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A Virtual Sensor for Soot Load Estimation in Diesel Particulate Filters

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ABSTRACT

In this paper, a new method for measuring the DPF soot load is proposed which does not require any physical sensors for its operation. This method is applicable for all the automobiles equipped with a turbocharger. The proposed virtual sensor utilizes the information on the turbocharger turbine speed variations to estimate the DPF soot load. Simulation results show that the proposed method offers an effective way to accurately estimate the soot load in DPF. The proposed method can have a significant impact on improving the DPF regeneration process efficiency (and thereby fuel efficiency) by eliminating the use of less reliable differential pressure sensor based DPF soot load estimation.

Keywords: Diesel particulate filter, soot load, virtual sensor, turbocharger turbine, fuel efficiency.

INTRODUCTION

As the air pollution norms get more stringent, there is a need for the automotive companies to implement new methods to reduce air pollution. One of the most important component released in the atmosphere by vehicles is the Particulate Matter. Particulate Matter (PM) are formed because of incomplete combustion of hydrocarbons in the diesel fuel. This PM mainly consist of impure carbon particles, some inorganic oxides and hydrocarbons including some highly toxic polyaromatic hydrocarbons. The most important factor that makes PM so hazardous is their size. The PM are classified into two size groups. The particles whose size is less than 10µm is classified under the group of PM10, and the particles whose size is less than 2.5µm is classified under the group of PM2.5. Such tiny particles when inhaled by humans can cause severe health problems including the diseases of the respiratory tract. To prevent this, the Environmental Protection Agency (EPA) has set some norms for the emission of the PM. Currently, the maximum allowable limit set by EPA for PM emissions in the United States is 15$\mu m/m^3$ annually [1]. To achieve this, the automotive companies must implement newer methods and technologies to reduce the PM emissions into the atmosphere. Apart from that, more research is being conducted to reduce the formation of PM and also to limit the tailpipe emission of this PM.

To reduce the emission of PM in to the atmosphere, the exhaust after-treatment system consists of a Diesel Particulate Filter (DPF). The DPF does the work of filtering the PM from exhaust gases before they are released in to the atmosphere. The DPF is typically made up of some porous ceramic material (Silicon Carbide or Cordierite) which filters out 90% of the PM from the exhaust gases. These deposited PM particles inside the DPF are called as Soot. This soot must be cleaned off from the DPF after certain amount of time to avoid clogging of the DPF. If the DPF is clogged, the efficiency of the after-treatment system is reduced as well as back pressure is created on the engine. This back pressure is not acceptable as it reduces the performance efficiency of the engine. The cleaning is done by injecting some fuel into the exhaust gases upstream of the diesel oxidation catalyst (DOC) which burns of the soot from the DPF leaving only ash as a residue. This process is called as Active Regeneration. It is important to know when an Active Regeneration should be done to avoid fuel wastage. The key factor is determining how much DPF is full with soot. If the amount of soot inside the DPF is estimated, then it becomes more cost saving to determine when an Active Regeneration should be initiated.

Currently, soot load estimation is done by using the differential pressure measurement across the DPF which is not very accurate [4]. As a result, the dosing of fuel for active regeneration may not be optimal. The fuel penalty caused by regeneration (2.2% to 5.3%) is more than the fuel penalty due to backpressure (1.5% to 2.0%) [8]. It is important to have an accurate knowledge of soot load to reduce the fuel wastage and to improve the performance of the automobile.

In this paper, we present a novel method of estimating the DPF soot load by using the turbocharger turbine as a virtual sensor to measure the soot load. The readings obtained from this virtual sensor can be used by the controller to accurately estimate the DPF soot load. Based on this estimation, correct amount of fuel can be injected upstream of the diesel oxidation catalyst (DOC) thus improving the overall performance of the DPF and reducing fuel wastage.

