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ABSTRACT

Diesel fuels derived from Fischer-Tropsch processes have a number of beneficial properties, including zero sulfur, high cetane, and near-zero aromatics content. Previous researchers have shown emissions benefits for using these fuels in light and heavy-duty diesel engines. A series of experimental fuels using neat F-T material or blends of F-T material with conventional cracked stocks was tested in diesel engines and produced lower emissions when compared to current diesel fuel. These experimental fuels cover a variety of boiling point ranges, extending from light naphtha to materials that are significantly heavier than conventional diesel fuels. All of the fuels show lower NOx and particulate emissions. F-T material can be used to increase the use of marginal refinery streams as diesel blend stocks and so increase the volume of low emission diesel fuels produced in current refineries.

INTRODUCTION

Diesel fuels can be produced from natural gas in a gas-to-liquids process (GTL) consisting of three steps: syngas generation, Fischer-Tropsch synthesis, and wax upgrading. These fuels consist almost entirely of paraffinic molecules and contain extremely low levels of sulfur, nitrogen, and aromatics, and they exhibit high cetane numbers. These characteristics of F-T products make them attractive as diesel fuels, either in their pure form or preferably as blending components with other refinery streams. Illustrative examples are given in US patents [1]. F-T fuels are not currently a significant fraction of the global diesel fuel market due to the large capital investment required for production. The well-to-wheels production efficiency and CO_2 emissions resulting from natural gas-derived fuels must also be evaluated in comparison to fuels derived from petroleum. In the future, F-T fuels have the potential to compete in the market with conventional diesel fuel. The initial market penetration will be slow, with F-T fuel serving as a compliment to conventional fuel in special situations.

Fuel specifications will be set to meet future emissions specifications. Advanced vehicles are becoming increasingly sophisticated in the search for lower exhaust emissions and improved fuel economy. For diesel engines the main challenges are nitrogen oxides (NOx), which are typically much higher than from spark engines, and particulate emissions (PM) which arise as a consequence of the non-homogeneous combustion process in the diesel engine. Although catalysts have been used on gasoline vehicles for many years, their use in diesel vehicles is relatively new. However, use of catalytic exhaust treatment systems in diesel-powered vehicles is expected to increase in the future in order to control particulate and perhaps also NOx emissions. In this context, fuel sulfur is the important enabling variable to ensure effective operation of catalyst devices which can achieve •90% reduction in PM and NOx emissions with a properly tuned after-treatment system. F-T fuels, having zero sulfur, are compatible with these advanced after-treatment devices.

The impact of other fuel properties such as cetane number, aromatics, and density has been extensively studied [2-18]. Low aromatics content and high cetane number, as provided by F-T fuels, are features

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associated with lower emitting fuels, although cetane numbers higher than ca. 55 may offer no additional benefit in modern light duty direct injection engines. The benefits that can be obtained from fuel changes of this type tend to be less than can be achieved through vehicle hardware changes (e.g. advanced aftertreatment systems), so the costs and benefits need to be carefully assessed on a case-by-case basis. However, F-T fuels can produce emission reductions [2,12,15-18], providing benefits where lower emissions from existing diesel engines are required.

Studies in Europe and the US [19, 20] have identified sulfur as the key fuel property to control; however, limits on other fuel properties can present challenges for the refinery. F-T fuels are attractive as blending components, and through their high cetane number and near-zero aromatics and sulfur levels provide one way to improve refinery flexibility.

In this paper we report the results of studies of the engine-out emissions of F-T diesel fuels, both alone and in blends with refinery streams. The effects of fuel boiling range were also included to explore the ways in which F-T fuels can be most effectively used.

EXPERIMENTAL SECTION

FUEL PREPARATION - Fischer-Tropsch wax-containing feed was prepared by the reaction of hydrogen and carbon monoxide over a proprietary cobalt-containing catalyst. F-T naphtha was prepared by separating a roughly C_5-C_{15} fraction from the product of the Fischer-Tropsch synthesis reactor. This product was primarily normal paraffins of this carbon number range, but also contained a significant minor component of olefins and alcohols. These materials could be eliminated, if desired, through mild hydrotreating. Low cloud point diesel fuel was prepared by passing the fraction of the F-T feed boiling above 150 ºC through a two-step upgrading process that converts normal paraffins to isoparaffins. Olefins and alcohols are also eliminated in the upgrading process. Various distillation fractions of the upgrading product were used as test F-T fuels.

HEAVY-DUTY DIESEL EMISSION TESTS - Heavy duty emissions were measured in a 1991 DDC series 60 engine with the following characteristics:

Engine	6-cylinder, 11.1 L, 130 mm bore x 130 mm stroke
Aspiration	Turbocharged, after-cooled (air-to-air)
Emissions	Electronic management of fuel injection and timing (DDEC-II)
Power/Torque	33 hp at 1800 rpm, 1270 lb.-ft. at 1200 rpm
Injection	Direct injection, electronically controlled unit injectors

Regulated emissions were measured during hot-start transient cycles. The emission test procedures specified by the EPA in CPR 40, Part 86, Subpart N for emissions regulatory purposes were used and the testing was performed at Southwest Research Institute. The emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter (PM) were measured.

