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INTEGRATED ANALYSIS OF HYDROGEN PASSENGER VEHICLE TRANSPORTATION PATHWAYS

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Abstract

Hydrogen-powered fuel cell vehicles will reduce local air pollution, greenhouse gas emissions and oil imports. Other alternative vehicles such as gasoline- or methanol-powered fuel cell vehicles, natural gas vehicles and various hybrid electric vehicles with internal combustion engines may also provide significant environmental and national security advantages. This report summarizes a two-year project to compare the direct hydrogen fuel cell vehicle with other alternatives in terms of estimated cost and estimated societal benefits, all relative to a conventional gasoline-powered internal combustion engine vehicle.

The cost estimates used in this study involve ground-up, detailed analysis of the major components of a fuel cell vehicle system, assuming mass production in automotive quantities. We have also estimated the cost of both gasoline and methanol onboard fuel processors, as well as the cost of stationary hydrogen fueling system components including steam methane reformers, electrolyzers, compressors and stationary storage systems. Sixteen different vehicle types are compared with respect to mass production cost, local air pollution and greenhouse gas emissions.

Introduction

Hydrogen could become an important energy carrier in the 21st century, supplementing electricity as a non-polluting method of delivering energy. Hydrogen would be particularly beneficial in the transportation sector, since hydrogen can be stored onboard a moving vehicle more readily than electricity. Zero emission electric or hydrogen vehicles would help to clean the air we breathe and reduce our dependence on foreign oil. Battery-powered electrical vehicles might also benefit society, but even EVs with advanced batteries would have limited range, high cost, and possibly limited battery life and long recharging times. If customers do not accept these limitations of battery-powered EVs, then market penetration would be restricted, and air pollution and oil independence gains would be marginal, too.

Hydrogen-powered fuel cell vehicles (FCVs), however, have the potential to provide the same range, acceleration, refueling time and other creature comforts associated with modern internal combustion engine vehicles (ICEVs). In the long run, FCVs could cost less to manufacture than the mechanically complex ICEVs they would replace, and maintenance and operating costs of a FCV would most certainly be less than those of conventional gasoline-powered ICE vehicle. With more potential driver appeal, FCVs have a greater chance than battery powered electric vehicles (BPEVs) of succeeding in the marketplace, and thereby to make a significant contribution to cleaner air and reduced oil imports.

Despite the existence of effective onboard hydrogen storage options (James 1996) and economic hydrogen supply options (Thomas 1997, Thomas 1998a), some decision makers in both industry and government are still skeptical of direct hydrogen FCVs. We therefore need to compare the alternatives to the direct hydrogen FCV. The two primary alternative vehicle classes are FCVs with onboard fuel processors to convert liquid fuels to hydrogen, and hybrid electric vehicles using low power internal combustion engines (ICEs) or other thermal engines operating at a fixed or limited range of speeds and power levels. This report analyzes the cost and societal benefits of 14 different vehicles:

1. Fuel Cell Vehicles (FCV)
    - -Direct hydrogen FCV
    - -Methanol FCV (probable and best case)
    - -Gasoline FCV (probable and best case)

2. Natural gas Vehicles
    - -Pure natural gas
    - -Hydrogen/Natural gas mixtures

3. Hybrid Electric Vehicles (HEV) with Internal Combustion Engines (Nine Combinations)
    - -Hydrogen, natural gas and diesel fuel
    - -Thermostat series, load-following series, and parallel HEV.

For each vehicle type, we analyzed four attributes:

* Vehicle cost in automotive-scale mass production
* Local emissions (VOCs, CO, NOx and PM)
* Greenhouse gas (GHG) emissions
* Oil imports

The last three attributes all depend on fuel economy. Fuel economy in turn depends on vehicle weight, so vehicle weight and fuel economy on various driving schedules were estimated for all 14 vehicle types.

Vehicle Descriptions

All vehicles are based on the Ford AIV (aluminum intensive vehicle) Sable, with a curb weight of 1,168 kg, compared to about 1,490 kg for the standard Sable. All other features of the vehicle such as aerodynamic drag (0.33), cross sectional area (2.13 m^2) and tire rolling resistance (0.0092) are maintained at the same level as the production Ford Taurus. The resulting fuel economies calculated below are therefore lower than would be expected if future vehicles incorporate some of the improved body characteristics being developed under the U.S. Partnership for a New Generation of Vehicles (PNGV) program. However, all types of vehicles would achieve higher fuel economy with improved body characteristics, so the relative comparisons shown here should be applicable to a PNGV type future vehicle.

Direct Hydrogen Fuel Cell Vehicle

The direct hydrogen fuel cell vehicle in this analysis has an onboard 5,000 psi compressed gas tank to provide hydrogen for the proton exchange membrane (PEM) fuel cell system. The ICE, 4-speed automatic transmission, exhaust system including catalytic converter, starter motor, alternator and other ICE related components are removed from the AIV Sable glider, replaced by the PEM fuel cell system, peak power battery bank, inverter, traction motor, motor controller and single speed transmission.

Methanol Fuel Cell Vehicle

To eliminate the need for onboard hydrogen storage, several companies have built or are proposing to use methanol-powered fuel cell vehicles. Daimler-Benz has demonstrated an A-Car FCV (Necar-3) that has an onboard methanol steam reformer to extract hydrogen to power the fuel cell. While new infrastructure would be required to supply large quantities of methanol FCVs, there are at least some methanol pumps available and consumers are more used to liquid than gaseous fuels.

However, developing a low-cost, low weight, efficient and time responsive methanol reformer and gas cleanup system to remove all but traces of carbon monoxide from the hydrogen stream is a significant challenge. Methanol does have the advantage of being the most easily reformed liquid fuel with only one carbon atom (CH_3OH) and hence no carbon-carbon bonds. Methanol can be reformed at 250 to 300°C, compared to 850 to 900°C typical of steam methane reformers or even higher for gasoline partial oxidation reformers.

Gasoline Fuel Cell Vehicle

The primary focus of the U.S. Department of Energy's fuel cell vehicle program is currently the development of onboard multi-fuel partial oxidation (POX) reformers to allow the use of existing fuel infrastructure, including gasoline. This approach eliminates the need for a totally new fuel infrastructure[1], but places the greatest burden on the vehicle itself. Reforming gasoline or other fuels such as diesel fuel, natural gas or ethanol is much more difficult than reforming methanol, generally requiring much higher temperatures in the 800 to 1000°C with somewhat lower efficiency.

