Effect of In-line Post Diesel Filtration on Engine Exhaust Emissions and Fuel Consumption

Jefrey Pilusa, Edison Muzenda and Mukul Shukla

***Abstract*—**The work presented in this article investigated the effect of a Whale diesel filter on engine's exhaust emissions, fuel consumption and performance. A stationary ADE 407T heavy duty diesel engine coupled to a hydraulic dynamometer was used to investigate the performance, fuel efficiency and emissions tests under controlled conditions in a laboratory. Exhaust emissions were analysed using Applus-Autologic and Testo 350 emissions analysers. Further emissions validation tests were conducted on three different engine categories including a bus, CAT 320C Excavator and Toyota Hilux. The results showed a significant average reduction in carbon monoxide CO (28%), nitrogen oxides NO_x (92%) , sulphur oxides SO_x (48%) and un-burnt hydrocarbons HC (22%) and increased carbon dioxide CO_2 (27%) emissions after the Whale filter was installed. The engine performance increased by 3%, whereas average fuel consumption under controlled conditions decreased by 24%.

***Keywords*—**Compression Ignition, Diesel Injectors, Engine Performance, Fuel Filtration, Internal Combustion.

I. Introduction

PARTICULATE contamination is one of the most common problems associated with diesel fuel. Particulates found in typical fuels come from a range of sources including but not limited to dust, pump wear debris, filler caps and corrosion debris from bulk tank [1]. This contamination is related to the poor transportation and handling of diesel fuel. As the larger particles are removed from the fuel by the primary filter, it remains a challenge to deal with larger quantities of particles that are small enough to pass through the primary filtration system and eventually reports in the fuel injection system. Previous studies have been conducted on South African diesel fuel to evaluate the relationship between the numbers of particles and the particle size at any given batch of diesel fuel. An exponential growth relationship between the quantity of particles and the particles size less than 0.5 µm was obtained [2]. These findings indicated that in a given batch of diesel fuel, the quantity of particle contaminants less than 0.5 µm in size is 7 times the number of particles larger than 15 µm. The conventional primary diesel filtration system is capable of capturing particle contaminants of up to 10 µm leaving the bulk of contaminants to report to the fuel injection system.

The primary fuel filter offers low restriction because it is mounted on the suction side of the fuel pump where normally a suction pressure of only 34.5 kPa- 41.3 kPa is available. This filter has the function of protecting the transfer pump and lightening the load of the secondary fuel filter if installed. Primary fuel filters typically have a nominal rating of 10 - 30 µm; these filters are designed to remove up to 90% of particles 20 µm or larger [3]. In contrary, secondary fuel filters are mounted between the transfer pump and the injectors. The secondary fuel filter is designed to offer full protection to the fuel injectors. Since these filters are mounted after the transfer pump they tend to handle much higher pressures than primary filters. Secondary fuel filters typically have a nominal rating of 2-10 µm. A Whale filter is designed to protect the transfer pump and injectors by capturing between 0.2 and 0.5µm particles directly from the primary filters without the use of a conventional secondary filter; it also offers low restriction since it is installed between the primary filters and the transfer pump which subjects it under a suction pressure.

All diesel fuels to a degree contain a substance known as asphaltene. Asphaltene is a by-product of fuel as it oxidizes. Asphaltene particles are generally thought to be in the 0.5-2 µm range and are believed to be harmless to the injection system, as they are soft and deformable [4]. As these tiny particles pass through the filter media they tend to stick to the individual fibers and can easily collect finer particle below 0.2 µm forming a cluster of particles that is harmful to the injection system [5].

Removal of these particles is vital to ensure that only clean fuel is introduced into the injection system. Efficient fuel atomisation is mainly dependent on the velocity at the injector nozzle at optimum pressure. Diesel injectors are machined to precision with nozzle diameters of up to 2.5 µm, when larger quantities of micro-particles of 0.5 µm or more are present in

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the fuel; they accumulate at the injector nozzle tip, resulting in flow restriction and pressure build up. Higher pressures promote cavitations and poor fuel atomization which contributes to the imbalance of air-fuel ratio in the combustion chamber [6]. This results in higher combustion temperatures promoting the formation of noxious emissions. McVea *et al*. (2011) [7] evaluated the effect of vehicle filter media characteristics upon the filterability of automotive diesel fuel. It was observed that the probability of the clusters of organic particulate matter passing through a filter paper is reduced by the presence of other insoluble such as microbiological and inorganic material (asphaltene). Once retained, the clusters of small spheres collect the micro particle and mould them to fill voids in the filter media. In these circumstances, the presence of organic particulate matter in fuel will lead to very rapid filter blockage. This study investigated the effect of Whale diesel polishing filter on engine's exhaust emissions, fuel consumption and performance.