THE DIESEL EXHAUST SYSTEM

A schematic of a Diesel Engine after-treatment is shown in Fig. 1. As shown in the figure, the exhaust gases coming out of the diesel engine pass through a variable geometry turbocharger (VGT) where the energy of the exhaust gases is used to rotate the turbine of the VGT which in turn rotates the compressor connected to it. The compressor is used to compress the intake air flowing to the cylinder thus providing a boost to the engine. Exhaust gases flow from inlet to outlet of the VGT and cause the turbine to rotate because of the pressure differential created between the inlet and outlet of the turbine.

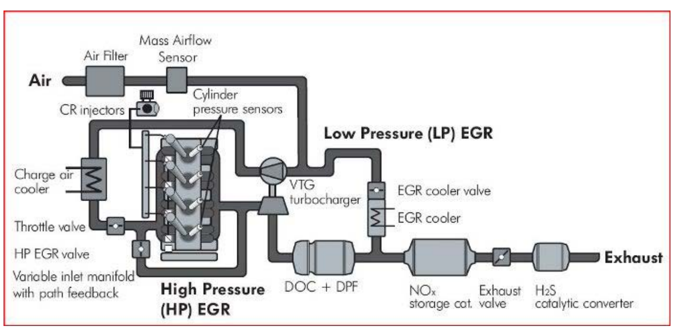

Figure 1: Hybrid EGR system for US EPA Tier 2 Bin 5 diesel application [7].

The operation of a VGT is shown in Fig. 2. The inlet side of the VGT is connected to the engine, thus becoming the high-pressure side and the outlet side is the low-pressure side. Just before the VGT, there is an exhaust gas recirculation (EGR) valve which is used for recirculating some of the exhaust gases back to the intake of the engine. After the VGT the exhaust after-treatment devices are placed. These devices restrict the flow of the exhaust gases thus increasing the pressure of exhaust gases at the outlet of the VGT. This pressure is called as backpressure to the VGT. As the back pressure to the VGT increases, the pressure differential between the inlet and outlet of the VGT reduces. This reduction in the pressure affects the rotation of the VGT turbine. Apart from that, the VGT itself adds restriction to the flow of exhaust gases and its variable geometry design makes it even more sensitive.

The closing of the vanes of the VGT result in more turbine work and delivers high boost pressure, but it also increases the backpressure on the engine, which is induced by reduced turbine effective area. The combined backpressure of the VGT as well as the exhaust after-treatment devices affect the proper working of the engine and reduces its efficiency.

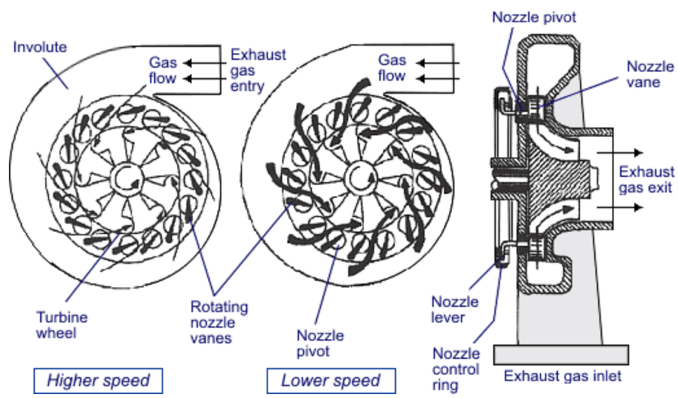

Figure 2: Operation of Variable Geometry Turbocharger [9].

All the components which restrict the flow of exhaust gases add backpressure to the engine. Even the size and geometry of the exhaust pipe add restriction to the flow. But the main component which contribute to the backpressure on the engine apart from VGT is the diesel particulate filter (DPF). DPF is made up of a porous material (Silicon Carbide or Cordierite) that traps the particulate matter from the exhaust gases. Over a period, soot is collected within the DPF pores and adds more restriction to the flow of exhaust gases thus adding more backpressure to the VGT and ultimately the engine.