A partial oxidation system is very effective at reforming virtually any type of hydrocarbon fuel. Table 1 lists the output characteristics from a Texaco industrial POX system using pure oxygen, illustrating that even oil bottoms or asphalt can be converted to a stream of over 90% hydrogen and carbon monoxide. The CO can then be converted to more hydrogen by the water-gas shift reaction:

$$CO + H_2O = CO_2 + H_2$$

A gasoline POX system with existing gas cleanup technology would produce lower hydrogen content than a methanol processor, with as little as 30 to 40% hydrogen, compared to 75% hydrogen from a steam methanol processor. A partial oxidation system, as the name implies, adds some oxygen directly into the reactor. Industrial POX systems usually include an air separation plant to provide pure oxygen, but this would not be economic for a mobile reformer. Rather, air is added which introduces 3.76 moles of nitrogen for each mole of oxygen. Nitrogen is the primary diluent in the POX reformate, along with the carbon dioxide that is also present in methanol reformate. These diluents affect the ability of the hydrogen to reach the electrochemically active catalyst sites on the anode, reducing peak fuel cell power. The peak power of an older technology Ballard fuel cell system was reduced by 26% operating on 35% hydrogen content. It is not clear whether this drop in peak power with dilute hydrogen mixtures can be reduced with new fuel cell designs.

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[1]While the primary intent is to use gasoline fuel, in all likelihood a new grade of gasoline would be required for onboard reformer systems. A fuel cell grade gasoline would probably require much lower (near zero?) sulfur content than existing grades, effectively requiring a separate set of gasoline tanks, pumps, tanker trucks, etc., and modified refinery equipment. Thus there will probably be some required infrastructure investment even if onboard POX processors are developed.

Table 1. Output Gas Composition (mol %) from Texaco Partial Oxidation Reactor with Pure Oxygen

	Natural Gas	Naphtha	Fuel Oil	Vacuum Residual	Oil Bottoms	Asphalt
Hydrogen	61.1	51.2	45.9	44.2	41.4	42.1
Carbon Monoxide	35.0	45.3	48.5	48.3	51.2	49.3
Carbon Dioxide	2.6	2.7	4.6	5.2	5.3	6.5
Methane	0.3	0.7	0.2	0.6	0.3	0.4
Nitrogen + Argon	1.0	0.1	0.7	0.2	0.4	0.4
Hydrogen Sulfide	-	-	0.1	1.4	1.3	1.2
Efficiency (HHV - %)	83.8	82.7	83.1	84.1	82	81.9

Hybrid Electric Vehicles

We have analyzed three different ICE hybrid electric vehicles, each with three different fuels or a combination of nine different HEVs. Each HEV is described briefly below. Energy flow diagrams are provided for each HEV type in Figures 1 through 3, assuming constant vehicle weight. In reality each HEV will have different total vehicle weights, so these three figures illustrate the effects of the hybrid driving mode on fuel economy independent of weight changes.

Thermostat Mode Series Hybrid Electric Vehicle

An electric motor supplies all mechanical power to the wheels. The ICE plus generator are used to provide electrical energy to the motor and to recharge the batteries. The ICE is turned on at a fixed power level when the battery state of charge (SOC) reaches a pre-set minimum (40%), and turned off when the SOC exceeds a maximum (60%). Since the ICE in turned off when the battery is within the set SOC levels, the battery bank must have enough power to provide the peak required acceleration for the vehicle. The weight and cost of this peak power battery reduces the performance of the thermostat series HEV.

Load-Following Series Hybrid Electric Vehicle

The ICE is turned on when the vehicle power demand (road power plus accessory power assumed to be 500 watts) exceeds a threshold, and turned off whenever the vehicle stops, the battery SOC exceeds a maximum set point, or the power demand falls below a lower threshold. Both upper and lower power thresholds vary according to pre-programmed algorithms as a function of battery SOC to maintain the battery SOC within a narrow range. The ICE output power varies over a limited range to optimize system efficiency by minimizing the energy passing into and out of the battery. That is, the computer algorithms keep the ICE operating as long as possible. The ICE is only turned off when its efficiency falls below the battery round trip efficiency. The load-following series HEV can have a smaller peak power battery, since the engine is turned on whenever the driver demands peak power.

Parallel Hybrid Electric Vehicle

The ICE and a supplemental traction motor are both mechanically coupled to the transmission through appropriate gear sets. A computer algorithm determines when to turn the ICE on, what power level to produce, and when to turn the ICE off. Since the ICE is now mechanically coupled to the road (unlike the two series hybrids describe above), the one-speed transmission used in FCVs and series HEVs must be replaced with a 4-speed automatic transmission. This increases weight and cost and reduces engine efficiency, since the ICE must now operate over a wider range of output powers away from its "sweet spot" of maximum efficiency. However, the parallel mode does eliminate the need for the generator that is required for a series hybrid, and some of the ICE energy passes directly from the engine to the transmission without the efficiency losses associated with the generator, rectifier, inverter and AC induction motor used in the series HEVs.

Vehicle Weight Estimates

The detailed weight estimates are shown for the fuel cell vehicles below. For details on weight estimate of the other vehicles, refer to (Thomas 1998b).

Direct Hydrogen Fuel Cell Vehicle Weight Estimate

The weight of the fuel cell vehicle power train is summarized in Table 2 to illustrate the method used to calculate all vehicle weights. We have assumed a net fuel cell system specific power of 500 watt/kg, which is also the DOE goal for mobile fuel cell systems for 2004 (DOE 1998, p. 3-40). The specific power of the electric motor, inverter and controller is assumed to be just over 1 kW/kg, near the DOE goal of 1.2 kW/kg for the total motor/electronics package -- 1.6 kW/kg for the motor and 5 kW/kg for the inverter/controller by 2004 (DOE 1998, p. 3-68). The battery specific power (560 watts/kg) is based on demonstrated performance of the Bolder thin plate, high peak power lead acid battery at 50% state of charge (SOC)[2]. Specific power is even greater at higher SOC, but we assume here that the battery is normally maintained near 50% SOC to accommodate regenerative braking energy on long hill descents. The DOE goal for a power-assist battery subsystem for a hybrid vehicle

[2]Battery sizing is normally determined by specific energy, not specific power, since energy storage is critical for EVs to attain adequate range. The peak power battery for a FCV is only needed for brief accelerations which might last for 10 to 20 seconds, requiring very little energy. Indeed the Bolder battery technology provides much more energy storage capability than is needed for the FCV. Sizing is therefore determined exclusively by specific power.

is 800 Watts/kg (DOE 1998, p. 3-56). We have added a 10% margin to the peak power of both the motor and the battery system.

