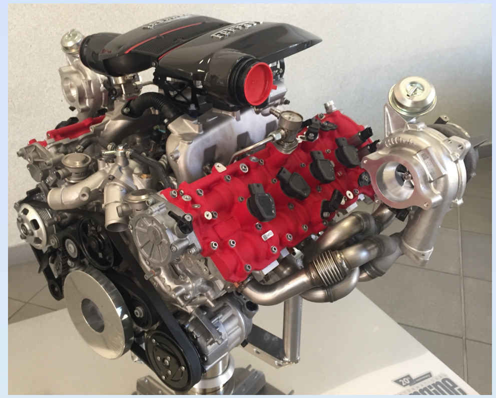
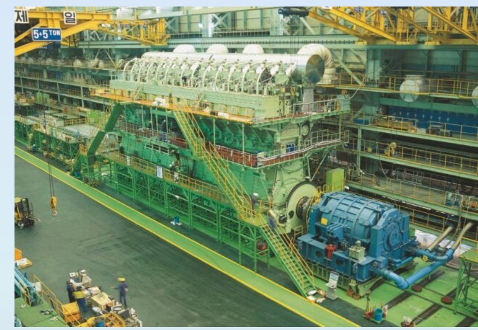
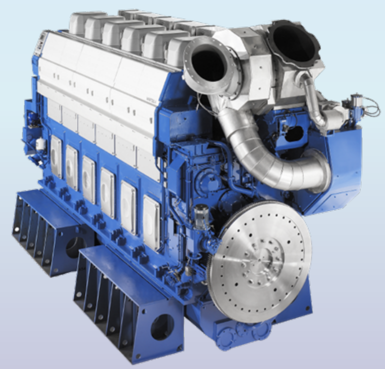
Corso di Laurea Magistrale in Ingegneria Gestionale





Motori a Combustione Interna



Prof. Ivan Arsie

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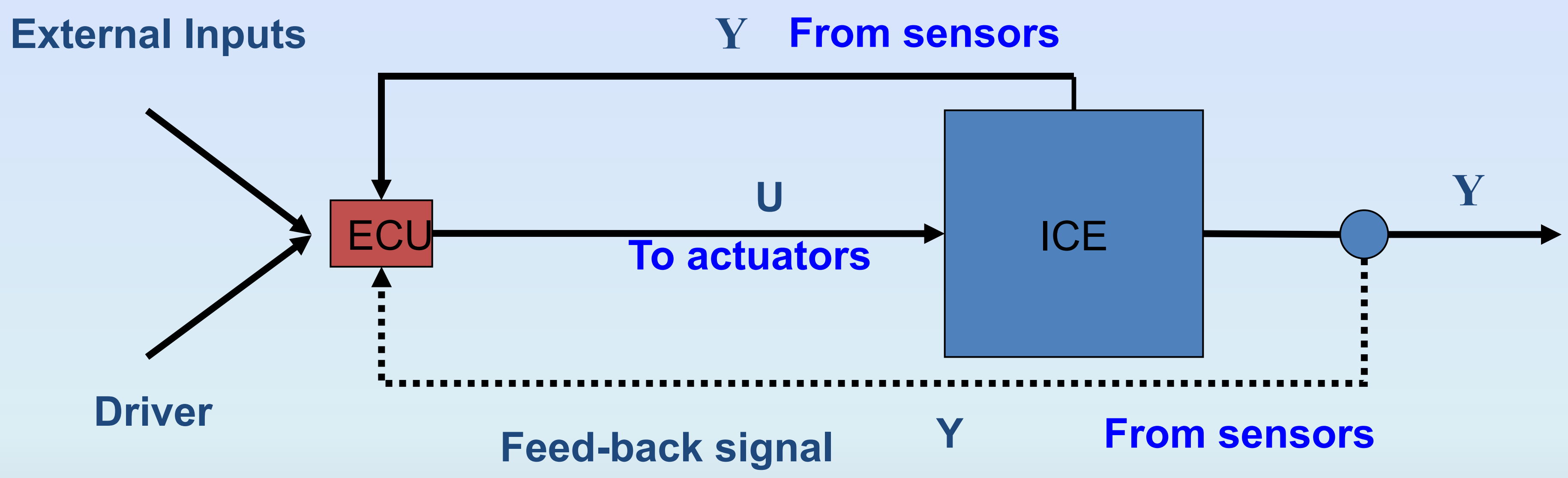
Controllo Motore A.C.

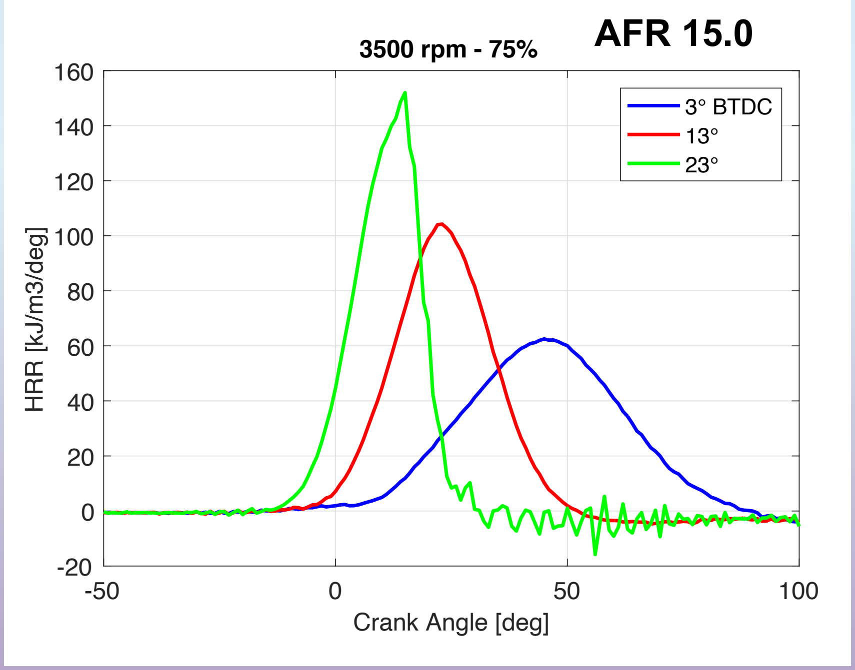
Electronic Engine Control

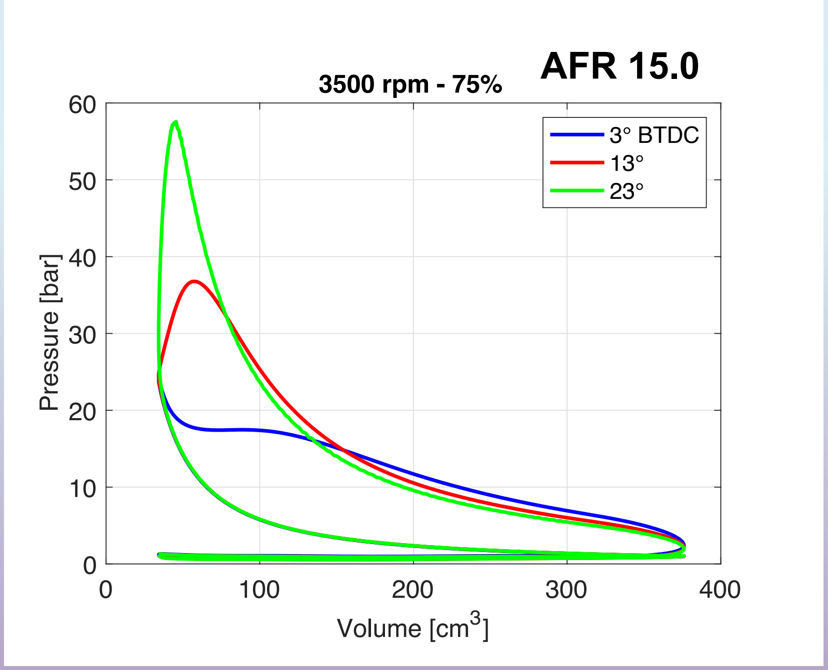


Automotive engines control is accomplished by an electronic device named Engine Control Unit. The ECU processes the signals coming from both external disturbancies and engine sensors and provides an output signal for the engine actuators (i.e. injectors, ignition coils). Unlike mechanical devices (i.e. carburetor), ECU allows flexible and robust control by both feed-forward and feed-back tasks.

Spark Advance Control

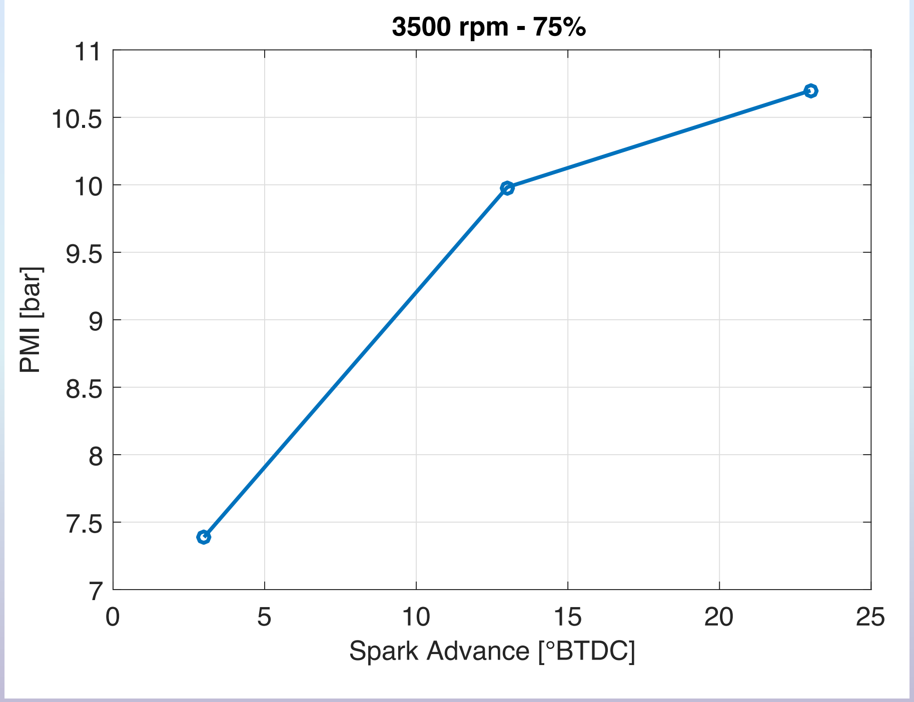
- Increase Thermal Efficiency
- Avoid Knocking
- Speed up engine warm-up

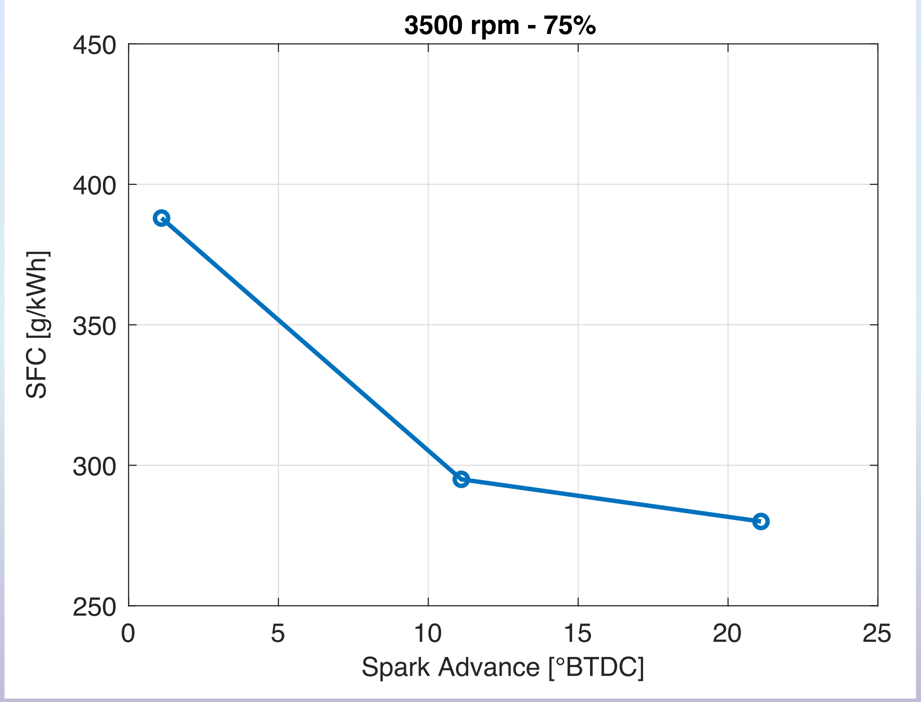




Spark Advance Control

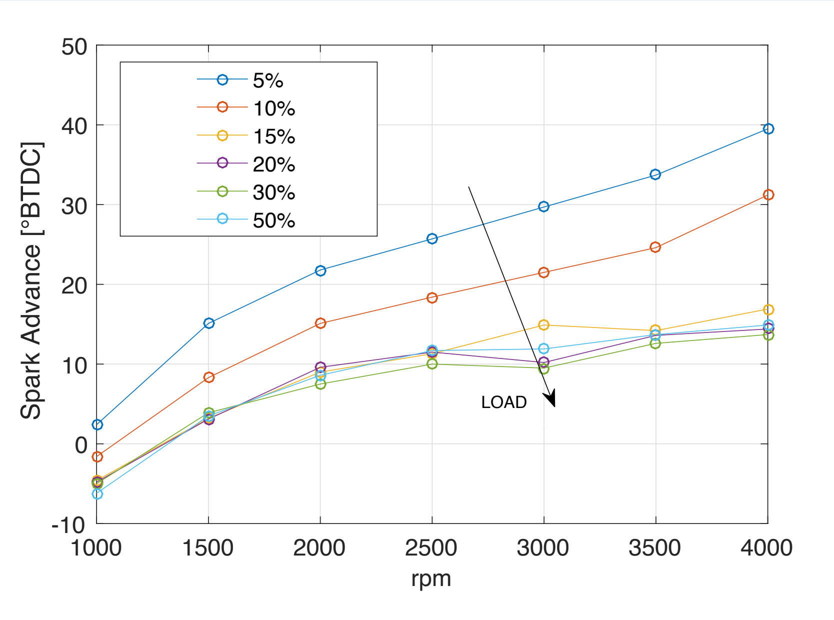
- Impact on Thermal Efficiency



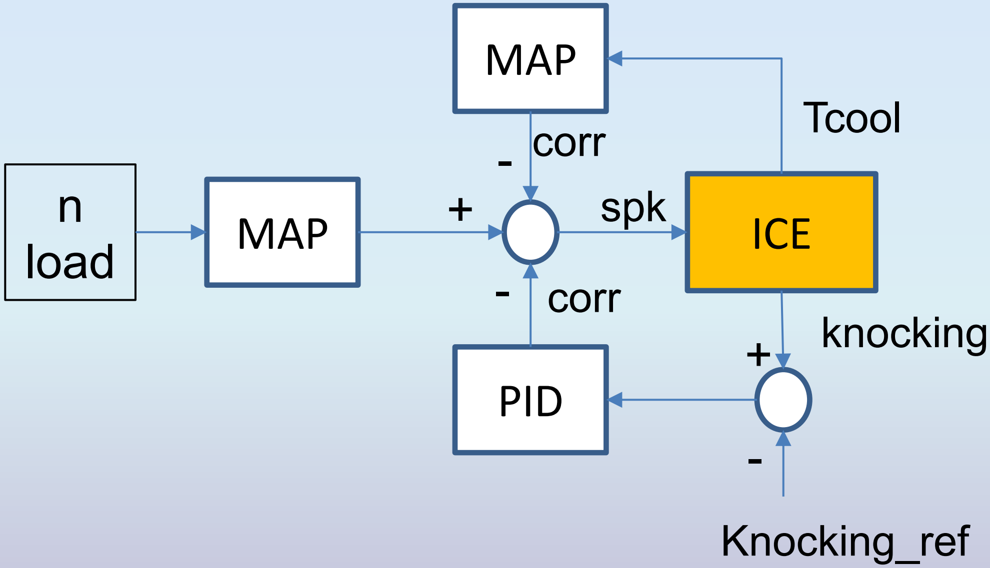


Spark Advance Control

Spark advance map in std conditions



Spark advance control scheme



Map output is corrected by two additional control tasks:

- Closed loop control based on accelerometer signal to detect knocking
- Offset or Gain term depending on coolant temperature to enhance warm-up

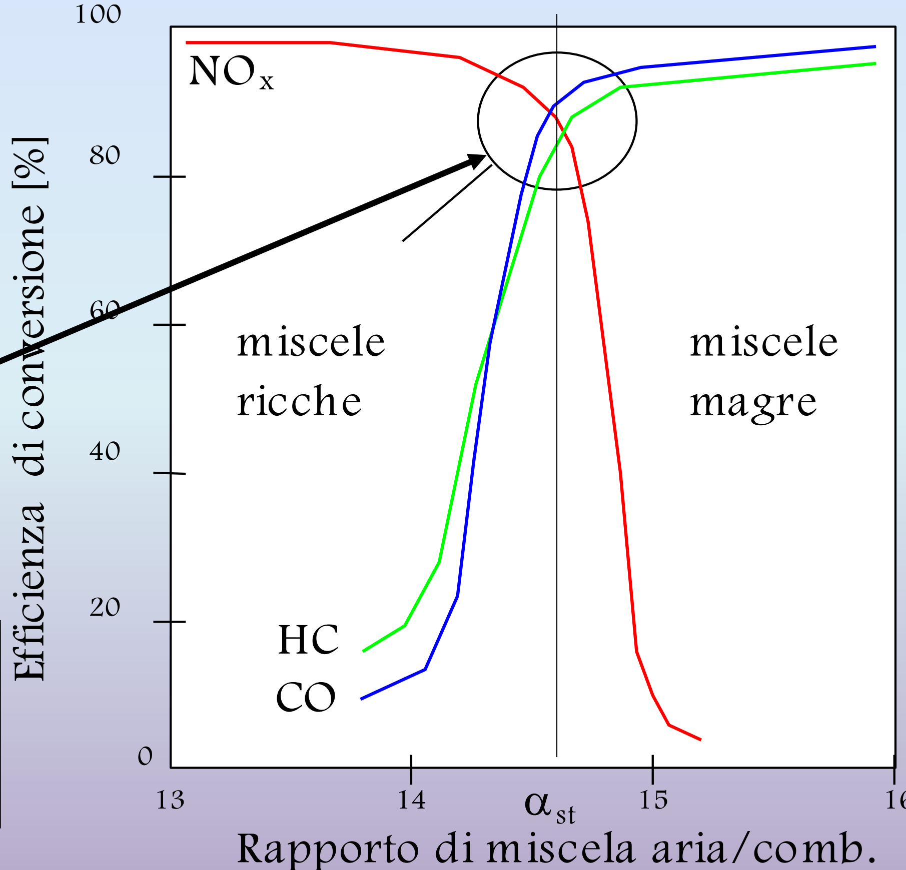
Motivations for AFR Control

Three Way Catalyst

Reduction promoted by lack of oxygen

Oxidation promoted by excess of oxygen

In a narrow range around stoichiometric mixture, a suitable effiociency can be reached for both oxidation and reduction reactions.



The efficiency is strongly dependent on . Temperature. During engine warm-up (**cold-start**) tail pipe emissions of CO and HC reach the maximum values.

Fuel Metering

- In order for the fuel metering system to provide the appropriate amount of fuel for the current engine operation, the mass flow rate of incoming air (i.e. air charge) must be evaluated:

$$F_m = \frac{A_m}{AFR_{req}}$$

F_m is the fuel mass flow rate
A_m is the air mass flow rate
AFR_{req} is the requested AFR

- There are two methods commonly used to evaluate the air charge:
  - Estimation by Speed density method
  - Measurement by vane meter or hot wire meter

Fuel Metering

- In the speed density method, the air charge is calculated by the ECU from measurements of intake manifold pressure, air inlet temperature and engine speed. Temperature and pressure signals are used to evaluate the air density, while the engine speed is used to estimate the volume flow rate:

$$A_m = \dot{m}_a = \frac{\lambda_v \rho_a V_D n}{2} = \frac{\lambda_v V_D n p_a}{2RT_a}$$

λ_v is the volumetric efficiency
V_D is the engine displacement
p_a is the inlet air pressure
T_a is the inlet air temperature
R is the gas constant for air
n is the engine speed

- In an engine using exhaust gas recirculation (EGR), the volume flow rate of EGR must be subtracted from the calculated volume flow rate:

$$A_v = A_m - A_{EGR}$$

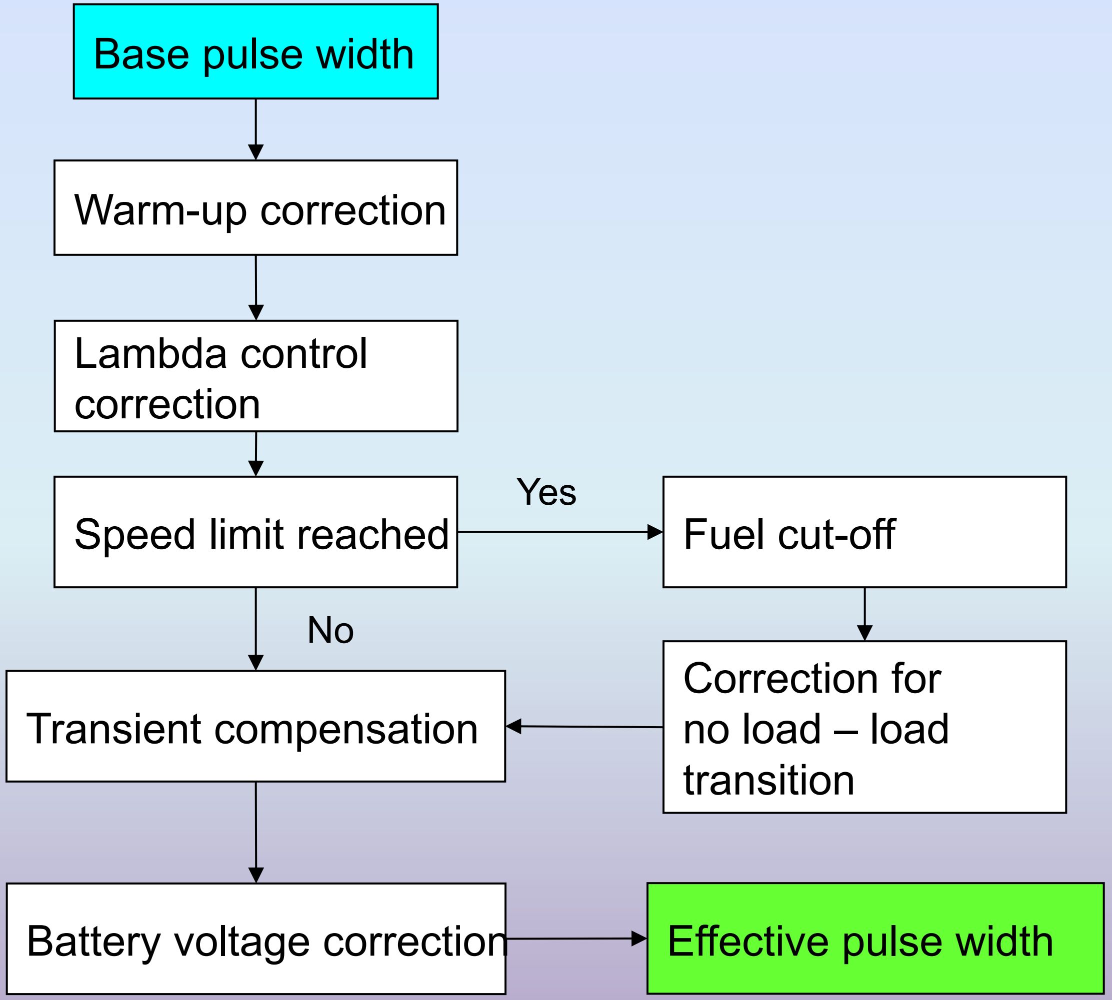
Fuel Metering

- The vane meter uses the force of incoming air to move a flap though a defined angle. This angular movement is converted by a potentiometer to a voltage ratio. Because only the fresh air is measured no compensation is needed for EGR.

- In the hot-wire or hot-film air mass flow sensor, the inlet air passes a heated element, either wire or film. The element is part of a bridge circuit that keeps the element at a constant temperature above the inlet air temperature. By measuring the heating current required by the bridge circuit and converting this to a voltage via a resistor, the air mass flow passing the element can be determined. Again, because only the fresh air charge is measured, no compensation for EGR is required. However, sensing errors may occur due to the strong inatke manifols reverse pulses which occur under certain operating conditions. In such cases a correction factor must me applied.

Fuel Metering

- The base pulse width is determined from the required fuel mass flow through an empirical injection constant.
- The injection constant accounts for a static flow rate measured for a fixed pressure ratio between fuel rail and intake manifold.
- The effective pulse width is a modification of the base pulse that is adjusted for a number of correction factors depending on the current engine/vehicle operation.

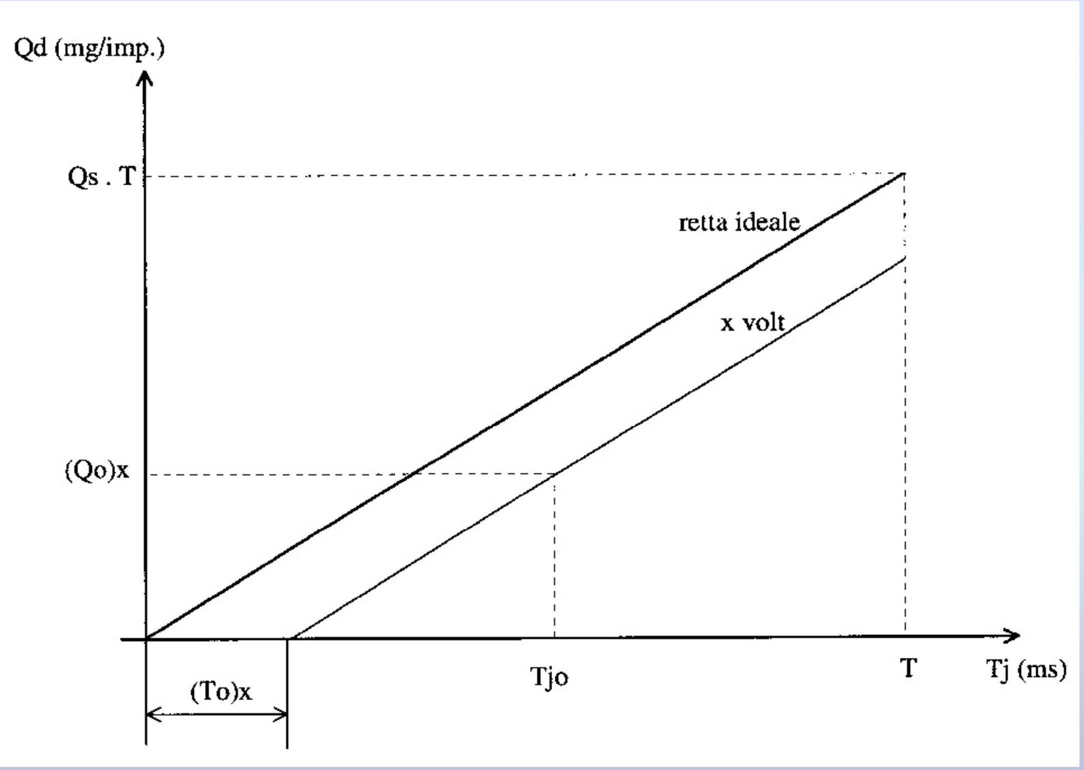


Fuel Injection

- Once the effective pulse width (*tinj*) has been computed, the injected fuel per impulse is given by:

$$m_f = Q_{stat}(t_{inj} - t_0)$$

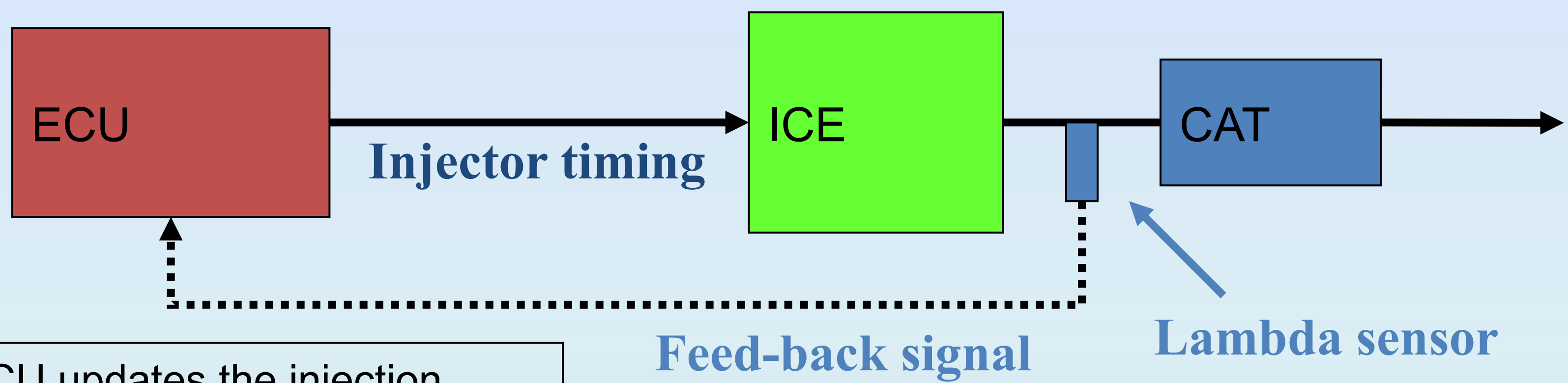
- Qstat is the static flow rate, estimated by measuring the fuel mass injected in 5 seconds in a tank, at ambient pressure with a rail pressure of 350 Kpa; it corresponds to the angular coefficient of the lines in the figure.
- t_0 is an offset and corresponds to the threshold time for which the jnected fuel per impulse is zeroed; it depends on the battery voltage.



Lambda Feedback Control

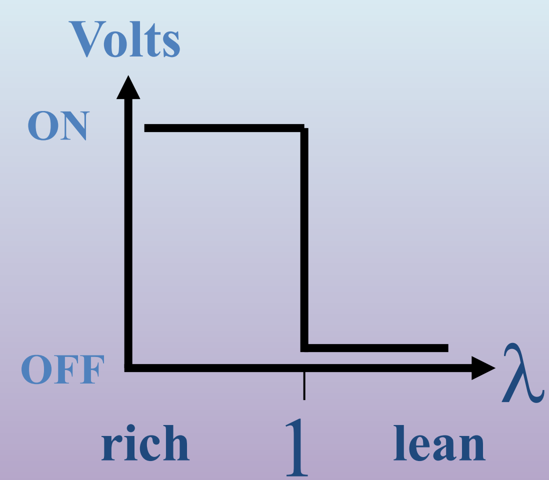
ICE Internal Combustion Engine
ECU Electronic Control Unit
CAT Catalyst

The Lambda sensor located in the exhaust manifold, detects the presence/lackage of oxygen in the exhaust gas (**lean/rich mixture**).

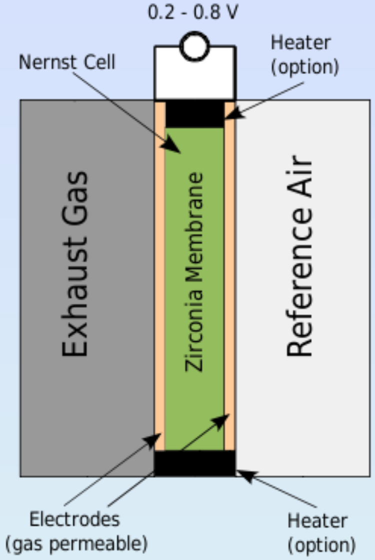


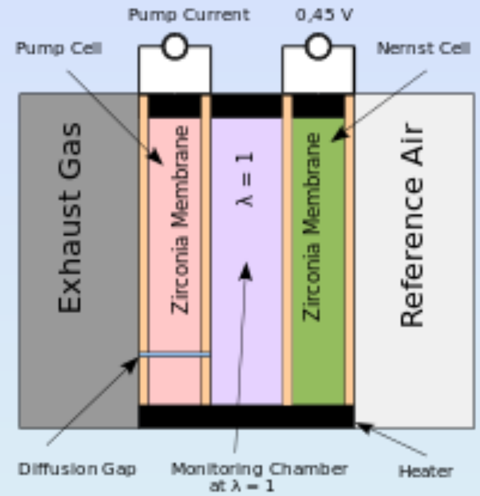
The ECU updates the injection timing in order to run the engine around stoichiometric mixture.

