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# Feasibility and Emissions of Compression Ignition Engines Fueled with Waste Vegetable Oil

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Feasibility and Emissions of Compression Ignition Engines Fueled with Waste Vegetable Oil

By

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A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science  
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# Feasibility and Emissions of Compression Ignition Engines Fueled with Waste Vegetable Oil

Morgan Crawford

## ABSTRACT

Research and experience has shown that vegetable oil can be processed, by transesterification, into a useable fuel for compression ignition engines. Earlier research examined using straight vegetable oil as a fuel, but found it to cause detrimental engine problems. Trial and error has shown that heating the vegetable oil prior to injection, is a viable option. A diesel vehicle engine was operated for over 188 hours or approximately 7,000 miles, using waste cooking oil as fuel. The longevity of the vehicle engine was limited by an undetermined engine failure.

Using stationary testing, with no engine load and various power settings, engine emissions of several engines operating on waste cooking oil were compared to emissions from two other fuels, diesel and Biodiesel, and found to be very positive. Waste vegetable oil (WVO) had lower overall emissions than diesel and lower levels of nitrogen species than Biodiesel.

Agricultural yield predictions estimate that currently only 5%, and at most 20% of all diesel fuel needs can be met with vegetable oil. Currently WVO is a disposal problem. It is primarily used as a feedstock. WVO is not a commodity and has disposal fees associated with it. If WVO is used as a fuel, it would not only provide another source for disposal, but it may also increase the value of WVO making it a commodity instead of a disposal burden.

# Feasibility and Emissions of Compression Ignition Engines Fueled with Waste Vegetable Oil

Morgan Crawford

## CHAPTER ONE INTRODUCION

### **Introduction**

The use of petroleum has led to air pollution, environmental degradation, declining health, economic and political problems. Agricultural based biomass fuels offer promise to offset these problems. Biodiesel, a vegetable oil derivative, has been researched extensively and found to be a suitable alternative to diesel petroleum. Unprocessed vegetable oil, including waste vegetable oil, was also researched but resulted in detrimental engine problems (Knothe, 1999; Peterson, 1996; Peterson 2003). However, there has been no conclusive research done on heated, unprocessed vegetable oil. There are several manufacturers and suppliers of heated fuel systems and related products that have had success with long term use of heated vegetable oil as a fuel (Greasecar, Neoteric, Greasel). Very little data exists relating to this as a result of the earlier research which overlooked heating the fuel.

Heating vegetable oil requires a more complex fuel system, which requires little modification on some engines and is slightly more difficult on others. It increases the cost of the engine and with current, crude systems is often trouble prone. However, it offers great promise in the form of reduced emissions, reduced dependence of fossil fuels, increased demand for agricultural products and a clean way to eliminate an escalating waste problem.

The purpose of this research is to analyze the regulated emissions of three fuels, two with known emissions characteristics and one, waste vegetable oil (WVO), with undetermined emissions characteristics. Emissions profiles have been established by the EPA for No. 2 Diesel and Biodiesel, but not for WVO. The emissions from these two fuels will be used as a base line for comparison in order to establish validity and repeatability. Regulated emissions will be determined using a four gas analyzer, with an opacity meter and a dynamometer. Regulated emissions include nitrous oxides (NO<sub>x</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), particulate matter (smoke) and unburned hydrocarbons (H-C). Emissions will be tested using the 14 mode EPA FTP Heavy Duty Cycle tests. These tests include idle and load testing to simulate real world conditions. If possible, more than one vehicle will be used and the results will be averaged to represent as accurate an aggregate emissions profile as possible.



All of the test vehicles are equipped with catalytic converters, which reduce NO<sub>x</sub>. By passing exhaust gasses over a heated platinum/rhodium coated aluminum surface several chemical reactions are promoted. CO and volatile organic compounds (VOCs) are oxidized into CO<sub>2</sub> and H<sub>2</sub>O. NO<sub>x</sub> is also decomposed and oxidized into NO and elemental nitrogen and oxygen, which is easier to absorb in the environment (Kureti, 2003).

### Production of Vegetable Oil

Soybean oil is the primary type of vegetable oil used in the United States. The 2 billion gallons of soybean oil produced annually accounts for about two-thirds of all domestic vegetable oil production (Duffield, 1998). Soybeans can be grown throughout most of the U.S. but most production is centered in the Midwest, where six states account for 80% of production. In descending order of magnitude of production, these states include: Illinois, Iowa, Indiana, Minnesota, Ohio and Missouri (Ibid.). Average production of soybean per acre (in 1995) is 35.3 bushels, which equates to 50.9 gallons of soybean oil per acre. Not all harvested soybean is crushed and made into oil. 33.4% is exported and 5.4% is sold as seed, feed, and residual. Of the 61.2% of the soybeans that are crushed, other commodities are extracted besides soybean oil, primarily meal (Ibid.). Sale of this meal helps to keep soybean oil prices low. Soybean meal has a market value of about 30 cents per pound and vegetable oil is about \$2 per gallon or \$0.26 per pound. The main use of soybean oil is for cooking applications. It is used to keep foods from sticking to cooking surfaces and also for deep frying foods. Usually it is partially hydrogenated before being sold for deep frying purposes. Hydrogenation makes the oil more stable and thereby extends its shelf-life.

### Physical and Chemical Properties

The physical and chemical properties of waste vegetable oil are not well known. However, there is a substantial database on the properties of soybean oil, the starting product of waste vegetable oil. These properties are important for the combustion and storage of vegetable oil as a fuel. A list of the properties and their values are given in **Table 1**.

**Table 1. Physical Specifications of Fuels Tested**

FUEL TYPE	CALORIFIC VALUE	DENSITY	VISCOSITY		CETANE #	FLAME POINT	CLOUD POINT	POUR POINT
			(kJ/Kg)	(g/dm <sup>3</sup> )				
Diesel Fuel	43,350	815	4.3	1.5	47	58	-15	-28
Biodiesel	39,760	872	11	4.3	37	69	-8	
Soybean Oil	39,623	914	65	9	37.9	230	-3.9	-12.2

Source: Altun, Selim and Huseyin, 1999.

The iodine value of a substance is a measure of the degree of chemical unsaturation in a chemicals olefinic bonds. Iodine values are used to determine the oxidative stability of a fuel in order to determine storage-stability. Higher iodine values indicate more unsaturated bonds, which equates to less storage stability. The iodine value of soybean oil ranges from 117-143 depending on the breed of soybean being utilized. Diesel fuel does not have an iodine value because it has no olefinic bonds. However, it has a computed iodine value of 10. Duffield, suggests that iodine values greater than 115 are unacceptable (Duffield, 1998). However, application has shown this to be incorrect. While storage life may be limited due

to the high iodine value of vegetable based fuels, it does not preclude their use. This is evidenced with Biodiesel, which has an iodine value of 50-133 and has been shown to be acceptable for use as a fuel (Baines, 1982). The higher iodine values of the vegetable oil based fuels indicate that care should be exercised when storing for long periods of time (Altun, 1999). Visual inspection of the fuel to check for bacteria growth, which would result in fuel delivery problems, should be completed if vegetable oil is to be used after being stored for more than a couple of months.

The calorific value of a fuel is a measure of the amount of energy (Calories) that the fuel contains per unit mass. The calorific value of soybean oil is 39,623 kJ/Kg, and 39,760 kJ/Kg for Biodiesel (Altun, 1999). This is very close to the calorific value of petroleum diesel, 43,350 kJ/Kg, indicating that diesel fuel contains slightly more energy per unit than the other fuels. This equates to 8.5% less energy per Kg of soybean oil than for diesel fuel.

The density of the fuel is a measure of its weight per volume. The density of the fuel is important because many diesel engine fuel injection pumps use the weight of the fuel for measurement and dispensing. A denser fuel would therefore be dispensed in a lower volume. Soybean oil has the highest density at 914 g/dm<sup>3</sup>, diesel has lower density of 815 g/dm<sup>3</sup> and the density of Biodiesel is in between at 872 g/dm<sup>3</sup> (Altun, 1999). This indicates that soybean oil would be dispensed at 10.8% less than diesel fuel.

Viscosity is a measure of the thickness of a fluid. It is an important measure of a fuel because the atomization characteristics of the fuel are affected by viscosity. Viscosity of fluids varies with temperature. At lower temperatures, fluids are more viscous and flow less readily. Under the application that is being used for this research, the vegetable oil is heated to a temperature of 70-80°C. At this temperature the viscosity of soybean oil is very close to that of diesel fuel at ambient temperature (which is about 27°C) 9.0 mm<sup>2</sup>/s vs. 4.3 mm<sup>2</sup>/s, respectively (Knothe, 1999). Since the viscosity of the two fuels is similar, they should flow at a similar rate, and atomization should not be affected (Nwafor, 2000).

The cetane number is a measure of a fuels ignition delay. This is the amount of time it takes for the fuel air mixture to ignite, once it is injected into the combustion chamber. Higher cetane numbers have a shorter ignition delay. The cetane number of soybean oil is 37.9. Biodiesel is very close at 37 but petroleum diesel is somewhat higher at 47. Due to the differences in cetane number, it is often suggested that injection pump timing be retarded by one degree from the standard diesel fuel setting to attain more complete combustion of vegetable oil based fuels (Von Wedel, 1999).