LIGHT-DUTY DIESEL EMISSION TESTS - Emissions characteristics of the fuels were evaluated with a Peugeot 405 indirect injection (IDI) light duty diesel vehicle. Emissions of HC, CO, NOx, and PM were measured using the combined Urban Drive Cycle and Extra-Urban Drive Cycle (ECE-EUDC) hot and cold test protocols at Esso Research Centre, Abingdon UK. Test fuels were examined at least in duplicate in a randomized design. Bosch T100 free-accelerat smoke tests, as used for in-service control of emissions, were performed.

The light-duty European test cycle is performed in two parts. The ECE cycle represents inner city driving conditions after a cold start with a maximum speed of 50 km/h, and the EUDC is typical of suburban and open-road driving behavior with a maximum speed of 120 km/h [7,9]. Emissions are reported here as percentage change when compared with a standard European low sulfur diesel fuel. A similar US #2 low sulfur diesel fuel (ASTM D975-98b) was also included in the test matrix.

As reported elsewhere at this conference [14,21], fuel changes can affect engine calibration through physical interactions with the fuel injection equipment and electronic engine control systems. To fully understand how a new fuel impacts engine-out emissions when the engines are properly optimized for their use, these interactions should be controlled. The emissions impact of F-T fuels could be attenuated with engine systems more modern than those used in these tests. For this study, however, tests were conducted in standard production engines and vehicles. Results are summarized in the Appendix and described in the following sections.

F-T NAPHTHA AS AN ENGINE FUEL

Petroleum naphtha (containing C_5-C_{15} molecules) is not considered as a diesel fuel because it has poor cetane value. However, naphtha derived from F-T processes is composed of mostly linear paraffins with higher cetane values. This allows a fuel with high cetane to be produced even when the initial boiling point is low. A fuel for compression ignition engines with improved emissions properties can thus be constructed using material boiling outside the range of conventional diesel fuel, potentially expanding the product output of the GTL plant used for transportation fuels. Inclusion of these lower boiling fractions can result in fuels with a flash point lower than the minimum required for conventional diesel fuel. This factor needs to be considered in assuring safe operation with such fuels. Since some modification to the vehicle's fuel system would be needed to accommodate the higher fuel volatility, this fuel is best considered as an alternative fuel rather than a normal diesel fuel. Additional changes in the fuel supply/distribution system would also be necessary to ensure safe operation.

F-T naphtha, F-T fuel with a typical 160-370 ºC diesel boiling range, CARB diesel, and a US 2-D diesel were tested in a heavy-duty diesel engine. The properties of the fuels are listed in Table 1. Emissions results were compared among the four fuels as shown in Figure 1, where the results for the test fuels are displayed as % change in emissions with respect to the values for the US standard fuel. Negative values signify emission reductions.

Clearly, both F-T fuels produce fewer emissions than either the conventional US LSADO or the CARB diesel. However, the F-T naphtha produced the lowest amount of particulate matter by a significant margin. The F-T naphtha produced nearly 50% reduction in PM emissions, and also a small reduction in NOx. The engine was not modified to run the F-T naphtha and its high volatility results in an increase in hydrocarbon emissions. Vehicle hardware modifications would be needed in order to use a low flash point fuel, and it is possible that hydrocarbon emissions could also be controlled by such methods, for example through an oxidation catalyst.

TABLE 1. Fuel Properties of Petroleum and Fischer-Tropsch Diesel Fuels

		US LSADO	CARB	F-T Diesel	F-T Naphtha
Cetane No.	ASTM D-613	45.5	50.2	74	>74
IBP, °C	ASTM D-86	191	210	194	71
T10, °C		226	229	231	113
T50, °C		261	253	286	167
T90, °C		308	291	327	220
Endpoint, °C		344	344	338	253
Gravity	ASTM D-287	0.845	0.842	0.774	0.731
Sulfur, %	ASTM D-2622	0.03%	0.03%	0	0
Aromatics, %	ASTM D-1319	31.9	8.7	0.26*	0.01*
Flash Point, °C	ASTM D-93	69	82	60	<40
Viscosity, cSt	ASTM D-455	2.63	2.79	2.66	0.87

