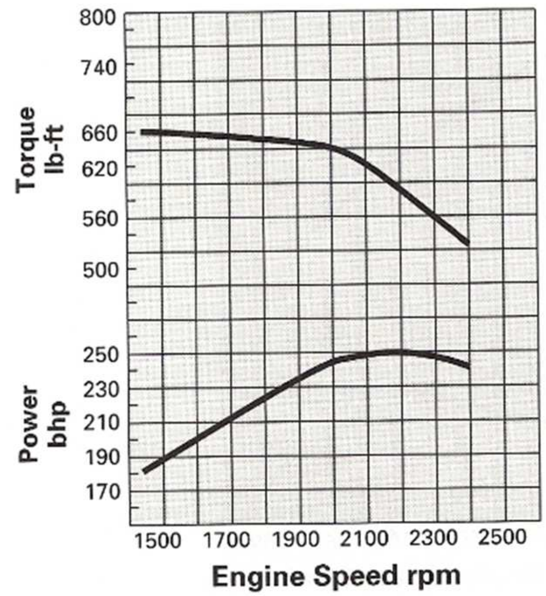




# Caterpillar 3126 Midrange Truck Engine

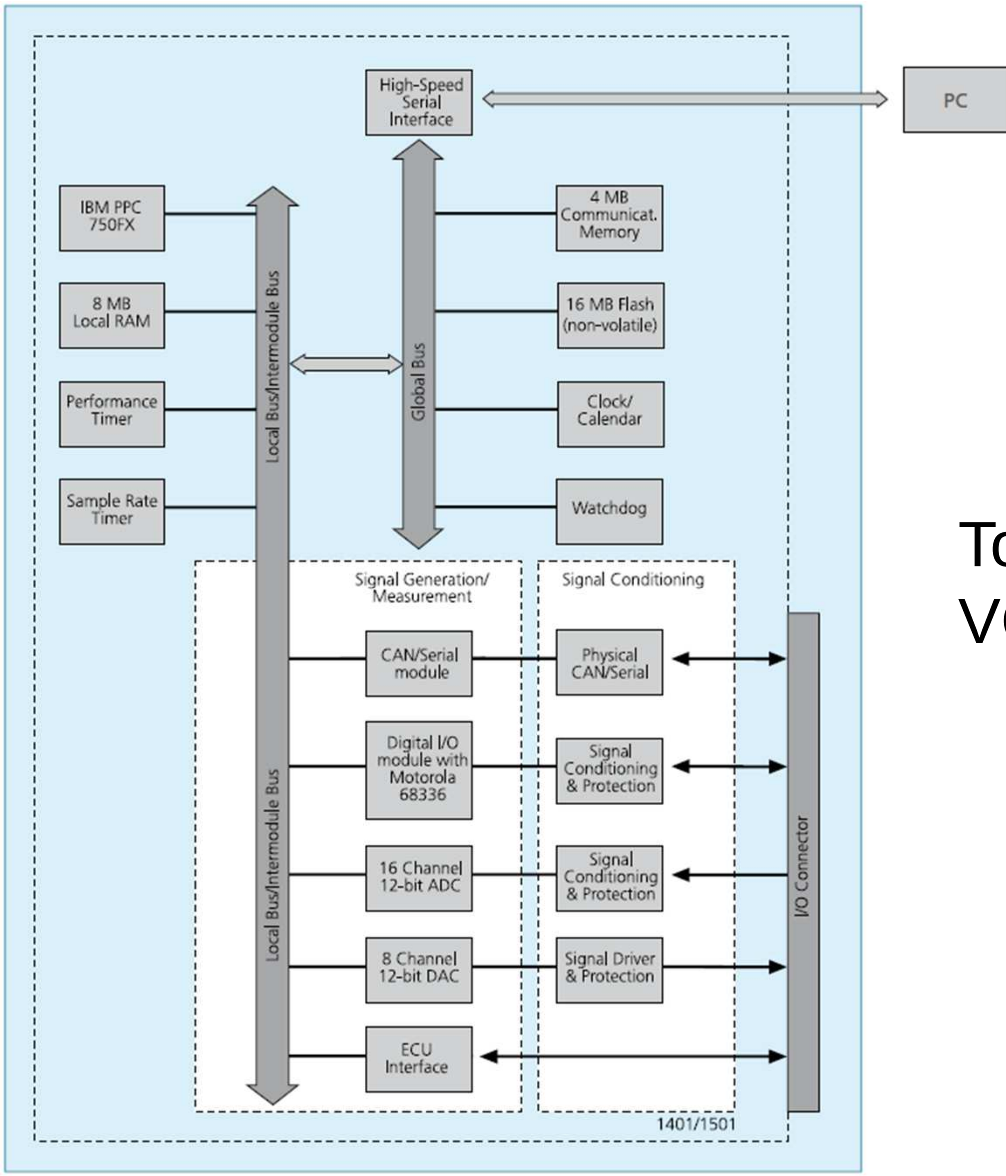
**Parameters**

- In-Line 6-Cylinder Diesel
  - Bore: 110mm
  - Stroke: 127mm
  - Total Displacement: 7.2L
  - Dry Weight: 588kg




| | |
|---|---|
| Rated hp (kW) | 250 (186) |
| Rated rpm | 2200 |
| Governed rpm | 2400 |
| Low Idle rpm | 700 |
| Operating Range (rpm) | 960 |
| Altitude Capability – ft (m) | 10 000 (3050) |
| Peak Torque – lb-ft (N•m) | 660 (895) |
| Peak Torque rpm | 1440 |
| Torque Rise (% from governed speed) | 26 |