The cloud point of soybean oil is -3.9°C and of diesel fuel is -15°C. The pour point is -12.2°C for soybean oil and -28°C for diesel. The flame point for soybean oil is 230°C and for diesel is 58°C (Altun, 1999). Cloud point is the temperature at which a fluid develops ice crystals and begins to clog small openings, such as fuel filters. Pour point is the lowest temperature at which a fluid will flow. Flame point is the temperature of ignition. Petroleum diesel has slightly lower pour and cloud points, which means it flows better in cold temperatures. The flame point of soybean oil is much higher than that of diesel, which

makes it much safer, since it takes much hotter temperatures to ignite. The higher flame point may have some effect on the ignition delay of the fuel, but does not prevent combustion in the engine as it is in aerosol form and under high temperature and pressure. The higher pour point and cloud point of soybean oil, compared to diesel fuel, is problematic in cold climates. However, since a heating system is needed to use soybean oil as a fuel, soybean oil can be used at temperatures below its cloud point.

After soybean oil is produced it is processed for use. The main use of soybean oil is for deep fat frying. For frying, soybean oil usually has citric acid added as a preservative and silicone added as an anti-foaming agent. It is 22% fat by weight, 10% of which is saturated fat (Qaulifry, 2002). Other important factors to consider are the variations in soybean oils due to production with different strains of soybean. The amounts and types of fatty acids, which impact combustion and ultimately emissions, vary from strain to strain of soybean (Altun, 1999). Also, the impact of frying food in the oil may change its chemical composition. Since the type of food being cooked in the oil varies at each locale, the chemical composition changes from locale to locale. There is very little information on how used oil is altered and this needs to be further examined, especially if fuel certification standards are to be obtained.

### **Consumption of Vegetable Oil**

Soybean oil for deep fat frying is typically sold in 5 gallon plastic containers, which are poured into fryers. All types of foods are cooked in the deep fat fryers, including meats, vegetables, doughnuts and other breads. Most restaurant fryers use about 10 gallons of vegetable oil, but it is not uncommon to find fryers that use thousands of gallons in commercial applications for mass distribution. The “fryer grease”, as it is now called, is typically changed every 2-3 days as use dictates (Morre, 2003). However, there are some chemical additives available that can extend the useful life of the vegetable oil to over a week. Much of the oil is absorbed into the food; however, the majority remains in the fryer. Once the oil reaches the end of its useful life, it is drained into buckets and dumped into disposal containers.

### **Disposal of Vegetable Oil**

The typical disposal container is a plastic, dumpster style container with a volume of about 100 gallons (Ibid). Containers have a metal grid mesh to exclude large contaminants and a flip lid to minimize moisture contamination. They are emptied in a variety of methods, primarily by pumping or by physically flipping the container into a collection truck. Restaurants pay several hundred dollars per year to have the waste cooking oil picked up and disposed.

The waste vegetable oil is commonly called “yellow grease” because of its color and viscosity. It is primarily used as an additive for animal feed. It provides a cheap source of fat for domesticated livestock. Other uses include emulsifiers for cosmetics, pharmaceuticals and vegetable oil based diesel fuel called Biodiesel (Duffield, 1998). Biodiesel use as fuel will be examined later.

Yellow grease is not a monitored waste product. It is simply classified as a non-edible food product. The Department of Environmental Protection has ultimate oversight over the disposal of yellow grease, but there is no specific disposal protocol. Yellow grease is not considered a hazardous substance, it is not considered recyclable, nor is it a solid at room temperature, so it is not regulated under solid waste disposal guidelines. Yellow grease is considered a liquid and cannot be disposed of in a land fill, under the Free Liquid Act. Yellow grease can be combined with an absorbent material, such as kitty litter, and disposed of in a landfill in this manner. This however, increases the disposal cost of yellow grease and is not commonly practiced. It has been noted on several occasions that some of the corporate restaurants pour the yellow grease over trash in the hopes that the trash will absorb most of the fluid. This is technically illegal, unless all of the liquid is absorbed, but monitoring and enforcement is difficult at best. Disposal of yellow grease by dumping is a violation of the Storm Water Discharge Act. Discharging yellow grease through the sewer system is a violation since discharging oil and grease is prohibited under the Sewage Treatment Act, § XI.U. However, it has been the source of reoccurring problems with sewer systems in many areas. New York City's China Town is probably the best example and is cited by an article in the Wall Street Journal as the heart of the cities "5,000 fat-based backups a year"(Cgnur, 2003). Dumping of waste cooking oil in New York City is attributed with more than 40,000 illegal sewer spills annually. Given that the average price for collection of yellow grease is \$110 per month (Moore, 2003), and the nature and difficulty of properly disposing of the waste product, it is a wonder that improper disposal has not reached epidemic proportions.

Disposal of waste vegetable oil has been the center of some controversy, especially in the U.K. The main source of disposal of WVO is as a feedstock additive. This is thought to be a pathway for Bovine Spongiform Encephalopathy (BSE) and public health proponents are opposed to further such use. Using waste vegetable oil to produce Biodiesel eliminates the risk of transmitting BSE, but it has other associated risks. Biodiesel production utilizes methanol or ethanol, both flammable and toxic liquids and sodium or potassium hydroxide, both of which are caustic. Using unmodified oils eliminates problems such as residual Biodiesel alkalinity and by-product disposal (Calais, 2003).

### **Use as Fuel**

Yellow grease can be used as fuel in a compression ignition engine in several different ways. It is sold as an ASTM certified fuel under the name Biodiesel (ASTM standard D6751). In order to be certified as such it must undergo a chemical transesterification process in which a methyl or ethyl ester is removed by adding methanol or ethanol. The alcohol is then separated out along with a glycerol co-product, which is a market commodity. This transesterification process is commonly used to produce 60 million gallons of Biodiesel per year (as of 1998) and production is increasing annually (Baines, 1982). Yellow grease can be used directly in diesel engines without modifications. However, for long term use, it must be heated prior to injection to provide proper atomization. Both transesterified and non-esterified (yellow grease) waste vegetable oil can be blended with diesel fuel, kerosene, or each other for use in any diesel engine.

### **Benefits of Biodiesel**

Biodiesel, which is defined as any vegetable oil used as diesel fuel, has many benefits over petroleum based diesel fuel (Duleep, 1998). It is renewable, has a positive energy balance, is much lower in emissions, can be used with existing distribution systems, can be domestically produced and has better lubrication properties than petroleum diesel. Since soybeans (and other vegetable oil crops) are planted seasonally, there is a constant supply of virgin vegetable oil. Additionally, the emissions from burning one crop of Biodiesel are absorbed by the production of future crops. Therefore, Biodiesel is essentially a zero emission fuel, since all emissions are reabsorbed in future crops nutrient uptake. In fact, more nitrogen is removed from the air and fixed in the soil through the growth of soybeans and other vegetable oil crops, than is produced from the emissions of the combustion of soybean oil in a compression ignition engine (Duran, 2003).

Production of Biodiesel has a very favorable, positive energy balance. Even using virgin vegetable oil to produce Biodiesel yields a 4.2 to 1 return in available BTU's (Duffield, 1998). Greater energy return is seen when used cooking oil, instead of virgin material, is used to produce Biodiesel. Of all commonly used fuels; petroleum, natural gases, alcohols; Biodiesel has the highest energy balance. It takes more energy to produce other plant fuels (alcohols) than they yield, thus they have a negative energy balance. Fossil fuels contain more energy than they take to produce, but the amount of energy returned from them is only slightly higher than the amount of energy used to find, extract, process and transport the fuels. Therefore, fossil fuels have only a slightly positive energy balance.

Emissions from Biodiesel are much lower than from petroleum diesel (**Table 2**). For transesterfied Biodiesel total unburned hydrocarbons are decreased by 67%, carbon monoxide is decreased by 47%, particulate matter is decreased by 48%, however oxides of nitrogen increase by 10% compared to petroleum diesel (Durbin, 2000). Non-esterfied vegetable oil (including WVO) is thought to have similar reductions in emissions except there is no increase in oxides of nitrogen because of the abundance of saturated fatty acids. The fat causes longer ignition delay and lower combustion temperature, which results in less formation of nitrogen compounds. Also, toxic emissions are significantly decreased for both types of vegetable based fuels, as compared to petroleum diesel (EPA, 2002). The emissions data does not include the polyaromatic hydrocarbon content (PAC) of the total unburned hydrocarbons, which is an important aspect of engine emissions. It is theorized that vegetable oil does not contain PAC's yet the combustion of fats in non-esterfied vegetable oil does produce PAC's. The exact amount of PAC's is not well documented, but is suspected to be much lower than that of petroleum diesel emissions. The PAC is important because it is mutagenic and is suspected to be cancer causing.

**Table 2. Emissions Reductions for Biodiesel Compared to Petroleum Diesel**

Total Unburned Hydrocarbons (HC)	-67%
Carbon Monoxide (CO)	-47%
Particulate Matter (PM)	-48%
Oxides of Nitrogen (NO <sub>x</sub> )	+10%

Source: EPA, 2002

Lubrication of diesel engines is accomplished in large part by the fuel. Fuel injector pumps, fuel pumps, piston rings and valves are all lubricated by the fuel. Vegetable based fuels are better lubricants than petroleum diesel and increase engine life due to lessened engine wear. Additionally, engine deposits are decreased due to lack of sulfur and more complete combustion (Duffield, 1998).