As the amount of soot within the DPF increases, the backpressure to the VGT increases. This backpressure to the VGT affects the rotation of the VGT turbine, i.e. it reduces the speed of the turbine. If this reduction in speed of the turbine is measured, it is possible to accurately estimate how much soot is accumulated within the DPF. For this, it is necessary to study how the speed of the turbocharger turbine is affected because of the DPF soot load.

THE DIESEL ENGINE MODEL

A mean-value model of diesel engine with variable geometry turbocharger and exhaust gas recirculation has been developed, parameterized and validated by Johan Wahlström and Lars Eriksson [5]. They have also developed a Simulink model with a MATLAB code for simulating the model for certain conditions. In this model, they have proposed eight stages, i.e. the inlet manifold pressure, the exhaust manifold pressures, the oxygen mass fraction in the intake manifold, the oxygen mass fraction in the exhaust manifold, the turbocharger speed, and three states describing the actuator dynamics for the two control signals [5]. The model is represented in Fig. 3.

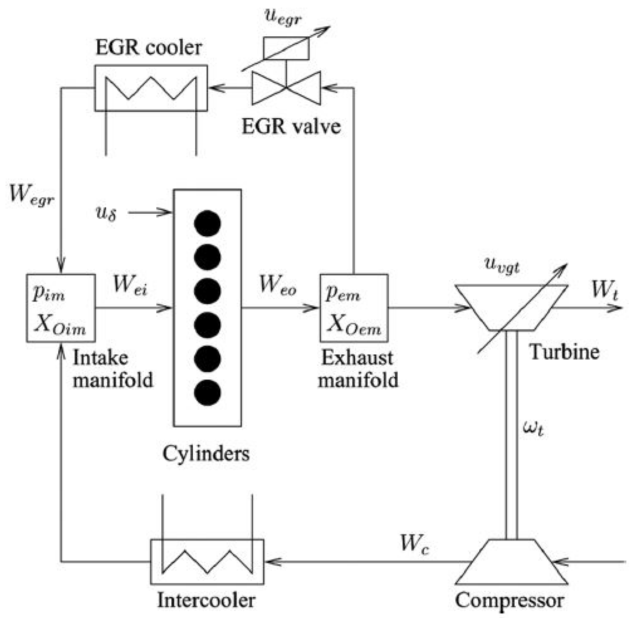

Figure 3: A model structure of the diesel engine [5].

This model structure along with the Simulink model and MATLAB code are used for finding out the relationship of the VGT turbine rotation speed and the DPF soot load. Some alterations were made in the MATLAB code and the Simulink model for this research.

In the model proposed by Johan Wahlström and Lars Eriksson, the outlet pressure of the VGT is considered to be atmospheric pressure and they have neglected the effect of diesel after-treatment devices at the outlet of the VGT. Hence, another system variable was added in this model which accounts for the DPF backpressure on the VGT. As the DPF soot load increases, the pressure in the inlet channel of the DPF increases. An experiment conducted by O. A. Haralampous *et al.* [6] for validating one-dimensional pressure drop model of the DPF, provides the relationship between the increase in soot load and the inlet channel pressure of the DPF. This relationship is represented in Fig. 4.

It can be seen from the figure that at 0 g/l soot load, the pressure is approximately equal to the atmospheric pressure and as the soot load increases to 8 g/l, the inlet channel pressure increases to 1350 mbar (135000 Pa). For this research, a linear relationship between the DPF soot load and inlet channel pressure is considered. The pressure values at the DPF inlet channel are considered equal to the outlet pressure of VGT and are modelled in our integrated Simulink model for the outlet pressure of the VGT.

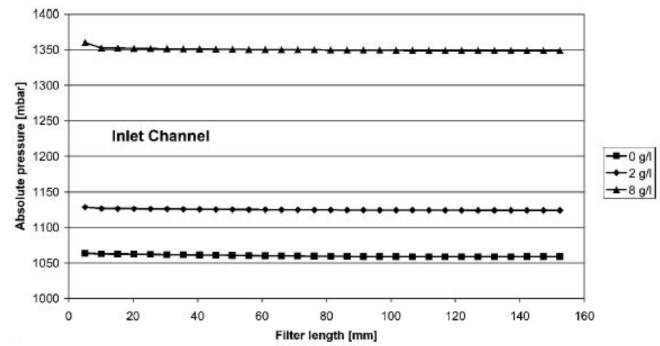

Figure 4: Computed DPF inlet channel pressure profiles for different soot loadings [6].

