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## **ETHANOL-DIESEL BLENDS: A STEP TOWARDS A BIO-BASED FUEL FOR DIESEL ENGINES**

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**Abstract.** *The global fuel crises in the 1970's generated awareness amongst many countries of their vulnerability to oil embargoes and shortages. Considerable attention was focused on the development of alternative fuel sources, with particular reference to the alcohols. Blends of ethanol and diesel fuel were investigated and found to be technically feasible, however, the high costs of ethanol production meant that the fuel could only be considered in cases of fuel shortages. In the last two decades of the 20th century, major advances in engine technology have occurred, leading to greater fuel economy in vehicles. The reduction of emissions from engines has become a major factor in the development of new engines and manufacturers are trying to meet the requirements specified by EPA. As a result the use of alternative fuels as a means of meeting these requirements has generated much attention. Today the economics are much more favorable in the production of ethanol and it is able to compete fairly well with standard diesel. Hence there has been renewed interest in the ethanol-diesel blends with particular emphasis on emissions reductions. When considering an alternative fuel for use in diesel engines, a number of issues are important. This purpose of this paper is to review these issues with particular reference to safety and distribution, integrity of the fuel being delivered to the engine, emissions, engine performance and durability.*

**Keywords.** biofuel, alcohol, ethanol, blend, diesel engines

## **Introduction**

The global fuel crises in the 1970's triggered awareness amongst many countries of their vulnerability to oil embargoes and shortages. Considerable attention was focused on the development of alternative fuel sources, with particular reference to the alcohols. A blend of 10% dry ethanol and unleaded gasoline (E10) was commercially introduced into the USA and is still marketed in the Midwest. More recently, the oxygenated and octane enhancing benefits of ethanol have been highlighted as a potential substitute for Methyl Tertiary Butyl Ether (MTBE), an oxygenated additive used to enhance octane and also reduce CO emissions. MTBE has been shown to be highly toxic even in small quantities when it contaminates groundwater. Flexible fuel vehicles introduced in the early 1990's can be operated on up to 85% ethanol, straight unleaded gasoline or any mixture of the two fuels.

The use of ethanol blended with diesel was a subject of research in the 1980's and it was shown that ethanol-diesel blends were technically acceptable for existing diesel engines. The relatively high cost of ethanol production at that time meant that the fuel could only be considered in cases of fuel shortages. Today the economics are much more favorable in the production of ethanol and it is able to compete fairly well with standard diesel. Hence there has been renewed interest in the ethanol-diesel blends with particular emphasis on emissions reductions.

In the last two decades of the 20th century, major advances in engine technology have occurred, leading to greater fuel economy in vehicles. The reduction of emissions from engines has become a major factor in the development of new engines and manufacturers are trying to meet the requirements specified by Environmental Protection Agency (EPA). As a result the use of non-conventional fuels as a means of meeting these requirements has generated much attention. When considering an alternative fuel for use in diesel engines, a number of issues are important. These issues include supply and distribution, integrity of the fuel being delivered to the engine, emissions and engine durability.

An additional factor that makes ethanol attractive as a fuel extender or substitute is that it is a renewable resource. The dwindling fossil fuel sources and the increasing dependency of the USA on imported crude oil have led to a major interest in expanding the use of bioenergy. A national biobased products and bioenergy initiative was formally proposed in 1999 and steps have been taken to identify areas of research presently underway and those that need to be expanded (Bioenergy, 2000). Research into the use of ethanol in diesel engines fits well into this initiative.

The objectives of this paper are to review the studies that were completed on ethanol-diesel blends in the 1980's when the emphasis was on providing a diesel fuel extender or substitute, and to review research undertaken recently where emissions reductions and technical feasibility in the new generation of diesel engines have been the main focus.

## **Blend Properties**

There are a number of fuel properties that are essential to the proper operation of a diesel engine. The addition of ethanol to diesel fuel affects certain key properties with particular reference to blend stability, viscosity and lubricity, energy content and cetane number. Materials compatibility and corrosiveness are also important factors that need to be considered. Properties that affect safety should be foremost in any fuel evaluation. These include flashpoint and flammability and are discussed in a latter section.

## **Blend Stability**

Ethanol solubility in diesel is affected mainly by two factors, temperature and water content of the blend. At warm ambient temperatures, dry ethanol blends readily with diesel fuel. However, below about 10°C the two fuels separate, a lower limit that is easily exceeded in most parts of the USA for a large portion of the year. Prevention of this separation can be accomplished in two ways: by adding an emulsifier which acts to suspend small droplets of ethanol within the diesel fuel, or by adding a co-solvent that acts as a bridging agent through molecular compatibility and bonding to produce a homogenous blend. Emulsification usually requires heating and blending steps to generate the final blend, whereas co-solvents allow fuels to be “splash-blended”, thus simplifying the blending process.