Biodiesel has some drawbacks that diesel fuel does not have. The alcohol used to remove the glycerin from the vegetable oil is not completely removed and reacts with fuel deposits and fuel system components. Deposits from diesel fuel are often dissolved by Biodiesel and collect in fuel filters. This causes the fuel filter to become clogged which necessitates replacement. Most users of Biodiesel report only needing to change the fuel filter one time, after the initial switch to Biodiesel. Of course the amount of deposits and the purity of the Biodiesel will impact filter use. Fuel lines and gaskets often fail when used with Biodiesel. This is also due to the alcohol content and the solvent nature of Biodiesel. Fuel lines made of vitron or nitrile are resistant to Biodiesel and replacement with such lines and gaskets should eliminate any problems with dissolution. Newer engines usually are equipped with these synthetic parts and usually do not need upgrading.

### **Health Impacts**

Vegetable oil is an ingestion hazard in large quantities since it is high in saturated fat. However, it is non-toxic, non-mutagenic and poses no other threats to human health. The residence time of vegetable oil is 28 day (Von Wedel, 1999). LC 50 (concentration required to kill 50% of the population) tests on marine organisms indicated an order of magnitude less susceptibility to Biodiesel as compared to petroleum diesel. LC 50 effects only occurred at very high levels of vegetable oil concentration, indicating that oxygen deprivation and not toxicity was the causative issue (Ibid.).

The EPA released a paper attributing diesel emissions to lung cancer (EPA, 2002). Particulate matter and aromatic content are thought to be carcinogenic. They are products of hydrocarbon combustion, present in all diesel exhaust. However, diesel engines constitute the majority of engines used in shipping, construction and public transportation sectors as well as 20% of the European private vehicle sector and an even greater percentage of many developing countries private vehicle sectors. This is a significant proportion of engines in use today. With this many engines burning a fuel that is carcinogenic, a major health issue is raised. Reducing the amount of particulate matter and aromatics emitted from combustion processes is important for improving public health. An alternative fuel source, such as yellow grease, could be a solution.

Exhaust of internal combustion engines include many byproducts. Of the ones examined by the EPA each one was measured and is regulated for its impact on humans. Unburned hydrocarbons are unburned fuel and are a major component of smog. Carbon monoxide is a highly poisonous product of partial combustion. Particulate matter is a result of combustion. It is a component of smog and is toxic and carcinogenic. Nitrogen oxides are a result of lean fuel combustion conditions and contribute to the formation of photochemical smog (Cooper, 1994).

**Table 2** shows emissions reductions of transesterified vegetable oil compared to petroleum diesel. As the table indicates emissions are significantly reduced, except for oxides of nitrogen. However, it has been indicated that non-esterified vegetable oil actually decreases NOx emissions. Also, as previously discussed PAC content is suspected of being much lower from vegetable based fuels. Overall, impacts from combustion of vegetable oil are much less than from diesel fuel.

### **Policy Issues**

The Senate finance committee has recently approved an excise tax exemption for Biodiesel. The exemption is a one-cent reduction in the diesel fuel excise tax for each percentage of Biodiesel blended with petroleum diesel up to 20 percent (§ 355). Yellow grease does not qualify for this exemption due to its lack of fuel status. It is not certified as a fuel by the Association of Standards and Testing Materials (ASTM) and therefore cannot be sold as a fuel. If yellow grease were certified as a fuel it would most likely automatically receive the same excise tax exemption as Biodiesel.

In order for yellow grease to be sold as a fuel it must be certified as a fuel by the Association of Standards and Testing Methods (ASTM). This involves designing a fuel specification that all yellow grease must meet. Also, types of oils as well as strains of various plants and the blend ratios that constitute yellow grease must be determined in order to have a fuel specification standard. Vegetable oils are genetically engineered to reduce saturated fats for human consumption. For combustion, saturated fats reduce nitrous oxide emissions. Therefore it is beneficial to have more saturated fats for combustion purposes and fewer for cooking purposes. This may pose a problem for setting a yellow grease fuel standard, since vegetable oil may be engineered for human consumption instead of combustion. Also, a specification may be necessary for fuel systems that use yellow grease, since it must be heated.

Untaxed, Biodiesel is slightly more expensive than petroleum diesel, but its status as an alternative fuel makes it eligible for reduced tax sale. Biodiesel can be produced for 80 cents per gallon, about half the cost of taxed petroleum diesel. Federal and state taxes make the fuel more expensive than petroleum diesel, even when blended at the 20% level. Yellow grease is not a certified fuel and cannot be sold as fuel in the United States. The full impact of using yellow grease without paying fuel taxes is poorly understood. But if the waste product is rendered and no actual purchase takes place, it is thought that no tax should be levied. At any rate, yellow grease has a cost benefit over Biodiesel and petroleum diesel.

The impact of selling a fuel without levying a road tax, would reduce the amount of transportation trust fund revenue, which is how state road maintenance is funded. Ideally, alternative fuels could be economically beneficial without a tax incentive so that their sale does not impact transportation funding. Also, it should be noted that vegetable based fuels may have a lessened impact on roads, since the production, processing and distribution of vegetable based fuels can be accommodated in a more localized fashion than fossil fuels.

Since vegetable oil can be produced locally, Biodiesel is seen as increasing overall domestic productivity. Also, use of Biodiesel decreases U.S. dependence on foreign oil, which is especially important in light of escalating conflict with foreign oil producing countries.

The EPA has set new emissions standards starting in 2007. These emissions standards mandate a significant reduction in sulfur dioxide, particulate matter and unburned hydrocarbons. Diesel fuel processed to meet these standards has caused problems with fuel delivery, engine components. Fuel injector pumps, fuel pumps and other components that rely on fuel for lubrication have shown increased wear and premature failure. Even with reformulated fuel, emissions standards will not be met without using additional emissions equipment. This equipment will increase the purchase price, operating cost and decrease the reliability and efficiency of diesel engines. Installation and use of existing emissions reduction equipment has been forestalled until lower sulfur levels in the fuel are met. Sulfur emissions foul trap oxidizing equipment more rapidly than is acceptable and also render catalytic devices ineffective in a short time span. Use of yellow grease may solve these problems as well as exceed emissions standards. Official emissions tests are necessary to validate this claim.

### **Emission Reduction Methods and Devices**

There are several emission reduction devices and methods for diesel engines that are benefited by the use of vegetable oil. The selective catalytic reduction unit, lean NOx catalyst and diesel particulate filters are all capable of reducing diesel emissions. These devices are only effective if they are clean so that they do not block the exhaust and so they offer the most surface area to absorb and react with the emissions. Sulfur and particulate matter in diesel emissions plagues these systems by coating them with deposits. Since yellow grease has no sulfur and a significantly reduced amount of particulate emissions, problems are not evident.

Diesel engines are tuned to run optimally on diesel fuel. When a different fuel is used, some changes may be necessary to achieve the same performance. Since yellow grease has a longer ignition delay (lower cetane number) than petroleum diesel, it is necessary to change the engine timing. This is a simple procedure that involves removing the timing belt from the fuel injection pump and turning the pump one degree and then replacing the belt. By retarding the timing, the pressure and therefore temperature, are increased in the combustion chamber before the fuel is injected. This prevents early detonation of the fuel, which is damaging to the engine and inefficient.



To optimize performance and longevity, yellow grease must be heated prior to injection. By heating the fuel it atomizes more completely upon injection. This enhances fuel air mixture and facilitates more complete combustion. The optimum temperature at injection is 70°C (Nwafor, 2003). Nwafor noticed no beneficial changes in the vegetable oil above 70°C. The maximum efficiency of compression ignition engines is usually attained with the fuel at ambient or slightly below ambient temperature. Therefore, it is important not to heat the fuel higher than necessary in order to obtain optimum atomization and efficiency. Fuel can be heated in several ways before being delivered to the injection system. One method is by using a heated fuel system where the heat is provided by the engines coolant system. A similar method utilizes electric heaters in the fuel system. The fuel can also be circulated around the engine before injection to ensure optimum temperature is achieved. These methods all have distinct advantages and disadvantages. The important factor to note about these various heating methods is if they can preheat the yellow grease prior to starting the engine. This is especially important in cold climates. Some systems require that the engine be started on petroleum diesel in order to heat the yellow grease to optimum temperature. This is not always desirable because it necessitates having two separate fuel systems.

Yellow grease was researched thoroughly in the late 70's and early 80's by many agricultural universities as an alternative fuel. The research concluded that yellow grease was not a suitable fuel for long term use because it creates engine deposits, nozzle coking and ring sticking (Peterson, 1996). These research efforts did not examine the effects of heating the yellow grease prior to injection. Several private companies have since developed heated fuel systems and have shown the long term viability of this method of fuel delivery. However, no documentation of this processes effectiveness exists.

Engine design, emissions control devices, exhaust technology and tuning also contribute to the longevity and emissions formation from yellow grease. The next chapter will discuss these variables and their effects on emissions formation. Engines are designed and tuned for optimum operation on a designated fuel or fuels. By manipulating engine tuning and design, emissions can be minimized and longevity can be maximized.

## CHAPTER TWO ENGINE TECHNOLOGY

Fuel is not the only factor that affects emissions formation. Different types of engines produce different quantities and types of emissions. Exhaust and engine components, emissions reductions devices, and engine tuning also affect how emissions are formed. By utilizing various components and engine tuning, it is possible to reduce the amount of emissions produced from a specific type of fuel. This chapter discusses the benefits of various types of engines, emissions control technology, the types of emissions produced, the process of emission formation, and how the emissions react in the atmosphere. All of these factors must be taken into account when designing an engine to operate optimally on a specific fuel.

