3. Transportation Fuels Market

For the past seventy years, the principal fuels for motor vehicle transportation in the U.S. have been gasoline and diesel fuel derived from crude oil. Gasoline is consumed by automobiles and light duty trucks while diesel fuel is primarily consumed by heavy duty vehicles, buses and heavy trucks. In 1992 over 110 billion gallons of gasoline were consumed in the U.S. and diesel fuel consumption was about 24 billion gallons. A small amount of propane has been used as a vehicle fuel over the years but currently propane powered vehicles account for less than 0.2% of the vehicle population.

While the use of alternative fuels in motor vehicles has not been significant in the U.S., there is a substantial volume of alcohols (primarily ethanol) and ethers (primarily methyl tertiary butyl ether) blended into the gasoline product as shown in Exhibit 3-1.

In recent years pressure in the transportation fuels market has been growing for additional use of alternative fuels. The pressures come from several sources - environmental, government policy and market economics.

3.1. Pressure for Market Change

During the 1970s and 1980s in the U.S., there has been an effort to reduce harmful vehicle emissions. The approach during this time period was to change gasoline fuel requirements and to modify the design of gasoline vehicles. The Clean Air Act of 1970 began the effort to reduce vehicle emission. The 1970 Clean Air Act (CAA) permitted the regulation of fuel additives and it established a schedule for reducing lead use in gasoline. In 1973 the catalytic converter was introduced to reduce vehicle tail pipe emissions. As lead was eliminated, its octane boosting effect was replaced by increasing the aromatic content of gasoline and by adding high octane blending components such as methyl tertiary butyl ether (MTBE).

In the late 1980s and early 1990s the question of vehicle fuels was revisited by government policy makers. Two policy positions were reached and translated into new legislation:

(1) Lower vehicle emissions can be achieved with the use of new clean fuels.

(2) The growth in U.S. oil imports can be diminished with economic incentives and mandates to use clean alternative fuels not derived from crude oil.

Exhibit 3-1. Summary of U.S. Vehicle Fuel Consumption, 1992

Fuel	Consumption	Gasoline Equivalent (Million Gallons)
Traditional		
Gasoline[1]	110,135 million gallons	110,315
Diesel	21,375 million gallons	23,866
Alternative Fuels		
M-85[2]	2 million gallons	1
M-100[3]	*	*
E-85[4]	*	*
E-95[5]	*	*
LPG	250 million gallons	184
CNG	511 million cubic feet	4
LNG	*	*
Hydrogen	*	*
Replacement Fuels (Included in Gasoline)		
Ethanol in Gasohol[6]	1,061 million gallons	701
MTBE	1,445 million gallons	1,175

*Value represents a negligible amount.
[1]Gasoline includes the replacement fuels, ethanol and MTBE.
[2]A fuel mixture of 85 percent methanol and 15 percent gasoline.
[3]A fuel consisting of 100 percent methanol.
[4]A fuel mixture of 85 percent ethanol and 15 percent gasoline.
[5]A fuel mixture of 95 percent ethanol and 5 percent gasoline.
[6]A fuel mixture of 10 percent ethanol and 90 percent gasoline.
Notes: Fuel terms are defined as follows: LPG, liquefied petroleum gas (propane); CNG, compressed natural gas; LNG, liquefied natural gas; MTBE, methyl tertiary-butyl ether, E-85 (15% gasoline and 85% ethanol), M85 (15% gasoline and 85% methanol), M100 (100% methanol).
Sources: Gasoline consumption: Energy Information Administration, Petroleum Supply Annual 1992, Vol. 1, DOE/EIA-0340(92)/1, (Washington, D.C., May 26, 1993), Table S4, adjusted to include field ethanol blended and to cover only highway uses. Highway use was estimated as 97.1 percent of total gasoline supplied, based on 1990 data published in the Transportation Energy Data Book: Edition 13, prepared by Oak Ridge National Laboratory for the U.S. Department of Energy (Oak Ridge, TN, March 1993), Table 2.7.Highway diesel consumption:Energy Information Administration, Fuel Oil and Kerosene Sales 1991, DOE/EIA-0535(01) and Fuel Oil and Kerosene Sales 1992, DOE/EIA-0535(92); and Federal Highway Administration, Spastics of Highway Special Fuels Use, Table 1. M-85: California Energy Commission (facsimile provided). CNG: Energy Information Administration, Natural Gas Annual 1992, DOE/EIA-031(92)(Washington, DC, December 1992), Table 1. LPG: Estimated as 50 percent of engine fuel reported by American Petroleum Institute, 1992 Sales of Natural Gas Liquids and Liquefied Refinery Gases (Washington, D.C., October 1993) which shows a total of 500 million gallons engine fuel use. Ethanol and MTBE: Energy Information Administration, Petroleum Supply Monthly, DOE/EIA-0109(93/01)(Washington, DC, January 1993), Appendix D.
Reference: "Alternatives to Traditional Transportation Fuels: An Overview", DOE/EIA-0585/0, June 1994, Table ES2, page xiii.

The three legislative acts of the late 1980s and early 1990s that impact transportation fuels are summarized in Exhibit 3-2. The Alternative Motor Fuels Acts of 1988 provided an incentive to auto makers, in the form of a CAFE credit, to produce alternative fuel vehicles.

Exhibit 3-2. New Transportation Fuels--Government Policy Steps

I ALTERNATIVE MOTOR FUELS ACT 1988

- CAFE credit for Alternative Fuel Vehicle Production

II CLEAN AIR ACT AMENDMENTS OF 1990

- 1992 Winter Oxygenated Gasoline for CO Non-Attainment Areas
- 1995 Reformulated Gasoline for Ozone Non-Attainment Areas
- Requirements for Fleets to Use Clean Alternative Fuels
- Clean Alternative Fuels: Alcohols, Reformulated Gasoline, Natural Gas, LPG, Reformulated Diesel, Hydrogen, Electricity

III ENERGY POLICY ACT OF 1992

- Primary Aim -- Reduction of Oil Imports
- Alternative Fuel Vehicle Fleet Requirements
- Tax Deduction, Tax Credits, Etc.
- Alternative Fuels: Alcohols, Natural Gas, LPG, Hydrogen, Biomass Derived, Coal Derived, Electricity

The Clean Air Act Amendments (CAAA) of 1990 focused on the environment and took a number of steps to reduce vehicle emissions by requiring a number of new standards for motor vehicle fuels. The CAAA provided for the EPA to issue regulations and delineate clean fuel requirements and vehicle emission standards. The implementation of the CAAA has required the use of oxygenated gasoline in the winter months in areas that exceed CO air quality standards. In these "non-attaining" CO areas a minimum oxygen content provided by adding alcohol or ether, such as MTBE to the gasoline is required. For areas not attaining the ozone standard the use of reformulated gasoline is required year around. Reformulated gasoline has a number of composition requirements, one of which is a minimum oxygen content requirement. The consequence of the CAAA is that in 1995 over 40% of the gallons of U.S. gasoline sold will contain from 2-2.7% oxygen. A 2.7% oxygen requirement translates to 15% MTBE or 7.7% ethanol by volume. The CAAA also requires the production of clean fuel vehicles. The Act defines clean alternative fuels as methanol, ethanol, other alcohols, reformulated gasoline, reformulated diesel (trucks only), natural gas, liquefied petroleum gas (LPG), hydrogen, or electricity.