Both emulsifiers and co-solvents have been evaluated with ethanol and diesel fuel. Moses *et al.* (1980) investigated micro-emulsions of aqueous ethanol (5% water) and diesel fuel using a commercial surfactant. They reported that the blends formed spontaneously and required only minor stirring. They also appeared transparent indicating that the dispersion sizes were less than  $\frac{1}{4}$  wavelength of light and were regarded as “infinitely” stable, i.e. thermodynamically stable with no separation even after several months. Approximately 2% surfactant was required for each 5% aqueous ethanol added to diesel fuel. Boruff *et al.* (1982) developed formulations for two micro-emulsion surfactants, one ionic and the other detergentless. Blends of these surfactants with aqueous ethanol and diesel were transparent and stable at temperatures as low as -15.5 °C. Researchers in Sweden tested a blend of 15% aqueous ethanol (5% water) with diesel containing DALCO, an emulsifying agent developed in Australia. Meiring *et al.* (1981) and Letcher (1983) identified ethyl acetate in early studies as an effective co-solvent that could be made at relatively low cost from ethanol. Letcher (1983) found that the ratio of ethyl acetate to ethanol to ensure complete miscibility down to 0°C was consistently 1:2.

The aromatic content of diesel fuel also affects the solubility of ethanol in diesel and therefore the effectiveness of emulsifiers and co-solvents. The polar nature of ethanol induces a dipole in the aromatic molecule allowing them to interact reasonably strongly, while the aromatics remain compatible with other hydrocarbons in diesel fuel. Hence aromatics act to some degree as bridging agents and co-solvents. Reducing the aromatic content of diesel fuels will influence the miscibility of ethanol in diesel fuel and hence will affect the amount of additive required to achieve a stable blend.

Recent studies in the USA have made use of additives from three different manufacturers. Pure Energy Corporation of New York was the first manufacturer to develop an additive package that allowed ethanol to be splash-blended with diesel fuel using a 2-5% dosage with 15% anhydrous ethanol and proportionately less for 10% blends (Marek and Evanoff, 2001). A small amount of commercially available cetane improver (less than 0.33% by volume) was also added to restore the cetane value of the blend. The second additive manufacturer is AAE Technologies of Great Britain, who are currently testing 7.7% and 10% ethanol-diesel blends containing 1% and 1.25% AAE proprietary additive in Nevada, Nebraska and Illinois (Marek and Evanoff, 2001). The third manufacturer is Betz-Dearborn, a division of Hercules, Inc., who has developed a proprietary additive derived purely from petroleum products, compared to the previous two, which are produced from renewable resources. This additive has also been used in a number of tests in Illinois, especially with 10% ethanol-diesel blends (Hansen *et al.*, 2001; Marek and Evanoff, 2001).

The percentage of additive required is affected by the lower limit of temperature to which the blend must be stable. Hence ethanol-diesel blends require less additive in Summer conditions as compared to Winter. Pure Energy Corporation specified 5% additive for stability at temperatures well below 0 °F (-17.8°C), making it suitable for winter fuel formulation. Marek and Evanoff (2001) stated that an added benefit was that the fuel remained a liquid at these

temperatures, allowing it to be pumped through the fuel injection system, as opposed to No. 2 diesel fuel, which tended to gel. In the Summer, the additive requirement drops to 2.35% with Spring and Fall concentrations being 3.85% by volume (Marek and Evanoff , 2001).

### **Viscosity and Lubricity**

Fuel viscosity and lubricity play significant roles in the lubrication of fuel injection systems, particularly those incorporating rotary distributor injection pumps that rely fully on the fuel for lubrication within the high pressure pumping mechanism. In the common rail accumulator fuel - injection system, the high-pressure pump that delivers fuel to the rail also relies on the fuel for lubrication. In in-line pumps and unit injectors, there is less reliance on the fuel for lubrication, however, there are still some metal interfaces that require lubrication by the fuel such as between plunger and barrel. Injector lubrication is also affected, particularly at the needle guide-nozzle body interface.

Lower fuel viscosities lead to greater pump and injector leakage reducing maximum fuel delivery and hence power output. Hot start problems may also be encountered as insufficient fuel may be injected at cranking speed when fuel leakage in the high-pressure pump is amplified because of the reduced viscosity of the hot fuel.

The addition of ethanol to diesel lowers fuel viscosity and lubricity. Wrage and Goering(1980) investigated the variation of viscosity with percentage of ethanol present and generated the graph shown in Figure 1. They concluded that a blend of 18.5% dry ethanol (1.1 mm<sup>2</sup>/s viscosity) with No. 2 diesel (2.46 mm<sup>2</sup>/s viscosity) would equal the ASTM minimum viscosity of 2.0 mm<sup>2</sup>/s at 37.8°C and would be well above the minimum for No. 1 diesel as shown in Figure 1. Investigations of the effect of additives on viscosity could not be found. However, Speidel and Ahmed (1999) report a viscosity of 2.25 mm<sup>2</sup>/s for a blend containing 15% dry ethanol, 5% PEC additive and 80% diesel. It should be noted that the final blend viscosity is dependent on the viscosity of the diesel fuel. Blending ethanol with a diesel fuel that has a viscosity close to the minimum is likely to yield an overall viscosity lower than the ASTM minimum.