### **Engine Technology**

Compression ignition (CI) engines, commonly known as diesel engines, are an important component of the transportation and energy sectors of the world. Millions of units are used on a daily basis and the emissions of CI engines is an important aspect of pollution control. CI engines are designed to operate on a less refined petroleum distillate than gasoline which contains less energy content. Yet CI engines are more efficient at translating fuel energy content into output than their gasoline (Spark Ignition) counterparts. CI engines also have fewer overall emissions than gasoline engines and are preferred for emissions reductions (Korbitz, 1999). Unfortunately, lagging technological improvements in CI engines and fuel have hindered emissions reductions, performance and acceptance of these engines. In order to reduce vehicular pollution a change in engine type and design for the majority of the transportation sector is needed. By switching to new, efficient diesel engines, substantial reductions in ambient pollution may be achieved. Compared to gasoline engines, diesel engines produce 30% as much hydrocarbon, 5% as much carbon monoxide and about 50% as much particulate emissions (Ibid). Utilizing diesel engines in a hybrid electric configuration can more than double these reductions in emissions. Exhaust equipment and fuel modification or substitution can further these reductions to an even greater extent. All of these technologies and improvements are currently available and proven. Increased initial costs can easily be offset by substantially decreased operating costs, improved environmental and health benefits and mass production. By optimizing fuel type, engine design, exhaust equipment and power-train systems vehicular pollution can be effectively regulated and minimized.

The major emissions components of compression ignition engines are particulate matter (PM) and nitrogen oxides (NO). Other emissions include carbon monoxide (CO), sulfur oxides (SO), hydrocarbons (H-C) and noise. Unburned hydrocarbons are responsible for many of the severe health problems and are linked to cancer, mutations and toxicity. One

group of hydrocarbons, Aldehydes, are responsible for the odor constituent from diesel engines. Minimization of PM and NO is the primary focus of emissions reduction work, yet reducing all emissions is important. PM is responsible for smog and respiratory problems. NO contribute to acid rain and reduce aesthetic air quality. CI engines operate at a much leaner air fuel ratio than gasoline engines which facilitates lower CO and volatile organic compounds. However, due to higher operating temperature and pressure in diesels, NO and PM emissions are higher (Hohmann, 2003).

There has been probably more health research on diesel emissions (DE) than on any other single source, possibly excepting cigarette smoke. Emissions from diesels are a mixture of gases, vapors, semi-volatile organic compounds and particles. The particles are all respirable and fall into two general chemical classes: 1) “soot” or elemental carbon particles coated with condensed organic and inorganic compounds, and 2) ultra fine particles of condensed organic material and sulfur compounds having little or no elemental carbon content (Mauderly, 2001).

### **Engine Design and Tuning**

Engine design and tuning are the primary variables in emission control. There are two types of CI engines that operate in a similar manner, but have different exhaust emissions profiles. Direct injection (DI) is the newer, more powerful CI engine design used for high speed engines. The traditional, more widely manufactured and utilized engine design is in-direct injection (IDI). The primary physical difference in these engines is the IDI engine has a pre-combustion chamber and typically is designed to use glow-plugs to facilitate cold starting.

The main benefit of the in-direct injection design is that it facilitates better fuel air mixture. Air and fuel are injected into the pre-combustion chamber of an IDI engine. The downward movement of the piston during the inlet stroke and the upward movement of the piston during the compression stroke force the air and fuel to mix in a swirl pattern that is created by the changing volume of the combustion chamber. The velocity of the swirl has been measured at over 21 times the velocity of the engine speed (Hohmann, 2003). The resulting thorough mixing of the fuel and air in the pre-combustion chamber results in more complete combustion. The result is that there is less smoke (particulate matter), carbon monoxide (CO), oxides of nitrogen (NO), hydrocarbons (H-C) and fewer Aldehydes produced than in an equivalent direct injection engine.

IDI and DI engines also employ different fuel injection systems. IDI engines use a split rail system to deliver fuel from the fuel injection pump to the fuel injectors. DI engines use a common rail system that allows more precise and higher pressure fuel control and injection. Fuel in IDI engines is typically injected once per compression stroke at pressures up to 3,000 psi. DI engines often inject fuel at anywhere from 5,000 to 25,000 psi and some of the more sophisticated fuel injection systems inject the fuel multiple times per compression stroke to facilitate better fuel mixing and flame characteristics. This facilitates fewer emissions from incomplete combustion.

The design and placement of the fuel injectors are also important components of exhaust emission control. The smaller the opening of the injector, the more the fuel atomizes upon injection. Atomization of fuel affects the mixing of fuel and air as well and the duration of the flame, ultimately affecting the completeness of fuel burn. The fuel injection nozzle width and length also affect atomization. For optimum atomization of fuel it is necessary to inject the fuel at as high a pressure as possible to maximize the spray area and air saturation, but it is necessary to minimize the amount of fuel contacting the cylinder wall as it reforms into droplets where it is less prone to vaporization.

The timing and rate of fuel injection are also very important components of emissions control. As the injection is advanced the ignition delay (the time between when fuel is injected and combustion begins) is increased. This increases the total amount of fuel that is injected before ignition begins. The longer ignition delay also heats the fuel to higher temperatures which ends the combustion process earlier. This increases the residence time of the fuel and exhaust gases in the combustion chamber, which effects the emissions formation. The longer the exhaust gases are trapped in the combustion chamber the hotter they become. This allows for the recombination and formation of polycyclic aromatic hydrocarbons. Smoke intensity is also reduced but combustion noise, higher mechanical and thermal stresses and increased NO emissions result. Delayed injection timing has the opposite effect as exhaust gases are cooler when released. The rate of injection is also an important factor. High initial rates of injection reduce exhaust smoke because the injection process is ended earlier which improves elimination reactions, through better fuel air mixing.

Combustion in a compression ignition engine is initiated by a sharp increase in pressure which creates high temperatures and leads to ignition. The nuclei of fuel particles ignite first, followed by the rest of the fuel particle. Some fuel is not burnt because it is not mixed with oxygen. Once the fuel is injected it is compressed until it ignites. This is called the ignition delay. The ignition delay affects the rest of the combustion process, the mechanical and thermal stresses, noise, and exhaust emissions. Many reactions take place during the ignition delay and are broken into two categories, physical and chemical processes. The physical processes include:

- 1) Spray disintegration and droplet formation,
- 2) Heating of the liquid and fuel evaporation and
- 3) Diffusion of the vapor into the air to form a combustible mixture.

The chemical processes include:

- 1) Decomposition of the heavy hydrocarbons into lighter components and
- 2) Chemical reactions between the decomposed particles and oxygen.

The chemical and physical processes occur simultaneously as the fuel vapor makes contact with the air. The chemical processes are actually the rate controlling processes for combustion. Peroxides and Aldehydes are formed during the ignition delay and reach their peak concentrations just before combustion (Cooper, 1994).

## **Parts of the Flame**

As noted earlier the fuel air mixture is very important to the combustion process. The fuel air mixture varies in many ways, but has general characteristics which can be described. The outside of the spray mixture is called the low flame out region (LFOR). It is the area where the fuel is too lean for combustion and the flame ends. Just inside of the LFOR is the low flame region (LOR). It is the area where combustion is the most complete. The majority of the fuel remains in the spray core. This area constitutes the majority of the fuel and is in a rich mixture. Inside and behind the spray core is the spray trail and after injection, which are the richest areas of fuel in the combustion chamber. It is too rich to burn and should be minimized for best emissions reductions. Fuel is also deposited on the walls of the combustion chamber where it reforms as a liquid (Perola, 2003).

Each region of the flame is responsible for various emissions formation. The LFOR consists of decomposed hydrocarbons and partial oxidation products. The partially oxidized products contain Aldehydes and this region is responsible for the majority of the unburned hydrocarbons in the exhaust. Temperature, pressure, air mixture (swirl) and fuel type are the controlling factors of the LFOR. Minimizing the width of the LFOR reduces the amount of unburned hydrocarbons and aldehyde formation (Lanni, 2003).

The LFR is responsible for most of the NO formation due to high temperatures during combustion. Under light loads, temperatures are lower in this region and NO production decreases in the LFR. The border between the LFOR and the LFR is where the primary reactions take place and the initial hydrocarbons are attacked and reduced to CO, H<sub>2</sub>, H<sub>2</sub>O, and the various radical species (H, O, OH). Other unburned hydrocarbons, with less carbon atoms than the initial fuel molecules are formed (Springer, 1973).

The spray core consists of large spray droplets. The amount that these droplets evaporate before combustion begins determines how completely they will burn. Under part-load operation, combustion is the most complete and NO levels are highest. The temperature of the fuel, the heat of combustion of the droplet, and the temperature of the flame are major factors affecting NO formation.

The spray trail and after injection are part of injection that are not intended. They occur at low pressure and low temperature which leads to rapid evaporation and decomposition. The result is a large amount of unburned hydrocarbons, a high percentage of CO, carbon particles (smoke). Partial oxidation also results in formation of Aldehydes.

Fuel deposited on the cylinder walls can be a large constituent of emission formation depending on several factors. The amount of mixing with air is dependant on the fuel temperature, the temperature of the cylinder wall, gas velocity, gas pressure and properties of the fuel. Other important factors are the amount of fuel deposited on the walls and the ignition delay. These are called the “further formation” and “further elimination” factors, respectively. Lower values and longer ignition delays lead to further formation, which increases nitrous oxides. The opposite, further elimination, results in incomplete oxidation products such as carbon monoxide and Aldehydes.

