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Field Trials of Biodiesel (B100) and Diesel Fuelled Common Rail Direct Injection Euro-III Compliant Sports Utility Vehicles in Indian Conditions

Avinash Kumar Agarwal*, Dhananjay K. Srivastava, Gayatri Dwivedi, Gaurav Kawatra, M. R. Prem Kumar
Engine Research Laboratory, Department of Mechanical Engineering
Indian Institute of Technology Kanpur, Kanpur – 208016, India
Omprakash Bhardwaj, Mathew Abraham, Arun Jaura
Mahindra & Mahindra Ltd, Nashik, India
*Corresponding Author's email: akag@iitk.ac.in

ABSTRACT

Biodiesel is being explored as a sustainable renewable fuel for vehicles in India due to mounting foreign exchange expenditure to import crude petroleum. Significant amount of research and development work is being undertaken in India to investigate various aspects of biodiesel utilisation in different types of engines.

This study is an effort to jointly investigate the use of biodiesel (B100) in an unmodified BS-III compliant sports utility vehicle (SUV) by a consortium of academia (IIT Kanpur) and Industry (M&M) to realistically assess whether biodiesel is compatible with modern engine technology vehicles. Two identical vehicles were operated in tandem using biodiesel (B100) and mineral diesel (B00) respectively for 30,000 kilometers in field conditions. The lubricating oil samples were collected and detailed analysis for assessing the comparative effect of new fuel (B100) vis-à-vis mineral diesel was carried out. After completion of the field trails, the vehicles and the engines were dismantled for assessment of carbon deposits and wear of various vital components/ parts.

This paper reports some of the comparative emission results under vehicle running conditions, lubricating oil tribology results and carbon deposits on various vital engine components.

INTRODUCTION

Diesel fuels have an important role in the industrial economy of any country. The high energy demand in the industrialized world and widespread use of fossil fuels is leading to fast depletion of fossil fuel resources as well as environmental degradation. The world petroleum reserves are so unevenly distributed that many regions have to depend on others for their fuel requirements. The degrading air quality due to emissions is the main adverse effect of petroleum based fuels. All these factors necessitate continued search and sustainable development of renewable energy sources that are environmentally friendly.

Biomass sources, particularly vegetable oils, have attracted much attention as an alternative energy source. They are renewable, non-toxic and can be produced locally from agriculture and plant resources. Their utilization is not associated with adverse effects on the environment because they emit less harmful emissions and green house gases.

Vegetable oils can be used directly or blended with diesel to operate compression ignition engines. Use of blends of vegetable oils with diesel has been conducted successfully by various researchers in several countries [1–5]. However, long-term endurance tests reported some engine durability issues related to vegetable oil utilization such as severe engine deposits, piston ring sticking, injector coking, gum formation and lubricating oil thickening [6–8]. These problems are primarily attributed to high viscosity and poor volatility of straight vegetable oils due to large molecular weight and bulky molecular structure. High viscosity of vegetable oils (30–200 cSt @ 40^0C) as compared to mineral diesel (4 cSt @ 40^0C) lead to unsuitable pumping and fuel spray characteristics. Larger size fuel droplets are injected from injector nozzle instead of a spray of fine droplets, leading to inadequate air-fuel mixing. Poor atomization, lower volatility, and inefficient mixing of fuel with air contribute to incomplete combustion. This results in an increase in higher particulate emissions, combustion chamber deposits, gum formations and unburned fuel in the lubricating oil.

Since straight vegetable oils are not suitable as fuels for diesel engines, they have to be modified to bring their combustion related properties closer to diesel. This fuel modification is mainly aimed at reducing the viscosity to eliminate flow/atomization related problems. Four techniques can be used to reduce the viscosity of vegetable oils; namely heating/pyrolysis, dilution/blending, micro-emulsion, and transesterification [9–12].

Transesterification is the reaction of a fat or oil with an alcohol to form esters and glycerol. Alcohol combines with the triglycerides to form glycerol and esters. A catalyst is usually used to improve the reaction rate and yield. Since the reaction is reversible, excess alcohol is required to shift the equilibrium to the product side. Among the alcohols that can be used in the transesterification process are methanol, ethanol, propanol, butanol and amyl alcohol [13]. Alkali-catalyzed transesterification is much faster than acid-catalyzed transesterification and is most often used commercially [14–19].