Two ASTM lubricity tests are commonly used to characterize the lubricity of fuels, the Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SBOCLE), D6078-99 and the High Frequency Reciprocating Rig (HFRR), D6079-99. Relatively few lubricity tests have been carried out on ethanol-diesel blends. Speidel and Ahmed (1999) report a SBOCLE test value of 5200g for the blend containing 15% dry ethanol, 5% PEC additive and 80% diesel, as compared to the minimum of 3100g specified for No. 2 diesel.

Bio-based oils have been effective in increasing fuel lubricity and are commercially available. Hardenberg and Schaefer (1981) included 1% castor oil in a 95% ethanol fuel that was used successfully in a fleet of trucks and busses in Brazil.

Minimum specifications for viscosity and lubricity of ethanol-diesel blends are required in order to ensure that fuel injection system durability is not compromised relative to diesel fuel usage and that engines are able to start reliably when hot.

### **Materials Compatibility**

The use of ethanol in gasoline engines in the early 1980's resulted in numerous materials compatibility studies, many of which are also applicable to the effect of ethanol-diesel blends in diesel engines and particularly in the fuel injection system. The quality of the ethanol has a strong influence on its corrosive effects (Hardenberg and Schaefer, 1981). In addressing the problems of ethanol corrosion associated with gasoline blends, Brink *et al.* (1986) divided ethanol corrosion into three categories: general corrosion, dry corrosion and wet corrosion. General corrosion was caused by ionic impurities, mainly chloride ions and acetic acid. Dry

corrosion was attributed to the ethanol molecule and its polarity. De la Harpe (1988) reviewed reports of dry corrosion of metals by ethanol and found that magnesium, lead and aluminum were susceptible to chemical attack by dry ethanol.

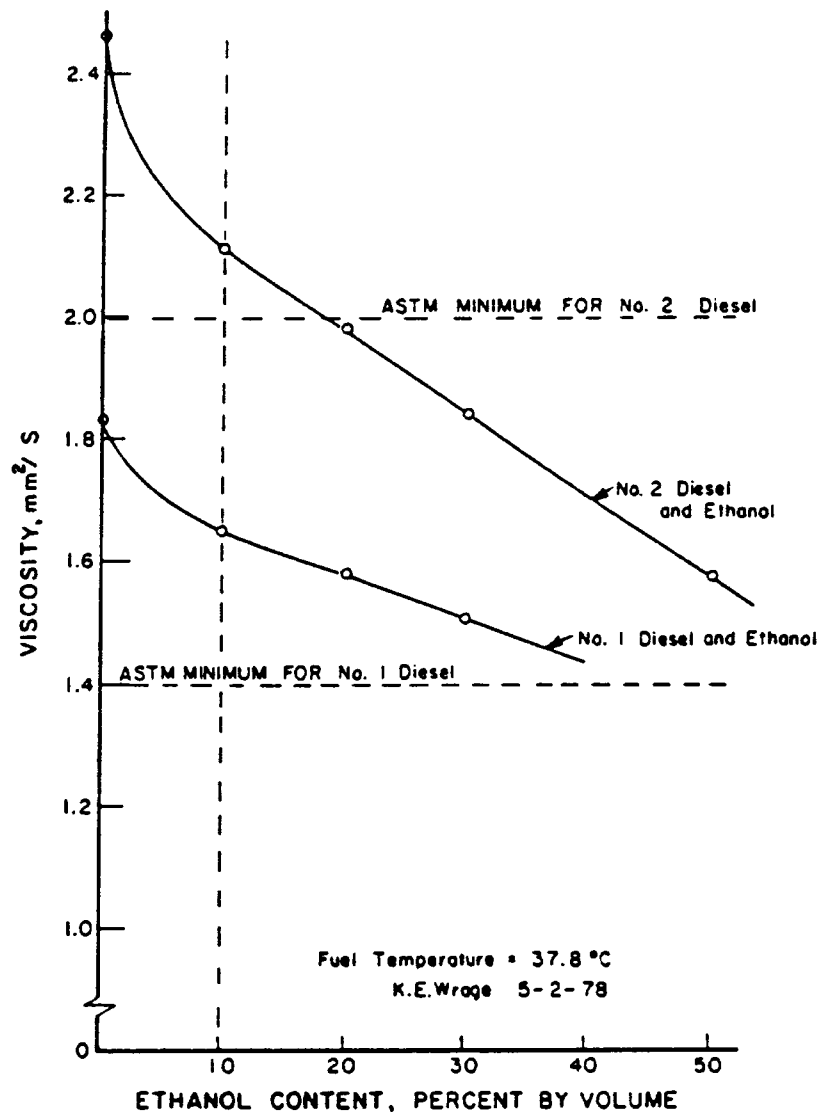


Figure 1 Effect of ethanol content on fuel viscosity (Wrage and Goering, 1980)

