

Airpath controllers for high speed diesel engine

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Abstract. *Air quality in the urban centers has been one worldwide concern in the last years and internal combustion engines are significant pollutant sources. This paper focus on the pollutant emissions control of diesel engines equipped with electronic injection system, exhaust gas recirculation (EGR) and variable geometry turbine (VGT). Some distinct air-path controllers are designed and evaluated according to their capability to track the air-path set-points. In order to enable more realistic data for analysis and controller design, a specific high speed diesel engine was modeled. A %CO₂ model was also validated and applied for real time observation of the engine recirculation as an indirect factor for NO_x estimation for simulation purposes.*

Keywords: *EGR, VGT, airpath controller, diesel engine, engine emissions.*

1. INTRODUCTION

Compression-ignition diesel engines are widely used due to their efficient energy conversion. The disadvantage of diesel engine is the high level of emissions of nitrogen oxides (NO_x). Due to the increased necessity to care the environment concern, emissions standards have been reviewed periodically and one of the main is European Standard, defined as Euro. That normalization disciplines European vehicles and other countries - like Brazil - concern it as a model. To accomplish such a goal, engine components, after treatment and control units have to be designed to contribute toward lower emissions and several approaches have been developed in recent years aiming this. Both in cylinder techniques and after treatment systems are solutions currently in use.

Focusing in engines equipped with exhaust gas recirculation and variable geometry turbine, the controllers applied for air mass flow and intake boost pressure are important actors to control the NO_x emission.

As high-frequency NO_x sensors are not widely available, controllers design and tuning have often to be developed to reduce a not directly measurable concentration of nitrogen oxides.

Current commercial air-path control systems usually apply decentralized PID controllers which consider engine air-path as two independent systems, however, such approach is not fully representative because both actuators share the same energy from the engine exhaust gases and some consequences of such coupling can affect the control system performance.

This work focus on the controller design and the emissions resulting from some of the control system's main characteristics. For a more realistic analysis it was modeled a high speed diesel engine and also modeled and validated a real-time recirculation observer based on %CO₂ models.

2. POLLUTANT CONTROL

In cylinder pollutant formation (NO_x and PM) are significantly impacted by the exhaust gas recirculation rate, as widely described and demonstrated, for example Heywood (1988) and Wagner *et al* (2009), and the NO_x and PM trade off can be seen in Figure 1.

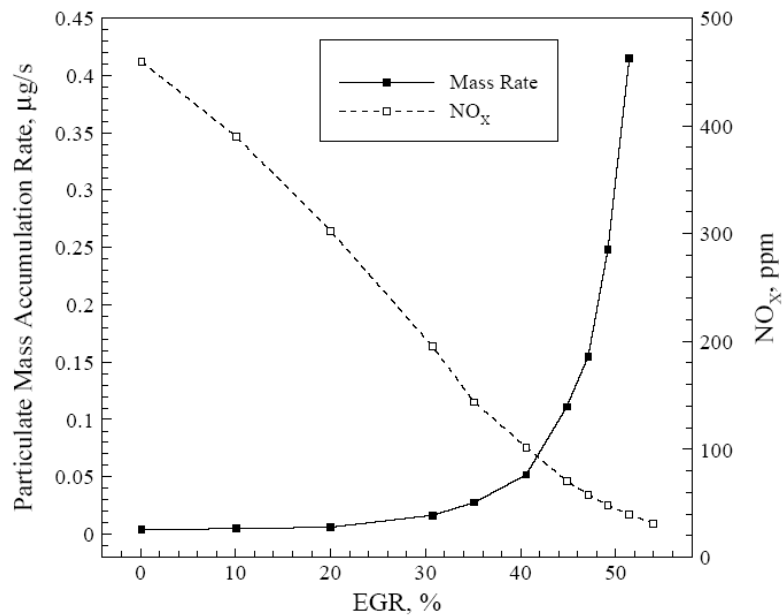


Figure 1. NO_x and PM pollutant formation per recirculation rate. “Wagner *et al* (2009)”

The recirculation rate in a Diesel engine is controlled by the recirculation valve (EGR) opening and variable geometry turbine (VGT) position. These components directly affect the intake air mass flow, intake and exhaust pressures and the whole mass and pressure balance is dynamically affected during engine load transients.

Current applied technology for emissions reduction through exhaust gas recirculation (EGR) often control the intake air mass flow and intake manifold pressure, as major controlled variables to define the recirculation rate desired in order to lower the engine out pollutant emissions.