* For better accuracy, SFC analysis was performed instead of D1319

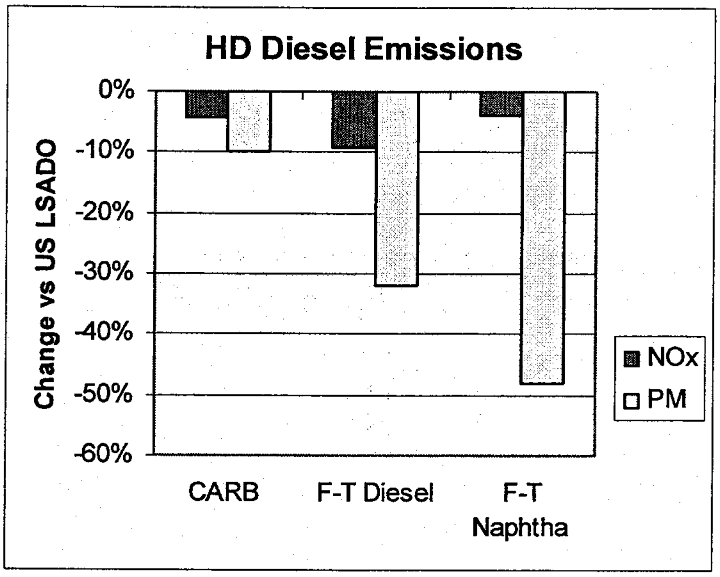

Figure 1. HD Emissions vs US LSADO

EFFECT OF BOILING RANGE ON EMISSIONS OF F-T FUELS

It is known that raising the T95 point of conventional diesel fuels can have some impact on vehicle emissions. To investigate the effects of boiling range when F-T fluids are used, four F-T diesel fuels were prepared by hydroisomerizing a Fischer-Tropsch reactor product and separating it into different boiling point cuts by distillation. The cuts were reblended in the relative proportions that they would be produced in a GTL plant to make the fuels shown in Table 2. The hydroisomerization process facilitates the production of low cloud point diesel fuels even when the boiling range is extended higher than in conventional petroleum diesel fuels, by converting high-boiling normal paraffins into iso-paraffins. The paraffinic nature of the F-T fuel results in high cetane numbers and allows lower boiling components to be included in the fuels as well. Table 2 lists the properties of the fuels tested in the light duty IDI vehicle. The nominal boiling ranges of the F-T fuels are listed along with the measured initial boiling point, T50, and T95 points. The properties of the US LSADO and European LSADO used as the reference fuel in the emission tests are also listed. The F-T fuels contain no sulfur or aromatics detected by the standard tests cited in the table. The cetane values are high, ca. 70, and the densities are low when compared to those of petroleum diesel fuels. The cloud point remains low even when T95 is extended beyond the range of normal diesel fuels.

The results of the emission testing are displayed in Figure 2, where the results for the test fuels are reported as % change in emissions with respect to the values for the European standard fuel. Negative values signify emission reductions. The F-T fuels show lower values for all four of the measured emissions when compared with the two petroleum diesel fuels. This is consistent with the results reported earlier by Erwin and Ryan [2] and more recently by others [12,13,15-18]. Emission reductions of 54-62% were observed for hydrocarbons, 15-25% for NOx, 52-55% for carbon monoxide, and reductions of 58-63% for particulate matter.

Past studies in the US [3-6] and in Europe [7-11] have examined the effect of fuel parameters on diesel emissions in both heavy and light duty engines. As part of the European Programme on Emissions, Fuels, and Engine Technologies (EPEFE) studies, correlations were developed to predict the emission levels of diesel fuels based on the fuel density, polyaromatics content, cetane number, and T95 distillation point [11]. Although the properties of the fuels tested here extend well beyond the range of those of the fuels used in the EPEFE test matrix, the EPEFE predictions give an insight into the observed test results and are used here as an aid in evaluating the F-T results. In Figure 3 the projected changes in emissions are compared to those actually observed in testing.

The EPEFE equations are not very successful at predicting the NOx performance of the F-T fuels, which have densities well outside the range tested in EPEFE. For particulate emissions, the EPEFE predictions for the normal boiling range fuels are remarkably close to the F-T test results. However, the EPEFE correlations, based on results from standard diesel fuels, predict that as the fuel becomes heavier, particulate emissions will increase. As the T95 of the F-T fuels increased from 330 to 390ºC, no significant increase in particulate emissions was observed. Although the 280-900 FT fuel contains a significant high molecular weight component, it did not cause increased particulate emissions. This suggests that the heavy component of the F-T fuel behaves differently from the material found in the back-end of conventional diesel fuels. These data show that the use of F-T fuels has the potential to simultaneously lower both the particulate and NOx emissions, although the effect on NOx emissions is lower than that on PM.