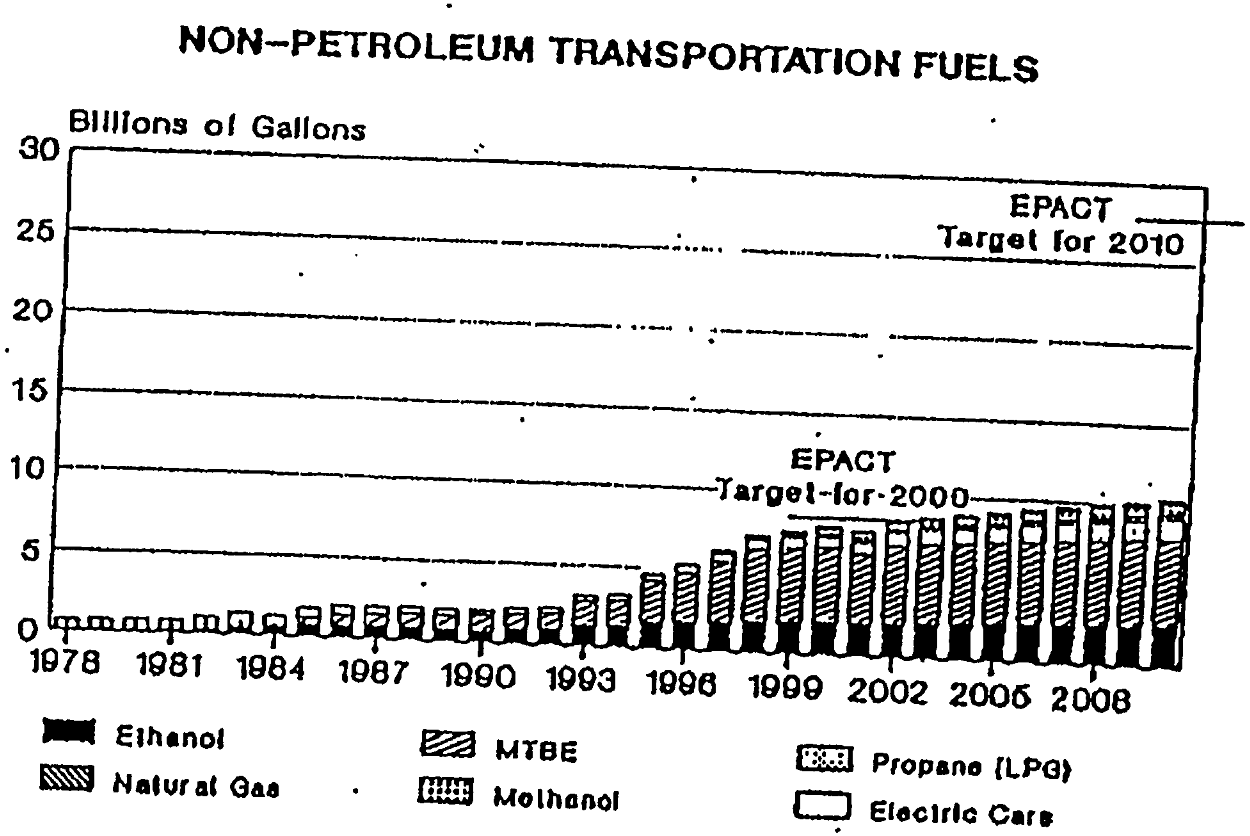
The primary aim of the Energy Policy Act of 1992 (EPACT) is the reduction of crude oil imports. EPACT set a national goal of 30% penetration of non-petroleum fuels in the light-duty vehicle market by 2010 and requires the purchase of alternative fuel vehicles for government fleets and also for private fleets, if needed to achieved volume usage goals. The Act also creates tax incentives for vehicle buyers and for alternative fuel service station operators. As indicated in Exhibit 3-2, the alternative fuels defined by EPACT includes the alcohols, natural gas, LPG, hydrogen, biomass derived fuels, coal derived fuels and electricity.

There has been concern expressed that the EPACT goal of 30% will not be reached by 2010. For example, a projection by David Gushee of the Congressional Research Service [10] shows that the volume of non-petroleum fuels will fall far short of the 30% target in 2010 (see Exhibit 3-3).

3.2. Market Segments

In addressing the question of possible entry of new fuels into the U.S. motor vehicle market there are two important ways to break the market down. The first is the type of use (e.g., bus versus personal passenger car) and secondly, by the way the vehicle is fueled (e.g., at a service station versus a fleet vehicle terminal). As shown in Exhibit 3-4 gasoline is currently the primary fuel for automobiles and light trucks. Diesel fuel is the primary fuel for the heavy trucks and for many of the off-highway vehicles and buses.

EXHIBIT 3-3
NON-PETROLEUM TRANSPORTATION FUELS



Source: USHEE

MTBE includes all methyl ethers
Ethanol includes ethyl ethers

Exhibit 3-4. Transportation Energy Use By Vehicle Type, 1990

Vehicle Type	Gasoline (Trillion Btu)	Diesel (Trillion Btu)	Gasoline (Percent Total Btu)	Number of Vehicles (Thousands)
Highway				
Automobiles	8,946	121	98.7	143,550
Motorcycles	24		100	4,260
Buses				
Transit	0.2	79	0.3	61
Intercity		22	0.0	21
School	30	33	47.4	508
Trucks are Highway				
Light Trucks	4,002	152	96.3	38,650
Other Trucks	604	2,779	17.9	4,538
Off-Highway				
Construction	31	179	15.0	
Farming	64	392	14.0	

Source: "Transportation Energy Data Book: Edition 13", ORNL-6743, by Stacy C. Davis, Sonja G. Strang, March 1993.

Fleet vehicles are a logical target market for new alternative fuels. There is a markets dilemma in vehicle fuel markets - to make the fuel/vehicle system attractive to potential users there have to be sufficient refueling locations to provide consumer comfort about fuel supply, and at the same time there have to be enough customers for a refueling location to justify installation of equipment to provide the fuel. That dilemma is overcome with fleet vehicles since many fleets refuel at their own fleet terminal locations. Of the 143.6 million automobiles in the U.S., about 8.2 million are cars in fleets of ten or more as shown in Exhibit 3-5 below.

Exhibit 3-5. Automobile Fleets by Use in 1991 (Thousands)

Type of Fleet[1]	Number of Automobiles	% of Total
Business	3,466	42.3
Individual Leased	2,008	24.5
Government	619	7.6
Utilities	544	6.6
Police	250	3.1
Taxi	141	1.7
Rental	1,160	14.2
TOTAL	8,188	100

Source: ORNL-6743 from Bobit Publishing Company, Automotive Fleet Research Department, "1992 Automotive Fleet Fact Book", Redondo, CA, 1992
[1]Ten or more cars in fleets

Many heavy duty trucks also operate from fleet terminals that have fueling tanks as shown in Exhibit 3-6 below.