However, pressure and mass flow variables do not give a clear picture of the final pollutant emissions effects. For effective controllers development and tuning it would be desirable to have a NO_x concentration measurement sensor with high sampling rate or an accurate model, but such resources are not often available. A recirculation observer can be used, when all other engine parameters are controlled, to indirectly estimate the NO_x emission.

This paper uses the CO₂ modeled estimation to determine the recirculation rate to evaluate controller performance for design and tuning.

3. RECIRCULATION OBSERVER

It is known that the exhaust gas recirculation rate can be determined by the intake and exhaust CO₂ concentration. Baert (Baert *et al.*, 1999) and Darlington (Darlington *et al.*, 2006) have developed and proved a fast and accurate CO₂ concentration estimator using fast analyzers. These two previous developments are combined in this work to build a real time recirculation rate observer. The model can be seen in Figure 2.

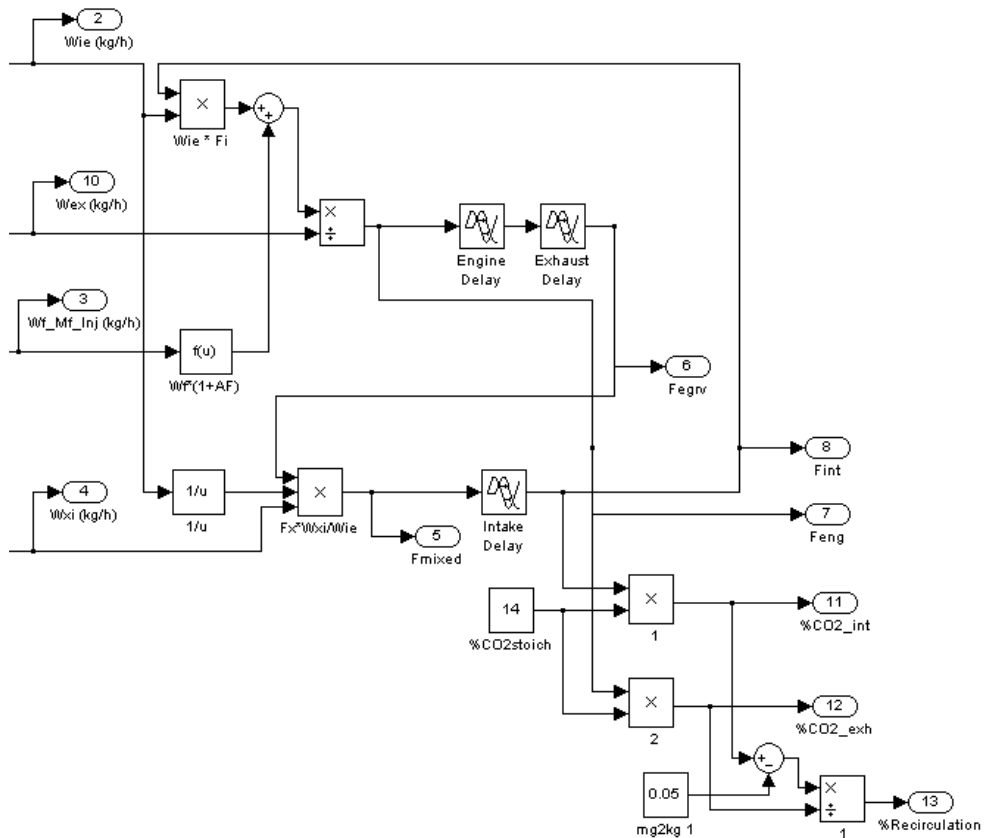


Figure 2. CO2 observer model

The model inputs are:

- W_{ie} (kg/h), total intake air flow admitted in the cylinders;
- W_{ex} (kg/h), total exhaust manifold gas flow out of the cylinders;
- W_{f_inj} (kg/h), total fuel flow injected; and
- W_{xi} (kg/h), total exhaust gas flow recirculated from exhaust to intake manifold.

The outputs are:

- F_{egr} (%), the fraction of recirculated gas at the EGR valve;
- F_{int} (%), the fraction of recirculated gas at the intake manifold;
- F_{eng} (%), the fraction of recirculated gas inside the cylinders;
- F_{mixed} (%), the fraction of recirculated gas at the mixing point (it is the point where exhaust gas is mixed with fresh air);
- CO2 int (%), the intake CO2 concentration;
- CO2 exh (%), the exhaust CO2 concentration; and
- Recirculation(%), the total exhaust gas recirculation.