Table 2. Fuel properties of Fischer-Tropsch fuels of different boiling range

F-T nominal boiling range, ºF		280-700	300-700	280-800	280-900	US LSADO	UK LSADO
Density	AP-635	0.768	0.772	0.778	0.785	0.846	0.854
Sulfur, %	RD 86/10	0	0	0	0	0.04	0.05
IBP, ºC	ASTM D-86	136	173	174	174	197	184
T50, ºC		252	257	273	291	294	288
T95, ºC		330	332	375	390	339	345
Cetane	ASTM D-613	70.0	71.8	71.8		53.0	50.1
Cetane Index	ASTM D-4737	80.2	81.0	80.2	82.3	56.5	50.8
Aromatics, total, %	IP-391	0	0	0	0	27.9	26.7
Polyaromatics, %	IP-391	0	0	0	0	7.1	6.4
Cloud Point, ºC	ASTM D-5771	-36	-36	-33	-10	-6	-5
CFPP, ºC	IP-309	-45	-46	-33	-15	-7	-18
Flash Point, ºC	ASTM D-93A	41.1			69.5		77.5

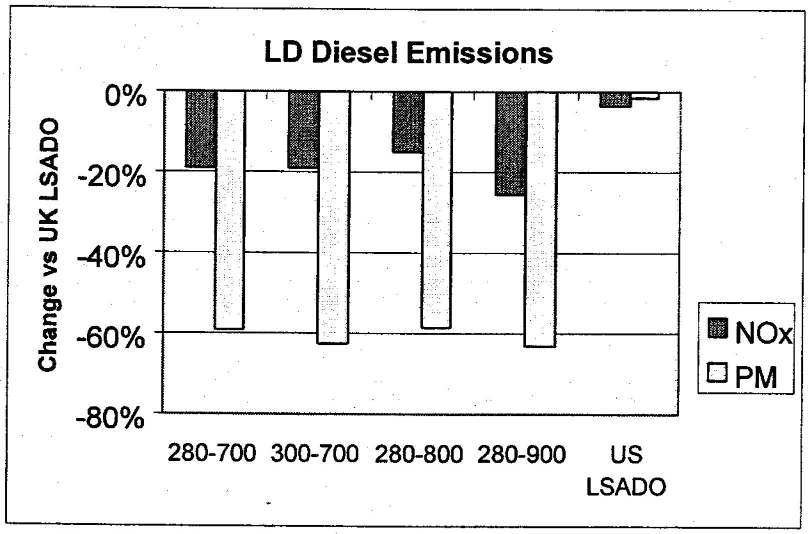

Figure 2. Emissions vs UK LSADO

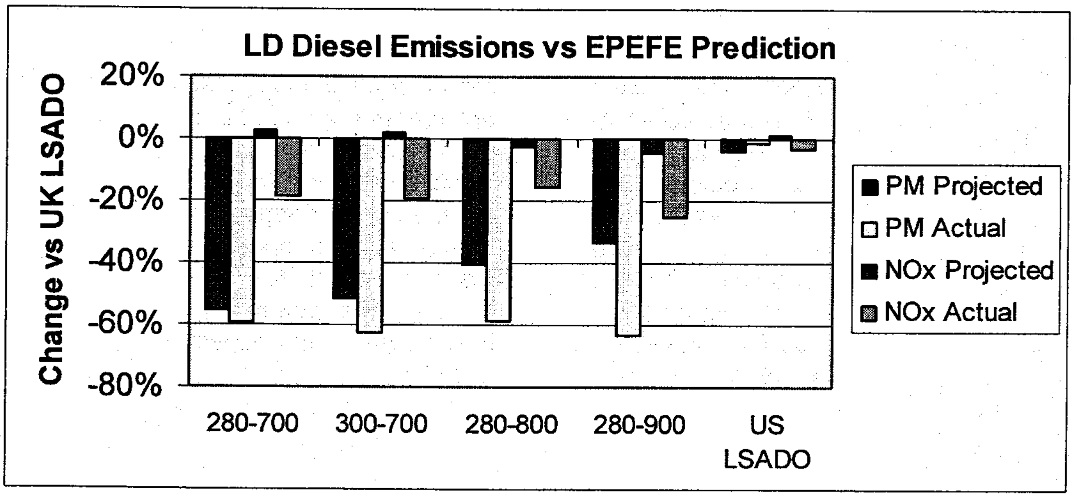

Figure 3. Emissions vs EPEFE predictions, LD diesel

Results from the free-acceleration smoke tests are shown in Table 3. No smoke emissions were detected for the first three F-T fuels, and only a small amount of smoke was observed for the heaviest F-T fuel. However, the energy content of F-T fuels is less than that of conventional diesel fuels by ca. 5%. This lower energy density reduces the maximum engine power available, which may impact the full load emissions.

Table 3. Bosch smoke results

Fuel	Bosch Smoke Number
280-700	0
300-700	0
280-800	0
280-900	0.39
US LSADO	2.02
UK LSADO	2.07

FISCHER-TROPSCH STREAMS AS PETROLEUM STOCK BLENDS

Used neat, F-T fuels provide reductions in emissions when compared to conventional fuels. The unique properties of F-T fuels also make them attractive for blending into conventional petroleum diesel fuels and diesel fuel blending stocks. A series of test fuels was blended to explore the emissions performance of fuels blended using F-T and conventional components. First, F-T fuel was blended with two cracked stocks that are typically difficult to blend into conventional diesel fuel due to high density, low cetane number, and high aromatic content. Second, we used an asymmetric blend of a lighter, lower sulfur conventional diesel with a heavier F-T fuel to produce a full boiling range diesel.

