THE DIESELIZATION OF AMERICA: AN INTEGRATED STRATEGY FOR FUTURE TRANSPORTATION FUELS

J.J. Eberhardt
U.S. Department of Energy

BACKGROUND

Recently the spectre of another looming energy crisis has been raised [Hodel 1994, Romm and Curtis 1995]. In addition, there is growing concern about the environmental air quality issues related to vehicle exhaust emissions of criteria pollutants and global climate change from greenhouse gases such as carbon dioxide [Romm and Ervin 1996]. Despite these concerns there still is the economic imperative of continuing to produce and transport goods, and provide services important for economic growth.

Gross domestic product (and hence, economic activity and growth) is directly related to freight transport (in ton-miles of travel) as shown in Figure 1. Meeting energy demand for movement of goods is, therefore, critical to the economy. Since the Arab oil embargo in 1973, essentially all of the increase in highway transportation energy use has been due to trucks because of the continued growth of freight transport provided by heavy duty trucks and more recently, because of the explosive growth in popularity for personal transport of low-mpg (miles per gallon) multi-purpose light trucks such as pickups, vans, and sport utility vehicles (see Figure 2). Data from the Energy Information Administration (EIA) show that by 1995 trucks of all classes consume almost as much fuel as automobiles.

Since commercial truck energy use is less discretionary, even imperative if economic growth is to be maintained, the question then is how can we sustain this continuing expansion of economic activity in an environmentally sound manner. Two issues have to be faced in reducing highway energy of trucks, namely: a) how to meet energy demand for commercial transport to sustain continuing expansion of economic activity in an environmentally sound manner; and b) how to increase the efficiency (without compromising the functionality) of multi-purpose (commercial and personal transport) light trucks such as pickups, vans, and sport

