DIESEL FUEL ISSUES

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ABSTRACT

In recent years, environmental regulations have had a dramatic effect on the formulation of diesel fuel. The trend toward low-environmental impact diesel fuel has resulted in new formulations that not only benefit the environment but can enhance diesel engine performances as well. The sulfur content of highway diesel fuel has been reduced to a maximum of 0.05% by weight nationwide. California has an additional requirement of a maximum of 10% aromatics content that covers most highway and non-highway vehicles. However, fuels with higher aromatics levels can be certified if they demonstrate equivalent emissions. Development of such certified fuels has been the focus of much research by fuel producers.

The introduction of new fuels, coupled with the rapid changes in engine design to meet new emission regulations, has created the need to address several fuel properties to ensure proper performance while protecting certain engine components. Diesel fuel lubricity and its effect on some fuel system injection equipment, such as a rotary distributer pump, is one such issue which is being investigated by several groups. Other issues are also being addressed by joint groups in industry and regulatory agencies. Their goal is to find practical solutions, in each case, in a relatively short time.

To maximize the reduction of diesel exhaust emissions, both engines and fuels have been regulated. On the engine side, elements such as electronic management systems, engine geometry changes, higher injection pressures and timing optimization have been used to reach new emissions goals. On the fuel side, properties such as sulfur and aromatics contents, and also cetane index, have been regulated. Fuel regulations were based on the best technical data available at the time. In some cases, different properties might have been targeted had the results of new research been available.

Additional changes to diesel fuel properties, beyond the regulated ones, have been proposed by engine manufacturers to make meeting future engine emissions regulations more feasible. These changes in fuel properties and those imposed by the regulations, while environmentally beneficial can sometimes, cause performance problems. These problems would need to be investigated rapidly and solved simultaneously with the introduction of new fuels.

This article includes the description of some pertinent fuel properties, a summary of the Federal and California fuel regulations, and a brief review of several fuel related issues, such as lubricity. In some areas, such as diesel fuel dye requirements, rapid changes are in progress. Therefore, developments may replace some information provided at this time.

INTRODUCTION

Conventional diesel fuel and practices associated with its production, handling, and use are well established and have been understood for many years. Recent and rapid changes in this area have created many new challenges. Environmental requirements and demands, much like the ones in the gasoline area, were initiated in the 1980s to regulate and limit the emissions related to the use of diesel fuel. Oxides of nitrogen (NOx) and particulate matter (PM) have been the main focus of the regulations. Compression ignition engines have the advantage of operating more efficiently since they have a higher compression ratio. This, however, translates to higher peak combustion temperatures, which leads to higher NOx levels. Hydrocarbon (HC) and carbon monoxide (CO) emissions, on the other hand, are not as serious issues as they are in gasoline engines.

FUEL PROPERTIES

The American Society for Testing and Materials, ASTM, has specified fuel properties for various grades of diesel fuel (1). Table I contains the specifications for No. 1 and No. 2 diesel fuels. In both cases a new category has been established for the new low sulfur fuels. The following is a brief discussion of the effect of some fuel properties.

Sulfur

Some sulfur in the fuel contributes directly to particulate emissions. Reducing diesel fuel sulfur content, therefore, is an effective way to reduce particulate emissions. Sulfur oxides can also combine with water in the engine to form acids that can attack metals (2).