Other primary variables which are used in the model proposed by Johan Wahlström and Lars Eriksson are Engine Speed (500-2000 RPM), Amount of fuel injected (1-250 mg/cycle), EGR valve position (0-100%) and VGT turbine blade position (20-100%) [5]. For the purpose of this research, the range of these variables is kept same, and the system is simulated within these values only. The VGT outlet pressure is varied between 1.0111 MPa (1 atmosphere) and 1.35 MPa for soot loads between 0 g/l and 8g/l [6].

RESULTS AND OBSERVATIONS

Various simulations were performed using the improved and integrated MATLAB code and Simulink model. The results obtained are summarized as follows:

Effect of DPF Soot Load on Turbocharger Turbine Speed (RPM) according to varying Engine Speed (RPM)–

Simulations were performed for engine speeds varying from 500 to 2000 RPM as these are the design limits for the selected Simulink model. The EGR valve was kept at 80% open for this simulation and the VGT position was kept at 30% open. It can be seen from the Fig. 5, as the Soot Load increases, the turbocharger turbine speed reduces

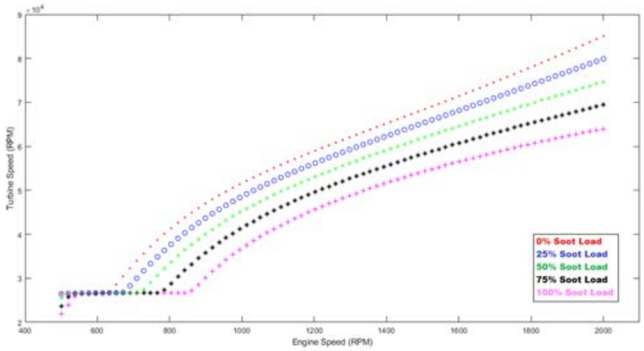

Figure 5: Engine Speed vs Turbocharger Speed for varying DPF Soot Loads.

The percentile variation in Turbocharger Turbine Speed with respect to change in Soot Load for maximum Engine Speed is listed in Table 1.

Table 1: Change in Turbocharger Turbine Speed according to changes in DPF Soot Loads

Sr. No.	DPF Soot Load (%)	Turbocharger Turbine Speed (RPM)	Percentage Change in Turbocharger Turbine Speed (%)
1	0	85067	0
2	25	79886	6.09
3	50	74659	12.23
4	75	69402	18.41
5	100	63957	24.81

From the table, it can be observed that the difference between the turbocharger turbine speed at 0% soot load and 100% soot load is 21117 RPM or 24.81% which is significant.

The other important variables which play a vital role in altering the Turbocharger Turbine RPM are the VGT position and EGR valve position. To understand the effect of these parameters on the turbine rotational speed while the DPF soot load is changing, the following sections are provided.

Effect of VGT position on the Turbocharger Turbine Speed for varying Engine Speeds at 0% and 100% Soot Load –

These simulations are carried out for engine speed varying from 500 to 2000 RPM and for VGT position of 20%, 60% and 100% open. It can be inferred from the Fig. 6 and 7 that as the VGT position opens, the speed of turbocharger turbine decreases at the same Soot load and EGR position. The percentage change in Turbocharger Turbine Speed with respect to change in VGT blades position for varying engine speed is demonstrated in Table 2.