II. MATERIAL AND METHOD

A. The Whale Filter

The Whale concept filter is a South African patented diesel filter designed to function as a polishing filter prior to diesel injection, the filter has been filed under patent number 2005/08375. The filter has a cylindrical shape of 140 mm in diameter and 92 mm width as shown in Fig. 1. The filter is made of transparent polypropylene plastic filter housing and the polypropylene base is covered with perforated mild steel backing plates on the suction and delivery sides. The fuel inlet and discharge nozzles are made from stainless steel 6 mm standard fitting compatible with any diesel engine. The porous filter medium is made of natural cotton fibres arranged in a specific pattern for uni-directional and uniform fuel flow throughout the filter. The contaminants are captured through the filter media by physical filtration process and accumulate from the inlet side to the suction side. The end life cycle of the filter can also be verified by visual inspection of the filter media through the transparent filter media housing. The filter has a larger active filtration area compared to conventional primary filters and it targets micro particles of 0.5 μm and smaller. The Whale filter works as an in-line polishing fuel filter in ensuring that smaller particles passing through the primary filter are trapped in the Whale filter prior to entering the injection system [8]. It is installed after the primary fuel filter, just before the high pressure fuel pump as shown in Fig. 2. The Primary fuel filters are ideal for removing particle contaminants larger than 0.5 μm.

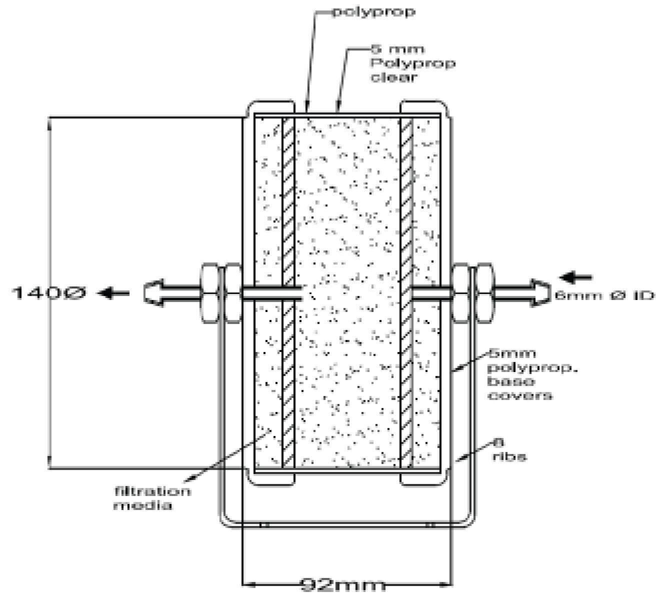

Fig. 1 Two dimensional schematic diagram of the whale filter [8]

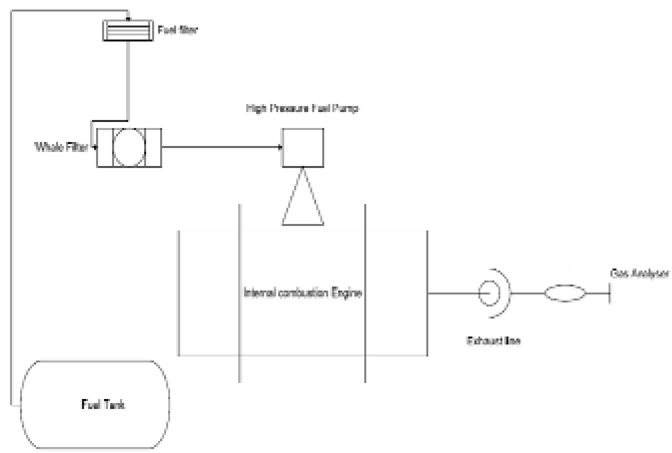

Fig. 2 Diesel fuel flow path showing Whale filter position and gas analyser sampling point [8]

B. Experimental System

a) Emission tests

The longitudinal tests on the effect of Whale concept filter on vehicle exhaust emissions took place in Klerksdorp between the 25th September and 3rd December 2012. Three vehicles engine categories were selected for the tests; these include the CAT 320C excavator, ADE 407T Truck engine and Toyota Hilux. The vehicles underwent pre-emissions testing prior to fitment of the Whale concept filter. Each test was conducted for a period of 20 minutes at varying engine speeds in revolutions per minute (rpm) commencing cold idling, 1000, 2000 and hot idling. A Testo 350 and Autologic emissions analysers were used to measure the emissions at each stage. The whale filter sample was provided by the Whale filter patent holder and the fitment was carried out by qualified technicians on site. Similar testing procedure was followed to measure the emissions after fitment of a new Whale filter. Average test data was collected over a long period of time and analysed to verify emissions reduction after installation of whale filter.

b) Power, Efficiency and Fuel Consumption

Preliminary performance tests were conducted on the 12th September 2012 at City of Johannesburg-Metrobus. Power and torque were measured at various speeds and the smoke was also measured using the opacity smoke meter belonging to Metrobus. This was followed by Whale filter installation and subsequent post performance and smoke tests.

The power, efficiency and fuel consumption test took place between the 26th of October and the 6th November 2012. ADE 470T six cylinder turbocharged truck engine provided by the Mechanical Engineering Department at the University of Johannesburg was commissioned for this purpose. The engine consisted of a Froude Hydraulic Dynamometer and digital sensors for the following parameters; Force (kN), fuel flow (l/s), water and air thermocouple, analogue speed gauge (rpm) and a calibrated volumetric flask fuel tank (ml) from which the test data was collected every 5 minutes at various engine speeds before and after the installation of the Whale filter. The tests were done indoors at standard conditions. Sufficient test data was collected over a pre-determined period of time and the average data was used to draw a conclusion.