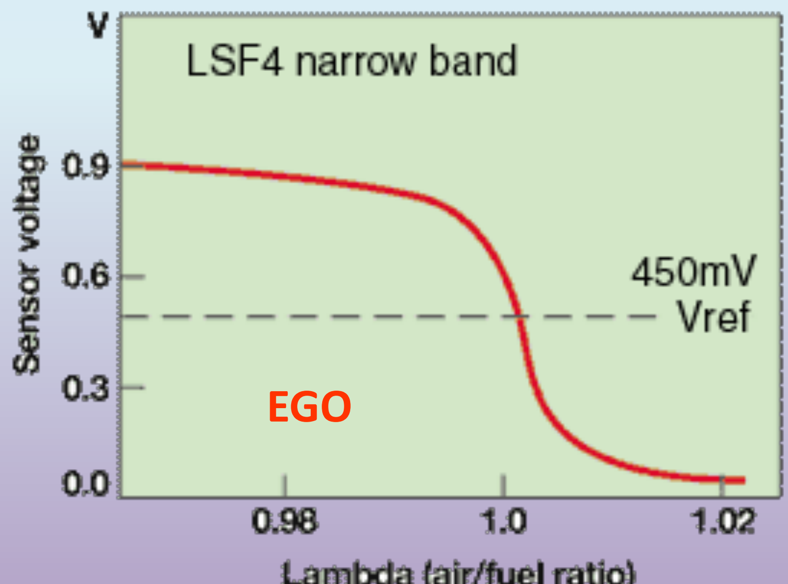
$$\lambda = \frac{\alpha}{\alpha_{st}}$$

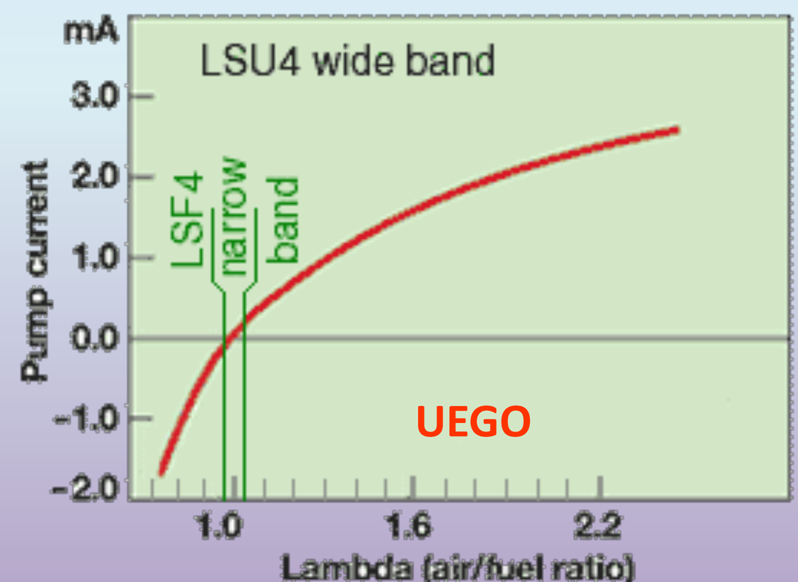


Lambda sensors

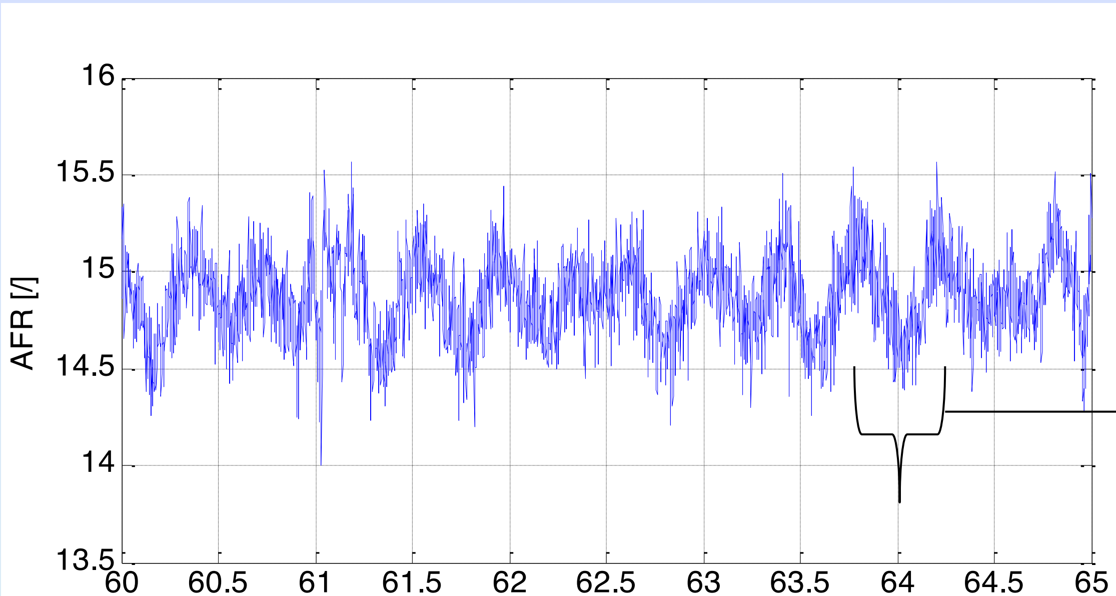




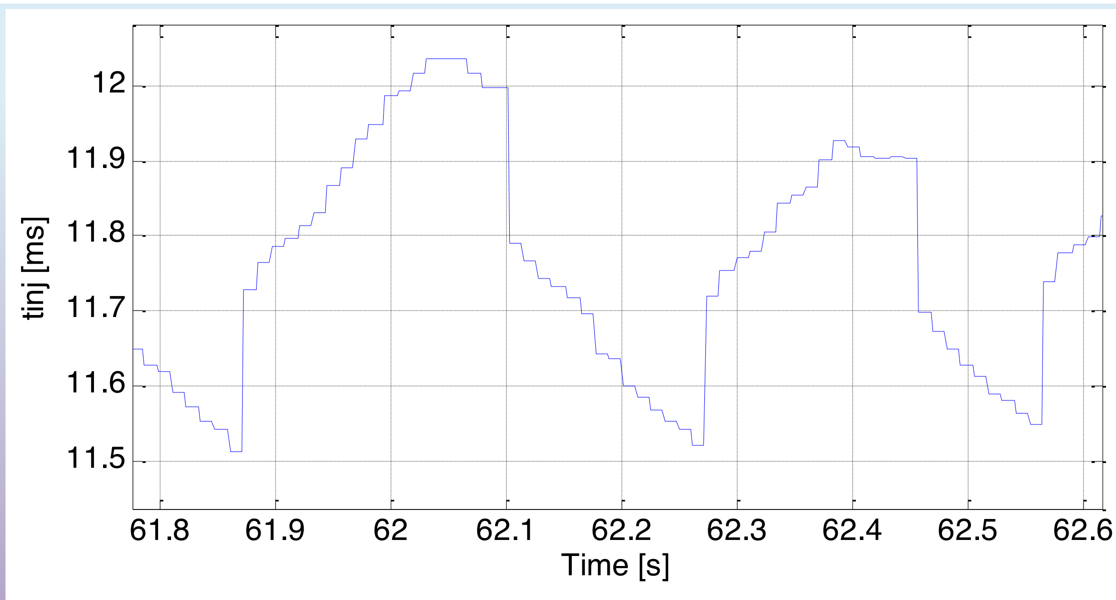




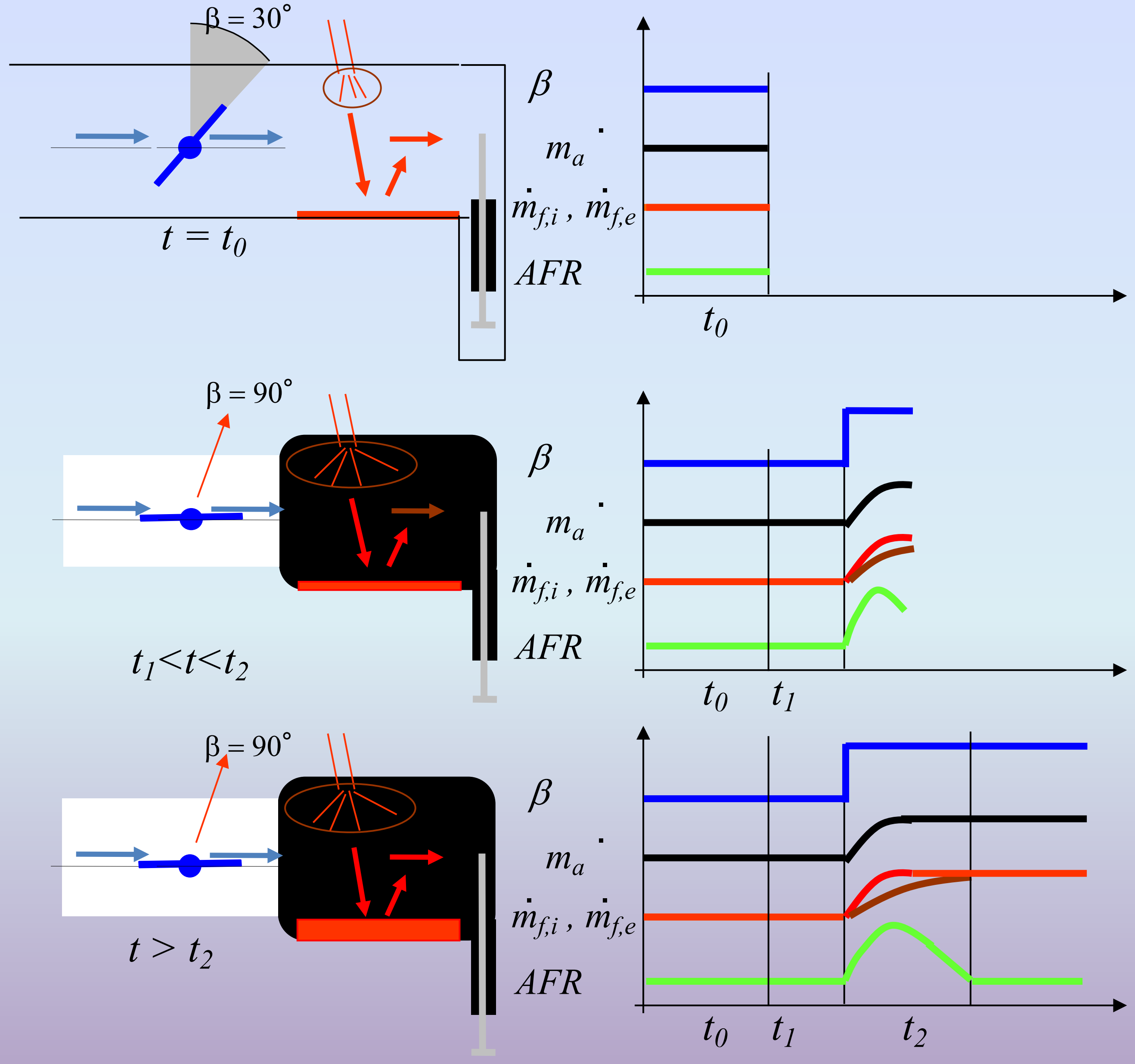
Lambda Feedback Control



Time period ~ 400 ms
@2500 rpm
(1 PMS ~ 12 ms)



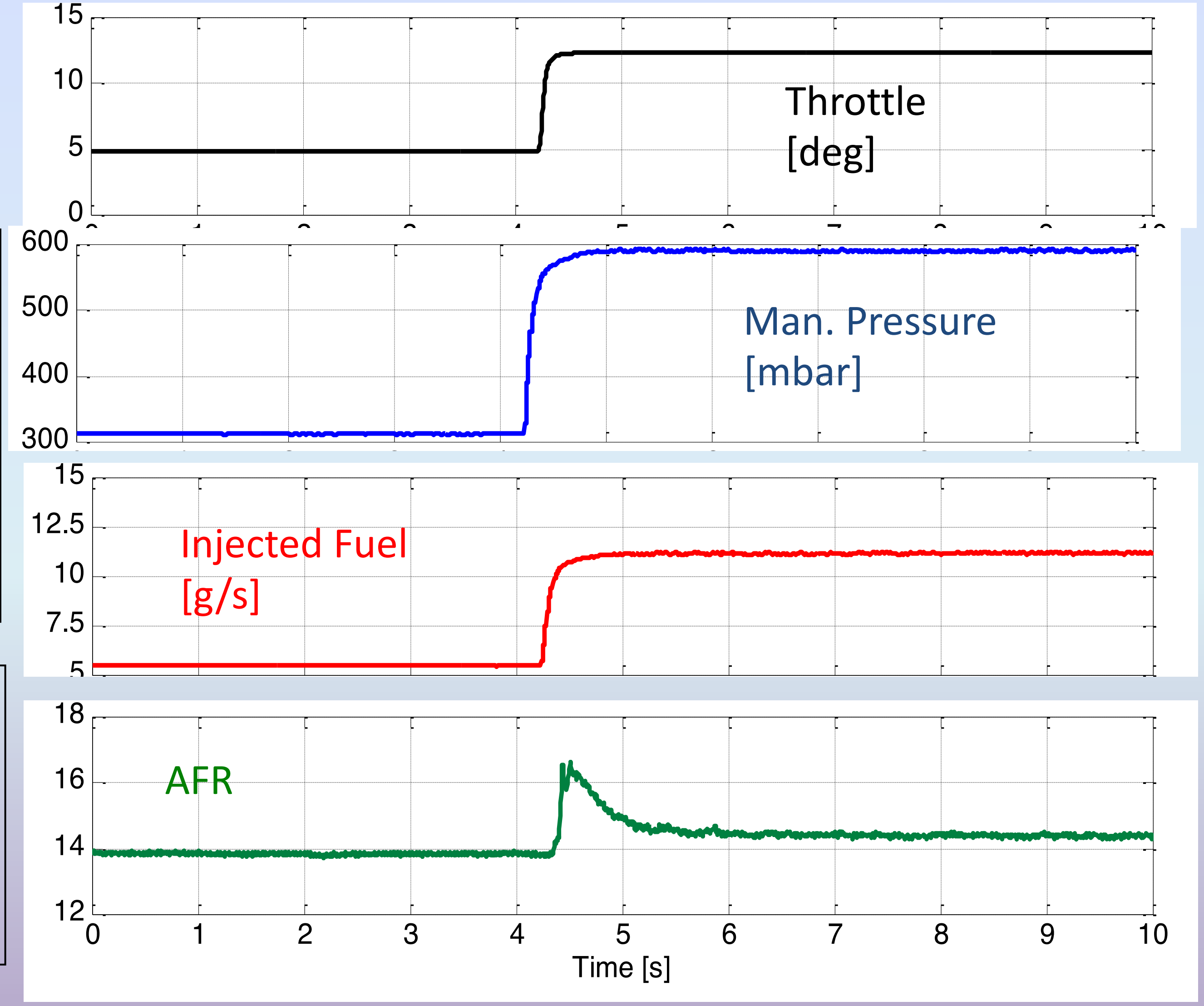
Transient Behavior



Transient Behavior

The figures show the dynamic response of **manifold pressure**, **injected fuel flow rate** and **exhaust AFR** to a step transient of **throttle valve** without transient compensation

The wide excursion of **AFR** toward lean mixtures is evident. This behavior results in **poor drivebility** and **large emissions**