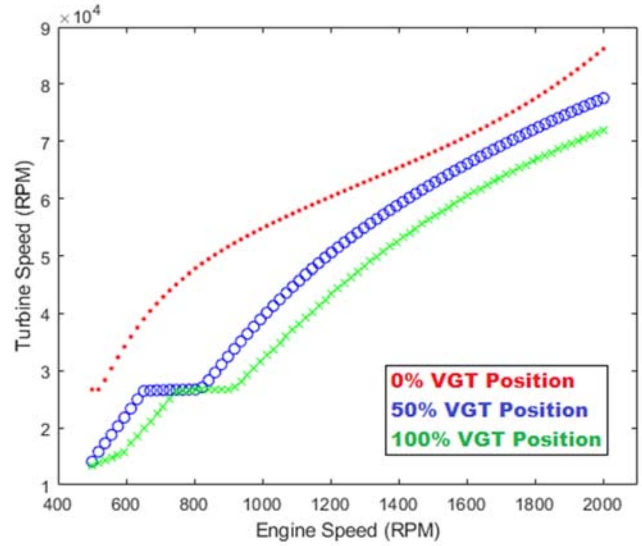

Figure 6: Engine Speed vs Turbocharger Turbine Speed for varying VGT positions at 0% soot load.

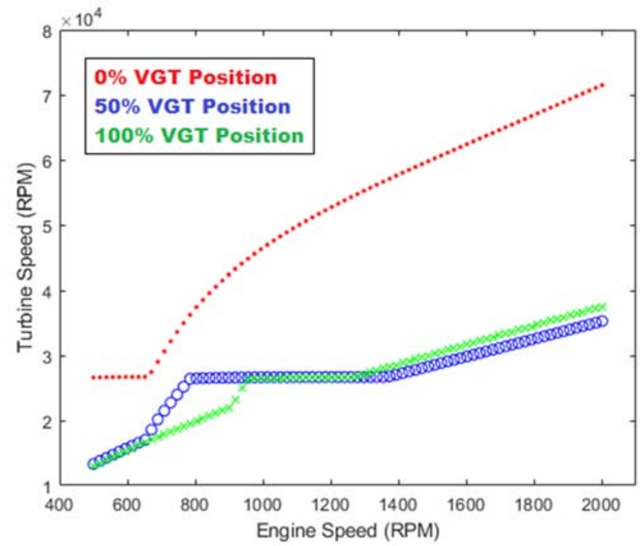

Figure 7: Engine Speed vs Turbocharger Turbine Speed for varying VGT positions at 100% soot load.

Table 2: Change in Turbocharger Turbine Speed according to changes in VGT position

Sr. No.	VGT Position (%)	Turbocharger Turbine Speed (RPM) for 0% Soot Load	Change in Turbocharger Turbine Speed (%) for 0% Soot Load	Turbocharger Turbine Speed (RPM) for 100% Soot Load	Change in Turbocharger Turbine Speed (%) for 100% Soot Load
1	20	86183	0	71496	0
2	60	77554	10.01	35291	50.63
3	100	71904	16.56	37498	47.55

From the table it is observed that there are significant changes in the turbocharger turbine RPM when compared between 0% DPF Soot Load readings and 100% DPF Soot

Load readings for the similar conditions of the engine operation. These comparisons are tabulated in Table 3.

Table 3: Comparison between Turbocharger Turbine Speed for 0% DPF Soot Load and 100% DPF Soot Load at varying VGT positions

Sr. No.	VGT Position (%)	Turbocharger Turbine Speed (RPM) for 0% Soot Load	Turbocharger Turbine Speed (RPM) for 100% Soot Load	Comparison between Turbocharger Turbine Speed for 0% and 100% Soot Load (%)
1	20	86183	71496	17.04
2	60	77554	35291	54.49
3	100	71904	37498	47.84

It is observed that the DPF Soot Load plays an important role for variations in Turbocharger Turbine Speed. A 47.84% turbine speed variation is observed from the 0% soot load to the 100% soot load condition. This significant speed variation can be observed and used to detect the DPF condition.

Effect of DPF Soot Load on Turbocharger Turbine Speed according to change in position of VGT –

To further observe precise change in Turbocharger Turbine Speed for every position of the VGT Blades, the speed of the engine was kept constant at 1500 RPM and the Turbocharger Turbine Speed was plotted against VGT Blade positions. Fig. 8 shows these variations.