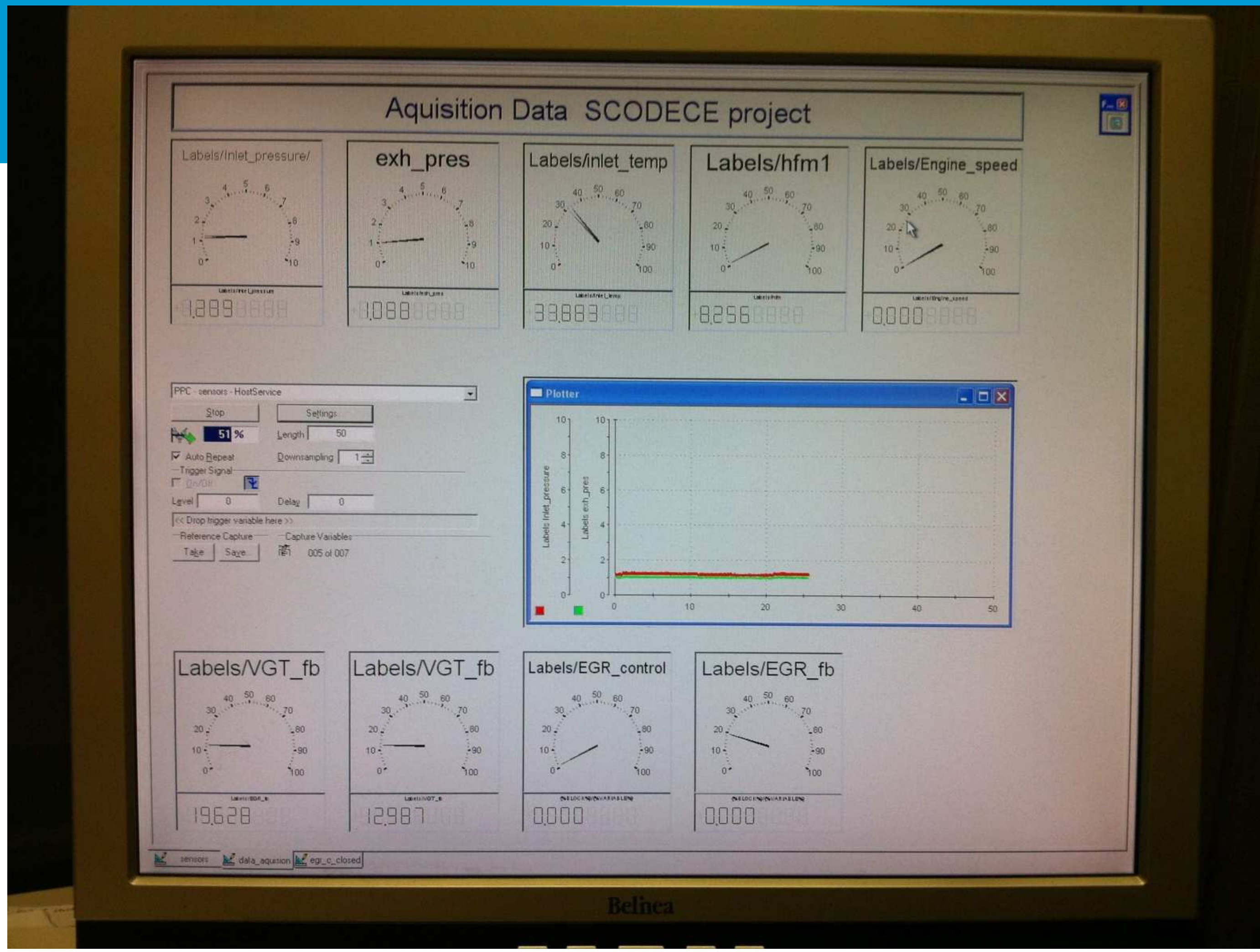
# MicroAutoBox 1401/1501

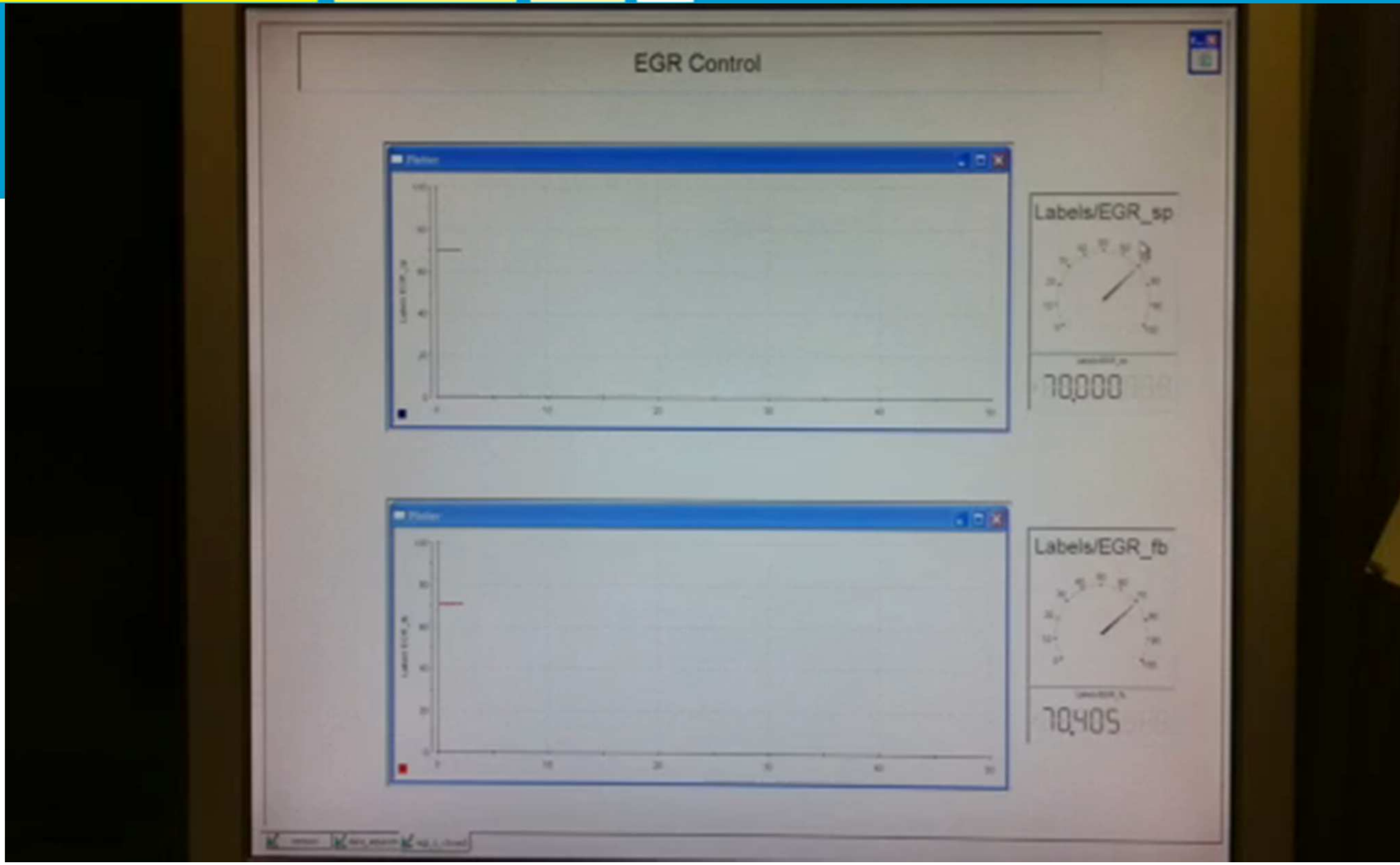



To Control the EGR and VGT

# Sensors wiring to MicroAutobox

- Analog Input Type
  - Temperature sensor
  - Pressure sensor
  - EGR feedback sensor
  - VGT feedback sensor
  - Flow meter
- Digital Input Type
  - Encoder
- Analog Output Type
  - EGR drive
  - VGT drive


Aquisition Data SCODECE project
Labels/Inlet_pressure/
exh_pres
Labels/inlet_temp
Labels/hfm1
Labels/Engine_speed
Plotter
Labels/VGT_fb
Labels/VGT_fb
Labels/EGR_control
Labels/EGR_fb
Belinea


EGR Control
Labels/EGR_sp
70,000
Labels/EGR_fb
70,405

# Outline

- **Problem formulation**
- **Engine model**
- **Model validation**
- **Residual generation**
- **Decision system**

# Problem formulation

- **Model-based fault detection and isolation systems requires physical models**
- **Diesel engines are complex systems**

  ↳ **It contains two parts : linear parameter varying (LPV) and a high nonlinear part having a large Lipschitz constant,**

- **Presence of disturbances and unknown parameters**
- **Actuator faults : EGR-valve position (EGR) and vane position VGT**

# Highlights

The contribution of the proposed work can be summarized as follows:

- The proposed method concerns a more general class of nonlinear parameter varying systems with unknown inputs for which the literature in this field is very limited.
- The problem of fault detection for nonlinear parameter varying systems with unknown inputs has been investigated. The advantage of the proposed method is that no a priori assumption on the unknown input is required
- The perturbations are also considered in this work;
- The sufficient conditions of the existence of the NUIO are formulated, in an elegant way, in terms of linear matrix inequalities
- The MMVD (Modied Mean Value Theorem) approach is used for reducing the number of LMIS to solve;
- The performances are applied in the tesbed

# Considered Air-Path system

Le moteur considéré dans ce travail est un moteur diesel à 4 cylindres équipé par la vanne de recyclage des gaz d'échappement (RGR) et du turbocompresseur à géométrie variable (VGT).

