Model Predictive Control of Turbocharged Diesel Engine with Exhaust Gas Recirculation

U. Yavas, M. Gokasan

***Abstract*—**Control of diesel engine's air path has drawn a lot of attention due to its multi input-multi output, closed coupled, non-linear relation. Today, precise control of amount of air to be combusted is a must in order to meet with tight emission limits and performance targets. In this study, passenger car size diesel engine is modeled by AVL Boost RT, and then simulated with standard, industry level PID controllers. Finally, linear model predictive control is designed and simulated. This study shows the importance of modeling and control of diesel engines with flexible algorithm development in computer based systems.

***Keywords*—**Predictive control, engine control, engine modeling, PID control, feedforward compensation.

I. Introduction

TURBOCHARGED diesel engines with exhaust gas recirculation (EGR) have become popular rapidly due to the fact that having low emission, good fuel economy and high torque output in low engine speeds. In principle, turbochargers work with a coupled compressor and turbine system which are connected to the each other with a shaft. Turbine is rotated by the exhaust flow because of combustion process and the energy of the turbine is transferred to the compressor by the shaft. The compressed air, which will be sucked to the cylinders, creates the advantage of better power to size ratio and volumetric efficiency. On the other hand, EGR directs the exhaust manifold flow to intake manifold in order to reduce NOx emission by reducing peak combustion temperatures. Most of the turbochargers used in industry are VGT (variable geometry turbocharger) which is able to change angle of its turbine blades to manipulate exhaust flow energy. Therefore, it is possible to generate desired MAP (manifold absolute pressure) via VGT turbine blades. On the other hand, the amount of exhaust gas recirculate to the intake is determined by EGR valve. Briefly, a turbocharged diesel engine has two control loops in the air path as the control of MAP via VGT blades and control of the fresh air which will be sucked to the cylinders via EGR.

Fig. 1 shows the travel of fresh air through to cylinders then to exhaust. Due to target of increased air density, both compressed air and redirected exhaust air is intercooled. MAP is measured right after intercooler via pressure sensor and MAF (mass air flow) is measured via flow sensor before compressor. In terms of system dynamics, both EGR and VGT is driven by the exhaust gas, and therefore, strongly coupled. However, today's ECU (engine control unit) has two separate single input single output systems described before. There are many different approaches to the coupled non-linear control problem of air path in [8], [6]; but, none of these get commercial yet, instead separate SISO control loops are further linked with open loop feedforward methods, gain scheduling, rate limiting. Increasing number of parameters linked to controller causes long development periods, which is not an intention in the automotive industry considering costs and tight development targets.

U. Yavas is with the AVL Turkey Research and Development, Istanbul, Turkey (Tel: +905064330135; e-mail: ugur.yavas@avl.com).

M. Gokasan is with the Controls and Automation Department, Istanbul Technical University, Istanbul, Turkey (Tel: +905043320134; gokasanm@itu.edu.tr)

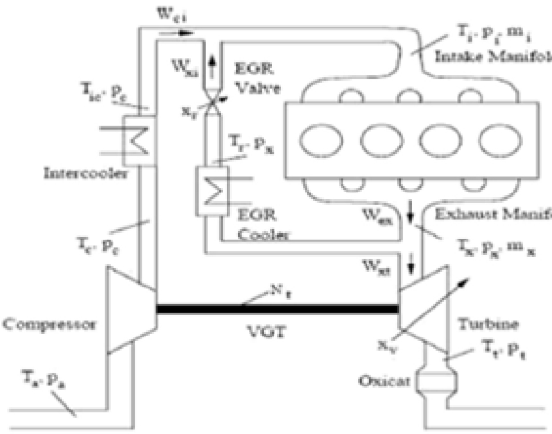

Fig. 1 Air path of modern diesel engine [7]

This study covers the following steps: Model of a turbocharged diesel engine with EGR is developed by AVL Boost RT. The engine model is validated with real life data. Then, model is used to calibrate diesel engine air path with different approaches. Consequently, classic PID, PID + feedforward control loops tuned by Ziegler Nichols. Finally, linear model predictive control algorithm has applied to the diesel engine air path problem and results are compared. Application of MPC to the diesel engine air path problem is trending subject, other notable work which differs from this one by the different modeling and tuning methods may be find in [4], [5].

II. Diesel Engine Model

Considering previously described relations in the air path and the use of components as compressors, valves, intercoolers, the air path of diesel engine is highly non-linear with dead zone, hysteresis and delays [2]. In the literature, mean value engine models are often used. Once a mean value model is created, it may give realistic results and it is applicable with different control algorithms. However, development of mean value engine models requires a very high effort due to great amount of parameters and derivation. AVL Boost RT is real time simulation capable, modeling environment which is flexible and easy to adapt to different engines [1]. Basically, each components of the diesel engine shall be parameterized in order to have precise simulations. In automotive terminology, the transfer of air and fuel into cylinders are described as air path and fuel path, similar approach might be used in Boost RT to determine engine layout to be modeled. Besides, there are three different connections that are available between components as follows: air or fuel flow, heat transfer and mechanical coupling. According to energy transfer linkage, following layout has been designed which shows mainly the key factors to produce torque and power.