### **Constituents of Exhaust Emissions**

Unburned hydrocarbons in the diesel exhaust consist of either original or decomposed fuel molecules, or recombined intermediate compounds. Some hydrocarbons are the result of lost lubricating oil. At high loads the hydrocarbon emissions originate from the fuel molecules in the core and on the cylinder walls. Under these conditions the temperatures reached are fairly high and cause decomposition of some of the original fuel molecules. Since the fuel-air ratio in the core and near the walls is generally rich, there is a great possibility that some recombination reactions may occur between the hydrocarbon radicals and the intermediate compounds. The result is higher concentrations of the heavier hydrocarbons. The process of recombination of the hydrocarbon compounds and radicals may also result in compounds having a different structure than the original fuel (Duran, 2003).

Carbon monoxide is formed during intermediate combustion stages of hydrocarbon fuels. During combustion, CO is oxidized to CO<sub>2</sub> through combination reactions between CO and different oxidants. If these recombination reactions are incomplete, CO will be left. Higher temperatures reduce the amount of CO that is not oxidized. However, as combustion temperatures increase, available oxygen decreases and CO is left unoxidized. Therefore, CO levels typically are low at low loads, but become higher at higher loads, due to failure to be oxidized.

Smoke is the most visible type of emission emitted from CI engine exhaust. Smoke consists of different types of particulate matter, which vary with load. They can be divided into two categories:

- 1) Liquid particles appearing as white clouds of vapor emitted under cold starting, idling and low loads. These particles consist of mainly unburned fuel and lubricating oil and may be accompanied by partial oxidation products and disappear as load is increased.
- 2) Soot or black smoke is emitted as a product of the incomplete combustion process, particularly at maximum loads (Duleep, 2003).

Smoke is measured as the opacity of the exhaust. The maximum opacity for new diesel engines is regulated by the EPA at .01grams per brake horsepower per hour (g/bhp-h) for particulate matter less than 10 microns in size (PM<sub>10</sub>) (U.S. EPA, 2002). Smoke is affected by the ignition delay. Later ignition leads to greater amounts of smoke in the emissions. The Cetane number of fuel is a measure of the ignition delay. The higher the Cetane number, the shorter the ignition delay and less smoke is produced. Regulation of particulate matter is important because it causes health problems. PM from .1 microns to 10 microns can penetrate deep into the lungs where they are deposited in the respiratory bronchioles or alveolar sacs. These deposits have been shown to increase cancer formation in humans and lab animals (Zirvin, 1997). An interesting factor that occurs in the exhaust of CI engines is that the amount of nitrogen and sulfur absorbed by the particulate matter fluctuates depending on the exhaust temperature. Higher exhaust temperatures, which correlate with higher engine loads, will absorb more sulfur and less nitrogen than lower temperatures (Duran, 2003).

Nitric oxide (NO) is formed during the combustion process at various concentrations in all the spray regions. NO results from the disassociation of oxygen molecules into atomic oxygen as a result of high combustion temperatures. Nitrogen attaches to atomic oxygen after combustion has occurred and forms NO and other Nitrogen-Oxygen isomers (NO<sub>x</sub>) (Springer, 1973). NO emissions increase with cetane number due to longer ignition delay and higher combustion temperature (Cngur, 2003). NO emissions are regulated by the EPA at .02 g/bhp-h (U.S. EPA, 2002).

Sulfur dioxide (SO<sub>2</sub>) is formed by the oxidation and combustion of sulfur throughout the combustion process. SO<sub>2</sub> is a result of the amount of sulfur in the fuel. New diesel fuel standards require that sulfur be limited to 15ppm to minimize SO<sub>2</sub> pollution (U.S. EPA, 2002). SO<sub>2</sub> causes acid rain and low level smog formation. It is also linked to respiratory problems.

Polycyclic aromatic hydrocarbons (PAHs) are byproducts of the incomplete combustion of organic matter. They are of major health concern, due to their well-known carcinogenic and mutagenic properties. The presence of PAHs in engine emissions is not determined solely by the presence of PAHs in fuel. PAHs can be formed by a mixing of various exhaust gases in the atmosphere, a catalytic reaction with exhaust equipment, or from the combustion of lubricants and other fluids present in the engine (Pitts, 1973). PAHs are normally associated with small particles that generally have long residence times in the atmosphere and therefore have the potential to be transported quite long distances (Perola, 2003).

While the exhaust may not contain a certain PAH, such as nitrobenzo(a)pyrene, a carcinogen, it may contain benzo(a)pyrene, which is not a known carcinogen. However, when exposed to NO<sub>2</sub> and trace amounts of nitric acid in the atmosphere, the benzo(a)pyrene forms nitrobenzo(a)pyrene (Pitts, 1973). Another interesting change that takes place is that the benzo(a)pyrene that is emitted as part of the exhaust is a promutagen, it needs activation to cause mutation. However, the nitrobenzo(a)pyrene is a direct mutagen and requires no chemical activation to cause mutations on the Ames test (a test used to determine mutagenic activity) (Lanni, 2003). Typical PAH constituents of diesel exhaust are chrysene(21%), pyrene (18%), and benzo[a]anthracene (17%); all of which are considered mutagenic (Perola, 2003). Surprisingly, PAH emissions are not specifically regulated, emissions of non-methane hydrocarbons are limited by the EPA at .14 g/bhp-h (U.S. EPA, 2002).

### **Fuel Variables**

The components of fuel are one of the main determinants of the amount and type of pollutants that will be present in exhaust emissions. Sulfur is one of the most problematic compounds found in diesel fuel currently. Sulfur is oxidized in the combustion process and forms various isomers. These isomers, such as sulfur dioxide, are responsible for acid rain, respiratory problems and other and environmental problems. Sulfur and sulfates are detrimental to catalytic emissions reduction equipment. They bind to the surfaces of the exhaust equipment and render it useless for the catalytic reduction of other pollutants. New EPA standards for on-road diesel require a reduction from .05 g/bhp-h to .01 g/bhp-h. However, sulfur is responsible for most of the lubricating quality of diesel fuel, which is

essential for certain engine components such as the fuel injection pump. Olefins and aromatics are being used for lubrication, replacing sulfur content in diesel fuel. As noted earlier olefins and PAHs are known to be mutagenic and carcinogenic (Baines, 1982; Mauderly, 2001). Essentially, a pollutant is being replaced by cleaner, but more dangerous compounds.

Nitrogen, carbon, phosphorus and other elements as well as trace amounts of many metals are often constituents of diesel fuels. By limiting the amount of such compounds in fuels, overall pollution from CI emissions can be controlled.

There are many different pieces of equipment that have an impact on emissions formation from compression ignition engines. Equipment attaches to the engine or the exhaust and modifies the way that exhaust gases are formed. Most of these technologies are proven, but not widely used for various reasons. A change in fuels with a focus on emissions reduction may include the use of some or all of these technologies. Also, some of these technologies are not used because they are not compatible with current fuels, but may be compatible with WVO.

### **Turbo Charging**

To increase the amount of air in the combustion chamber, CI engines are often turbocharged. This not only increases the amount of air available for combustion and the mixing process, but it also increases the compression ratio. This allows for more power to be developed from the same amount of fuel. By turbo charging an engine the average gas temperature over the whole engine cycle is increased. The higher temperature increases the rate of oxidation reactions and reduces the amount of unburned hydrocarbons. Exhaust temperatures are also higher and oxidation is improved in the exhaust system which further reduces the amount of unburned hydrocarbons (Cooper, 1994).

### **Exhaust Gas Recirculation**

Exhaust Gas Recirculation (EGR) devices simply recirculate some of the exhaust gases back into the combustion chamber. By adding hot exhaust to the combustion chamber, the gas temperatures increase. This decreases the amount of NO, but increases the amount of CO, H-C and increases the brake specific fuel consumption (BSFC) (Zvirn, 1997).

### **Intercooling/Precooling**

Cooler air is denser than warmer air. Therefore, it contains more available oxygen for combustion and oxidation reactions. By passing intake air through a cooling system, commonly referred to as an intercooler or precooler, the air inlet temperature can be significantly reduced. Not only does this enhance the effect of a turbocharger, by packing more air into the combustion chamber, but it also lowers the reaction temperatures. By increasing compression and decreasing combustion temperatures, power output is increased while H-C, CO, and volatile organic compounds are decreased (Lee, 2002).



### **Water Addition**

Water is added to the fuel air mixture to decrease the NO formation. It has the trade off of increasing the CO and H-C emissions under most circumstances. Essentially the water is just lowering the gas and combustion temperatures, which has the same effect as advancing the injection timing or intercooling (Zvirn, 1997).

### **Selective Catalytic Reducers**

Catalyzing exhaust emissions has long been employed in spark ignition engines as a way to reduce emissions. This technology has recently begun to be used with the exhaust system of CI engines. By passing exhaust gasses over a heated platinum/rhodium coated aluminum surface several chemical reactions are promoted. CO and volatile organic compounds (VOCs) are oxidized into CO<sub>2</sub> and H<sub>2</sub>O. NO<sub>x</sub> is also decomposed and oxidized into NO and elemental nitrogen and oxygen, which is easier to absorb in the environment (Kuerti, 2003).