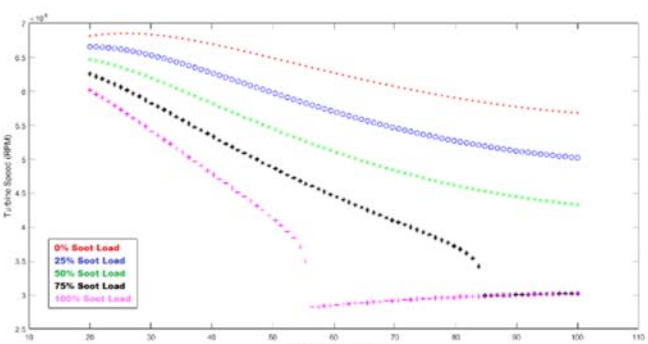

Figure 8: VGT position vs Turbocharger Turbine Speed for varying DPF Soot Load.

These simulations were carried out for VGT position of 20% to 100% open and the EGR valve was set at 80%. As the DPF soot load increases, the turbocharger turbine speed decreases for every position of the VGT. The percentage change in turbocharger turbine speed with respect to change in soot load for maximum possible VGT position is given in Table 4.

Table 4: Change in Turbocharger Turbine Speed according to DPF Soot Load

Sr. No.	DPF Soot Load (%)	Turbocharger Turbine Speed (RPM)	Change in Turbocharger Turbine Speed (%)
1	0	56765	0
2	25	50180	11.60
3	50	43290	23.73
4	75	30222	46.57
5	100	30151	46.88

From the table the maximum change in turbocharger turbine speed is 26614 RPM or 46.88%. From Fig. 8 and Table 4, it is observed that for higher soot loads, the turbocharger turbine speed reaches a lower saturation point before reaching the maximum position of VGT and the speed of turbocharger turbine remains approximately same after that. However, it was also noticed that as the DPF soot load increased, the saturation point speed of the turbocharger turbine was achieved at a lower engine rpm.

Effect of EGR valve position on the Turbocharger Turbine Speed for varying Engine Speeds at 0% Soot Load –

The role of EGR is very important for the working of the Turbocharger Turbine. This is because the EGR valve is situated just before the inlet of VGT. As the EGR valve opens, the amount of exhaust gas passing through the VGT reduces, thus reducing the inlet pressure of the VGT. The variations in the Turbocharger Turbine Speed for different EGR valve positions can be demonstrated in Fig. 9 and 10.

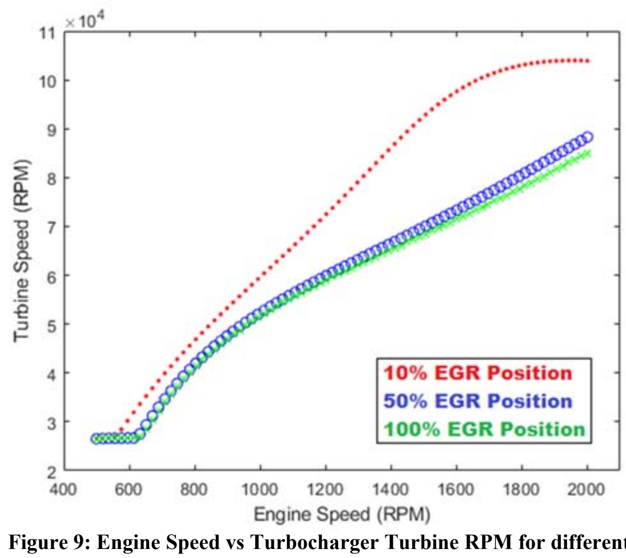

Figure 9: Engine Speed vs Turbocharger Turbine RPM for different positions of the EGR valve at 0% Soot Load.