Exhibit 3-6. Diesel Fuel Tank Storage Data For Trucking Operations*

Category of Respondent By Truck Fleet Size	% of Trucking Firms	Operate From Only 1 Terminal (% of Category)	Have Diesel Tank Storage (% of Category)
1 - 9	22	81	71
10 - 24	24	66	65
25 - 99	26	61	74
100+	28	31	87

* Data for Sample of 437 Trucking Operations Survey by Newport Research in 1988
Source: Data provided by Robert Crump, Newport Research, Bethesda, Md.

Having company-owned fuel storage at terminals should not, however, be taken to mean that these terminals are the **only** fueling locations for the firm's trucks. Despite the large percentage of truck firms with company-owned fuel storage, shown above, there appears to be a trend towards greater use of truck stops for fueling trucks. The National Petroleum Council (NPC) study on "Petroleum Storage and Transportation in 1989 [11] estimated that in 1986, 60% of the diesel fuel used was obtained at truck stops and 40% at company owned facilities. The National Association of Truck Stop Operators provided an estimate of about 70% purchased at truck stops based on 1989 data.

Even though fleet operators may prefer the added convenience of refueling at highway service locations they remain a favored target market for potential alternative fuel producers seeking to establish a market position.

3.3. Use of Gas and Gas-Derived Products

There are three routes by which natural gas can be used in the transportation fuels market:

1) Synthesize a conventional gasoline or a diesel product from natural gas,

2) Produce a material that can be blended into gasoline, such as an oxygenate,

3) Use gas directly as compressed natural gas (CNG) or convert the gas to other, new alternative transportation fuels, such as methanol.

For the first option the question is whether gasoline or diesel fuel can be synthesized from natural gas at a cost which is competitive with gasoline and diesel produced from crude oil. This issue will be discussed in the Economic Analysis Section (Section 8). As has already been described, there is an existing and growing market for oxygenates. Oxygenates must be included in gasoline product to meet CAAA requirements. The oxygenate market presently exists and is growing as the CAAA requirements expand in the 1995-2000 time frame. The primary use of gas and gas-derived liquid products in the transportation market is now in the production of MTBE. There are ways to improve MTBE synthesis routes and to produce other oxygenate products (other ethers and alcohols) that may be worth pursuing to maximize the opportunities for natural gas uses in transportation. Gas derived oxygenate products face competition in the oxygenate market from biomass derived ethanol. Ethanol is not cost competitive but is highly subsidized by the Federal Government and some state governments and there has been heavy political lobbying to expand its use as an oxygenate.

The third option listed above is to use gas as an alternative fuel. The primary routes are to use gas directly as an engine fuel or to convert it to the liquid fuel product methanol. Section 3.4 describes the attributes of natural gas and methanol relative to gasoline and diesel and discusses the potential problems that are faced in successfully establishing these fuels in the U.S. transportation market. Vehicle and engine systems will be discussed along with the delivery and fueling systems that will have to be established for successful market penetration.

3.4. Fuel Physical Properties

Exhibit 3-7 provides an overview of the physical properties of gasoline, diesel, methanol, MTBE and CNG. These properties have important impacts on the vehicle and engine systems and on the distribution and refueling processes. The following discussion will contrast CNG, methanol and MTBE with fuels now in use.

Exhibit 3-7. Physical Properties of Gasoline, Diesel, and Selected Alternative Fuels

Properties	Gasoline	Diesel Fuel	MTBE	CNG	Methanol
Constituents	Hydrocarbon Mixture (C_2 - C_{10})	Hydrocarbon Mixture (C_{12} - C_{20})	$(CH_3)_3$ $COCH_3$	Approx. 90% Methane (C_2, C_3, CO_2, H_2, He, N_2)	CH_3OH
Boiling Range (°F)	80 to 420	320 to 720	131	-259	149
Reid Vapor Pressure	8-12	0.2	7.8	2400	4.6
Density (lb/gal)	5.8 to 6.5	6.5 to 7.3	6.19	1.07	6.6
Energy Content (LHV)					
Btu/lb	19,000	18,900	15,100	21,300	8,600
Btu/gal	115,000	128,000	93,500	22,800	56,560
Heat of Vaporization Btu/lb	140-170	100-200	138	219	506
Autoignition Temperature (°F)	450 to 900	400 to 500	815	1,350	878
Flashpoint (°F)	-45	125 (min)	-14	-300	52
Octane Number (R + M)/2	87 to 93	N/A	108	120	99
Flammability Limits (vol% in air)	1.4 7.6	0.7 5.0	1.6 8.4	5.3 14.0	6.7 36.0
Water Solubility (%)	Negligible	Negligible	4.3	-	100
Flame Speed (ft/sec)	1.3	1.3		1.1	1.3

There is wide variation in the composition of natural gas at the wellhead but gas processing removes much of the light hydrocarbons, CO_2, N_2 and S before entering the pipeline system. While pipeline gas is predominantly methane, there are still some variations in composition based on gas processing practices and the time of the year. Exhibit 3-8 shows the range of variation for pipeline gas quality in ten major urban areas. This variation can increase because some local gas utilities inject propane/air mixtures into natural gas during seasonal periods to reduce the need for gas. Variations in the natural gas quality can cause some problems during fueling. For example, the heavier hydrocarbons condense out when the compressed gas expands at the regulator, and any water content in the gas can also pose a problem with the water forming ice or hydrates with the gas.

Exhibit 3-8. Weighted National Statistics for Natural Gas in Ten Major Urban Areas of the United States Without Propane/Air (P/A) Peakshaving[1]

Component	Mean	10th Percentile	90th Percentile
Methane (Mole %)	93.2	88.5	96.4
Ethane (Mole %)	3.6	1.8	5.0
Propane (Mole %)	0.8	0.3	1.3
C_4+ (Mole %)	0.5	0.1	0.6
$CO_2 + N_2$(Mole %)	2.7	1.0	4.7
Heating Value (Btu/scf)	1,037	1,023	1,050
Specific Gravity	0.603	0.578	0.628
Wobbe Number[2]	1,338	1,312	1,357
Air/Fuel Ratio (Mass)	16.3	14.7	16.8

[1] Propane/Air peak sharing" (P/A) refers to the addition of propane/air mixtures to natural gas during peak demand periods in order to reduce the need for natural gas.
[2] Wobbe number is the high heating value on a volumetric basis divided by the square root of the specific gravity relative to air. It represents a measure of energy flow through an office.

Source: William E. Liss and William H. Thrasher, "Natural Gas as a Stationary Engine and Vehicular Fuel," Society of Automotive Engineers (SAE), Paper No. 912364 (Warrendale, PA, 1991), p. 46.