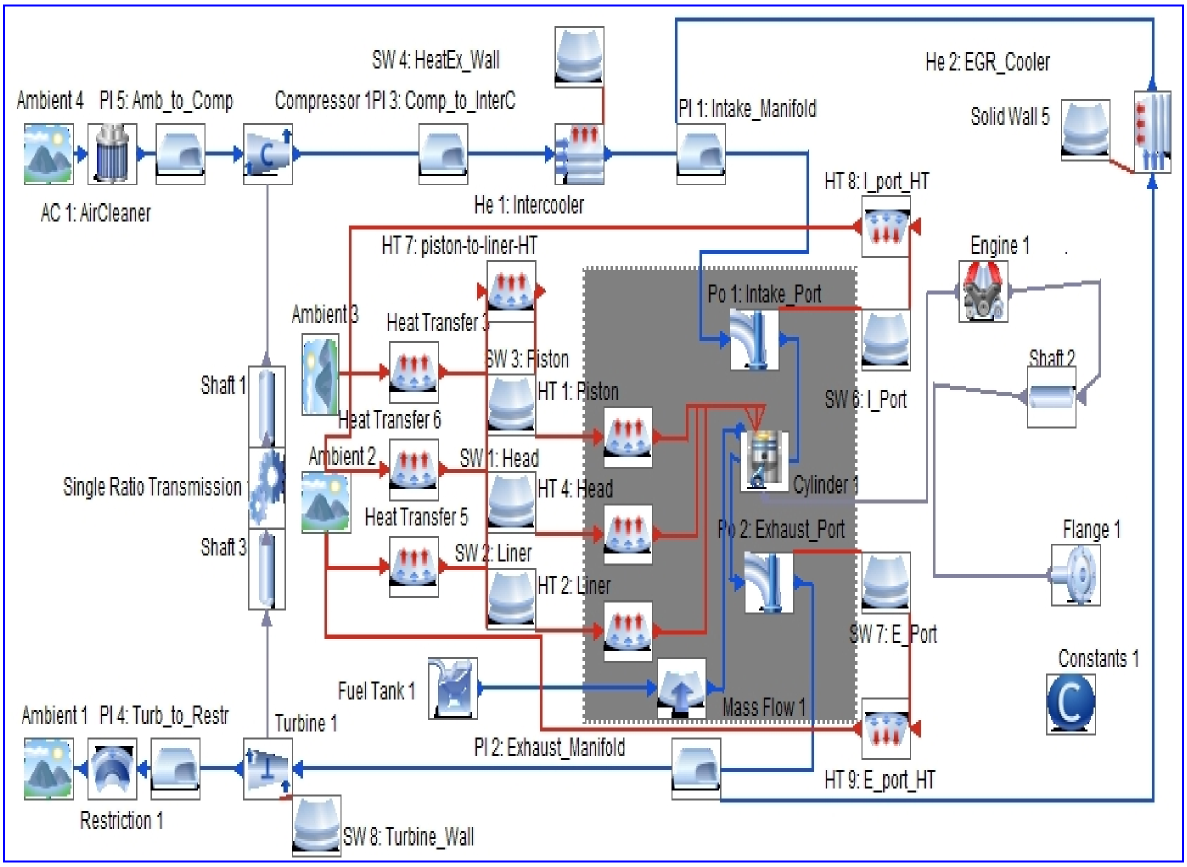

Fig. 2 AVL Boost RT model

In order to validate Boost RT model, real world test bench data is collected, its inputs are supplied to model then the outputs are compared. The model has five inputs: Target engine speed, fuel set point, start of injection, position of EGR valve, and position of VGT blades. Starting from the ambient air conditions, fresh air is passed by air filter then it is compressed by turbocharger. Due to temperature rise during compression event, the air is cooled down by intercooler. Then it is sucked to cylinders via intake port. Meantime, depending on the EGR valve position, exhaust gas flows to intake manifold and it is mixed with fresh air.

In Fig. 3-5, main characteristic of the engine model is compared with the measurements taken in engine test cell. These outputs are the resultant of the inputs in Fig. 6. In internal combustion engines, according to engine speed and load (either torque or fuel set point) different operating ranges are defined due to changing dynamics. According to model and measured data comparison, modelling error is not constant but changing in each different engine speed and torque range. However, it is clear that model output is tracking the real data very well and catching the main system dynamics. There are some assumptions to simplify and speed up the simulations which also cause further modeling errors for instance using single injection whereas real engine has multiple injections and using simplified friction characteristics and parameter estimation for the turbocharger flow characteristics.