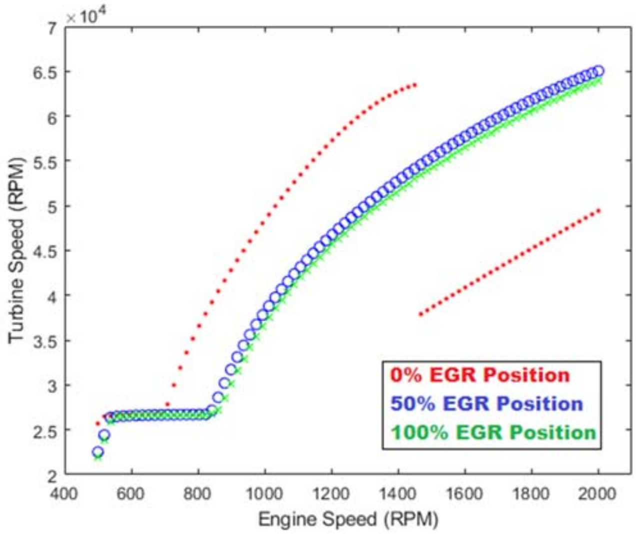

Figure 10: Engine Speed vs Turbocharger Turbine RPM for different positions of the EGR valve at 100% Soot Load.

It is observed that at 100% soot load and lower position of EGR value opening, the speed of the Turbocharger Turbine reaches a certain maximum point and then falls to a certain minimum before rising again. This irregular behavior of the turbine speed is probably because of the turbine rpm maximization at the breaking points. The operating points beyond the breakaway points is not be possible with 100% soot load and the VGT position being fixed. In actual situation, the VGT position will be variable and it compensates for the turbine speed for low EGR values. Another observation that can be made is that for higher EGR values, the speed of the turbocharger turbine does not show much change at fixed value of soot load. The following table summarizes the Fig. 9 and 10.

Table 5: Change in Turbocharger Turbine Speed according to changes in EGR position

Sr. No.	EGR Position	Turbocharger Turbine Speed (RPM) for 0% Soot Load	Change in Turbocharger Turbine Speed (%) for 0% Soot Load	Turbocharger Turbine Speed (RPM) for 100% Soot Load	Change in Turbocharger Turbine Speed (%) for 100% Soot Load
1	0	103897	0	56241	0
2	50	88292	15.01	65044	-15.65
3	90	85067	3.65	63956	1.67

Comparing the Turbocharger Turbine Speeds for 0% and 100% soot loads, the difference in speeds can be clearly observed. This comparison is tabulated in Table 6.

Table 6: Comparison between Turbocharger Turbine Speed for 0% DPF Soot Load and 100% DPF Soot Load at varying EGR positions

Sr. No.	EGR Position (%)	Turbocharger Turbine Speed (RPM) for 0% Soot Load	Turbocharger Turbine Speed (RPM) for 100% Soot Load	Comparison between Turbocharger Turbine Speed for 0% and 100% Soot Load (%)
1	0	103897	56241	45.86
2	50	88292	65044	26.33
3	90	85067	63956	24.81

To further observe precise change in Turbocharger Turbine Speed for every position of the EGR valve, the speed of the engine was kept constant at 1500 RPM and the Turbocharger Turbine Speed was plotted against EGR valve positions.

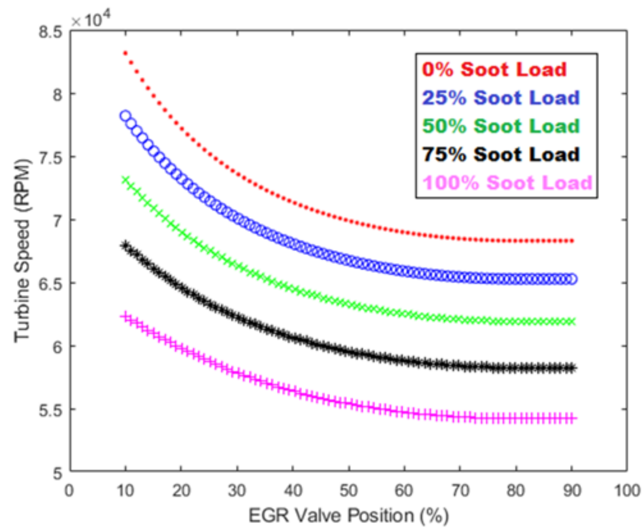

Figure 11: EGR valve positions vs Turbocharger Turbine Speed for varying DPF Soot Loads.