Table 4. Fuel Properties of blend stocks

	FT-A	FT-B	US LSADO	CARB	UK LSADO	CS-C	CS-D
Boiling Range (°F)	250-700	320-700	376-651	410-652	347-678	249-788	361-725
Cetane Number	79.1	74	45.5	50.2	51.1	33.7	~27
Aromatics (wt %)	0	0	31.9	8.7	29.2	54.4	70.2
Polyaromatics	0	0	*	0.3	9.2	25.4	40.7
Sulfur	0	0	0.033	0.0345	0.14	0.066	0.27
Density (g/ml)	0.775	0.783	0.845	0.842	0.851	0.892	0.929

*polyaromatic/aromatic split not measured

Table 5. F-T/Cracked Stock Blend Properties

	Blend X	Blend Y	Blend Z	CARB	UK LSADO
BP Range (°F)	250-700	250-700	345-700	410-652	347-678
Cetane Number	56.3	51	48.2	50.2	51.1
Aromatics (wt %)	27.2	32.1	36.9	8.7	29.2
Polyaromatics	12.7	17.5	21.2	0.3	9.2
Sulfur	0.033	0.14	0.15	0.0345	0.14
Density (g/ml)	0.829	0.838	0.851	0.842	0.851

BLENDS WITH CRACKED STOCKS TO MEET CURRENT STANDARDS - A series of fuels designed to examine blending characteristics of F-T fuel with cracked gas oil stocks is shown In Table 4 below. Two F-T fuels, three reference fuels, and two cracked stocks (CS-C and CS-D) were used as base blending components or reference fuels for comparison. The two F-T fuels differ slightly with FT-B having a higher initial cut point and a higher fraction of isoparaffins than FT-A. The reference fuels include a typical US No. 2 diesel (ASTM D975-98b), a California CARB certified diesel, and a typical European low sulfur diesel.

The term cracked stocks refers to the distillate fraction of products that result from a thermal or catalytic process such as fluid catalytic cracking, thermal cracking, or vis breaking. These materials are typically denser and contain higher levels of sulfur, aromatics, and polyaromatics than diesel fuels. They can be further processed by hydrotreating to reduce sulfur content or by aromatic saturation to reduce aromatics and density.

Three blends were made with the F-T fuels and cracked stocks CS-C and CS-D to match the density and cetane of the reference diesel fuels. These fuels were then compared to the reference fuels in standardized emissions test procedures. The blends were made as follows:

Blend X: 50% FT-A + 50% CS-C
Blend Y: 57% FT-B + 43% CS-D
Blend Z: 52% FT-B + 48% CS-D

Properties for these blends are shown in Table 5 above.

Heavy-duty diesel emissions tests were performed using blend X and the results were compared with those from tests on neat Fischer-Tropsch fuel FT-A, reference US diesel, and California CARB diesel. The data in Figure 4 are reported as % change in emissions with respect to the values for the base US LSADO. Negative values signify emission reductions. Light-duty diesel emission tests were performed using blends Y and Z and the results were compared with those from tests on neat Fischer-Tropsch fuel FT-A and a typical LSADO from Europe. The data in Figure 5 are reported as % change in emissions with respect to the values for the base UK LSADO.

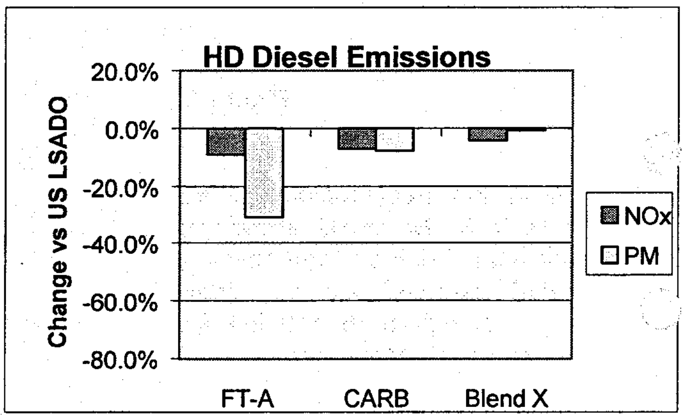

Figure 4. HD emissions vs US LSADO

In line with previous results, the F-T fuel gave lower values of all four measured emissions. Blend X, made of the F-T fuel and a cracked stock in equal proportion, compares favorably with CARB diesel. Figure 4 shows that the blend produces similar levels of NOx emissions, and slightly more PM emissions. However, this blend achieves these emission levels with much higher aromatics (27.2 vs. 8.7%) and polyaromatics (12.7 vs. 0.3%) contents at identical sulfur content. The high cetane and low density of F-T fuel make it possible to blend a fuel with good emissions performance from distressed refinery streams, even though the blended fuel contains high levels of aromatics and polyaromatics.

