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Zero-Sulfur Diesel Fuel from Non-Petroleum Resources: The Key to Reducing U.S. Oil Imports

SEPTEMBER 2012

FTA Report No. 0029
Federal Transit Administration

PREPARED BY

Stephen P. Bergin, Ph.D., P.E
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COVER PHOTO

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT

Zero-sulfur diesel fuel of the highest quality, the fuel used in this project, can be made by Fischer-Tropsch (FT) synthesis from many non-petroleum resources, including natural gas, which is increasingly abundant in the United States. Zero-sulfur FT diesel fuel can upgrade, and more-than-proportionally increase the supply of, conventional ultra-low-sulfur diesel (ULSD) fuel by targeted blending. Zero-sulfur FT diesel fuel could eventually even replace conventional ULSD, which has become the most valuable and profitable bulk-fuel product (supplanting gasoline's former dominance) of petroleum refineries for about the past seven years; and production of zero-sulfur FT diesel fuel at the margin would not add incrementally more to the global-surpluses of gasoline and other products with low or negative profit potential which inevitably result from refining crude oil. Demand for ULSD is greater (especially when the US and world economies are growing satisfactorily) than the refining capacity available to produce ULSD from customary and readily available high-sulfur crude oils. This has caused, through market-driven increases in the prices of low-sulfur crude oils, and the follow-on increases in high-sulfur crude oil prices by the OPEC cartel (which would be illegal under US law), the prices of all petroleum-derived fuels to more than double (and to triple during price-spikes) since the middle of the last decade. Since the demand for ULSD, not the demand for gasoline, determines the amount of foreign crude oil imported into the US, any effort focused solely on "conserving" gasoline, will have no impact on reducing US imports of crude oil.

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ABSTRACT

Zero-sulfur diesel fuel of the highest quality—the fuel used in this project—can be made by Fischer-Tropsch (FT) synthesis from many non-petroleum resources, including natural gas, which is increasingly abundant in the United States. Zero-sulfur FT diesel fuel can upgrade and more-than-proportionally increase the supply of conventional Ultra-Low-Sulfur Diesel (ULSD) fuel by targeted blending. Zero-sulfur FT diesel fuel could eventually even replace conventional ULSD, which has become the most valuable and profitable bulk-fuel product (supplanting gasoline's former dominance) of petroleum refineries for about the past seven years. Production of zero-sulfur FT diesel fuel at the margin would not add incrementally more to the global surpluses of gasoline and other products with low or negative profit potential that inevitably result from refining crude oil.

Demand for ULSD is greater (especially when the U.S. and world economies are growing satisfactorily) than the refining capacity available to produce ULSD from customary and readily-available high-sulfur crude oils. This has caused, through market-driven increases in the prices of low-sulfur crude oils and the follow-on increases in high-sulfur crude oil prices by the OPEC cartel (which would be illegal under U.S. law), the prices of all petroleum-derived fuels to more than double (and to triple during price-spikes) since the middle of the last decade. Since the demand for ULSD, not the demand for gasoline, determines the amount of foreign crude oil imported into the U.S., any effort focused solely on "conserving" gasoline will have no impact on reducing U.S. imports of crude oil.

EXECUTIVE SUMMARY

The primary purpose of this project, which is one of a series of related projects, has been to evaluate the operating performance benefits and develop market acceptance of synthetic Fischer-Tropsch (FT) diesel fuel. The approach has been to understand and resolve, within the transit-bus context, the issues that make FT fuel different or unique in comparison to conventional diesel fuel, prominently including the virtual absence of both aromatics and sulfur from FT diesel fuel. This project and report add to the existing base of data and experience, demonstrating again that FT diesel fuel is indeed a fully functional "drop-in" replacement for conventional diesel fuel in a U.S. Air Force transit bus, equipped with a Caterpillar C-7 engine, as used over a wide range of operating conditions in Michigan for a period of three years.

The FT diesel fuel was used "neat" or unblended in this evaluation, because this represents a "worst-case scenario" with respect to the possibility of fuel-injector nozzle-fouling in the Caterpillar C-7 engine by potential chemical and physical mechanisms (discussed later) related to the virtual absence of aromatics from neat FT diesel fuel. However, even under this worst-case condition, no nozzle-fouling was observed during this evaluation. Furthermore, it has now been fully appreciated that, as will be described in this report, the greatest value, by far, of FT diesel fuel to both the U.S. and world economies will be as a sulfur-free component in blends with conventional petroleum-derived diesel fuel. If the FT diesel fuel is indeed used as a blendstock with conventional diesel, rather than neat as in this worst-case evaluation, the possibility of nozzle fouling would be virtually eliminated by the continued presence of aromatics in the conventional diesel portion of the blend.

Interest in FT fuel was driven over most of the past decade by the desirability of having a domestic source of the highest quality middle-distillate fuels as a physical backup to petroleum, as a matter of U.S. national energy security. However, recent events have demonstrated that production of FT fuels from U.S. domestic resources is, in fact, even more necessary for economic reasons and for safeguarding U.S. economic security. During the spring/summer periods of both 2008 and 2011, severe, global-scale petroleum price-spikes occurred. These price-spikes, along with an almost "perfect storm" of other negative economic factors (notably the global "credit-crunch" and the bursting U.S. "housing bubble" in 2008), contributed to causing a severe global recession in 2009–2010, and then impeded the recovery from that recession in 2011.

The basic cause of both petroleum price-spikes was the same: the inability of the global petroleum refining system to produce enough Ultra-Low Sulfur Diesel (ULSD) fuel at the margin to meet the robust demand (during the times in early 2008, and again in early 2011, when the global economy was growing and ULSD demand was high), using the available supply of crude oil. The "available" supply of crude was fully adequate at all times in terms of the total quantity of crude available, but inadequate in terms of its quality. The "marginal" refineries of the world must have light, sweet (i.e., low-sulfur) crude in order to contribute their share of ULSD to the global market, and light, sweet crude was in short supply both in early 2008 and in early 2011.

In addition to the disruptive, ULSD-related petroleum price-spikes that occurred while this project was being conducted, there are several additional reasons that this Federal Transit Administration (FTA) sponsored project expanded its focus from merely evaluating FT diesel fuel in a particular transit-bus engine to considering the broader aspects and opportunities for sulfur-free FT diesel fuel to enhance U.S. energy and economic security:

- The ULSD concept "originated" in conjunction with the retrofit-application of catalyzed particulate filters to transit buses as an effective means to reduce diesel soot and odor emissions in congested urban areas.
- Although urban transit buses use only about 1 percent of total U.S. diesel fuel, the basic equipment-technology and fuel-modification approaches pioneered on urban transit buses were subsequently mandated "across-the-board" for all diesel engines by the U.S. Environmental Protection Agency (EPA).
- Sulfur-free FT diesel fuel produced from U.S. domestic resources can offer extraordinary leverage in reducing crude oil imports and enhancing security:
  - Each barrel of FT can reduce crude-oil imports in a leveraged 3:1 ratio from unfriendly areas of the world, all without producing more global-surplus gasoline.
  - Furthermore, with targeted blending, FT can enable refiners to get more conventional ULSD out of each barrel of crude oil they refine.

SECTION 1

Introduction

This Project: Last in a Series of FT Fuel Evaluation Projects

This project is one of a series of related projects; the goal of all the projects in the series has been to evaluate the operating performance benefits and develop market acceptance of synthetic Fischer-Tropsch (FT) diesel fuel by understanding and resolving, within the transit-bus context, the issues that make FT fuel different or unique in comparison to conventional diesel fuel. The projects have all been conducted by successfully running neat (i.e., unblended) sulfur-free, FT diesel fuel in diesel engines, but over a broad spectrum of operating environments and climates, and in a range of diesel engines, produced by different manufacturers, and used in different types of service. The results obtained in previous projects will be reviewed briefly in the next section of this report.

The current project is the last of the series, and this report, therefore, is intended to serve as a compilation of lessons learned during this particular project and during the overall series of projects, and as a roadmap for charting a course for the most effective use of FT diesel fuel into the future.

As will be described in more detail later in this report, the current project consisted primarily of running an Air Force bus with a Caterpillar C-7 engine on neat S-2 FT diesel fuel for three years, from the fall of 2008 to the fall of 2011. This was a direct follow-on to two previous/ contemporaneous projects using the same neat S-2 FT fuel: running a new Tulsa Transit bus in revenue service in Tulsa, OK, for three years from 2005 until 2008, and running an Air Force Bus at Edwards Air Force Base in the California desert for three years from 2006 to 2009. One of the most striking things that occurred over the combined period of these directly-related projects from 2005 to 2011 was the extreme volatility of the prices of both crude oil and petroleum products, and the effects that this price-volatility has had on both the U.S. and global economies.

Oil Prices

It is difficult to imagine a subject more fraught with potential controversy than attempting to prioritize, in approximate order of their relative importance, the dozens of factors that have been known to have an influence on global oil prices. Nevertheless, this report will assemble such a prioritized list of major factors, based upon the available evidence, especially with respect to the oil price spikes that occurred during the spring/summer periods of 2008 and 2011, both of which had major negative effects on the global economy.

The purposes of listing the relevant factors is to try to understand first "what happened" and then to develop a strategy that could reduce oil price spikes and their negative effects in the future. In particular, development of this strategy will include those factors that are directly related to the properties of the FT diesel fuel used in these evaluations and those factors directly related to the mandated changes in diesel fuel specifications over the past decade—changes that indeed "originated" from technical evaluations of emission reduction approaches first applied in urban transit-bus service.