Table 2. Estimated Weight of a 5-Passenger Direct Hydrogen Fuel Cell Vehicle

	Peak Power Required (kW)	Specific Power (kW/kg)	Total Weight (kg)
Fuel Cell System	38.1	.5	76.2
H_2 Storage Tank			34.9
Hydrogen			4.7
Electric Motor/Inverter/Controller	82	1.09	75.2
Peak Power Batteries	40.3	.56	71.9
Battery Controller			9.0
Gear Box			27.0
Radiator & Coolant			14.0
Cables & Misc.			21.0
Total Fuel Cell-Unique Components			334
Glider[3]			821
Curb Weight			1,155
Test Weight			1,291

The FCV net test weight is estimated at 1,291 kg, which is almost the same weight as the AIV Sable with an internal combustion engine drivetrain at 1,304 kg. In other words, the fuel cell power train weight is projected to be very close to that of the current ICEV drivetrain weight, with room for net improvements if electric motors and particularly their controllers can be manufactured with less mass. On the other hand, the specific power of conventional ICE power trains will undoubtedly improve, although the current PNGV front-runner, the direct injection diesel, will need major weight reductions just to reach the specific power of spark ignition engines assumed in this ICEV comparison.

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[3]"Glider" weight here means vehicle curb weight minus the ICE power train, 4-speed automatic transmission, gasoline fuel tank and exhaust system -- all components not used in the fuel cell vehicle.

Methanol Fuel Cell Vehicle Weight Estimates

Estimating the weight of a methanol FCV is complicated due to the closed-loop nature of an onboard reformer/fuel cell system. In a direct hydrogen fuel cell, virtually all of the hydrogen can be consumed in the anode of the fuel cell. In principle the fuel cell can be operated "dead-ended," with no exhaust from the anode chamber. In practice, though, a small portion of the fuel cell anode gas is recirculated to the anode input to help manage water vapor and to prevent buildup of other trace gases.

The output gas stream from a methanol reformer is not pure hydrogen with current technology.[4] The methanol reformate from a steam reformer is typically 75% hydrogen with most of the rest CO_2 (all CO down to 10 to 50 ppm must be removed in a special gas cleanup step, currently using a preferential oxidation (PROX) step.) If methanol is processed with a partial oxidation (POX) system, hydrogen content will be even lower due to nitrogen dilution. As a result, the anode chamber of the fuel cell stack must have significant exhaust gas to remove the CO_2. By definition, then, some hydrogen must also exit the system; otherwise the last section of the fuel cell near the exit would have zero hydrogen partial pressure and would not produce any electricity. Typically 10 to 20% of the hydrogen passes through the anode of the fuel cell unreacted. To avoid a safety hazard and to limit excessive efficiency losses, this unused hydrogen must be burned, and the heat utilized in some manner such as to raise steam for the reformer.

Existing fuel cell systems also experience a drop in peak power operating on 75% hydrogen compared to pure hydrogen. The peak power of an early generation of the Ballard fuel cell system dropped 10 to 12% operating on simulated methanol reformate (See Appendix B, section 2 of Thomas-1998b for details). Since the fuel cell peak power must be sized to provide the necessary vehicle hill climbing capability, the fuel cell suitable for a FCV with an onboard reformer must be larger to make up for this lost peak power capability, thereby increasing vehicle weight and cost. In addition. all other components of the vehicle must be increased in size to maintain a given vehicle performance. That is, the vehicle power to weight ratio must be kept constant. Adding any weight to the vehicle technically requires a resizing of all power train components. But this added weight in turn requires small increments in all other components -- the weight compounding effect.

This weight compounding effect is discussed in detail in Appendix B-2 of (Thomas-1998b) for the methanol FCV. Given the uncertainty regarding the performance and characteristics of onboard reformers, we have estimated a "probable" and "best case" set of parameters for all onboard fuel processors. For the methanol FCV, we are projecting a total vehicle weight increase of 100 to 123

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[4]Several companies are working on thin metal membranes to separate out pure hydrogen from the methanol reformate. If these efforts are successful, then the fuel cell would operate on pure hydrogen, but the exhaust from the membrane separation system would contain some hydrogen, reducing system efficiency to the degree that not all of the hydrogen exiting the membrane could be used to raise steam for the reformer.

kg -- 1390 to 1414 kg test weight compared to 1291 kg for the direct hydrogen FCV. The actual methanol reformer weight is only 46 to 60 kg (best case/probable case), or 49.5 to 65.7 kg after weight compounding (The reformer size itself must grow to accommodate the higher vehicle weight.) The final vehicle weight increment is about twice the initial estimate for extra reformer weight, due to larger fuel cell systems, and slightly larger battery banks, motors and controllers. Only 15% of this weight compounding is due to structural weight to hold the extra components. The estimated weights for the key power train components are summarized in Table 3 for the direct hydrogen FCV and the two methanol FCV cases.

Table 3. Methanol Fuel Cell Vehicle Weight Estimates after Weight Compounding (kg)

	Direct Hydrogen Fuel Cell Vehicle	Methanol Fuel Cell Vehicle	
		Best Case	Probable Case
Fuel Weight	4.71	41.4	41.4
Fuel Tank Weight	34.9	14	14
Reformer System	0	49.0	64.8
Peak Power Battery	71.9	77.1	78.4
Fuel Cell System	76.2	89.0	91.9
Motor/Controller	75.3	79.9	81.0
Glider[5], Gear Box, Radiator, Cables & Misc.	892	904	905
Curb Weight	1,155	1,254	1,277
Test Weight	1,291	1,390	1,414

The initial 46 to 60 kg reformer weight estimates could be much too low. DTI has analyzed a stationary steam methane reformer in some detail. We estimate that a stationary reformer with a 66-kW peak hydrogen capacity (48 kg/day) would weigh over 310 kg. The reformer would provide enough hydrogen to generate 33 kW of electrical energy -- almost enough for one FCV.[6] While we have not yet conducted a thorough analysis of onboard methanol steam reformers, achieving 46 to

[5]"Glider" here refers to all vehicle weight except the power train -- those components that are common to both fuel cell vehicles.

[6]This one 66-kW stationary reformer could produce enough hydrogen to support an average of 96 FCVs, graphically illustrating the economic advantage of placing the fuel processor on the curb: a processor barely large enough to support one FCV placed onboard that vehicle can provide hydrogen for almost 100 FCVs.

60 kg steam reformer weights will be a significant challenge.