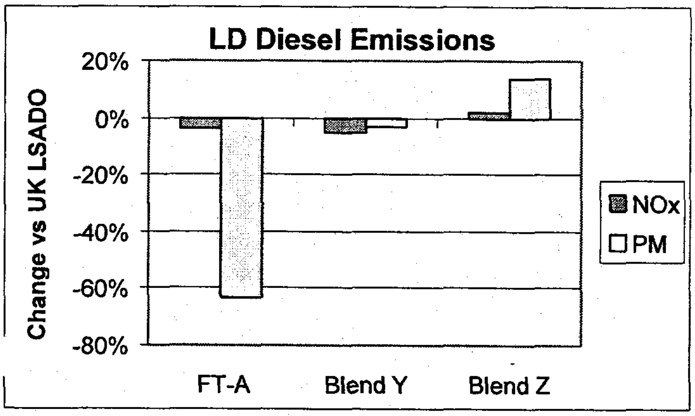

Figure 5. LD emissions vs UK LSADO

›nd Y (FT-A/CS-D 57/43) closely matches the standard UK LSADO in emissions performance (Figure 5). All four emission parameters decreased slightly, but not statistically significantly except for NOx. Note that blend Y contains substantially more polyaromatics than UK LSADO (17.5 vs 9.2%), yet achieved equal or better emissions performance at the same sulfur and cetane number levels, and only slightly lower density. This result is similar to that observed in the heavy-duty engine, indicating that the positive effects of blending with F-T fuel are likely to extend to a large number of engines, and work in both light and heavy-duty vehicles. Blend Z demonstrates that when the level of aromatics and polyaromatics reach high enough levels, the beneficial effects of F-T diesel cannot compensate for the other fuel properties.

-ENDING WITH F-T FUEL TO REDUCE SULFUR AND EMISSIONS - In conventional petroleum distillate fuels, sulfur concentration increases as a function of boiling point. This allows preparation of a very low sulfur asymmetric blend of light conventional and heavy F-T fuel. The sulfur distribution by boiling range is illustrated for a typical US diesel fuel in Table 6 below.

Table 6. Sulfur in LSADO by Boiling Fraction

Boiling Range, F	Yield, %	S, ppm
IBP –600	61.43	22
600-625	11.48	238
625-640	6.03	685
640-650	3.81	1054
650-660	4.44	1632
660-675	9.69	1834
IBP-675	100	417

The entire fuel (IBP-675 ºF) contains 417 ppm S by weight. By undercutting the fuel, using only the fractions from IBP-640 ºF, 79% of the conventional fuel is used to obtain blend stock with 104 ppm S. A full boiling range fuel (Blend W) was prepared by blending the undercut stock with a F-T stock cut from 300-800 ºF in equal proportions. Due to the low sulfur level of the undercut component of the conventional fuel, Blend W is a very low sulfur fuel with ~50 ppm S. This technique can be used to create blends with even lower sulfur levels as the cut point of the LSADO and its percentage in the blend are varied. The fuels used for comparative emissions tests are shown in Table 7.

Light-duty diesel emission tests were performed using blend W and the results were compared with those from tests on a US No. 2 diesel (ASTM D975-98b) and a typical LSADO from the UK. The data in Figure 6 are reported as % change in emissions with respect to the values for the base UK LSADO. Negative values signify emission reductions.

Table 7. Fuel Properties of asymmetric F-T/petroleum blend

		Blend W	US LSADO	UK LSADO
Density	IP-365	0.809	0.846	0.854
Sulfur, %	RD 86/10	0.0052%	0.04%	0.05%
IBP, °C	D-86	179	197	184
T50, °C		280	294	288
T95, °C		355	339	345
Cetane	D-613	61.5	53	50.1
Aromatics, %	IP-391	15.0	27.9	26.7
Polyaromatics, %	IP-391	0.4	7.1	6.4
Cloud Pt, °C	D-5771	-19	-6	-5
CFPP, °C	IP-309	-26	-7	-18