Fig. 3 ADE 407T diesel engine complete with hydraulic dynamometer and instruments, Mechanical Engineering Laboratory, University of Johannesburg

Fig. 4 Testo Emissions analyzer

Fig. 5 Autologic vehicle emissions analyser

Figs.4 and 5 show the equipment set-up used to measure emissions from the engine's exhaust stream. The technical specifications are presented in Tables I and II.

TABLE I
TESTO GAS ANALYZER TECHNICAL SPECIFICATIONS

Parameter	Range	Resolution
Oxygen(O_2)	0-025vol.%	0.01vol. %
Carbon Monoxide(CO)	0-10000ppm	1ppm
Nitrogen Oxides(NO_x)	0-500ppm	0.1ppm
Sulpher Oxides(SO_2)	0-5000ppm	1ppm
Carbon dioxide(CO_2) -(IR)	0-50vol.%	0.01vol.%(0-25vol. %) 0.1vol.%(>25vol. %)
Hydrocarbons(HC)	100-40000ppm	10ppm

TABLE II
TECHNICAL SPECIFICATIONS FOR 5 GAS APPLUS AUTOLOGIC VEHICLE EMISSIONS ANALYZER USED

	Range	**Resolution**	**Measure**
Hydrocarbons(HC)	0-3000ppm	1ppm	Non-dispersive Infrared(NDIR)
Carbon Monoxide(CO)	0-15000ppm	1ppm	Non-dispersive Infrared(NDIR)
Carbon dioxide(CO_2)	0-20%	0.01vol%	Non-dispersive Infrared(NDIR)
Oxygen(O_2)	0-25%	0.01vol%	Electrochemical Sensors
Nitrogen Oxides(NO_x)	0-5000ppm	1ppm	Electrochemical Sensors
Warm-up time	120 Seconds		
Temperature	0-500C operating; -200C-700C Storage		
Altitude	-300-2500m		
Humidity	Up to 90% Non-condensing		
Vibration	1.5 G sinusoidal 5-1000 Hz		
Data storage	Internal memory/ real time data logging and graphing		
Operating system	Runs on any PC running Windows® 95, Windows® 98, Windows NT®, Windows® ME, Windows® 2000, Windows XP® and Windows Vista®		
Response time	0-90% <= 8Seconds for NDIR measurements		
Condensation trap	Automatic water removal to remove water from the vehicle's exhaust		
Accuracy specifications	ASM/BAR 97, OIML, BAR90		
Power supply	90-230 VAC, 50-60 Hz. 12 Volt Cigarette lighter plug and 12 volts battery		

III. Results and Discussion

A. Theoretical Considerations

c) Torque

Torque (τ) is the tendency of a force to rotate an object about an axis or pivot. Mathematically, torque is defined as the cross product of perpendicular force and the lever-arm distance, which tends to produce rotation. In simple terms, torque is a measure of the turning force on an object such as a bolt or a flywheel in case of engines. For example, pushing or pulling the handle of a wrench connected to a nut or bolt produces a torque (turning force) that loosens or tightens the nut or bolt. The magnitude of torque depends on three quantities: the force applied, the length of the lever arm connecting the axis to the point of force application, and the angle between the force vector and the lever arm [9]. It is represented by the formula;

$$\tau = F \times r \tag{1}$$

τ is the torque (N.m); r is the length of the lever arm vector which is 668mm for the Froude Hydraulic Dynamometer used in this tests; F is the Load vector (N).

d) Brake Power Output

Brake power is described as a function of brake torque. The brake torque applied to the cradled housing was calculated by the moment arm connected to the balance weights [9]. Brake power for each tested speed was calculated using the torque value and angular speed measured. The brake power delivered by the engine and absorbed by the dynamometer is the product of torque and angular engine speed which is given in the equation below.

$$P_b = \frac{2.\pi.\omega.F.d}{1000} \tag{2}$$

Where F applied load in (N), and d is a distance from the centre of rotor in (m) P_b is brake power in kW, ω is angular speed in revolutions/s.

e) Brake Mean Effective Pressure

The mean effective pressure is a quantity to the operation of a reciprocating engine and is a valuable measure of an engine's capacity to do work that is independent of engine displacement. Mean effective pressure is another engine performance parameter which is a specific parameter for internal combustion engines (IC). It is defined as the average pressure that the gas exerts on the piston(s) through one complete operating cycle of the engine [9]. Brake Mean Effective Pressure is usually calculated from measured dynamometer torque or brake power.

$$P_{meff} = \frac{p_b.n_r.1000}{V_d.\omega} \tag{3}$$

Where n_r is the number of crank revolutions for one complete cycle, which is 2 for a four-stroke engine, V_d is the total volume of the engine cylinders in liters.

