# Fuzzy Logic Control of Diesel Engine Turbocharging and Exhaust Gas Recirculation

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## ABSTRACT

The work presented in this paper is taken from a wider program to examine the effects of the engine control strategy on the emissions, fuel consumption and driveability of a high speed direct injection diesel engine. The overall object is to access the potential for emissions and fuel consumption reductions during transient events whilst maintaining and even improving driveability. The focus of this work is to consider the interactive gas management behaviour of the engine concentrating on the control of Exhaust Gas Recirculation (EGR) and Variable Geometry Turbocharging (VGT) parameters.

Classical control methods, as used on production engines, are examined and contrasted with an alternative strategy that utilises fuzzy logic in an attempt to improve the control and simplify the development process. The relative performance of these strategies are evaluated in simulation using a transient engine model.

The results show how fuzzy control can give improvements in airflow response at low engine speed and load, a critical region during legislative emissions cycles. The fuzzy logic controller achieves this with considerably reduced complexity when compared to classical Single Input Single Output Proportional Integral Derivative controller.

## KEYWORDS

EGR, VGT, Diesel Engine, Control, Fuzzy Logic, PID, transient control.

## INTRODUCTION

The drive to reduce emissions and fuel consumption whilst meeting improved performance targets has led to many advances in diesel engine technology over the last decade. In particular, exhaust gas recirculation (EGR) and variable geometry turbocharging (VGT) have played a key role in achieving these aims by permitting flexible control of the engine inlet gas charge (see Figure 1). However, the added flexibility comes at the cost of increased control system complexity. The full potential of these devices are difficult to achieve due to limitations in the classical control methods as well as the actuation hardware employed. However, alternative approaches offer scope for improving emissions, fuel consumption and driveability through co-ordinated control of these devices. Of these approaches, fuzzy logic is particularly appealing due to its simple heuristic nature, tolerance to noise and lack of the tedious mathematical derivation associated with modern control theory methods. Fuzzy Logic is a control structure which emulates the way humans arrive at decisions of what to do given a certain set of circumstances. A complete description of the workings of fuzzy logic is beyond the scope of this paper, but the interested reader is referred to [1, 2, 3] for a deeper insight. The controller used in this work was designed using the MATLAB Fuzzy Logic Toolbox, employing a graphical interface to simplify the task.

## EXHAUST GAS RECIRCULATION

EGR is a well-established technique for reducing in-cylinder engine oxides of nitrogen ($NO_x$) production. A fraction of the exhaust gas is fed into the inlet manifold to mix with the incoming fresh air. The resultant effect for diesels is a dilution of the oxygen content and reduction of peak combustion temperatures, reducing NOx formation as shown by Ladommatos et al [4, 5, 6]. The EGR flow is controlled by a valve between inlet and exhaust manifolds.

## VARIABLE GEOMETRY TURBOCHARGING

A conventional fixed geometry turbocharger (FGT) will provide a fixed compressor pressure ratio for a given engine speed and load, whereas a variable geometry turbocharger can provide a range of compressor pressure ratios for any given engine condition. The VGT achieves this by adjustable nozzle vanes at the entry to the turbine that swivel, altering the flow area and angle of flow impingement onto the turbine blades as shown in Figure 2. The VGT has an obvious advantage over a fixed geometry turbine in that it is possible to develop optimum boost pressure over the engines wide operating range.

## EGR AND VGT CONTROL OVERVIEW

The gas flow rates through the engine, turbine, compressor and EGR valve are all complex non-linear functions of several interactive variables, as indicated in Figure 3, which together present a complex, highly coupled plant with undesirable properties. These are principally non-minimum phase responses to EGR and VGT inputs and steady state gain reversals from EGR and VGT inputs to measurable gas properties such as inlet manifold pressure (boost) and compressor mass airflow across the engine operating range.

The performance of the VGT and EGR controllers plays a critical role in emissions, fuel consumption and driveability of the vehicle. The settings of the VGT vanes and EGR valve alter the engine pumping work and charge composition, affecting fuel consumption and emissions as demonstrated by Hawley et al [7]. With the EGR valve open, any fluctuations in VGT vane position will cause fluctuations in exhaust backpressure, this will cause EGR flow fluctuations which can have a detrimental effect on emissions and driveability. Acceleration response is determined by the availability of fresh air in which to burn fuel, any delays in providing adequate charge air, due to EGR residuals for instance, will be perceived as a lag in torque production. Excessive boost pressures will increase the strain on the cylinder head leading to durability problems, therefore large boost overshoots must be minimised. For these reasons the VGT and EGR system responses need to be fast but well damped. Improvements to the transient airflow response can be interpreted as resulting in either better acceleration (by allowing fuel to be burnt sooner hence more rapid torque production) or reduced transient smoke by maintaining a higher transient air fuel ratio.

At low engine speeds and loads, the overall gas flow through the engine is low hence energy available to the turbine is low, limiting turbocharger response. With the EGR valve open, changes in VGT vane position have more effect on EGR flow than turbocharger speed due to the modulation effect the VGT mechanism has on exhaust manifold pressure. Therefore, in this operating region, compressor mass airflow will respond more rapidly to the action of both devices than to EGR setting alone. Van Nieuwstadt et al [8] and Walker [9] both perform linear analysis of the Multi Input Multi Output plant, from VGT and EGR to boost and airflow. Their results show that in the low speed / low load region, the steady state gains from VGT and EGR to boost and airflow have significant off-diagonal terms. The diagonal terms represent the negative-gain relationships between VGT position and boost, and EGR position and airflow, i.e. decrease VGT position to increase boost, decrease EGR position to increase airflow. The off-diagonal term shows strong positive-gain relationship between VGT and airflow in this region, i.e. increase VGT position to increase airflow, including this cross coupling into the controller will therefore yield better airflow response. However, as speed and load increase, the off-diagonal term reduces and eventually changes sign. The physical interpretation of this is that as more energy becomes available in the exhaust, turbine mass flow has a greater effect on turbocharger speed and hence compressor delivery. Opening the vanes will reduce compressor delivery, as a result more recirculated gases will be drawn through the engine (i.e. increase VGT position to decrease airflow, negative-gain). The region of this gain-reversal is uncertain, which makes an analytical control solution very difficult, for this reason production controllers use the open-loop term to drive the VGT shut throughout the approximate region to avoid difficulties.

In [8] an H-infinity controller is synthesised to give co-ordinated control in the low speed low / load region, bringing improvements to airflow response. In [9] a ‘diagonalising precompensator’ is applied in an attempt to decouple the low speed / low load interaction and a dynamic compensator included to give the necessary closed loop dynamics. This aims to minimise the influence of the off-diagonal terms, allowing classical Single Input Single Output design techniques to be employed to each loop. Dekker and Sturm [10] describe an alternative approach using boost controlled regions where the EGR valve is closed and VGT is modulated, and EGR controlled regions where VGT is fixed and EGR is modulated, though this does not exploit any of the potential offered by co-ordinated control. Fuzzy logic lends itself well to the problem of EGR and VGT control as the imprecision involved in identifying the co-ordinated operating area can be encapsulated into a rule such as: If SPEED is LOW and LOAD is LOW then DECREASE EGR and INCREASE VGT. The fuzzy controller does not require a linearised plant model as is the case for many modern control alternatives (including H-infinity), the generalised behaviour is encapsulated in the rules. Fuzzy logic has been applied to many non-automotive problems, Schram [11] describes the design and performance of a fuzzy aircraft flight controller, this is a complex MIMO system to which the fuzzy controller provides a low order, deterministic and transparent control solution, dealing well with the coupled nature of the plant. The fuzzy control of VGT on a heavy-duty diesel engine without EGR is described by Ikeya et al [12]. The controller employed 2 different rule sets, one for normal operation utilising 20 rules, and 1 for gearchange operations using 3 rules, with a total of 14 membership functions. Other examples of automotive applications of fuzzy logic are given by Bolander [13] who presented automatic gearshift control and knock detection applications, Abate and Dosio [14] with gasoline idle speed control, and Deacon et al [15] with co-ordinated engine and Continuously Variable Transmission control .