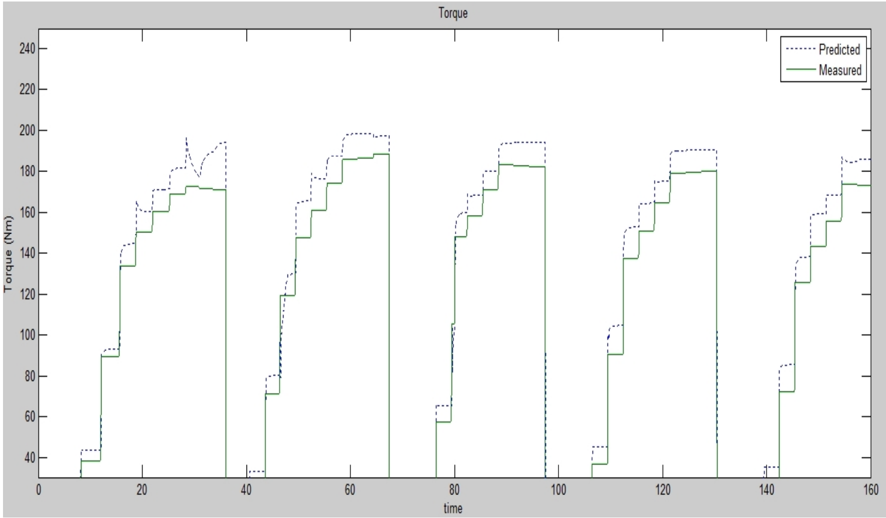

Fig. 3 Torque comparison

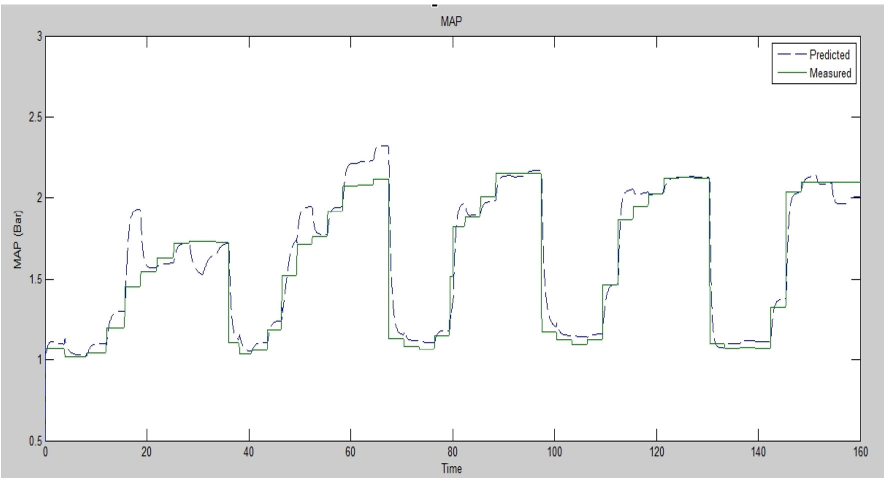

Fig. 4 MAP comparison

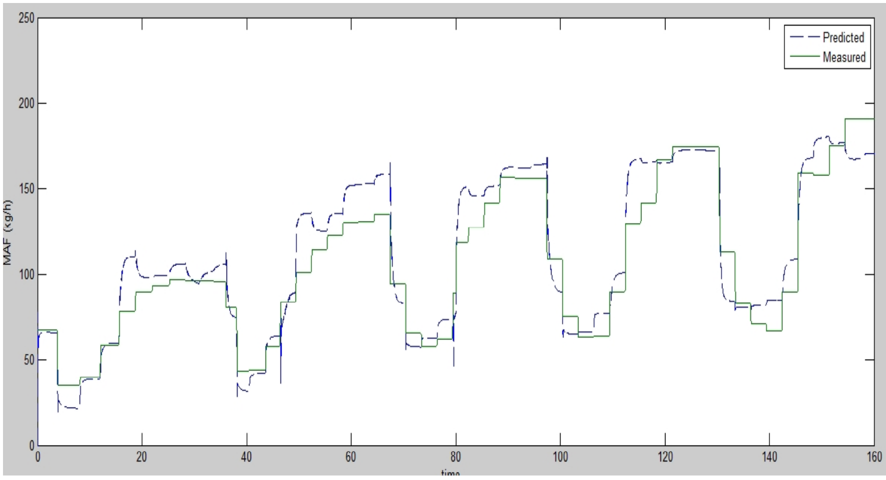

Fig. 5 MAF comparison

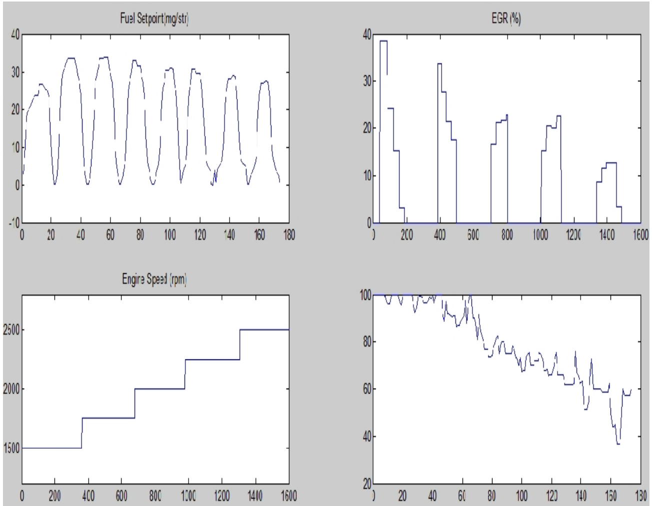

Fig. 6 System Inputs

III. Controller Simulation

In engine control unit, there are predefined set point interpolation maps, which are generated according to emission and performance considerations. Generation of these maps is depend on collecting large amount of data which surrounds each operating range of engine in terms of load and engine speed. Once the data is collected, by using 2D interpolation methods, set point surfaces are created and imported into 2D interpolation maps, known as look up tables, which have the axis as engine speed and load. In this study, simulation environment is designed in a manner, which is a reflection of the real engine control unit. As it stated before, engine model needs five inputs to generate outputs. In the simulation, there are only two inputs required fuel and engine speed. Once, the operating range is defined in terms of engine speed and fuel, MAP, MAF and start of injection set points built by the 2D interpolation tables. According to MAP and MAF set points, SISO controllers determine the position of VGT and EGR.