f) Brake specific fuel consumption

Another important parameter for CI engines is brake specific fuel consumption ($B_s f_c$) which is defined as a measure of volumetric fuel consumption for any particular fuel [10]. Brake specific fuel consumption is also defined as a measure of fuel efficiency within a shaft reciprocating engine. It is the rate of fuel consumption divided by the power produced. For this reason, it may also be thought of as power-specific fuel consumption. $B_s f_c$ allows the fuel efficiency of different reciprocating engines to be directly compared.

$$B_s f_c = \frac{m_{f.}}{P_b .1\times10^{-3}} \tag{4}$$

Where $B_s f_c$ is brake specific fuel consumption in g/kWh, and m_f is fuel mass flow rate in kg/h.

g) Brake thermal efficiency

The brake thermal efficiency is related to the effective power, fuel mass flow rate and lower heating value of the fuel [11].

$$\eta_{bt} = \frac{P_b.3600}{m_f.cv_l} \tag{5}$$

Where $cv_1 = 43{,}400 kJ.kg^{-1}$ (lower heating value of diesel fuel)

B. CAT 320C Excavator: JBS Plant Hire

The conditions of the engines appeared to be good as the vehicles initial CO; NO_x emissions complied with the Euro V standards before the Whale filter was installed except for HC which was higher than the minimum Euro V specifications as presented in Table IV. The filter reduced the vehicles emissions by 37.8%, and 63.5% NO_x and un-burnt hydrocarbons (HC) respectively whereas the CO emissions increased by 54.4%. There was a huge NO_x decrease because of the drop in the engine’s temperature after the introduction of the Whale concept filter.

Table III
Vehicle details

Vehicle Owner	JBS Plant Hire
Vehicle Type	Excavator
Engine Type	CAT -320C
Engine Power(kW)	103kW
Mass(kg)	21,000
Vehicle hours	65921

TABLE IV: EMISSION STANDARDS FOR DIESEL TRUCK AND BUS ENGINES, [14]

Year	**Reference**	**CO (g/kWh)**	**HC (g/kWh)**	**NO_x (g/kWh)**
2005	Euro II	4	1.1	7
2006	Euro III	2.1	0.66	5
2009	Euro IV	1.5	0.46	3.5
2010	Euro V	1.5	0.46	2

TABLE V
EMISSION TEST RESULTS FOR CAT 320C

ω (rpm)	CO(ppm)		NO_x(ppm)		HC(ppm)		Exhaust T(°C)	
	Before	After	Before	After	Before	After	Before	After
Idle	94.7	356.3	6.1	6.1	392.6	162.4	169.4	92.0
500	147.5	192.5	8.3	5.0	434.0	129.3	191.8	136.6
1000	234.2	385.3	11.1	7.4	481.0	180.3	229.5	162.5
500	368.0	369.3	13.3	5.7	511.3	192.8	279.3	170.7
Average	211.1	325.9	9.7	6.0	454.7	166.2	217.5	140.5
Average(g/kWh)	0.8	1.2	0.1	0.0	0.9	0.3		
Euro V limits(g/kWh)	1.5		2		0.46			
Compliance (*No filter*)	Pass		Pass		Fail			
Compliance (*Whale filter*)	Pass		Pass		Pass			
% Reduction	-54.4%		37.8%		63.5%			

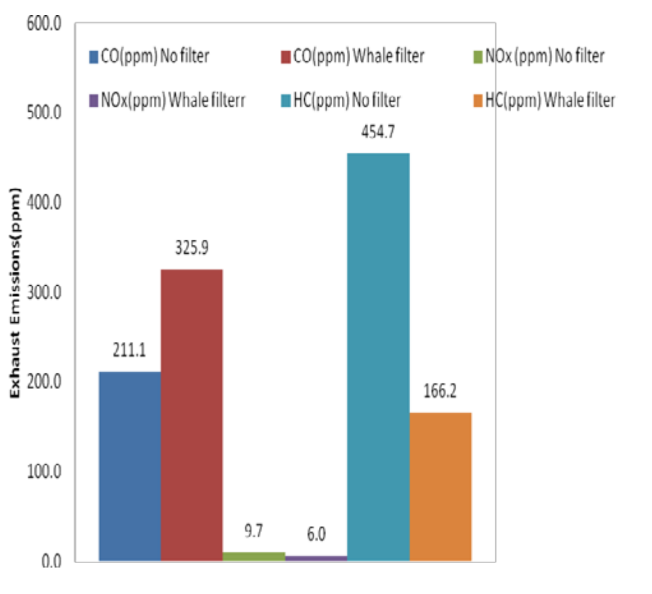

Fig. 6 Emissions profile for CAT 320C before and after Whale filter installation.