## STANDARD CONTROL STRATEGY

The production control strategy for VGT and EGR systems uses the Proportional + Integral + Derivative control structure with feedforward term as illustrated in figure 4. Although the EGR-VGT plant is highly coupled Multi Input Multi Output system, it is regulated by two Single Input Single Output loops. Inlet manifold boost pressure is used as feedback for the VGT vane actuator demand and compressor mass airflow is used to close the loop on the EGR valve actuator demand. The setpoints for these two controllers are derived from extensive engine mapping, involving the sweeping of VGT vane and EGR valve positions at fixed engine speed and fuelling inputs to determine the optimum settings with respect to emissions, fuel consumption, driveability and engine durability considerations. The controller is designed to use the open-loop term to drive the EGR and VGT actuators as close to the positions required to attain the desired airflow and boost as possible. The closed-loop is used to trim the position to converge upon the setpoint, ideally with the closed-loop term doing as little work as possible for best control response. Due to the highly non-linear nature of the mechanical systems as illustrated in [16] and [9], and additional factors such as ageing and driving environment, the open loop term can never guarantee locating the actuators repeatably to the desired position. Indeed, changes in the open-loop term are often insufficient to move the actuators at all, and so the closed-loop system tends to be highly active. The response of boost and airflow to VGT and EGR varies with engine operating point, therefore gain scheduling is employed extensively.

## ENGINE MODEL

A mean value engine model based on a 2 litre high-speed direct injection diesel engine with EGR and VGT was used for the development and evaluation of control strategies. The model was provided by the Ford Motor Company, its basic structure is detailed in work published by Kolmanovsky et al [17]. The model has 8 states, inlet manifold pressure, density and burnt gas density fraction, exhaust manifold pressure, density and burnt gas density fraction, turbocharger speed and engine speed. The model and subsequent controllers run in the Matlab Simulink environment.

## FUZZY LOGIC CONTROLLER DESIGN

The first stage of the fuzzy controller design was to decide on a structure. From the analysis of the problem it was clear that the inputs to the system needed to be boost and airflow errors ($\varepsilon_{MAF}$ and $\varepsilon_{MAP}$), engine speed ($N_{ENG}$) and fuelling ($\omega_F$). VGT position ($\chi_{VGT}$) was included for the cross coupling rules as it was found that the VGT to airflow dependency was significant only for lower VGT settings. EGR position was also included initially but found to be of no benefit. Outputs are the rate of change of EGR and VGT duty cycles, $\Delta_{EGR}$ and $\Delta_{VGT}$. These are integrated and added to open-loop and proportional terms to give a duty cycle demand to the actuator.

The next step involved defining membership functions for the inputs and outputs. These are illustrated in figure 5. Initial iterations of the controller divided $\varepsilon_{MAF}$ and $\varepsilon_{MAP}$ into large and small negative and positive errors, but it was found that the added complexity brought no performance benefit and made rule design more difficult. Similar effects were experienced with the outputs. Therefore these are covered by only 3 membership functions, POSITIVE (P), NEGATIVE (N) and ZERO (Z). $N_{ENG}$, $\omega_F$ and $\chi_{VGT}$ are classified with only 1 membership function, LOW (L).

The final step is to define the rules for the controller, shown in Table 1. These are simply an embodiment of the control action one wishes to be achieved.

Rules 1 and 2 represent the independent closed-loop from EGR to airflow. Rules 3 and 4 represent the independent closed-loop from VGT to boost pressure. Rule 5 is the cross coupling from VGT to airflow, this rule is active when trying to increase airflow at low load, speed and VGT setting, it has the effect of opening the VGT vanes for $\varepsilon_{MAF}$. This rule will work in conjunction with rule 1 to provide co-ordinated airflow action. Rule 6 is also a cross coupling from VGT to airflow for low load and low speed, acting to reduce airflow by closing the vanes in conjunction with rule 2 opening EGR.

Initial attempts at designing controllers employed large rule sets, especially when using 5 membership functions to classify the input errors instead of 3. The rule design became very tedious for this arrangement and the controller performance was far from satisfactory, largely due to the difficulty involved in understanding how so many rules would interact.

## RESULTS OVER CONSTANT SPEED FUELLING PROFILES

The controllers were tested in simulation using a fuelling staircase profile (see figure 6) at 1500 rev/min and 2000 rev/min, chosen as these speeds straddle the region where the plant cross coupling-reduces significantly, i.e. the boundary of the low speed region. The setpoints for airflow and boost are generated from look-up tables using engine speed and fuelling as references, therefore the fuelling profile causes changes to the airflow and boost setpoints to which the controller must respond.

The setpoints used here are a custom set generated using an optimisation routine performed on the model based on the FGOALATTAIN function in the Matlab Optimisation Toolbox. The routine automatically searches through combinations of VGT and EGR positions over a grid of speed and fuelling points to find settings that best achieve a target AFR and engine pressure differential. Four 2-D tables are returned; the target boost and airflow setpoints and the corresponding VGT and EGR valve settings, these valve settings are used as open-loop demands in the controller.

The reason that setpoints used for the actual engine calibration were not used here is that they have been manipulated to force the VGT shut over most of the low speed / low load operating region by demanding unattainably high boost pressures. This is done to avoid the problem of the steady-state gain reversal from VGT to airflow in this region as discussed previously.

Two sets of tests were performed, the first set used the generated feedforward terms in both controllers, whilst the second set used a fixed 50% feedforward demand. The purpose of this is to illustrate the effect of a well optimised feedforward term in any controller, as this will minimise the work of the feedback controller. The tests using the fixed 50% open-loop term give better comparisons of the relative behaviour of each feedback controller.

The standard controller also incorporates additional features such as overboost protection which disables EGR above a certain overboost level, these features have been disabled for the purposes of this comparison in order to isolate the responses of the actual controllers.

## ENGINE SPEED OF 1500 rev/min

Figure 7 shows the tracking of boost and airflow setpoints by both controllers. Both controllers track well, the fuzzy controller typically exhibits slight overshoot though its responses are well damped. The fuzzy controller also closes steady state errors better than the standard controller, this is due to the gain scheduling for standard controller. The gains are scheduled with respect to speed and fuelling, the I gains are generally low to ensure global stability of the closed-loop system, this results in poor steady state error behaviour.