New Realities of Petroleum Refining

There is a significant gap between the actual technical and economic issues that drive decision making within the global petroleum industry, and the general public's perception of those

issues. For example, most members of the general public still think that gasoline is the product that the petroleum industry is focused on. In fact, gasoline has now become a global-surplus by-product; the real focus of global petroleum refining in the new century is production of sufficient quantities of middle-distillate fuels—diesel and jet fuel. Furthermore, the refining task has been made much more difficult and expensive, and, thus, the prices of all fuels from refineries have been increased significantly, by the legal requirements implemented within the past few years, in virtually every developed country of the world, that the sulfur level of diesel fuel must be in the single-digit parts per million (ppm) range when the ultra-low diesel fuel (ULSD) leaves the refinery.

As will be demonstrated, FT diesel fuel from alternative domestic resources, with a sulfur level of virtually zero ppm, is the ideal diesel fuel to bolster ULSD supplies most cost effectively. At the same time, FT diesel fuel can significantly reduce crude-oil imports in a leveraged 3:1 ratio from unfriendly areas of the world, all without producing more global-surplus gasoline.

The S-2 Fuel Used in This Project

Synthetic fuels produced by FT synthesis could, in their own right, provide a significant volume of the U.S. transportation fuel demand from secure domestic resources. However, FT synthetic fuels can provide much greater overall benefits than simply adding to fuel volume, especially if their unique attributes are fully recognized and employed within the conventional petroleum refining industry in an optimum manner, particularly with respect to the production of ULSD fuel. FT synthetic fuels can, thus, provide extraordinary "leverage" if they are used in the following ways, which are listed here first, then explained in more detail within the report:

- Zero-sulfur FT diesel fuel can be used as blendstock to "bring-back" (and thus avoid the down-grading to lower-value, higher-sulfur product category that would otherwise be required) for conventional ULSD fuel batches that slightly exceed the rigorous 15 ppm sulfur limitation, thus greatly improving refining capability and flexibility in crude sourcing.
- Since diesel (not gasoline) demand drives global refining, each barrel of FT diesel fuel produced from U.S. domestic alternative resources can "back-out" more than three barrels of crude oil imported from unfriendly or unstable areas of the world.
- Producing a barrel of FT diesel fuel from alternative resources avoids the production (and ultimate combustion) of yet more global-surplus gasoline and other surplus petroleum products such as residual fuel oil and petroleum coke.
- Producing FT diesel fuel can also provide extraordinary financial leverage, because the prices of low-sulfur crude oil (and even high-sulfur crude oil, as a result of the OPEC cartel's crude pricing policies), as well as other petroleum products including gasoline, are all ultimately determined by supply/demand balance of ULSD at the margin.

While natural gas was the feedstock for the fuel used in this project, the FT process is also capable of converting coal and biomass into liquid synthetic fuels. The demonstrations have covered a range of climates in several locations across the United States, including military installations, and all have been aimed at determining how the FT diesel fuel works in conventional diesel bus engines.

FT Diesel Fuel: Ideal for Boosting ULSD Output without Producing More Surplus Gasoline

ULSD has now become the environmentally-mandated fuel-type for virtually all diesel applications throughout the developed world. The technical and economic factors responsible for the high cost of ULSD, and the directly related high cost of other fuels including gasoline, were examined and are discussed in detail. This will also show how FT diesel fuel, with virtually zero sulfur content, can provide major environmental and financial benefits to both the U.S. and the world at large.

The goal of this examination is not to engage in the ongoing political debate about whose "fault" it may be that the prices of crude oil and its fuel-products are so high. The first goal is to understand the technical and economic factors that determine crude oil and product prices, prominently including the fact that overall commodity prices are almost always determined at the margin, or by the last increment of available supply, and whether it is "too much" or "too little" relative to its basic demand. The second goal is to use this information to formulate a strategy that can provide disproportionately-large benefits, both to the environment and to the

U.S. economy by producing FT diesel fuel with virtually zero-sulfur content from domestic resources.

In addition to simply increasing the volume of ULSD, FT diesel with virtually zero sulfur can be blended in the required proportions with conventional diesel fuel that has a sulfur level somewhat over the ULSD limit, and thus “save” that particular much-needed but marginal batch of fuel from otherwise falling into a higher-sulfur, lower-quality, already-surplus, and thus lower-value product tier, such as diesel fuel for export only, or into the heating-oil category.

SECTION 2

Project Background: Summary of Previous S-2 Fuel Demonstrations

Demonstration of Neat S-2 Fuel in a Desert Climate

The desert transit-bus project at Edwards AFB demonstrated and tested Syntroleum's S-2 FT diesel fuel in the newest and most-used transit bus at the base, a 2004 Thomas 44-passenger bus with a Caterpillar model No. 3126 engine. The Edwards demonstration bus began running on neat (unblended) S-2 FT diesel fuel on September 19, 2006. This same bus was used to transport visitors invited by the Commander of Edwards Air Force Base Flight Test Center, Major General Curtis Bedke, to and from the first Air Force test flight of blended FT jet fuel. During the test flight, the B-52 bomber successfully used, in two of its eight engines, a 50:50 blend of Syntroleum FT jet fuel and conventional petroleum-derived jet fuel.

The Air Force Advanced Power Technology Office purchased a new 8,000-gallon (30,283.3 L) stationary fuel tank for storing and dispensing the neat FT diesel fuel into the bus at Edwards AFB. No desert storage problems were encountered with the new tank. The desert bus demonstration of neat FT S-2 diesel fuel at Edwards continued through the 2009 calendar year, for a total duration of just over three years. A total of 1,997 gallons (7,559.47 L) of FT S-2 diesel fuel were consumed and 8,828 miles (14,207.29 km) were accumulated, for an overall bus fuel consumption rate of 4.4 MPG (53.46L/ 100 km). The bus was used to transport visitors and military personnel for many Air Force events, both on base and in the surrounding desert environment communities. No operational problems attributable to the FT S-2 fuel were encountered.

Demonstration of Neat S-2 Fuel in Revenue Service by Tulsa Transit

The Metropolitan Tulsa Transit Authority (MTTA) demonstrated the utility of S-2 FT diesel fuel in a new Gillig transit bus with a Cummins ISL engine beginning August 23, 2005, and continuing until July 3, 2008. This was a long-term (i.e., approximately three years) demonstration of the ability of FT fuels to meet the operational requirements of diesel-fueled engines under severe inner-city bus service. A total of 24,000 gallons (90,849.88 L) of S-2 were used by the bus, and 121,111 miles were accumulated, for an average fuel consumption of 5.05 MPG (46.58L/ 100 km).

The MTTA demonstration was designed to demonstrate long-term operability of neat (or unblended) FT diesel fuel under urban transit-bus driving conditions with inspection of fuel-injector nozzles for any possible fouling. The demonstration also included comparison of nozzle deposits formed during use of FT fuel with deposits formed during use of conventional petroleum derived diesel fuel in a similar bus and engine.

The S-2 test fuel for MTTA was treated with additives common to commercial ULSD fuels to improve lubricity, conductivity, corrosion resistance, oxidation stability, and foaming. It was also treated with a Syntroleum-proprietary additive system that contained a fuel dispersant, or injector deposit control additive, as prior laboratory fuel system durability testing under the DOE Ultra-clean Fuels program had indicated that metals derived from combustion of lubricant additives found in the engine lubricating oil can be deposited on the outside of the injectors and lead to partial plugging of the fuel-injector nozzle orifices under some circumstances, as described below.

Previously, ICRC conducted laboratory testing to demonstrate fuel system durability of Ultra–Clean FT diesel fuel under a Department Of Energy–National Energy Technology Laboratory (DOE-NETL) cooperative agreement [1]. Under this program, two bus engines, a DDC Series 50 and a Caterpillar C-7, were operated for 1,500 hours under the Urban Bus Driving Cycle. This testing showed that under laboratory conditions, deposits can form on the external surfaces of injector nozzles, leading to partial plugging of the nozzle holes and resulting in power loss. It is not known if these deposits are formed only under laboratory conditions or are related to only one engine type. Scanning Electron Microscope (SEM) analysis of the injectors showed conclusively that the deposits were formed only on the outside of the injectors and that the source of the deposits was from combustion of metallic (ash) components of the additive package in the engine lubricating oil. Therefore, one of the goals of this project was to inspect fuel injector nozzles from the MTTA demonstration bus engine for deposit formation.

After approximately one and a half years of operation on February 8, 2007, the first injector (Injector 1) from the Tulsa Transit bus was removed for inspection. At the time of removal, the bus had accumulated 54,758 miles (88,124.46 km) and operated for approximately 3,800 hours, for an average speed of 14.41 miles/hour (23.19 km/hour). The bus had consumed approximately 9,800 gallons (37,097.04 L) of fuel, for an average fuel consumption of 5.6 MPG (42 L/100km). About six months later on July 6, 2007, a second injector (Injector 2) was removed for inspection. The bus had accumulated an additional 35,891 miles (57,760.97 km), for a total of 90,649 miles (145,885.42 km) by that date.

Optical microscopy indicated that deposits had formed on the tips of the injector nozzles removed from the Tulsa Transit bus. It appeared that the deposits formed preferentially on one side of the injector and not on the other. None of the injector nozzle holes was plugged, and no operational difficulties were noted during the test period. Due to the accumulation of deposits on the injector tips shown on the optical microscope images, it was concluded that additional SEM analysis of the injector tips was warranted to try to determine the source and composition of the deposits. A fuel- injector run in a similar engine on conventional diesel fuel was also studied for reference.

Based upon a relatively small sample of three fuel-injection nozzles from two different Cummins ISL engines, the morphology of deposits formed on the exterior surfaces of fuel-injector nozzles when using conventional No. 2D diesel fuel were different from the deposits formed when using synthetic FT diesel fuel.