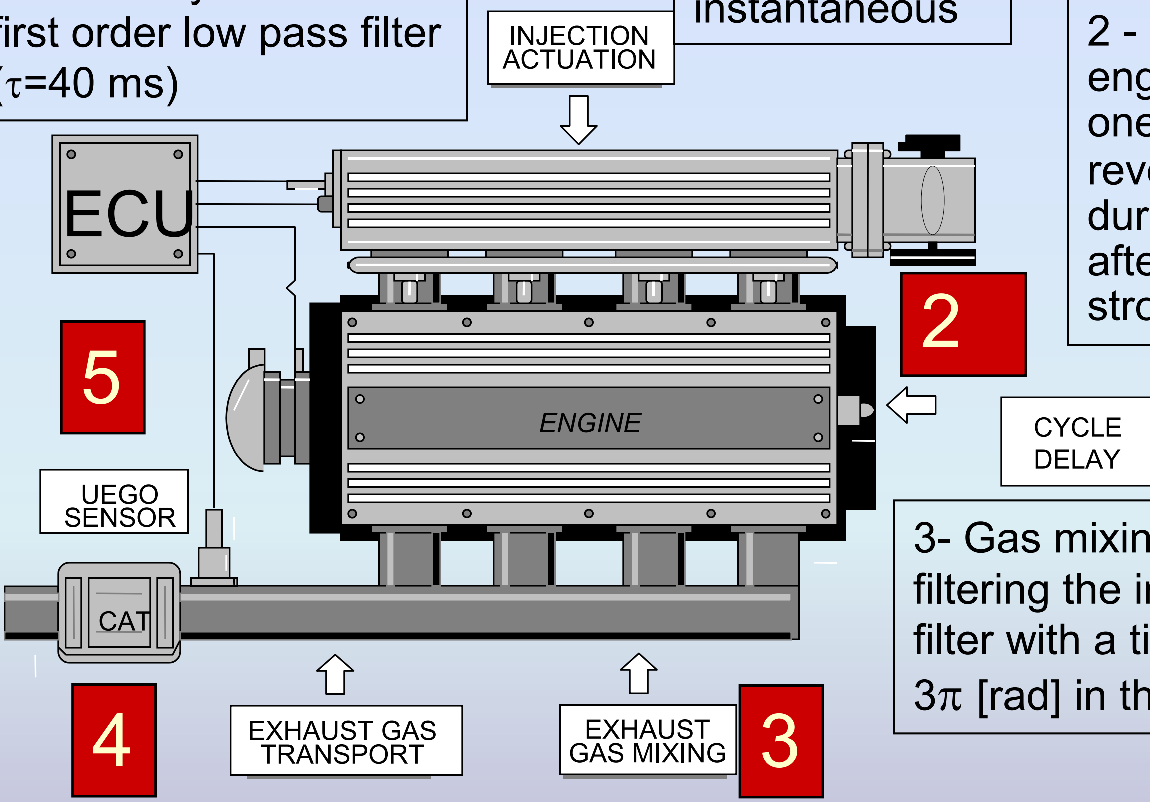


Time delays from injection to measurement location

5 - EGO sensor dynamic response modeled by means of a first order low pass filter (τ=40 ms)

1 - Injection actuation: instantaneous

2 - Pure time delay due to engine cycle approximated as one and a half engine revolution: from 90° after TDC during the intake stroke to 90° after BDC during the exhaust stroke



3- Gas mixing phenomena modeled by filtering the injected fuel flow with a low pass filter with a time constant corresponding to 3π [rad] in the crankshaft domain

4 - Pure time delay due to gas transport from exhaust port to UEGO sensor location modeled by means of a mass balance neglecting dynamic effects:

$$\Delta t_{gt} = \frac{\Delta l}{U} \qquad U = \frac{\dot{m}_{a,e}}{4\rho_{ex} A} \frac{1+AFR}{AFR}$$

Lambda Feedback Control

LIMITATIONS

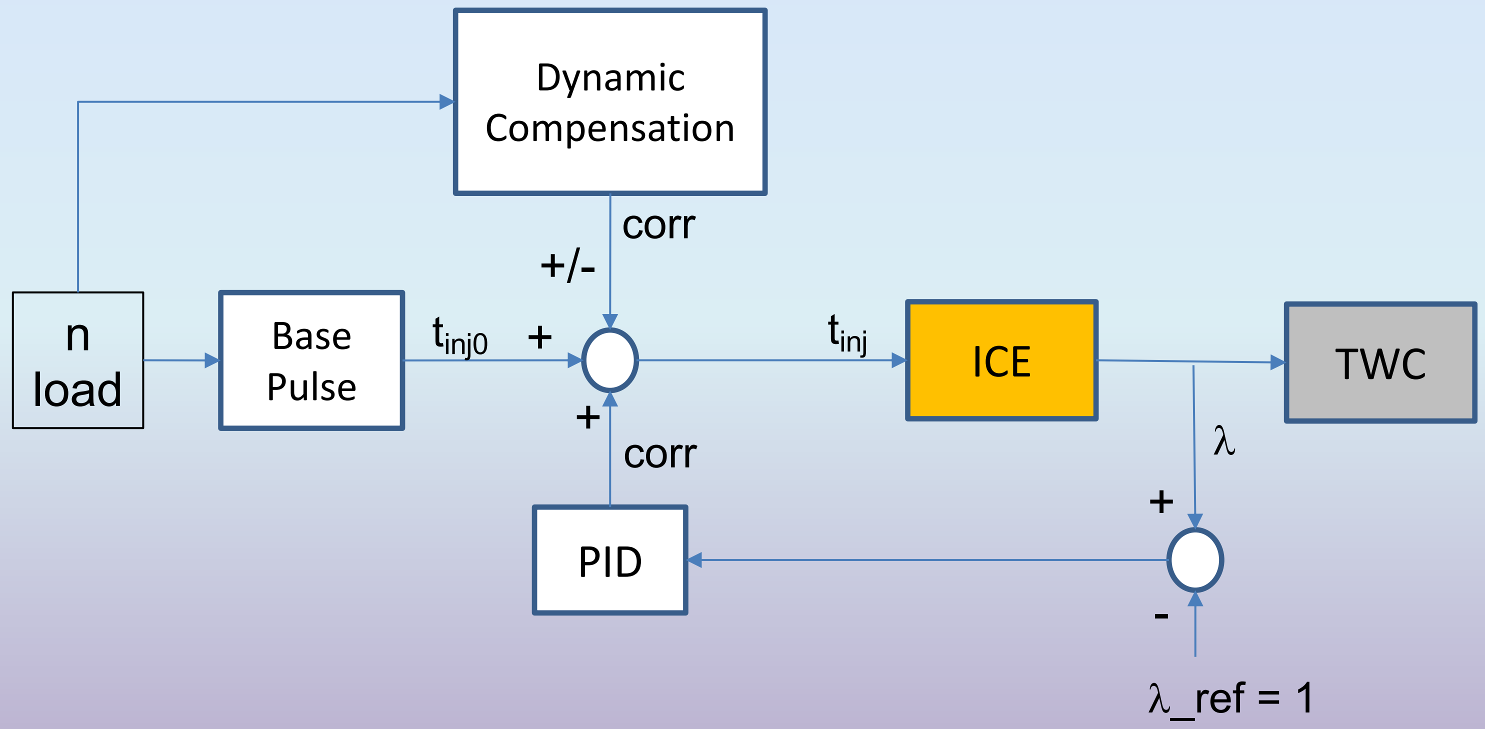
- In steady-state conditions, the lambda control system oscillates around the stoichiometric mixture between rich and lean. As the sensor switches from one side to the other, the injector pulse is adjusted by a control factor until the lambda sensor switches again on the opposite direction.
- The frequency of oscillation is determined by the time delay from air/fuel mixture formation to lambda sensor measurement.
- Under transient conditions, the gas transport time results in a delay before the lambda sensor can indicate that the operating condition has changed.
- Using only the lambda sensor and the closed loop control during transient conditions result in wide AFR excursions, poor drivebility and large exhaust emissions.
- An anticipatory or feed-forward control strategy is needed and this task can be accomplished by the recourse to Model Based Control.

Model Based Control

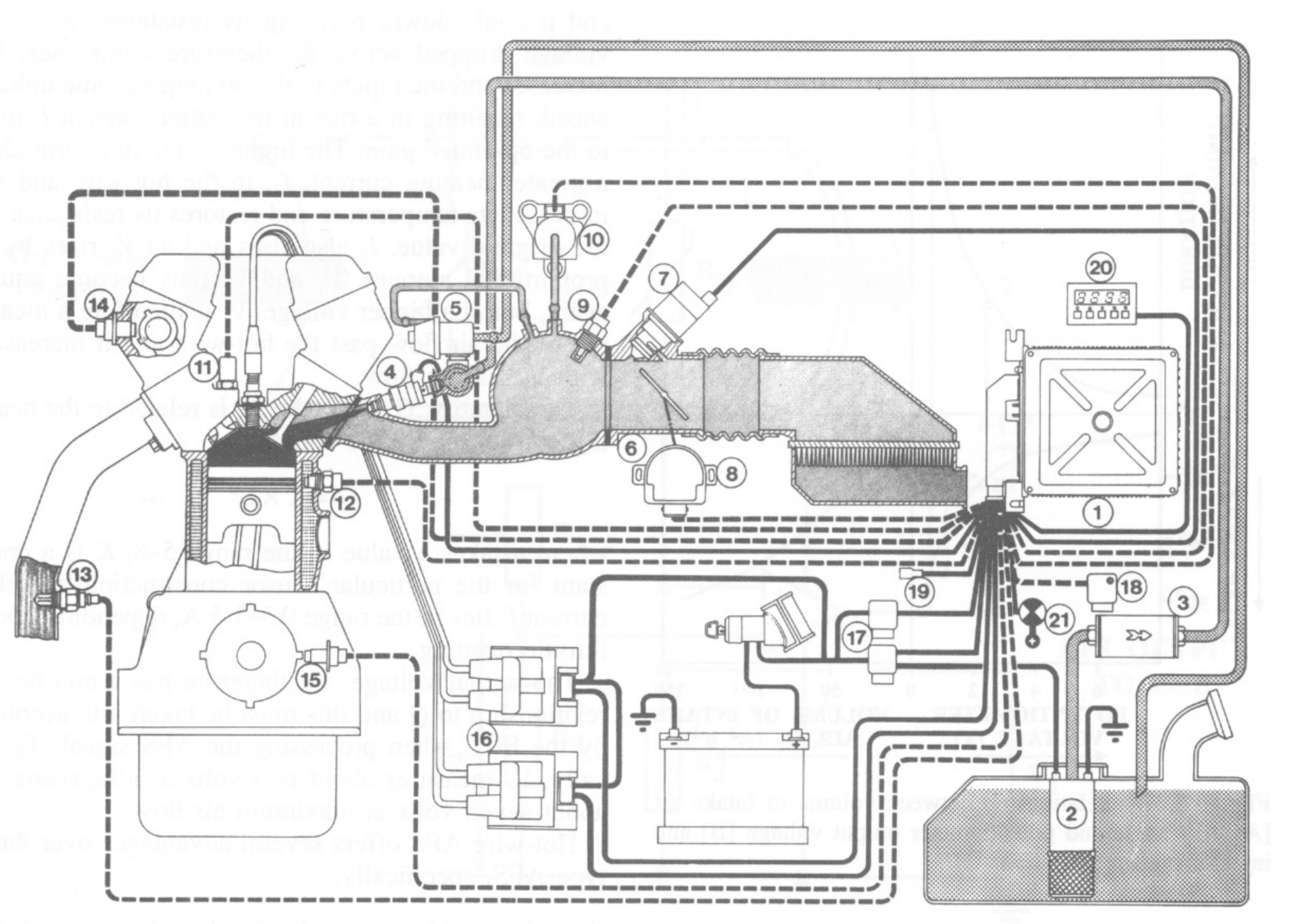
- Estimating correctly the air mass flow at the injector location and injecting the fuel in the right amount at the required time and with the correct time dependence is the only way to provide accurate AFR control.
- The dynamics of both air and fuel flows must then be described and/or estimated within a wide range of engine operating condition.
- In the framework of engine models for control applications, a key role has been played by the Mean Value Engine Models (MVEM), whose acronym was originally proposed by Hendricks & Sorenson [1991]. Earlier works have been however proposed by Aquino and Moskwa.
- The MVEMs are based on a simplified physical description of the understudy system/plant and allow simulating the main dynamics on a time scale of several engine events.
- This approximation does not make the models suitable for the design of the intake engine components, but at the same time it guarantees a satisfactory accuracy for control purposes with a reasonable computation time.
- Due to the physical description, the models need a minimum number of parameters to fit the engine behavior in a wide operating range and for different engine/intake systems.
- Most of the MV models have been proposed for the control of the fuel metering system, accounting for the air dynamics and for the fuel wall wetting in the intake manifold of SI engines.

Fuel injection / AFR Control

Fuel injection control scheme



Engine Control System

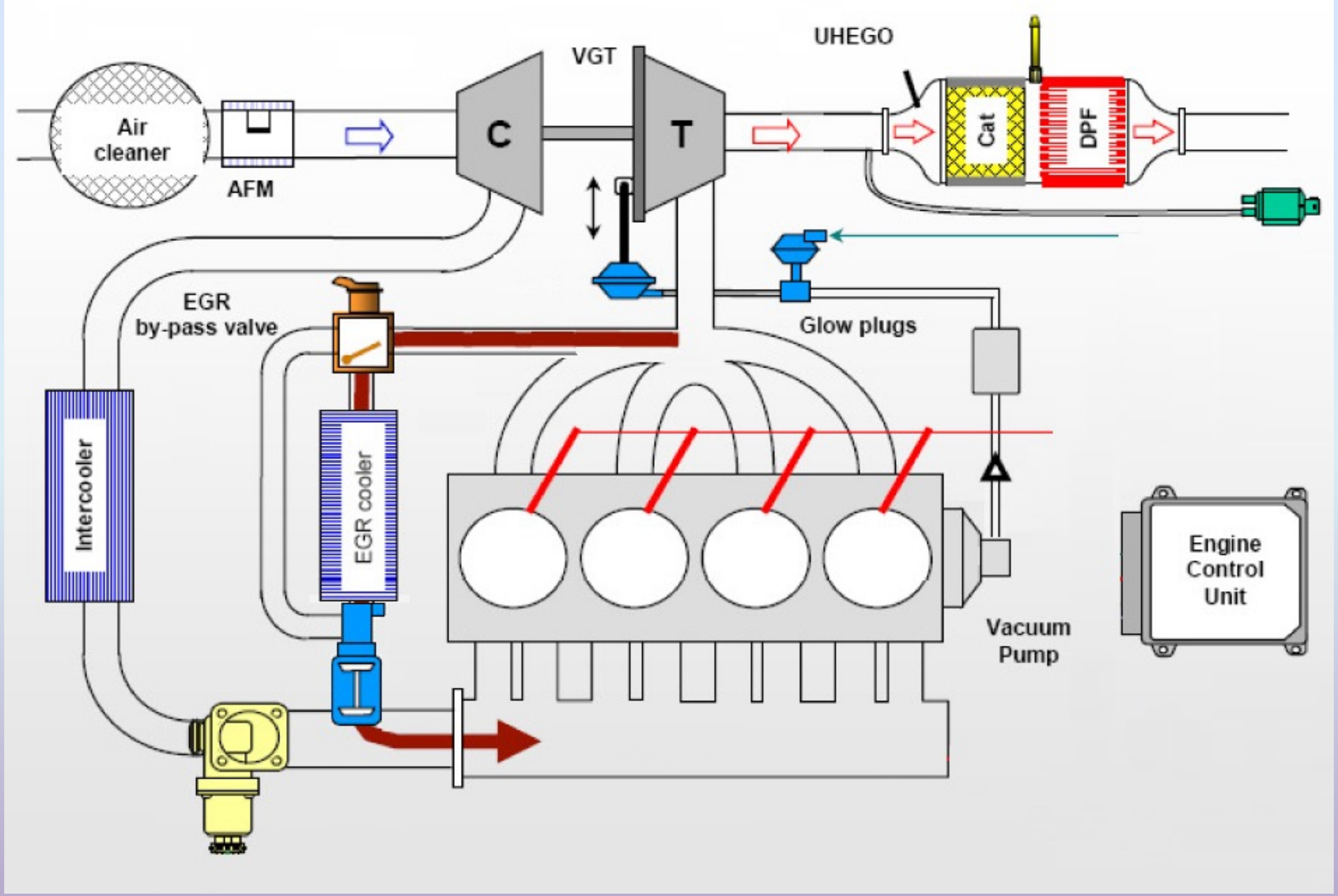


[1] microcomputer based ECU; [2] fuel pump; [3] fuel filter; [4] injectors; [5] fuel pressure regulator; [6] throttle body; [7] idle air control valve; [8] throttle position potentiometer; [9] inlet air temperature sensor; [10] MAP sensor; [11] knock sensor; [12] coolant temperature sensor; [13] exhaust gas oxygen sensor; [14] timing sensor; [15] engine rpm sensor; [16] doubled-ended ignition coils; [17] system relays; [18] trimmer; [19] diagnostic connector; [20] trip computer; [21] malfunction indicator light.