Figure 8 compares the performance of the standard and fuzzy controllers for the EGR valve, figure 9 shows the same comparison for the VGT vane control. Generally, the standard controller closed-loop term is fairly inactive due to the open-loop term being accurate enough to achieve the targets by itself. For the first step up (at 5 seconds), the new setpoints demand increased airflow and decreased boost. The fuzzy controller is biased towards airflow response in the low speed / low load region by virtue of rules 5 & 6, as a result the overshoot in airflow is settled first then the slight boost overshoot is gradually reduced whilst airflow is held steady. Rule 5 is active here as it opens the VGT whilst closing the EGR to increase airflow, then rule 6 performs the opposite action to converge the overshoots. The fuzzy co-ordination can be seen in the symmetry of movement between EGR and VGT closed-loop terms in the 5-10 second period. In the 10-15 second period, the fuzzy controller closes the VGT vanes further than the open-loop term alone to reduce airflow more rapidly, the EGR is gradually closed down to compensate the increased EGR flow.

Figures 10 to 12 show the same fuelling profile but with the EGR and VGT open-loop demand set to 50% for both controllers. The significance of the open-loop term is apparent immediately, with both controllers showing considerably slower response times. The standard controller experiences severe difficulty in tracking the demands. In response to the first step-up in fuelling (at 5 seconds), it acts to open the VGT and close the EGR (figure 11 and figure 12 closed-loop terms) in order to meet increased airflow and decreased boost demands. However, low gains combined with lack of co-ordination inhibit sufficient controller action to attain the targets. However, the fuzzy controller action is uninhibited by low gain scheduling and airflow response is aided through co-ordination between EGR and VGT actuators. The airflow error drives the VGT in conjunction with the boost error, this can be seen by the more rapid change in VGT position (figure 12) even though the boost error is low. It should be noted that there is room for improvement of the response of the fuzzy logic controller through optimal gain selection, the gains used here were tuned only approximately and are fixed across the engine operating range.

This comparison shows that the fuzzy logic controller can provide acceptable performance using a far from optimised set-up, where as without a well tuned open-loop term the standard Proportional + Integral controller displays unsatisfactory performance. Engine calibration of the open-loop map is a time consuming exercise, if the simulation can be used to generate approximate setpoints in conjunction with a better feedback controller then the calibration process can be improved significantly. In terms of robustness, reliance on open-loop term to do most of the work can cause problems as the engine ages, actuator effort may change increasing the demands of the feedback controller. Therefore a controller capable of maintaining good response is highly desirable.

## ENGINE SPEED OF 2000 rev/min

Figures 13 to 15 illustrate the same fuelling profiles as before but performed at 2000 rev/min. At this engine speed the relationship between VGT, EGR, boost and airflow becomes more decoupled and independent control loops from VGT to boost and EGR to airflow perform better. In figure 13, the standard controller provides faster boost response with no overshoot, whilst the fuzzy controller displays significant boost overshoot, especially in response to the final and largest step-up. The fuzzy airflow tracking is better however, with faster response to small step-ups in demand though this is at the expense of small overshoot. The step-down airflow response is also better for the fuzzy logic controller, meaning EGR can be added more rapidly allowing further NOx reduction potential. At this engine speed there is still a small activation of the co-ordinated rules, verified using the ‘Rule View’ function of the Matlab Fuzzy logic Toolbox which allows the visualisation of how much each rule contributes to the output for a given input. It is expected that tuning the Speed and Fuelling membership functions to reduce activation at this operating point will improve the performance by reducing the VGT response, leading to less overshoot.

Figures 16-18 again illustrate the same fuelling profile at 2000 rev/min but with the open-loop demand fixed at 50% throughout. As with the 1500 rev/min case, the standard controller is unable to achieve convergence on the majority of the setpoints. The standard controller appears to respond well to the first step-up. However, upon closer inspection of the controller performance (figures 17 and 18) it can be seen the first step-up requires very little work from the feedback controller as the 50% open loop demand is already driving the actuators into the correct area to achieve the targets. Higher integral gains are needed to drive the system towards convergence. The fuzzy logic controller gives good airflow response but slower boost behaviour, this time with no overshoot.

## CONCLUSIONS

It has been shown that a simple fuzzy logic controller can provide effective control of the engine gas charge in simulation. The rule-based structure of the controller facilitates the implementation of co-ordinated control of the VGT and EGR actuators, this in turn brings about improvements in the transient airflow response of the engine in the low-speed / low-load operating region, particularly when the feedforward term of the controller is inaccurate. From the point of view of calibration, careful thought needs to be put into the design of the membership functions and the selection of the rules, and subsequent performance analysis is difficult, but once established there remain only 4 gains to select (for this particular structure at least). The gains used in this exercise were fixed but benefits may be achieved through simple gain scheduling, however, fine-tuning of the membership functions may do away with the need for this. In comparison with the effort required in implementing a gain scheduling PID controller, the fuzzy logic approach is an attractive alternative, offering an intuitive approach to what is otherwise a complex control problem.

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## Figures

Table 1 – Fuzzy logic controller rules

| Rule Number | Rule |
|---|---|
| 1 | If $\varepsilon_{MAF}$ is P then $\Delta_{EGR}$ is N |
| 2 | If $\varepsilon_{MAF}$ is N then $\Delta_{EGR}$ is P |
| 3 | If $\varepsilon_{MAP}$ is P then $\Delta_{VGT}$ is N |
| 4 | If $\varepsilon_{MAP}$ is N then $\Delta_{VGT}$ is P |
| 5 | If $\varepsilon_{MAF}$ is P and $\chi_{VGT}$ is L and $N_{ENG}$ is L and $\omega_F$ is L then $\Delta_{VGT}$ is P |
| 6 | If $\varepsilon_{MAF}$ is N and $N_{ENG}$ is L and $\omega_F$ is L then $\Delta_{VGT}$ is N |