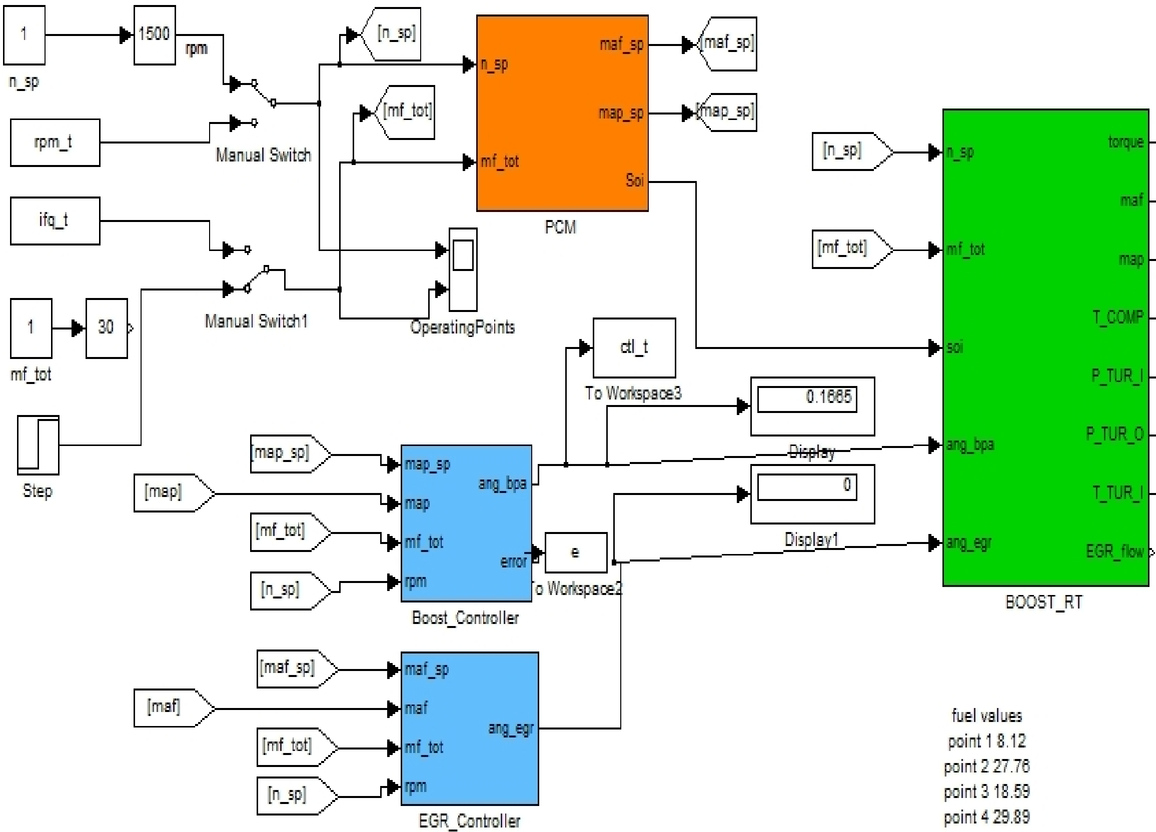

Fig. 7 Simulation environment

A. PID Controllers Tuned by Ziegler Nichols & Genetic Algorithm

In the industry, mostly, PID controllers are employed to cope with air path problem. To do so, there are two PID controllers are designed separately for MAP and MAF control. On the other hand, in order to deal with non-linear and multi input multi output nature of the system, there are additional functions added such as rate limiters, open loop feed-forward controllers gain scheduling.

As a starting point in the air path simulation, PID controllers first tuned by Ziegler Nichols critical oscillation method. Secondly, as a new approach, they are tuned by genetic algorithm. Finally, open loop feed-forward control action is added to both methods to increase controller performance. As a result of the study, genetic algorithm is a promising method because of the iterative optimized process. Considering control tuning by simulation, genetic algorithm works according to its configuration as number of populations, mutation etc. (nearly 1 day in this study), but this time in fact does not consume any source and gives a good starting point for the test bench. Fig. 8 shows the process of genetic algorithm method. Fig. 9 displays the open loop feed-forward controller, which is known as pre-control in the automotive industry with the standard PID.

Pre-control action is determined according to final position of the actuator regarding the current engine operating point. Hence, feed-forward action carries PID to the closer band to the set point to speed up the controller response.

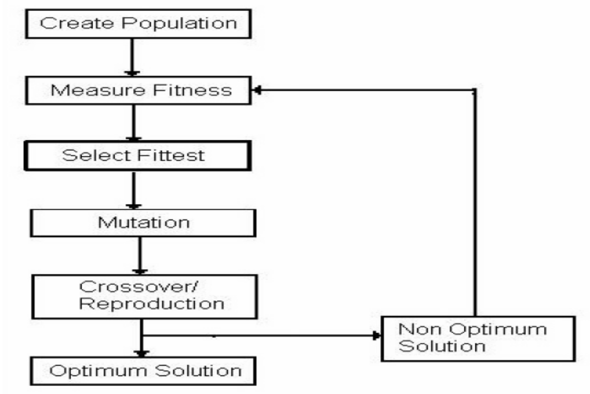

Fig. 8 Flow chart of genetic algorithm[3]