Wet corrosion is caused by azeotropic water, which oxidizes most metals. Freshly formulated blends containing pH neutral dry ethanol would be expected to have relatively little corrosive effect. However, if a blend has been standing in a tank for sufficient time to allow the ethanol to absorb moisture from the atmosphere, it may tend to be more corrosive as it passes through the fuel injection system. In addition, the fuel may stand in the fuel injection pump for a number of months, for example in a combine harvester engine, thus allowing the fuel time to corrode parts of the pump internally. Corrosion inhibitors have been incorporated in some additive packages used with ethanol-diesel blends (de la Harpe, 1988).

Non-metallic components have also been affected by ethanol with particular reference to elastomeric components such as seals and O-rings in the fuel injection system. These seals tend to swell and stiffen. Resin-bonded or resin-sealed components are also susceptible to swelling and seals may be compromised (Bosch, 2001).

## **Energy content**

The energy content of a fuel has a direct influence on the power output of the engine. Wrage and Goering (1980) stated that it would be desirable for ethanol-diesel blends to have gross energy contents at least 90-95% of that for No. 2 diesel to permit existing engines to deliver adequate power for the loads for which the vehicle is designed. The energy content of ethanol-diesel blends decreases by approximately 2% for each 5% addition of ethanol by volume, assuming that any additive included in the blend has the same energy content as diesel fuel.

## **Cetane number**

The minimum cetane number specified by ASTM for No. 2 diesel is 40. Typical No. 2 diesel fuels have cetane numbers of 45-50. With the inverse relationship of octane number and cetane number, ethanol exhibits a low cetane rating. Hence, increasing concentrations of ethanol in diesel lower the cetane number proportionately. Hardenberg and Ehnert (1981) stated that using cetane numbers to describe the ignition characteristics of ethanol-diesel blends was unreliable, because of discrepancies in the determination of cetane numbers below 30. However, they estimated that the cetane number of ethanol was between 5 and 15. Lower cetane numbers mean longer ignition delays, allowing more time for fuel to vaporize before combustion starts. Initial burn rates are higher causing more heat release at constant volume, which is a more efficient conversion process of heat to work. Nevertheless, it is preferable to add an ignition improver to raise the cetane number of ethanol-diesel blends so that they fall within an acceptable range equivalent to that expected of No. 2 diesel fuel.

Schaefer and Hardenberg (1981) evaluated a number of ignition improvers for ethanol fuel with special emphasis on biomass-derived nitrates. They noted a significant dependence of the energy release per equivalent nitrate on the molecular weight of the ignition improving nitrate. Hardenberg and Schaefer (1981) found triethylene glycol dinitrate (TEGDN) to be the most satisfactory ignition improver in tests performed in Brazil, especially as it could be manufactured from ethanol. Meiring *et al.* (1983b) added 4.5% octyl nitrate ignition improver to a 30% ethanol-diesel blend to achieve the same ignition delay as for diesel fuel.

Moses *et al.* (1980) found differences in cetane numbers between ethanol-diesel emulsions and stable blends of aqueous ethanol and diesel containing no additive. The emulsified ethanol had less effect on cetane than the ethanol in solution. They thought that this was due to a shielding effect of the emulsion structure delaying evaporation of the alcohol from the fuel droplets, while in the solution, the ethanol molecules were free to evaporate immediately.

## **Engine Performance with Blends**

Comparisons of engine performance between ethanol-diesel blends and standard diesel in unmodified engines generally show reductions in power that are approximately equivalent to the reductions in energy content of the blends relative to diesel fuel. Increased leakage in the fuel injection pump with the lower viscosity fuels also contributes to reduced power in the load control range of the engine. Meiring *et al.* (1983b) reported a 5% drop in maximum fuel delivery when evaluating a 30% ethanol-diesel blend in a tractor engine fitted with a rotary distributor pump. They adjusted the maximum fuel delivery setting on the pump to partially restore the power lost from reduced energy content and fuel pump leakage.

In recent studies, Hansen *et al.* (2000) measured a 7-10% decrease in power at rated speed with a 15% dry ethanol, 2.35% PEC additive and 82.65% No. 2 diesel fuel blend run in a Cummins 5.9 L engine. Kass *et al.* (2001) checked the torque output from the same model engine with two blends containing 10% and 15% dry ethanol respectively and 2% Betz-Dearborn additive, and reported an approximate 8% reduction for both fuel blends.

In-field studies of a tractor and combine running on 10% dry ethanol, 1.3% Betz-Dearborn additive and 88.7% No. 2 diesel fuel yielded increases in fuel consumed of 4-5% compared to the same model tractor and combine operating on No. 2 diesel fuel, which was approximately equivalent to the reduction in energy content (Hansen *et al.*, 2001). The operators of these vehicles indicated that they did not notice any significant differences when operating their machines in the field.