The process of transesterification brings about drastic change in viscosity of vegetable oil. The biodiesel thus produced by this process is totally miscible with mineral diesel in any proportion. Biodiesel viscosity comes very close to that of mineral diesel hence no problems in the existing fuel handling system. Flash point of the biodiesel gets lowered after esterification and the cetane number gets improved. Even lower concentrations of biodiesel act as cetane number improver for biodiesel blend. Calorific value of biodiesel is also found to be very close to mineral diesel [20].

The best way to use vegetable oil as fuel is to convert it in to biodiesel via the process of transesterification. Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as new/used vegetable oils and animal fats. The resulting biodiesel is quite similar to conventional diesel in its main characteristics. Biodiesel contains no petroleum products, but it is compatible with conventional diesel and can be blended in any proportion with mineral diesel to create a stable biodiesel blend. The level of blending with petroleum diesel is referred as Bxx, where xx indicates the amount of biodiesel in the blend (i.e. B10 blend is 10% biodiesel and 90% diesel. It can be used in CI engine with no major modification in the engine hardware. The properties of some of the biodiesel fuels are compared in Table 1. The characteristics of biodiesel are close to mineral diesel, and, therefore, biodiesel becomes a strong candidate to replace the mineral diesel if the need arises. The conversion of triglycerides into methyl or ethyl esters through the transesterification process reduces the molecular weight to one-thirds that of the triglycerides, the viscosity by a factor of about eight and increases the volatility marginally. Biodiesel has viscosity close to mineral diesel. These vegetable oil esters contain 10–11% oxygen by weight, which may encourage combustion than hydrocarbon-based diesel in an engine. The cetane number of biodiesel is around 50. Biodiesel has lower volumetric heating values (about 10%) than mineral diesel but has a high cetane number and flash point. The esters have cloud point and pour points that are 15–25 C higher than those of mineral diesel [6].

Table 1: Properties of biodiesel prepared from vegetable oils [21]

properties	Biodiesel (vegetable oil methyl ester)					
	Peanut	Soyabean	Palm	Sunflower	Linseed	Tallow
Kinematic viscosity @ 37.80C	4.9	4.5	5.7	4.6	3.59	-
Cetane number	54	45	62	49	52	-
Lower heating valve (MJ/l)	33.6	33.5	33.5	33.5	35.3	-
Cloud point	5	1	13	1	-	12
Pour point	-	-7	-	-	-15	9
Flash point	176	178	164	183	172	96
Density (g/ml)	0.883	0.885	0.88	0.86	0.874	-
Carbon residue (wt%)	-	1.74	-	-	1.83	-

Prior to adopting any alternative fuel for regular use in the conventional engines, it is essential that the tribological investigations related to lubricating oil be conducted. Various lubricating oil tribology studies can be conducted to assess the effect of different fuels on engine's health. A number of factors affect lubricating oil performance e.g. oil thickening, depletion of wear protection additives and deposit control additives are of primary concern in high temperature, high load conditions. Oil thinning, depletion of corrosion protection additives, and low temperature sludge formation are of concern primarily in short engine runs.

The lubricating oil samples were drawn from the two vehicles after a predetermined interval and analyzed. Atomic absorption Spectroscopy was carried out on all the lubricant samples drawn for evaluating the concentration of various wear metals such as Fe, Cr, Pb and Zn.

After the field tests were completed, the engine was dismantled as per the standard engine protocols and deposits on various parts were investigated in detail.

TEST VEHICLES

Figure 1: Two vehicles running in the field trials

The entire field trails were planned in a scientific manner and we tried to simulate the lab conditions, as much as possible, in the field. Almost during the entire run, both the vehicles were tail-gating each other, i.e. they were running under identical load and speed condition, under similar atmospheric conditions, and terrain. The drivers were swapped after 15,000 kms. So that if there is any variation because of the driving habits, that can also be nullified. Technical specification of vehicle is given in table 2.

Table 2: Engine specification

Type	SZ CRDe, 4 stroke, Turbo-charged, Intercooler, DI, Common Rail Diesel Engine
Cubic Capacity	2609 cc
Max Gross Power	115 bhp (85 Kw) @ 3800 rpm
Max Gross Torque	28.3 kgm@1700-2200 rpm
Emission Compliance	EURO III / BS III
Gear box	5 speed, Manual
Tyres	P 235/70 R16, Tubeless
Max GVW	2510 Kg.