### **Diesel Electric Hybrid**

Diesel engines have an optimum rpm and load range at which they operate most efficiently and produce the least amount of emissions. By keeping the engine at this optimum speed, economy and cleanliness can be maximized. The best way to do this is to use an electric engine and battery system to power the vehicle while the diesel engine provides electrical power. This allows for a smaller, lighter engine to be used. Also, engine mounting and drive-train layout is more flexible. FedEx is using a new delivery van that employs this diesel hybrid design, which realizes significant reduction in emissions and fuel consumption. A prototype diesel-electric hybrid sedan, based on the Dodge Intrepid, has been designed that achieves over 100 miles per gallon (mpg). This vehicle chassis is identical in all regards to the gasoline powered version, which is only capable of achieving 25 mpg. Power is actually improved, as noted by a 3 second reduction in the 0-60 mile per hour acceleration. By implementing a vehicle fleet which utilizes a diesel hybrid system, fuel consumption and emissions could be reduced by as much as 70% (Duffield, 1998).

By optimizing the fuel chemistry, engine design and tuning, the amount of harmful engine emissions can be minimized. This is important as the emissions can be mutagenic, carcinogenic, contribute to respiratory problems or other health related problems. Engine emissions also contribute to the formation of smog, acid rain, and other environmentally degrading pollutants. Fuel is an important characteristic of pollution reduction, but all factors of the combustion process must be taken into account in order to minimize engine emissions. The next chapter describes the engine and exhaust variables of the engines tested. The engine equipment and engine design of the test engines affect the longevity and emissions formation. The test environment of the engine

## CHAPTER THREE METHODS

This is a multipart project with two main focuses. First the long term viability of using waste vegetable oil as a fuel is to be determined. Second the regulated emissions from using waste vegetable oil as a fuel are to be ascertained as well as the emissions from other fuels, to give a basis for comparison.

### **Long Term Viability**

The test platform for long term viability is a 1987 diesel Mercedes. The engine is a 3.0 liter, indirect injection, six cylinder compression ignition engine equipped with a waste gated turbo charger and an electronically manipulated fuel injection pump. The injection pump is a piston type design with individual pistons per injector. Fuel is delivered to mechanically actuated injectors via a split rail system, where all fuel lines are independent of each other. The fuel system has been modified over the course of testing to optimize reliability and improve functionality. Changes include adding an additional six gallon plastic fuel tank, which is heated by the coolant system. The auxiliary fuel (**PHOTO 1**) system has all fuel lines jacketed with engine coolant and the tank and fuel filter are heated in the same manner. For simplicity and added volume, the original fuel system was also modified to facilitate the use of waste cooking oil. The OEM fuel heating system, which consists of a manifold bypass, was reconfigured to pass fuel through the intake manifold in order to heat the fuel. The bypass is configured so that fuel from both the main tank and the auxiliary tank pass through the manifold before injection. The manifold reaches operating temperature faster than the coolant system does, so the fuel is heated sooner. The fuel system was originally configured with a dual solenoid set-up that allowed fuel from either tank to flow from one tank to the other in order to purge the system with diesel fuel. However, it was found that this wasn't necessary in Florida's climate, as the temperature never drops below the cloud point for any significant length of time, therefore no diesel was needed to purge the system. To minimize the complexity of the system one solenoid was removed. Cold starts on vegetable oil were not a problem because the ambient temperature seldom decreased below 40°F, which is the cloud point for soybean oil. On the two occasions that the temperature was below 40°F, the OEM block heater was utilized and the fuel maintained a high enough temperature to prevent solidification.

The vehicle originally was equipped with an odometer, however the internal planetary gears broke at 261,401 miles. Therefore no actual mileage data is available. However an hour meter was installed shortly after experimentation began. The hour meter is controlled by a switching system that is linked to the fuel system, so that the engine time only reflects actual time the engine has operated on vegetable oil. The hour meter reflects slightly less time than the engine was run on waste cooking oil as it was installed after the experiment began. Also

the fuel transfer pump is equipped with a flow meter which records the amount of fuel that passes through it. It too was installed after the experiment began indicates less fuel than has actually been consumed. Approximately 80.4 gallons of vegetable oil were used prior to installation of the flow meter. Also the flow meter does not operate at low flow rates (< .5 gallon/min.) so its overall value is lower than the actual amount of fuel that has passed through it.

### **PHOTO 1. Heated Fuel System**



A log of fuel filters has also been kept to allow for an economic evaluation of the project and also to gauge the life span various fuel filters in this application.

### **Emissions Collection**

Regulated emissions using waste vegetable oil, petroleum diesel and Biodiesel were collected and analyzed. An Allen Bar 90 (**PHOTO 2**) emissions machine with opacity was used to collect emissions data. The Bar 90 uses three infrared optical benches to measure the concentration of carbon monoxide, hydrocarbons and carbon dioxide. A chemical fuel cell measures oxygen. A light meter is used to measure the opacity of emissions. The emissions of a one cylinder Hartz, normally aspirated, direct injection, 7Hp engine were tested with the Bar 90. A 1.25" ID hose was fitted to the muffler to redirect the exhaust so that it could be measured by the emissions and the opacity probes. The emissions were checked at start-up, idle and at full load. Also the ambient readings were recorded. After each fuel was tested, the fuel system was completely drained of fuel and then partially filled with the next test fuel. The engine was run dry and then refilled with fuel and the emissions data were collected. This was done to ensure no contamination of the test fuel with a previous fuel.

The Mercedes emissions were tested using a Land Instruments Lancom Series II portable stack analyzer, courtesy of the Hillsborough County Environmental Protection Commission. The portable stack analyzer is capable of measuring carbon monoxide, sulfur dioxide, oxygen, nitrogen oxide, nitrogen dioxide, carbon dioxide and hydrocarbons. It also measures and displays the ambient air temperature, the exhaust gas temperature and the difference between the two. It uses all of this information to compute the efficiency, loss, excess air, water and normal oxygen level. Only heated WVO emissions were tested on the Mercedes

using the Landcom emissions equipment. Further testing of other fuels on the Mercedes has been postponed due to failure of the cars on-board computer. For comparison purposes a 2001 Ford F-250 was tested using the same instrument. The Ford was equipped with a direct injection diesel engine, fueled with Biodiesel. The Ford is completely stock, including the fuel system. Emissions were tested with fuel at ambient temperature.

**PHOTO 2. Bar 90 Emissions Equipment and Dynamometer**



**Fuel Collection and Processing**

For the lawnmower test, ASTM certified fuels were used, with the exception of the waste vegetable oil, which was rendered. Biodiesel and petroleum diesel were purchased and pumped into fuel containers. The Biodiesel was purchased from Ward Oil in Tampa and produced by Griffin Industries at their Kentucky plant to meet ASTM certification D6751. Diesel was purchased from Amoco and meets ASTM D975. Waste vegetable oil was rendered from various restaurants in the St Petersburg area. They all use the same brand of hydrogenated soybean oil, however, the waste products differ slightly due to the different foods, duration of use and cooking methods used. The waste oil was rendered and filtered on site using a 10 micron filter. It was pumped directly into the fuel tank that was used for the testing. The majority of the waste vegetable oil was rendered from Harvey's Fourth Street Grill in St Petersburg, Florida. The WVO was similar in appearance to virgin soybean oil, except that it had a brown tint and a burned food odor. Viscosity and purity after filtration were not noticeably different than the original oil.

## CHAPTER FOUR DISCUSSION OF RESULTS

This chapter details the results of this experiment. First the longevity of the test engines is examined and problems are detailed. The problems are undetermined, but possible causes are discussed. Second the emissions from the test engines are examined. The emissions data are not conclusive, due to premature engine failure, but they indicate that emissions from WVO have positive benefits compared to the other fuels tested.

### **Longevity**

Several platforms were tested to see if they could operate on waste vegetable oil. A 1995, 6.5 liter, turbo diesel suburban was operated for approximately 725 miles on waste vegetable oil. The fuel system and engine were not modified in any way. The fuel filter was located on top of the engine injection manifold and therefore heated the fuel substantially before it was injected into the engine. The engine is an in-direct injection type, which is also more resilient to changes in fuel. The fuel used was a blend of diesel and WVO, however only a very small amount of diesel was in the system as the tank was run as close to empty as feasible before it was filled with WVO. The vehicle was filled twice with WVO for a total of about 60 gallons. It was sold with a quarter tank of WVO still in it. The only fuel related problems that arose with the vehicle were hesitation caused by a dirty fuel filter. This occurred twice and was immediately remedied when the filter was changed.

The Mercedes was operated for a total of more than 189.4 hours on waste vegetable oil. This is a lower than actual figure as the hour meter was not installed in the vehicle until after the experiment had begun. The vehicle used approximately 247.8 gallons of WVO over this time period. 167.4 gallons of WVO was metered by the flow meter attached to the fuel transfer pump and an estimated 80.4 gallons was used prior to the installation of the fuel meter. To figure out how many miles were actually driven on WVO an average speed of 30 mph was used for a total distance of 5682 miles. This is a conservative estimate of the distance traveled as most of the driving was highway use and the average speed was most likely much greater. The computed distance driven based on fuel consumption is 6442.8, assuming a fuel economy of 26 miles per gallon (mpg). This too is a conservative estimate as average mileage was most likely closer to 30 mpg. Unfortunately, the total longevity of the vehicle on waste vegetable oil could not be determined for two reasons. 1) The engine had a substantial amount of use before the testing started, greater than 241,000 miles. 2) The engine had a computer failure and was rendered inoperable. The on-board computer failure could not be attributed to the use of WVO as the computer and its attached components have no direct interaction with the fuel.