As would be expected, the specific fuel consumption (SFC) in kg/kWh increases with increasing concentrations of ethanol in the blend because of the reduced energy content. However, specific energy consumption (SEC) in MJ/kWh is approximately the same as for diesel fuel or has been shown to be slightly better. Moses *et al.* (1980) stated that the improvements in SEC were small but consistent for the ethanol-diesel blends tested and they were assumed to be the result of an improvement in the thermal cycle efficiency. Hansen *et al.* (2001) reported similar trends for a combine operating under field conditions on 10% ethanol, in which the combine on the blend ran consistently with a 2-3% higher brake thermal efficiency.

## Engine Durability

A limited range of durability tests have been conducted on ethanol-diesel blends both in the laboratory and in the field. In early studies, tests with blends containing approximately 10% and 15% dry ethanol indicated no abnormal wear in engines correctly adjusted for injection timing (Hansen *et al.*, 1982; Hashimoto *et al.*, 1982; Meiring *et al.*, 1983a). Some engines included in these tests were more sensitive to a lowering of the cetane number and hence an increased ignition delay causing piston erosion. However, a small retardation of injection timing was recommended so as to reduce rates of pressure rise. In the durability tests conducted by Meiring *et al.* (1983b) no abnormal deterioration of the engine or fuel injection system was detected after 1000 hours of operation on a blend containing 30% dry ethanol, small amounts of octyl nitrate ignition improver and ethyl acetate phase separation inhibitor, and the remainder diesel fuel.

Recent over-the-road tests by Archer Daniels Midland (ADM) in Decatur, Illinois on two trucks operating on 15% ethanol blend of E diesel have resulted in an accumulation of over 400,000 km (250,000 miles) on each vehicle with no abnormal deterioration in condition (Marek and Evanoff, 2001). The Chicago Transit Authority (CTA) monitored the condition and overall performance of a fleet of 30 buses, of which 15 operated on the 15% ethanol blend and 15 were the control and ran on No. 1 diesel. After 434,500 km (270,000 miles) accumulated by the 15 buses running on the blend, no abnormal maintenance or fuel-related problems were encountered (Marek and Evanoff, 2001).

Hansen *et al.* (2001) have been running a farm demonstration project with two John Deere 9400 tractors, two Caterpillar Challenger 95E tractors and two John Deere 9650 combines, one of each vehicle type running on a 10% ethanol blend of "E diesel" using the Betz-Dearborn additive, and the other on No. 2 diesel. One of the objectives was to monitor the durability of the vehicles. The John Deere tractors have operated for two Spring seasons and one Fall season accumulating approximately 700 hours with no abnormal deterioration in engine condition, based on oil analyses. The Caterpillar tractors and combines have completed one season with approximately 250 hours and 400 hours accumulated respectively, again with no abnormal wear patterns according to oil analysis.

A laboratory-based 500-hour durability test was performed by Hansen *et al.* (2000) on a Cummins ISB 235 engine running on a 15% dry ethanol, 2.35% PEC additive and 82.65% diesel fuel. The engine operated at rated speed and maximum load in order to maximize the fuel throughput in the fuel injection system. With the exception of the fuel injection system, no abnormal deterioration in engine condition was detected based on detailed engine component

measurements and examination. Calibration checks of both injection pump and injectors showed that they were within normal tolerances. However, one resin-sealed sensor in the injection pump failed because of possible chemical interaction with the fuel and the injectors exhibited heavy wear from the needle valve action. Further tests are required to verify these results.

Long-term durability tests of at least 1000 hours are necessary to provide confirmation that ethanol-diesel blends do not adversely affect engine wear compared to the norms established for diesel fuel usage.

## Emissions

Early studies of the effect of ethanol-diesel blends on engine performance included measurements of soot output in the exhaust with a smoke-meter (Wrage and Goering, 1980; Meiring *et al.*, 1983a). Substantial reductions in particulate matter (PM) were observed in these tests. Recent studies have shown that the improvement in exhaust emissions provided by oxygenate fuels depended almost entirely on the oxygen content of the fuels, regardless of the oxygenate to diesel fuel blend ratios or the type of oxygenate (Miyamoto *et al.*, 1998). In their study of the effect of oxygen enhancement on emissions from a direct injection diesel engine, Donahue and Foster (2000) found that the improvement in emissions depended on the local oxygen concentration in the fuel plume regardless of the method of oxygen enhancement.

Emissions tests conducted specifically on ethanol-diesel blends confirm the effect of substantially reducing PM (Spren, 1999; Schaus *et al.*, 2000; Kass *et al.*, 2001). The effect on carbon monoxide (CO), total hydrocarbon (THC) and oxides of nitrogen (NO<sub>x</sub>) are less clear (Kass *et al.*, 2001). In addition, comparative emissions data are influenced by a number of factors that may have cause greater differences than those brought about by the fuel (Sinor and Bailey, 1993). These factors include engine fuel metering technology, exhaust control technology, age of the vehicle, maintenance history, test procedure, and test conditions. Nevertheless, these tests provide a means of gauging the relative benefits of introducing these blends as a substitute for traditional diesel fuel.