Methanol is synthesized by replacing one of the hydrogens in methane with an OH radical. The addition of the OH radical adds polar characteristics to these molecules. Alcohols with small hydrocarbon structures like methanol have strong polarity, while alcohols with larger hydrocarbon structures have weak polarity. MTBE and ETBE, which are made from methanol and ethanol respectively, are ethers. Ethers do not have the OH radical, and have little or no significant polarity. Polarity in a molecule is a highly cohesive molecular bonding force.

At room temperature, low molecular weight substances like methanol would be gases if polarity did not keep them collapsed into liquids. When methanol is dissolved in a nonpolar solvent like gasoline, the alcohol molecules become separated, and the molecular cohesion is weakened. The alcohol behaves more like a gas in such a mixture and results in a larger than anticipated increase in vapor pressure for the gasoline mixture than would be expected based on the vapor pressures of the pure alcohol or gasoline. However, when alcohol concentrations in gasoline are at the 85 percent level, the Reid Vapor Pressure of the mixture is lower than that of gasoline alone. In addition, if water exists as a second phase with the gasoline, the polar alcohols will be drawn to the water, which is also highly polar. This becomes an issue in transporting and storing fuels because water frequently exists in tank bottoms and pipelines. Methanol is highly toxic, and raises safety concerns for human ingestion, eye or skin contact, and inhalation. Extra precautions are needed when handling methanol compared with gasoline.

Volumetric energy density can be an important consideration for a transportation fuel. Conventional gasoline, oxygenated and reformulated gasoline, and diesel, which are liquids, have the highest energy densities. Methanol is a liquid at atmospheric pressure and ambient temperatures, so it is stored and handled similarly to gasoline. However, on a volume basis methanol has about half the energy content of gasoline. The lower energy density implies that at equivalent engine efficiency (miles per Btu), a pure-alcohol-fueled vehicle would travel half to two-thirds as far as a gasoline-fueled vehicle using the same size tank. These efficiency differences are compensated for, slightly, by improvements in efficiency that can be realized in spark ignition engines using alcohols compared to gasoline. E85 (a mixture of 85% ethanol and 15% gasoline) and M85 (85% methanol, 15% gasoline) have slightly higher energy densities than neat ethanol and methanol because of the addition of gasoline. Natural gas is stored in the vehicle fuel tanks under pressure as a compressed gas. Even under fairly high pressure, both the density and energy density of natural gas is considerably less than those of a liquid fuel.

The difference in energy densities has a pronounced effect on vehicle storage equipment. At 3000 psi, a typical pressure for CNG vehicle fuel tanks, the volumetric energy density of natural gas is about one fifth that of diesel fuel and one fourth of gasoline. Thus, if all other efficiencies were equal, a CNG vehicle tank would be four times the size of a gasoline tank to cover the same driving range [12]. For comparison, the weight of the fuel and tank in pounds per gallon of diesel fuel equivalents are 47 lbs for natural gas in a steel cylinder, 36 lbs for natural gas in a fiber-reinforced steel tank, 26 lbs for natural gas in an advanced fiber-wrapped aluminum cylinder, 18.4 lbs per gallon diesel equivalent for methanol in a conventional tank, and 9 lbs per gallon for diesel in a conventional tank [12].

Despite the large variation in vehicle storage requirements that results from energy density differences, the energy density impact on engine performance is less dramatic. When fuels are combusted in spark ignition engines, they are primarily in a vapor or gaseous phase, and gas energy densities are related to molecular weight and the relative hydrogen/carbon/oxygen content of the molecules. While considerable energy volume density differences exist between methane and the higher molecular weight compounds in gasoline, in all cases, the gas that enters the cylinder is a mixture of fuel and air. The air is a far larger component of the gas entering the chamber than the fuel. The volume of air coming in is regulated to contain the amount of oxygen needed to combust all the fuel (a stoichiometric mixture), and since air is about 80 percent nitrogen, a large amount of air is added to the fuel to provide the required oxygen.

Volatility indicates a fuel's ability to vaporize under different temperatures and pressures. It is the property that affects startup engine performance the most. While high volatility is desirable in cold weather, it can cause loss of power or vapor lock in warmer weather. High volatility can also lead to increased evaporative emissions. Thus volatility is controlled both for engine performance as well as emissions.

Volatility is not an issue with CNG. As a gas it does not need to vaporize before burning, making cold-start enrichment or further blending for cold start reasons unnecessary. Cold-start enrichment is a primary source of carbon monoxide emissions in gasoline-fueled vehicles.

The alcohols are less volatile than gasoline when methanol is used in neat form or as an 85 percent alcohol blend (M85). The Reid Vapor Pressure for methanol as a pure component is 4.6, and varies for gasoline blends with between 8 and 15. Methanol is insufficiently volatile for cold engine starts, even at moderate temperatures. Because of the low volatility, the most critical performance issues for the methanol fueled-vehicles are the cold start-up problem and misfiring during warmup [13].

Various solutions to the cold start problem have been identified for neat alcohols, including carrying an on-board supply of a volatile fuel such as gasohol or propane for start-ups. The addition of gasoline to alcohol fuels helps to improve the cold start-up problem. Current engine technology for dedicated methanol fuel use is designed for M85 [14]. One original equipment manufacturer demonstrated engine cold-start capability with M85 down to temperatures as low as -20°F using computer-controlled starting systems [13].

Octane number measures a fuel's tendency to knock in a spark ignition engine. Knocking occurs when the gasoline-air vapor mixture prematurely self-ignites as the mixture is compressed during the upward movement of the piston. The self-ignition occurs before the cylinder reaches the top of its stroke, causing the cylinder to push against the crank shaft instead of with it. This creates a knock, which not only works against the motive power of the engine but also puts a strain on the mechanical parts. Generally, the higher the octane number, the higher the compression ratio that can be tolerated without knocking. Engines with higher compression ratios have more power and higher efficiencies.

Pure methane has a road octane number, (R + M)/2, of over 120. High quantities of other constituents in natural gas, such as propane, increase the tendency of this fuel to knock, while the inert elements such as carbon dioxide and nitrogen decrease the tendency. Generally the content of propane and inert elements in pipeline quality gas is such as to cancel their opposing impacts on tendency to knock. Thus, pipeline quality gas exhibits antiknock characteristics similar to methane [14]. Natural gas can be used in engines with compression ratios as high as 15:1 (versus 8-10:1 for 91 octane gasoline) [11]. An optimum compression ratio of 15:1 might result in a 15 to 22 percent increase in power and engine efficiency over a base compression ratio of 8.4:1 which is more typical of gasoline-fueled engines [15].

Neat methanol's road octane number at 100 is intermediate between CNG and gasoline. Compression ratios for alcohol fuels might be raised to 13.0:1.

Heat of vaporization affects engine power and efficiency. It measures the amount of heat absorbed by a fuel as it evaporates from a liquid state, which occurs when the fuel is mixed with air prior to combustion. Higher heat of vaporization leads to improved cooling ability. Higher cooling during the intake stroke of a spark ignition engine results in a denser air/fuel mixture. A denser mixture has two effects. First, by itself the denser charge allows for greater power. Second, a denser charge permits a greater compression ratio, which improves power and efficiency. Although a high heat of vaporization improves power and efficiency, it also adds to cold start problems when there is little heat in the air or in the engine to vaporize the fuel prior to sparking ignition.