Problems encountered when using waste vegetable oil were all related to fuel supply. Fuel line failure occurred with some of the original braided, natural rubber fuel return lines. However, the majority of the original fuel lines are still being used and have not suffered any problems. Fuel quality was ascertained by visual inspection only and cannot be compared on this basis. Fuel filters clogged on varying intervals, causing loss of power and severe hesitation. The greatest problem with this experiment was finding appropriate fuel filters for pre-filtration of the fuel (prior to pumping it into the vehicle) and for in-line filtration of the fuel before it reached the engine. It was found that at the minimum the fuel needs to be filtered through a 10 micron filter, if not smaller. The overall size of the filter was very important for fuel flow and for lifespan of the filter. The more surface area the filter had the longer its useful life. This was even more evident with the pre-filter system since it was used to filter large quantities of very contaminated fuel. It was observed that the better the fuel was filtered before it was pumped into the vehicle, the longer the engine fuel filter would last. The smaller the initial filter size (ie. 10 micron) less contamination would collect in the engine filter. Due to the variety and frequency of filter replacement and accumulation of deposits in the main fuel tank, a statistically relevant comparison of fuel filters is not possible. Fuel filters vary by filter surface area and filter replacement method. Filters of larger surface area with top loading canisters are preferred due to their ease of replacement and ability to filter more fuel.

Apparently the WVO had a chemical interaction with the lining of the main tank and formed some type of solid substance shown below (**PHOTO 3**). It appears that any coating on the tank reacted with the WVO and left a fat like deposit over the entire fuel system. This severely impacted the lifespan of the fuel filters. The interaction of the WVO with the tank lining was not expected and is thought to be due to the tank linings interaction with the free glycerin in the WVO. OEM tanks are often used with Biodiesel and no such problems are reported. Most experiments with straight vegetable oil use dual fuel tanks which are dedicated to the test fuel. Also, most tanks used for vegetable oils are plastic or unlined non-ferrous metal. It is also thought that the WVO has a reaction with ferrous metals which precipitates a solid deposit on the metal surface. Further research is needed to understand the cause and effects of this interaction.

**PHOTO 3. Fuel Tank Deposits**



Fuel injectors were removed and examined three times during the experiment. Each time the carbon deposit was removed from the tip of the injector. The carbon deposit would re-accumulate in a very short period of time, regardless of the type of fuel being used. There was no discernable difference between the injectors when diesel and WVO were used. However, the injectors were replaced at 188 hours. They were pressure tested and found to be fouled. Three of the injectors had no spray and three had a weak spray pattern. They were replaced with new injectors and the vehicle ran again. It is hypothesized that the deposits in the main fuel tank in conjunction with inadequate fuel filters, allowed deposits to accumulate in the injectors. Ironically, problems began to occur immediately after diesel was introduced into the fuel system for the first time since the experiment had begun in November of 2002. The engine operated for a short time with the new injectors and then died completely. A faulty on-board computer, as well as poor compression due to the high amount of engine wear, are thought to have caused the engine to cease operating. The fuel injection system was examined and a good spray pattern was noted at the injectors. Therefore, fuel system failure is not thought to be an issue. More than 10 OEM fuel filters were clogged, as well as 5 fuel filters that were dedicated to the auxiliary fuel system. Also, more than twenty in-line fuel filters were used before the engine ceased operating. The pre-filtration system used 7 filters of various size and make. The largest problem encountered with pre-filtration (filtering the unprocessed WVO into the car) was due to fat build-up. A layer of fat would often accumulate near the surface of a WVO collection container, which clogged the filter well before it had served its useful life. Using a different source of WVO (i.e. From another restaurant) was found to alleviate this problem. The quality of the WVO could usually be ascertained fairly accurately by visual inspection. The more fluid and clean the WVO appeared, the longer the filters would last and the better the overall operation of the engine. Heating was found to allow the fat to pass through the filter, but the fat would re-accumulate somewhere else in the fuel system causing another problem. The best success was encountered when using the cleanest source of WVO.

Of the major components of the fuel system; the fuel pump, fuel injection pump and the fuel injectors; there is no evidence that WVO was detrimental. The fuel injection pump and fuel pump function properly, however, the injectors clogged and had to be replaced. This could be a result of the fuel, not allowing the fuel to reach operating temperature before injection, inadequate fuel filtration or a combination of all of these factors. This also could have been prevented by periodically running fuel injector cleaner through the fuel system. The injectors operated without any problems until diesel fuel was used and problems resulted immediately upon fueling. No direct causation was determined, yet the coincidence is overwhelming. Therefore, the injector fouling, is not to be attributed to the WVO. Diesel Purge was pumped through the fuel system and allowed to soak for a 24 hour period. No improvements in the engines operating condition were noted.

The Hartz 7hp engine is a direct injection, air cooled engine. The lack of a liquid cooling system made it difficult to install a heated fuel system. Therefore the fuels were tested at ambient temperature. The engine was observed to be running rough and missing frequently after running on WVO for several minutes. This was attributed to the sensitivity of the direct



injection system of the engine. It does not mix the air and fuel as violently as does an indirect injection system and therefore is more sensitive to fuel parameters (Kureti, 2003). The actual cause of the engines poor performance has not yet been determined.

### **Physical Characteristics of WVO**

There are several noticeable physical differences when using WVO instead of petroleum diesel. The most notable is that the exhaust usually smells like french fries. However, this could vary and the smell would reflect whatever had been cooked in the vegetable oil. The pungent diesel odor was noticeably absent. The engine also ran significantly quieter. The injector pump on most diesels makes a very pronounced noise and this was greatly reduced by the use of WVO. This is attributed to the higher lubricity of WVO as compared to diesel fuel (Zhang, 1996). The increased lubricity lubricates the fuel injection pump better and results in quieter operation. The cranking time also seems to increase slightly when using WVO as opposed to DF. This could be attributed to the longer ignition delay of the fuel and the higher flashpoint (Altun, 1999). It follows that it would take longer for the appropriate temperatures to be achieved in order to ignite the fuel air mixture. Blockage of fuel filters, weak or broken glow plugs or declining engine compression could also be contributing factors for the necessary longer cranking times.

### **Emissions Data**

The emissions from the 7 hp Hartz engine are compiled in **Table 3**. The waste vegetable oil emissions were very similar to diesel emissions except that the opacity, or smoke, was significantly lower. It is interesting to note that all of the emissions from Biodiesel were much lower than for both vegetable oil and diesel fuel. Examination of the chemical structure of the vegetable oil and the Biodiesel would be helpful to gain insight into why the emissions varied so much. Both Biodiesel and WVO are forms of vegetable oil. Both were presumably made from waste cooking products (Griffin – the producer of the Biodiesel is the world’s largest renderer of WVO). The discrepancy between the emissions data may be from the WVO being contaminated with diesel fuel. The tank on the engine may have contained some diesel fuel. Also the pre-filter, used to process the WVO was used to pump diesel fuel and may have introduced diesel into the WVO. However, the lower opacity of the WVO, similar to the opacity of Biodiesel, may be an indicator that the fuel was not contaminated.

The emissions responded as expected from this type of engine. Carbon emissions decreased with increasing RPM, which is expected from a direct injection engine. The higher RPM is necessary for proper fuel/air mixing in the combustion chamber. This reduction in emissions at higher RPM would not have been as pronounced in an in-direct injection engine.



**Table 3. Emissions Test from a Direct Injection 7hp Engine Comparing WVO, Biodiesel and Petroleum Diesel**

<b>HARTZ EMISSIONS TEST 10/8/03</b>						
<b>Fuel</b>	<b>Engine Load</b>	<b>% CO</b>	<b>% CO2</b>	<b>Ppm HC</b>	<b>% O2</b>	<b>Opacity</b>
Ambient		0	0	2	20.8	0
Biodiesel	Start-up					1
	Idle	0.02	0.9	6	19.4	0
	Full Throttle	0.01	0.5	5	20	0
Diesel	Start-up					
	Idle	0.07	1.6	34	17.3	3
	Full Throttle	0.02	0.9	21	19.1	4
WVO	Start-up					2
	Idle	0.06	1.6	29	17.7	0
	Full Throttle	0.03	0.9	23	19.4	1
<b>HARTZ EMISSIONS TEST 10/14/03</b>						
<b>Fuel</b>	<b>Engine Load</b>	<b>% CO</b>	<b>% CO2</b>	<b>Ppm HC</b>	<b>% O2</b>	<b>Opacity</b>
Ambient				0 – 2	20.8	
WVO	Start-up					7
	Idle	0.02	0.4	10	19.9	0
	Full Throttle	0.06	1.2	75	18.5	0

The emissions from the Mercedes are compared to the emissions from the Ford in **Table 4**. The Ford is fueled with Biodiesel and the Mercedes is fueled with WVO. The emissions from the Mercedes are actually less for NO, NO<sub>2</sub> and NO<sub>x</sub> than for the Ford. There are several variables that could contribute to this. The Ford is a direct injection engine, which has less air fuel mixture at lower RPM as the indirect injection engine of the Mercedes. This could result in higher emissions of nitrogen species. However, the glycerin in the WVO is suspected of causing an ignition delay in the combustion of the fuel which decreases the combustion temperature. Lower combustion temperatures contribute to less formation of free nitrogen.