Table 1 provides a summary of the emissions tests performed by Spren(1999), Schaus *et al.* (2000) and Kass *et al.* (2001). The test engines, test procedures and base fuels vary considerably. The results of Spren (1999) and Kass *et al.* (2001) showed a consistent reduction in PM of 20-27% and 30-41% for 10% and 15% ethanol blends respectively. Reductions in NO<sub>x</sub> varied from none to 4-5 %. Both decreases and increases in CO emissions occurred, while HC increased substantially, but both were still well below the regulated emissions limit. The measurements reported by Schaus *et al.* (2000) vary considerably for both PM and NO<sub>x</sub> with both decreases and increases in emissions being dependent on speed and load of the engine. Both Schaus *et al.* (2000) and Kass *et al.* (2001) emphasize the potential to optimize injection characteristics, so as to minimize emissions over the complete performance map of the engine. The major variations in emissions measured by Schaus *et al.* (2000) are an indication of the reductions in emissions that could be obtained with ethanol-diesel blends. Further factors that need to be considered are the influence of ethanol-diesel blends on exhaust gas recirculation systems (EGR). Kass *et al.* (2001) stated that the higher CO and THC emissions suggested that fuel blends might offer a means to enhance advanced emission control systems that require regeneration, such as NO<sub>x</sub> adsorbers, by supplying reducing agent.

Kass *et al.* (2001) concluded from their tests that ethanol-diesel blends could be applicable as low emission fuels for current and older model vehicles that were not required to meet future EPA emission standards. However, extensive testing of these fuel types in older and late model diesel engines, needed to be performed in order to accurately assess performance.

The addition of ethanol to diesel naturally reduces the content of sulfur in the fuel in proportion to the amount added, including any sulfur-free additive. As much as a 20% volumetric reduction in sulfur may be provided, thus significantly reducing SO<sub>2</sub> emissions (Marek and Evanoff, 2001).

Table 1 Summary of emissions test results from 10% and 15% ethanol-diesel blends

Reference	Spreen (1999)		Schaus <i>et al.</i> (2000)		Kass <i>et al.</i> (2001)	
<b>Test Engine</b>	1991 DDC series 60 6-cyl, 12.7 L DI with turbocharger and intercooler		1997 VW TDI 4-cyl, 1.9 L DI with turbocharger, EGR and oxidation catalyst		1999 Cummins ISB 6-cyl, 5.9 L DI with turbocharger and intercooler	
<b>Test Procedure</b>	Hot-start transient tests based on EPA Federal Test Procedure (CFR 40-86N)		Steady-state 5x5 speed-torque test matrix (SAE J1003)		Steady-state AVL 8-mode test cycle	
<b>Reference Fuel</b>	Emissions grade fuel meeting 1998 EPA specifications		Standard no. 2 diesel		Phillips Petroleum certification fuel containing 350-ppm sulfur	
<b>Test Fuel(%vol.):</b>						
<b>Ethanol</b>	10	15	10	15	10	15
<b>Additive</b>	2.35 PEC*	2.35 PEC*	~2 BD**	~2 BD**	~2 BD**	~2 BD**
<b>Diesel</b>	87.65	82.65	~88	~83	~88	~83
<b>Ave. Emissions (blend/ref. fuel ratio %):</b>						
<b>PM</b>	73	59	27-159	25-157	80	70
<b>NO<sub>x</sub></b>	96	95	80-125	40-125	100	100
<b>CO</b>	80	73	-----	-----	160	140
<b>HC</b>	171	210	-----	-----	200	175

\*PEC - Pure Energy Corporation additive

\*\*BD - Betz-Deardon additive

## Safety and Biodegradability

The flammability of alternative fuels during handling and storage is a major concern when considering their introduction into existing facilities. The vapor produced by the evaporation of motor fuels can create flammable conditions in partially filled fuel tanks during refueling, and when damage or a leak occurs in tanks or other fuel system components (Vaivads *et al.*, 1995). In the fuel tank headspace, rising temperatures will produce fuel vapors, which progress from too-lean-to-burn to combustible to too-rich-to-burn (Boruff *et al.*, 1982).

Flammability of a fuel is typically described in terms of its flammability limits and its flashpoint. Flammability limits are the minimum and maximum concentrations of combustible vapor in air,

and the temperatures at which the vapor occurs, that will propagate a flame after sufficient ignition energy is provided (Battelle, 1998). Flashpoint is the lowest temperature at which the vapor pressure of a liquid is sufficient to produce a flammable mixture in the air above the liquid surface within a vessel. Battelle (1998) provide a comparison of these variables for neat diesel fuel, ethanol and gasoline given in Table 2, which showed that ethanol fell between diesel fuel and gasoline in terms of flashpoint and flammability temperature limits. However, both the minimum and maximum concentration limits were higher than those for diesel fuel and gasoline.