The alcohol fuels have much higher heats of vaporization than gasoline or diesel. For methanol, typical power increases of 10 percent from increased charge density have been observed in unmodified automotive engines using methanol instead of gasoline.

High flame speeds allow for more complete combustion and potentially leaner fuel mixtures. While the liquid fuels have similar flame speeds, methanol is thought to have a higher flame speed than gasoline. Natural gas, however, has a slower flame speed than the other fuels, which impairs spark-engine efficiency unless the spark timing is advanced to compensate. The need for advanced timing can be offset by use of high compression ratios and compact, turbulent compression chambers that decrease the distance the flame must travel. The alcohol fuels distinguish themselves in the area of flame temperature and luminosity. For alcohol fuels, the flame temperature is lower than that of gasoline and the luminosity is low so that less thermal energy is lost through conduction or radiation. Low flame temperature also helps reduce nitrogen oxides formation. The lower luminosity, however, is a safety issue. When alcohol burns, the flame is essentially invisible. When gasoline is added to the neat alcohol fuels as in M85 it increases the luminosity.

Autoignition temperature is a measure of when a fuel will self ignite. Self ignition is a concern in environments where the fuel might escape and come into contact with hot engine parts. As a safety feature, high autoignition temperatures are desirable. Natural gas has the highest autoignition temperature at 1004°F. Gasoline and diesel have the lowest autoignition temperatures at 495°F. Flammability limits measure the range of fuel/air mixtures that will ignite. From a safety perspective, a wide range is less desirable than a narrow range. Of the hydrocarbon fuels, methanol has the widest flammability limits (7.3 percent to 36 percent). In partially filled or empty storage tanks, the methanol fuel is more likely to produce a combustible mixture above the fuel than the other alternative hydrocarbon fuels. Gasoline tank vapors are too rich in fuel to ignite, and the addition of gasoline to the methanol reduces the flammability limits of M85 compared to M100. Relative to gasoline, the safety concerns associated with the wide flammability limits of methanol are offset by the safety advantages of methanol's relatively high lower-flammability limits, higher flashpoint temperature, higher autoignition temperature, and lower vapor pressures than gasoline [16]. For example, the high lower-flammability limit of methanol keeps it from igniting in air at concentrations below about 6 percent, while gasoline will ignite at concentrations as low as 1.4 percent [17].

While wide flammability limits are not good from a safety perspective, they can be a positive characteristic for engine performance. Wide limits increase the flexibility to vary engine power or speed under different conditions by adjusting the fuel/air ratio.

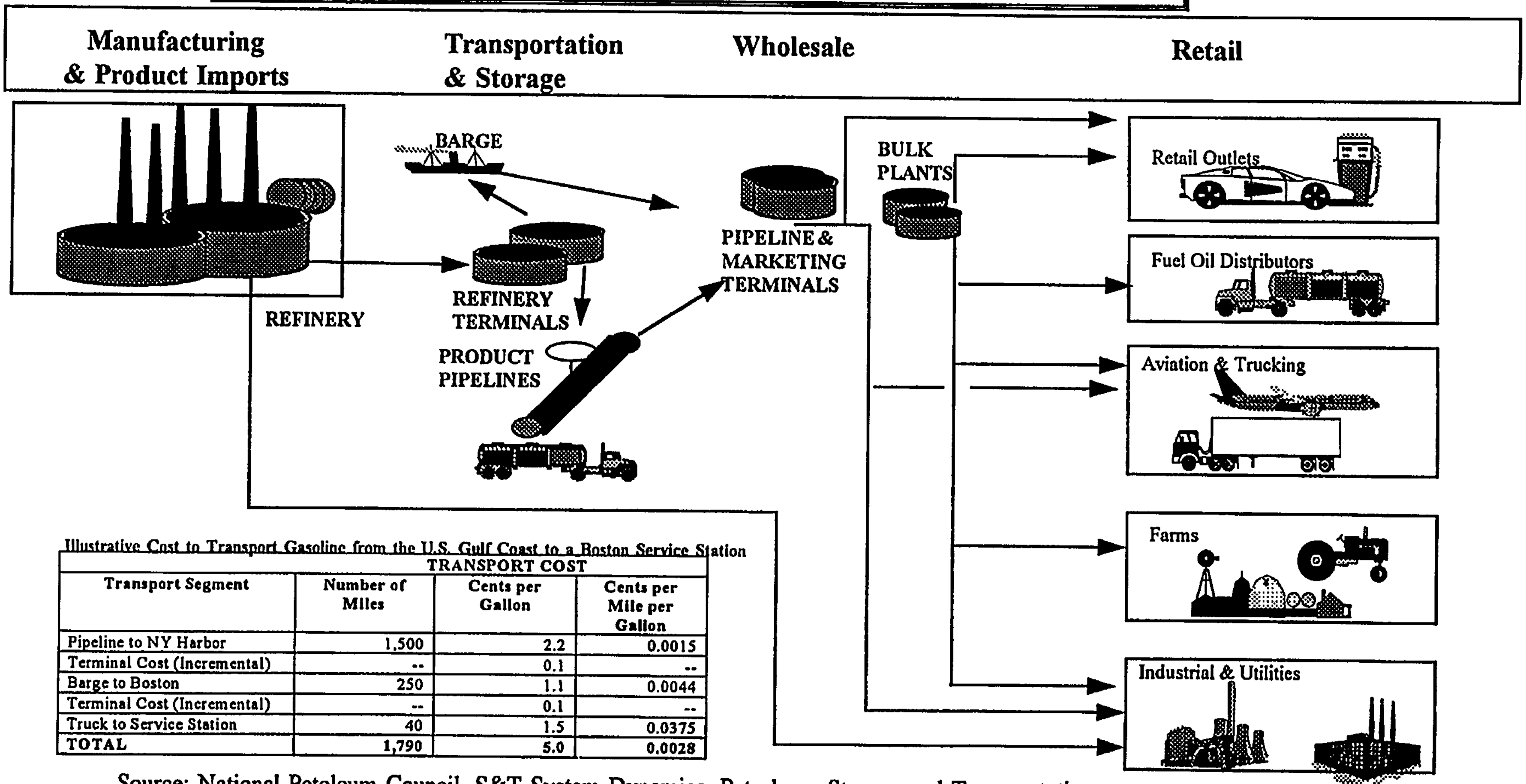
3.5. Fuel Distribution

Alternative fuels have to penetrate a conventional fuel market that has a well-developed infrastructure. Unfortunately, they generally cannot make use of the existing petroleum fuel infrastructure. Some fuels, such as natural gas, already have a significant infrastructure in place because of their other uses. Other fuels, such as methanol, have very little infrastructure to serve a vehicle market. Therefore, infrastructure needs for alternative fuels in some cases may be a hurdle to market penetration. This section will briefly review the distribution system for each fuel.