Gasoline Fuel Cell Vehicle Weight Estimates

As a result of lower fuel cell peak power due to the low hydrogen content in a gasoline POX reformate (typically 35%), the gasoline FCV will require a larger fuel cell system to provide the necessary vehicle hill climbing capability. The extra weight of the larger fuel cell combined with the added weight of the processor itself also requires slightly larger battery capacity and motor power, as summarized in Table 4. As with the methanol FCV, the weights for the fuel processors are very optimistic. DTI has completed a very thorough design and costing exercise for onboard POX systems for the U.S. Department of Energy. We estimate that the POX reformer alone would weigh 100 kg. However, Arthur D. Little, Inc., the company developing the POX system for DOE, has estimated that a fully functioning POX system including gas cleanup would weigh only 87 kg. The DOE has set a specific power target of 1 kW/kg for the POX processor system, which would amount to 55 kg for a 55-kW system. We have used this 55 kg initial processor weight estimate for the best case, even though we have seen no credible design that could be built with this low weight. We have assumed the DTI calculated weight for the POX system (100 kg) as the probable case POX processor total weight.

Table 4. Gasoline Fuel Cell Vehicle Weight Estimates after Weight Compounding (kg)

	Direct Hydrogen Fuel Cell Vehicle	Gasoline Fuel Cell Vehicle	
		Best Case	Probable Case
Fuel Weight	4.71	22.7	22.7
Fuel Tank Weight	34.9	14	14
Reformer System	0	58.5	112.1
Peak Power Battery	71.9	77.0	81.6
Fuel Cell System	69.3	97.7	115.5
Motor/Controller	75.3	79.8	83.9
Glider, Gear Box, Radiator, Cables & Misc.	899	901	909
Curb Weight	1,155	1,251	1,339
Test Weight	1,291	1,387	1,475

Hybrid Electric Vehicle Weight Estimates

Weight estimates for the diesel hybrid electric vehicles are summarized in Table 5. Weights are similar for other HEVs. Representative weights are summarized in Table 6. For details of the other vehicles, see (Thomas-1998b).

Table 5. Diesel Hybrid Vehicle Weight Estimates after Weight Compounding (kg)

	Thermostat Series Hybrid		Load-Following Series Hybrid		Parallel Hybrid	
	Peak Power (kW)	Weight (kg)	Peak Power (kW)	Weight (kg)	Peak Power (kW)	Weight (kg)
Fuel		20.9		19.1		15.0
Fuel Tank		14		14		14
Peak Power Battery	94.5	163.9	38.1	68.3	35.5	63.9
Motor/Inverter/Controller	94.5	84.4	86.7	78.7	35.5	41.1
Internal Combustion Engine	46.3	115	43.2	108.5	33.5	85.1
Generator + Rectifier & Controls	46.3	40	43.2	37.8	0	0
Glider, Gear Box, Radiator, Cables & Misc.		918		899		890
Curb Weight		1,357		1,225		1,109
Test Weight		1,493		1,361		1,245

Vehicle Fuel Economy Estimates

Three of the four major vehicle attributes analyzed here (local air pollution, greenhouse gas emissions and oil imports -- all except cost) depend on the net vehicle fuel economy. We have developed a vehicle driving simulation computer spreadsheet program to estimate the fuel economy of various alternative fueled vehicles.

Table 6. Weight Estimates for Alternatively Fueled Vehicles (kg)
[AIV Sable Test Weight = 1,304 kg]

	Direct H_2 FCV	Methanol FCV[7] (Probable)	Gasoline FCV (Probable)	FC Range Extender	H2 Parallel Hybrid[8]	NG Parallel Hybrid	Diesel Parallel Hybrid
Fuel	4.71	41.4	22.7	6.71	5.92	14.8	15
Fuel Tank	34.9	14.0	14.0	49.7	45.8	15.7	14.0
Fuel Cell System	76.2	91.9	115.5	36.0			
Fuel Processor		64.8	112.1				
ICE					71.9	71.0	98.2
Motor/Controller	75.3	81.0	83.9	100.0	41.2	40.6	41.1
Battery	71.9	78.4	81.6	497.0	64.0	62.6	63.9
Transmission	27.0	27.0	27.0	27.0	44.0	44.0	44.0
Glider[9]	865.0	878.5	882.2	973.6	838.2	834.3	832.8
Curb Weight	1,155	1,277	1,339	1,690	1,111	1,083	1,109
Test Weight	1,291	1,413	1,475	1,826	1,247	1,219	1,245

The estimated fuel economy[10] for three classes of vehicles are summarized in Figure 4:

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[7]Both methanol and gasoline FCV's include a "best case" estimate in addition to the "probable" case shown here.

[8]Two types of series hybrid vehicles are also analyzed for each of the three fuels in the main report (Thomas 1998b).

[9]"Glider" includes all components of the AIV Sable common to the ICEV and the alternative vehicle, including extra structure to carry additional weight of the alternative vehicles.

[10]All fuel economies are expressed in miles per gallon of gasoline equivalent -- for fuels other than gasoline, this measure represents the fuel energy consumed per mile on a lower heating value basis. Assuming that gasoline has a lower heating value of 0.115 MBTU/gallon, then 30 mpg-equivalent is equal to fuel consumption at the rate of 260.9 miles/MBTU. Natural gas with a lower heating value of 913 BTU/SCF would then have a fuel economy of 0.238 miles/SCF of natural gas consumed.

conventional internal combustion engine vehicles (ICEVs), fuel cell vehicles (FCVs) and hybrid electric vehicles (HEVs). Each vehicle group is represented by three fuels: for ICEVs, gasoline, natural gas and hythane[11] -- in this case a 30% mixture of hydrogen in natural gas. We assume here that all ICEVs have the same fuel economy of 30 mpg-equivalent in the 2000 time period. For the fuel cell vehicles, the fuels are hydrogen, gasoline and methanol. For the hybrid vehicles, the fuels are natural gas, hydrogen and diesel fuel.

Two sets of data are shown for the methanol- and gasoline-powered fuel cell vehicles: a probable case (lower fuel economy), and a best case, assuming a more optimistic outcome for several onboard fuel processor parameters as described in Sections 2.2 and 2.3 of (Thomas-1998b).

For all fuels, the thermostat mode series hybrid produces the lowest fuel economy, the load-following series hybrid slightly higher fuel economy, and the parallel hybrid the highest fuel economy.

Many analysts estimate the fuel economy of vehicles on the Federal Urban Driving Schedule (FUDS) and the Federal Highway Driving Schedule. However, these driving schedules are notoriously anemic. For example, the average speed on the highway schedule is 48.6 mph, and the maximum speed in 60 mph, which does not represent modern highway driving. To better reflect actual driving conditions, we have multiplied all speeds in the federal schedules by a factor of 1.25, as suggested by Harold Haskens of the Ford Motor Company. The fuel economy shown in Figure 4 is the combination of 55% urban and 45% highway driving, each with the 1.25 times accelerated speeds. For details of the vehicle and fuel economy calculations, see (Thomas 1998b.)

