Tyre Derived Fuel as an Alternative Fuel for CI Engines

T.J Pilusa, M. Shukla and E. Muzenda

***Abstract*—**The study presented in this article investigated the potential use of tyre derived fuel-diesel blends as an alternative low cost fuel for compression ignition engines. A short review was conducted on waste tyre pyrolysis technology and its benefits in addressing the waste tyre management while providing an alternative usable fuel for diesel engines. Crude oil obtained from slow pyrolysis of waste tyres was distilled and its respective fractions were characterized and blended with low sulphur diesel fuel for fuelling a stationery truck engine linked to a hydraulic dynamometer. The test results revealed that fuel fraction blends with low sulphur diesel can be used to fuel a conventional compression ignition engine, however special attention is required to manage the exhausts emission due to high concentration of sulphur dioxide. There is no doubt that tyre derived fuel has a potential as future alternative fuel for compression ignition engines.

***Keywords*—**Compression, Crude Oil, Ignition, Diesel, Engine Performance, Internal Combustion.

I. INTRODUCTION

DISPOSAL of waste tyres and rubber products in South Africa is a growing concern, since these products do not decompose easily and take up a significant portion of landfill space. An estimated 60 million scrap tyres have been disposed of across South Africa [1]. South Africa generates approximately 0.12% of the global new tyre production. In 2011 alone, 7.25 million new tyres, excluding mining tyres and belting, were sold in South Africa. Fig. 1 shows the distribution of new tyres nationally as reported by the Recycling and Economic Development Initiative of South African (REDISA) in 2012. Approximately 55% of these tyres were sold in Gauteng Province being the heart of the country's gross domestic product. The majority of these tyres are expected to add into the existing waste tyre matrix [2].

Gauteng is the smallest province out of nine provinces in South Africa, with only 1.5% of the land area, but it is highly urbanised and contributes up to 33.9% of the South African Gross Domestic Product (GDP) valued at $78.7 billion, and the major cities of Johannesburg and Pretoria are located in the province. In 2011 it had a population of nearly 12.3 million (25% of the population), making it the most populous province in South Africa [3].

TABLE I
DISTRIBUTION OF NEW TYRE SOLD IN SOUTH AFRICA IN 2011[2]

Province	New Tyre Quantities(tpa)
Gauteng	151,250
Western Cape	27,500
Kwa-Zulu Natal	27,500
Eastern Cape	16,500
Mpumalanga	13,750
Limpopo	13,750
Free State	13,750
North West	6,875
Northern Cape	4,125
Total	275,000

The South African government has now recently passed legislation which incorporates an initiative to give waste tyres social, economic and environmental value. Under the new plan, tyre manufacturers and importers will start paying a levy of $223.20/ton, plus 14% value added tax, for any new tyre they introduce to South African roads [4].This levy can provide an investment leverage of up to US$ 58.3 million per annum towards waste tyre recycling initiatives in South Africa.

Pilusa *et al*. (2013) [5] conducted a study to investigate the economic feasibility of operating a modular waste tyre pyrolysis plant with a total treatment capacity of 30 tons per annum. The study revealed a potential return on investment and gross margin of 29.79% and 34.59%, respectively based on capital injection of $4.27 million at a total operating cost of $213/ton.

Production of alternative fuels and products from waste tyres and rubber products by pyrolysis technology is a proven technology but yet not been applied in South Africa due to variations in economy of scale. Resistance towards adoption of this technology is mainly influenced by non-existence of market for products generated from this technology, national environmental laws and processes pertaining to permitting of such a technology.

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A. Waste Tyre Pyrolysis Technology

Tyre derived oil is obtained in its crude form through thermal decomposition "Pyrolysis" of waste rubber products such as automotive tyres and industrial rubber products as presented in fig. 1. Other products produced from this process include unrefined carbon black, high tensile steel and fuel gas.