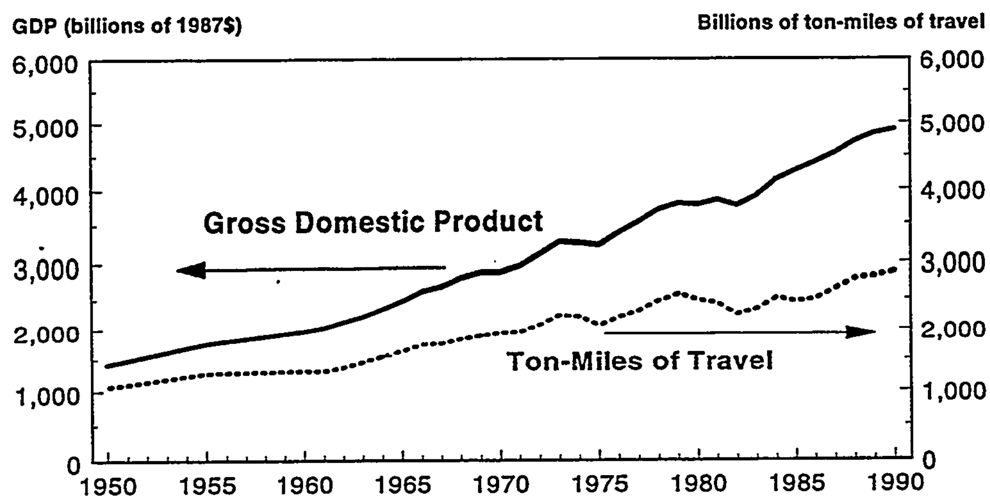


Figure 1. A Healthy Economy is Linked to Efficient Heavy Vehicle Transportation

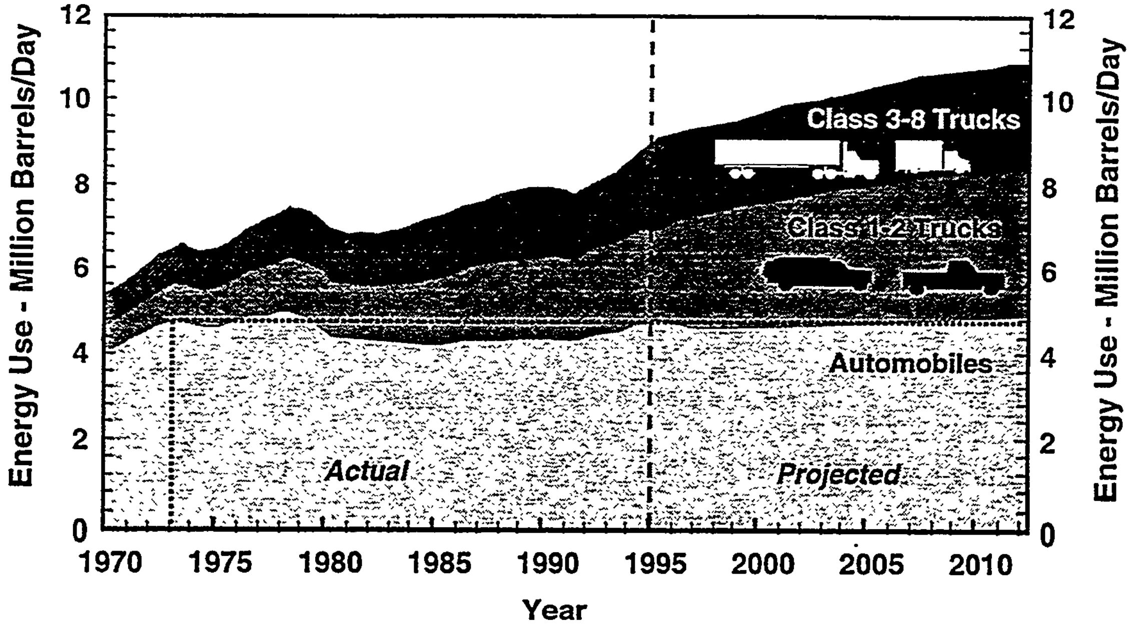


Figure 2. Essentially All of the Increase in Highway Transportation Energy Use Since 1973 Is Due to Trucks

utility vehicles while reducing emissions of exhaust gases to very low levels.

THE DOE HEAVY VEHICLE TECHNOLOGIES R&D PROGRAM

The mission of the DOE Office of Heavy Vehicle Technologies (OHVT) under the Deputy Assistant Secretary for Transportation Technologies, Office of the Assistant Secretary for Energy Efficiency and Renewable Energy is to conduct, in collaboration with its heavy vehicle industry partners and their suppliers, a customer-focused national program to research and develop technologies that will enable trucks and other heavy vehicles to be more energy efficient, able to use alternative fuels, and simultaneously reduce exhaust emissions. The strategy that is both real and viable is to increase the use of the most efficient engine in production today, the Diesel (compression-ignition cycle) engine.

The Case for the Diesel Engine

The Diesel Cycle engine is the engine-of-choice for heavy-duty freight transport where efficiency, low speed power requirements, durability, and reliability are important. It is much more efficient than the Otto cycle gasoline engine, which accounts for its dominance in commercial transport where cost competitiveness is key to staying in business. Truck, rail, and inland marine transport are almost completely diesel powered, and by widespread industry consensus, are expected to remain so in the foreseeable future (for the next 20 years or so). The trend in heavy-duty diesel engine thermal efficiency is shown in Figure 3.

Because of higher efficiency, diesel engines produce lower greenhouse gas emissions than comparable gasoline engines (20 percent less in the 1970s and now over 30 percent due to a widening efficiency gap). With mounting international pressures to reduce greenhouse gas emissions of the U.S. transportation sector, the diesel engine is the technology for doing so rather quickly without adverse economic impacts. The infrastructure for manufacturing and servicing the engine is already in place.

Besides the diesel engine, there are no promising technologies that could radically improve the fuel efficiency of light trucks.