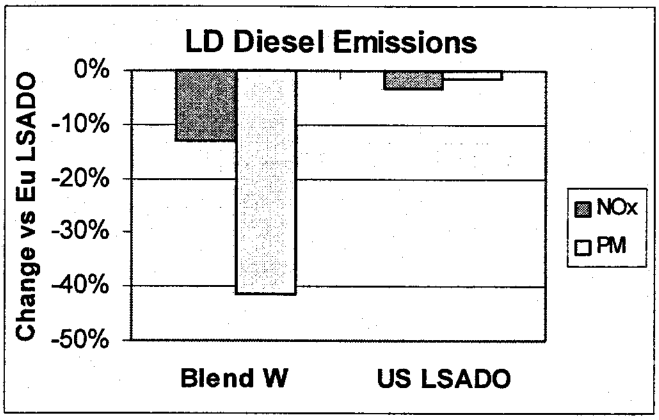

Figure 6. LD Emissions vs UK LSADO

The asymmetric blend decreased all four measured emissions significantly compared to the standard fuels. The emissions produced by blend W, a 50/50 blend of F-T and petroleum-derived fuel, are comparable with those observed for a neat F-T fuel as shown in Figure 5. To judge the effect of the F-T fuel on the blend properties, we have again employed the EPEFE equations [11]. These equations predict how emissions are expected to change as a function of cetane, density, polyaromatics, and T95. When these equations are applied using the values for the fuel properties given in Table 7 above, the results displayed in Figure 7 demonstrate that the expected reductions in NOx and PM emissions are exceeded by the actual results for the asymmetric F-T blend. It should be noted that the density of F-T fuel (0.77-0.78 g/ml) and of Blend W (0.809 g/ml) is significantly below the density range of the conventional diesel fuels (0.828-0.855) used in the determining the EPEFE correlations.

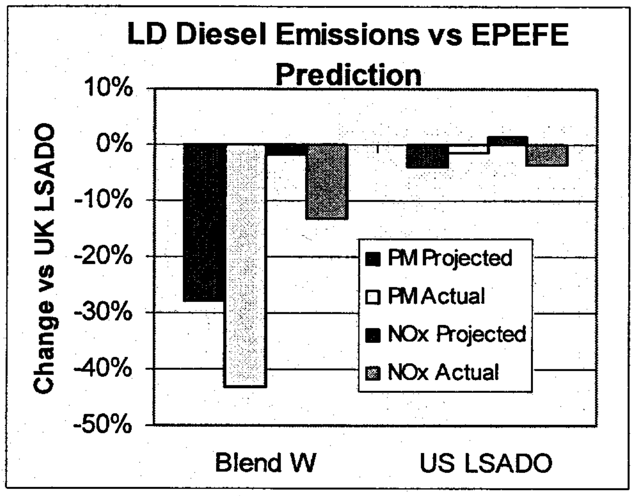

Figure 7. LD Emissions vs EPEFE predictions

DISCUSSION

The durability and energy efficiency of diesel vehicles provide substantial advantages for many automotive applications. Nevertheless, they face the challenge of controlling NOx and PM emissions if they are to meet future vehicle emission standards. Fischer-Tropsch fuels can lower vehicle emissions, yet the changes demanded by future emission limits call for even larger reductions than can be provided by fuel substitution alone. Exhaust after-treatment systems seem the likely technology that will produce required emission reductions. The catalytic systems for PM and NOx control will require zero-sulfur (<10 ppm) fuels, but changes in other fuel properties are not necessary for their effective operation. PM traps are already capable of emission reductions of over 90%, and NOx catalyst systems, using either SCR or NOx-storage techniques, have the potential to reach similar levels of performance. The relative performance of fuel and vehicle changes is illustrated in Figure 8. Even the most extreme fuel changes, as exemplified by the F-T fuels do not provide an alternative to an effective after-treatment system.

Although the F-T process has been known for many years, F-T fuels are produced only in relatively small volumes. The high initial investment required for F-T fuel production and the need to compete effectively with conventional fuels means that the segment of the diesel fuel market provided by F-T fuels will remain small for many years. In deciding the future of F-T fuels, the well-to-wheels energy efficiency and the resulting CO2 emissions will undoubtedly be a factor [22]. The well-to-tank energy efficiency of conventional fuels is very high, and the relative performance of F-T fuels in this area needs to be evaluated alongside their emissions performance. One component of this analysis is the energy content and density of F-T fuels. Lower density is one of the causes of the good emissions performance of F-T fuels, but density also impacts the fuel's energy content. This in turn will affect peak engine power and fuel economy. The effects of retuning engines to recover the lost power needs to be factored into the evaluation.