Transportation delays (dead times) were determined by applying step stimulus to EGR valve and measuring the delay to detect the disturbance in the downstream and upstream flow. Engine internal transportation delay can be estimated from the measured engine speed.

In order to validate the model, the engine %CO2 measurement was compared with the modeled %CO2 in steady state engine operation in the selected point. Table 1 contains the results, where we can conclude that the model is well adjusted to the actual measurements done in the engine test cell.

Table 1. Measured and modeled %CO2 at intake, exhaust and total recirculation

	Engine test emissions	Modeled
%CO2 Intake	2.35%	2.21%
%CO2 Exhaust	8.35%	7.98%
% Recirculation	27.54%	27.06%

4. ENGINE ARCHITECTURE

Engine used in the tests is a 3.2 liter diesel engine equipped with electronic fuel injection, with maximum power of 180HP @ 3800rpm.

Air-path architecture can be seen in Figure 3.

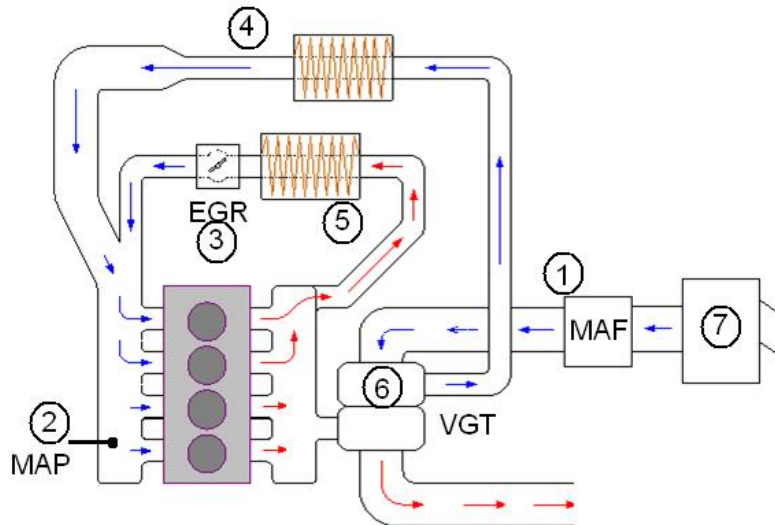


Figure 3: Air-path architecture

Main components are identified in the list below.

- 1 – MAF: Air mass flow sensor (mg/stroke).
- 2 – MAP: Manifold intake pressure sensor (hPa).
- 3 – EGR: Proportional valve for exhaust gas recirculation-EGR (Control range 0 to 100%).
- 4 – Intercooler (air-air).
- 5 – Exhaust gas cooler (air-water).
- 6 – VGT: Variable geometry turbine (Control range 0 to 100%).
- 7 – Intake air filter

VGT turbine controls the intake manifold pressure (MAP) and the exhaust gas recirculation rate is controlled by the EGR valve. Both actuators (VGT and EGR) are electronically controlled by serial CAN communication.

5. ENGINE MODELING

For emission control, air-path control systems usually apply decentralized controllers (PID) and it considers the engine air-path as two independent systems but such approach is limited because both actuators share the same energy from the exhaust gas.

A model that considers such coupling can better describe the engine behavior for controller design. This model can be seen in Figure 4 and will be used for controller design purposes.

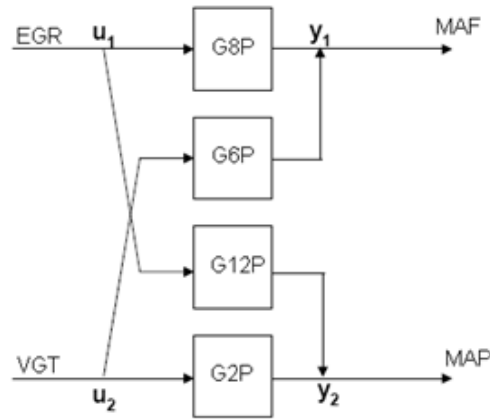


Figure 4: Process model with coupling

For engine modeling, it was chosen a fixed steady state operating point. This operating point was taken from the region with most probable concentration of points in the ETC (European Transient Cycle) distribution. Pollutant reduction is desirable in all operating regions but due to higher contribution identified from the point around 60% of maximum engine speed and 40% of maximum torque it was selected as the first one to be studied.