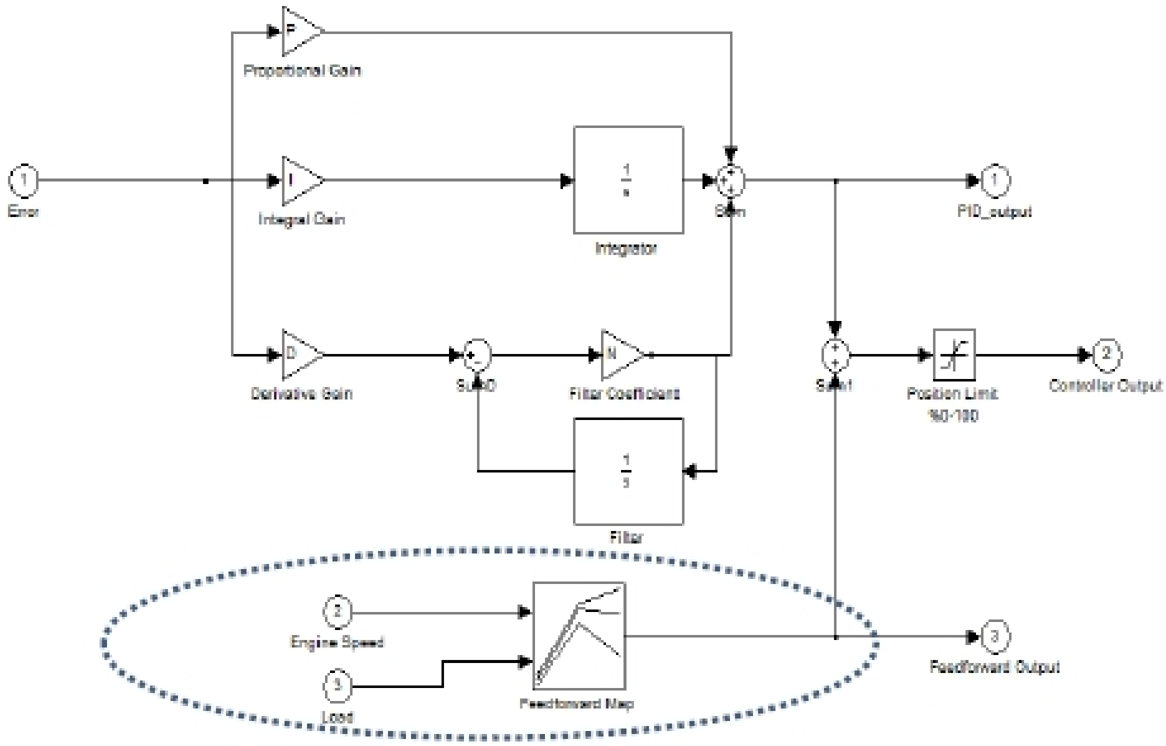

Fig. 9 PID+open loop feed-forward control

B. Linear Model Predictive Control Design

In this study, linear model predictive controller is designed by using MATLAB Model Predictive Toolbox to deal with air path problem better than PID controllers due to the fact that MPC is naturally capable of working MIMO systems with constraints. Since, the actual air path system is non-linear, linear plant model is identified using input output relations in the 2250 rpm. Figs. 10 and 11 show the identified model and applied inputs. In order to increase accuracy of the model, pseudo random signal generation method is used to add low level of actuation to the inputs.