TABLE 1 ASTM REQUIREMENTS FOR DIESEL FUEL OILS

Property	Grade Low Sulfur No. 1-D	Grade Low Sulfur No. 2-D	Grade No. 1-D	Grade No. 2-D
Flash Point, °C (°F), Min.	38 (100)	52 (125)	38 (100)	52 (125)
Water and Sediment, % Vol, Max.	0.05	0.05	0.05	0.05
Distillation Temperature, °C (°F) 90% % Vol Recovered				
Min.	-	282 (540)	-	282 (540)
Max.	288 (550)	338 (640)	288 (550)	338 (640)
Kinamatic Viscosity, mm^2/s at 40°C (104°F)				
Min.	1.3	1.9	1.3	19
Max.	2.4	4.1	2.4	4.1
ASH. % Mass, Max.	0.01	0.01	0.01	0.01
Sulfur, % Mass, Max.	0.05	0.05	0.50	0.50
Copper Strip Corrosion Rating Max. 3 Hr at 50°C (122°F)	No. 3	No. 3	No. 3	No. 3
Cetane Number, Min.	40	40	40	40
One of the Following Properties Must be Met				
(1) Cetane Index, Min.	40	40	-	-
(2) Aromatic, % Vol, Max.	35	35	-	-
Cloud Point, °C (°F), Max.	-	-	-	-

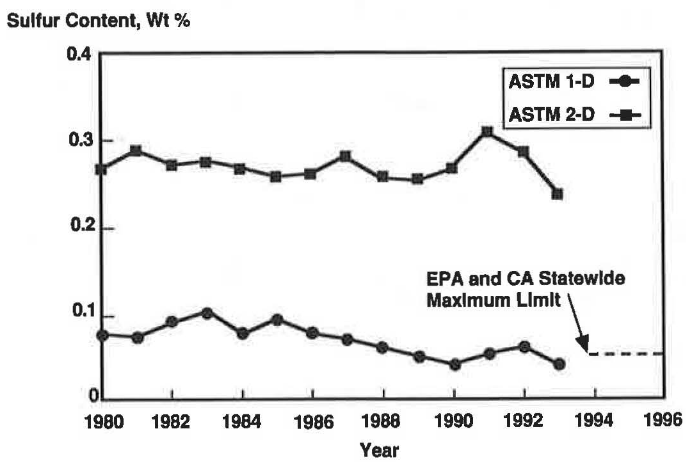

FIGURE 1 U.S. diesel fuel sulfur content trends.

These acids contribute to wear and deposit formation. There is ongoing pressure on fuel suppliers to reduce the fuel's sulfur content. The trend for diesel fuel sulfur content in the U.S. is presented in Figure 1 (3). There had not been a substantial change in the trend until the introduction of the low sulfur fuels in 1993.

Cetane Number

This property is a measure of the ignition quality of the fuel. In a gasoline engine, it is necessary to avoid autoignition prior to spark ignition to have a well-managed combustion process. The diesel engine, however, depends on the fuel to autoignite in the absence of spark plugs. Cetane number affects cold starting and smoke. Engine manufacturers and fuel producers have been engaged in research to determine the cost effectiveness of raising the ASTM cetane number requirement, affecting both emissions and performance. Figure 2 provides the yearly cetane number averages of the U.S. fuels (3). Note that in most cases these values are well above the ASTM required minimum of 40.

Aromatics

Aromatics are the more compact and less reactive hydrocarbon fractions of diesel fuel (4). They resist

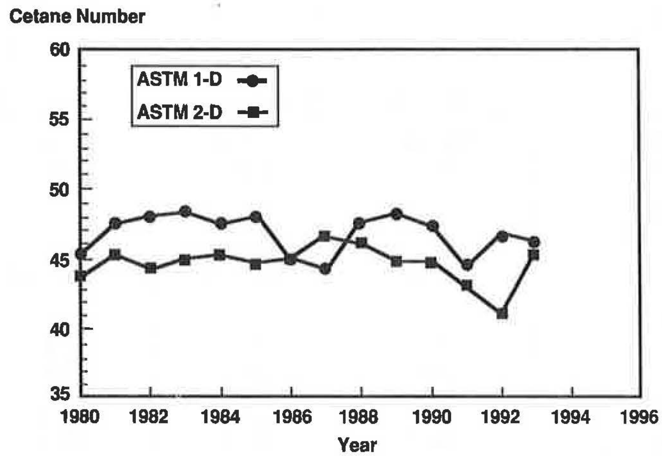

FIGURE 2 U.S. diesel fuel cetane number trends.