Table 2 Fuel characteristics related to flammability of neat diesel fuel, ethanol and gasoline (after Battelle, 1998)

Fuel Characteristic	Neat Diesel Fuel	Neat Ethanol	Neat Gasoline
Vapor Pressure @ 37.8°C (kPa)	~0.3	~17	~65
Flashpoint (°C)	~64	~13	~ -40
Auto-ignition Temperature (°C)	~230	~366	~300
Flammability Limits (%)	~0.6 to ~5.6	~3.3 to ~19.0	~1.4 to ~7.6
Flammability Limits (°C)	~64 to ~150	~13 to ~42	~ -40 to ~18

Battelle (1998) conducted flammability tests on neat diesel, neat ethanol, 10%, 15% and 20% ethanol-diesel blends and obtained the results illustrated in Figure 2. They found the data for the three blends to be almost identical to those of neat ethanol. They concluded that for tank-storage purposes, 10-20% ethanol blends with No. 2 diesel fuel had similar flashpoints (~12°C) and upper flammability limit temperatures (42°C), making fire-safety independent of the amount of ethanol in the blend. Also, the flammability characteristics of ethanol-diesel blends were more like those of ethanol than diesel fuel with headspace vapors of these blends being flammable within storage tanks at approximately 12°C to 42°C compared to diesel fuel at approximately 64 to 150°C. Temperatures of fuel in the tank of diesel-fueled vehicles are raised because of fuel recirculation needed to cool the fuel injection system. Temperatures as high as 93°C (200°F) may be expected (Battelle, 1998).

A key hazard of the higher flammability limits is ignition of the plume of vapor leaving the tank during refueling as a result of external sparks, static discharge or smoking materials (Vaivads *et al.*, 1995). In the case of ethanol-diesel blends, static discharge may not be as much of an issue because of the higher conductivity of ethanol. In guidelines established by the National Fire Protection Agency (NFPA) for safe storage and handling of flammable liquids, the discriminating fuel property is the flashpoint (Battelle, 1998). Liquids such as gasoline and ethanol are Class I liquids as they have flashpoints below 37.8°C (100°F), whereas Diesel fuel is Class II with a flashpoint above 37.8°C. Hence the addition of ethanol to diesel would change the NFPA classification from Class II to Class I, thus requiring more stringent storage requirements such as greater distance in location of storage tanks from property lines, buildings and other tanks. Flame arrestors should be installed in filler necks (Battelle, 1998).

A further source of ignition is the use of in-tank electrical fuel pumps (Vaivads *et al.*, 1995). It has been shown that the typical energy in a spark caused by a break in the inductive circuit at the current levels typical of these pumps is sufficiently strong to ignite a flammable mixture (Vaivads *et al.*, 1995).

In tests conducted so far, no specific evaluations have been carried out to establish conclusively that co-solvents used in ethanol-diesel blends have no effect on flammability limits. Further work is required in this area. In tests carried out in the field on ethanol-diesel blends in Illinois, no problems or accidents have occurred through handling, storing or dispensing the blends (Marek and Evanoff, 2001).

Speidel and Ahmed (1999) evaluated the biodegradability of alternative fuels, including a diesel blend with 15% ethanol and 5% PEC additive. They found that this blend was 70% more biodegradable than diesel fuel. The impact of sunlight and heat exposure on long term storage stability of this blend was also investigated. Diesel fuel formed a dark irreversible residue under such conditions, while the blend coloration deepened but no residual matter was detected (Ahmed and Marek, 1999).