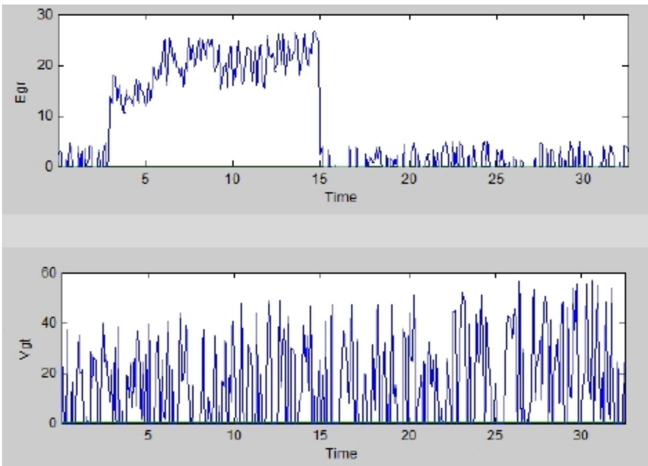

Fig. 10 Position of EGR and VGT as inputs

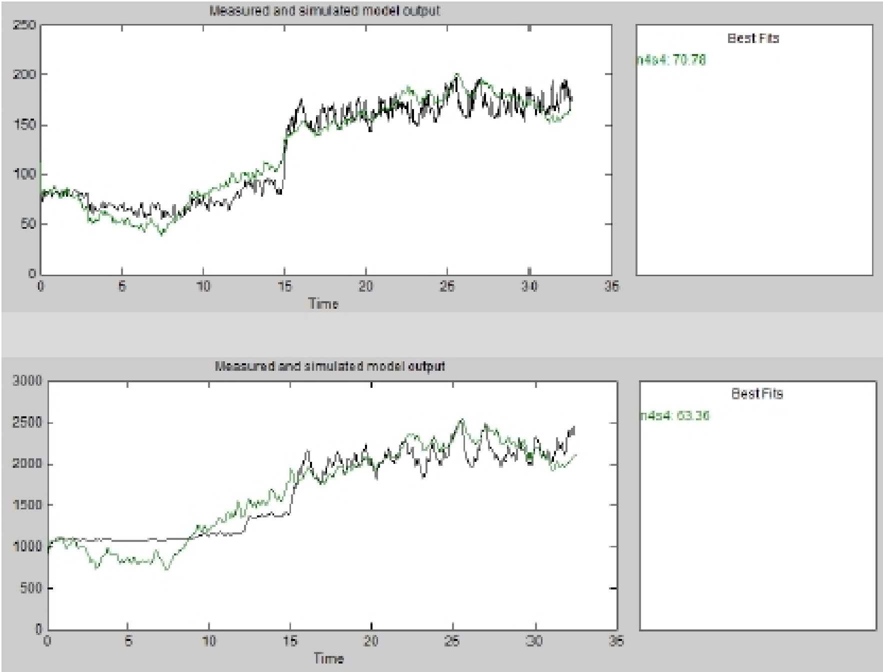

Fig. 11 Identified linear plant model in green

Identified system is in the form of fourth order state space system. After reaching the linear plant model, next step is parameterizing MPC scheme by using the toolbox. Main idea of MPC control is displayed in Fig. 12. Basically, each sample, by using plant model, set of control actions are calculated depending on the pre-defined future samples which is called horizon. Control moves are in fact solution of the quadratic optimization problem which satisfies the constraints. After the actuation of first control move, system calculates

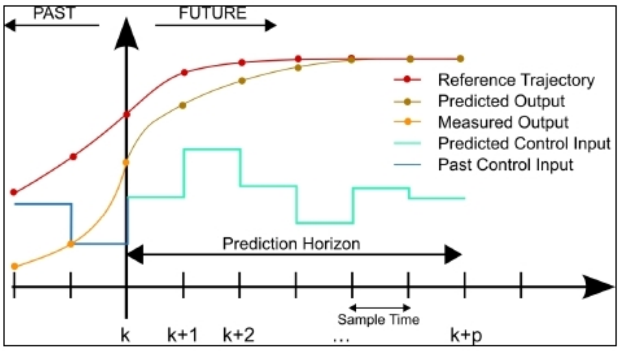

Fig. 12 MPC receding horizon approach [9]

Cost function of linear MPC algorithm is listed in the equation sets (1) and (2). In the first equation set, one can see that final cost function is the sum of output, input and input rates functions. Each function has separate weighting factors.

$$
\begin{aligned}
J_{mpc}(z) &= J_y(z) + J_u(z) + J_{\Delta u}(z) + J_c(z) \\
J_y(z_k) &= \sum_{j=1}^{n_y}\sum_{i=1}^{p}\left(w_{i,j}^{y}\left[r_j(k+i\setminus k) - y_j(k+i\setminus k)\right]\right)^2 \\
J_u(z_k) &= \sum_{j=1}^{n_u}\sum_{i=0}^{p-1}\left(w_{i,j}^{u}\left[u_j(k+i\setminus k) - u_{j,target}(k+i\setminus k)\right]\right)^2 \\
J_{\Delta u}(z_k) &= \sum_{j=1}^{n_u}\sum_{i=0}^{p-1}\left(w_{i,j}^{\Delta u}\left[u_j(k+i\setminus k) - u_j(k+i-1\setminus k)\right]\right)^2
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
u_{\min}(i) &\le u(i) \le u_{\max}(i) \\
\Delta u_{\min}(i) &\le \Delta u(i) \le \Delta u_{\max}(i) \\
y_{\min}(i) &\le y(i) \le y_{\max}(i)
\end{aligned}
\tag{2}
$$

In (2), constraints on input, input rates and outputs are shown. Within these equations, MPC scheme solves the linear quadratic optimization problem with constraints. There are two different MPC tuned with different advantages in terms of transient performance. Fig. 13 displays the performance of two different MPC responses during a step input in terms of MAP and MAF. During the all simulations, a step of fuel increase is applied to the engine in 2250 rpm. Considering previously explained set point generation logic, increase in the fuel turn into increase in the MAF and MAP set points.

Both MPC schemes give a good result in terms of robustness and smoothness. However, one has faster response with higher overshoot which would be useful for the performance oriented approach but bad for emissions and the other one is vice versa. In the last section, these MPC schemes are compared with the PID controllers tuned by Ziegler Nichols and genetic algorithm.