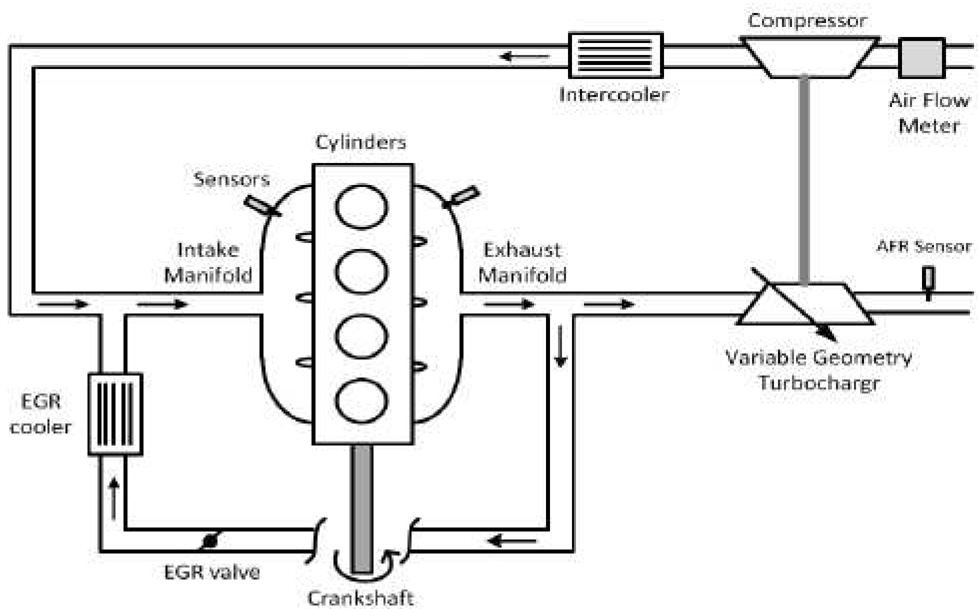



FIGURE: Schéma de la boucle d'air

# Engine model

$$
\begin{aligned}
\dot{P}_{Inlet} &= \frac{1}{V_{Inlet}}\left(\frac{R_{Air}c_{p,Air}}{c_{v,Air}}W_{HFM}T_{CAC}\right.\\
&\quad +\frac{R_{Exh}c_{p,Exh}}{c_{v,Exh}}W_{EGR}T_{EGR}\\
&\quad \left.-\frac{R_{Inlet}c_{p,Inlet}}{c_{v,Inlet}}W_{Inlet}T_{Inlet}\right)\\
\dot{m}_{Air} &= W_{HFM}-\frac{m_{Air}}{m_{Air}+m_{EGR}}W_{Inlet}\\
\dot{m}_{EGR} &= W_{EGR}-\frac{m_{EGR}}{m_{Air}+m_{EGR}}W_{Inlet}\\
\dot{m}_{Exh} &= W_{Exh}-W_{Turb}-W_{EGR}
\end{aligned}
$$

with

$$
\Psi\left(\frac{p_1}{p_0}\right) = \begin{cases} \sqrt{\frac{2\kappa}{\kappa-1}\left\{\left(\left(\frac{p_1}{p_0}\right)^{\frac{2}{\kappa}}-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa+1}{\kappa}}\right)\right\}} \\ if\left(\frac{p_1}{p_0}\right)\geq\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \\ \sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \quad otherwise, \end{cases}
$$

**Where:**

- **Pressure in intake manifold :** $P_{inlet}$
- **Air mass flow :** $m_{Air}$
- **EGR mass flow :** $m_{EGR}$
- **Exhaust mass flow :** $m_{Exh}$

# Engine model

$$
\begin{aligned}
\dot{P}_{Inlet} &= \frac{1}{V_{Inlet}}\left(\frac{R_{Air}c_{p,Air}}{c_{v,Air}}W_{HFM}T_{CAC} + \frac{R_{Exh}c_{p,Exh}}{c_{v,Exh}}W_{EGR}T_{EGR} - \frac{R_{Inlet}c_{p,Inlet}}{c_{v,Inlet}}W_{Inlet}T_{Inlet}\right) \\
\dot{m}_{Air} &= W_{HFM} - \frac{m_{Air}}{m_{Air}+m_{EGR}}W_{Inlet} \\
\dot{m}_{EGR} &= W_{EGR} - \frac{m_{EGR}}{m_{Air}+m_{EGR}}W_{Inlet} \\
\dot{m}_{Exh} &= W_{Exh} - W_{Turb} - W_{EGR}
\end{aligned}
$$

with

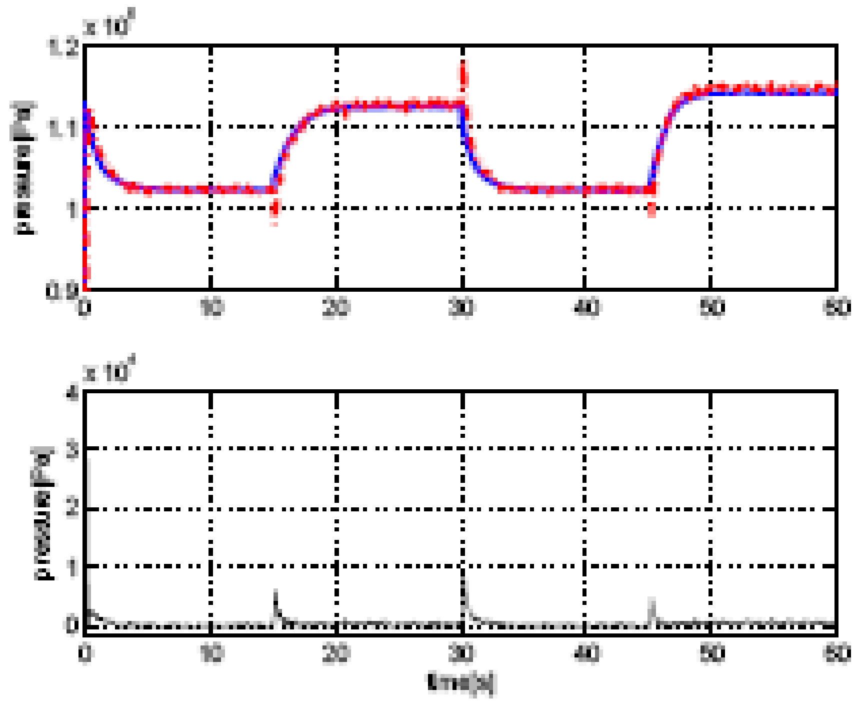
$$
\Psi\left(\frac{p_1}{p_0}\right) = \begin{cases} \sqrt{\frac{2\kappa}{\kappa-1}\left\{\left(\left(\frac{p_1}{p_0}\right)^{\frac{2}{\kappa}} - \left(\frac{p_1}{p_0}\right)^{\frac{\kappa+1}{\kappa}}\right)\right\}} \\ if\left(\frac{p_1}{p_0}\right) \geq \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \\ \sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \quad otherwise, \end{cases}
$$