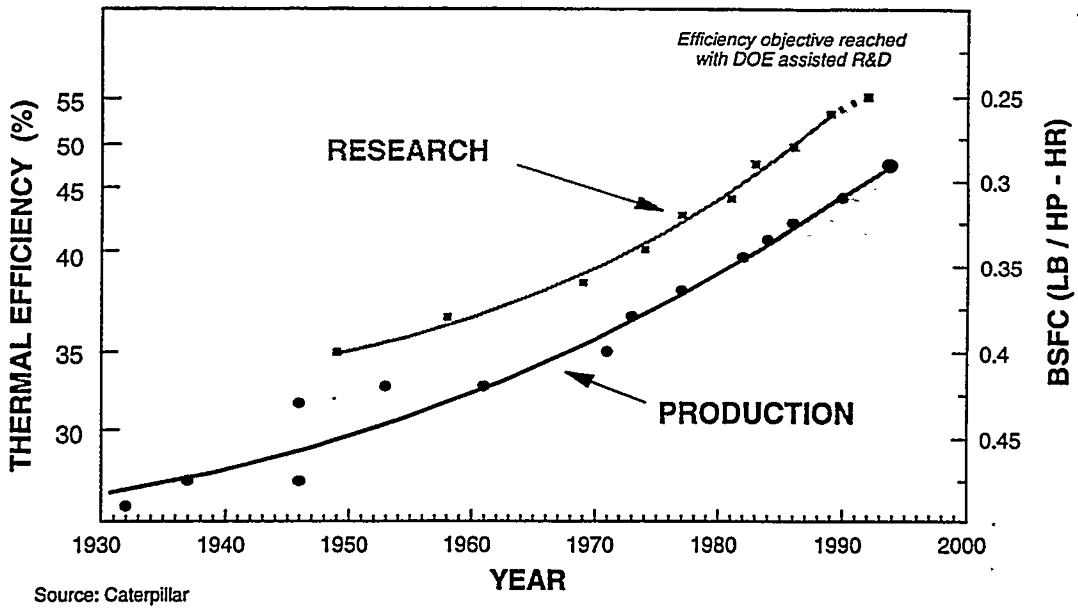


Figure 3. Increasing Diesel Engine Thermal Efficiency

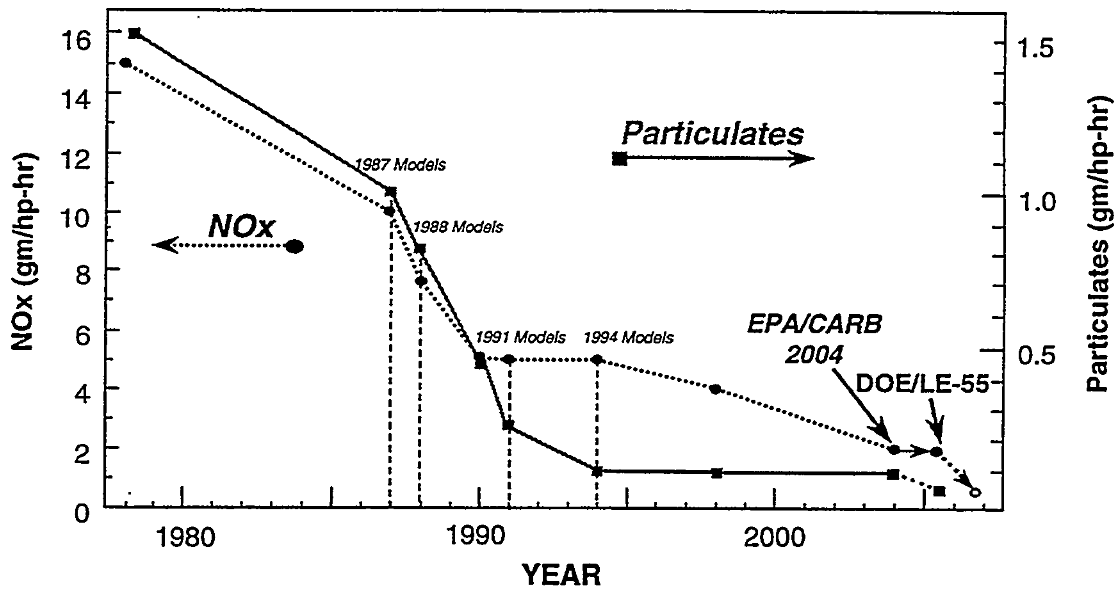
STRATEGY FOR FUTURE FUELS

Perhaps the most significant barrier to the use of alternative, nonpetroleum based fuels for heavy duty trucks is the lack of a fuel production and distribution infrastructure. Commercial transport operators depend on the availability of cost-competitive fuel for continued operation and profitability. In addition, the cost and expected service life of engines in commercial applications (e.g., one million miles or more expected of diesel-fueled engines in tractor trailer combinations) preclude these operators from investing in alternative-fueled engines for which the fuel production and distribution infrastructure is limited or even non-existent. For a future fuels strategy, it would be logical to focus on fuel properties that are suitable for the heavy-duty diesel cycle engine and utilize plentiful feedstocks to produce the fuel with these properties (in contrast to producing a diversity of fuels and forcing them on the engine, and ultimately on the end-users - the truck operators).

What fuel properties are required by the diesel engine? Cetane number has traditionally been an empirical measure of fuel ignitability. Fuels with a cetane number of 50 or higher are suitable for compression ignition in diesel engines. Table I shows the properties of some of the alternative fuels that have been tested as well as those of petroleum based diesel fuel. Comparing cetane numbers, one is led to a reasonable explanation as to why certain fuels do not perform very well in Diesel Cycle engines.