As shown in Figure 4, the direct hydrogen FCV has the highest estimated fuel economy at 66 mpg-equivalent, or a factor of 2.2 times greater than the conventional gasoline ICEV. However, this ratio would be larger for the slower federal driving schedules used by some analysts, as shown in Table 7. On the FUDS, the FCV would have over three times the fuel economy of a conventional car, or a factor of 2.6 on the EPA combined schedule. The FCV advantage drops on the more realistic 1.25 times accelerated schedule because fuel cell efficiency decreases almost monotonicly with increasing power level above a low power threshold, whereas the ICE engine map has maximum efficiency at an intermediate power level -- the ICE efficiency will improve with higher acceleration over low power portions of the driving cycle.

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[11]"Hythane," a mixture of natural gas and hydrogen, is a registered trademark of Hydrogen Components, Inc. of Littleton, Colorado.

Table 7. Fuel Economy of Fuel Cell Vehicle Compared to Conventional ICEV (mpg-equivalent)

	Standard Federal Schedules			1.25 Times Accelerated Schedules		
	Urban	Highway	Combined (55/45)	Urban	Highway	Combined (55/45)
FCV	79.7	85.4	82.3	68.6	62.7	66.0
(FCV without Regen Braking)	(71.6)	(83.2)	(76.8)	(60.4)	(61.2)	(60.8)
ICEV	25.5	38.5	31.4	26.4	34.4	30.0
Ratio FCV/ICEV	3.13	2.22	2.62	2.60	1.82	2.20

Returning to Figure 4, the two liquid-fueled FCVs have lower fuel economy than the direct hydrogen FCV, due to a combination of added vehicle weight, the inefficiency of the onboard fuel processor, and the reduced efficiency of the fuel cell operating on reformate. We estimate a modest drop in fuel economy for methanol FCVs compared to direct hydrogen FCVs, and a significant decrease for gasoline FCVs. In fact, the "probable" case of the gasoline FCV has slightly lower fuel economy than the gasoline ICEV, which would mean no reduction in oil imports. However, the best case gasoline-FCV estimate would increase ICEV fuel economy by 40%. This large spread in estimates reflects our degree of uncertainty regarding the performance of onboard POX fuel processors and gas cleanup devices.

For the hybrid ICEs, we assume spark ignition engine efficiencies of 38% for natural gas, 40% for hydrogen, and 43% for the diesel fuel compression ignition, direct injection (CIDI) engine. The series hybrid vehicles all have fuel economies comparable to the methanol FCV and the best case gasoline FCV. But the parallel hybrids have better fuel economy than liquid-fueled FCVs, with the diesel parallel hybrid fuel economy (58 mpg-equivalent) approaching that of the direct hydrogen FCV at 66 mpg-equivalent.

Comparison of Fuel Economy Estimates

Fuel economy estimates in the literature vary widely, particularly for hybrid vehicles. While our analysis projects substantially higher fuel economy for parallel hybrids than for series hybrids, some analysts have concluded that series hybrids would be more efficient. This diversity may simply reflect the wide range of operating strategies possible for hybrid vehicles. In this section we compare our fuel economy results with two recent analyses from the literature.

Wipke et al.(1997) from the National Renewable Energy Laboratory have recently analyzed the fuel economies of various vehicles. We ran the DTI vehicle simulation code, matching the specified NREL vehicle parameters including drag coefficient, cross sectional area (C_dA product of 1.6 m^2), rolling resistance (0.006), regenerative braking availability (70%), vehicle test weight (variable from

1,162 kg for a CIDI ICEV to 1,536 for the FCV[12]), and accessory load (700 watts). Other parameters were not specified in the NREL article, such as transmission efficiency map, motor efficiency map, generator and power electronics efficiencies, and battery efficiency. We assumed 96% one-way battery efficiency for this comparison only, which is higher than our battery standard efficiency of 80% charge efficiency and 89% discharge efficiency used in all other estimates in this report.

We have compared the NREL and DTI fuel economy estimates in Figure 5 for various diesel CIDI engines and for the FCV. Fuel economy is shown for the standard EPA cycles (no 1.25 factor acceleration). The DTI fuel economy estimates are consistently lower for the conventional ICEV, the series hybrid and the FCV. This is probably due to lower DTI efficiency estimates for the motor, generator, power electronics and transmission. However, our results for the parallel hybrid are comparable, indicating a relatively higher fuel economy, suggesting that our parallel hybrid control strategy may be more efficient that the strategy chosen by NREL.

We have also compared our fuel economy results (Figure 6) with those from Aceves and Smith (1997) at the Lawrence Livermore National Laboratory. Again we have matched the input parameters stated by LLNL, including a 96% one-way energy storage system efficiency to simulate their proposed flywheel storage system. In this case we match reasonably closely for the hydrogen spark ignition ICEV, assuming 36% peak efficiency. But our two analyses arrive at opposite conclusions regarding the efficiency of series vs. parallel hybrids -- LLNL shows a 15% drop from series to parallel (62.5 to 52.9 mpg-equivalent), while DTI projects a 21% improvement in fuel economy (55.6 to 67.6 mpg-equivalent) on the combined driving schedules. The lower series hybrid fuel economy is probably due to lower assumed motor/generator/ power electronic efficiencies that are not specified in the LLNL report. But the large relative improvement in fuel economy for the parallel hybrid must be the result of a more aggressive control strategy, as described in Section 4.1.3 of (Thomas 1998b).

Vehicle Emissions

Given the vehicle fuel economies, we can estimate both global greenhouse gas emissions and local emissions of criteria pollutants.

Greenhouse Gas Emissions

We have estimated the total greenhouse gas (GHG) emissions for each vehicle type, including all emissions due to fuel extraction, refining and delivery, as well as fuel consumption on the vehicle.

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[12]We estimate that the FCV weights will be comparable to those of current ICEVs; we ran this simulation with higher FCV weight only to compare DTI and NREL results.

Most GHG emission estimates are based primarily on the work of Mark Delucchi at the University of California at Davis (DeLuchi 1991, DeLuchi 1993, Delucchi 1996). In addition to CO_2 emissions, the primary greenhouse gas, we include emissions of five other GHGs (VOCs, CO, CH_4, N_2O, and NOx), with each converted to a CO_2-equivalent rating assuming a 100-year time horizon.

The GHG results are summarized in Figure 7. Starting at the bottom, the last three bars show a modest 19% reduction in GHGs with a conventional natural gas vehicle (NGV). Adding hydrogen to natural gas increases GHG emissions, since hydrogen produced from natural gas contains less energy than burning the natural gas directly in the car. Thus hythane (30% hydrogen) would only cut GHGs by 8% relative to gasoline ICEVs.