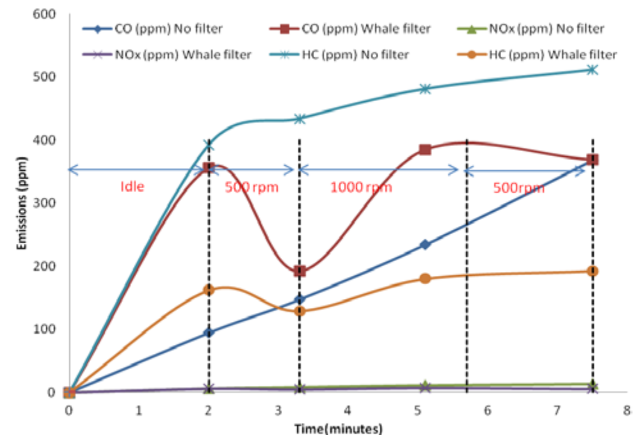

Fig. 7 Emissions profile for CAT 320C at various engine speeds

After the installation of the filter the curves indicate a fluctuating increased concentration of CO as the speed (rpm) increases, while NO_x concentration remained significantly the same from idle speed to 1000 rpm and then increased slightly when the speed was reduced to 500 rpm these occurrences may be because of low engine temperatures experienced. The concentration of un-burnt hydrocarbon reduced marginally after the installation of the filter, which is an indication of improved combustion.

C. Metrobus (City of Johannesburg)

Fig. 8 Whale Filter installed on the Metrobus

TABLE VI
METROBUS TEST RESULTS

No Filter $v(km.h^{-1})$	ω (rpm)	$P_s(kW)$	τ (kN .m)	F(kN)	Smoke%
80	2000	60	286.47	2.4	68.2
60	1900	76	381.96	4.2	
40	1900	87	437.24	7.2	
30	1900	90	452.32	11.5	
Average		78.25	389.50	6.33	
With-Filter $v(km.h^{-1})$	ω (rpm)	$P_s(kW)$	τ (kN .m)	F(kN)	Smoke%
80	2000	62	296.02	2.6	66.8
60	1900	78	392.01	4.3	
40	1900	87	437.24	7.2	
30	1900	91	457.91	11.7	
Average		79.50	395.80	6.45	
Reduction%		+1.60%	+1.62%	+1.98%	-1.4%

Although previous tests on the filter showed a significant reduction in power output which was attributed to the dense medium of the filter [12]. The tests were conducted for a period of approximately 5 minutes before and after the Whale filter was installed. The performance measuring apparatus located at Metrobus Johannesburg, South Africa were used for these tests. No emissions analyser was available during the tests, an opacity smoke meter was used to measure the smoke emitted through the exhausts gases. The results showed an increase in, torque and power 1.6%, 1.62% and 1.98% respectively, this could be result of better fuel injection. The smoke emission dropped by 1.4% and indication that the filter polished out some of the impurities in the fuel before combustion.

Previous performance tests conducted on the Whale filter using a light duty diesel vehicle reported a slight reduction in power output which was attributed to be as a result of fuel flow restriction [12]. This is not the case for heavy duty diesel engine as performance was found to be improving after Whale filter installation. The smoke emission decreased by 1.4% an indication that the filter polished out some of the impurities in the fuel before combustion. It is evident that the Whale filter increased performance and reduced smoke emissions.

Fig. 8 shows a Whale filter installed on one of the metrobus. It was noticed that the fuel flow arrangement varies per vehicle, in some cases the fuel line arrangement may be modified in insuring that the Whale filter is not subjected to positive pressure.

D. ADE 407T Truck engine (University of Johannesburg)

Fig. 9 shows the Whale filter installed on 407T 4 stroke diesel engine used to measure performance, emissions and fuel consumption. The Whale filter was connected between the conventional filters and lift pump, which subjected the filter under negative pressure. Fuel was sucked from the Whale filter by the high pressure fuel pump to the injection system. The technical specifications of the engine are presented in Table VII.

Fig. 9 ADE 407T diesel engine, Mechanical Engineering Laboratory, University of Johannesburg

TABLE VII
ENGINE TECHNICAL SPECIFICATIONS

Engine Owner:	University of Johannesburg
Engine Type:	ADE 407T Stationary truck engine
Aspiration	Turbocharged
Operation	4 stroke diesel
Dynamometer	668mm torque arm Froude Hydraulic
Max Torque & Power(kW):	1140N.m @ 1200rpm & 206kW
Wet Mass(kg)	815
Bore/stroke(mm)	125/155mm
Volume displacement(ml)	11,416

TABLE VIII
ENGINE EMISSIONS TESTS DATA OBTAINED FROM ADE 407T, 6 CYLINDER TURBOCHARGED DIESEL ENGINE.