Optical and electron-microscopic analysis of injector nozzle from the engine operated on conventional No. 2D fuel showed thick, flaky deposits. Energy-dispersive X-ray spectroscopy (EDS) analysis of these deposits indicated that the deposits contained predominantly carbon and elements that are commonly found in heavy-duty diesel engine oils—sulfur, phosphorus, zinc, calcium, and magnesium. Deposits formed on the exterior nozzle surfaces when a similar engine was operated on synthetic S-2 FT diesel fuel were distributed differently (primarily on the nozzle tips) and did not show a tendency to flake off, as was seen with the deposits from conventional No. 2D fuel. EDS analysis of the deposits with FT fuel showed substantially less carbon and relatively higher amounts of elements found in engine oil additives. Despite differences in morphology of the deposits, there was no indication that there were any operational problems with either engine or any of their injectors.

Additional information on both the most recent past demonstrations, namely at Tulsa Transit and at Edwards Air Force Base in California, can be found in reference 2.

Demonstration of Neat S-2 Fuel in Cold-Climate Transit-Bus Service

The primary purpose of this related FTA-sponsored project was to study the potential use of ultra-clean FT synthetic diesel fuel in cold-climate transit applications. The cold arctic climate of Fairbanks, Alaska, represented the cold end of the spectrum. The cold-climate project activities included a 24,000-mile (38,624.26 km), 5,000-gallon (18,927.06 L) winter demonstration of Syntroleum arctic-grade FT fuel in two urban transit buses in Fairbanks. Additionally, the University of Alaska, Fairbanks (UAF) ran a soil biodegradability analysis to determine the environmental effects of potential FT fuel leaks. The Alaska-centered project focused primarily on running and storing FT fuel in cold climates, both major issues.

The objective of the Fairbanks transit-bus demonstration was to show that highly-isomerized arctic-grade FT diesel fuel can be routinely stored, dispensed, and run successfully in buses at the coldest temperatures likely to ever be encountered in any urban area in the U.S. Data collected included transit personnel observations, fuel usage/fuel economy, and on-road gaseous emissions using a portable analyzer on-board a bus operating on both FT and conventional No. 2 diesel fuels. ULSD was not yet required for on-road use when this demonstration took place in 2004 and 2005.

The cold-weather phase of demonstration ran from mid-December 2004 to late April 2005 on an urban transit route in Fairbanks, with temperatures ranging from below -40°F (-40°C) up to about +50°F (10°C). The two buses running exclusively on FT fuel covered a total of 23,720 miles (38173.64 km) during the cold-weather phase and consumed 5,451 gallons (20634.28 L) of arctic-grade FT fuel. When the weather warmed up in late April 2005, the same buses continued to use the arctic-grade FT fuel for some fill-ups, but No. 2 diesel fuel use was interspersed because the transit agency had concerns about continuing the exclusive use of the very light arctic-grade fuel at (what they considered to be) very warm temperatures.

The concern was apparently based upon the perception by the agency that the lubricity of arctic-grade FT fuel, if used exclusively, might not be sufficient to protect the engine's fuel injection system at warm temperatures. However, several previous evaluations of the lubricity of the Syntroleum FT fuel during the NETL project [1] have shown that the commercially-proven lubricity additive treatment applied to all Syntroleum diesel fuels, including arctic-grade, is fully capable of protecting diesel fuel systems under the full range of real-world operating conditions.

The most significant conclusion from the demonstration is that Fairbanks North Star Borough staff observed no fuel-related problems, and no maintenance issues were attributable to the use of FT over the approximately 2,000-hour, 30,000-mile (48,289.32 km) test. The operation demonstrated that FT fuel can directly replace conventional diesel fuel without modification to engines or significant changes in performance, since switching between FT and No. 2 diesel fuel remained uneventful. The use of FT fuel did not have an adverse effect on emissions.

Cold-weather characteristics are an important consideration in any arctic endeavor, and the FT fuel performed well during cold-weather operations in temperatures as low as -40˚F (-40˚C). This project showed that FT fuel can be stored, dispensed, and successfully run in transit buses at extremely low temperatures, without any modifications to the bus engines.

Summary of Fuel Consumption Comparisons

The majority of U.S. diesel fuel is used in trucks, with urban buses using only about 1 percent of total U.S. diesel fuel. Therefore, any "new" type of diesel fuel that might be able to provide benefits when used in urban transit buses, such as lower emissions, for example, will also need to work acceptably in diesel trucks. In determining the acceptability of such a "new" low-emission fuel, effects on fuel consumption will be a matter of significant concern in any application, including in urban transit buses, but fuel consumption is always the primary concern in trucking.

The purpose of using the National Center for Asphalt Technology (NCAT) Pavement Test Track in Auburn, Alabama, was to conduct a well-controlled, on-road fuel economy comparison of Syntroleum S-2 and conventional diesel fuel over many thousands of miles using heavy-duty diesel-powered trucks. The NCAT uses five nearly-identical trucks, with identical maximum loads, driving together in single file around the test track at constant speed to stress the instrumented asphalt pavement(s) that make up the track, each test-pavement section being evaluated for its endurance.

The primary object under test on this test track is the asphalt pavement itself, but this configuration also allows for other simultaneous testing, such as fuel consumption comparisons. In addition to documenting fuel economy using accepted methods, any potential fuel-related operational issues that might be experienced (i.e., equipment problems, performance problems, etc.) were also to be tracked. The following summarizes the major elements of this controlled fuel economy comparison as well as summary findings.

Based on the total miles driven and the total amount of S-2 fuel pumped, an average fuel economy of 4.24 MPG (55.48 L/100km) was measured with the S-2 FT synthetic fuel that was used exclusively in NCAT truck number 4. To assess the significance of this number, it was necessary to normalize the data to account for any change in fuel economy that would have been experienced by the entire fleet (e.g., slight changes in speed of the vehicles, weather conditions, etc.). The American Trucking Association's (ATA) Technology and Maintenance Council (TMC) has developed a standardized method for relating fuel economy in a treatment vehicle to fuel economy in a designated control vehicle in Recommended Practice (RP) 1102 entitled "TMC/SAE In-Service Fuel Consumption Test Procedure—Type II."

To facilitate Type II testing, NCAT's truck number 3 was designated as the track's control vehicle. Regardless of what treatments, changes, etc., were evaluated in the other four trucks, truck number 3 was never altered in any way. Because it never changed, fuel economy in the other trucks could be divided by the fuel economy in number 3 to produce a fuel economy ratio as specified in RP 1102. Resulting fuel economy ratios were then passed through a 2 percent filtering band in order to be included in the analysis. In accordance with the Type II procedure, all groups of three or more trips that fall within this band in each work week (five calendar days) are averaged to produce a single number that has statistical significance.

It was found that filtered fuel economy ratios, as calculated according to the preceding paragraph, averaged 1.000 before the treatment, then averaged 0.937 during the treatment period. This amounts to a 6.3 percent increase (i.e., 1.000 – 0.937 = 0.063) in fuel consumption as a result of the use of S-2 synthetic diesel fuel in truck number 4. An increase in fuel consumption was expected since lighter FT synthetic diesel fuel contains less energy per gallon than heavier petroleum-derived diesel fuels.

The track's trucking coordinator reported no difference in starting with truck number 4; however, drivers reported that power was reduced until the engine had been running long enough to become heated. With the engine hot, drivers reported excellent power. It appeared the synthetic fuel produced less visible smoke as truck number 4 pulled through the slight grade in the west curve, although this observation was not objectively quantified.

Summary of FT Fuel Engine Exhaust Emission Findings

One of the goals of this series of FTA projects is to provide a summary of the transit-relevant emissions testing that had been completed on Syntroleum FT fuel. ICRC/VSE collected emission data during the two major bus demonstrations that were part of the NETL FT fuels project referred to previously reference 1. These included an urban transit-bus demonstration at the Washington Metropolitan Area Transit Authority (WMATA) in Washington, DC, and in wilderness tour buses at Denali National Park in Denali, Alaska. Emission data were also collected from dynamometer emission tests that were conducted on bus engines identical to those used in the WMATA and Denali demonstrations.

Measurement of the difference in diesel engine exhaust emissions attributable to as subtle an influence as differences in fuel properties requires an excellent degree of control over all other potential variables. This demands, in addition to excellent control of operating conditions, exhaust sampling, instrument calibration, etc., and back-to-back emission testing on the test fuels to be compared to minimize engine and vehicle variations.

The buses and engines tested ranged from the 1999 through 2004 model-years and were equipped with standard Diesel Oxidation Catalysts (DOCs). DOCs were commonly-used diesel exhaust after-treatment devices prior to the 2007 model year, when more advanced exhaust after-treatment systems were mandated that reduce unburned hydrocarbon emissions primarily, but DOCs also provide a modest reduction in particulate and carbon monoxide emissions, all without requiring sophisticated control systems integrated with the engine's electronic control system. Particulate Matter (PM) and Nitrogen Oxide (NOx) emissions are the most difficult diesel exhaust emissions to control from legacy diesel vehicles. Without the use of expensive, dedicated exhaust after-treatment systems (which would require the use of ULSD fuel) and their control systems that must be integrated with the engine's control system, there are few workable approaches other than switching to lower-emission fuels.

Syntroleum's FT diesel fuel reduced particulate matter emissions for the stock-DOC bus by more than 30 percent compared to the lowest-emission conventional diesel fuel, Ultra Low Sulfur Diesel No. 1 (ULSD1). Furthermore, despite the "trade-off" that often accompanies attempts to reduce either particulate or NOx emissions from diesel engines, the FT diesel fuel also reduced NOx emissions for the stock-DOC buses by about 20 percent (on average) compared to the lowest-emission conventional diesel fuel, ULSD1.