Engine exhaust emissions were measured from biodiesel and diesel fuelled vehicles for the comparative analysis, when the vehicles were running at different speeds on the highway. The probes of the exhaust gases were put into the exhaust muffler and then the vehicle's engine was operated at different vehicle speeds. Emissions were measured only after the vehicle stabilized at that speed (approximately after 5 minutes).

AVL Digas Emission Analyzer (AVL digas-444) and AVL Smoke Opacimeter (AVL 423) were used. The instrument required a lower supply for these tests. One 3 KVA UPS was put on-board the vehicles, which could support the instrument for 4-5 hours continuously.

RESULTS & DISCUSSIONS

Biodiesel Characterisation

The biodiesel was used as a fuel and fuel properties evaluation was done to ensure that major fuel properties meet the BIS standards.

Table 3: Biodiesel fuel properties

Characteristics	Method	B-100 Sample
Density at 15^0C, kg/m^3	ISO 3675, ISO 12185	884.9
Kinematic Viscosity at 40^0C, cSt	D-3104	4.65
Flash Point (PMCC) ^{0}C, min	IS 1448, P-21	169
Carbon residue (Ramsbottom)*, % by mass, max	IS-4530 / ISO 10370	0.017
Sulphated ash, % by mass, max	ISO 6245	0.006
Water content, mg/kg, max	D 2709 ISO 3733 ISO 6296	<0.005
Total Contamination, mg/max.	EN 12662	6.5
Cu corrosion, 3 hrs at 50^0C, max	ISO 2160	Yellow Deposits on strip No rating
Acid value, mg KOH/g, max	D-1448, P: 1/Sec 1	0.23
Free Glycerol, % by mass, max	D-6584	22 ppm
Total Glycerol, % by mass, max	D-6584	22 ppm

Emissions at Different Vehicle Speeds

Engine exhaust emissions were measured from biodiesel and diesel fuelled vehicles for the comparative analysis, when the vehicles were running at different speeds on the highway. Emissions of CO, CO_2, O_2, NOx and HC are measured in normal running condition of both the vehicles with increasing speed starting from 10 kmph to 100 kmph with the interval of 10 kmph and then again at a decreasing speed from 100 kmph to 10 kmph. The average emission values with statistical deviations are reported.

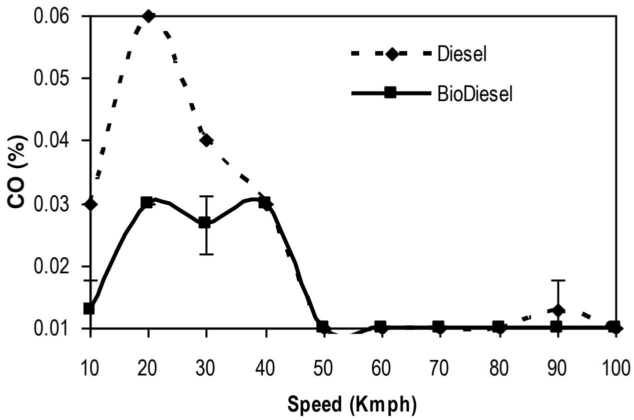


Figure 2: CO emissions from biodiesel and diesel fuelled vehicle at different vehicle speeds

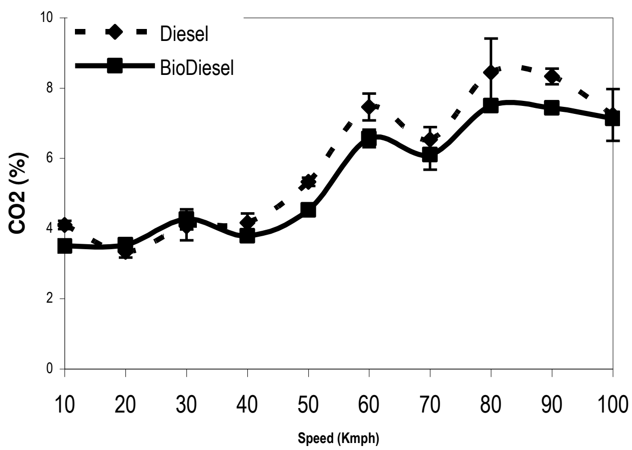


Figure 3: CO_2 emissions from biodiesel and diesel fuelled vehicle at different vehicle speeds