Gasoline, diesel, and other refined oil products travel through an extensive distribution and marketing chain beginning at the refineries as shown in Exhibit 3-9. Refineries are clustered on the Gulf Coast, the East Coast and West Coast where they can receive crude from both international and domestic locations. While refineries serve some large industrial and utility customers directly, product is usually distributed by pipeline or barge to large terminals closer to the end user. From these pipeline and marketing terminals, some product is again sent directly to large industrial and utility users, but most product is sent to bulk storage facilities that act as hubs for final distribution to retail outlets and large customers. Product is moved to the bulk plants and on to retail outlets or wholesale customers by tank trucks, which typically haul from 5,000 to 10,000 gallons each. Pipelines are the cheapest means of transportation on a cents per mile-gallon basis followed by barge and finally by truck. Exhibit 3-9 illustrates the cost differences in transportation modes. Transportation cost becomes important when gasoline is competing with other alternative fuels that do not have an efficient delivery infrastructure. The data in Exhibit 3-9 shows trucking costs per mile-gallon to be 25 times as high as pipeline costs. Inability to use cheap pipeline delivery systems can quickly hurt the economics of other fuels. While terminal costs shown in Exhibit 3-9 are generally not significant compared with the delivery costs, storage is an important part of the delivery system in assuring that product is available when needed.

The pervasive need for gasoline and diesel fuel requires many retail outlets. Since diesel mainly serves the commercial trucking industry, the number and character of diesel retail outlets are considerably different than gasoline outlets. A typical gasoline station has two or three pump islands, each with three pumps and size nozzles. A station will also have three underground storage tanks to handle three

EXHIBIT 3-9
DISTRIBUTION OF REFINED PETROLEUM PRODUCTS



Illustrative Cost to Transport Gasoline from the U.S. Gulf Coast to a Boston Service Station

Transport Segment	Number of Miles	TRANSPORT COST Cents per Gallon	Cents per Mile per Gallon
Pipeline to NY Harbor	1,500	2.2	0.0015
Terminal Cost (Incremental)	--	0.1	--
Barge to Boston	250	1.1	0.0044
Terminal Cost (Incremental)	--	0.1	--
Truck to Service Station	40	1.5	0.0375
TOTAL	1,790	5.0	0.0028

Source: National Petoleum Council, S&T System Dynamics, Petroleum Storage and Transportation, Volume II (Washington, D.C., April 1989), p. 65.

grades of gasoline (regular, premium, and some mid-grade). The total number of gasoline retail outlets in the United States as surveyed by National Petroleum News was 207,406 in 1993. Average gasoline sales per outlet was estimated to be almost 75,000 gallons per month [18].

Methanol will probably be transferred from import terminals or production facilities by barge, rail or truck to retail outlets. While methanol is a liquid at ambient temperatures and pressures, it cannot be moved easily through the existing petroleum product network to the end users. First, methanol cannot use the current petroleum pipeline system. It may suffer water contamination, phase separation in the case of M85, or cross contamination from other petroleum products. Second, methanol's corrosive properties make many of today's existing storage facilities as well as pipelines unsuitable for use with these fuels. The contamination and corrosive issues are solvable [19], but in the near term the petroleum system cannot be used. Third, while splash blending of methanol and gasoline will be possible in the initial stages of growth, if large volumes of M85 are to be used, petroleum product terminals may have to be altered to deal with automatic blending of the two products. However, because new dedicated truck loading racks will be needed to prevent water and product cross contamination, in-line blenders can be added at the new truck loading racks when they are installed [20].

Different safety concerns will also require different equipment and handling procedures for methanol along the distribution system than are used for gasoline. Generally, M85 is offered at a gasoline retail outlet that contains the appropriate storage and dispensing facilities for alcohols. At the retail outlet, materials must be compatible with alcohols' corrosive characteristics. For example, methanol underground storage tanks must be made of carbon steel or specially formulated fiberglass. A fuel filter must be added to remove dust particles that are loosened from the tank walls by the methanol. Dispenser materials must also be compatible with the alcohols.

Since methanol is not widely used, retail outlet information is limited. California reported 49 retail outlets planned for operation by the end of 1992 (compared to over 13,000 gasoline outlets in the state). When all planned outlets are considered, California may soon have 82 outlets [21]. California probably has the majority of U.S. retail outlets selling M85 today.

A development in the methanol retail outlet area was recently reported. Methanex (Metallgesellschaft Refining and Marketing, Inc.), a subsidiary of Metallgesellschaft Corporation (MG Corp.), announced it will assist independent refiners in putting up 2,500 fuel sites across the United States over the next three years. Methanol pumps will be added at independent refiners' stations in big cities and in non-attainment areas where M85 fuel-flexible vehicles are expected to be used.

Market penetration of M85 and methanol is projected by DOE to develop around marine terminals because of the high cost of shipping the product by rail or truck and the potential need for imports. Based on an analysis indicating that trucking gasoline for a 100-mile radius around marine terminals is economical, it was assumed the same would be true for methanol. Since approximately 75 percent of the vehicle miles traveled in the United States are within these 100-mile radii, methanol should ~~be able~~ to reach a large market in spite of current distribution limitations.

Natural gas is distributed throughout the United States in extensive pipeline systems that extend from the wellhead to the end user. Every continental state has access to natural gas through pipelines. The pipeline system consists of long-distance transmission systems followed by local distribution systems. Some underground storage is also used to help supply seasonal peak needs. The distribution system is operated at lower pressures than the transmission system. In 1992, the distribution system was able to serve 52.3 million residential consumers, 4.4 million commercial consumers and 0.2 million industrial establishments.

The main issue with CNG distribution for transportation purposes is the lack of refueling stations. The rest of the distribution is well developed. Refueling CNG vehicles requires connecting a manifold on the vehicle to a high-pressure gas line. A refueling station takes natural gas from the low pressure distribution pipeline and compresses it for transfer to the vehicle.

Slow-fill stations attach the vehicle directly to a compressor, and have little or no storage capacity. Refueling time is dependent on the compressor, but might be 6 to 8 hours for automobiles [22]. Slow-fill stations are used for fleet vehicles that can remain idle in a single location for a period of time. The pressure in the vehicle cylinders rise as they fill, and when they reach a specified pressure, the compressor automatically shuts down. Fast-fill stations are similar, but they have storage capacity to allow filling in a short period of time comparable to gasoline refills (5-7 minutes for automobiles). The compressor must be able to handle peak demand without falling behind. A cascade of high pressure cylinders, each containing gas at different pressures, provides the storage. Refueling occurs by equalizing pressure with each cylinder in turn, in ascending sequence. A home slow-fill compressor is also available for individual use sized to refuel one or two vehicles in a residential driveway.

In 1992, the National Renewable Energy Laboratory reported 349 CNG public and private refueling sites.