Table 2-1 is a summary of back-to-back particulate and NOx emission measurement results comparing Syntroleum S-2 FT diesel fuel to the same conventional low-emission fuel, ULSD1, for three separate data sets. The first column of results summarizes the results for the single WMATA bus in its stock configuration with the diesel oxidation catalyst. The second column of results gives the average reductions in PM and NOx for three similar WMATA buses measured under the same conditions at a later time. The third column of results is for a Caterpillar C-7 engine run on a laboratory dynamometer using the AVL 8-Mode emission measurement cycle. The AVL 8-Mode test is an eight-mode steady-state engine test procedure designed to correlate with exhaust emission results of the U.S. Federal Test Procedure Heavy-Duty Transient Cycle.

Table 2-1

Emission Reduction Percentages in PM and NOx Attributable to Switching to Syntroleum S-2 FT Fuel from Conventional ULSD1 Fuel in Back-to-Back Tests

Back to Back Data Source	1 WMATA Bus	3 Bus Average (WMATA Buses)	Dynamometer Emission Test
Engine	DDC Series 50	DDC Series 50	Caterpillar C-7
Exhaust After-treatment	DOC	DOC	DOC
Test Cycle	WMATA Cycle	WMATA Cycle	AVL 8-Mode
Reference Fuel	ULSD1	ULSD1	ULSD1
S-2% Reduction in PM	35	35	42
S-2% Reduction in NOx	28	16	19

Table 2-1 shows that the reductions in both PM and NOx emissions obtainable by switching to FT fuel, even from the lowest-emission conventional diesel fuel ULSD1, are significant and fairly consistent from test to test. Data from other testing (not back-to-back), while not as definitive, provides additional support for the data in Table 2-1, as is discussed in references 1 and 2.

Overall Summary of Past Operations and Testing of S-2 FT Diesel Fuel

VSE/ICRC has conducted demonstrations and tests of Syntroleum Corporation's S-2 FT diesel fuel in a new transit bus that ran a large total volume of FT fuel in revenue service over a period of almost three years in Oklahoma, in a desert-climate demonstration of S-2 FT diesel fuel in an Air Force passenger bus at Edwards AFB in Southern California, in a cold-weather transit bus demonstration in Alaska, and in a Class 8 truck run at the National Center for Asphalt Technology at Auburn University in Alabama.

Additionally, VSE has worked to compile and provide summary documentation on the emission testing programs and results for Syntroleum's S-2 and S-1 (arctic-grade) ultra-clean diesel fuel tested under several related projects, including the Department of Energy's (DOE) NETL Ultra-Clean Fuels Program, FTA, and other organizations (including the University of Alaska, Fairbanks (UAF), Massachusetts Institute of Technology (MIT), West Virginia University (WVU), and AVL Powertrain Engineering). This project report provides a single point of reference for all transit-relevant emission measurements and comparisons associated with Syntroleum's ultra-clean diesel fuel as tested, including those done prior to the demonstration program with FTA.

Long-term testing of neat FT diesel fuel in transit bus service over the full range of climatic conditions has concluded that:

- No fuel-related operational problems occurred.
- The environmental impacts of FT diesel fuel are even less severe than those associated with conventional ULSD fuel.
- Fuel consumption of FT and ULSD are comparable.

SECTION 3

Long-Term Test of Neat S-2 Fuel in a Caterpillar C-7 Bus Engine

The Test at Selfridge

The primary technical objective of this project has always been to understand and resolve, within the transit-bus context, issues unique to FT fuel, which has virtually zero levels of aromatics and sulfur. As described briefly in the Background section and fully in reference 1, fuel-injector nozzle-fouling and a resultant 20 percent loss of engine peak power had occurred during a previous 1,500-hour dynamometer test of a Caterpillar C-7 engine running on neat S-2 fuel under relatively severe bus-engine operating conditions (i.e., the Chicago Transit Authority Dynamometer Test Cycle). The primary technical purpose for this demonstration of neat S-2 fuel at the Selfridge Air National Guard Base, beyond simply obtaining more in-use data, was to assess whether or not such nozzle-fouling with perceptible power loss would occur in normal transit bus operation. As shown below, the bus did not experience any perceptible loss in power or any other problem related to fuel throughout the three-year duration of the test.

During the three-year test from October 3, 2008, to September 29, 2011, the military transit bus ran for 400.6 engine operating hours and 5,932 odometer miles (9,546.63 km) and consumed a total of 744.4 gallons (2,817.86 L) of S-2 diesel fuel. Based upon this overall data, the calculated overall fuel consumption rate, in miles per gallon, would be 7.97 MPG (29.51 L/100 km). While the new-technology Caterpillar C-7 engine is known for good fuel economy, almost 8 MPG (29.4 L/100 km) is undoubtedly "too good to be true." Transit-bus diesel fuel consumption rates are more typically in the 5–6 MPG (47.04 L/100 km to 39.2 L/100 km) range.

Furthermore, it is known that on at least one occasion near the end of the test, when military personnel at Selfridge were preparing to be deployed to another part of the world, this military transit bus was used essentially as a "shelter" during a day-long training exercise on the flightline in inclement weather. This type of usage would involve relatively little mileage accumulation, but perhaps significant fuel consumption, thus reducing the expected MPG value.

One of the risks of doing a research project on an active military base is that the military mission will always take priority over all other considerations, especially when deployment of personnel to a war zone is on the horizon. As part of the preparation for deployment, the bus was also used for travel to other military bases that were too far away from Selfridge to allow exclusive use of the S-2 fuel supply at Selfridge, so some conventional diesel fuel was added to the fuel tank of the bus on these occasions. This type of usage increased the odometer miles (km), but the conventional fuel usage did not appear in the S-2 Fuel Consumption Log, thus increasing the calculated MPG (L/100 km) value.

The fact that some conventional diesel fuel was used in the bus during preparations and training for deployment in 2011 contributed to the decision to wrap up the project at the three-year point, even though some S-2 fuel still remained at Selfridge. But this situation also prompted a re-analysis and reconsideration of the assumptions that had been made early in the overall project, which had begun in 2005 with the Tulsa Transit bus demonstration described previously.

Implications of the Test at Selfridge

The potential for fuel-injector nozzle-fouling when FT fuel is used neat is associated with the virtual absence of aromatics from FT fuel. Aromatic hydrocarbons, which make up a significant fraction of conventional diesel fuel, are generally much better solvents than the hydrogen-saturated hydrocarbons that comprise aromatic-free FT diesel fuel. Therefore, the worst case, with respect to potential fuel-injector nozzle-fouling, is the use of zero-aromatic, neat FT fuel. The reason is that without aromatics, the neat FT fuel may be less able than conventional diesel fuel to dissolve and thus "wash-out" deposits that originate from the minerals in the engine oil additive package, which are present to some extent in the engine combustion chambers.

But in today's world, the virtual absence of sulfur in FT fuel is the real game-changer, because the entire global petroleum refining and fuels production system is now driven by the need to produce sufficient supplies of ULSD, at the margin, to meet the basic global ULSD demand. Since 2005, when this particular project began with the Tulsa Transit demonstration, ULSD has replaced gasoline as the product that drives decision making within the global refining/fuels-manufacturing system.

As will be described in the next section, these same ULSD-focused changes within the refining/fuels-manufacturing system have also been directly responsible for the rapid increases in global fuel prices and the global fuel-price spikes that have occurred over the past several years. Furthermore, production of a barrel of zero-sulfur FT fuel from U.S. domestic resources other than petroleum has the ability to "back-out" over three barrels of imported oil.

FT fuels produced from resources other than petroleum could increase global ULSD supplies, both by adding additional ULSD volume and by using targeted blending, to allow refiners to get a significantly higher proportion of ULSD out of each barrel of crude oil than is possible today.

This means that the original objective of the project, to assess the potential for problems to occur with neat FT diesel fuel, is a usage strategy that is exactly opposite the most effective strategy, namely blending of FT with conventional diesel, for using whatever quantity of FT fuel could be produced over at least the next several decades. Furthermore, blending of FT with conventional diesel virtually eliminates the potential problems, such as fuel-injector nozzle-fouling, that could be caused by zero-aromatic neat FT fuel. And, as described in the next section, if implemented on a large-enough scale (100,000s barrels per day), FT fuels produced from resources other than petroleum also have the capability of actually moderating the market prices of both ULSD and gasoline over the long term.

SECTION 4

Diesel Fuel Realities, and Implications for the U.S. and Global Economies

Summary

The following facts are arranged initially as bullet points for easier assimilation and comprehension. They lead to the conclusion that the economies of the developed world are ultimately being threatened by the increasingly high costs inflicted on these economies by a combination of factors, prominently including the environmentally-driven requirements for extremely low (near zero) sulfur levels in middle-distillate fuels, particularly diesel fuel, for virtually all uses "across the board." The key points are stated here as bullets, then discussed further and supported by publically-available evidence and data.

- Developed economies of the world are absolutely dependent upon secure and affordable supplies of middle distillate fuels, diesel fuel in particular, for:
  - All agriculture and distribution of foodstuffs
  - Virtually all movement of materials and distribution of products, whether by truck, rail, ship, barge, or aircraft
  - Virtually all heavy construction
  - There are no large-scale substitutes that can be implemented in the short term
- Demand for middle distillate fuel, and for diesel fuel in particular (not the demand for gasoline), determines the amount of crude oil that both the U.S. and Western Europe must import.
  - The decisions of Western European governments about 30 years ago to provide large tax incentives favoring diesel passenger cars have resulted in a growing increase in global demand for diesel fuel and in a global surplus of gasoline.
    - o Western European governments made an assumption that is no longer valid, namely that refineries can easily adjust their relative output of products to "fit" their individual demands.
    - o In the past, when gasoline was still the primary product, European refineries could use their catalytic-crackers to crack "excess" middle-distillate streams to more gasoline, thus maintaining product balance.
    - o Now that middle-distillate demand is primary and increasing, while gasoline is a surplus by-product, adjustments in product outputs are much more difficult and expensive, if they can be made at all.