Scheme of a Speed-Density Engine Control System

Controllo Motore Diesel

Controllo Motore Diesel



Controllo Motore Diesel

Control Variables

- Injection pattern
  - Rail pressure
  - # of injections
  - SOI
  - Pulse widths
- EGR (H/L pressure)
- VGT

Goals

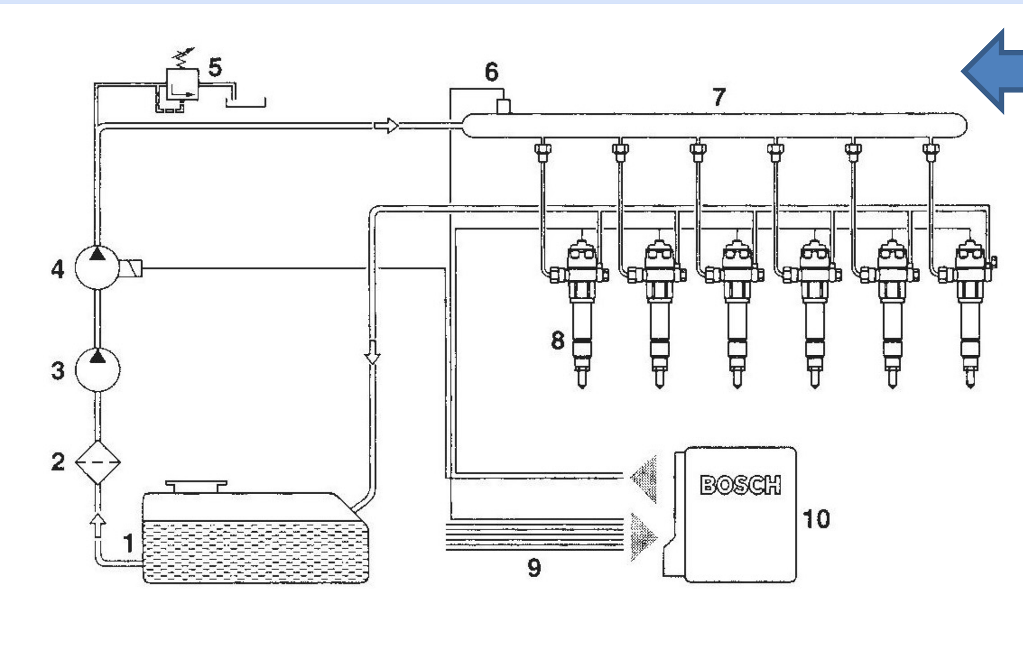
- Find optimal combination(s) of control variables for given Driver request (Load and Speed)
- Guarantee fuel economy, low engine emissions, efficient operation of after-treatment devices (DPF, LNT/SCR)
- Large calibration effort
- Control oriented models to reduce experiments

Sistema di iniezione del combustibile

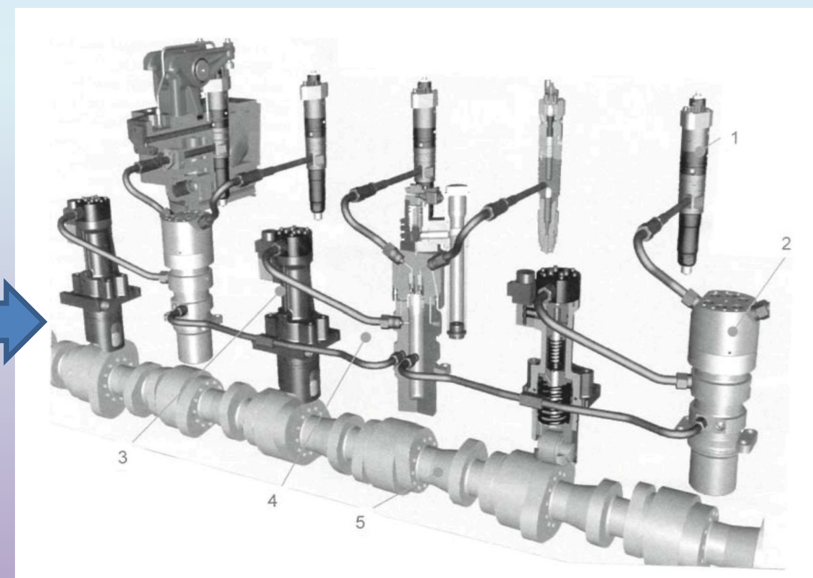
Obiettivi

- Dosare la stessa e corretta quantità di combustibile a tutti i cilindri
- Iniettare il combustibile nell'istante più opportuno, al variare della quantità (carico) e del regime di rotazione
- Modulare la portata istantanea di combustibile iniettata
- Polverizzare il combustibile in modo da favorire l'evaporazione e la miscelazione con l'aria
- Imprimere elevata velocità allo spray in modo da favorire la diffusione in camera di combustione e la miscelazione con l'aria
- Garantire prestazioni uniformi nel tempo in relazione alla vita del motore

Sistema di iniezione Common-rail

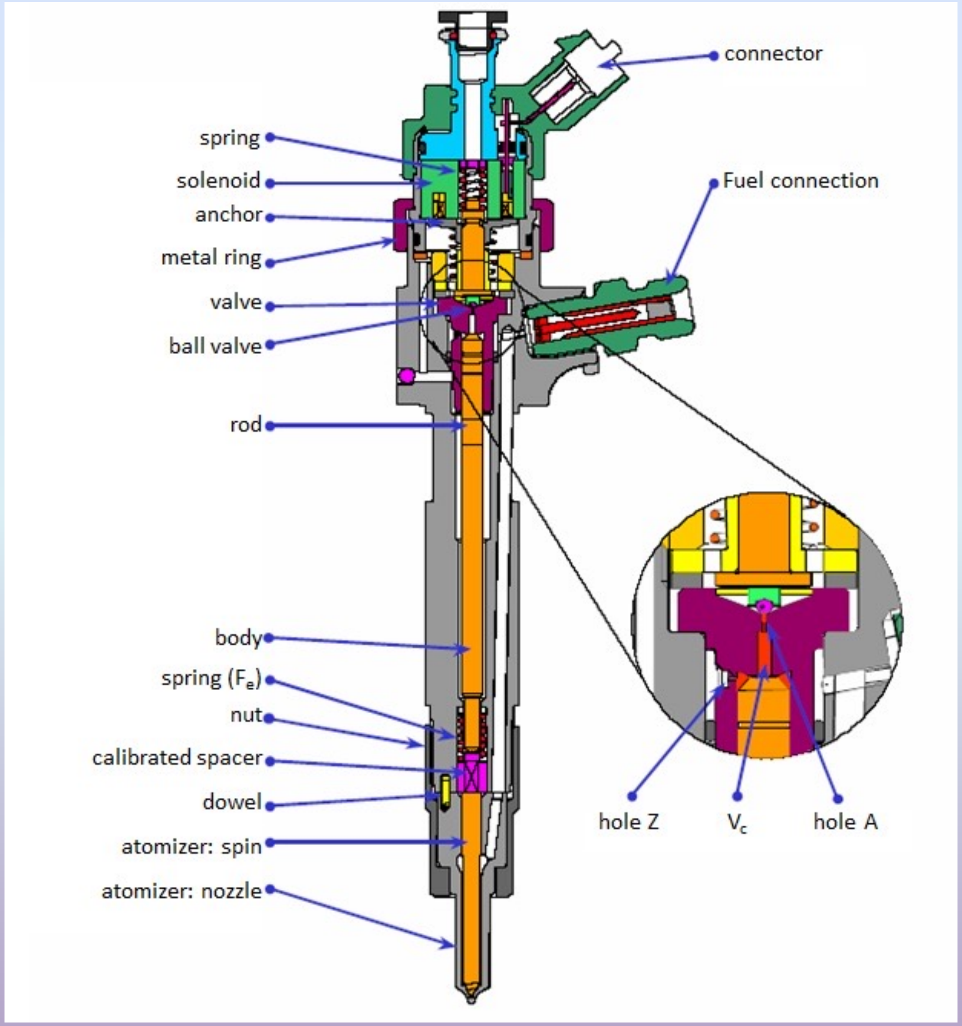


3- pompa di alimentazione
4- pompa di alta pressione
5- valvola di regolazione pressione
6- sensore pressione
7- rail
8- iniettori



1- iniettori
2- accumulatori combustibile
3- pompe di alta pressione

Sistema di iniezione Common-rail



The injector can be divided in two main parts:

- the atomizer composed by spin and nozzle;
- the solenoid valve controller.

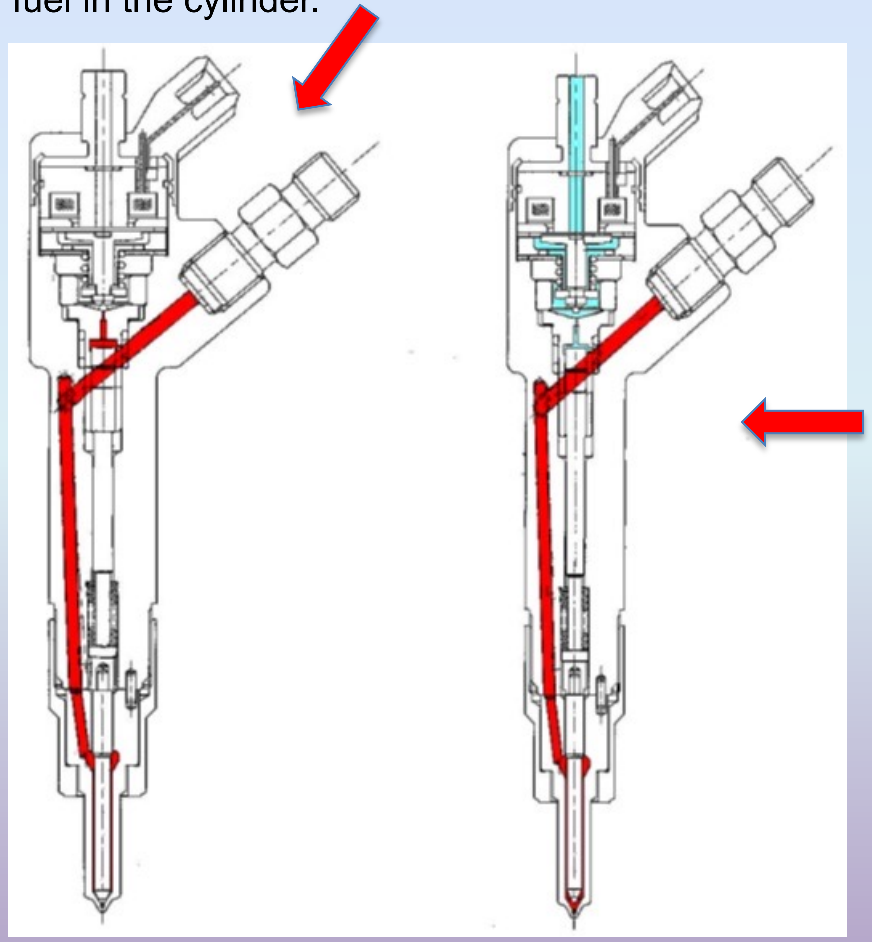
The control volume (V_c) is permanently fed with the fuel by means of the hole Z, while the discharge of the fuel is left to the hole A, controlled by the solenoid valve. The force acting on the pressure rod is proportional to the pressure ruling in the V_c.

The dynamics of the pressure rod depends mainly by the equilibrium of the following forces:

- F_e: acting in closing direction due to the spring on the spin.
- F_c: acting in closing direction due to the pressure of the fuel in the control volume at the top of the spin
- F_a: acting in opening direction due to the pressure of the fuel in the control volume on the anchor

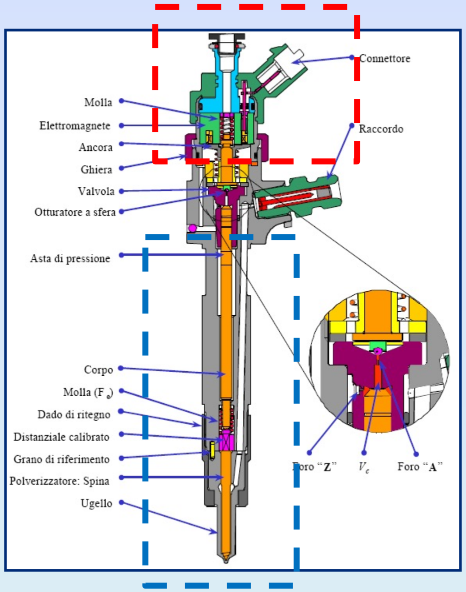
Common-rail Injection

The solenoid valve throws off the forces. In resting position the solenoid is not excited and the valve is closed by means of a spring. In the control volume, fed by the hole Z, there is the rail pressure and then the closing forces (F_c+F_e) are greater than the opening force (F_a). For this conditions, there is no injection of fuel in the cylinder.

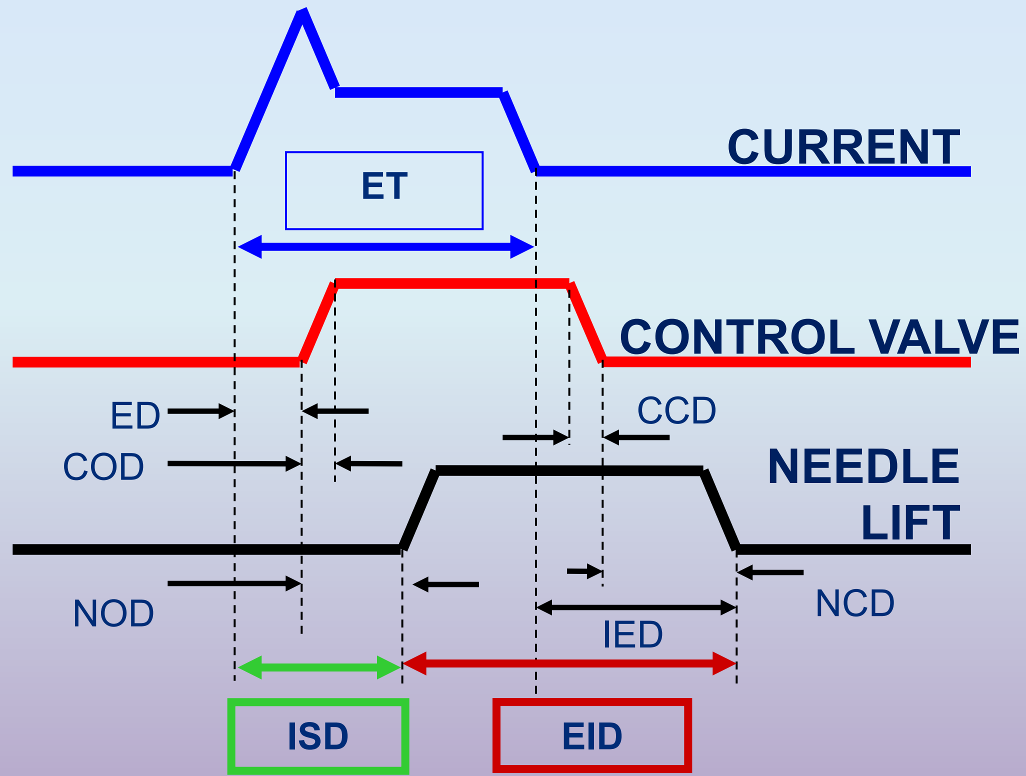


By exciting the solenoid valve, the raising of the anchor is obtained, allowing the ball valve to open the hole A. This hole has a discharge diameter greater than that of hole Z, and then the control volume empties.
This generates a pressure drop in the control volume that causes a decrease in the force F_c.
When the force drop verifies the inequality , the rod begins to raise causing the opening of the atomizer. In this condition the fuel injection starts. The stop in the solenoid alimentation causes the closing of the hole A and a fast increasing of the control volume pressure till the equilibrium conditions for the closing of the injector. The quick movement of the rod, in order to guarantee a fast interruption of the injection, is due to a spring.