$$
\begin{aligned}
W_{EGR} &= \frac{A_{EGR}P_{Exh}}{\sqrt{R_{Exh}T_{Exh}}}\Psi_{\kappa_{Exh}}\left(\frac{P_{Inlet}}{P_{Exh}}\right) \\
W_{Inlet} &= f_{vol}\left(N_{eng}, \frac{P_{Inlet}}{T_{Inlet}R_{Inlet}}\right)\frac{N_{eng}P_{Inlet}}{T_{Inlet}R_{Inlet}}\frac{V_{Eng}}{120} \\
T_{Inlet} &= \frac{P_{Inlet}V_{Inlet}}{(m_{Air}+m_{EGR})R_{Inlet}} \\
T_{EGR} &= \left(\frac{P_{Inlet}}{P_{Exh}}\right)^{\frac{\kappa_{Exh}-1}{\kappa_{Exh}}} T_{Exh} \\
W_{Exh} &= W_{Inlet} + W_{Fuel} \\
T_{Exh} &= T_{Inlet} + \frac{Q_{LHV}\,h(W_{Fuel}, N_{Eng})}{c_{p,Exh}(W_{Inlet}+W_{Fuel})} \\
P_{Exh} &= \frac{m_{Exh}T_{Exh}}{V_{Exh}} \\
W_{Turb} &= \frac{P_{Exh}}{\sqrt{T_{Exh}}}\tau\left(\frac{P_{Exh}}{P_{Atm}}, X_{VNT}\right) \\
R_{Inlet} &= \frac{R_{Air}m_{Air} + R_{Exh}m_{EGR}}{m_{Air}+m_{EGR}} \\
c_{v,Inlet} &= \frac{c_{v,Air}m_{Air} + c_{v,Exh}m_{EGR}}{m_{Air}+m_{EGR}} \\
c_{p,Inlet} &= c_{v,Inlet} + R_{Inlet}
\end{aligned}
$$

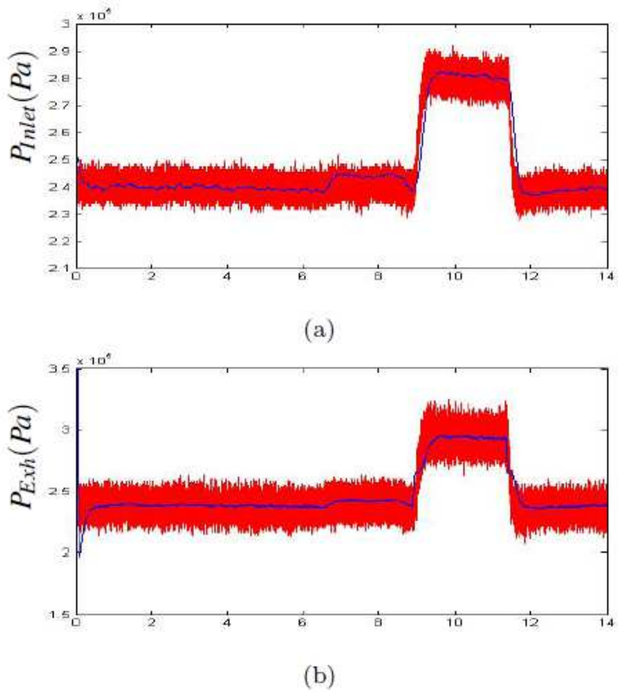
# Engine model parameters

| Symb. | Quantité | Unité |
|---|---|---|
| $P_{Inlet}$ | Pression dans le collecteur d'admission | $Pa$ |
| $V_{Inlet}$ | Volume du collecteur d'admission | $m^3$ |
| $R_{Air}$ | Constante des gaz parfaits d'air frais | $J.(Kg.K)$ |
| $c_{p,Air}$ | Chaleur spécifique, pression constante, de l'air | $J.(Kg.K)$ |
| $c_{v,Air}$ | Chaleur spécifique, volume constant, de l'air | $J.(Kg.K)$ |
| $R_{Exh}$ | Constante des gaz parfaits dans le collecteur d'échappement | $J.(Kg.K)$ |
| $c_{p,Exh}$ | Chaleur spécifique, pression constante, du gaz d'échappement | $J.(Kg.K)$ |
| $c_{v,Exh}$ | Chaleur spécifique, volume constant, du gaz d'échappement | $J.(Kg.K)$ |
| $R_{Inlet}$ | Constante des gaz parfaits dans le collecteur d'admission | $J.(Kg.K)$ |
| $c_{p,Inlet}$ | Chaleur spécifique, pression constante, dans le collecteur d'admission | $J.(Kg.K)$ |
| $c_{v,Inlet}$ | Chaleur spécifique, volume constant, dans le collecteur d'admission | $J.(Kg.K)$ |
| $\kappa$ | Rapport des chaleurs spécifiques | $c_p/c_v$ |
| $W_{HFM}$ | Débit d'air entrant | $kg.s^{-1}$ |
| $T_{CAC}$ | Température de l'air après l'échangeur | $K$ |
| $W_{EGR}$ | Débit d'EGR | $Kg.s^{-1}$ |
| $T_{EGR}$ | Température du gaz d'EGR | $K$ |
| $W_{Inlet}$ | Début d'air entrant | $kg.s^{-1}$ |
| $T_{Inlet}$ | Température dans le collecteur d'admission | $K$ |
| $m_{Air}$ | Masse de l'air dans le collecteur d'admission | $Kg$ |
| $m_{EGR}$ | Masse du gaz d'EGR dans le collecteur d'admission | $kg$ |
| $W_{Exh}$ | Débit du gaz d'échappement | $kg.s^{-1}$ |
| $m_{Exh}$ | Masse du gaz d'échappement dans le collecteur d'échappement | $kg$ |
| $P_{Exh}$ | Pression dans le collecteur d'échappement | $Pa$ |
| $T_{Exh}$ | Temperature in exhaust manifold | $K$ |
| $A_{EGR}$ | Ouverture effective de la vane EGR | $m^2$ |
| $V_{Eng}$ | Volume des cylindrées totale | $m^3$ |
| $N_{Eng}$ | Vitesse du moteur | $min^{-1}$ |
| $W_{Fuel}$ | Débit de fuel injecté | $kg.s^{-1}$ |
| $Q_{LHV}$ | Pouvoir calorifique | $J.kg^{-1}$ |
| $V_{Exh}$ | Volume du collecteur d'échappement | $m^3$ |
| $p_{Atm}$ | Pression atmosphérique | $Pa$ |
| $W_{Turb}$ | Débit d'échappement après la turbine | $kg.s^{-1}$ |
| $X_{VNT}$ | Position de la vanne VGT | % |

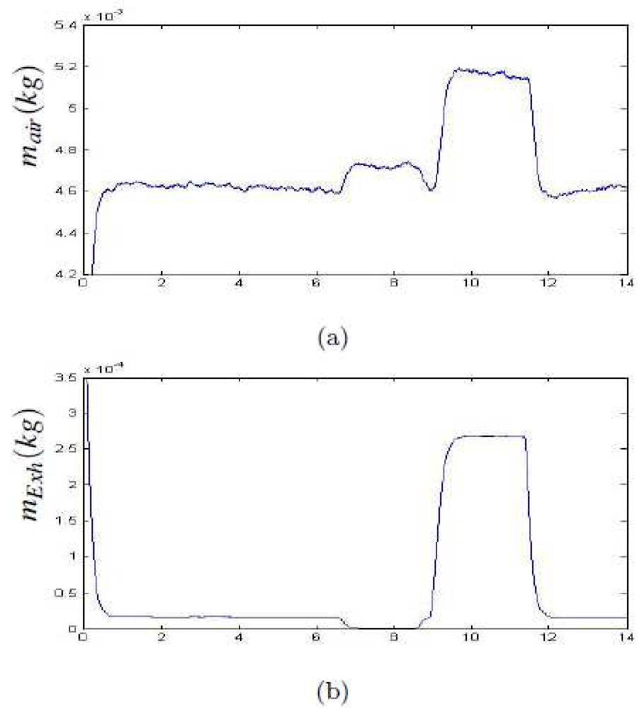
# Model validation by AMEsim



# Model validation in testbed




Simulated (blue color) and measured (red color) inlet and exhaust pressures.