  - U.S. refiners have maximized their output of middle distillates (to the extent reasonably possible) while reducing gasoline production, because excess gasoline from Europe is literally being “dumped” on the U.S. east coast [4].

- Since the sulfur level of diesel fuel must now be extremely low (15 ppm in the U.S., 10 ppm in Europe), marginal refineries must use a high proportion of low-sulfur, or “sweet,” crude oil or they cannot make legally-acceptable diesel fuel and other products.
  - Sweet crude, at 0.5% sulfur or less, represents no more than 20% of total world crude oil production capacity.
  - Global sweet crude production capacity has been insufficient to meet demand since early 2005; as refiners fully understood the upcoming requirements for ULSD, they began contracting for higher fractions of sweet crude.
  - The cost of sweet crude began increasing significantly in 2005, clearly beyond the range of its variations during the previous 30 years.
  - Production of sweet crude from Libya, with a sulfur content of 0.1% or even lower, was reduced significantly by the revolution of 2011.

- The OPEC Cartel is dominated by Saudi Arabia; most Saudi crude is sour, not sweet.
  - Saudi Arabia has established (and enforced) the policy within OPEC since the 1990s that sour crude is priced at a fixed, stated-in-advance discount with respect to the sweet crude price, which does vary with market conditions.
  - The discount set by Saudi Arabia is relatively small (typically a few dollars per barrel), and the discount is not allowed to “float” in response to market conditions.
  - Therefore, the sour crude price has “kept pace” with the increases for sweet crude, even though there is significant excess sour-crude production capacity.

- ULSD has been the driver of virtually all refining decisions in the entire developed world for most of the past decade.
  - The refining margin, or profit, on ULSD is now usually the highest of any bulk fuel.
  - Although many people in the U.S. focus on gasoline, it is actually now a global-surplus by-product of producing ULSD and jet fuel.
  - The price increase of all crude oil has led directly to increases in the prices of <u>all</u> fuel products, including gasoline which still represents a large volume of the crude

    - With minimal sour-crude discount, there is little or no net incentive for more refiners to make the huge capital investments necessary to process "expensive" sour crudes into ULSD, despite ULSD's normally high margin.

- Marginal FT diesel produced from abundant U.S. domestic resources can provide disproportionately large benefits, both to the environment and to the U.S. economy.
    - The virtually zero level of sulfur in FT diesel greatly multiplies its value over and above its direct contribution to increasing the volume of ULSD available.
        - o Sorely-needed batches of conventional diesel fuel, with sulfur levels marginally over the limit, can be "saved" by blending with FT diesel.
        - o FT diesel blendstock could allow refiners to use a higher-sulfur crude mix, thus easing the price-pressure on limited supplies of low-sulfur crudes.
    - Production of the marginal, or "last-needed," increments of ULSD by FT from non-petroleum resources avoids the excess co-production, reduced-price marketing, permanent demand-enhancement, and ultimate combustion of the global-surplus by-products of petroleum refining such as gasoline, residual fuel oil, petroleum coke, etc.

Historical Background: Drivers of Today's Petroleum-Product Imbalance

Setting the Stage: Response of Western Europe's Governments to the Oil Shocks of 1973–1980

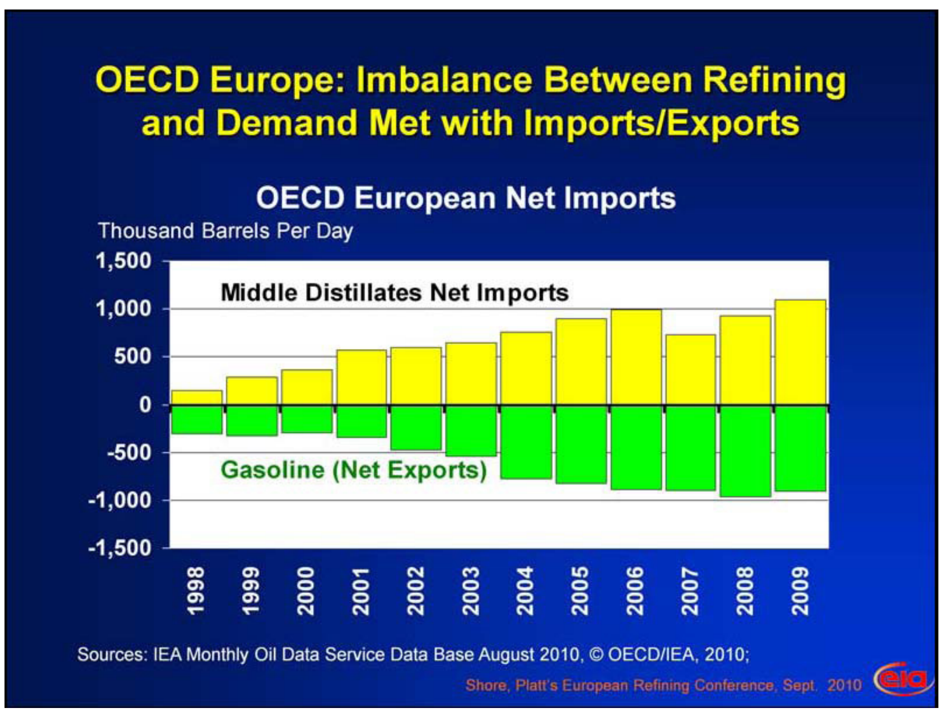
The primary response of most Western European governments to the oil shocks of 1973–1980 was to use fuel-tax incentives to encourage European drivers to switch from gasoline-powered to diesel-powered passenger vehicles, based upon the assumption that more efficient diesel vehicles would ultimately result in a reduced need for imported crude oil. This approach "seemed to work for a while," but it is now clear that this was a major policy blunder based upon a flawed assumption. The flawed assumption was that refineries would always (somehow) be able to adjust their relative output of their two primary products, gasoline and diesel fuel, to match their respective demands.

As long as gasoline was still the primary product driving the demand for crude oil, this adjustment could be made. The primary "mechanism" for this adjustment was the catalytic cracking unit, or fluidized catalytic cracker (FCC), with which virtually every commercial-scale refinery was (and still is) equipped. The FCC converts heavier refinery streams into lighter products, primarily gasoline. Therefore, refinery streams that would otherwise have yielded "too much" diesel fuel and other middle distillates could be cracked to yield more gasoline and less middle distillate. However, over time, as the demand for diesel fuel increased, while at the same time the demand for gasoline dropped, there was no longer an affordable mechanism to maintain the balance between the supply and demand of both gasoline and diesel fuel. The requirement for diesel fuel to be ULSD further increased the constraints on refiners, as will be discussed.

The result of this situation, in which the demand for diesel fuel and other middle distillates, not gasoline, now determines the amount of crude oil that must be run through European refineries, is shown graphically in Figure 4-1 (OECD, the Organization for Economic Cooperation and Development, includes virtually all of the countries of Western Europe). Note that Western Europe, in addition to producing as much diesel fuel, now ULSD, and other middle distillates as possible in its refineries, has been obliged to import an increasing amount, now about an additional million barrels per day, of middle distillates, including ULSD, the most expensive fuel in the global market today, when it can be obtained at all. Furthermore, the surplus gasoline produced by Europe's refineries must be exported because there is no market for it at home. It is, thus, virtually impossible for Western European refiners to make a profit on the substantial portion of the gasoline they produce but that they must export [5].

Figure 4-1

Europe's growing import/export imbalance, 1998–2009



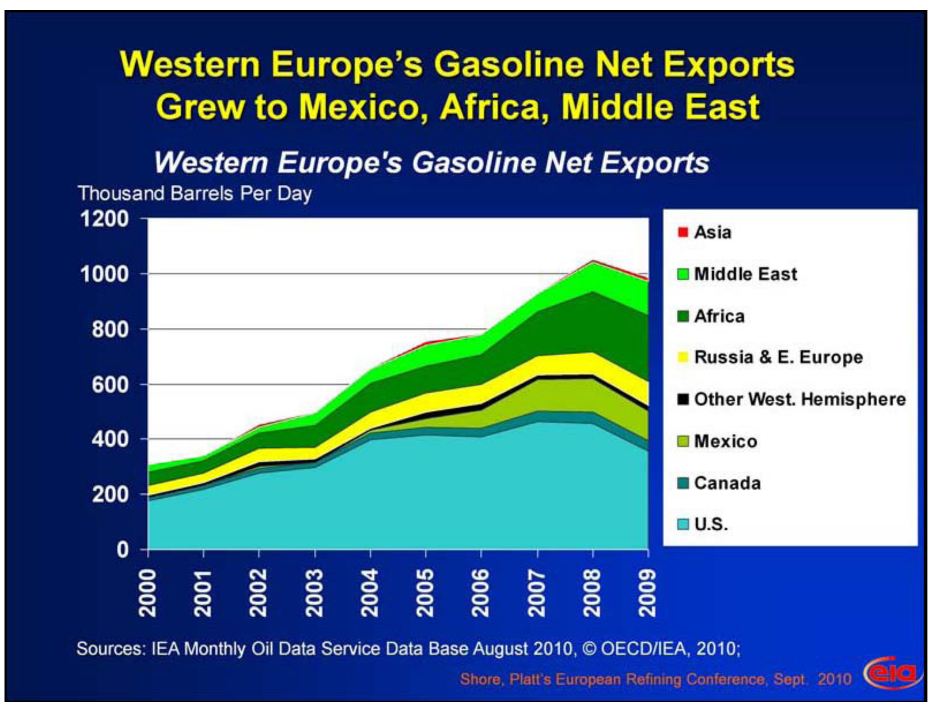
It should be noted that Figure 4-1 includes only finished gasoline exports from Europe. In addition to almost 1 million barrels per day of finished gasoline, Western Europe also exports almost another million barrels per day total of gasoline blending components and "unfinished oils" that yield mostly gasoline fractions when they are processed further, mostly by U.S. refineries.