Common-rail Injection



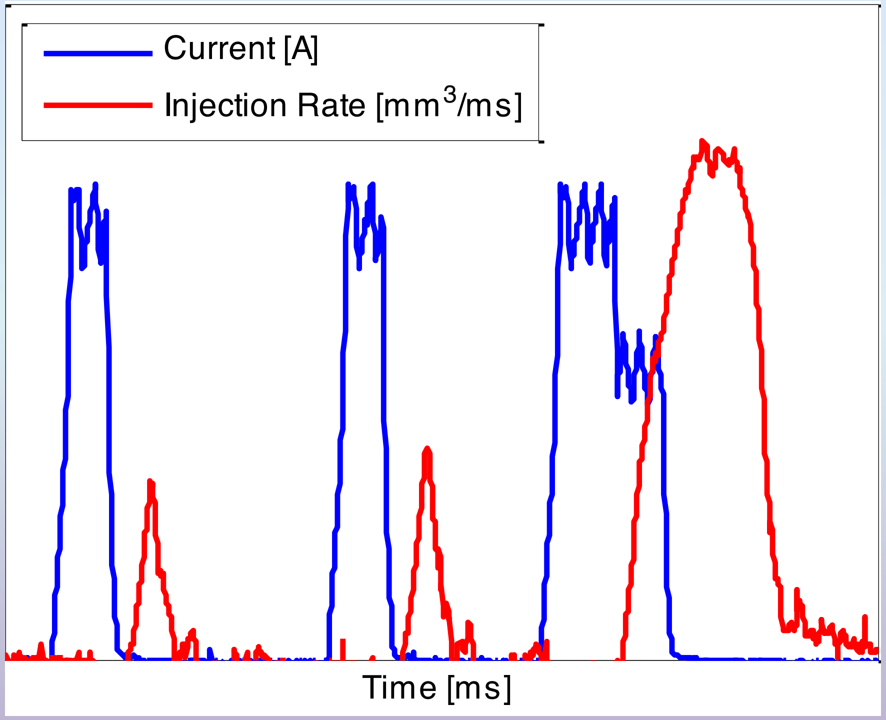
- **Actuator/atomizer** (mechanical and hydraulic model)
- **Solenoid** (magnetic model)

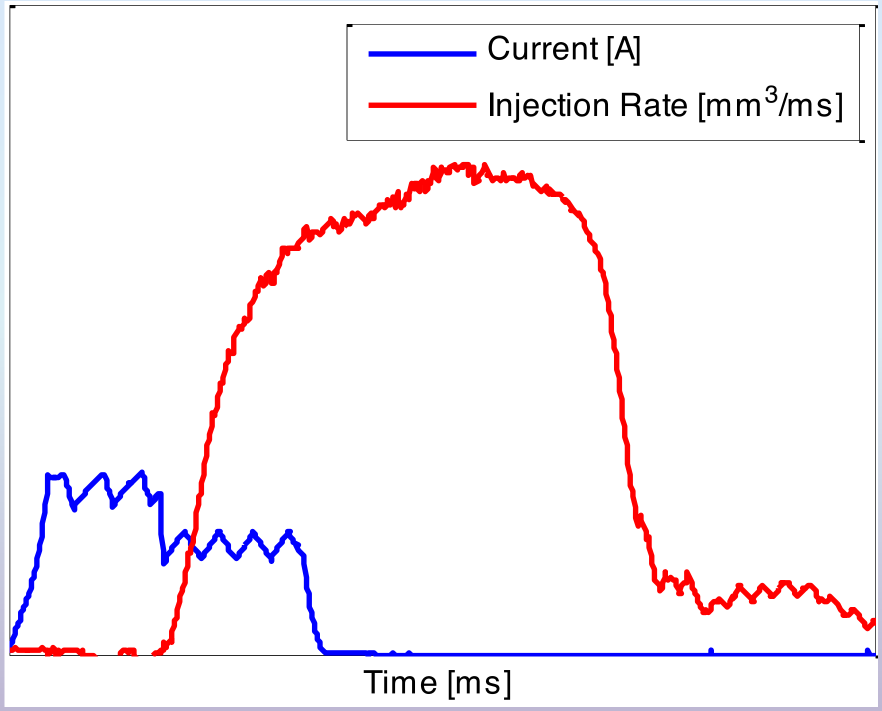


ET	Energization time
ED	Excitation delay
COD	Control valve opening delay
CCD	Control valve closing delay
NOD	Needle opening delay
ISD	Injection start delay
NCD	Needle closing delay
IED	Injection end delay
EID	Effective injection duration

Common-rail Injection

Experimental injection rate shape obtained on a flow test bench at Magneti Marelli Powertrain labs.

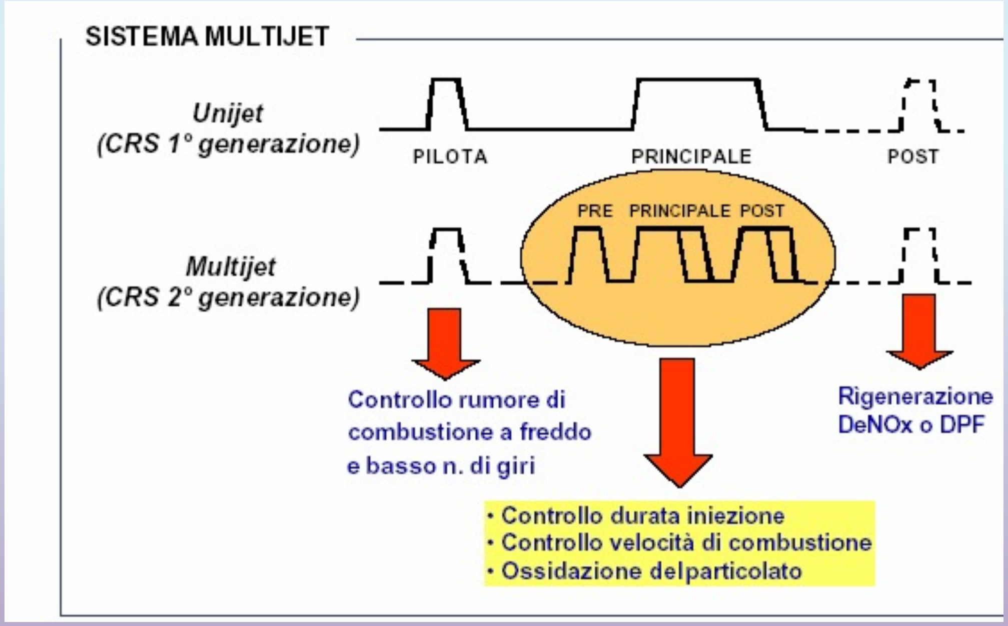




Sistema di iniezione Common-rail

Vantaggi

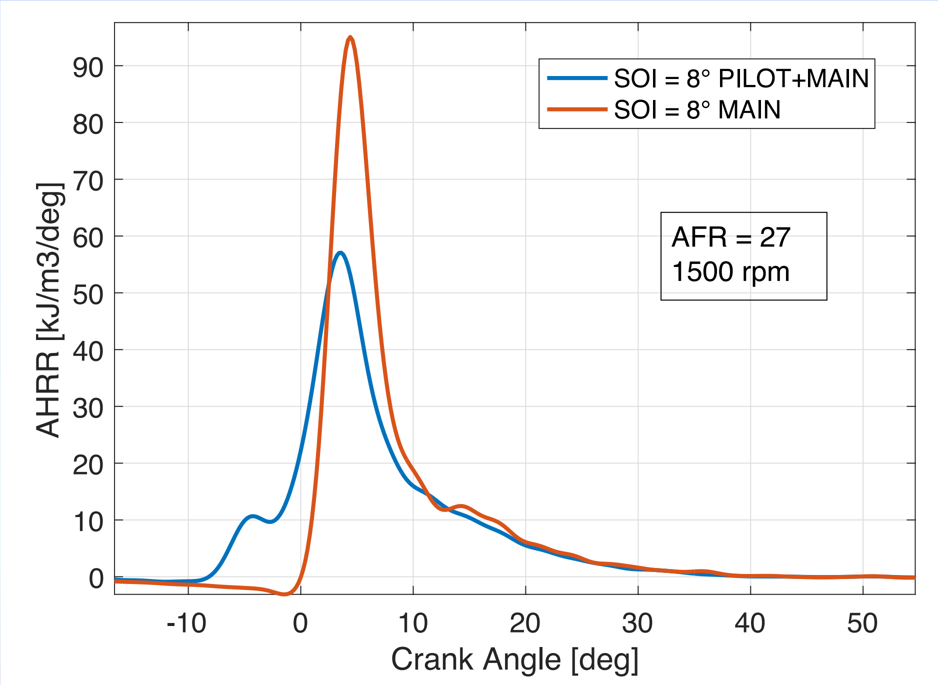
- incremento di pressione ed iniezione sono svincolati
- Pressione di iniezione indipendente dal regime di rotazione
- Anticipo e profilo di iniezione del combustibile controllabili attraverso la ECU in funzione di regime, carico, regimazione termica etc..
- Possibilità di realizzare iniezioni multiple

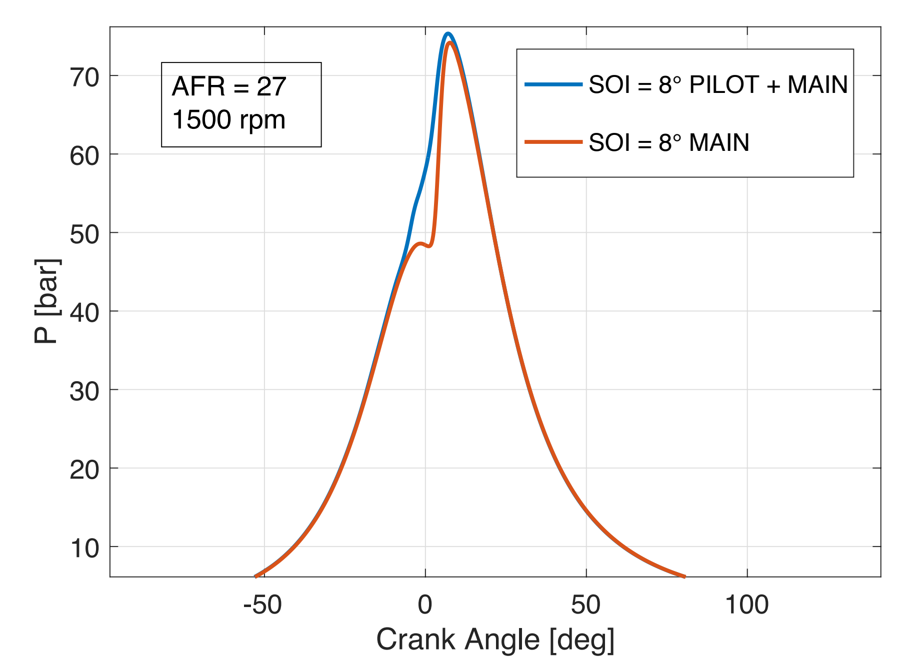


Controllo elettronico iniezione

- Rail pressure
- # of injections
- SOI
- Pulse widths

Sistema di iniezione Common-rail



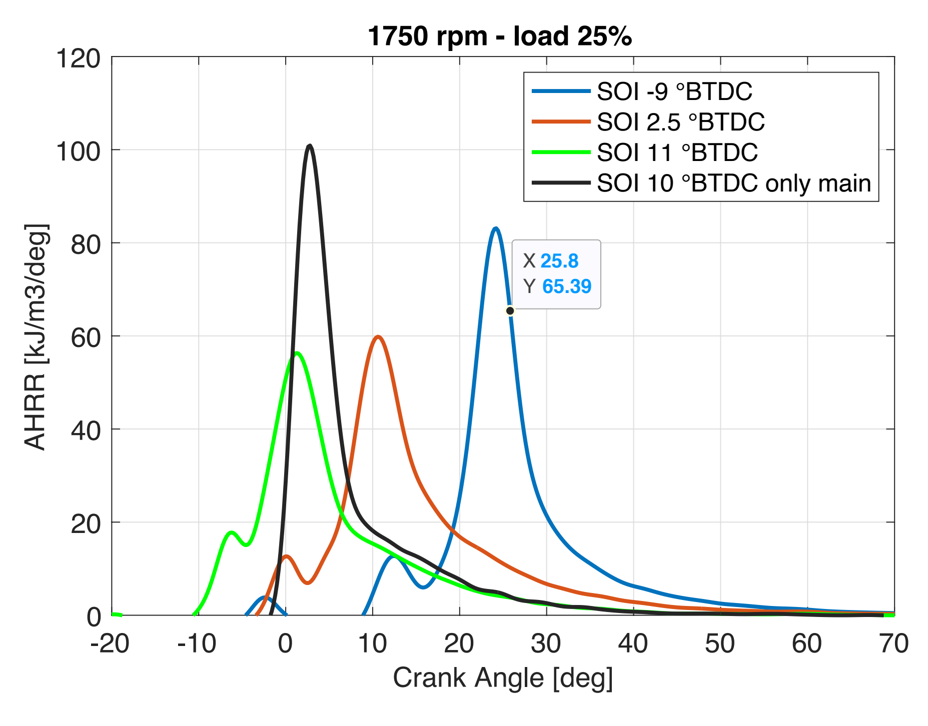


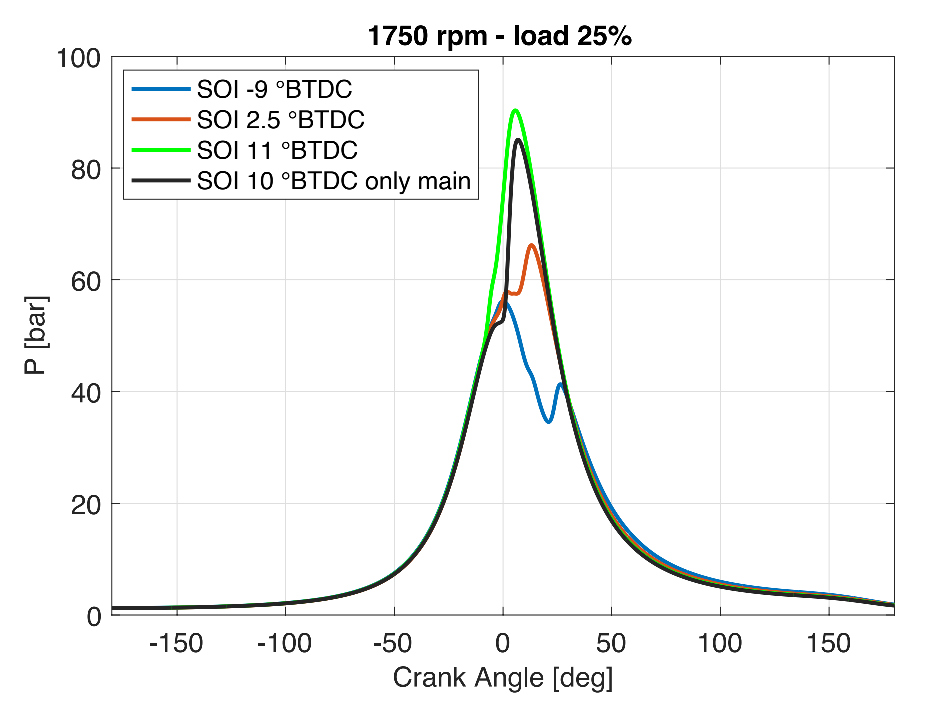
Vantaggi iniezione pilota

- Riduzione rumorosità e ruvidità di funzionamento
- Riduzione Tmax ed emissioni NOx