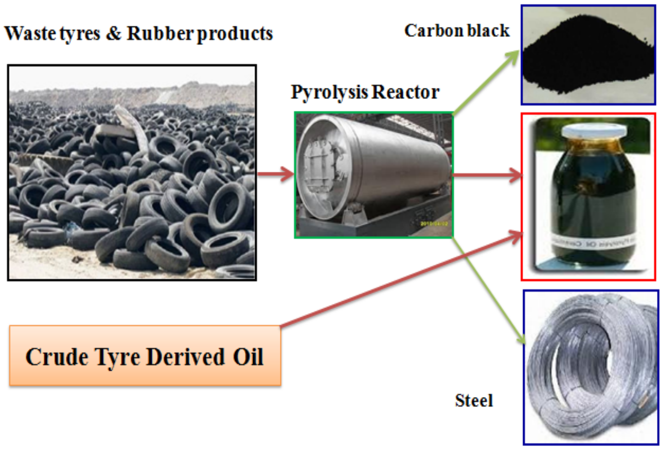

Fig. 1 Process Flow Diagram of Waste Tyre Pyrolysis

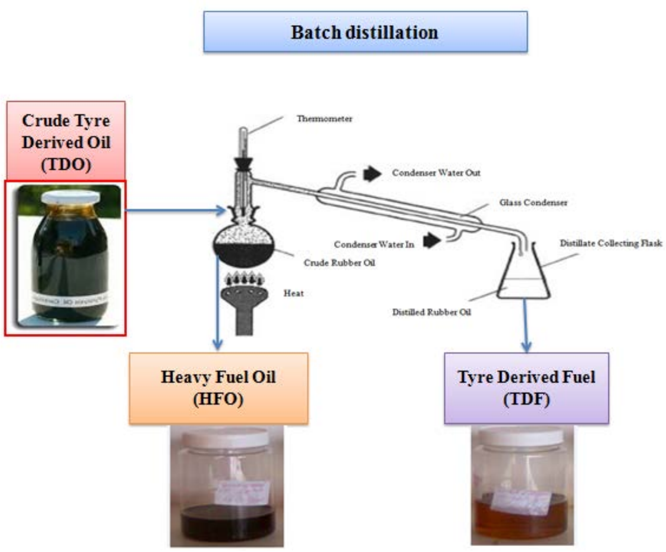

Fig. 2 Batch Distillation of crude tyre fuel oil into fuel fractions

The crude rubber derived oil contains up to 9100 ppm sulphur and when it is distilled at temperature ranges of 150-250 ^{o}C the sulphur content of the distillates is in the order of 3500 ppm whereas the bottoms is at 5600 ppm. The distilled fuel is a cleaner light fraction exhibiting physical and chemical properties of diesel and petrol and the bottoms fraction is called industrial heavy fuel oil (HFO) fuels as shown in fig 2. The diesel equivalent fraction also referred to as tyre derived fuel (TDF) contains up to 7 times the sulphur content of diesel and tends to oxidize to form asphaltenes. Preliminary tests have shown that this fuel becomes more stable when blended with up to 30% diesel by volume[6]. Previous studies have confirmed that HFO can be used in conventional diesel engines without any problems when diluted with diesel fuel up to 70 volume percent concentration and TDF can be used with up to 90 volume percent concentration [6].

During pyrolysis process, for every 1000kg of waste rubber feed, 465 litres (375kg) and 220 litres (188kg) of distilled tyre derived fuel (TDF) and HFO can be obtained respectively at an average recommended selling price of $0.516/liter and $ 0.28/liter [1]. These fuels cannot be used in conventional diesel engines in their pure form, but can be blended with diesel fuel at volume concentrations of up to 90% and 70% fuel in diesel. Further inline filtration system is also required to remove the micro-particle contaminates and alpalternes.