The U.S. has benefited from the availability of this virtual "flood" of surplus gasoline available from Europe under very favorable terms. Availability of this gasoline has allowed U.S. refineries to maximize their production of diesel fuel and other middle distillates, within limits (see feference 6 for a discussion of these limits), and to reduce their gasoline output. The net result has been that the U.S. has needed to import less crude oil from unfriendly areas of the world than would have otherwise been necessary without the surplus European gasoline.

But as shown in Figure 4-2 (which again includes finished gasoline only [5]), the U.S. and other areas that are relatively close to Western Europe are no longer able to absorb all the surplus gasoline available from Europe, and it now must be shipped even further away. Europe has had to actively seek new customers for its surplus gasoline. Some of this gasoline is now being sold at prices significantly below market value in nations with populations that are among the largest on earth, thus literally creating increases in gasoline demand that are likely to be permanent.

Figure 4-2

Exports of surplus finished gasoline from Western Europe, 2000–2009



It is indeed ironic that the decisions made by Western European governments more than 30 years ago, with the intention of improving energy security, have now brought about exactly the opposite situation, because these decisions were based upon a flawed assumption. The imbalance between the European demand-ratio for diesel fuel and gasoline and the increasingly opposite production-ratio that European Refiners are able to supply, and the financial consequences of this imbalance, have now become a significant issue of energy-security in the United Kingdom [7].

This report demonstrates that similar unintended consequences are still resulting from fuel and energy policies being made by some governments today, primarily because the policies are based upon assumptions that may seem reasonable (or virtually "obvious" to everybody), but that nonetheless turn out to be wrong.

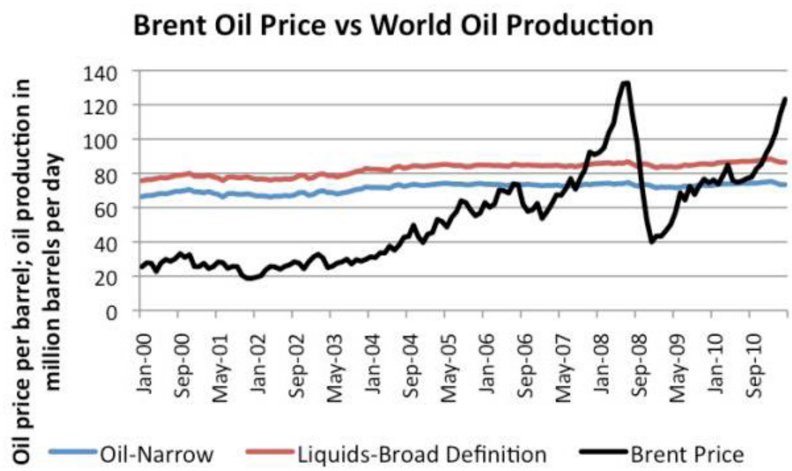
More Recent History: New Global Requirements for ULSD in the 21st Century

The new century began with relatively stable (and low, by 2008–2012 standards) oil prices. As shown in Figure 4-3, from the beginning of 2000 through at least 2003, global oil prices were nearly constant in the range of approximately $30 per barrel [8]. (Figure 4-3 shows the price of Brent crude, a high-quality, North-Sea crude oil that serves as a global oil price benchmark. "Oil-Narrow" refers to world crude oil production; "Liquids-Broad Definition" includes both crude oil and Natural Gas Liquids (NGLs) obtained from processing natural gas to make it pipeline-ready.) The only significant change in oil's price from 2000 to 2003 was a few months of even lower oil prices during the economic slowdown in the wake the September 11, 2001, terrorist attacks.

This global oil price stability persisted in spite of the beginning of wars in Afghanistan and Iraq in 2001 and 2003, respectively. The period of 2000 through 2003 was the most recent during which oil prices can be accurately described as "stable." Oil prices began to increase in 2004, and by 2005, high prices and increased oil price volatility made it clear that something had changed. However, as shown by the world oil production data in Figure 4-3, total oil production did not change rapidly, and the shortage of oil in total (i.e., irrespective of its properties) did not cause the increases in oil prices or in oil price volatility.

Figure 4-3

Oil price stability, 2000–2003



Although many factors can have an influence upon oil prices, this report shows that the predominant cause of rapid price increases, and the price spikes, during the middle of the past decade up to 2008 and again from mid-2009 to early 2011, was the inability of the global refining industry to produce sufficient ULSD, at the margin, to meet the increasing ULSD demands inherent in economies that are expanding normally, and thereby keep prices of ULSD and of all petroleum products at moderate levels using the crude oil supply available.

The total quantity of crude oil available was always more than adequate, but its quality at the margin, specifically the amount of "sweet" or low-sulfur crude oil available, was not adequate for many of the world's marginal refineries, which cannot process the higher sulfur crudes that were, and still are, abundantly available. Although the available higher-sulfur "sour" crudes would not, under purely market-driven conditions, have been able to command continuing price increases comparable to those of the light sweet crudes most in demand, the OPEC cartel effectively controls the prices of sour crudes so that they increase in-step with the market-driven prices of sweet crudes.

Data supporting the foregoing conclusion has been assembled, analyzed, and the results published over the past several years by Dr. Philip Verleger, an oil-industry economist, consultant, and retired Professor of Management at the University of Calgary School of Business. All the elements relating to this general scenario are covered in three of Dr. Verleger's recent presentations, two of which are entitled, ominously, "Blundering to $300 per Barrel" [9–11]. Furthermore, as will be described in more detail, the International Energy Agency (IEA) has demonstrated, by both its (relatively diplomatic) statements and its actions over the past several years, that it recognizes that the general scenario outlined above has been responsible for the recent increases and volatility in global oil prices.

This report traces the primary transit-relevant events of the recent past that have played a role in the increases in oil prices shown in Figure 4-3. One of the first of these was the promulgation, in early 2001, of the "Highway Diesel Rule; Clean Diesel Trucks, Buses and Fuel" [12]. Several documents published by the EPA accompanied the new Highway Diesel Rule, one of which [13] was focused on technical feasibility. The primary field data presented in reference 13 to support the new across-the-board U.S. diesel engine and diesel fuel regulations were obtained using diesel transit buses operating in several European cities, prominently including Stockholm, Sweden, where ULSD with a maximum sulfur level of 10 ppm had been available for approximately six years at the time the new U.S. diesel rules were promulgated in 2001.

The incorporation of the across-the-board ULSD requirement into U.S. law forced all petroleum refiners in the U.S., and many outside the U.S. as well, to quickly develop and implement strategies for complying with, or somehow continuing to operate despite, the new U.S. ULSD requirements taking effect in 2006. Some refiners, especially those that were part of well-capitalized, integrated oil companies with in-house refinery process research and development capabilities, elected to make the capital-intensive modifications to their refineries necessary to produce ULSD using their own proprietary technologies, which they developed internally as a means, they hoped, to gain a competitive advantage in the industry.

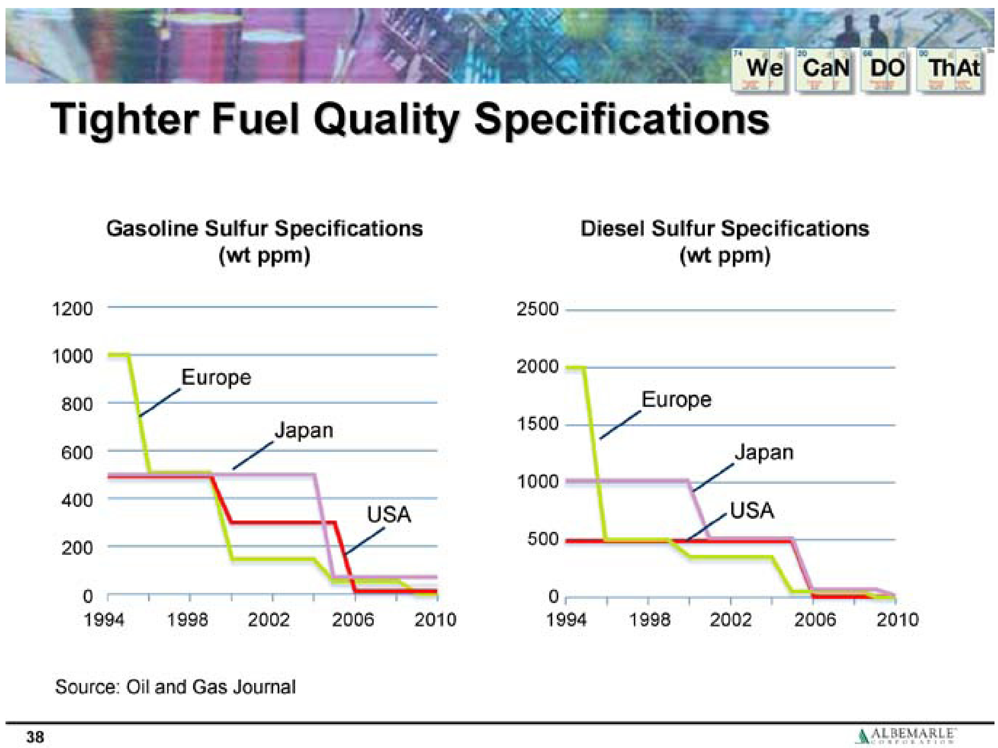
Other large companies in the refining industry, whether refiners themselves or major refining technology vendors, have developed ULSD production catalysts and technologies and made them available to other, primarily smaller, refiners for a price, while maintaining ownership and control of the underlying intellectual property to the maximum extent possible. The cost of the catalysts and technologies for the small-refiner-customer were effectively in addition to the large capital costs for the required refinery equipment and its installation. References 14 and 15 are examples of technical papers describing both the difficulties of making all the diesel fuel produced by a refinery comply with the severe ULSD sulfur requirement and the refining technologies that were made available for refiners to purchase.