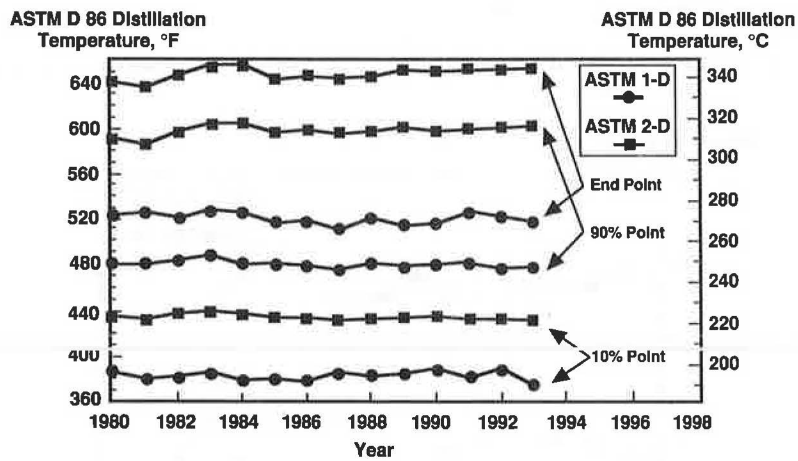

FIGURE 3 U.S. diesel fuel distillation trends.

ignition, which results in a fuel with a lower cetane number. It is generally believed that higher aromatics-containing fuels contribute to higher NOx and PM emissions. Federal regulations include aromatic control and California mandates a substantial reduction.

Distillation

Diesel fuel is a mixture of hydrocarbons with a range of heating value, density, flash point and volatility. One convenient way to characterize the fuel is to determine the boiling point of each fraction of these hydrocarbons. The ASTM specification, in its current form, includes the 90% distillation point of the fuel. Some engine manufacturers have asked for an endpoint specification to prevent the exposure of the engine to heavy oils. The average distillation trend for U.S. diesel fuels is presented in Figure 3 (3). No significant change has occurred in the last few years.

Viscosity

Proper injection system lubrication and optimum fuel atomization require the fuel to have a viscosity between 1.3 and 2.4 mm^2/s at 40° C for No. 1 fuel, and 1.9 and 4.1 for No.2 fuel (1). Poor combustion results from high viscosity fuel because the fuel droplets are too large. If the viscosity is too low, the fuel will not travel far enough in the combustion chamber (2). This will result in poor mixing and power loss.

Cloud Point

Wax formation in the engine's fuel handling system can lead to filter plugging. This process is a function of fuel composition and temperature. Therefore, no universal value can be specified for this property. Cloud point specifications are based on geographic location and time of the year. Fuel purchased in the winter in a warm region of the country should not be used in colder regions. In areas where refineries cannot produce a No. 2 fuel with a low enough cloud point, blending with No. 1 fuel or additives can be used.

REGULATIONS

Federal regulations required all highway diesel fuel to be limited to a maximum sulfur content of 0.05% by weight starting October 1993. Such fuels also are limited to a minimum cetane index of 40 or a maximum aromatics content of 35% by volume. Cetane index is a calculated value that tends to increase as fuel aromatics decrease. It was selected as a parameter to control fuel aromatics. Cetane number was not chosen because it can be raised with cetane improver additives with no effect on aromatics.

California regulations have the additional requirement of a maximum aromatics content of 10% by volume. The California Air Resources Board's (CARB's) decision to lower the aromatics content of the fuel was based on the best information available at the time. This included data generated in a cooperative study sponsored by the Coordinating Research Council, CRC (5). CARB's emphasis on aromatics at the time might have been altered to recognize the effect of fuel cetane number had the results of the next phase of the CRC program been available (6). This phase of the program concluded that cetane number was effective in reducing HC, CO, NOx, and PM emissions.

Alternative Formulation Fuels

Lowering the aromatics content of diesel fuel from well over 30% by volume to below 10%, requires major capital investments and increased operating costs to most California refineries for severe hydrotreating processes. This is a significant financial burden during a period in which capital funds are needed to make changes required for producing reformulated gasoline, and for complying with a range of other environmental regulations.