The middle bars of Figure 7 compare the fuel cell vehicles (FCVs). A direct hydrogen FCV would reduce GHGs by 41%. Methanol-FCVs would emit more GHGs than direct hydrogen, but still less than the NGV. The probable case gasoline -FCV would only reduce GHGs by 4%, although the best case gasoline-FCV could provide a 34% reduction, similar to the best case methanol-FCV.

The upper set of nine hybrid ICE vehicles illustrate that either natural gas or diesel parallel hybrid vehicles could produce greater GHG reductions than the direct hydrogen FCV, providing a 52% reduction compared to the gasoline ICEV[13]. Hydrogen hybrids fare worse, due to the extra natural gas consumed to produce the hydrogen and also the electrical power plant emissions necessary to run the steam reformer plant and to compress the hydrogen. We conclude that either natural gas or diesel parallel hybrid vehicles would provide the greatest reduction in GHG emissions.

The data in Figure 7 assume that all hydrogen is produced by steam reforming of natural gas, with the hydrogen compressed to 5,000 psig by electric motor-driven compressors. If, however, hydrogen were generated by electrolyzing water with grid electricity, then the picture changes dramatically for all hydrogen powered vehicles, as shown in Figure 8 (note the large scale change compared to the previous figure). The direct hydrogen FCV GHG emissions would surge from an estimated 245 g/mile for hydrogen derived from natural gas to 936 g/mile with electrolytic hydrogen, assuming the projected average U.S. utility generation mix for the post-2000 time period -- the FCV would increase GHGs by a factor of 2.3 compared to the gasoline ICEV with electrolytic hydrogen. A conventional ICEV powered with hythane would also increase GHGs by 33%, and the hydrogen hybrids would produce up to 3.8 times greater GHGs than conventional gasoline vehicles. From a strictly GHG perspective, then, electrolytic hydrogen is not a viable option for the transportation sector until such time as a significant fraction of the utility generation capacity has been converted

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[13]To minimize GHG emissions, the hydrogen for a FCV could be compressed with a natural gas-driven ICE compressor instead of a motor using grid electricity generated with 70% coal as assumed here. We estimate that this natural gas-powered compressor would reduce the FCV GHG emissions from 245 to 234 g/mile, still above the 200 g/mile for the NG or diesel parallel hybrids.

to some combination of renewables and nuclear energy, or the hydrogen was produced by electrolysis from off-grid renewable sources.

Local Criteria Pollutant Emissions

One major motivation for developing alternatively fueled vehicles is to reduce local emissions of volatile organic compounds (VOCs)[14], carbon monoxide (CO) and oxides of nitrogen (NOx). VOCs and NOx combine in the presence of sunlight to form ozone, the primary summer smog irritant, while CO is the primary cold weather pollutant. Particulate matter (PM) emissions are also a health hazard, but most vehicular PM is produced by diesel fuel, although other tailpipe emissions including VOCs and NOx can also combine in the atmosphere to produce secondary particulates. Since diesel engines are now prevalent in Europe and are being considered as a hybrid vehicle option in the U.S., California is proposing to limit PM emissions in their new super ultra-low emissions vehicle (SULEV) standard to below 0.01 grams per mile.

All local emissions reported here are based on real world driving averaged over the life of the vehicle. These estimates are higher than the results published from laboratory tests of various vehicles, due to several factors. Actual vehicles are accelerated and driven faster than the standard federal test procedure (FTP)[15], resulting in "off-cycle" emissions. Some small fraction of actual vehicles have malfunctioning emission control devices, resulting in excessive emissions. Furthermore, laboratory tests are run on Federal "certified gasoline," which contains less than 100 ppm of sulfur, compared to 300 to 350 ppm average sulfur content for gasoline in the U.S.[16] Additional sulfur tends to degrade the performance of catalytic converters. As a result of all of these effects, actual emissions averaged over the life of the car may be five times the emissions measured in the laboratory. Therefore a vehicle may be "certified" to meet various standards such as the California ultra-low emission vehicle (ULEV) standard, while those same vehicles driven in the real world exceed those standards by a large factor. Hence the emissions reported here are larger than those found in some of the literature. All vehicles have been treated the same, however, so the relative emissions levels should be comparable to other evaluations.

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[14]VOC's include a wide variety of hydrocarbons. Related terms for these HC emissions are non-methane hydrocarbons (NMHC), non-methane organic gases (NMOG), etc. We use the term VOC here, with the assumption that methane is excluded, since methane does not readily form ozone in the atmosphere.

[15]The FTP utilizes the rather anemic federal urban driving schedule, split into three "bags" or segments to catch the affects of cold start versus warm vehicle emissions.

[16]California has imposed stricter sulfur standards: 50 ppm average and 80 ppm maximum sulfur content.

Volatile Organic Compound Emissions

The estimated "real world" VOC emissions are summarized on a logarithmic scale in Figure 9 for the nine primary vehicles. The horizontal lines correspond to various emissions standards: the federal "Tier II" standard which begins in 2004, the California ULEV standard which started in 1994, the newly proposed California SULEV standard, and the old proposed (but now abandoned) equivalent zero emission vehicle (EZEV) standard. As in previous figures, two bars are shown for the liquid-fueled FCVs corresponding to the probable (higher emissions) and best cases, and three bars are shown for each hybrid fuel, corresponding to thermostat series hybrids (highest emissions), load-following series hybrids, and parallel hybrids (lowest emissions).

Although some NGVs have been certified as ULEVs, this analysis of real world emissions indicates that only hythane NGVs[17], direct hydrogen and methanol FCVs and hydrogen hybrids could meet the ULEV standard for VOCs. And only direct hydrogen FCVs and hydrogen hybrids would qualify for the SULEV VOC standard. The high gasoline-FCV VOCs are due primarily to evaporative emissions.[18] The small VOC emissions from the direct hydrogen FCV and the hydrogen hybrid are due primarily to emissions from the local steam methane reformer plant. While these are not strictly "tailpipe" emissions, they are released in the urban airshed, and could have the same effect on photochemical smog formation as tailpipe VOC emissions. We have not, however, included any upstream emissions from electrical generation plants, on the assumption that they would be located outside the urban airshed.

From a regulatory viewpoint, however, the direct hydrogen FCV would be the only vehicle considered here that would qualify as a zero emissions vehicle (ZEV), since it alone has no onboard tailpipe or evaporative emissions. Even if hydrogen hybrid vehicles did meet the proposed California SULEV standards, as currently written the SULEV certification could only be used to meet a maximum of 60% of each auto manufacturer's ZEV requirement. That is, beginning in 2004, each car company could supply up to 6% of its sales as SULEVs (60% of the 10% ZEV mandate), but the other 4% would still have to be true ZEVs -- battery EVs or direct hydrogen FCVs.