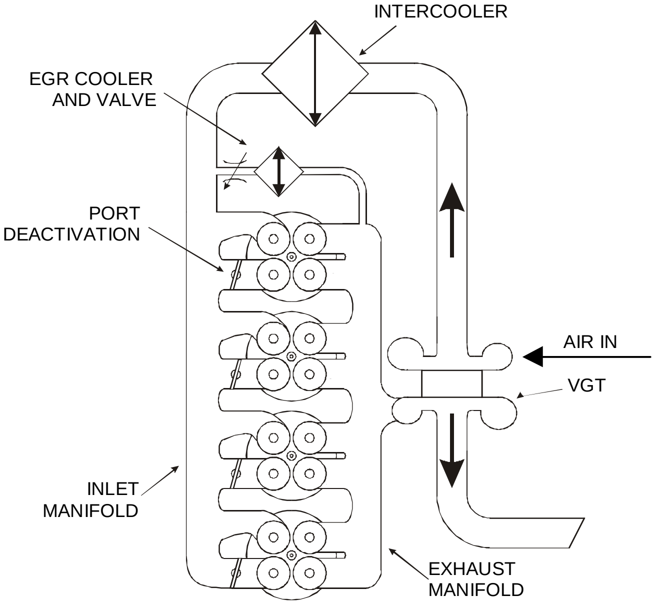


Figure 1 – Schematic of a modern diesel engine

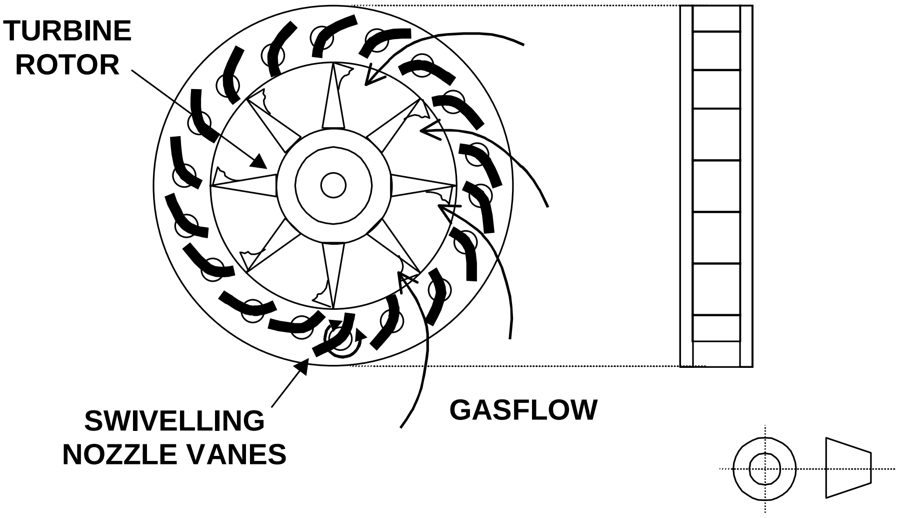


Figure 2 – Schematic of Variable Geometry Turbocharger

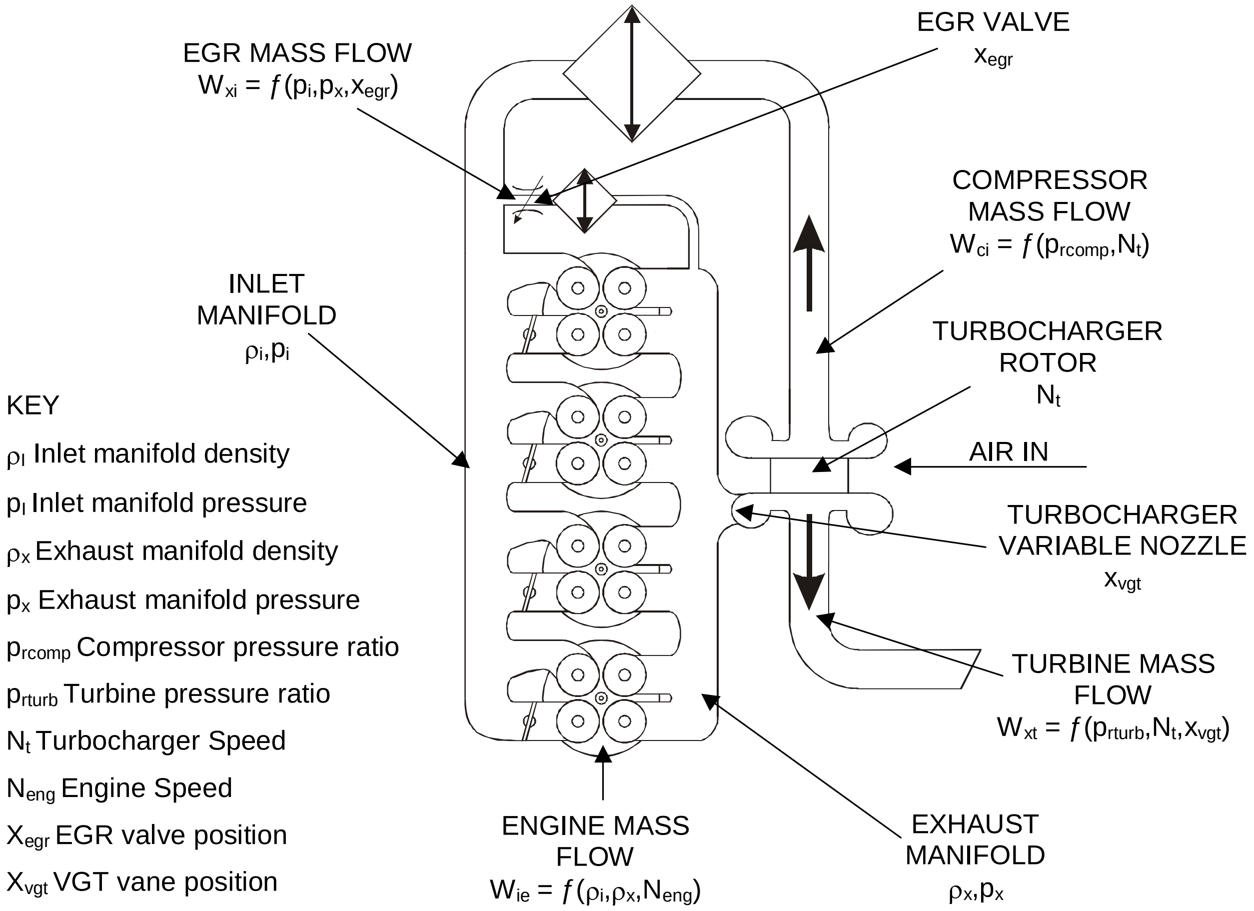


Figure 3 – Engine gas flow dependencies

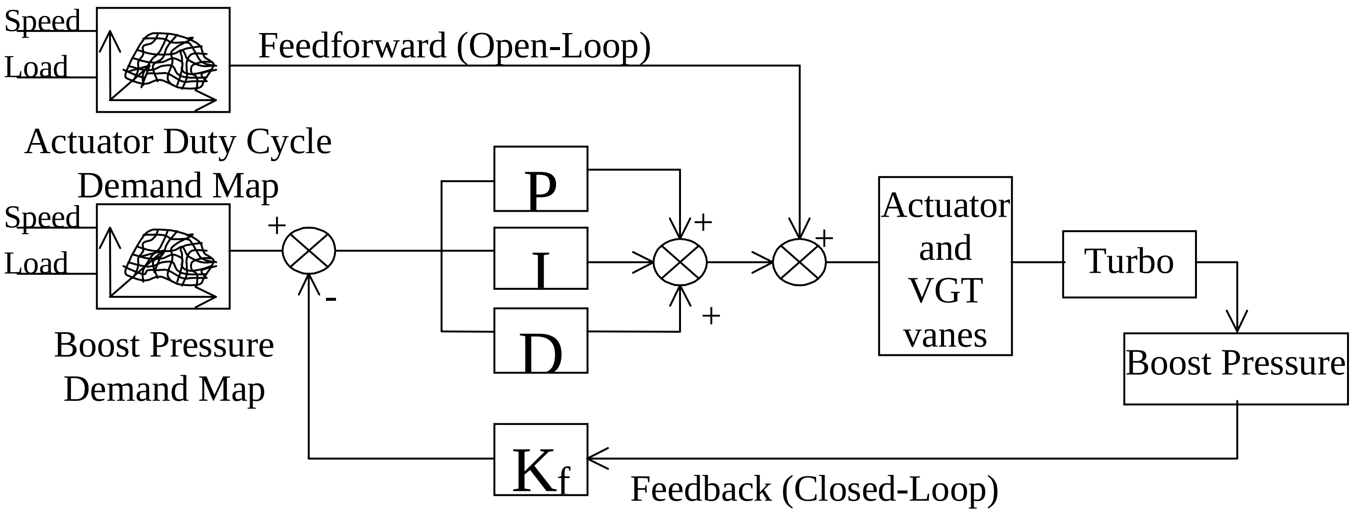
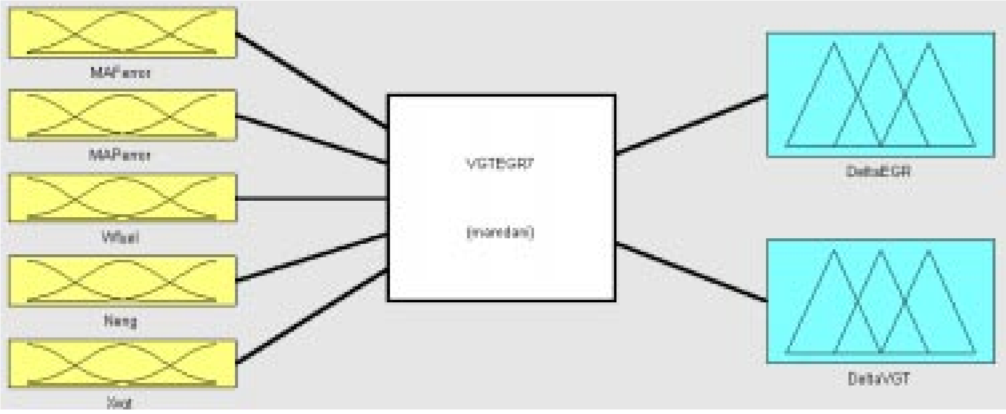
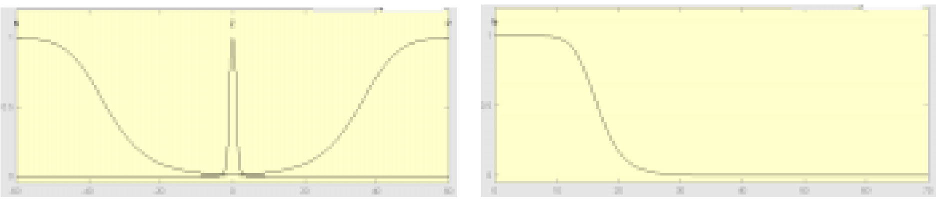


Figure 4 - PID with Feedforward controller structure (VGT to boost pressure as an example)