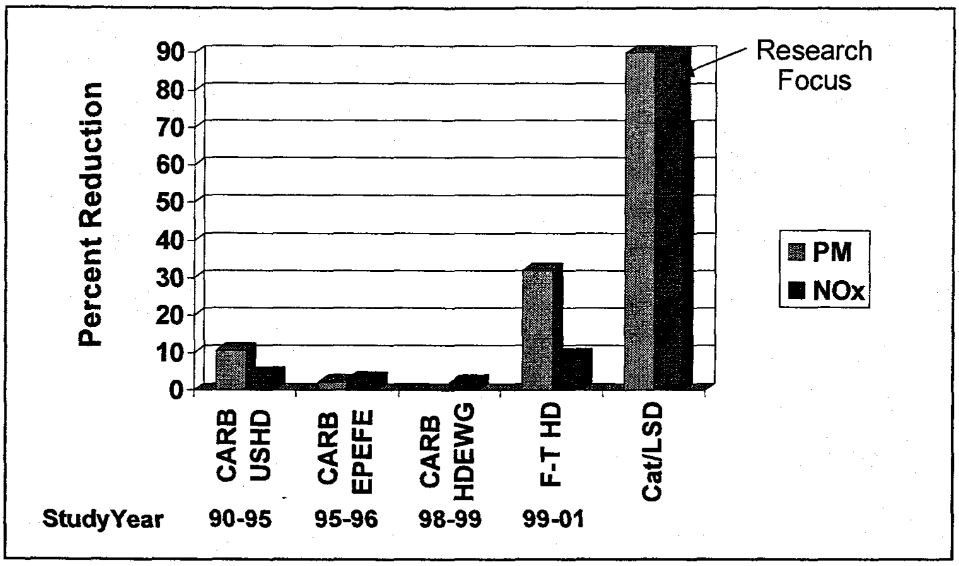

Figure 8. Emission reduction potential for fuels and after-treatment

Because of the small production volumes, F-T diesel is likely to remain a premium product, applied where its special properties can be most effectively used, either as a pure fuel or as a component in an integrated refinery blending plan.

CONCLUSION

The products of Fischer-Tropsch synthesis can be used to produce diesel fuels that give lower engine-out emissions than conventional petroleum-derived fuels. The paraffinic composition of F-T products means that streams with lower boiling point than conventional diesel fuels can be produced that still have high cetane numbers, and therefore perform well in diesel engines. However, provision would need to be made to safely handle the lower flash point if these products were to be used as diesel fuel.

F-T streams heavier than conventional diesel fuels can also be used in diesel engines without incurring increases in emissions. The differences in composition as a function of boiling point range between F-T and petroleum fuels result in emissions advantages for F-T fuels that are higher than predicted from the correlations with fuel composition variables derived from previous studies on petroleum fuels.

F-T fuels can also be used in blends with conventional refinery streams. Because they have low sulfur, high cetane number, low aromatics and low density they provide attractive components to help refineries meet fuel specifications. Good emissions performance can be achieved by blends containing F-T streams, even at high levels of aromatics. Such blends also increase the volume of fuel with good emissions performance available from a given quantity of F-T fuel.

The high investment needed for F-T plants and the need to compete with conventional fuels means that the proportion of F-T fuels in the diesel market will grow slowly. More study is required to utilize these valuable products in the most effective way.

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APPENDIX. TABULATION OF EMISSION RESULTS

Absolute emission figures at the right of the Tables A1 and A2 refer to emissions on the baseline fuel.

Table A1. Emissions vs US LSADO, HD diesel

	CARB	F-T Diesel	F-T Naphtha
HC	-22.2%	-41.3%	15.3%
CO	-15.6%	-44.6%	-39.2%
NOx	-4.4%	-9.1%	-4.1%
PM	-9.8%	-32.1%	-48.0%

US LSADO
0.6142 g/hp-hr
1.9483
4.2318
0.1815

Table A2. Emissions vs UK LSADO, LD diesel

	280-700	300-700	280-800	280-900	US LSADO
HC	-57.1%	-53.9%	-59.7%	-61.7%	-12.5%
CO	-54.1%	-51.9%	-53.8%	-55.1%	-11.6%
NOx	-18.8%	-19.1%	-15.2%	-25.3%	-3.4%
PM	-59.1%	-62.6%	-58.4%	-63.2%	-1.5%

UK LSADO
0.118 g/km
0.736
0.669
0.077

Table A3. Emissons vs EPEFE predictions, LD diesel

	280-700	300-700	280-800	280-900	US LSADO
Particulate emissions vs UK LSADO					
EPEFE prediction	-55.6%	-51.7%	-40.9%	-33.4%	-4.1%
Actual	-59.1%	-62.6%	-58.4%	-63.2%	-1.5%
NOx emissions vs UK LSADO					
EPEFE prediction	2.4%	2.0%	-2.7%	-4.6%	1.3%
Actual	-18.8%	-19.1%	-15.2%	-25.3%	-3.4%

Table A4. HD emissions vs US LSADO

	FT-A	CARB	Blend X
HC	-41%	-34%	-38%
CO	-47%	-17%	-30%
NOx	-9.2%	-7.3%	-4.1%
PM	-31%	-7.7%	-0.9%

Table A5. LD emissions vs UK LSADO

	FT-A	Blend Y	Blend Z
HC	-73%	-1%	18%
CO	-54%	-4%	3%
NOx	-4%	-5%	2%
PM	-63%	-3%	14%

Table A6. LD Emissions vs UK LSADO

	Blend W	US LSADO
HC	-55.8%	-12.5%
CO	-41.8%	-11.6%
NOx	-13.1%	-3.4%
PM	-41.3%	-1.5%

Table A7. LD Emissions vs EPEFE predictions

	Blend W	US LSADO
Particulate emissions vs UK LSADO		
Projected	-27.8%	-4.1%
Actual	-43.1%	-1.5%
NOx emissions vs UK LSADO		
Projected	-1.9%	1.3%
Actual	-13.1%	-3.4%