Simulated air and exhaust gas mass flows

# Fault detection and isolation system

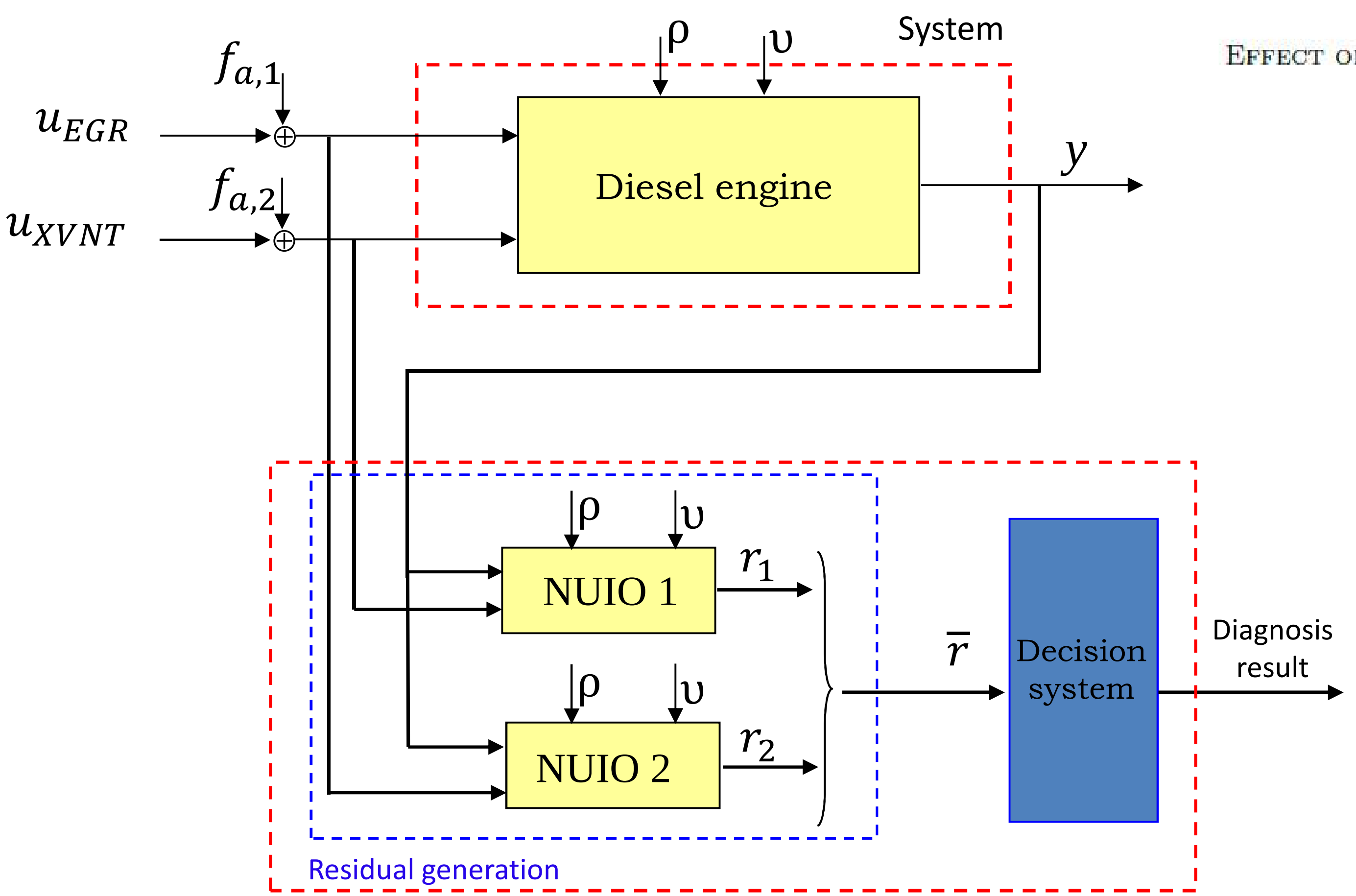



TABLE I

EFFECT OF THE FAULTS ON THE RESIDUALS

| $\bar{r}$ | $f_1$ | $f_2$ |
|---|---|---|
| $r_1$ | 0 | × |
| $r_2$ | × | 0 |

# Residual generation

-Engine model :

$$\dot{x} = \sum_{j=1}^{n_\rho} \rho_j A_j x + B_g g(v, y, u) + f(x,u) + B_d d + B_w w$$

$$y = Cx + D_w w$$

- The used diesel engine model is divided into two parts : linear parameter varying (LPV) and a high nonlinear part having a large Lipschitz constant
- The H-infinity performance is used to attenuate the presence of disturbances

The modified $H_\infty$ estimation problem consists to compute the matrices and $L$ such that

$$\lim_{t\to\infty} \bar{e}(t) = 0 \quad \text{for} \quad w(t) = 0$$

- $$\|\bar{e}\|_{\mathfrak{L}_2^{n_x}} \leq \gamma_{1,2} \|w\|_{1,2}^{r} \quad \text{for} \quad w(t) \neq 0;\ \bar{e}(0) = 0$$

- The modified mean value theorem (MMVT) is proposed to express the nonlinear error dynamics as a convex combination of known matrices with time varying coefficients,
- This method is applicable to a wide class of nonlinear systems,