3.6. Vehicle/Engine Systems

As indicated in the previous section, as the number of alternatively fueled vehicles grows there will be a transition period when a vehicle owner may find it difficult in some locations to find methanol or CNG available. That practical supply problem has given rise to the design of vehicles that can operate on either an alternative or a conventional fuel - referred to as "dual-fueled" or "bi-fueled" vehicles. Vehicles that can operate on a mixture of alternative and conventional fuel are referred to as "flexible-fueled" vehicles. The term "dedicated vehicle" refers to a vehicle that runs exclusively on a single fuel. The dual-fueled and flexible-fueled vehicles provide flexibility and convenience but do not allow for optimization of the engine performance for a specific fuel.

The gasoline engine used to power most light duty vehicles is a spark ignition engine. Both methanol and CNG are high octane fuels and are ideally suited as spark-ignition fuels. Diesel fuel is used in a compression ignition engine in which the fuel "auto" or self-ignites when the fuel contacts the compressed hot air in the cylinder. Methanol and CNG will not auto-ignite in a diesel engine. However, diesel engines have been modified to operate with those fuels employing a "glow plug" or another ignition source.

For methanol and CNG the vehicle/engine system can be described in terms of the two main elements:

(1) Vehicle fuel storage system
(2) Vehicle engine system

Methanol Vehicle Fuel Storage: Methanol corrodes lead-plated fuel tanks, magnesium, copper, lead, zinc, and aluminum parts in addition to some synthetic gaskets. Hence, alcohol-compatible vehicles require special lines, hoses, valves and fuel tanks that can resist corrosion. Other than material composition, the mechanical parts of methanol-fueled vehicles are the same as those in gasoline vehicles. Supplementary components that are included in flexible-fueled vehicles include: a flame arrester to prevent sparks from entering the fuel tank during refueling; a fuel sensor to determine the amount of alcohol in the fuel; and sometimes a cold start system, which may not be a feature on all flexible-fueled vehicles. Since methanol has a lower energy density per unit volume than gasoline, vehicle range is reduced unless a larger fuel tank is supplied.

Methanol Vehicle Engine Systems: Since methanol fuel is a high octane fuel, flexible-fueled engines are optimized with a somewhat advanced ignition timing and an adjusted air/fuel ratio. Overall, neat methanol in spark ignition engines can provide improved power output and greater thermal efficiencies over gasoline. Emission considerations can result in some limitations to elevated compression ratios and lean combustion permitted by methanol's physical characteristics. Difficulty in cold starts and warm-up misfiring are methanol's major performance problems, but solutions are being developed to deal with these issues.

Neat methanol is best suited for spark ignition engines. Methanol has a high octane value, and hence has a corresponding low cetane value (somewhere below 15 versus 40-55 for diesel). In addition, methanol fails to provide adequate lubrication to the high pressure pumps used to inject fuel into the compressed air in the combustion chamber of a compression engine. These characteristics make neat methanol unsuitable for compression ignition engine use, but various means are available to modify either the engine or the fuel to address the situation.

In order to address some of the spark ignition engine performance problems that result form methanol's characteristics, methanol is blended with gasoline mainly to mitigate cold start and warmup problems. Current spark-ignition engine technology for dedicated methanol fuel use is designed for M85. The addition of gasoline to methanol improves flame visibility when the mixture burns and increases energy density over neat methanol. Compression engines have been modified for use with methanol, but that modification includes the addition of an ignition source, such as a glow plug.

While the addition of gasoline can help performance and safety, it detracts slightly from the emissions gains that neat methanol offers. Emission considerations also limit the engine efficiency gains that could be obtained from elevated compression ratios and lean fuel mixtures. Even with these considerations, one estimate indicates that spark ignition engine efficiency gain of about 18 percent over gasoline could be obtained with dedicated vehicles, and 6 percent could be obtained with flexible-fuel methanol vehicles that can use mixtures of M85 and unleaded gasoline [14].

Engines for flexible-fueled vehicles are being designed for the transition period between now and some future date when advanced vehicle technology will use neat methanol. These engines must deal with the entire range of gasoline/methanol mixes since a wide range of blends can occur in a tank when gasoline and M85 are purchased interchangeably. For example, the control system must be able to monitor the fuel composition and carry two sets of calibrations for fuel flow and spark timing - one each for gasoline and methanol - and interpolate for the mixtures. Oxygen sensor changes may also be needed to deal with emission control adjustments.

When alcohol fuels are used in flexible-fueled vehicles, they must accommodate the lower octane fuel used, namely gasoline. Consequently the compression ratio in these vehicles is not usually modified to produce the maximum engine efficiency advantages of M85.

CNG Vehicle Fuel Storage: A compressed natural gas vehicle stores gaseous fuel at a pressure of 2,400 to 3,600 psi. Even at a pressure of 3,600 psi, a unit volume of compressed natural gas has less than one-fourth of the energy content of gasoline, which means a much greater storage requirement for the vehicle.

Compressed natural gas tanks are larger and fuel plus tank weight is higher than for the liquid fuel/tank alternative; however, natural gas fuel tanks have been improved by recent technological advances. A refueling port and lines with pressure safety valves must be installed on vehicles fueled by compressed natural gas. High pressure fuel lines from the storage cylinder lead to a pressure reducer, which lowers gas pressure in one or two steps. Historically gaseous fuel systems used simple air-valve air-fuel mixers to create proper air/fuel mixtures for combustion. Today's emission limitations require more precision and control. One original equipment manufacturer (OEM) vehicle, for example, is using a fuel injection system containing an electronic control module that processes information from oxygen sensors (for emissions) and provides signals to adjust the fuel flow both for better performance and for better emissions control.

The most significant influence on the efficiency of a natural gas vehicle is the fuel tank weight; the heavier the tank the less efficient the vehicle. Cumbersome fuel tanks, whose weight reduces power (3 to 5 percent), can also affect potential vehicular range. Light-duty vehicles operating on compressed natural gas are either dual-fueled or dedicated. The extra weight of carrying two fuel systems in the dual-fueled vehicles detracts from efficiency. Engine adjustments in dual-fueled vehicles may also compromise performance with both fuels.

CNG Vehicle Engine System: Natural gas has a higher octane value than gasoline with generally good performance characteristics. As a gas, it has few cold-weather starting problems. Its octane value allows for use of higher engine compression ratios than can be used with gasoline alone. Higher compression ratios allow for higher power and fuel efficiency. The efficiency and power gains achievable from higher compression ratios help to offset power losses relative to gasoline caused by the lower energy density of the natural gas.

Differences in density of natural gas and air keep these two gases from forming a homogeneous mixture when first combined. Fluctuations in the air-fuel mixture can result in an engine misfire. Time and turbulence are needed inside the engine to create a uniform mixture.

While the characteristics of natural gas just discussed indicate that an engine designed to improve efficiency and lower carbon monoxide emissions would be a high compression, lean-burn engine, other characteristics make optimization challenging. For example, lean-burn engines can encourage the formation of nitrogen oxides because excess oxygen is present, and the high flame temperature of natural gas increases the peak combustion temperature. Designers of compressed natural gas vehicles are considering catalytic emission controls to deal with the problem of nitrogen oxides. Nonmethane hydrocarbon emissions are low relative to gasoline. However, total hydrocarbon emissions from natural gas engines can be high because methane is slower to react than other hydrocarbons, and in lean fuel mixtures, the slow flame speed of natural gas may be too low for combustion to be completed during the power stroke.