B. Tyre Derived Fuel (TDF)

Tyre derived fuel is regarded as a material with excellent and consistent fuel properties with a high calorific value, thus it can be used directly as fuel or blended with other fuels. Giagou *et al*. (2012)[7] studied the engine design and reported that viscosity is an important characteristic as it affects the performance of the engine's fuel injection equipment, thus correct fuel atomisation depends on fuel viscosity, injection pressure and injector hole size. Therefore fuel must be injected such that the atomised fuel is dispersed evenly throughout the combustion chamber [7]. High viscosity fuel atomise into larger droplets with higher momentum and are more likely to collide with the cooler wall, thus extinguishing the flame and increasing the soot deposits and emission [8].

According to Cunliffe, and Williams, 1998 [8] distilled tyre derived fuel low viscosity and flash point. Suggestions have been brought forward that diesel with low flash point can be contaminated with a more volatile and explosive fuel such as petrol. Argawal and Rajamanoharan *et al*. (2008) [9] reported that low flash point has no effect on engine performance; however viscosity of the distilled tyre derived fuel affects the combustion of the fuel thus reducing fuel economy and power output.

The automotive industry is the main cause of air pollution, with 350 million tons of CO_2 generated every year especially during peak traffic hours in the inner cities. Sulphur oxides produced from internal combustion as a result of utilisation of high sulphur fuel have negative impact to the environment. The composition of sulphur oxides in the flue gas produced from combustion of heavy tyre derived fuel was reported to be in the order of 8g/kWh or 0.23vol. % as presented in table II [11]. The use of heavy fuel tyre derived fuel without emissions capture and chemical treatment for sulphur oxides neutralisation will negatively impact the environment. It is recommended that this fuel is only used in stationery compression ignition engines such as diesel generator sets and boiler plants whereby the emissions can be captured and chemically treated to produce valuable products.

This research focuses on South Africa as a case study in order to review pyrolysis technology's viability, particularly in the direction of alternative fuel production for diesel engines.

TABLE II
FLUE GAS EMISSIONS FROM THE COMBUSTION OF TYRE DERIVED FUEL [11, 12]

Component	Conc. (vol. %)	Emissions (g/kWh)
Suplher Dioxide (SO_2)	0.23%	8.0
Carbon Dioxide (CO_2)	12.5%	296
Nitrogen Oxides (NO_x)	0.003%	0.08
Hydrocarbons(HC)	0.02%	0.18
Carbon Monoxide (CO)	0.01%	0.15
Moisture (H_2O)	10.1%	98
Nitrogen (N_2)	73.6%	1110
Oxygen (O_2)	3.5%	60

II. MATERIAL AND METHOD

A. Experimental System

Two samples of fuel blends were prepared by making up a fuel blend with 10% low sulphur diesel and 90% TDF and the second sample consisted of 30% low sulphur diesel and 70% HFO by volume. The fuel samples were filtered to remove fine particle contaminants before characterization. The properties of the fuel blends were sent to an external fuel laboratory for analysis. The engine was run with pure diesel fuel for 90 minutes in order to flush the fuel line and internal combustion system. This was followed by performance and emissions tests using low sulphur diesel as a benchmark. TDF-diesel fuel (DF) blend was used to run the engine and test data was collected every minute and averaged for 5 minutes. Engine speeds were varies every 5 minutes for 15 minutes. The system was flushed for 90 minutes and the same procedure was repeated using HFO-DF blend.

B. Performance Tests

The power, efficiency, fuel consumption and emissions tests were evaluated for all the three fuels tested at various engine speeds. An ADE 470T six cylinder turbocharged truck engine belonging to the Mechanical Engineering Department at the University of Johannesburg was commissioned for this purpose, the engine specifications are presented in table III.

TABLE III
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

Fig. 3 ADE 407T Diesel Engine, Mechanical Engineering Laboratory, University of Johannesburg

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) as shown in fig 3. Exhausts emissions were measured using Testo 350 emissions analyzer with technical specifications presented in table IV.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

TABLE IV
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

III. RESULTS AND DISCUSSION

A. Theoretical Considerations

a) Torque

Torque 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 distance

$$\tau = F \times r \quad (1)$$

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

b) Brake Power Output

Brake power is described as a function of brake torque. 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.

$$P_b = \frac{2.\pi.\omega.F.d}{1000} \quad (2)$$

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.

c) Brake specific fuel consumption

Another important parameter for CI engines is brake specific fuel consumption ($B_s f_c$) that is defined as a measure of volumetric fuel consumption for any particular fuel

$$B_s f_c = \frac{m_{f.}}{P_b .1\times10^{-3}} \quad (3)$$

Where $B_s f_c$ is brake specific fuel consumption in g/kWh, and m_f is fuel mass flow rate in kg/h [13].