# Residual generation

**-Engine model :**

$$\dot{x} = \sum_{j=1}^{n_\rho} \rho_j A_j x + B_g g(\upsilon, y, u) + f(x,u) + B_d d + B_w w$$

$$y = Cx + D_w w$$

**-NUIO-based residual generation:**

$$\dot{z} = N(\rho)z + Gg(\upsilon, y, u) + Mf(\hat{x}, u) + L(\rho)y$$

$$\hat{x} = z - Ey$$

$$r = \Pi_r (y - C\hat{x})$$

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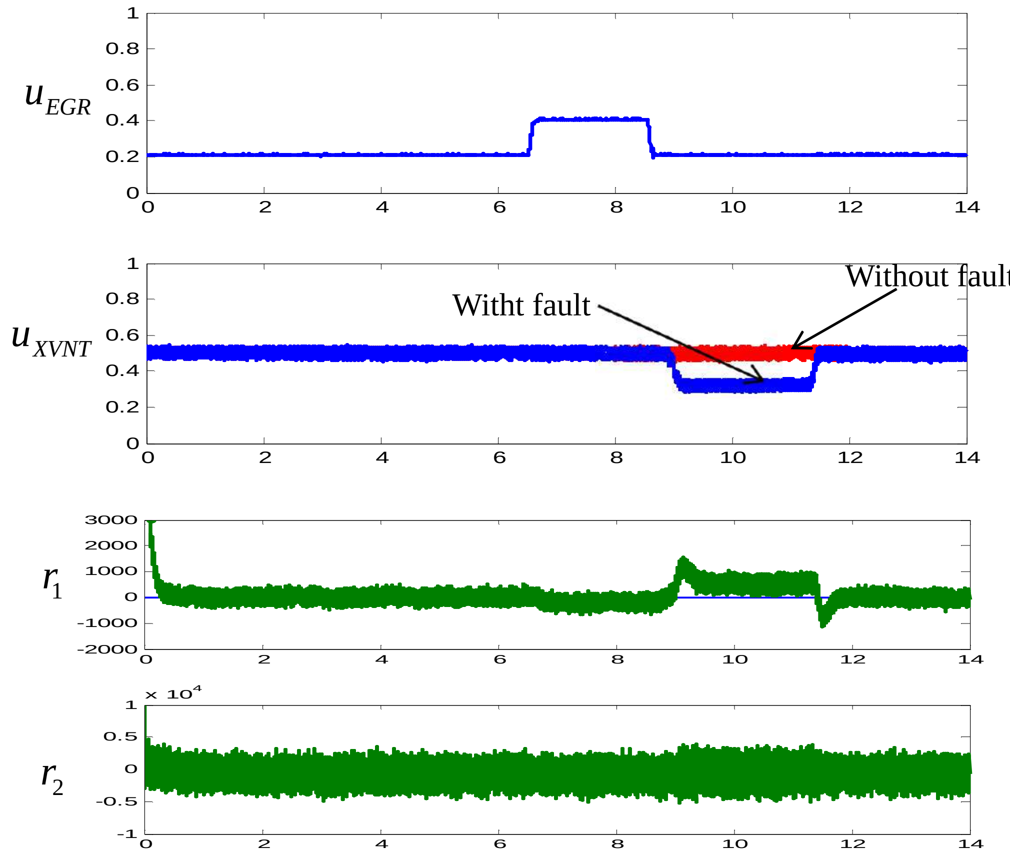
# Residual generation

TABLE I

EFFECT OF THE FAULTS ON THE RESIDUALS

| $\bar{r}$ | $f_1$ | $f_2$ |
|---|---|---|
| $r_1$ | 0 | × |
| $r_2$ | × | 0 |




**Simulation results : (a) EGR and VGT actuators. (b) Residuals.**

# **Decision system:**
# Residual evaluation

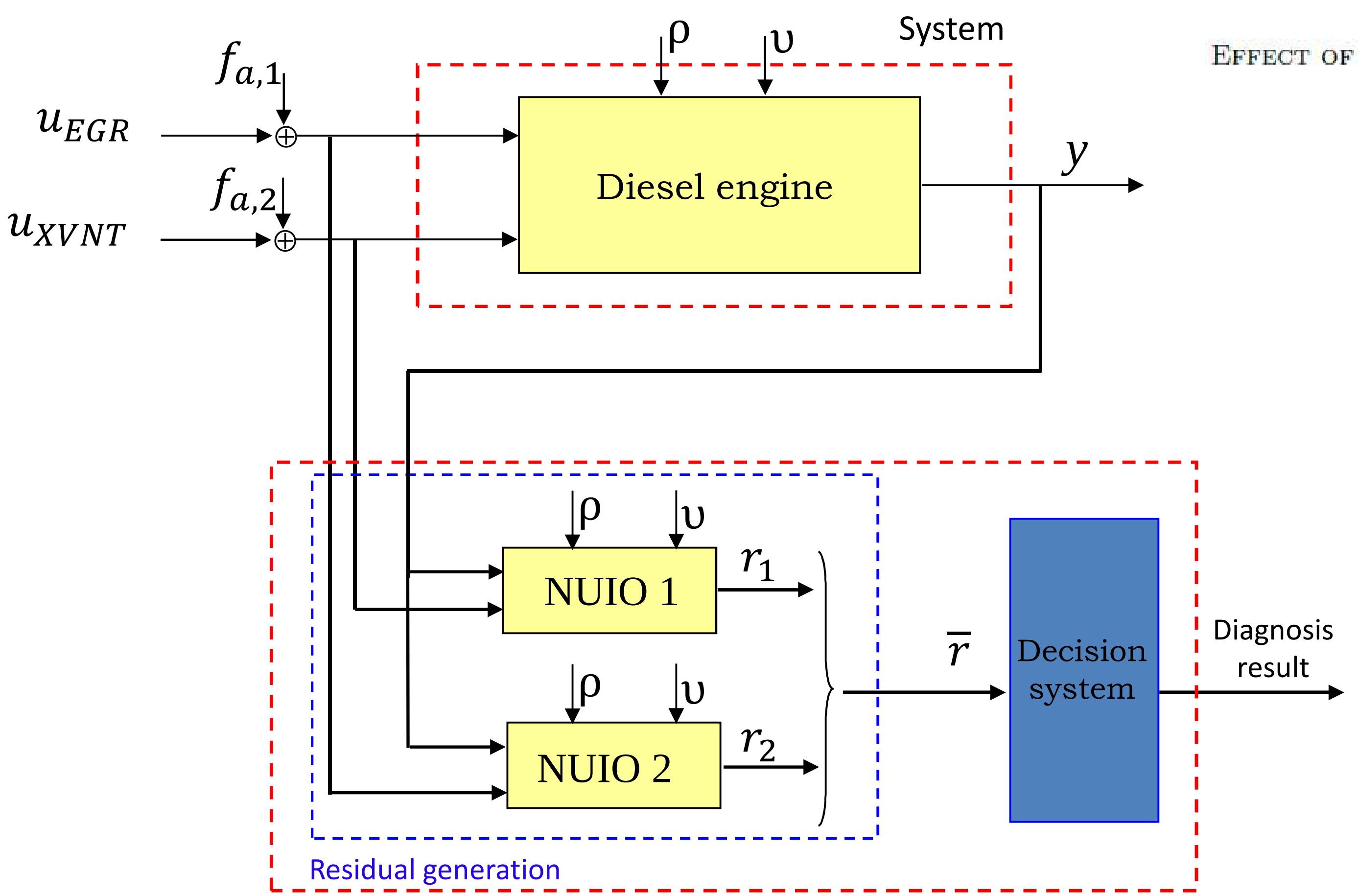



TABLE I
EFFECT OF THE FAULTS ON THE RESIDUALS

| $\bar{r}$ | $f_1$ | $f_2$ |
|---|---|---|
| $r_1$ | 0 | × |
| $r_2$ | × | 0 |

# **Decision system:**
# Cumulative Sum (CUSUM)

- **Residual vector :**

$$\bar{r}(k) = \bar{r}_0(k) + \sum_{\ell=1}^{2} \nu_\ell \Gamma_\ell(k) 1_{\{k \geq k_0\}} \delta_\ell$$

  - ➢ $\Gamma_\ell(k)$ **is the dynamic profile of the change on** $\bar{r}$**,**
  - ➢ $\nu_\ell$ **is the magnitude of fault .**