Engine was installed in dynamometer test cell and set for stable operation at 2300RPM and of 50% load.

For model identification it was applied a pseudo-random binary signal (PRBS) and sinusoidal stimuli to the actuators individually and measured the air-path related sensors. Amplitude of stimuli was +5% to -5% around nominal point. References for model identification methods can be found in Wang *et al.* (2008) and Karlsson, M *et al.* (2008).

As an example of such a signal, the PRBS stimulus applied to turbocharger (VGT) and the manifold pressure (MAP) response can be seen in Figure 5.

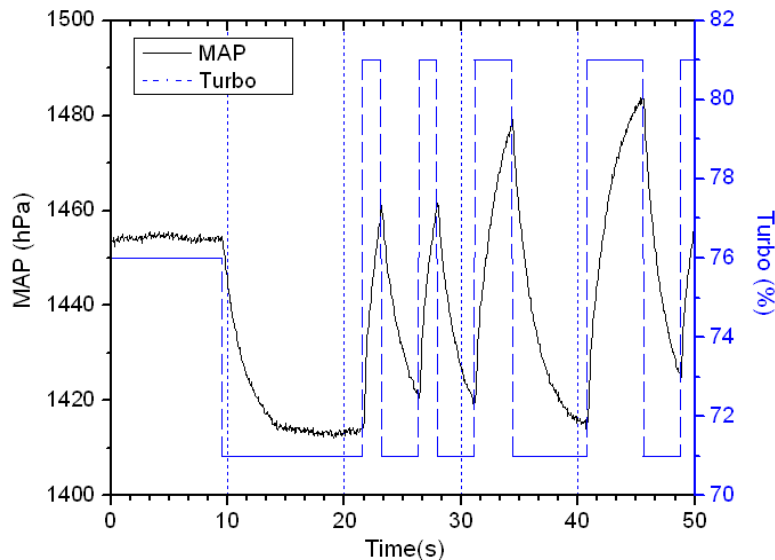


Figure 5. PRBS stimulus applied to VGT and MAP response

Figure 6 shows the sinusoidal stimulus applied to turbocharger (VGT) and the manifold pressure (MAP) response.

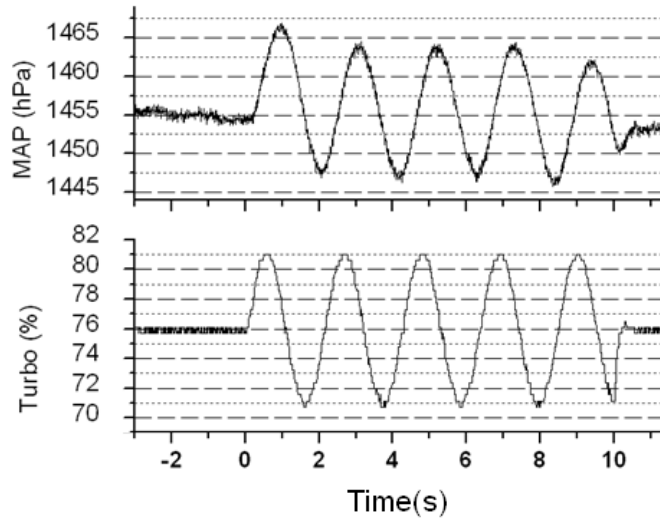


Figure 6. PRBS stimulus applied to VGT and MAP response

Based on the test results, it was determined the equivalent engine input-output models by two different methods, ARX and sinusoidal frequency response. Both methods produced good models but the fitting to the measured data indicated the best model to be used for control design and simulation. It was noticed that some dynamic characteristics (zero allocation) could be better handled in the sinusoidal frequency response model than the ARX model, that did not reproduced such dynamic characteristic very well in the model. Transport delays were estimated by applying step stimulus to each actuator input and measuring the disturbance in the downstream flow and/or pressures.

Bode diagrams for the developed models can be seen in Figure 7.