These simulations were performed by varying the EGR valve position from 10% to 90% open. The VGT position was kept constant at 30% open. It is observed that, as the DPF Soot Load increases, the turbocharger turbine speed decreases for every position of the EGR valve. These results are tabulated to find the total percentage decrease in the turbocharger turbine speed in Table 7.

Table 7: Change in Turbocharger Turbine Speed for different DPF Soot Loads

Sr. No.	DPF Soot Load (%)	Turbocharger Turbine Speed (RPM)	Change in Turbocharger Turbine Speed (%)
1	0	68293	0
2	25	65264	4.43
3	50	61907	9.35
4	75	58242	14.71
5	100	54201	20.63

From the table, the maximum change in Turbocharger Turbine Speed was 14092 RPM that translates into a 20.63% deviation over the course of soot load accumulation.

CONCLUSION

A model of a diesel engine was integrated with the model of DPF to study the effects of soot accumulation in the engine. A sensorless technique was proposed to estimate the DPF soot load accumulation for an accurate regeneration. It was observed that for every variable in the system, i.e. Engine Speed, VGT Blades Position and EGR Valve Position, the Turbocharger Turbine Speed decreases with increase in DPF Soot Load. This change in turbocharger turbine speed can be measured by the controller and the DPF Soot Load can be estimated. Even though these results were obtained for steady state conditions of the engine, a novel perspective for measuring the DPF Soot Load is introduced here.

REFERENCES

1. Robert Esworthy, Air Quality: EPA's 2013 Changes to the Particulate Matter (PM) Standard, Congressional Research Service, December 23, 2015
2. D. Blanco-Rodriguez, Modelling and Observation of Exhaust Gas Concentrations for Diesel Engine Control, Springer International Publishing Switzerland, 2014
3. G A Stratakis, D L Psarianos, A M Stamatelos, Experimental Investigation of pressure drop in Porous Ceramic Diesel Particulate Filters, Mechanical and Industrial Engineering Department, University of Thessaly, Volos, Greece
4. Mansour Masoudi, Alexander G. Sappok, "Soot (PM) Sensors", DieselNet.com. Copyright © Ecopoint Inc. Revision 2017.08
5. Johan Wahlström and Lars Eriksson, "Modelling diesel engines with a variable-geometry turbocharger and exhaust gas recirculation by optimization of model parameters for capturing non-linear system dynamics", 2011, Proceedings of the Institution of mechanical engineers. Part D, journal of automobile engineering, (225), 7, 960-986. http://dx.doi.org/10.1177/0954407011398177
6. O. A. Haralampous, I. P. Kandylas, G. C. Koltsakis and Z. C. Samaras, "Diesel particulate filter pressure drop Part 1: Modelling and experimental validation", International Journal of Engine Research 2004 5: 149, DOI: 10.1243/146808704773564550
7. Hannu Jääskeläinen, Magdi K. Khair, "EGR Systems & Components", DieselNet.com. Copyright © Ecopoint Inc. Revision 2012.06b
8. A. Sappok, J. Parks II, and V. Prikhodko, "Loading and Regeneration Analysis of a Diesel Particulate Filter with a Radio Frequency-Based Sensor", *SAE Paper No. 10FFL-0238, SAE International*, 2010.
9. Hannu Jääskeläinen, "Variable Geometry Turbochargers", DieselNet.com. Copyright © Ecopoint Inc. Revision 2016.08
10. A. Izadian, P. Magar, S. Anwar, "A Sensorless Soot Load Detection Technique," USPTO, Provisional Application no. 62/675,346, May 23, 2018.