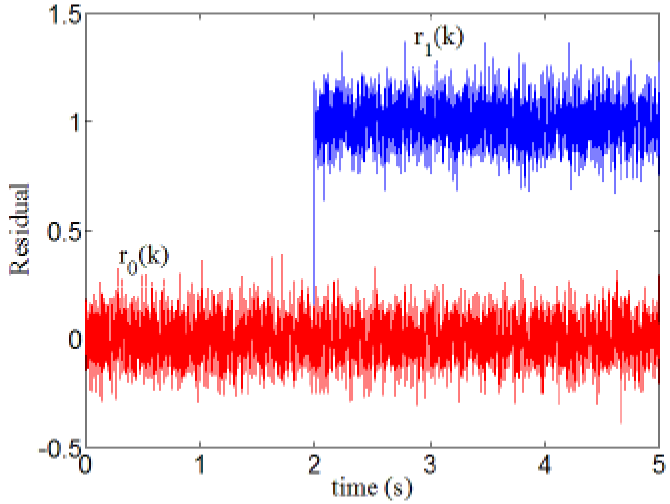



FIGURE: Example : Residual signal - scalar case

- **The decision system aims at choosing between the following hypothesis :**

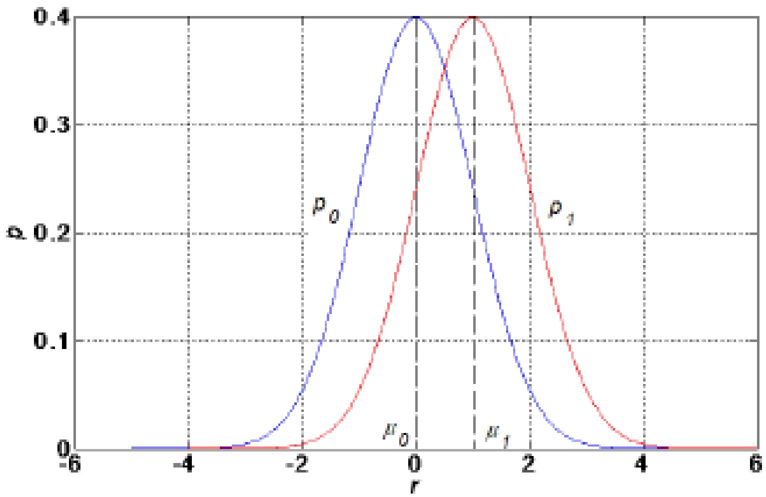
$$\begin{aligned}
\mathcal{H}_0 &: \mathcal{L}(\bar{r}(i)) = \mathcal{N}(\boldsymbol{\mu}_0, \boldsymbol{\Sigma}), i = 1, \ldots, k \\
\mathcal{H}_\ell &: \mathcal{L}(\bar{r}(i)) = \mathcal{N}(\boldsymbol{\mu}_0, \boldsymbol{\Sigma}), i = 1, \ldots, k_0 - 1 \\
&: \mathcal{L}(\bar{r}(i)) = \mathcal{N}(\boldsymbol{\mu}_\ell, \boldsymbol{\Sigma}), i = k_0, \ldots, k
\end{aligned}$$

with $\boldsymbol{\mu}_\ell = \boldsymbol{\mu}_0 + \nu_\ell \boldsymbol{\Gamma}_\ell$.

# **Decision system:** Cumulative Sum (CUSUM)

- **The CUSUM decision function is based on the log-likelihood ratio (LLR) between hypothesis $\mathcal{H}_\ell$ and $\mathcal{H}_0$, namely :**

$$s_k(\ell, 0) = \ln \frac{p_\ell(\mathbf{r}(k))}{p_0(\mathbf{r}(k))}$$

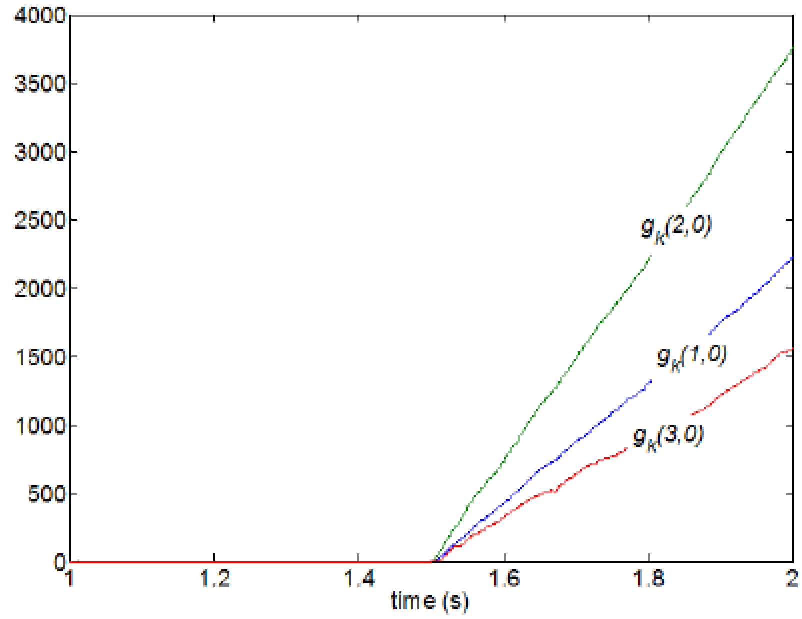



Example : Probability density function - scalar case

# **Decision system:**
# Cumulative Sum (CUSUM)

**The CUSUM decision function is computed recursively as :**

$$g_k(\ell, 0) = \max\left(0, g_{k-1}(\ell, 0) + s_k(\ell, 0)\right)$$



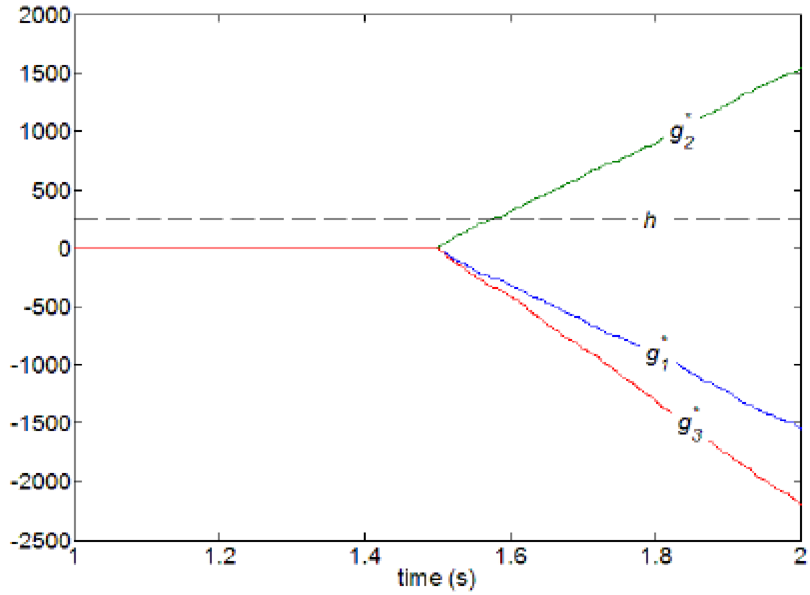
## **Decision system:**
## Cumulative Sum (CUSUM)