The previous DOE Alternative Fuels Program has demonstrated that Diesel engines can run on fuels that are not compression ignitable (i.e., fuels with very low cetane number such as natural gas, methanol, ethanol) using ignition assist (e.g., spark, glow plug, or pilot injection) but at lower efficiencies than those achieved with petroleum-based conventional diesel fuel. In addition, extensive tuning of the alternative-fueled engines has been necessary. Dimethyl ether, diethyl ether, and biodiesel have suitable cetane numbers and have been run in diesel engines without engine modifications. These alternative fuel-dedicated engines, however, have not made significant penetration into the heavy-duty transport market, for reasons already stated.

A diversity-of-feedstocks strategy as



Source: Cummins, modified by DOE

Figure 4. Decreasing Diesel Engine Emissions

Technologies being developed for the 80 mile per gallon (mpg) car, the third goal of the Partnership for a New Generation of Vehicles (PNGV), e.g., hybrid configuration (possibly turbine with batteries), may be appropriate for automobiles but may be impractical for the multipurpose light trucks. Towing and hauling capacity, torque and power for off-road, are some of the capabilities that account for the popularity of vans, pickups, and sport utility vehicles but which cannot be met by light weight, high mpg autos. The PNGV has recognized the efficiency advantage of Diesel engines over gasoline engines and has identified the fourstroke, direct injection Diesel engine (in stand alone or hybrid-electric configuration) as a principal powertrain candidate for the 80 mpg car. These engines are expected to be 90 horsepower or less, which is not sufficient for the power requirements of multi-purpose vehicles. Direct injection Diesel engines of the approximate power and size for multipurpose pickups, vans, and sport utility vehicles have efficiencies at peak power of 38 to 42 percent compared to gasoline engines at 34 percent. Using Diesel engines in this power range (200 horsepower and greater) can improve light truck fuel economy by as much as 35 percent.

In Europe where fuel prices have always been much higher than the U.S., the Diesel has achieved a substantial measure of acceptance even for personal transportation (14 percent of the passenger car sales in Europe, as much as 35 percent in France, in 1995). In the U.S., Diesel engines have not been popular for passenger cars with the experience with diesel-fueled cars in the mid-70s to early 1980s which were noisy, smokey, not very responsive on hills, and prone to fail due to engineering and design flaws. Also, they were hard to start in cold weather and refueling stations with diesel fuel pumps were very few. In spite of advances in diesel engine technology, the memory of a bad experience lingers and environmental groups continue to foster the image of the Diesel as being a "dirty" engine.

The Emissions Issue

Contrary to the old perception about diesel engines, high efficiency benefits can be obtained without penalizing the environment. Since the 1970s, advances in diesel (compression-ignition cycle) engine

Table 1. Selected Properties of Potential Diesel Engine Fuel(s)

Property	DF-2 Diesel	Fischer-Tropsch	Bio-diesel	CNG	Propane HD-5[h]	Methanol	Ethanol	Di-methyl ether	Di-ethyl ether
Formula	Hydrocarbons ~C10 - ~C21	Principally C_nH_{2n+2} n=10-21	Various oils and esters	Principally CH_4	Principally C_3H_8	CH_3OH	C_2H_5OH	CH_3OCH_3	$C_2H_5OC_2H_5$
Boiling Point, °F	370 - 650	350 - 670	360 - 640	-258.5	-43.9	149	172	-13	94
Vapor Pressure, psi @ 100°F	<0.2	n.a	n.a	n.a.	170	4.6	2.3	116	16.0
Cetane Number	40 - 55	>74	>48	low	low	low	<5[b]	>55	>125[a]
Auto-ignition Temperature, °F	~600	~600	-	990	870	867	793	662	320
Stoichiometric Air - Fuel Ratio, Wt.	15.0	15.2	13.8	16.4	15.7	6.45	9.0	8.9	11.1
Lower Heating Value, Btu/lb	18,500	18,600	16,500	20,750	19,940	8,570	11,500	12,120	14,571
Specific Gravity, 60°F	0.850	0.783	0.880	-	0.506	0.796	0.794	0.66	0.714

technologies have reduced particulate emissions by 95 percent and nitrogen oxide (NOx) emissions by 70 percent (see Figure 4). Today's heavy-duty diesel engines emit just under 5 g/bhp-hr of NOx and 0.10 g1bhp-hr of particulates (<0.05 g1bhp-hr for transit buses). Further reduction of NOx levels to 4 gfbhp-hr by 1998 is mandated by current legislation. In addition, the Environmental Protection Agency (EPA) and major engine manufacturers have issued a "Statement of Principles" that requires, by 2004, further reduction to 0.05 g/bhp-hr particulates and 2.4 g/bhp-hr of NOx plus non-methane hydrocarbons (NMHC) or 2.5 g/bhp-hr of NOx plus NMHC with a maximum of 0.5 gfbhp-hr of NMHC.