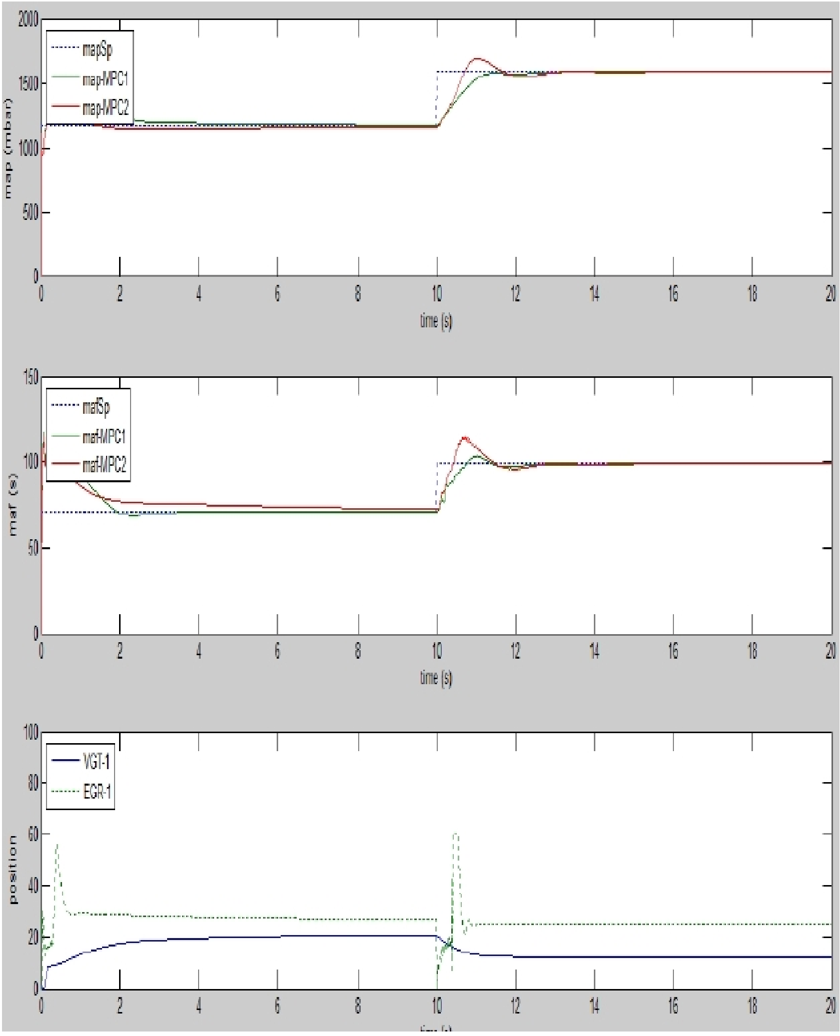

Fig. 13 Two different MPC scheme

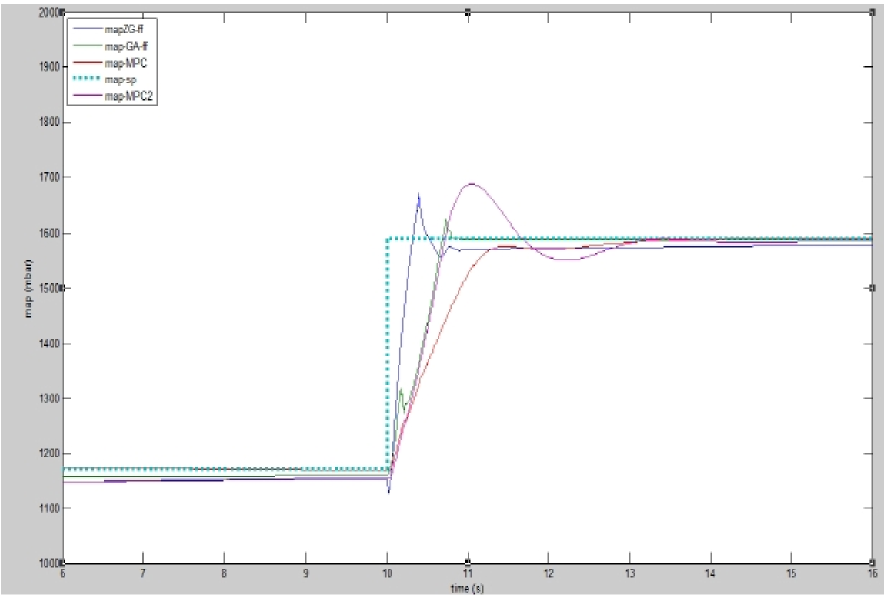

Fig. 14 MAP response of all controllers

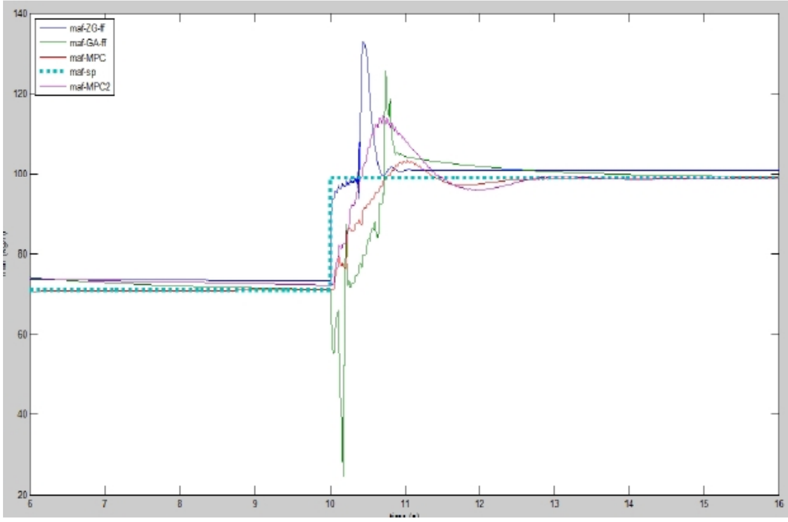

Fig. 15 MAF response of all controllers

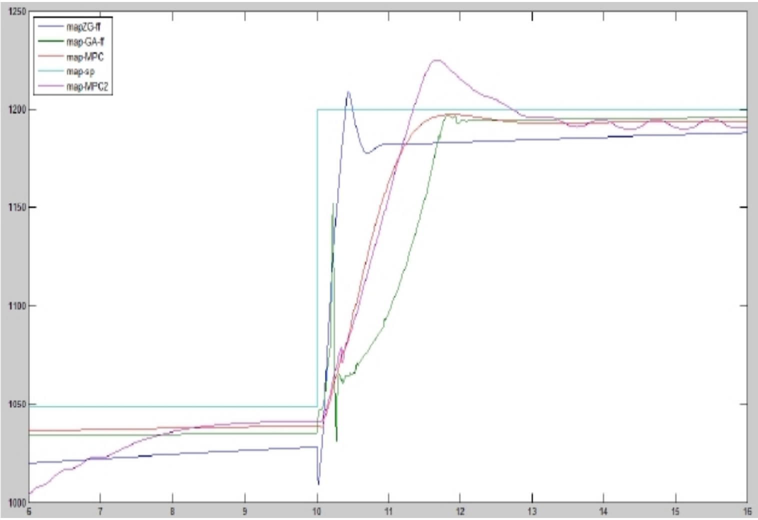

Fig. 16 Map response @1250 rpm

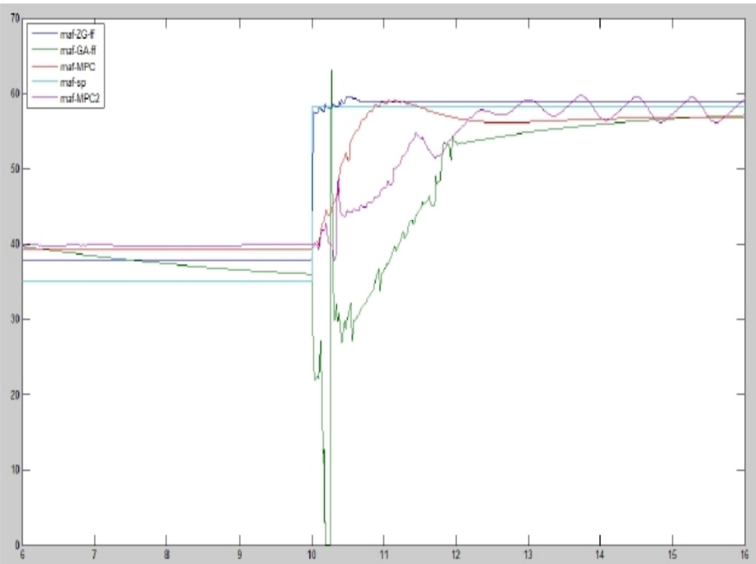

Fig. 17 MAF response @1250 rpm

IV. Results

Figs. 14 and 15 show the overall comparison of controllers with MAP and MAF performance. In terms of, MAP control, generic PID controllers give better performance. However, due to the coupled system behavior this leads to poor MAF control. Since, the ultimate target is to find best compromise; MPC finds the optimum result for both outputs.

Performance of MPC is quite promising with respect to the PID controllers. It should be noted that PIDs used in industry has different set of parameters for different engine speed load points and also for different error levels. Hence, their response would be better than here by the addition of gain scheduling and rate transition terms. However, one of the aims of this study is to prove that MPC algorithm can give better response than the PID controllers and in addition, it can reduce the development times due to parameterization of less parameter. On the other hand, the major drawback of MPC is the computational complexity and need of a linear plant model which also requires dividing engine operating ranges to the different sub-ranges to derive different models. For example, without changing any of the parameters for all controllers, same load step is applied to the engine at 1250 rpm. Figs. 16, 17 show the new response each controller and how they get worse considering change in the engine response due to non-linear behavior.

V. Conclusions