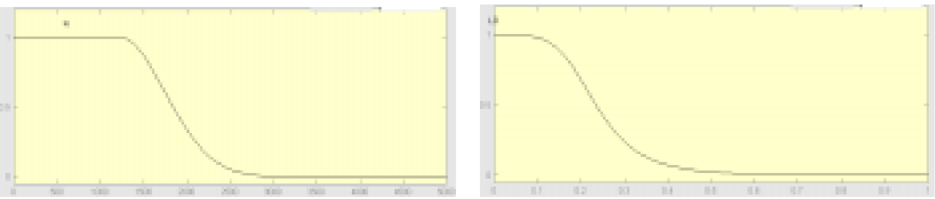


Fuzzy Logic Controller



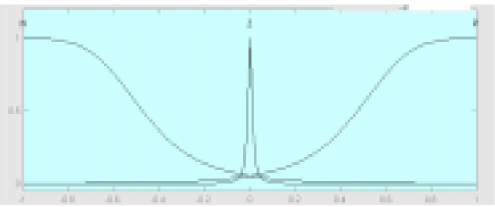
MAP and MAF error

Wfuel



Neng

Xvgt



Delta EGR, DeltaVGT

Figure 5 – Membership functions for the EGR VGT fuzzy logic controller

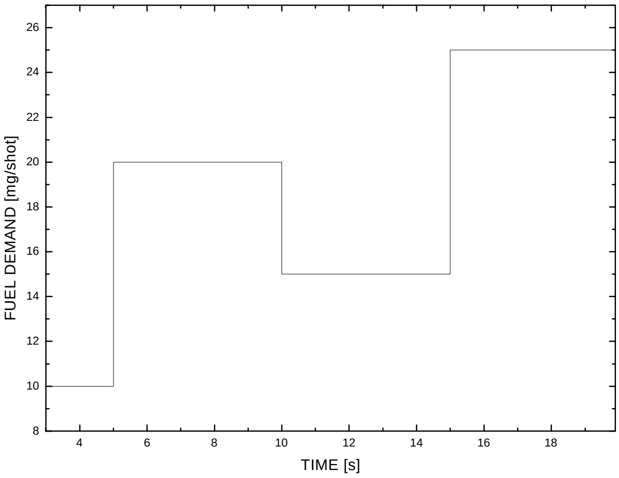


Figure 6 - Fuelling staircase profile