In conjunction with industry partners, the DOE Office of Heavy Vehicle Technologies is funding research and development of advanced low-emissions, 55 percent efficient (LE-55) diesel engine technologies to enable heavy-duty trucks to continue to operate efficiently and meet EPA emissions standards proposed for 2004.

Progress of research to date indicates that the heavyduty diesel is well on its way to being an environmentally sound engine for continued economic growth. The question is not if very low levels of emissions can be achieved. but rather, what is cost effective. A three-pronged systems approach that simultaneously addresses fuel formulation, in-cylinder combustion control, and exhaust aftertreatment, is being employed to arrive at the most cost-effective emissions control strategy.

As examples of what can be achieved with alternative fuels, three Cummins diesel engines running on natural gas have been certified as meeting the California Air Resources Board (CARB) and Environmental Protection Agency (EPA) 1998 on-highway heavy duty truck and bus emissions standards without the use of exhaust oxidation catalysts [Cummins 1997]. However, the thermal efficiencies that were achieved were lower than those achievable with conventional petroleum-based diesel fuel. Comparable efficiency and emissions levels have been achieved in diesel engines running on dimethyl ether (DME) with exhaust gas recirculation (EGR) [NREL 1997]. DME is a fuel having excellent compression ignitability (cetane number > 55).

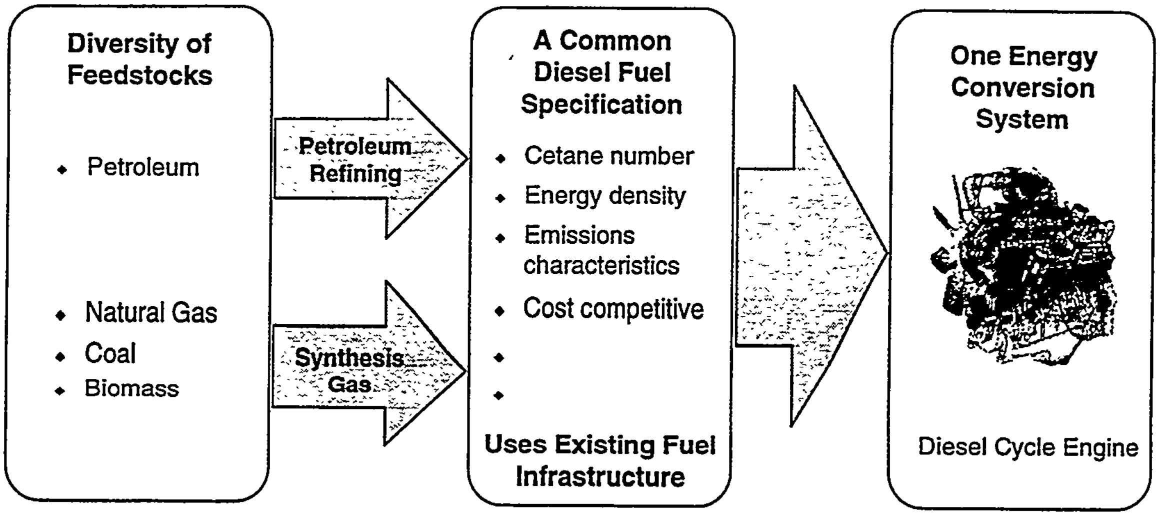


Figure 5. OHVT Future Fuels Strategy

envisioned by the DOE Office of Heavy Vehicle Technologies is shown in Figure 5. The current feedstock is almost exclusively petroleum. However, if other feedstocks such as naturaf gas, coal, and biomass can be converted cost effectively into fuels appropriate for the diesel engine, these fuels can be dispensed using the existing fuel infrastructure, and then utilized by a single energy conversion system, the Diesel Cycle engine. These future fuels from alternative, nonpetroleum resources could then find significant penetration into the heavy duty transport market.