B. Fuel Characterisation

The test results of fuel characterisations indicate that both fuel blends compare very well with commercial diesel fuel. However the sulphur concentrations of both blends are significantly higher that the allowable limit of 500 ppm as specifies by the South African National Standards (SANS 342) fuel specifications. Properties such as density, total contamination, and water content and lower calorific values are within the fuel specification range. The viscosity of TDF-DF blend is lower than the minimum recommended limit of 2.3cSt likewise, HFO-DF blend has higher that recommended viscosity level of 5.3cSt. The flash point of the diesel fuel is specified at 55°C or higher for safe storage and consumption a value below limit is noticed on TDF-DF blend. Variations in physical properties from commercial diesel fuel may result in performance and emissions inconsistencies when used in conventional diesel engines.

TABLE V
PHYSICAL PROPERTIES OF DF, TDF-DF (90:10) & HFO-DF (70:30)

Property	TDF-DF	HFO-DF	DF
Density @ 20°C (kg/m^3)	816.51	897.50	826
Viscosity @ 40°C (cSt)	1.91	6.61	2.3
Flash Point (°C)	47.17	82.00	56.21
Total Contamination (mg/kg)	4.03	18.00	3.31
Total Sulphur (ppm)	2,154	4,933	42
Water Content (%)	0.05	0.03	0.02
Gross Calorific Value (MJ/kg)	43.9	44.21	46.1

C. Performance and Emissions

Fig. 4 shows sulphur dioxide emissions for various flue blends used at different engine speeds. It was observed that high emissions level exists at lower engine speed for all the fuels used. Emissions produced by TDF-DF are reasonably closer to the ones generated by DF as presented in fig.4 and table VI. High emissions level produced when the engine is run using HFO-DF blend is related to the quality of the fuel itself, 4,933 ppm total sulphur is reported in table V. It is believed that a larger portion of the sulphur in TDF and HFO exits in the form of mercaptans which can be removed by adsorption over active membrane layer.

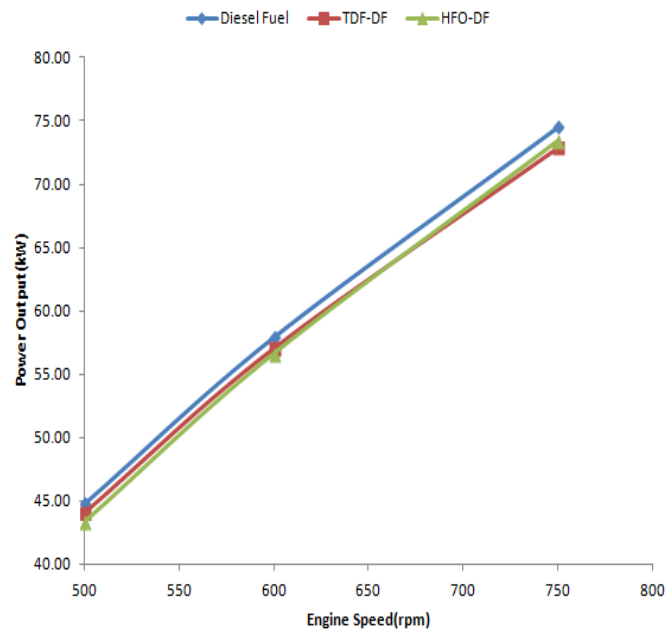

Fig. 5 Brake power output at various engine speeds

It was noticed that engine performs normal when fuelled with alternative TDF-DF. There was an average of 1.6% decline in power output when the engine was operated with alternative TDF & HFO-DF blends. The slight decline in performance is as result of the difference in fuel properties particularly, calorific value, flashpoint and viscosity.