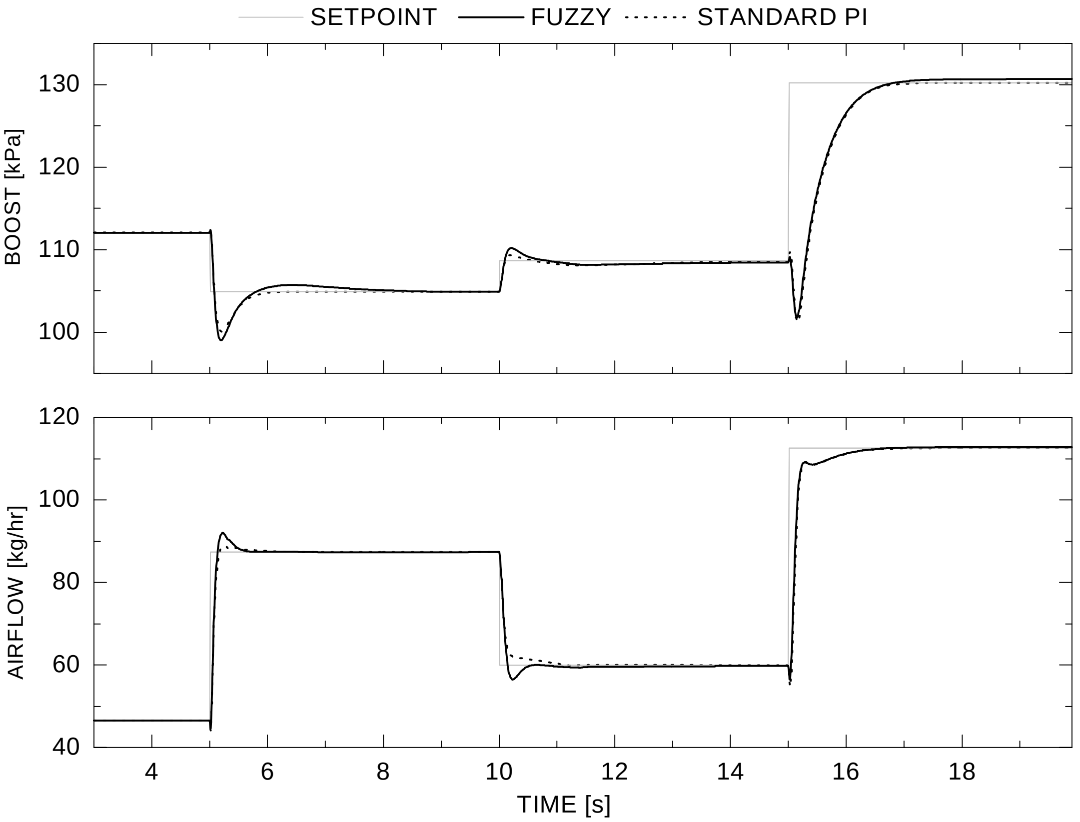


Figure 7 – 1500 rev/min boost and airflow tracking

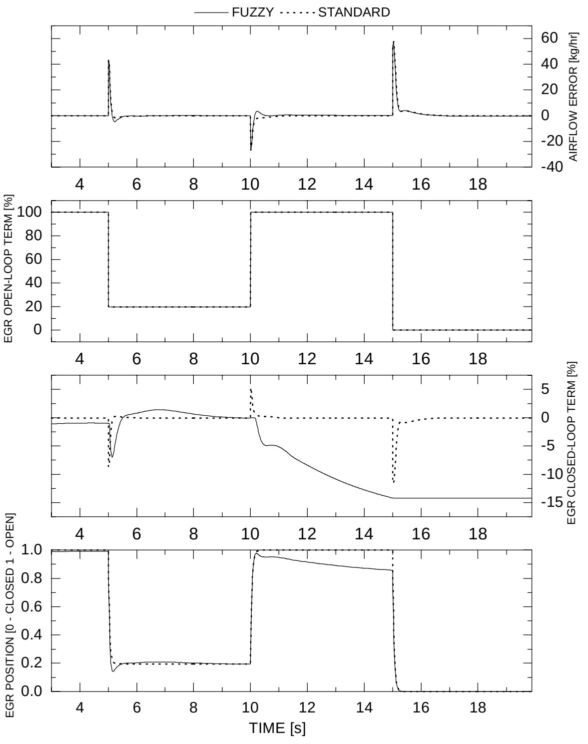


Figure 8 – 1500 rev/min EGR control detail

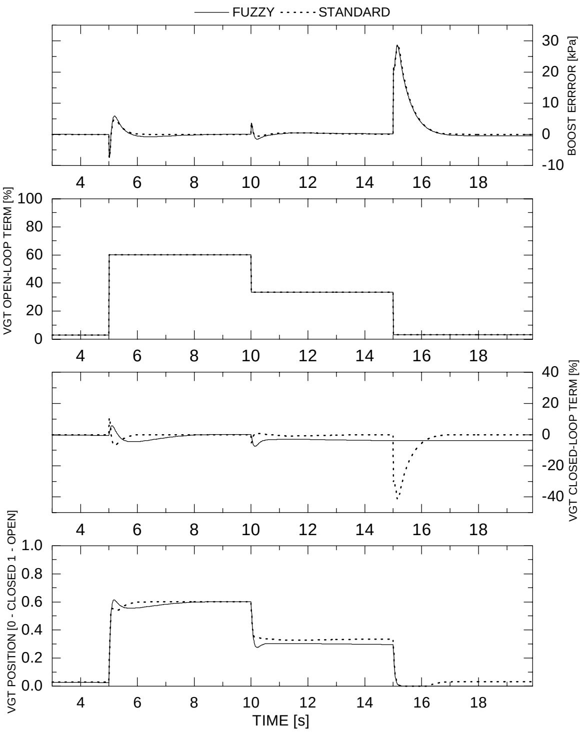


Figure 9 – 1500 rev/min VGT control detail

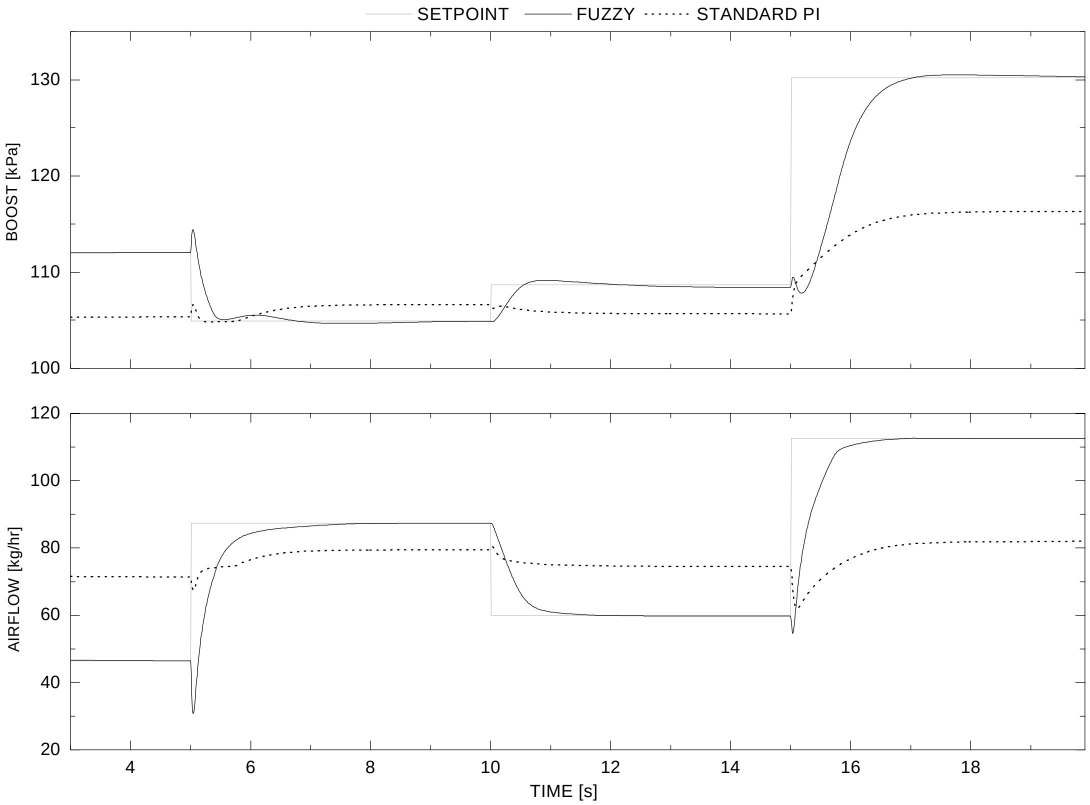
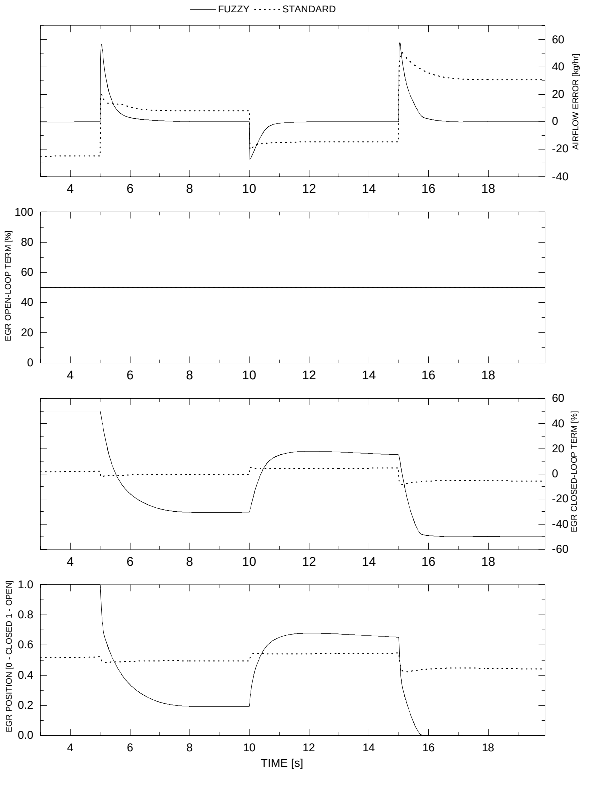