CARB has allowed fuel producers the option of producing a less-costly alternative formulation fuel with a higher aromatics content, if equivalent emissions can be demonstrated (7). A candidate fuel to be tested for emissions equivalency must meet the ASTM D 975 diesel fuel specifications. In addition, the following five fuel properties must be determined:

- Sulfur content (not to exceed 500 ppm);
- Total aromatic hydrocarbon content;
- Polycyclic aromatic hydrocarbon content;
- Nitrogen content; and
- Cetane Number.

Once the fuel is certified "equivalent" in a 1991 Detroit Diesel Corporation (DDC) Series 60 engine using a transient emissions cycle, a producer can market the equivalent fuel if the above first four certified properties are not exceeded. The cetane number is a minimum requirement. No further testing is required and any processing and blending scheme can be used to produce the fuel. Table II is a list of five fuels Chevron tested as equivalent candidates (8). Three resulted in successful certifications, including one that became the first CARB certified California alternative diesel fuel. Other fuel producers have certified a number of fuels since then, however, formulations for some of these fuels have been kept confidential.

PERFORMANCE ISSUES

Rapidly changing fuel properties required by environmental regulations can affect fuel handling practices and engine performance. A property that reduces emissions or improves performance in one area may have adverse effects in other areas. Examples of some performance related issues are described in this section.

Elastomer Compatibility

Coincident with the use of low sulfur fuel, some diesel vehicles developed fuel leaks. The leaks occurred at points where elastomers (O-rings) were used to seal joints in the fuel system. The most common incidents were injector fuel pump leaks. According to a task force report prepared for the Governor of California (9), it is estimated that about 2 percent of the heavy duty diesel vehicles were affected.

TABLE 2 FUEL CERTIFICATION ATTEMPT

Fuel Name	Aromatics, Wt % (SFC)	Cetane Number	Sulfur, Wt ppm	Test Result
E2	18.5	50	54	Failed
A2	19	58	54	Passed
D2	16	55	44	Failed
F2	19	59	196	Passed
G2	15	55	202	Passed

Leaks were not limited to any specific engine, fuel supplier or geographic area. They did, however, seem to be related to nitrile rubber (Buna N) seals that had seen long service at high load and high temperature (9). Two possible explanations are being investigated:

- Many new fuels contain less aromatics. Some have suggested that the change from a higher to a lower aromatics content fuel causes seals to shrink. Under this theory, aged seals, which do not have the elasticity to adapt to this change, can fail.
- Some new fuels may be more susceptible to oxidation. The resulting oxidation products (peroxides) might attack the seal material and prematurely age it.

It should be noted that this seal leak issue is not related to diesel fuel lubricity. There is no known relationship between the fuel properties that affect lubricity and those that affect seal leaking.

Lubricity

Diesel injection equipment manufacturers, diesel users, and diesel suppliers have expressed concern regarding the lubricity characteristics of No. 2-D low sulfur diesel mandated in 1993. One reason for their concern is that fuel lubricity problems occurred in Sweden in 1991 when a very severely hydrotreated low sulfur and low aromatics content diesel was mandated. Another reason for their concern is that marginal diesel lubricity may take some time to result in equipment failure.

Diesel fuel functions as a lubricant in certain parts of diesel injection equipment such as rotary distributor pumps and injectors. Both low viscosity and lack of sufficient trace components such as oxygen- and nitrogen-containing compounds and certain aromatics types can be responsible for equipment wear (10).

If the refinery hydrotreating process used to reduce sulfur and aromatics levels is severe enough, the levels of some trace components are reduced. This may also reduce the lubricity properties of diesel fuel. It is not established, however, what hydrotreating severity corresponds to reduced lubricity that affects the operation of a diesel engine's fuel system components such as pumps and injectors. Lubricity associated with severe hydrotreating, known as boundary lubrication, is not necessarily related to diesel fuel viscosity. For example, if two fuels have the same viscosity, and one gives lower friction, wear or scuffing, then it is said to have better lubricity (11). Lubricity is not related to 0-ring seal leakage.