The need to prepare for the new rules requiring ULSD unquestionably re-shaped the diesel fuel market [16], and ultimately the entire global fuels industry. As shown clearly in Figure 4-4, the U.S. was not the only country to require steep and rapid reductions in fuel sulfur levels. Figure 4-4 is a slide from an Albemarle Corporation presentation made in May 2004 [17]. Albemarle is a major supplier of refinery catalysts, prominently including desulfurization catalysts. Figure 4-4 and other slides in the same presentation demonstrate that the anticipated market for refinery desulfurization catalysts was expected to grow dramatically over the next several subsequent years.

As noted previously, gasoline demand no longer (since about 2005, as will be shown) drives the amount of crude oil that refineries must run. However, the tightening restrictions on the allowable level of sulfur in gasoline (Figure 4-4) contributed, along with the ULSD requirement, to the refiner's costs and problems if he chose to continue using his customary crude oil supply. Additional desulfurization equipment and greater hydrogen consumption were required for both the major products of the refinery, gasoline and diesel fuel, to meet the required steep reductions in sulfur content. Note that the refiner must be able to legally sell the relatively large volume of gasoline that virtually all refineries make, even though there is relatively little profit in gasoline, as will be shown.

Figure 4-4

Reductions in sulfur levels in gasoline and diesel fuel, 1994–2010



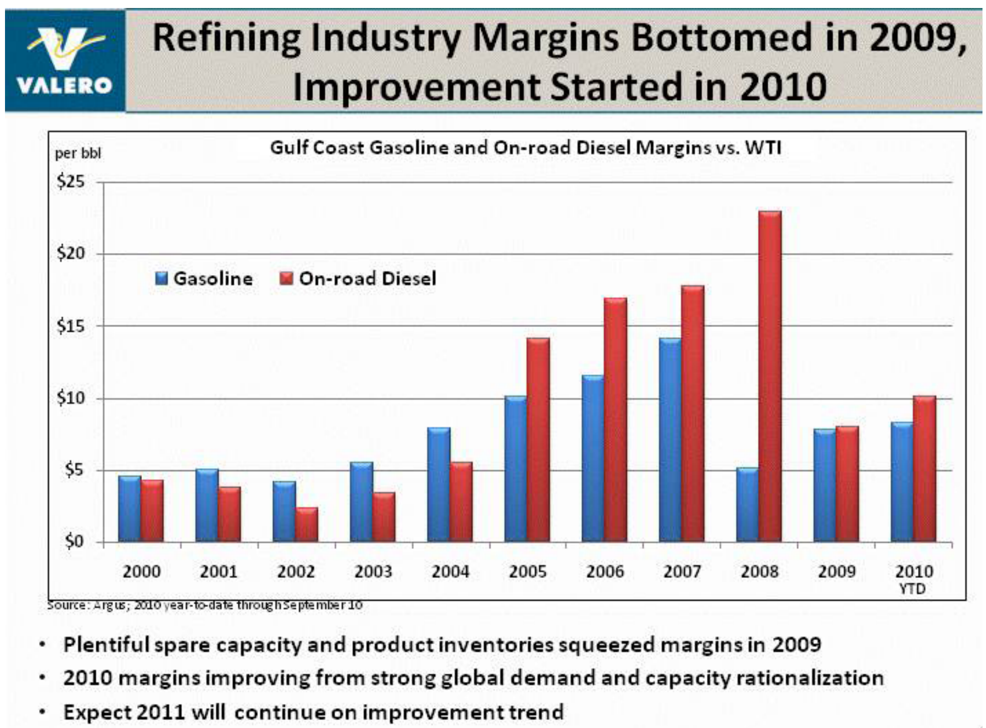
Rather than making the large capital investments required to implement new desulfurization technologies, some refiners decided that their strategy would be to simply pay the premium required, which they undoubtedly realized was likely to increase with increasing demand, to obtain an even higher proportion of low-sulfur or "sweet" crude oil. They hoped that this approach could minimize or even eliminate the need for major capital expenditures in their refineries, and thus be financially viable despite the higher (and likely increasing) cost of the light sweet crudes.

A few small U.S. refiners planned to export some or all of the higher sulfur diesel fuel, and even their gasoline, if its sulfur level occasionally ended up being too high for local sale. This approach was intended to allow them to continue producing these fuels from their customary crude supply without making large capital investments in desulfurization. A similar approach would be to downgrade their higher sulfur diesel to a lower value product such as heating oil, and thus avoid the major capital expenditures necessary to produce ULSD. These capital-cost-avoidance approaches undoubtedly contributed to a reduction in the supply of ULSD.

The net result, from the refiner's perspective, of the foregoing changes in the refining industry, brought on primarily by the ULSD requirement, is illustrated in Figure 4-5. As indicated previously by Figure 4-3, from 2000 through 2003 not much change occurred. The economic slowdown, for a few months after the September 11, 2001, terrorist attacks, reduced the prices, and the margins, on petroleum and petroleum products in 2002. In 2004, prices and margins began to increase somewhat.

Figure 4-5

Refining margins for diesel and gasoline, 2000–2010 [18]



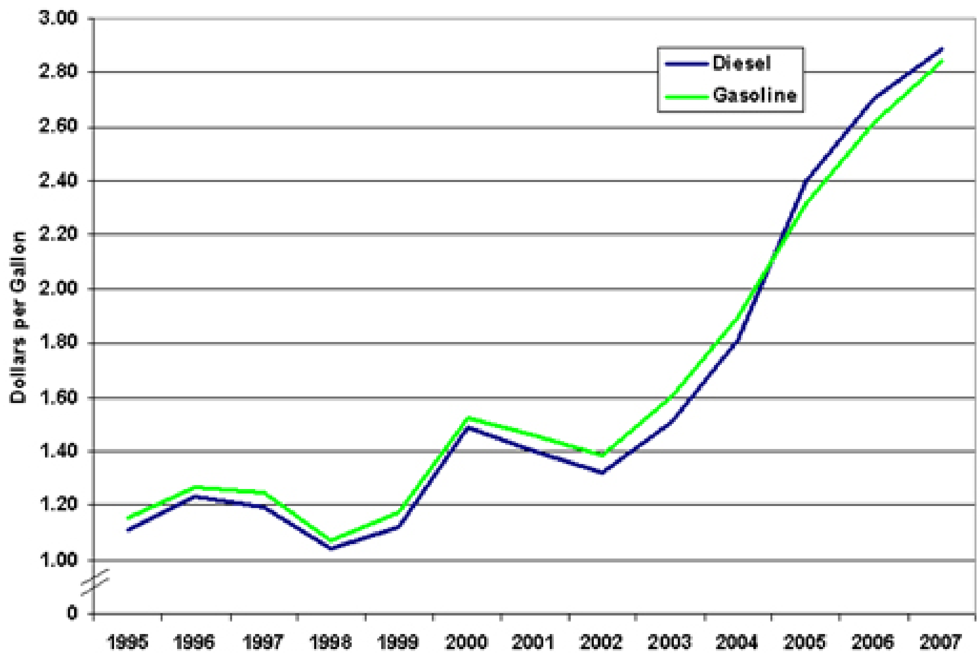
2005: The Year of Fundamental Changes in the Petroleum Industry

In 2005, as the full impact of the looming ULSD requirements began to be appreciated within the world business community, the refining margin for on-road diesel more than doubled and kept increasing. This increase in diesel margin reflected the new reality that demand for ULSD would be driving the refining industry from 2005 onward, and that gasoline was therefore relegated to the status of a by-product, albeit the most important by-product of petroleum refining since gasoline makes up such a large volume (typically ~45% in the U.S.) of a refinery's total output.

Figure 4-6 shows that the prices of both diesel fuel and gasoline increased rapidly from 2004 through 2007. (Note that both prices then literally "went off the chart" from 2007 to 2008.) This was caused by the market-based global price increase for light sweet crude oil, which was in high demand and relatively short supply (the supply of which would become significantly shorter during the spring of 2008 and of 2011), and by the parallel increase in heavy sour crude oil prices driven by the OPEC cartel.

Figure 4-6

Average annual U.S. sales prices for diesel and gasoline, 1995–2007 [19]



By comparing Figures 4-5 and 4-6, it can be observed that the refining margin on gasoline, as a percentage of its price, did not increase nearly as much as the diesel margin. Gasoline margin then plummeted in 2008 with the onset of the global recession. After an obvious and painful economic slowdown of almost three years from mid-2008 until early 2011, the global economy finally began showing some signs of recovery.

IEA Warning: Oil Prices Are a Threat to the Global Economic Recovery

In an unprecedented step, the Governing Board of the IEA issued a statement [20] regarding oil prices on May 19, 2011, that said in part: "Additional increases in prices at this stage of the economic cycle risk derailing the global economic recovery." This statement was in fact a prelude to action taken by IEA a few weeks later on June 23, 2011 [21], in which 60 million barrels of light, sweet crude oil and finished ULSD were released from the strategic reserves of the developed world. This action was not brought on by a physical shortage of crude oil (there was plenty of heavy, sour crude available), but rather by a shortage of light, sweet crude that could be processed by marginal refineries into sufficient supplies of ULSD, at the margin, to maintain price stability during the increase in demand for ULSD brought on by economic recovery.