TABLE VI
AVERAGE PERFORMANCE TEST RESULTS FOR ADE 407T TURBOCHARGED DIESEL ENGINE

Parameter	DF	TDF-DF	HFO-DF
Fuel Consumption (L/min)	0.0623	0.0709	0.0672
Mass flow(kg/s)	0.0008	0.0011	0.0009
Power Output(kW)	59.0	58.0	57.8
Torque(N.m)	908.4	892.8	888.4
Bsfc(g/kWh)	51.7	66.09	57.5066
SO2(g/kWh)	2.36	3.08	5.11
CO(g/kWh)	0.061	0.085	0.13
HC(g/kWh)	0.092	0.16	0.23
LCV(kJ/kg)	40,900	41,200	43,100
D(kg/l)	0.816	0.8970	0.8260
Load(kN)	1.36	1.34	1.33
SO2(ppm)	358	463	865
CO(ppm)	23	32	49
HC(ppm)	105	143	150

The brake specific fuel consumption is noticed to be higher on TDF-DF blend obviously because it has the lowest viscosity and calorific value compared to all the fuel samples tested. The lower density of TDF-DF also suggests ease of consumption. Fig.6 shown trend of break specific fuel consumption for the various fuels tested at various engine speeds.

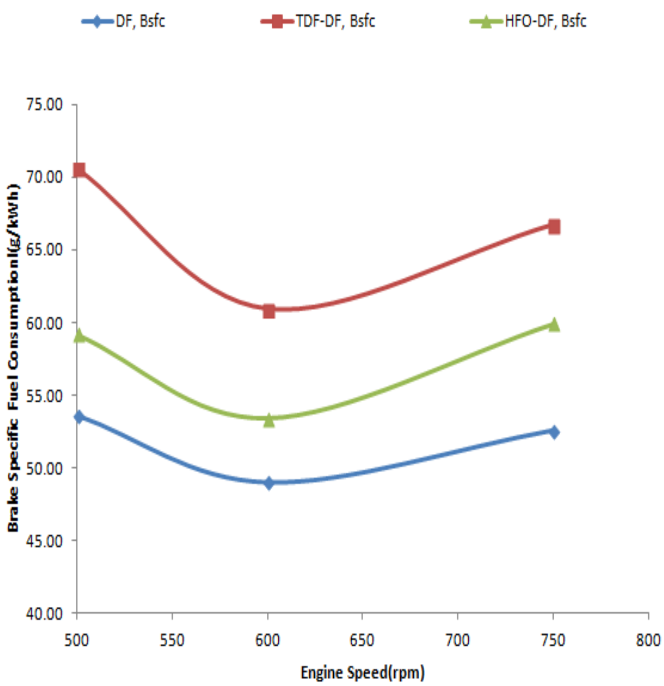

Fig. 6 Calculated Brake Specific Fuel Consumption at Various Engine Speed

IV. Conclusions

Both TDF and HFO can be used in conventional diesel engines without major engine modifications. Engine performance is expected to drop by slightly 1.6% when a blend of diesel, TDF and HFO is used. The overall specific fuel consumption is higher on TDF-DF blend compared to HFO-DF and DF due to the lower fuel viscosity, flash point and calorific value. The sulphur dioxide emissions are higher at low engine speeds for all the fuels, excessive sulphur dioxide emission is observed when the engine is run with HFO-DF blend. It is recommended that HFO-DF be used only in stationery compression ignition engines such as generator sets whereby the emissions can be treated with an aqueous solution of sodium hydroxide or calcium hydroxide for neutralization. Although fuel efficiency tests were only conclusive for a controlled system, there is no doubt that TDF-DF blend can be used as an alternative fuel for compression ignition engines provided the emissions are captured and neutralized in to value add products to prevent further pollution.

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