**Table 4. Emissions Test Comparing a Direct Injection Ford Fueled with Biodiesel and an Indirect Injection Mercedes Fueled with WVO**

<b>F-250 EMISSIONS TEST 10/14/03</b>									
<b>Fuel</b>	<b>Load</b>	<b>CO ppm</b>	<b>SO2 ppm</b>	<b>O2 %</b>	<b>NO2 pp</b>	<b>NO ppm</b>	<b>CxHx %</b>	<b>CO2 %</b>	<b>NOx pp</b>
Biodiesel	880 rpm	107	0	16.5	20	86	0.07	1.79	105
		111	0	16.5	23	88	0.07	1.82	111
	2000 rpm	107	0	16.3	23	86	0.07	1.99	110
		116	0	16.8	22	55	0.07	1.54	77
<b>MERCEDES EMISSIONS TEST 07/28/03</b>									
<b>Fuel</b>	<b>Load</b>	<b>CO ppm</b>	<b>SO2 ppm</b>	<b>O2 %</b>	<b>NO2 pp</b>	<b>NO ppm</b>	<b>CxHx %</b>	<b>CO2 %</b>	<b>NOx pp</b>
WVO	Idle	539	21	11.6	11	62	0.12	6.71	73
		484	23	12.3	7	61	0.12	6.19	68
	2000 rpm	612	11	16.1	19	32	0.11	3.4	51
		in gear	619	11	16.1	20	32	0.11	3.41

## CHAPTER FIVE

### CONCLUSIONS AND RECCOMENDATIONS FOR FUTURE RESEARCH

Vegetable oil is not an end all solution to the worlds energy problems, yet it could be a good fuel additive and alternative fuel for many uses. At current production levels, vegetable oil can only offset 5% the current 20 million barrels per day of petroleum use (Peterson, 1998). However, it should be noted this is more than is expected to be retrieved from the Alaskan National Wildlife Refuge, drilling off of the Florida coast, and other current U.S. oil endeavors. Peterson, projects that at maximum production levels, using current technology and available land, about 20% of U.S. diesel use could be offset by vegetable oil (Ibid). While this would result in a significant reduction in the use of petroleum, it still is not a permanent solution to current fossil fuel problems. This might be a convenient level of production though as WVO could be splash blended with diesel for all diesel fuel needs at a 20% level. This may lead to significant emissions reductions, benefits in technology application and improved fuel lubrication. Blended fuels may then be eligible for a tax incentive, but still provide a significant amount of proceeds for transportation funding. Perhaps the 20% vegetable oil blend could be tax free, while the 80% petroleum portion is taxed at its normal level. Ideally, no tax incentive would be needed as the WVO could be produced at lower cost than diesel fuel and would lower the overall price of the fuel, giving its use an economic incentive. By blending WVO with diesel, it may be possible to use in existing vehicles without a heated fuel system, but more research is needed to determine if this is feasible for long term use. Also, using WVO as a fuel would provide another source for disposal of the product and could improve disposal problems and decrease disposal costs. Using WVO on a large-scale basis would not only be helping solve problems associated with petroleum use, such as pollution, foreign oil dependence, destructive petroleum exploration and the hazards of transporting petroleum, but it would also help resolve the problem of disposing of waste vegetable oil. By providing a source of revenue for WVO, disposal costs may be eliminated and the oil may be treated as a commodity, providing a source of income for those disposing of WVO. Also, vegetable oil is a readily available fuel source that can be utilized in any diesel engine, oil heater, jet engine, and many other sources. The most appealing aspect is that it can be had for free, or can actually generate profit if it is disposed of as part of a disposal service. It has the highest energy balance of any available alternative fuel source, indicating it returns the most energy per unit of energy consumed in production. However, emissions analysis and long term feasibility must be completed to establish the usefulness of this fuel.

The emissions from engines using heated waste vegetable oil indicate that reductions may be possible compared to other fuels. More detailed research and evaluation is necessary to determine if this is an accurate indication of emissions or if this is simply a sampling or

methodology error. These results are not conclusive, but are an indication of what may be expected.

The longevity and feasibility of using heated waste vegetable oil as a fuel is also very positive. About 7,000 mi of use was demonstrated using WVO, but more duration and different test platforms are needed to determine the total impact of this fuel source. The causation of the engine problems in the Mercedes and the Hatz engine needs to be determined to address the cause of the problem. It needs to be determined if these engines performed poorly as a result of the fuel or if there are other contributing factors. Also, the impact these factors had on the emissions needs to be determined and taken into account in future investigations.

The test engines had various longevity and experimentation was terminated for different reasons.

- Suburban ran on WVO for 725 with no major problems
- Mercedes used 247.8 gallons of WVO, ran for over 188 hrs. or approximately 6500 miles.
  - Used over 23 fuel filters
  - Developed significant deposits in fuel tank
  - Engine failure – undetermined cause, no noted damage from fuel
    - Hatz engine failed on WVO very rapidly
    - Fuel not heated – caused fuel system failure

The emissions from the engines are not conclusive but some positive emissions reductions of emissions from WVO were observed compared to the base line fuels.

- Hatz engine had lower opacity on WVO than with diesel fuel.
- WVO emissions of NO, NO<sub>2</sub> and NO<sub>x</sub> from Mercedes less than Biodiesel emission of Ford
  - Due to higher glycerin and fat content of WVO compared to Biodiesel

Several fuel system manufacturers offer heated fuel systems that they report having excellent success with. They report hundreds of hours and thousands of miles using heated waste cooking oil and their fuel system in diesel engine vehicles. However there is no data available to verify their claims and no research to explain the functioning of their processes. Also, in order to maintain proprietary ownership and a positive advertising position, many specifics are left out of their success reports. For instance, none of the fuel system manufacturers report engine or engine component failure, but it seems unlikely that there could be all success and no failure with a trial and error approach to designing a fuel system. The only mention of difficulties is that direct injection engines are more susceptible to problems than in-direct injection engines. Since the majority of new diesel engines being manufactured today are direct injection, it is important to focus on the feasibility of using heated waste vegetable oil in these engines, even if it is only for partial blend applications. Also, the use of fuel additives and fuel system cleaners needs to be investigated.

Engines are not currently certified to run on waste vegetable oil, in fact, doing so is considered an improper use by engine manufacturers and will void the engine warranty. However, if WVO were to become a recognized fuel, equipping engines to operate properly would be a simple process. Many engines already are equipped with some type of fuel heater for cold temperature operation. These heaters can be modified to heat the WVO when necessary. If the engine does not have an existing system there are many available that use the engines waste heat or an electric heater to heat the fuel to an appropriate temperature. A fuel heating system is not expensive, approximately \$600 for an aftermarket one, and would be even less if designed into the engine. A dual fuel system would probably be necessary for starting and flushing the engine with Biodiesel or diesel, but an on demand electric fuel heater may be sufficient. The cost of a factory installed heated fuel system would probably be less than \$200 on average. A major deterrent to using WVO as a fuel is that Tier 1 and Tier 2 emission and health effects testing is required, which is a time consuming and expensive process.

Waste vegetable oil may also be a suitable fuel for other applications such as power generation, home heating and aviation fuel. Further research is needed to explore these possibilities.

#### **Recommendations for Future Research**

A chemical assay of waste vegetable oil from various sources is recommended to better understand combustion reactions and byproducts. Chemical structure of WVO varies depending on what it was used to cook, how long it was used, temperatures it was used at, etc. By analyzing the chemical structure of WVO from a descriptive sample population it is possible to ascertain what changes have occurred in the chemical structure of the vegetable oil as well as what nutrients, metals, aromatics and other compounds have been introduced. Also, the effect of specific cooking habits and foods on the WVO could be determined. This is important for determining how to minimize tailpipe emissions through selection and processing of WVO.

The emissions and longevity of using waste vegetable oil as a fuel could be further ascertained by using a new engine, so that it is known that there is no damage from other fuel. This engine could be installed in an existing vehicle and tested at set intervals for horsepower, torque and emissions. The emissions from diesel, Biodiesel and WVO could be measured using both the Bar 90 and Lancom Series II emissions equipment, while operating the vehicle on the dynamometer. Fuel consumption for the various fuels could also be calculated and compared.

The long term effects of using waste cooking oil are being further examined by using a 15 Kw diesel powered generator. This generator will provide all electrical needs for a four person household. The expected engine life of the generator is about 9,000 hours, or approximately one year of continuous use. The amount of time actually on the generator is not know for certain, but is thought to be less than 1,000 hours. By running the generator continuously, fueled entirely by waste cooking oil, long term effects of the fuel can be determined readily. The benefits of using the generator are that it will never be shut down,

other than for routine maintenance. Therefore it will rapidly accumulate a large amount of hours and consume a greater amount of fuel than an engine that is only in use part time. Also, the energy output, measured in watts, will be known and recorded. This will enable the emissions and fuel consumption to be analyzed on a power output basis, which is very useful for comparison purposes. Another benefit of the generator is that the engine is very simple in design. It is a 4 cylinder, normally aspirated, indirect injection engine, designed to run at a constant RPM. Since it can be kept at a constant load for long periods of time, the exact amount of emissions being produced can be measured very precisely. Also, it can be tuned to operate optimally at its working load, since it will never operate at any other speed. It is also a good platform to test different exhaust technologies, such as a trap oxidizer, catalytic converter, or a selective catalytic reducer. While the effectiveness of these exhaust treatment technologies is known for use with diesel fuel, no such data exists with WVO. It is thought that very low overall emissions could be obtained by using new exhaust treatment technology in conjunction with WVO.

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