3.7. Market Penetration

For the past fifty years, the U.S. transportation fuels market has belonged almost exclusively to the crude-derived products, gasoline and diesel fuel. However, government policy and legislature acts are now targeting a greater use of non-crude alternative transportation fuels. These policies are based on both environmental issues and concern about the rising dependence on oil imports.

The Clean Air Act Amendments of 1990 (CAAA) encouraged the use of alternative fuels and specifically required the inclusion of oxygenates (e.g., MTBE and ethanol) in the gasoline used in many parts of the U.S. The Energy Policy Act of 1992 (EPACT) targeted the growth of non-crude derived alternative transportation fuels requiring the use of alternative fuels in fleet vehicles and providing incentives for vehicle production and fuel outlets. EPACT set a national goal of displacing 30% of the crude-derived light-duty vehicle fuel with non-petroleum-derived-replacement fuels by 2010. Natural gas can help meet the 30% objective with CNG and the use of natural gas in production of methanol and MTBE.

Natural gas and natural gas derived products can enter the transportation fuel market by any of three possible routes:

- Conventional Fuel blend component -- MTBE or alcohol
- Conventional Fuel -- conversion of natural gas to gasoline or diesel
- Alternative Fuel -- methanol or CNG

Routes 1) and 2) are readily accessible to gas-derived products, if those products can be produced at an economically competitive price. The alternative fuels face a markedly difficult situation.

The first route that natural gas can take into the transportation market is conversion of natural gas to methanol and subsequent use of methanol to produce MTBE or tertiary amyl methyl ether (TAME).

MTBE is the most commonly used oxygenate in the production of oxygenated and reformulated gasoline when required by the CAAA. Production of reformulated gasoline requires 11-15% MTBE when it is used at the oxygenate. In 1995, production of MTBE and TAME in the U.S. should approach 250 thousand barrels per day (3.5% of total gasoline volume). Demand for MTBE and TAME will continue to grow to the year 2000 as use of reformulated gasoline expands. These are high octane, gasoline blending components containing the oxygen required to meet oxygenated and reformulated gasoline requirements and hence command a price premium above the price of gasoline. This is an attractive market for these and other oxygenates derived from natural gas. There is, of course, an upper limit to demand growth, as the reformulated gasoline program reaches full implementation.

The second avenue of access to the transportation fuel market is the oldest -- natural gas can, by various synthesis routes, be converted into gasoline or diesel. The various routes can go via synthesis gas in the case of the Fischer-Tropsch process, via methanol as in Mobil's MTG process or the direct conversion such as oxidative coupling. The appeal of these processes is that an established market exists for the products produced. The problem that all of these gasoline and diesel processes share is achieving cost competitiveness.

The third route is the production of alternative transportation fuels from gas, such as methanol and CNG. Like most alternative fuels, methanol and CNG require new or converted vehicles with engines and fuel storage and delivery systems designed for the fuels used. Distribution systems and fueling stations must also be developed so that vehicle owners can refuel their vehicles when needed. Since market penetration depends on the purchase of new vehicles and development of a new refueling infrastructure, the commercial establishment of a new alternative fuel faces major obstacles to success. There are three major hurdles to overcome in establishing new transportation fuel in the market:

- Building a customer base of vehicles which can use the fuel
- Developing infrastructure of delivery and refueling facilities
- Gaining consumer acceptance of fuel/vehicle systems

Building a customer base can be a time-consuming process. Only about 7-8% of the total stock of motor vehicles are replaced each year. Thus, new alternative fuel vehicles must try to gain some fraction of the new vehicle market. For some vehicles, engine conversions to accommodate the alternative fuel are possible and this has accounted for some of the alternative vehicles in the past. Conversion vehicles, however, are generally more expensive and more likely to have poorer performances. Establishing a significant market position requires the production and sales of new vehicles designed for the use of the alternative fuel. Finding a motor vehicle manufacturer (referred to in the trade as an OEM, original equipment manufacturer) who will produce a vehicle for an alternative fuel is a significant hurdle. Even modifying a version of an existing vehicle represents a significant cost commitment that vehicle manufacturers are reluctant to make without reasonably strong evidence the alternative fuel vehicles will sell in adequate numbers to justify the cost of design and production start-up.

Developing the infrastructure for delivery and refueling outlets represents the second major hurdle. The dimensions of the fuel distribution and refueling problems were described previously in Section 3.5.

Due to the hurdles posed by both vehicle manufacturing and delivery infrastructure, both EPACT and most industry promoters of alternative fuel have selected the fleet vehicle market as the initial segment of the vehicle market which they seek to penetrate. The fleet market is sizeable, with 8.2 million cars in fleets of 10 or more vehicles in the total U.S. automobile population of 143.6 million. Many fleet vehicles also refuel at central locations, which diminishes the problem of building fueling infrastructures. Fleets also have central maintenance facilities that can resolve some of the support needed for a vehicle system which is unfamiliar to most auto mechanical repair shops. Federal and state governments also own or operate a significant number of fleet vehicles that can be totally committed to alternative fuels.

The third significant hurdle is gaining consumer acceptance of the alternative-fueled vehicle. Potential vehicle buyers assess a number of factors in deciding on the possible purchase of an alternative-fuel vehicle:

- Cost--Vehicle cost, fuel cost, maintenance and repair cost
- Convenience--Fuel availability, refueling time, refueling frequency
- Performance--Start reliability, no stalling, power
- Safety perception--As safe or safer than current vehicles

New alternative fuels can fail to gain market acceptance if consumer perception turns against the fuel or vehicle system or any of the items listed above. Methanol and natural gas have very different strengths in trying to penetrate the transportation fuels market. CNG is very cost competitive, has good engine performance, and substantial elements of a delivery infrastructure. The problem with gas is that it is a *gas*. Vehicle storage is a problem, compared to gasoline; CNG fuel to drive an equivalent distance occupies 4-5 times the space. Perception about safety may also pose a problem, because to many people a gas seems inherently more dangerous. Moreover, CNG is also a gas under considerable pressure. Methanol, in contrast, is a liquid facing different problems, whose solutions need to be demonstrated to achieve consumer acceptance. It must be demonstrated that methanol's cold start and corrosion problems have been solved. Adequate infrastructure for the delivery of methanol must be developed, along with opening of an adequate number of fueling locations to meet consumer needs in areas where the fuel is used. Finally, a record of safe use for methanol must be established.

There are significant hurdles to overcome to establish an alternative motor fuel in the marketplace. The EPACT has done several things to promote establishment of alternative fuels and overcome the hurdles. These include mandated fleet usage of alternative fuels, incentive for manufacturers of alternative-fuel vehicles and incentives for infrastructure development. There are also active efforts by the natural gas industry, propane, methanol and ethanol producers to promote use of those fuels. Still, overcoming the hurdles for any of the alternative fuels may not be achieved.