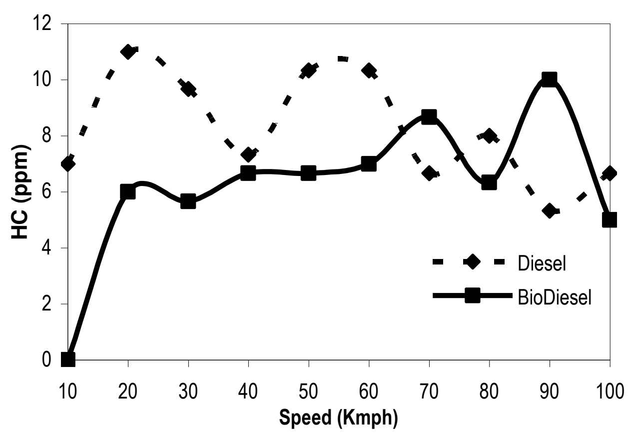


Figure 4: HC emissions from biodiesel and diesel fuelled vehicle at different vehicle speeds

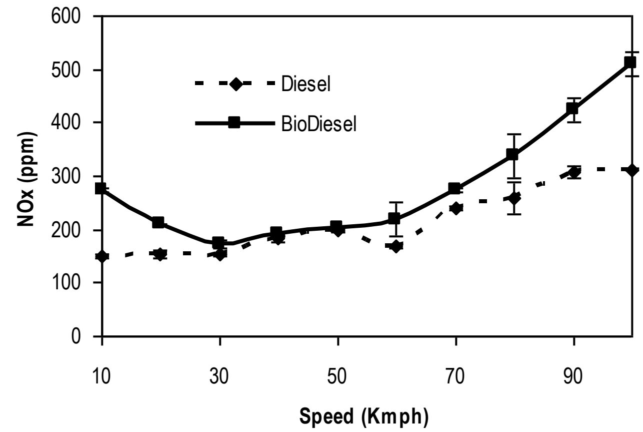


Figure 5: NOx emissions from biodiesel and diesel fuelled vehicle at different vehicle speeds

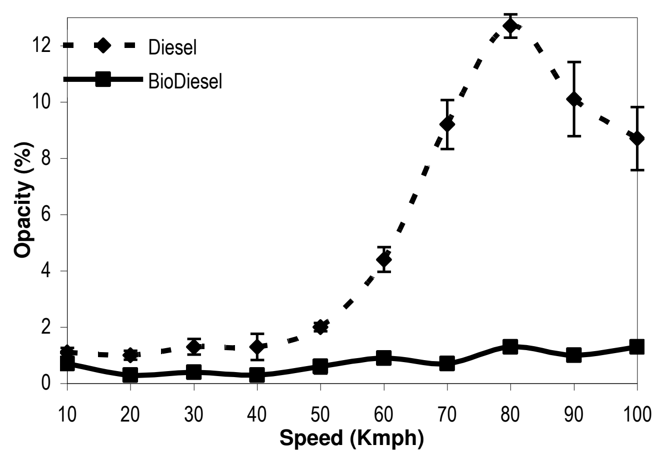


Figure 6: Opacity emissions from biodiesel and diesel fuelled vehicle at different vehicle speeds

Carbon monoxide emission from engines is controlled primarily by the air-fuel equivalence ratio. For fuel-rich mixtures, CO concentration in the exhaust increase steadily with increasing equivalence ratio, as the amount of fuel increases. For fuel lean mixtures, CO concentration in the exhaust vary little with equivalence ratio. However, diesel engines always operate well on the leaner side of stoichiometric; therefore CO emissions from diesel engine are low enough. CO is formed during intermediate combustion stages. As we can see from figure 2, emission of CO from biodiesel fuelled vehicle is lower than the CO emissions from diesel fuelled vehicle at different speeds. This may be possibly because of oxygenated nature of biodiesel fuel which converts the CO into CO_2. However the values of CO emissions are really insignificant. The emission of carbon dioxide is however within an acceptable limit and very closes for both the engines (Figure 2).