In this study, four cylinder passenger size turbocharged diesel engine with EGR has been modeled by AVL Boost Rt, and then the model is simulated to present non-linear multi input multi output coupled air path problem. In order to deal with air-path problem, open loop feed-forward compensation is used with PID controllers and finally linear MPC algorithm introduced. Results of MPC scheme seems promising for the further analysis and implementation in real time by using hardware in the loop facility in the future.

References

[1] AVL Boost RT – User Guide (2009), AVL List GmbH, Graz.

[2] Guzella, L., Amstutz A., (1998). "*Control of Diesel Engines*". IEEE Control Systems Magazine. Vol. 18, No. 5, pp. 53-71.

[3] Goldberg D.E., (1989). *"Genetic Algorithms in Search, Optimization, and Machine Learning*". Addison Wesley Publishing Co., Inc.

[4] Herceg M. (2006). "*Nonlinear Model Predictive Control of a Diesel Engine with Exahust Gas Recirculation and Variable Geometry Turbocharger"*, MSC Thesis, Sloavak University of Technology, Bratislava.

[5] Iwadere M., Ueono M., Adachi S., (2009). "*Multivariable Air-Path Management for a Clean Diesel Engine Using Model Predictive Control"*, SAE 2009-01-0733.

[6] Jankovic M., Kolmanovsky I., (1998). *"Robust Nonlinear Controller for Turbocharged Diesel Engines"*. Proc. Of the American Control Conference, Philadelphia.

[7] Ortner P., Del Re L., (2007). "*Predictive Control of a Diesel Engine Air Path"*. IEEE transactions on control systems technology, vol. 15, no. 3

[8] Plianos A., Stobart R., (2007) *"Real-time Adaptive Predictive Control of the Diesel Engine Air-path Based on Fuzzy Parameter Estimation"*. SAE Electronic Engine Controls SP-2087.

[9] Kumar A., Mohit B., (1989) "Implementation of Neural Model Predictive Control in Continuous Stirred Tank Reactor System". f Scientific & Engineering Research, Volume 4, Issue 6.