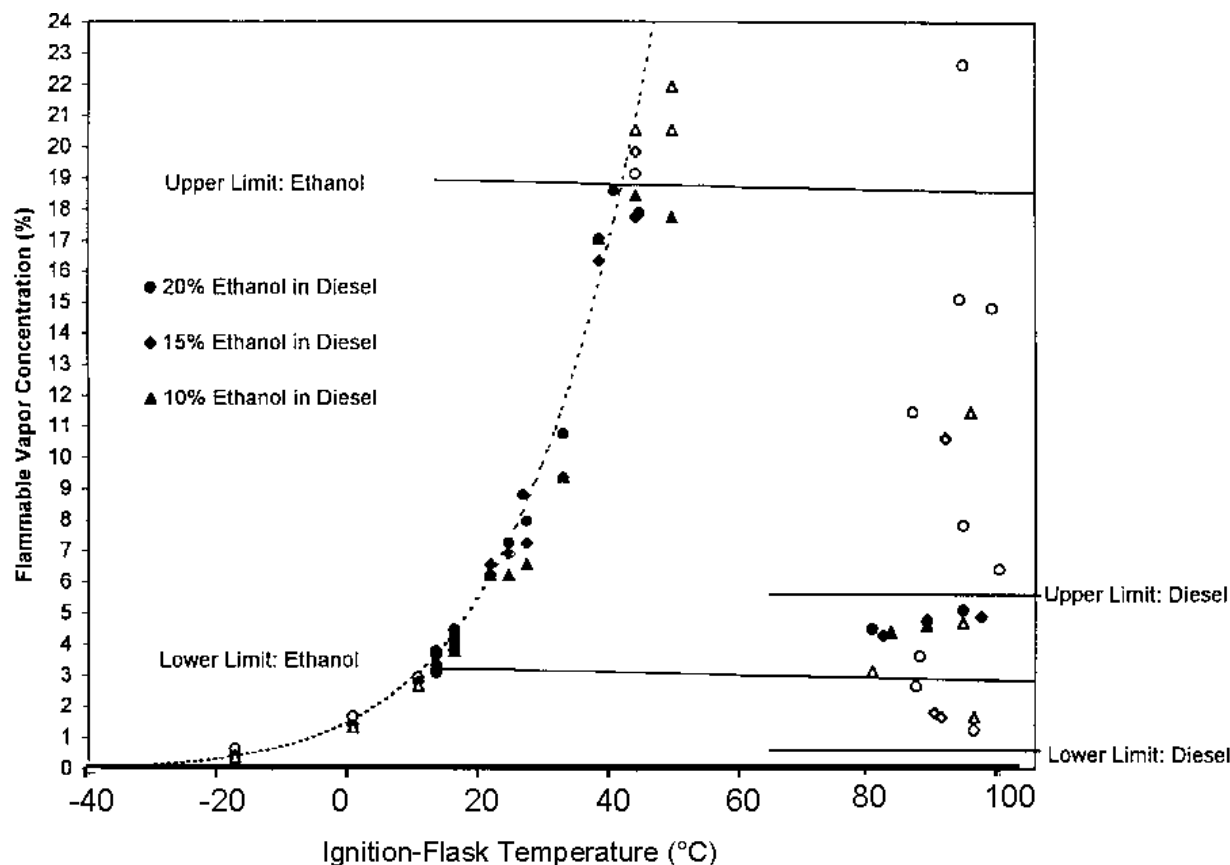


Figure 2 Flammability characteristics of ethanol-diesel fuel blends (after Battelle, 1998)

## Economic Implications

If ethanol-diesel blends were to capture a 10% market share, the demand for corn would raise the USA national price for corn by approximately \$0.05 per bushel and local economies of agricultural states such as those in the midwestern part of the USA would receive a tremendous boost (Marek and Evanoff, 2001). However, the cost of the fuel to the consumer must be able to compete favorably with the cost of conventional diesel fuel. With tax credits and exemptions, ethanol blended with diesel fuel has the potential to compete with No. 2 diesel fuel on a price per gallon basis. According to Marek and Evanoff (2001), under present circumstances in which ethanol-diesel fuel blends have not been commercialized, an increase in cost of \$0.10 to \$0.20 over the cost of No. 2 diesel fuel is anticipated, largely because of the cost of the additive. Once commercialized, a goal has been set to bring the overall cost of ethanol-diesel blends within \$0.05 per gallon of diesel fuel (Marek and Evanoff, 2001).

## **Conclusions**

The properties of ethanol-diesel blends have a significant effect on safety, engine performance and durability, and emissions. A set of specifications that define key fuel characteristics pertaining to ethanol-diesel blends and additives should be established in collaboration with fuel and additive manufacturers and with engine manufacturers before these blends can be commercialized.

An increase in fuel consumption approximately equivalent to the reduction in energy content of the fuel can be expected when using ethanol-diesel blends. With ethanol percentages of 10% or less, operators have reported no noticeable differences in performance compared to running on diesel fuel.

Long-term durability tests in a range of engines with different fuel injection system configurations will help to confirm that diesel oxygenated with diesel does not adversely affect engine wear compared to diesel fuel. Such tests should be performed with the assistance of engine manufacturers.

It is accepted that the addition of ethanol to diesel fuel will have a beneficial effect in reducing the PM emissions at least. The amount of improvement varies from engine to engine and also within the working range of the engine itself. While there is considerable value in being able to use the fuel directly in an unmodified engine, small adjustments to fuel injection characteristics may result in further gains in reducing emissions.

The flammability of ethanol-diesel blends indicates that they should be treated as Class I liquids as they have flashpoints below 37.8°C, in contrast to diesel fuel, which is a Class II liquid. Hence, appropriate measures when using ethanol-diesel blends need to be implemented to meet the storage, handling and dispensing requirements that are stipulated for Class I liquids.

The rapidly increasing use of ethanol as a fuel additive for gasoline provides an opportunity to expand its use further as an oxygenate for diesel fuel. Preliminary economic analyses suggest that ethanol-diesel blends can compete favorably with regular diesel in existing unmodified engines. The more stringent emissions regulations should add impetus to its adoption as a commercial fuel.

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