Hydrocarbon emissions are consequence of incomplete combustion of the fuel. There are two primary paths, by which, fuel can escape from normal combustion process, which contribute the hydrocarbon emissions. First, the fuel-air mixture can become too lean to auto-ignite or to support a propagating flame at the conditions prevailing inside the combustion chamber. Secondly, during the primary combustion process, the fuel-air mixture may be too rich to ignite or support a flame. Composition of fuel affects the nature and magnitude of hydrocarbon emissions. Significant reduction in HC emissions from biodiesel fuelled vehicle was observed compared to diesel fuelled vehicle (Figure 4). This may be because of absence of aromatic and olefins species from biodiesel. Further the combustion efficiency of biofuels is better than mineral based diesel because of oxygenated nature.

Nitric oxide (NO) and nitrogen dioxide (NO_2) are grouped together as NOx emissions. Nitric oxide is the predominant oxide of nitrogen produced inside the combustion chamber. NO is form by oxidation of atmospheric nitrogen. NO formation inside the combustion chamber is temperature dependent phenomena. NOx emissions from biodiesel fuelled vehicle were higher than the diesel fuelled vehicle (Figure 5). This may be because of higher peak temperature inside the combustion chamber when using biodiesel as a fuel. Literature also reports higher NOx emission from biodiesel fuelled engine compared to mineral diesel fuelled engine.

Opacity from biodiesel fuelled vehicle was significantly lower then the diesel fuelled vehicle (Figure 6) and this doesn't increase with increase in engine speed. One noticeable advantage of using biodiesel is the smoke emission is visibly cleaner and you hardly see any black smoke coming out. This may be due to the presence of oxygen in the biodiesel. This oxygen is readily available at the time of combustion and release itself from the fuel in rich core region of the flame during the formation of soot. Excess oxygen can also increase the post flame oxidation of the soot formed.

Lubricating Oil Tribology

The concentration of various metals present in the lubricating oil samples, drawn from Scorpio vehicles running with diesel and bio diesel (B100) fuels respectively, during field trial of the vehicles, are evaluated to study the wear of different parts and material compatibility of the two fuels with engine parts . Various metals such as Fe, Zn, Pb are analyzed and results are shown below.

Iron in wear debris originates from wear of cylinder liner, piston, ring, valves, gears, shafts, bearing, rust and crank shaft. It is clear from the figure 7 that concentration of Fe in lubricating oil drawn from vehicle running with biodiesel is lower compared to that of running with mineral diesel therefore suggesting that the wear of engine components of vehicle running with biodiesel is significantly lower than that of running with diesel.

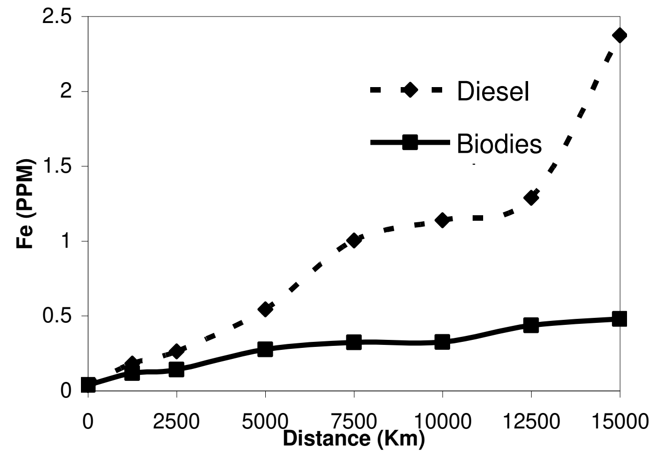


Figure 7: Iron Concentration in Lubricating oil samples as a function of distance traveled

Zn in wear debris originates from wear of bearings, plating, brass components, additives, and neoprene seals. Concentration of Zn in lube oil samples drawn from both the vehicles alternatively decreases and then increases (Figure 8). Further the rate of decrease and increase of concentration of Zn for biodiesel fuelled vehicle is lower than that of diesel fuelled vehicle therefore it can be inferred that bearings, plating, brass components, additives are more compatible with biodiesel compared with mineral diesel and thus lower wear is experienced.