Before Whale Filter

ω (rpm)	CO(ppm)	CO_2(vol%)	NO_x(ppm)	SO_2(ppm)	HC(ppm)	Exhaust T(°C)
500rpm	72.9	0.9	17.8	2.6	209.9	202.0
600rpm	137.9	1.1	30.9	2.6	246.5	185.0
750rpm	145.1	1.5	31.1	4.1	269.8	218.0
Average	118.6	1.2	26.6	3.1	242.0	201.7

After Whale Filter

ω (rpm)	CO(ppm)	CO_2(vol %)	NO_x(ppm)	SO_2(ppm)	HC(ppm)	Exhaust T(°C)
500rpm	47.4	1.2	1.3	1.5	163.7	88.0
600rpm	107.6	1.4	2.1	1.2	192.3	95.0
750rpm	100.1	1.8	3.1	2.1	210.4	100.0
Average	85.0	1.5	2.1	1.6	188.8	94.3

Table VIII presents the emissions results obtained on ADE 407T turbocharged diesel engine employed to conduct fuel efficiency tests. The fuel consumption tests showed that more fuel is consumed when the engine was operated without the Whale filter. The engine operated at high cylinder peak temperatures as a result of high nozzle injection pressures [3]. The pressure built up at injector nozzles is caused by the presence of large quantities of micro particles restricting fuel flow resulting in non-uniform fuel atomisation. High cylinder peak temperatures promote oxidation nitrogen in combustion air mixture to form nitrogen oxides. It was noticed that the exhausts temperature and nitrogen oxides formation reduced by 53.2% and 92.1% respectively after Whale filter installation. Oxidation of residual sulphur in the fuel is also reduced by lower peak cylinder temperatures; this was observed by 50% reduction in sulphur oxides after Whale filter fitment. Cleaner and well atomised fuel at the correct air-to-fuel ratio tends to combust efficiently resulting in more carbon dioxide, less un-burnt hydrocarbons and carbon monoxide [13]. It is evident that the fuel filtered through a Whale filter combust efficiently emitting 15.5% less carbon monoxide and 33.3% more carbon dioxide. The 13.1 % reduction in un-burnt hydrocarbon indicates that more fuel has larger surface area for combustion due to improved atomisation and is able to be completely combusted.

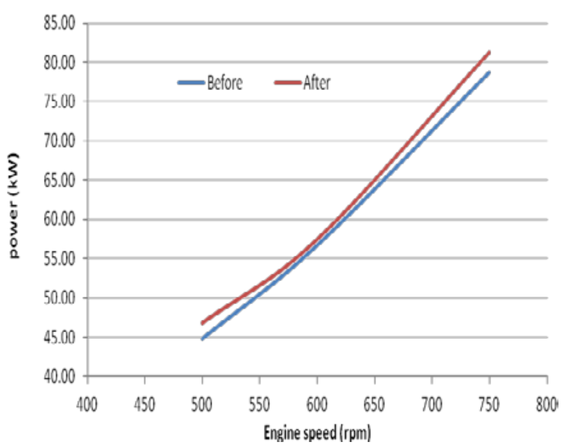

Fig. 10 Brake power output at various engine speeds

It was noticed that engine performs better, delivering more power at a given speed when it is running with Whale filter. There was an average of 3% increase in power output when the engine was operated with Whale filter.

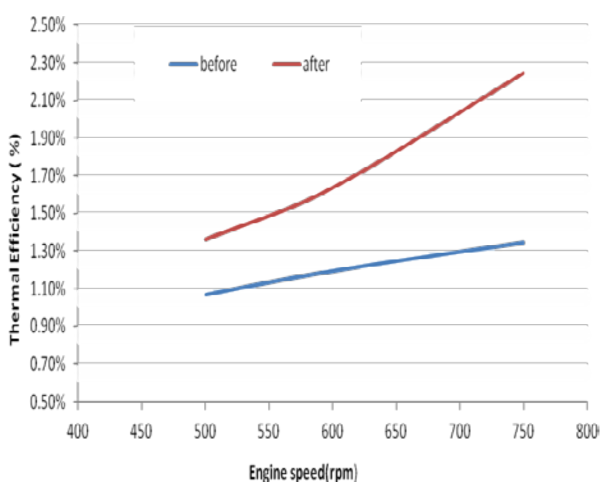

Fig. 11 Thermal Efficiency before and after Whale filter installation

Thermal efficiency is a performance measure of internal combustion engine such as a diesel engine. The test results presented in Fig.11 indicate that the engine's thermal efficiency was improved by 0.5% after whale filter installation. It is evident that the Whale filter does not only reduce the emissions, it also improves the overall engine performance. This was observed by increase in brake power output, toque and mean effective pressure as presented in Table IX.

TABLE IX
PERFORMANCE TEST RESULTS FOR ADE 407T TURBOCHARGED DIESEL

Before Whale filter

ω	V_f	m_f	F	P_b	τ	P_{meff}	$B_s f_c$	η_{bt}
rpm	ml	l/s	kN	kW	$N.m$	bar	g/kWh	%
500	245.00	0.11	1.28	44.76	855	9.41	7747.74	1.07%
600	250.00	0.13	1.35	56.64	902	9.93	6941.54	1.19%
750	400.00	0.16	1.50	78.67	1002	11.03	6178.52	1.34%
Average	298.33	0.13	1.38	60.02	919.61	10.12	6955.93	1.2%

After Whale filter

ω	V_f	m_f	F	P_b	τ	P_{meff}	$B_s f_c$	η_{bt}
rpm	ml	l/s	kN	kW	$N.m$	bar	g/kWh	%
500	45.00	0.09	1.34	46.85	895.12	9.85	6079.25	1.4%
600	115.00	0.09	1.37	57.48	915.16	10.07	5062.83	1.6%
750	55.00	0.10	1.55	81.29	1035.40	11.40	3694.16	2.2%
Average	71.67	0.09	1.42	61.88	948.56	10.44	4945.41	1.7%