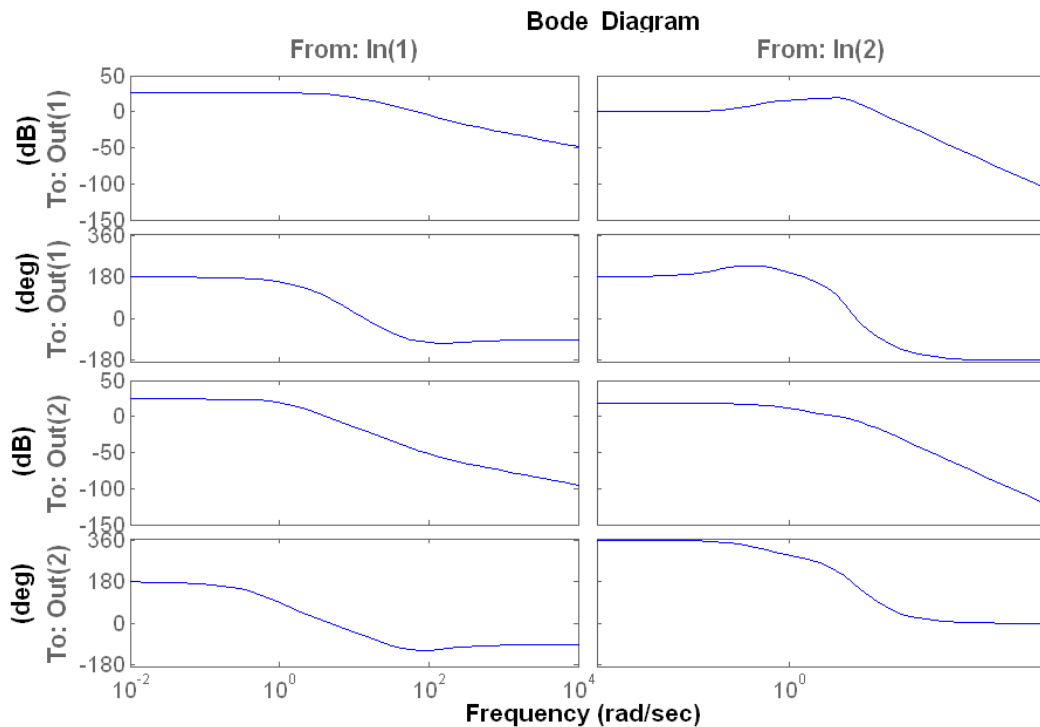


Figure 7. Bode diagram of the developed models

6. CONTROLLER DESIGN

PID controllers without feed-forward were tuned for this application. Engine operation in nominal condition has an EGR rate of 27.06%. For recirculation disturbance analysis, it was selected MAF and MAP step set-point values that produced, after the step transient, the same EGR rate (27.06%) as verified before the stimulus, applied in $t=0$ seconds (time before 0 seconds is used for model stabilization).

In order to identify control performance factors that would reduce emissions, it was selected and evaluated some typical performance characteristics applied to control the modeled air-path. The signal responses were evaluated using the real-time recirculation observer.

The response signal characteristics selected to simulation and analysis are:

- CASE1- Slow MAF response with unconstrained undershoots and overshoots and short MAP rise time
- CASE2- Short MAF and MAP rise times
- CASE3- Short MAF rise time and slow MAP response

The coupling among control loops was also evaluated and a decoupling proposal was tested. Similarly was done in (Wang et al., 2008) it was evaluated the decoupling of EGR rate (MAF) from the boost pressure (MAP). In order to improve decoupling in MAF loop, the MAF-EGR controller output was added to a decoupling term given by the ratio between the gain from MAF to VGT input (G6P in Fig.4) divided by the direct MAF-EGR gain (G8P in Fig.4) with the opposite sign for the opposite effect to ensure the decoupling. These gains were taken from the Bode diagram at chosen frequency of 3 rad/s.

To check the influence of decoupling in the air-path, it was then simulated:

- CASE4- Original engine plant (without decoupler)
- CASE5- MAF loop decoupled from the MAP control loop.

7. RESULTS

This section presents the results obtained from the simulations for the proposed study cases above.

For the following pictures, on the left side can be seen the intake manifold pressure (MAP) and the compressor air mass flow (MAF), and on the right it is the resulting recirculation rate calculated by the recirculation real time observer.