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[17]The hythane ICE emissions shown here are based on lean burn operation. We are projecting higher emissions for stoichiometric operation, as described in Section 3.2 of (Thomas 1998b).

[18]Strictly speaking, the Tier II, ULEV and other standards are tailpipe emission standards. Evaporative emissions are covered by other testing requirements. However, we have included both tailpipe and evaporative VOC emissions here, since both contribute to photochemical ozone formation.

Carbon Monoxide Emissions

The corresponding CO emissions for these vehicles are shown in Figure 10. The federal Tier II and California ULEV levels are identical for CO (and for NOx). In this case all vehicles except the gasoline and natural gas ICEVs would meet the proposed SULEV standard for CO. By raising the CO standard compared to EZEV, the SULEV standard would allow both natural gas and diesel hybrids to qualify although, again, the certified emissions of these hybrids would likely have qualified under the more strict EZEV proposal, since the certified emissions are consistently lower than the real world emissions estimated in this report.

Nitrogen Oxide Emissions

NOx emissions are summarized in Figure 11. In this case the proposed SULEV standard is identical to the previous EZEV proposal. According to our analysis of real world NOx emissions, only the fuel cell vehicles would qualify. We estimate very high NOx emissions for the hybrid vehicles, based primarily on the nonlinear relationship between NOx and engine power level. Both VOCs and CO increase nearly linearly with engine output power. In this case it makes no difference if the engine supplies the necessary power in one high power surge (to charge batteries, for example) or whether the engine cycles over a range of power levels as in conventional ICEVs. NOx, emissions, on the other hand, depend strongly on ICE power level. Below a threshold power level, very little NOx is produced. Above this threshold, however, NOx emissions grow rapidly. In a hybrid mode, when the ICE is consistently operated at moderate to high power, NOx emissions are high. When the wheel load demand is low and NOx emissions would be negligible for a conventional car, the ICE is usually shut off in the hybrid mode. As a result, we are projecting increased NOx emissions for hybrid operation for both natural gas and diesel fuel. In essence, the nonlinear increase in NOx at higher average engine power is not offset by the higher fuel economy due to hybrid operation.[19]

Particulate Matter Emissions

Only the diesel hybrid vehicles would emit substantial particulate matter. The proposed SULEV standard is 0.01 g/mile. We are projecting in the range from 0.023 g/mile for the diesel parallel hybrid up to 0.032 g/mile of PM-10 for the thermostat mode series hybrid diesel vehicle, or two to three times the proposed standard. The EPA has also issued new regulations on particles smaller than 2.5 microns (PM-2.5), on the assumption that the smaller particles cause the most damage to human lungs. This new ruling could further jeopardize the introduction of diesel hybrids. Over 90% of diesel particulates have been measured at less than one micron in diameter (Walsh 1997).

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[19]Jay Keller at Sandia National Laboratories (Livermore) estimates that NOx emissions can be reduced dramatically with the development and use of homogeneous charge, compression ignition engines. This development, if implemented in future parallel hybrid vehicles, would improve the emissions from diesel cycle engines, leaving only particulates to contend with.

Vehicle Cost Estimates

Clean vehicles will not reduce pollution if they are too costly for the consumer, as the makers of battery-powered electric vehicles are discovering. We have estimated the mass production cost of each of the alternatively fueled vehicles. We have used a combination of DTI mass production cost estimates for fuel cells, onboard processors, and compressed hydrogen storage tanks prepared under contract to the Ford Motor Company and the Department of Energy, along with DOE cost goals and other cost projections for electric vehicle components such as motors, controllers and batteries. In all cases we assume large automotive quantity production on the order of 300,000 vehicles.

The cost and power requirements for a direct hydrogen and a methanol FCV are summarized in Table 8 for a best case and a probable case methanol FCV. We estimate that the methanol FCV would most likely cost almost $900 more in mass production than the direct hydrogen FCV, but it could cost only $177 more in the best case analyzed here. We estimate that the gasoline FCV would cost between $900 (best case) and $3,000 more than a direct hydrogen FCV, as shown in Table 9. (See Appendix C of Thomas (1998b) for cost details of the other vehicles.)

Table 8. Power and Mass Production Cost Estimates for Methanol Fuel Cell Vehicles

		Direct Hydrogen FCV	Methanol FCV		Cost Differential	
			Best Case	Probable	Best Case	Probable
Vehicle Test Weight	kg	1,291	1,390	1,413		
Fuel Cell System	Power (kW)	38.1	44.4	45.9		
	Cost ($)	$1,911	$2,143	$2,370	$232	$459
Peak Power Battery ($15.7/kW + $100)	Power (kW)	40.3	43.2	43.9		
	Cost ($)	$728	$774	$785	$46	$57
Motor/Inverter/ Controller	Power (kW)	82	88.3	89.8		
	Cost ($)	$906	$945	$954	$39	$48
Fuel Tank		$760	$176	$176	($584)	($584)
Methanol Processor ($10/kW to $20/kW)	Power (kW)		44.4	45.9		
	Cost ($)		$444	$917	$444	$917
Gear Box		$200	$200	$200		
Controller & Misc.		$150	$150	$150	$0	$0
Total Drivetrain Costs		$4,655	$4,832	$5,552	$177	$897
Vehicle Cost		$20,179	$20,356	$21,076		

The increased mass production costs for all the alternative vehicles compared to a conventional gasoline ICEV are shown in Figure 12. The baseline AIV Sable price is assumed to be $18,000. The costs in Figure 12 represent the difference between the alternative fueled vehicle power train and the ICE powertrain it replaces. We currently estimate that the direct hydrogen FCV would cost about $2,200 more than a conventional car. Additional FCV cost savings are possible, but cannot be demonstrated at this time.

Table 9. Power and Mass Production Cost Estimates for Gasoline Fuel Cell Vehicles

		Direct Hydrogen FCV	Gasoline FCV		Cost Differential	
			Best Case	Probable	Best Case	Probable
Vehicle Test Weight	kg	1,291	1,387	1,475		
Fuel Cell System	Power (kW)	38.1	48.8	57.6		
	Cost ($)	$1,911	$2,371	$2,991	$460	$1,080
Peak Power Battery ($7.8/kg + $100)	Power (kW)	40.3	43.1	45.7		
	Cost ($)	$728	$772	$813	$44	$85
Motor/Inverter/ Controller ($12.7/kW)	Power (kW)	82	88.1	93.7		
	Cost ($)	$906	$945	$979	$39	$73
Fuel Tank ($133/kg)		$760	$176	$176	($584)	($584)
POX Processor ($20/kW to $40/kW)	Power (kW)		48.8	57.6		
	Cost ($)		$976	$2,305	$976	$2,305
Transmission		$200	$200	$200		
Controller & Misc.		$150	$150	$150	$0	$0
Power Train Costs		$4,655	$5,590	$7,614	$935	$2,959
Total Vehicle Costs		$20,179	$21,114	$23,138		

The hybrid vehicles fare surprisingly well in this analysis, considering that these hybrids have two separate power trains -- an ICE and an electric traction motor plus battery bank. While the hybrids have more drive train components, they are generally lower power and hence lower cost than the large ICE in a conventional vehicle. The thermostat series hybrids could cost $2,300 to $3,200 more than an ICEV. But the parallel hybrids could cost less than $1,370 more, with the natural gas parallel hybrid estimated at only $770 more -- the lowest cost HEV option and second only to the conventional NGV at an estimated $360 more than a gasoline vehicle in mass production. The cost accounting for the natural gas parallel hybrid and the direct hydrogen fuel cell vehicle is reconciled with the conventional ICEV in Table 10, to illustrate the cost differences between conventional, hybrid and fuel cell vehicles.