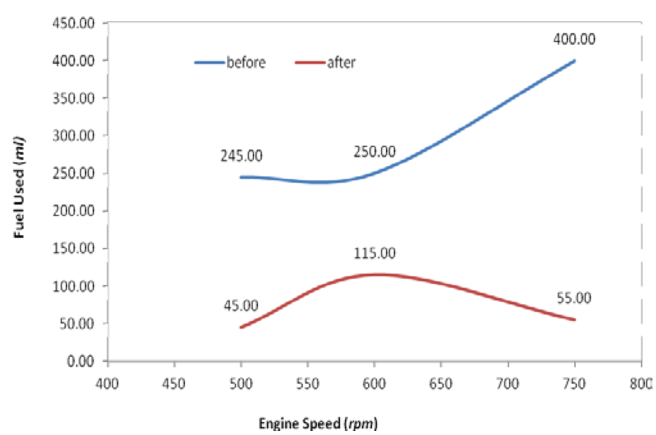

Fig. 12 Measured diesel fuel consumes at various engine speed

Fig. 12 shows the measured fuel consumed over the same time interval at various engine speeds. The fuel consumed before Whale filter installation increased by 2% when the speed was increased from 500 rpm to 600 rpm, a further 62.5% increase in fuel consumption was noticed when the speed was increased to 750 rpm. This may be as a result of high volume fuel being introduced to the injector nozzles containing large quantity of micro particles that eventually interferes with the normal fuel sprays resulting in poor fuel atomisation[3], [14]. Larger fuel droplets are introduced into the combustion chamber. These droplets are not fully oxidised due to their larger surface area, and the exhaust gas product tends to contain high un-burnt hydrocarbons, carbon monoxide and high peak temperatures promoting nitrogen oxides formation. Under these conditions, more fuel is used due to inefficient fuel oxidation [15].

On the other hand, 18% reduction in fuel consumption is noticed when the engine was run at 500 rpm under similar conditions with Whale filter installed. Further 39.1% increase was realised when the speed is increased from 500 rpm to 600 rpm. There was 47.8% a reduction in fuel consumption when the speed was increased from 600 rpm and 750 rpm, which is an inverse behaviour obtained when the engine was operated without a Whale filter. The average fuel consumption before and after the Whale filter fitment was 59.67 and 14.33ml/minute which is essentially a 24% reduction. This reduction is indisputably as a result of improved fuel atomisation and cleaner fuel oxidation in the combustion chamber. This is also justified by reduction in emissions and lower peak temperatures.

E. Toyota Hilux

TABLE X
VEHICLE EMISSIONS BEFORE AND AFTER WHALE FILTER INSTALLATION

Time(min)	ω (rpm)	CO (ppm)		NO_x (ppm)		HC (ppm)		T (°C)	
		Before	After	Before	After	Before	After	Before	After
5	1000	318	191	32	26	60	32	58.3	56.7
10	1500	274	165	42	34	57	30	65.8	63.8
15	2000	210	126	53	43	48	25	78.3	76.9
20	1000	184	111	45	37	48	25	72.7	70.8
Average	246.5	148.3	43.0	35.0	53.3	28.0	68.8	67.1	
Average (g/km)		2.4	1.4	1.2	1.0	0.3	0.2		
Euro II (g/km)		1.5	1.2						
Compliance (No Filter)		Fail		Pass				Pass	
Compliance (With Filter)		Pass		Pass		Pass			
% Reduced		39.9%		18.6%		47.4%		2.5%	