Effetto variabili di controllo

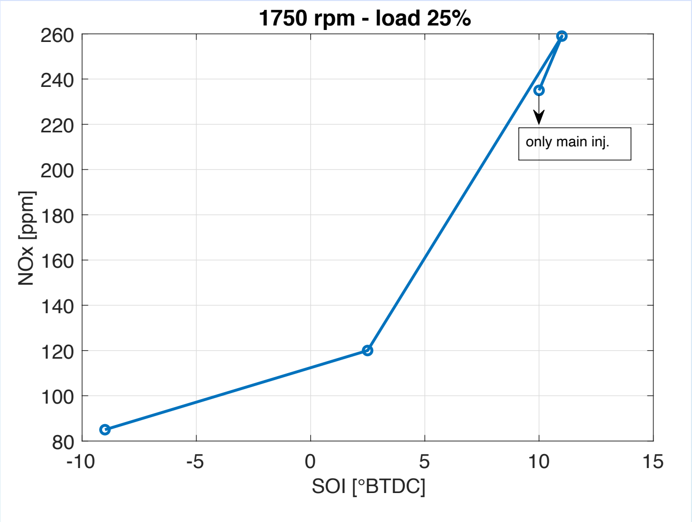
Anticipo iniezione - SOI

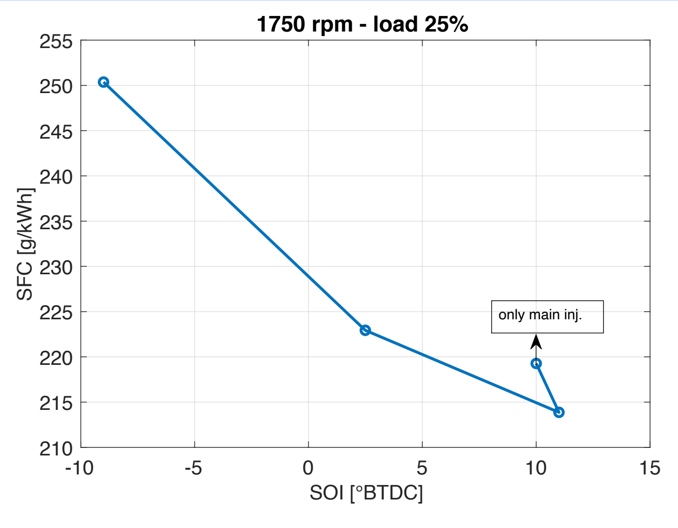


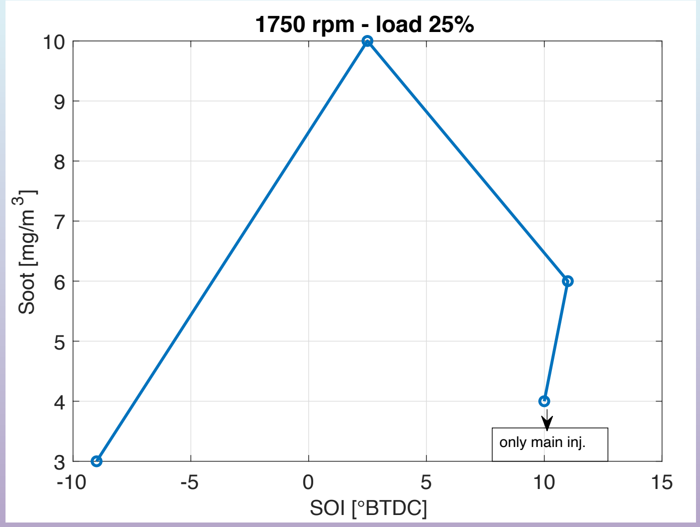


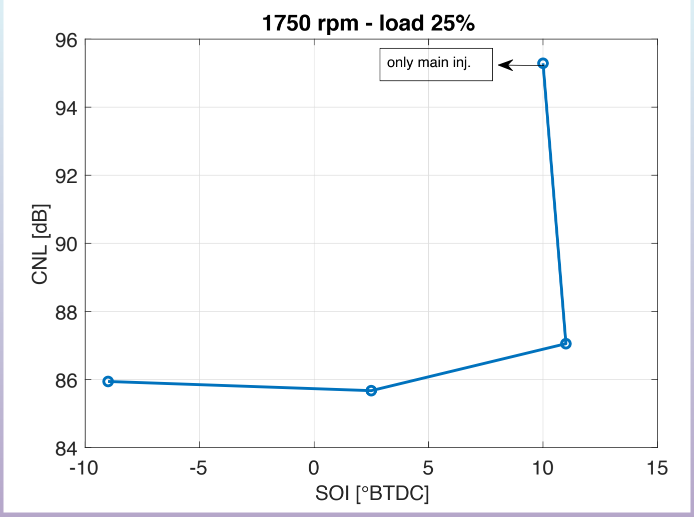
Effetto variabili di controllo

Anticipo iniezione - SOI



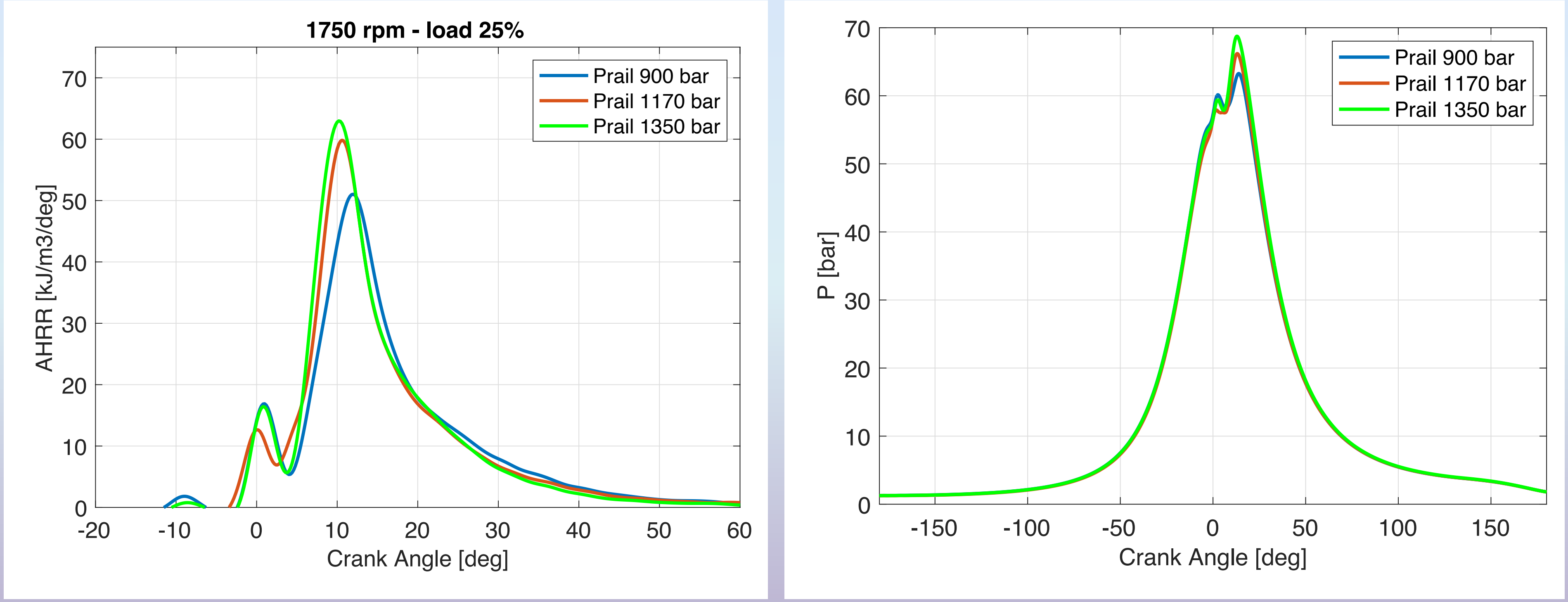






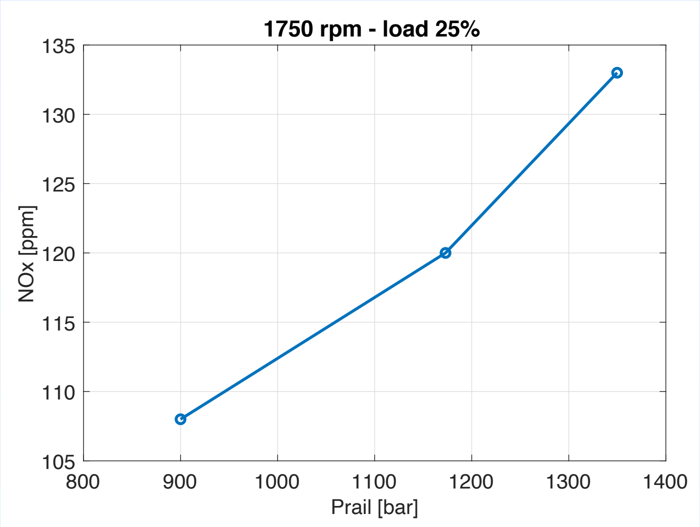
Effetto variabili di controllo

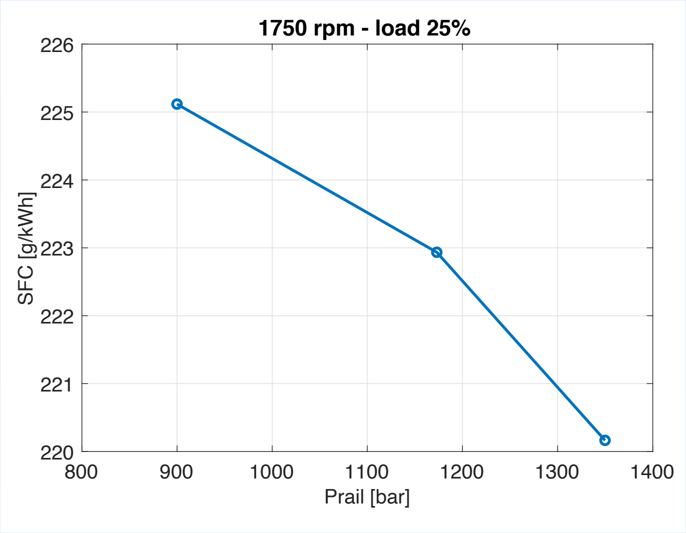
Pressione iniezione - Prail

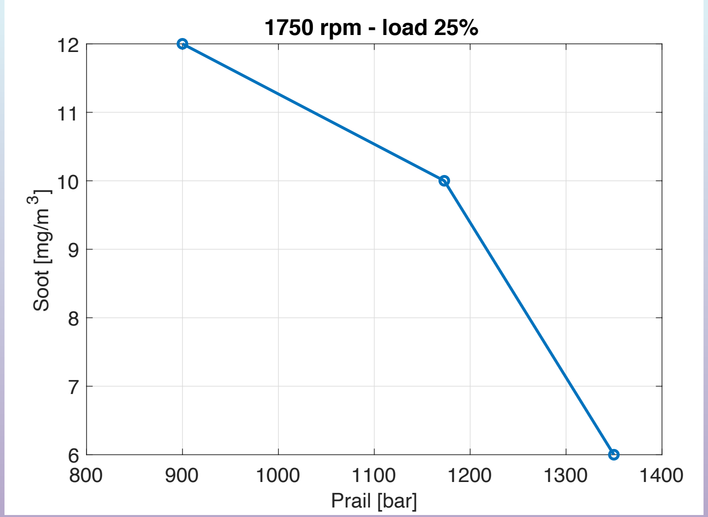


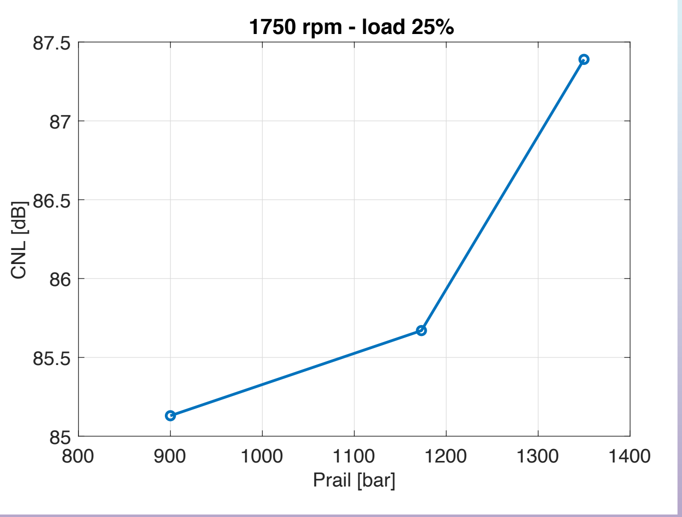
Effetto variabili di controllo

Pressione iniezione - Prail









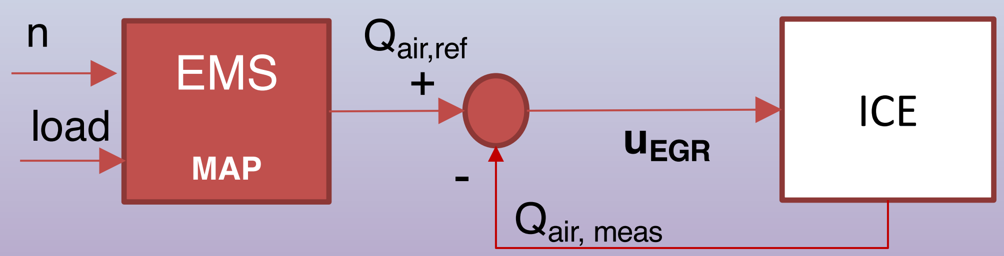
Effetto variabili di controllo

Ricircolo gas combusti - EGR

- Il ricircolo dei gas combusti consente l'incremento della frazione di gas residui in camera di combustione, determinando:
  - Riduzione della temperatura in camera per effetto della presenza di gas inerti che altera il rilascio del calore
  - Riduzione delle emissioni di NOx, aumento delle emissioni di soot
  - Riduzione del rendimento termico/indicato
  - Riduzione della portata di aria, per effetto del minor riempimento volumetrico, e della concentrazione di O2 in aspirazione e scarico.
  - Riduzione della velocità del turbo per effetto della minor entalpia dei gas di scarico

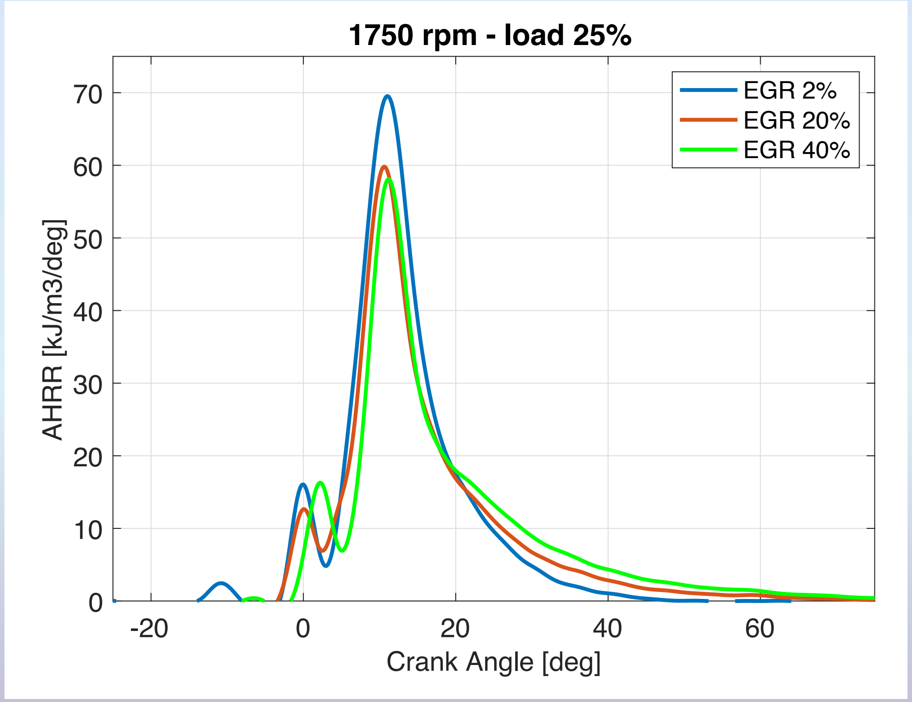
$$X_{EGR} = \frac{m_{EGR}}{m_{air} + m_{EGR}} = \frac{[CO_2]_{\text{int}} - [CO_2]_{amb}}{[CO_2]_{exh} - [CO_2]_{amb}} = \frac{[O_2]_{amb} - [O_2]_{\text{int}}}{[O_2]_{amb} - [O_2]_{exh}}$$