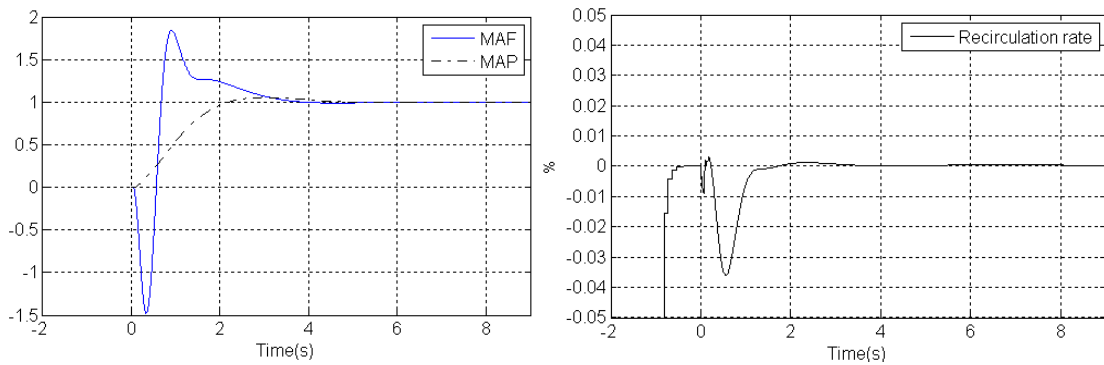


Figure 8. CASE 1- Slow MAF response with unconstrained undershoots and overshoots and short MAP rise time

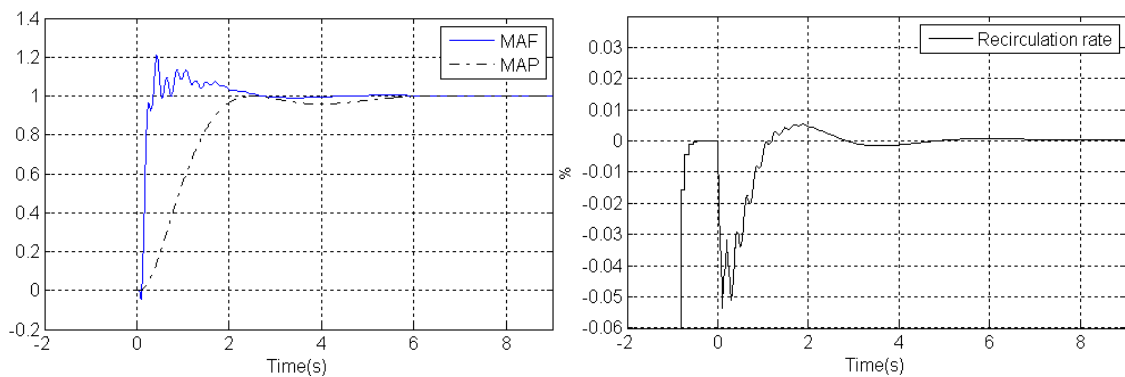


Figure 9. CASE 2- Short MAF and MAP rise times

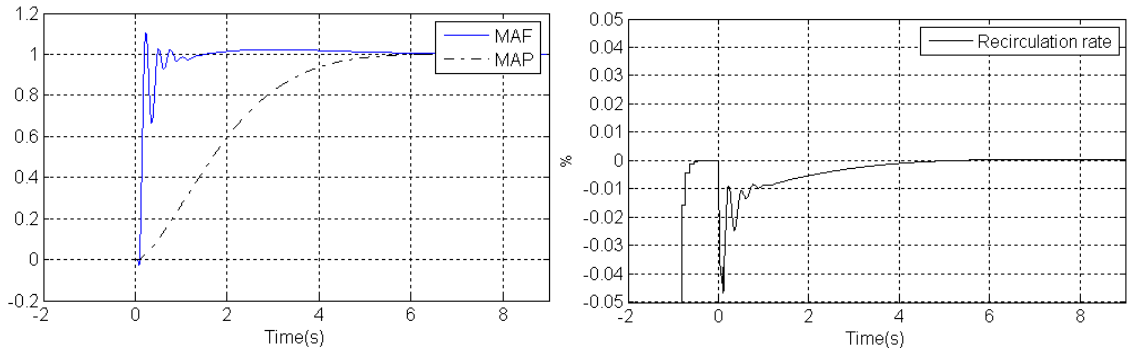


Figure 10. CASE 3- Short MAF rise time and slow MAP response

The overall analysis for the three cases indicates that all transients reduced the recirculation rate in different amounts, what can indicate a spike in NO_x in all cases. This NO_x correlation with recirculation rate, as presented in section 2, was also found by Darlington (Darlington *et al.*, 2006) where fast NO_x analyzers detected emission spike caused by the recirculation rate drop in similar tests.

Specially in case 3 (Fig.10) it is observed that the recirculation rate returned to initial desired value (0) just when the MAP variable reached the set point value, what indicates that better tracking in boost pressure leads to emissions reduction.