The IEA is an intergovernmental group of 28 industrialized nations, all OECD-member market-democracies, that was created by the governments of the developed world (prominently including the U.S., Canada, Japan, and most West European governments) through an international treaty known as the Agreement on an International Energy Program in 1974, in the wake of the first oil embargo. The missions of the IEA are to deal with supply emergencies, obtain and analyze data to assist member governments in decision making, and to present, when necessary, a well-informed and unified position of the governments of the developed world on energy, and particularly on oil-related issues.

The IEA knows full well that the developed world has been and is facing a complex problem of fuel price and availability that is driven more by the required level of fuel quality, specifically in terms of fuel sulfur content, than by the quantity of crude oil available. This fact was demonstrated by the IEA's Oil Market Report Overview entitled "The Cost of Sulphur" [22], which was published in early 2007 as the widespread requirements for use of ULSD were being implemented. This 2007 IEA overview states that mandatory reductions in fuel-sulphur levels could, if carried to an extreme:

- Put upward pressure on prices for light sweet crude oil.
- Reduce supplies of transportation fuels, further raising prices.
- Increase CO_2 emissions.

Then, in the aftermath of the record-breaking run-up in fuel and oil prices between 2007 and 2008, the IEA published a follow-up analysis on "Price Formation" in June 2009 [23]. This follow-up IEA analysis concluded, as described in the words of prominent petroleum economist Philip Verleger in his testimony [24] to the U.S. Commodities Futures Trading Commission (CFTC), that the 2007–2008 price increases were "caused by the incompatibility of environmental regulations with the then-current global crude supply. Speculation had nothing to do with the price rise."

As the expert technical staff of IEA knows better than almost anyone else, continued growth of the U.S. and developed-world economies is ultimately being threatened again by the high fuel prices that have resulted from the same basic scenario above, which was outlined in advance ("The Cost of Sulphur") by the IEA in 2007. Fuel prices rose in 2011, as in 2008, to levels that the developed world simply cannot afford. The primary driver of these high fuel prices is high demand for the diesel fuel that is absolutely required to keep these economies functioning and rebounding from a severe global recession, and the fact that its sulfur level must be near zero. Although the general public tends to focus on gasoline prices, gasoline has now become a global-surplus by-product of producing diesel and other middle-distillate fuels. Gasoline prices are a reflection of the cost of crude oil, which is ultimately determined by the demand for ULSD, not by the demand for gasoline.

Flawed and Outdated Assumptions Beget Fuel Policies with Unintended Consequences

Despite the consistent information and analysis provided by the IEA (and some others) from early 2007 up to the present time, the general media and general public have apparently not yet grasped the implications of the fundamental changes that occurred in the petroleum industry in the 2005 timeframe. An exception to the generalization above is an excellent recent, public-arena analysis of current trends in the petroleum industry entitled "The Diesel Problem and the Other GTL Play" by Robert Campbell of Reuters [25]. This should be required reading for all government officials who have any role whatsoever in setting fuel or energy policies. All the facts stated in the analysis are fully supported by data available to the public. An excerpt from Campbell's analysis is quoted below:

> The diesel problem, in short, is that demand for middle distillates is growing faster than demand for other products but refineries are unable to shift output to reflect this changed pattern. To get more diesel refineries have to produce more gasoline, that is increasingly hard to sell at a profit. This in turn crimps diesel output until the cost of the (diesel) fuel gets high enough to offset the losses from additional gasoline sales.

The Overall U.S. and Global Need: More ULSD at Affordable Cost

The primary fuel-related problem that both the U.S. and global economies face is having sufficient supplies of affordable ULSD available to support economic growth. Yet, much effort in the U.S. is focused on extreme conservation of gasoline, which, according to the analysis above, is directly contrary to the real goal of producing more ULSD at affordable cost.

Policies currently in place, such as Europe's decision to incentivize diesel cars more than 30 years ago, will not achieve the desired objectives, but instead are causing new and unanticipated problems. Most gasoline conservation measures consume economic resources (e.g., more expensive high-MPG [L/100 km] cars, ethanol subsidies, etc.) but may not provide any real return to the overall economy (or even to the individual car buyer, when all costs are taken into account). Gasoline is already a minimal-profit, global-surplus, by-product commodity of producing middle distillates, so conservation of gasoline simply makes the global gasoline surplus bigger.

Furthermore, conservation of gasoline in the overall U.S., as a stand-alone strategy, will neither reduce crude oil imports nor reduce global greenhouse gas (GHG) emissions. Crude oil import levels are determined by the demand for middle distillates, not the demand for gasoline. Surplus Atlantic-Basin gasoline is simply "pushed" further down the trade routes, now to places as far away as Pakistan, often to be sold at below-market prices to "get rid of it." This practice almost certainly stimulates additional long-term, indeed permanent, demand for such fuel in parts of the world with very large populations that are eager to upgrade their standard of living, especially if their fuel is effectively being subsidized by the developed world.

California: A Special Case

California is different, and this applies to California's gasoline as well. For purposes of this discussion, it does not matter how, or why, California's gasoline is different, only that it is mandated to be different. California consumes approximately 1 million barrels per day of gasoline, and its gasoline consumption is approximately equal to the global surplus of gasoline, when gasoline blending components exported from Europe are included in the total surplus. Most of the global gasoline surplus is in the Atlantic Basin, and California is a continent away, but this issue would not be insurmountable if its laws on gasoline specifications could be changed.

Since California's gasoline is different, only California's refineries produce it in significant quantities. (South Korean refineries produce a small portion of California's gasoline, but that says far more about South Korea and their national-security-based strategy of maintaining and operating a huge redundancy in their domestic refining capacity than it does about the general desirability of anyone else adopting California's special gasoline specifications.) Since there are fewer potential (legal) sources of gasoline supply, California is more susceptible to gasoline supply disruptions, even from relatively common occurrences such as refinery outages or bad weather, and the resulting price spikes, than other parts of the U.S.

While global-surplus gasoline is often sold at below-market prices in faraway places, California drivers pay far more for their special gasoline than anyone else in the U.S., an additional total of about $5 to $6 billion per year over and above the average U.S. gasoline cost. (Western European drivers pay even more for gasoline than Californians, as a result of the tax policies discussed previously.)

The reason that California's special gasoline is discussed in this report is because it requires that California's refineries, which are technically the most advanced in the country (even somewhat more advanced than the U.S. Gulf Coast refineries; see [6]), operate and use their input crude oil in ways that would now be considered "old-fashioned and less effective" by most other U.S. refineries. California's special gasoline requirements date back to the time in previous decades when maximizing gasoline production was the top priority for virtually all U.S. refineries. However, within the past decade, almost all refineries in California have done everything they can to maximize ULSD output to increase profit while reducing gasoline production, because relatively low-cost surplus gasoline and gasoline components from Europe can be obtained by U.S. refiners and then supplied fairly readily to most of the highly-populated areas of the country other than California.

California's refineries are still focused on maximizing special gasoline production for the local market. One could make the argument that California's approach is not making the most effective use of the crude oil resources it consumes, since the rest of the country (and, indeed, the world) needs more ULSD, and there is a global surplus of gasoline, although the surplus gasoline is not as "conveniently located" to California as it is to most of the rest of the country. Another reason for recognizing that California is a special case will become apparent in the following section.

A Recommended New Approach to Fuel Policy

As discussed in Campbell's analysis [25], U.S. refiners are currently attempting to de-couple, to some extent, ULSD production from gasoline production so that ULSD output can be maximized while gasoline output is reduced. One approach being implemented rapidly is to use natural gas as the primary source of hydrogen for hydro-desulfurization of ULSD, rather than continuing to be dependent on gasoline reformers to produce the required amount of hydrogen off-gas. But this scenario suggests an even more effective approach: use relatively cheap and abundant natural gas, not crude oil, as the primary resource for producing the last needed increments of ULSD at the margin.

The last increment of crude oil currently imported into the overall U.S. is needed only to meet the demand for middle distillates, namely ULSD and jet fuel. All the other incremental bulk products made from this last increment of crude oil, including gasoline, are either in the surplus category or, if not technically "surplus," are routinely sold at price less than that of crude oil. However, the "other" products, which typically account for more than two-thirds of the crude oil barrel, even if they generate no net profit for the refiner, will still ultimately be consumed by someone for some purpose, and thus will contribute to global GHG emissions.

Therefore, production of marginal ULSD from U.S. domestic resources other than petroleum has tremendous leverage, both for backing-out crude oil imports and for reducing GHG emissions. Each barrel of ULSD produced from a resource such as natural gas, for example, backs-out more than three barrels of imported crude oil. Furthermore, the carbon footprint associated with the marginal barrel of ULSD from natural gas will be much lower than if that same barrel of ULSD had been produced by running more than three additional barrels of crude oil through a conventional refinery.

Two large companies, Sasol and Shell, with between them the most gas-to-liquids experience in the world, have announced that they are actively studying the prospects for converting U.S. natural gas into ULSD and other fuels using FT synthesis [26–29]. Cost estimates for these potential plants are also discussed: Sasol estimates $10 billion for 96,000 barrels per day (b/d) of diesel and naphtha [27]; Shell refers to its $19 billion investment in Qatar for a plant that produces 140,000 b/d of Gas to Liquids (GTL) products plus 120,000 b/d oil-equivalent of Liquid Petroleum Gas (LPG), condensate and ethane [29, 30]. These cost estimates are very high, raising the possibility that they could be overstated to "scare away" potential competitors.

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