Figure 10 – 1500 rev/min (50% Open-Loop) boost and airflow tracking



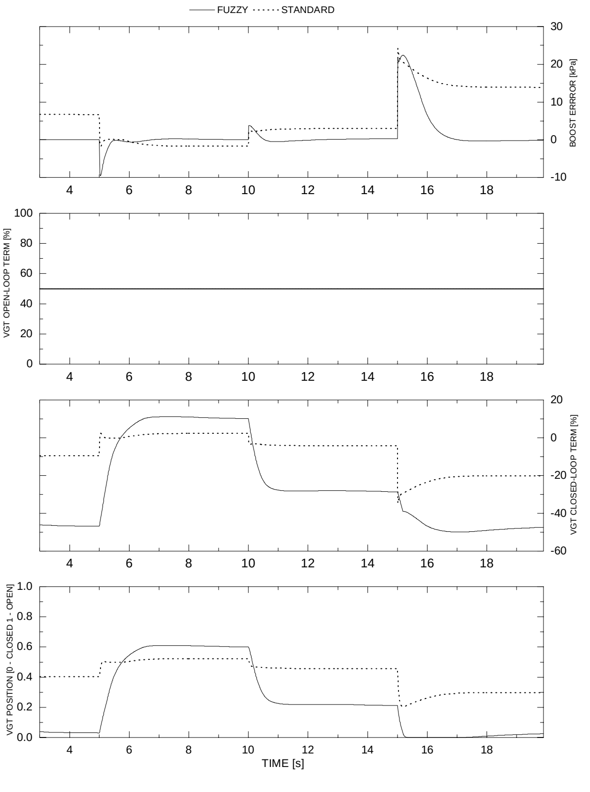


Figure 11 – 1500 rev/min (50% Open-Loop) EGR detail

Figure 12 – 1500 rev/min (50% Open-Loop) VGT detail

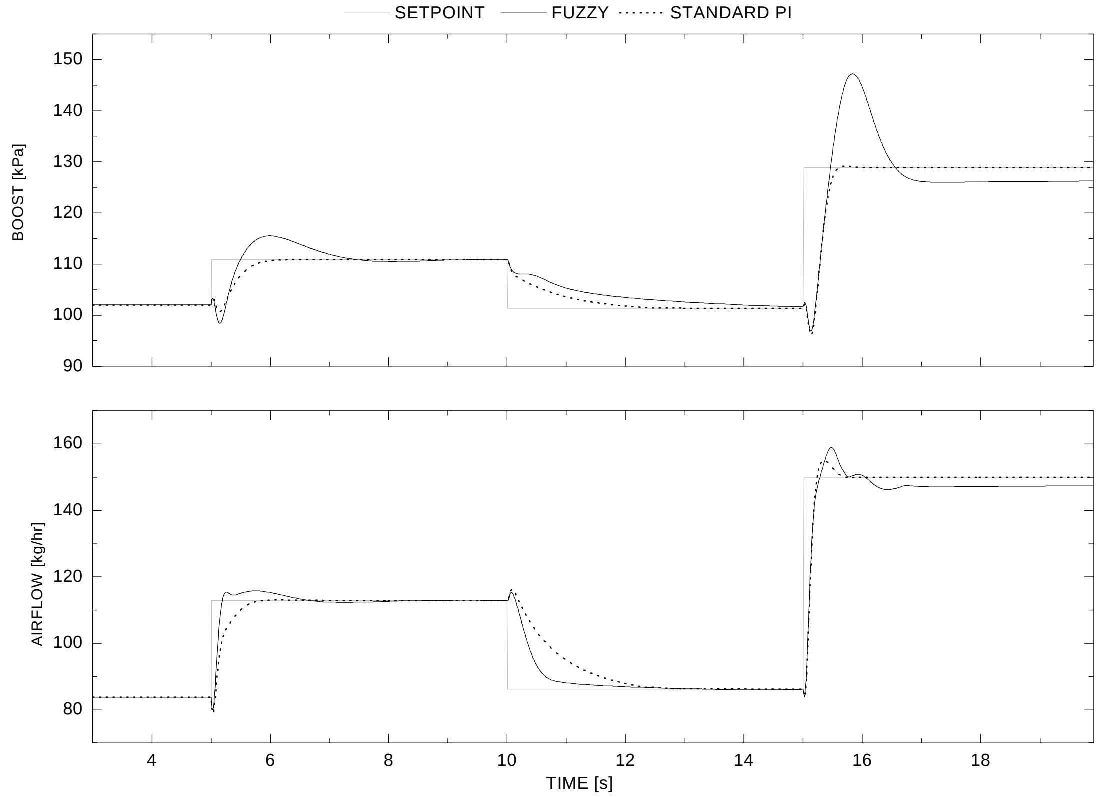


Figure 13 – 2000 rev/min boost and airflow tracking

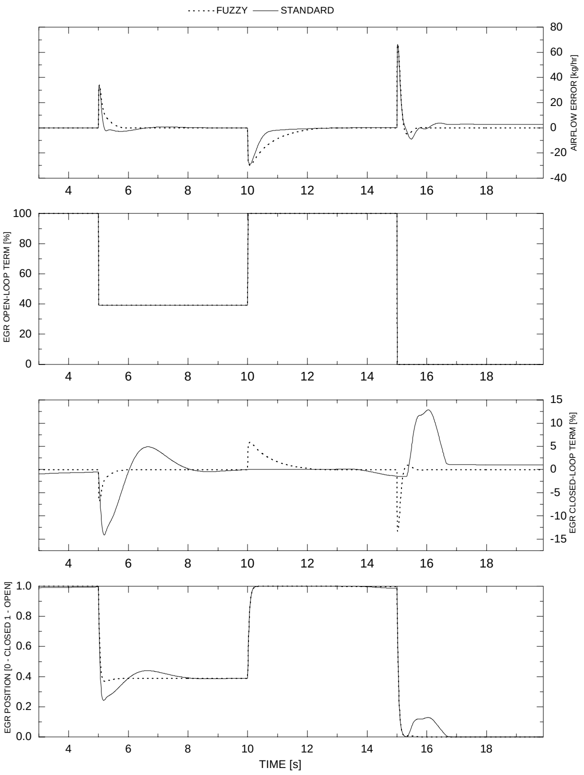


Figure 14 – 2000 rev/min EGR detail