The results for decoupling the MAF loop (cases 4 and 5) are now presented.

It was applied a step request in set points at different times, in MAF_SP (at t=0sec) and MAP_SP (at t=2sec). This time shift in step stimuli allows to detect that there is a coupling between the control loops, as seen in Fig.11 (Case 4) where the MAF signal is disturbed at t=2 seconds due to MAP_SP stimulus.

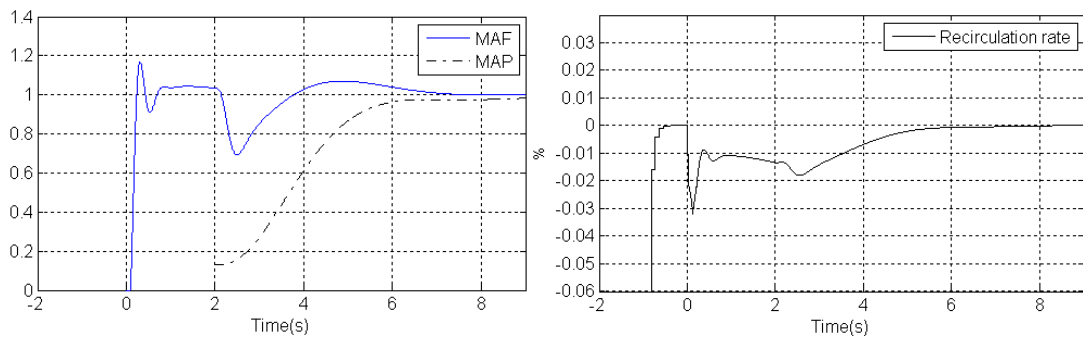


Figure 11. CASE 4- Naturally coupled system

When the decoupling gain is added to the controller (case5), can be seen in Fig.12 that there is a movement in the opposite direction (at t=2sec) that try to compensates the disturbance caused by the VGT actuator excited by the MAP_SP step stimulus.

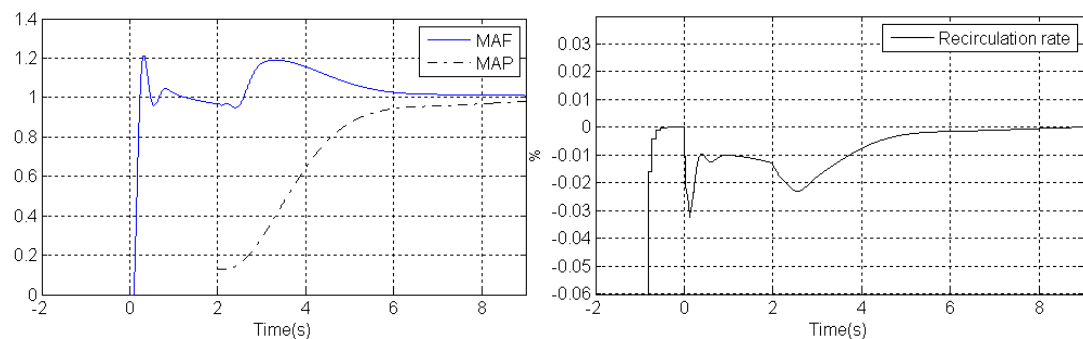


Figure 12. MAF loop decoupled from the MAP control loop.

However when evaluating the recirculation rate, it can be seen in Fig 12 that the decoupling applied by case 5 caused the recirculation to drop even more, what makes the NO_x emission spike to be even worse.

Therefore the decoupling in the MAF control loop, in this test scenario would bring a NO_x emission penalty instead of benefits.

8. CONCLUSION

In this work it was developed engine models and a recirculation observer for NO_x estimation, which was also validated to be applied in the design and tuning of dynamic systems by simulation software tools. Distinct control tuning parameters and architectures were applied to evaluate qualitatively the impact in recirculation rate and consequently in NO_x emissions. Results showed that conventional control schemes with faster time response can improve the emissions tracking based on step response evaluation and that the coupling among the loops can be, in some circumstances beneficial to the resulting emissions.

Results also suggest that using model based controllers that can track the recirculation rate to the set- points have potential to reduce the pollutant emissions in spite of their complexity.

9. ACKNOWLEDGEMENTS

Many thanks to MWM and IAV colleagues for their insights, support and test data.

10. REFERENCES

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