**Since the LLR between two faults is** $s_k(\ell, j) = s_k(\ell,0) - s_k(j,0)$ **, then :**

- **A modified CUSUM decision function is computed as :**

$$g_\ell^* = \min_{0 \le j \ne \ell \le 3} \left(g_k(\ell,0) - g_k(j,0)\right)$$

- **An alarm is raised when** $g_\ell^* \ge h_\ell$ **, where** $h_\ell$ **is a threshold**

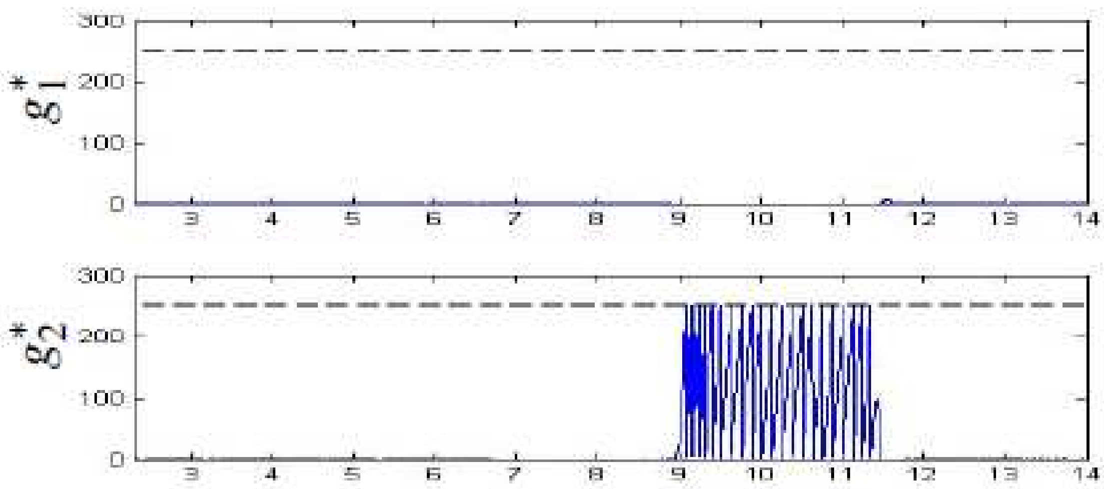


# **Decision system:**
# Cumulative Sum (CUSUM)

TABLE I

EFFECT OF THE FAULTS ON THE RESIDUALS

| $\bar{r}$ | $f_1$ | $f_2$ |
|---|---|---|
| $r_1$ | 0 | $\times$ |
| $r_2$ | $\times$ | 0 |




(c)

**Multi-CUSUM decision functions**

# AMESIM Results

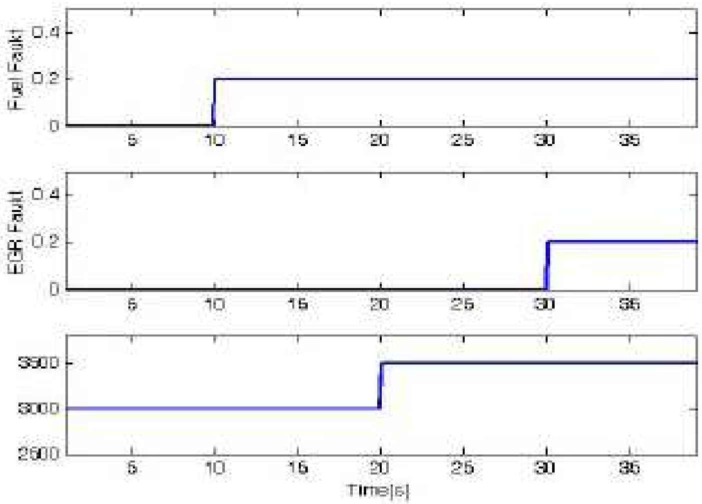



FIGURE: Simulated Fault and Engine Speed behavior

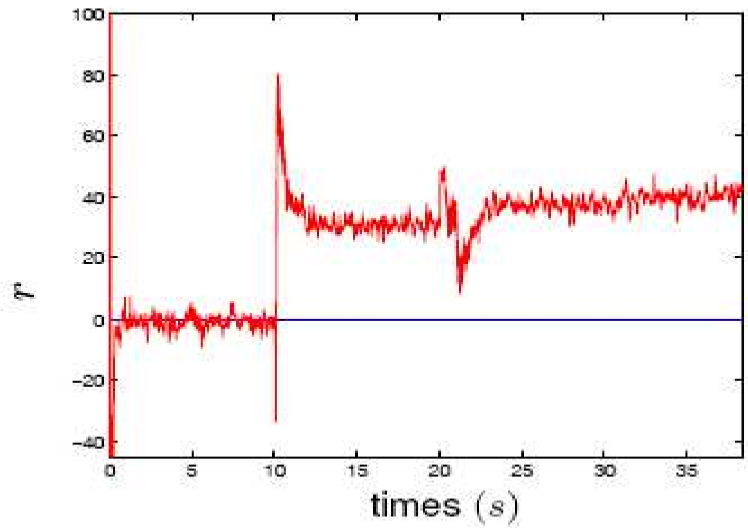



FIGURE: Residuals behavior

# AMESIM Results

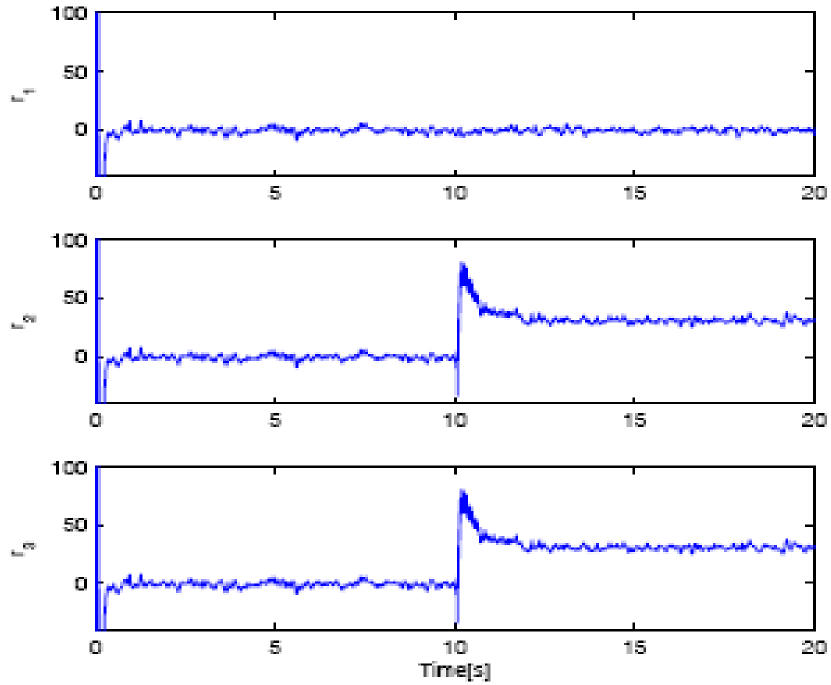



FIGURE: Actuator Fault Isolation

# Conclusion and perspectives

- **We have developed an actuator FDI for diesel engines**
- **A bank of observers based on nonlinear unknown input observer has been used as residual generator**
- **A multi-CUSUM algorithm for statistical change detection and isolation is used as a decision system**
- **The performances of the proposed approach are shown through a real application to caterpillar 3126b engine.**
- **Sensor fault diagnosis for diesel engines is under work.**

# Thank you for you attention