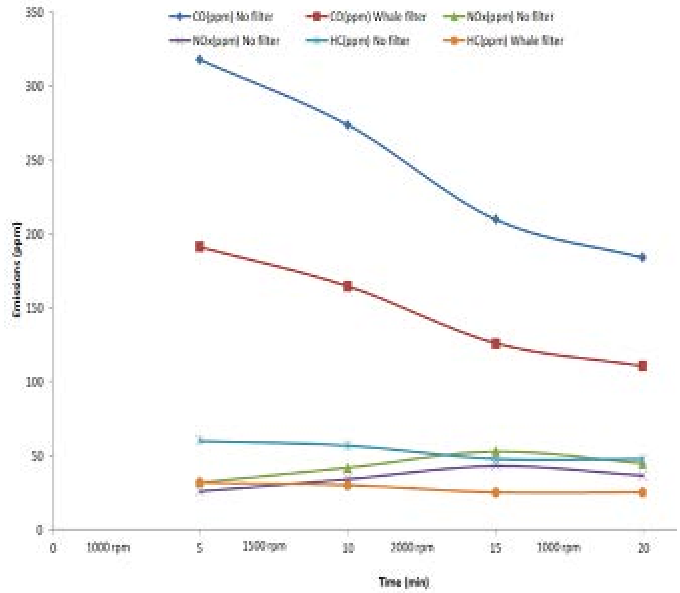

Fig. 13 Emissions for Toyota Hilux emission

Fig. 14 Whale filter installed in Toyota Hilux

The emissions results recorded in these tests follow a similar trend to the one performed previously by Pilusa *et al.*, (2012) [8]. The Whale filter was re-installed on the 22nd November 2012 with pre-emissions data reported in Table X. Longitudinal tests were conducted 1 week later after the vehicle has done 1405 km in a dusty farming environment. The effect of the filter was noticed when emissions were reduced by 38.9%, 18.6% and 47.1% for CO (ppm), NO_x (ppm) and HC (ppm) respectively. The reduction of CO and HC indicates engine combustion improvement while decrease in NO_x is affected by 2.5% reduction in engine temperature after the filter was installed. This is as a result of cleaner diesel combustion due to the presence of Whale filter. Fig. 14 show discolorations of the Whale filter, with black fine particulate being captured at the suction side of the filter. This is evident that as more ultra-fine solids are captured by the Whale filter, cleaner diesel is delivered to the injection system resulting in efficient combustion and reduced emissions.

IV. Conclusion

The Whale filter reduces the vehicle exhausts emissions from diesel engines by further filtering the fuel from the conventional in-line fuel filters. It provides cleaner fuel for the injection system resulting in improved fuel atomisation and efficient combustion at lower cylinder peak temperatures. Lower peak temperature reduces formation of nitrogen and sulphur oxides. Improved thermal efficiency and fuel atomisation reduces injector nozzle wear and promotes effective fuel oxidation producing less carbon monoxide, un-burnt hydrocarbons and more carbon dioxide. Engine operating with Whale filter has improved performance in terms of power output, toque, mean effective pressure and thermal efficiency. Based on previous validation tests conducted on the Whale filter, all the test results are showing a common trend in terms of emissions reduction. Although fuel efficiency tests were only conclusive for a controlled system, there is no doubt that the reduction in emissions and slight increased engine performance was as a result of diesel post filtration prior to injection using a Whale Filter. It is emphasized that the actual fuel consumption may vary from the measured experimental value as it mainly dependent on external factors such as weather conditions, driving behaviour, load, and engine condition and vehicle aerodynamics.

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References

[1] R.M. Shanmugam, N.M. Kankariya, J. Honvault, L. Srinivasan, H.C. Viswanatha, P. Nicolas, N. Saravanan, and D. Christian, “Performance and Emission Characterization of 1.2L MPI Engine with Multiple Fuels (E10, LPG and CNG),”, *SAE*, Paper No 2010-01-0740, 2010).

[2] N. Robinson, “Dirty Diesel,” *Wear Check Africa-Set Point Group Technical Bulletins*, 2011.

[3] A. Dorri, A. Lamani, and A. Hoxha, “Influence of Hole Geometry in the Cavitations Phenomena of Diesel Injector, a Numerical Investigation,” GOMABN vol. 47, pp. 351-371, 2009.

[4] U. Matter, and K. Siegman, “The Influence of Particle Filter and Fuel Additives on Turbo Diesel Engines,” *J. Aerosol. Sci.*, vol.28 pp. 551-552, 1997.

[5] M. P. Hirenkumar, and M.P. Tushar, “Emission Analysis of a Single Cylinder Fuelled with Pyrolysis Oil Diesel and its Blend with Ethanol,” *IJEST*, vol. 4, pp. 2834-2838, 2012.

[6] S. Cameron, R. Gary, M. Brian and B. Tracie “Investigation of Cavitations in a Large-Scale Transparent nozzle” *University of New South Wales*, Australia, 2008.

[7] G.G. McVea, A.J. Power, R.K. Solly, “The effect of vehicle filter media characteristics upon the filterability of automotive diesel fuel,” Materials Research Laboratory, *Defence Science and Technology Organisation*, 2011.

[8] T.J. Pilusa, M.M. Mollagee, and E. Muzenda, “Reduction of Vehicle Exhaust Emissions from Diesel Engines Using the Whale Concept Filter,” *Aerosol Air Qual. Res.*, vol. 12, pp. 994–1006, 2012.

[9] J.B. Heywood, *Internal combustion engine fundamentals*, New York: McGraw-Hill, 1988, pp.28-36.

[10] A.K. Agarwal, and K. Rajamanoharan, “Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine,” *Applied Energy*, vol. 86, pp.106–112, 2009.

[11] N.R. Banapurmath, P.G. Tewari, “Comparative performance studies of a 4-stroke CI engine operated on dual fuel mode with producer gas and Honge oil and its methyl ester with and without carburettor,” *Renewable Energy*, vol. 33, pp.2007-2018, 2008.

[12] M. Bond, “Technical report number SCT-EL 2007 R01 Whale concept filtering,” South African Bureau of Standards, unpublished.

[13] R. Alkama, F. Ait-Idir, and Z. Slimani, “Estimation and measurement of the automobile,” *Global Nest Journal*, vol. 8, pp. 227-281, 2006.

[14] D. Schnith, “Exhaust Emission Legislation-Diesel- and Gas engines,” VDMA, unpublished.

[15] Toyota Motor Sales, “Emissions Analysis report-USA”, unpublished.