Diesel fuel contamination with excessive sediment and water can also be responsible for equipment wear and failure. People often mistake these effects, as well as lack of proper diesel fuel viscosity, with the effects of inadequate diesel fuel lubricity. Recent research has shown that lower sulfur alone is not related to lower lubricity (12). In fact, low sulfur fuel has been successfully produced and sold in Southern California since 1985.

It has been shown that the lubricity of a poor diesel fuel can be restored if blended with 10 to 20 percent of a good lubricity diesel fuel. It has also been demonstrated that potential diesel lubricity problems can be corrected by the use of lubricity-enhancing additives. However, excessive quantities of additives or improper additives may cause other problems, such as sediment formation in diesel fuel and gum formation in crankcase oils, resulting in plugging of fuel and oil filters. The practice of adding used crankcase oil to diesel fuel can also lower diesel lubricity. Some diesel engine manufacturers warn against this practice in their engines.

More recently, other technical groups and societies such as SAE (Society of Automotive Engineers), ASTM (American Society for Testing and Materials), and ISO (International Organization of Standardization) have begun to address the lubricity issue. The ISO group, in cooperation with the Coordinating European Council (CEC), is defining laboratory bench tests to evaluate the lubricity characteristics of diesel fuels and additives. The goal of the ISO program is to generate sufficient data from these test methods, and from fuel injection equipment performance tests, to select a single test method as the universal method for determining diesel fuel lubricity. This group also aims to produce sufficient information to define a minimum lubricity level to protect fuel delivery system components. ASTM will be able to consider a No. 2-D low sulfur diesel lubricity specification for inclusion in D 975, the Standard Specification for Diesel Fuel Oils, when a single test method has been selected.

Dye Requirement

This requirement has no beneficial effect on emissions reduction or engine performance. It is strictly a government policing tool to deter the illegal use of high sulfur content and non-taxed fuel. Federal regulations prohibit the use of high sulfur fuel for highway application. The Environmental Protection Agency (EPA) initially required the fuel producers to add blue dye to all diesel fuel with a sulfur content above 0.05% by weight. The Internal Revenue Service (IRS), on the other hand, had required addition of 10 pounds per thousand barrels (ptb) of an active blue dye to high sulfur fuels and 5.6 ptb of an active red dye to low sulfur fuels which are exempt from the highway transportation tax. IRS's initial concentration requirements were based on the desire to detect such fuels even after they have been diluted five times.

Many groups have studied and discussed many concerns with respect to these dye requirements. The Federal Aviation Administration (FAA), for example, has expressed concern about misfueling potentials since red and blue dyes are used in certain aviation gasoline products. Fuel suppliers have pointed out problems with established quality monitoring methods, toxicity, dye carry over to jet fuel using a common pipeline, etc., if higher-than-necessary concentrations of these dyes are used. The current decision by EPA and IRS is to use a single dye, red, for both requirements. The concentration level has been set at 3.9 ptb of the solid dye standard Solvent Red 26. Depending on the type of product, this translates to using 8 to 15 ptb of the dye product as received (13). Several concerned parties including many fuel suppliers believe this level is unnecessarily high.

CONCLUSIONS

The primary driving force to alter diesel fuel formulation and properties is the need to reduce exhaust emissions. Major changes have been mandated at the Federal and state levels in a short time. These changes, most often, have been effective. Occasionally, however, further studies and additional time would have resulted in more efficient ways to reduce emission. Continued cooperation between the regulatory agencies and the industry is needed to balance the environmental needs of the society with cost-effective and practical means of producing fuels.

Engine manufacturers are also facing similar challenges to modify their products to comply with aggressive clean air regulations. Engine designs and fuel formulations obviously affect each other along the way to reaching a common goal of improving the environment. The current high level of discussions between the Engine Manufacturers Association (EMA) and the American Petroleum Institute (API) keeps the communication channels open. Through this cooperative effort, a more balanced set of engines and fuels regulations will result. The end user, who depends on both products, will benefit by operating a lower-emissions vehicle without sacrificing operational or performance advantages.

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