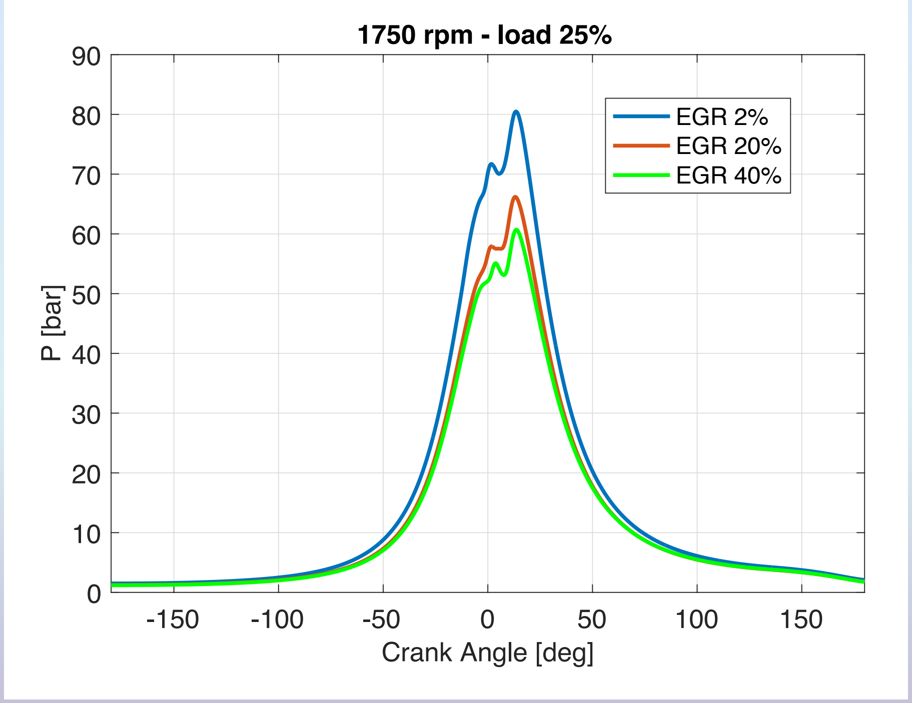
Schema di controllo dell'EGR



Effetto variabili di controllo

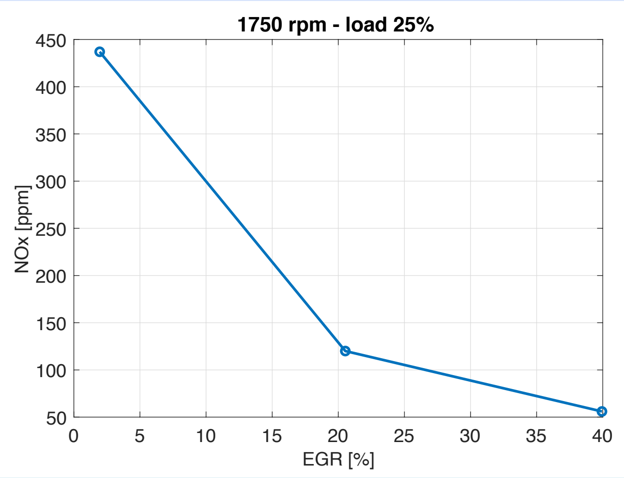
Ricircolo gas combusti - EGR

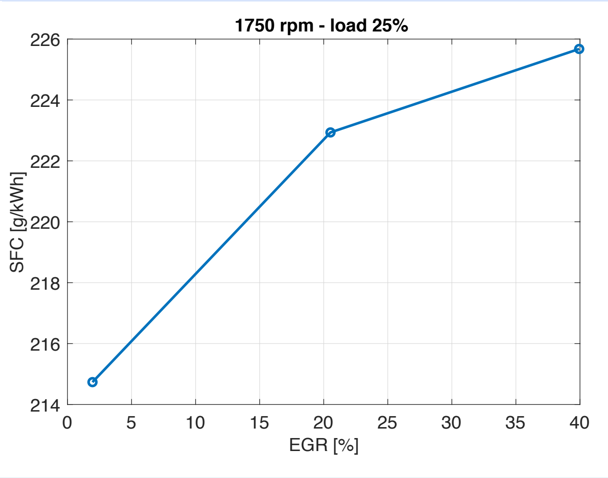


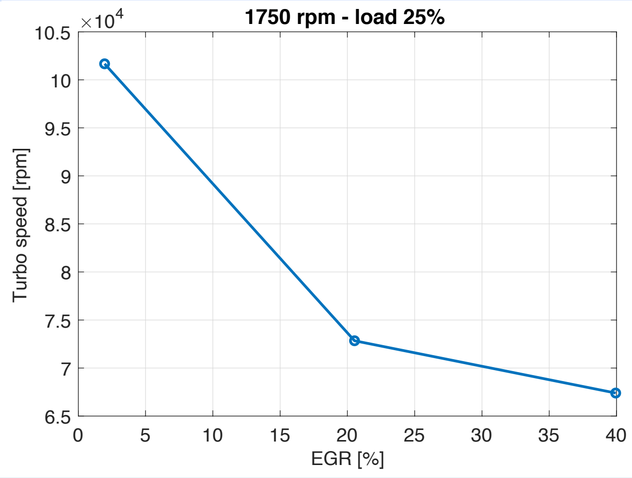


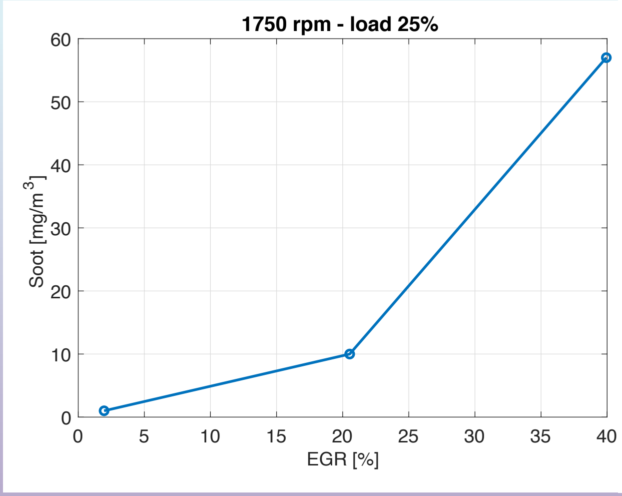
Effetto variabili di controllo

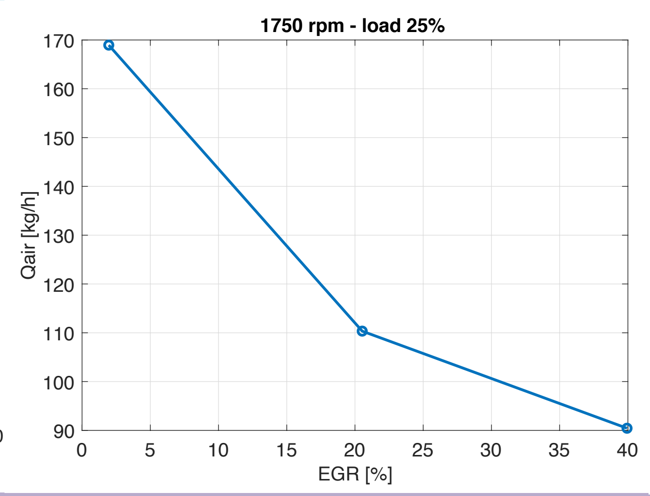
Ricircolo gas combusti - EGR

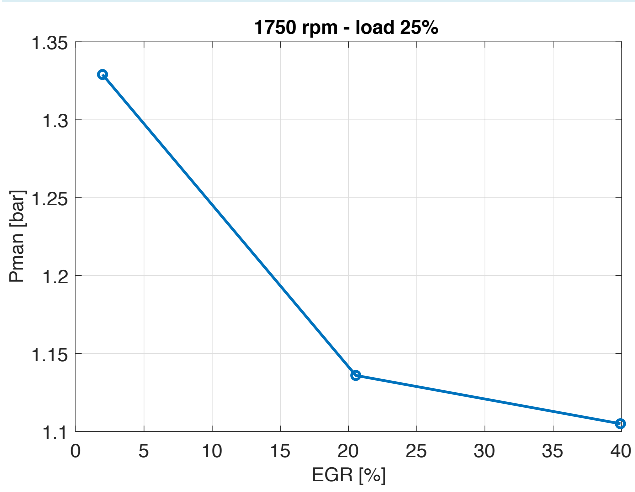








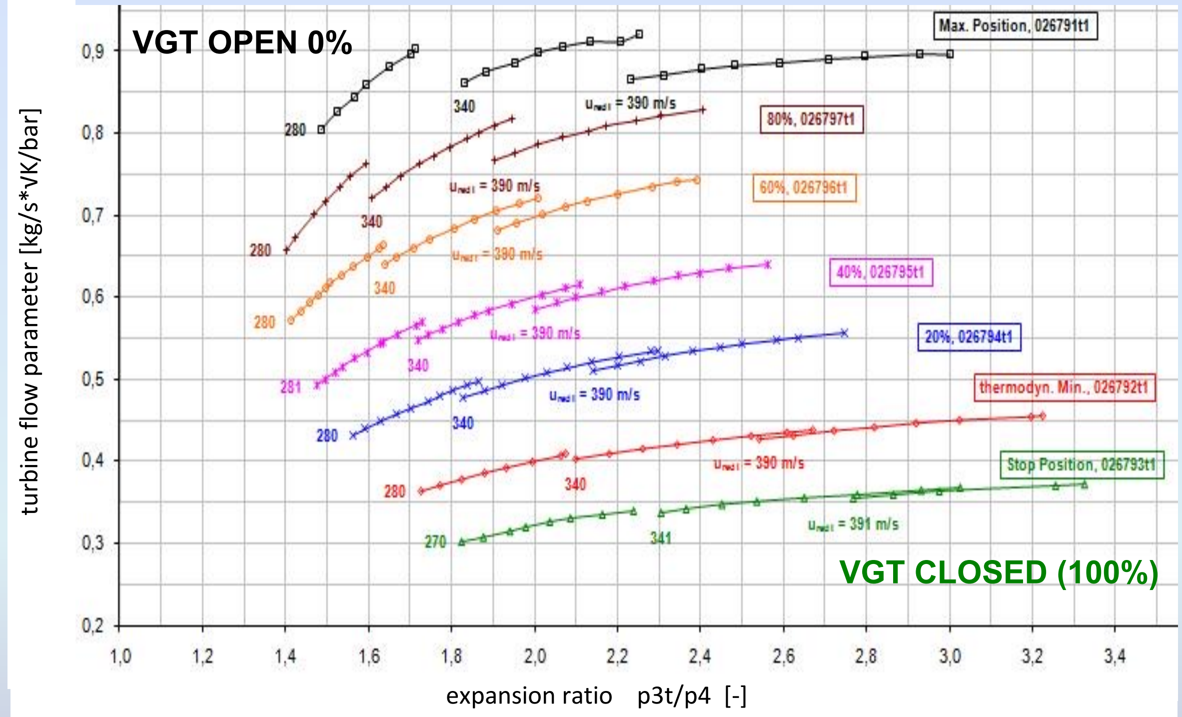




Effetto variabili di controllo

La regolazione dell'orientamento delle pale statoriche consente di adattare la curva caratteristica della turbina alle condd. operative del motore, aumentando la risposta dinamico del turbo-compressore e riducendo il turbo lag.
La chiusura del VGT (riduzione della sezione di efflusso) determina:

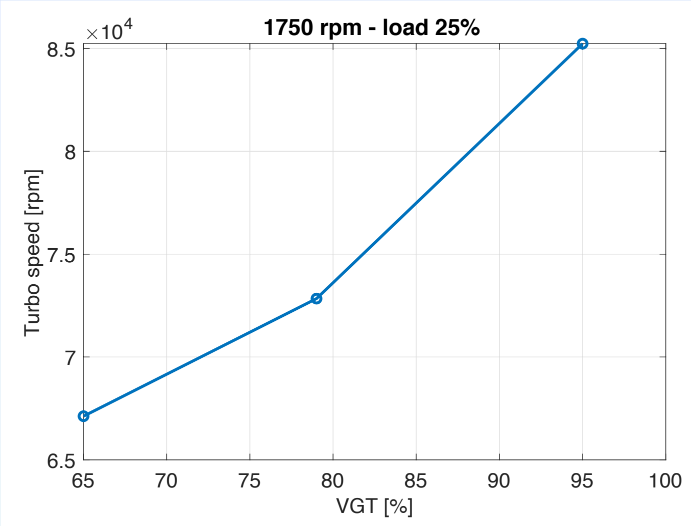
Turbina a geometria variabile - VGT

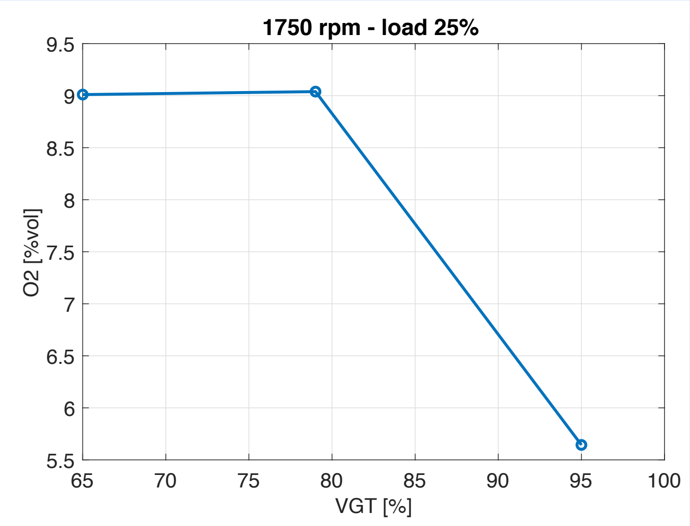


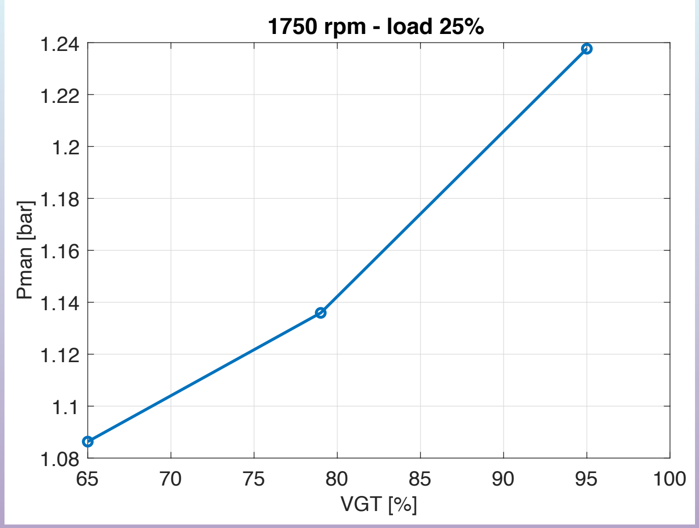
- Aumento della P_{exh} , del salto entalpico disponibile in turbina e della velocità del turbo-compressore;
- Aumento della pressione nel collettore di aspirazione;
- Aumento della frazione di gas combusti ricircolata (maggior rapporto P_{exh}/P_{man}), quindi alla chiusura del VGT deve corrispondere la chiusura della valvola EGR.

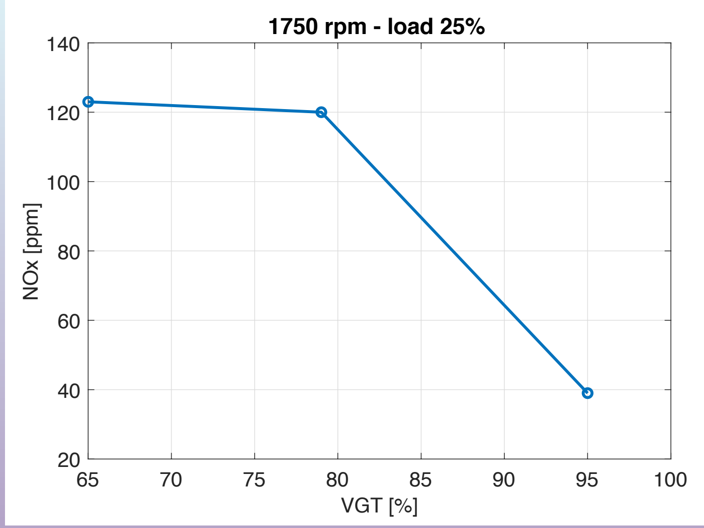
Effetto variabili di controllo

Turbina a geometria variabile - VGT









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