It is possible for the U.S. to take advantage of its indigenous feedstock resources (coal, natural gas, and biomass) to produce high quality fuels for heavy-duty diesel engines. It has been known since World War II that coal can be converted to diesel fuels through the synthesis gas route, commonly called Fischer-Tropsch (F-T) synthesis. What has not been so widely recognized is that the same process can be used to convert methane (natural gas) to F-T diesel fuel as well [Fritsch 1996, Ansell 1994, Tijm 1994, Marriott 1994]. Last but not least, biomass can be "gasified" (i.e., turned into a mixture of carbon monoxide and hydrogen called synthesis gas). From synthesis gas, commonly known as syngas, a number of high quality fuels appropriate for compression ignition engines can be made. These include dimethyl ether and F-T diesel.

Dimethyl ether (DME) has physical properties akin to propane (see Table 1) for which a distribution infrastructure already exists. In Canada, for example, there are significant numbers of propane pumping stations at gasoline retail outlets. F-T diesel is compatible with the current diesel fuel infrastructure. Indeed, the first usage of F-T diesel is as a blend for petroleum-derived diesel fuels to upgrade their cetane number and lower their sulfur and aromatic content. This is already being done in California to a limited extent.

In addition to being gasifiable, the renewable biomass feedstock has two additional routes to provide fuels for heavy duty diesels. Biodiesel can be made from vegetable oils by a simple esterification process. Reaction of soybean or canola oils high in carboxylic acids with methanol (or ethanol) produce the dimethyl or diethyl ester of these dicarboxylic acids which has good properties for diesel fuel. Indications are that biodiesel formulations may be useful in blends to upgrade petroleum-based diesel fuels or to provide lubrication properties for F-T diesel fuel.

Lastly, much research has been conducted to convert biomass to ethyl alcohol to a point where the cost of production of ethanol is nearly cost competitive with gasoline. However, ethanol has a poor cetane number and is not a suitable Diesel engine fuel. On the other hand, it is easily converted in a one step catalytic process to diethyl ether (DEE) which has extraordinary compression ignition characteristics. Indeed, it is diethyl ether ("e-ther") that is used to start diesel engines in very cold climates. Research is underway to explore the feasibility of using DEE to upgrade the properties of petroleum derived or biodiesel fuels.

CONCLUSION

The Diesel Cycle engine has already established itself as the engine-of-choice for the heavy duty transport industry because of its fuel efficiency, durability, and reliability. In addition, it has also been shown to be capable of using alternative fuels, albeit at efficiencies lower than that achieved with petroleum-derived diesel fuel. Alternative fuel dedicated engines have not made significant penetration of the heavy duty truck market because truck fleet operators need a cost-competitive fuel and reliable supply and fuel-ing infrastructure. In lieu of forcing diverse fuels from many diverse domestic feedstocks onto the end-users, the Office of Heavy Vehicle Technologies envisions that a future fuels strategy for the heavy duty transport sector is one where the diverse feedstocks are utilized to provide a single fuel speci-fication (dispensed from the existing fueling infrastructure) that would run efficiently in a single high efficiency energy conversion device, the Diesel Cycle engine. In so doing, the U.S. commercial transport industry may gain a measure of security from the rapid fuel price increases by relying less on a single feedstock source to meet its increasing fuel requirements.

REFERENCES

I. Hodel, D., Crisis in the Oil Patch, 1994.

2. Romm, J.J. and Curtis, C.B., "Mideast Oil Forever?" The Atlantic Monthly, April 1996.

3. Romm, J.J. and. Ervin, C.A., "How Energy Policies Affect Public Health," Public Health, Reports, September/October 1996.

4. Cummins In the News," Cummins News Releases in the Internet, February 1997.

5. "Development of a Production-Feasible Common Rail Fuel Injection System for Liquid Dimethyl Ether (DME) for Use in Heavy-Duty Vehicles," NREL Fact Sheet, 1997.

6. Fritsch, P., "Exxon Project to Expand Use of Natural Gas," The Wall Street Journal October 30, 1996.

7. Ansell, L.L., Eisenberg, B.,. Bauman, R.F and. Say, G.R "Liquid Fuels from Natural Gas An Update of the Exxon Process," Alternate Energy '94, La Quinta, CA, April 26-29, 1994.

8. Tijm, P.J.A., Marriott, M.M. Senden, M.M.G., and. van Wechem, H.M.H., "Shell Middle Distillate Synthesis -- The Process, the Products, the Plant," Alternate Energy '94, La Quinta, CA, April 26-29, 1994.

9. Marriott, J.N. and Geertsema, A., "Report on the Continuing Progress at Sasol," Alternate Energy '94, La Quinta, CA, April 26-29, 1994.