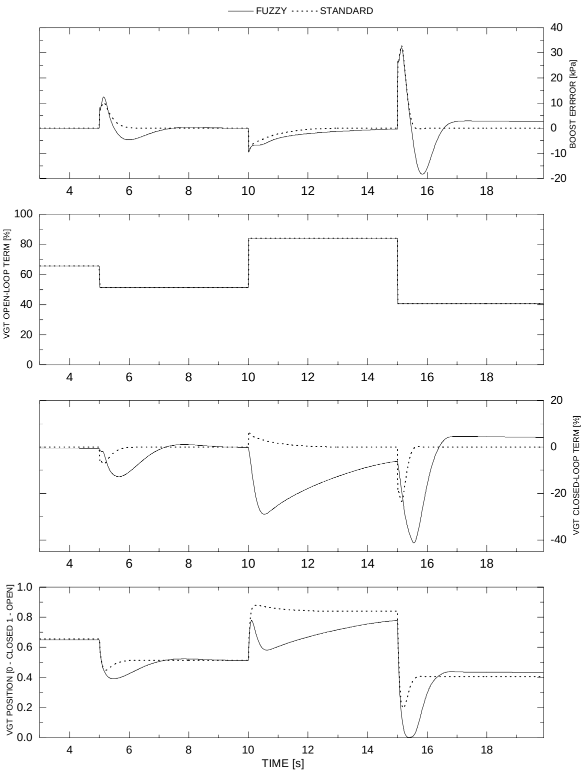


Figure 15 – 2000 rev/min VGT detail

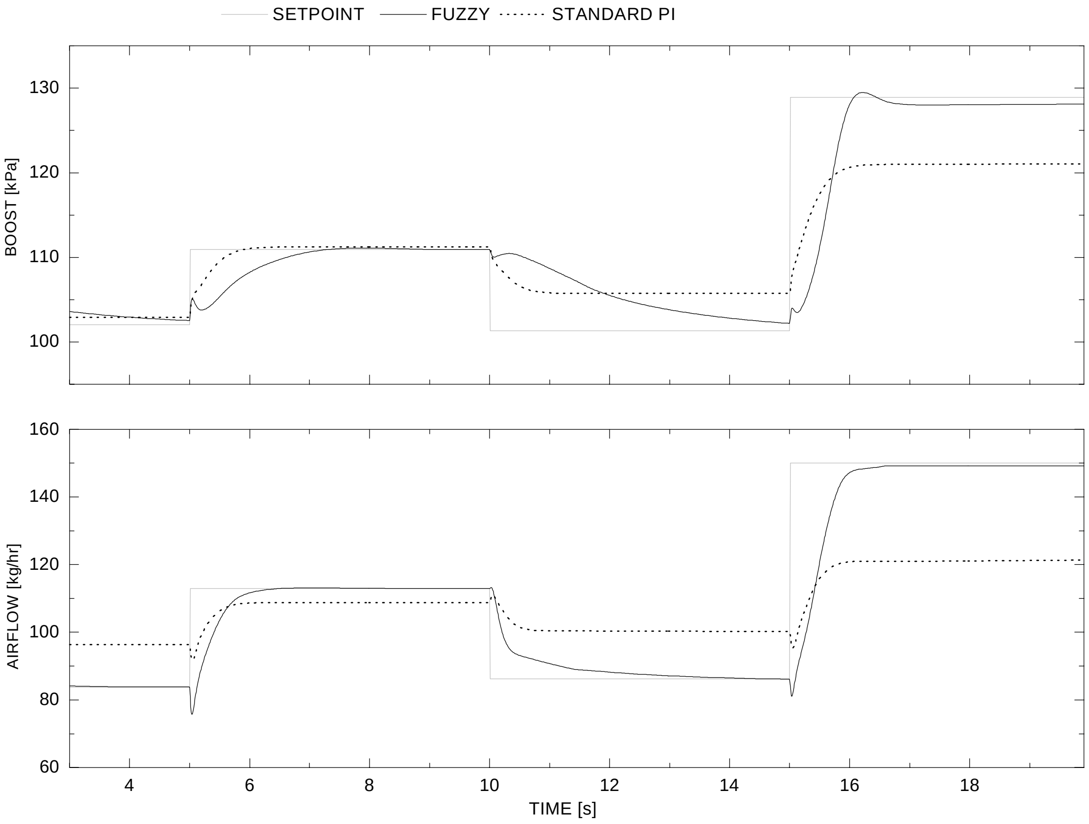


Figure 16 – 2000 rev/min (50% Open-Loop) boost and airflow tracking

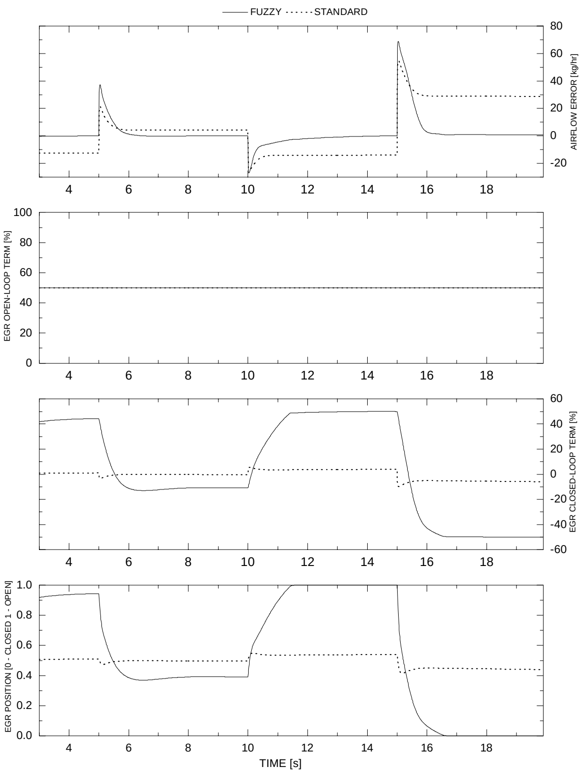


Figure 17 – 2000 rev/min (50% Open-Loop) EGR detail

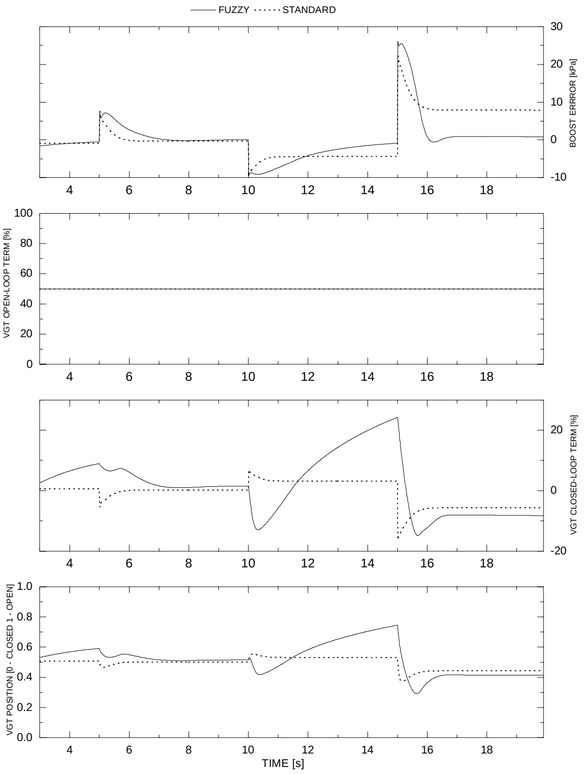


Figure 18 – 2000 rev/min (50% Open-Loop) VGT detail

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