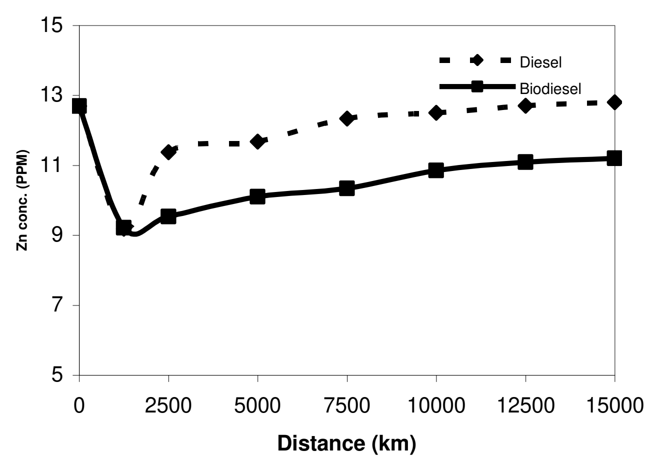
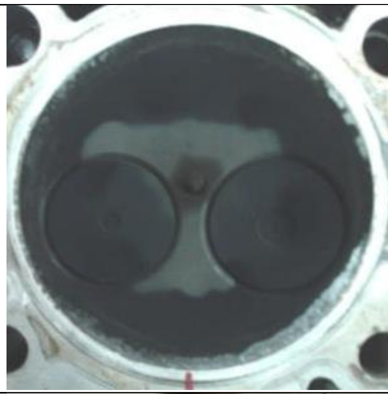
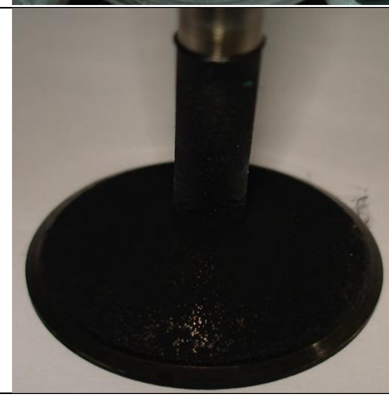


Figure 8: Zinc Concentration in Lubricating oil samples as a function of distance traveled

Overall, from these figures (8&9), it can be seen that the wear metals in lubricating oil samples drawn from biodiesel engine is significantly lower therefore indicating that the wear of the engine component with this new fuel is reasonably lower than that encountered with mineral diesel.

Table 4: Visual Recording of Deposits on Engine Parts

	Diesel	Biodiesel
Cylinder Head		
Inlet Valve		

After the field tests were completed, the engine was dismantled as per the standard engine protocols and deposits on various parts were investigated in detail.

Looking at the cylinder head deposits, one can clearly make out that the amount of carbon deposits on cylinder heads from diesel fuelled engine is much higher than biodiesel fuelled engine. However one can also see distinctly white deposits on the cylinder head as well as piston top of biodiesel fuelled engine. This can be possibly from the traces of catalyst left in biodiesel (NaOH or KOH). Fuel test report was suggested that Na, K, Ca and Mg were presented in biodiesel less than 10 ppm. These may be responsible for the whitish deposits. One can hardly notice any significant difference in carbon deposits in intake and exhaust manifold. Looking at the piston thrust side and anti-thrust side deposits, it can be glaringly noticed that deposits in biodiesel fuelled engine is much lower compared to mineral diesel. The rings groove deposits were also relatively lower in biodiesel fuelled engine.

CONCLUSION

The Scorpio with indigenously developed CRDE technology is the first Asian vehicle in its class to run on 100% bio-diesel. Two vehicles were running using biodiesel (B100) and mineral diesel (B0) respectively covered a distance of about 30,000 kilometers under field conditions. The emission test was also measured while running the vehicle on the highway at different speeds. All emissions from biodiesel fuelled vehicle were lower then the diesel fuelled vehicle except NOx emission. The lubricating oil samples were collected and analysis for assessing the comparative effect of new fuel (B100) was carried out vis-à-vis mineral diesel. Wear metals in lubricating oil samples drawn from biodiesel engine is significantly lower therefore indicating that the wear of the engine component with this new fuel is reasonably lower than that encountered with mineral diesel. Carbon deposit on the vital engine parts pictures after a field trial of 30,000 kms give a reasonable degree of confidence that the deposits on various engine parts will be lower than mineral diesel and in any case, they will not be on higher side suggesting that the use of new fuel will not reduce the time period for overhauling.

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