Table 10. Drivetrain Power and Mass Production Cost Comparison: Conventional Internal Combustion Engine Vehicle vs. Natural Gas Parallel Hybrid and Fuel Cell Vehicles

	Conventional ICEV		Natural Gas Parallel Hybrid		Direct Hydrogen Fuel Cell Vehicle	
	Power (kW)	Cost ($)	Power (kW)	Cost ($)	Power (kW)	Cost ($)
Fuel Cell System					38.1	1911
ICE & Ancillaries	100	1600	32.9	889		
Transmission[20]		700		700		200
Fuel Tank System		176	72.6 liters	334	4.71 kg	760
Motor/Controller		0	34.8	533	82	906
Battery System		0	34.8	642	40.3	728
Controller		0		150		150
Drivetrain Total Costs		2476		3,248		4,655
Additional Cost				772		2,179

For early market penetration, the initial vehicle costs for very low production volumes may also be important. GM, for example, has introduced its EV1 electric vehicle with production runs of a few hundred vehicles. As shown in Figure 13, the natural gas and hythane vehicles would have significant cost advantage over the other alternatives for such early market entry. The parallel hybrid vehicles might also have a significant cost advantage over fuel cell vehicles in low production volumes. The liquid-fueled FCVs would suffer a significant disadvantage over direct hydrogen FCVs in terms of initial vehicle cost. From a transportation system perspective, this increased cost for onboard liquid fuel reformers might equal or exceed the cost of providing stationary hydrogen fueling appliances for the direct hydrogen fuel cell vehicles.

Oil Import Reductions

Most of the vehicles considered here either use natural gas or derive their fuel from natural gas (hydrogen and methanol.) These vehicles will eliminate almost all demand for crude oil, except for lubrication, products derived from crude oil, and crude oil fuel used in vehicle manufacture or transportation of components. The diesel hybrid and gasoline-powered fuel cell vehicle are the only

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[20] Conventional and parallel hybrid vehicles have 4-speed automatic transmissions; fuel cell vehicles and series hybrids have single speed gear boxes.

two that would use fuel derived from crude oil.

Each ICEV requires about 7.8 barrels of crude oil each year to supply gasoline to travel 12,000 miles at 30 mpg fuel economy. This assumes that one barrel of crude oil supplies about 1.22 barrels of gasoline, due to its lower density -- mass is conserved in the refinery, not volume. The gasoline-powered FCV would achieve from 29.1 (probable) to 42.1 mpg (best case), so the likely outcome would be no reduction in oil imports. For the best case gasoline FCV, oil consumption would be reduced from 7.8 barrels per year per vehicle to 5.6 barrels -- a 28% reduction at best.

The diesel hybrid would benefit due to diesel fuel's 11.7% higher energy content relative to gasoline and higher onboard fuel economy, but this is offset slightly by its higher density. Each barrel of crude oil produces about 1.09 barrels of diesel. For the diesel parallel hybrid at 57.6 mpg-equivalent fuel economy, the actual diesel consumption would be 64.3 miles per gallon of diesel fuel, and the crude oil consumption would be 4.1 barrels per year -- a 47% reduction compared to the conventional ICEV. Therefore the diesel parallel hybrid has almost twice the oil import reduction potential than even the best case gasoline FCV.

Conclusions

We conclude from this detailed analysis of alternative vehicles that there is no clear winner. The choice of optimum vehicle from a societal viewpoint depends on the weighting factors given to our three main objectives: reduced local air pollution, reduced greenhouse gases and reduced oil imports. To help assess and compare the relative merits of each vehicle, we have assigned a dollar cost to each vehicle pollutant, based on the lowest avoided cost reported in the literature for each pollutant, as summarized in Table 11.

Table 11. Annual Pollution Avoided Costs (U.S. $)

	(Tellus 1990)	Massachusetts (Edison Electric Institute 1994)	Nevada	New York (Mark 1996)	Used Here:
VOC	5,300	6,140	6,190	17,300	**5,300**
CO	870	1,010	1,040	2,100	**870**
NOx	6,500	7,540	7,650	14,400	**6,500**
PM-10	4,000	--	--	--	**4,000**
CO_2	22	26	25		**22**

Conclusions Based on Local Air Pollution

Using these cost estimates, we then plotted the incremental vehicle cost vs. the resulting total pollution cost for the local criteria pollutants in Figure 14. The ideal vehicle would be plotted in the lower left hand corner -- no increase in vehicle cost and zero pollution cost. The gasoline ICEV is plotted on the x-axis (no increased vehicle cost by definition) at $200/year annual pollutant cost.

Based solely on local air pollution, we arrive at these conclusions:

1. Hydrogen is the superior "clean fuel," providing the only true zero emission vehicle (zero tailpipe and zero evaporative emissions) with the full range capabilities of conventional vehicles.

2. The direct hydrogen FCV produces the least local air pollution (with the methanol FCV and the hydrogen hybrids as close seconds).

3. From a cost-effective viewpoint, however, a conventional natural gas vehicle provides a 65% reduction in estimated real-world ICEV emissions with a modest increase in vehicle cost.

4. Adding hydrogen to natural gas (hythane) is cost effective for reducing local emissions, substantially reducing criteria emissions with a small increment in cost.

5. The diesel hybrids are not cost effective from the local air quality viewpoint.

Conclusions Based on Greenhouse Gas Emissions

Next we generated a plot of incremental vehicle cost vs. greenhouse gas emissions instead of local criteria pollutants, as shown in Figure 15. The ideal vehicle would be located in the lower left-hand corner of Figure 15 -- low cost and low greenhouse gas emissions. The internal combustion engine vehicle (ICEV) is plotted on the x-axis (no cost increase) at 415 g/mile. The alternative vehicles all reduce greenhouse gases to some degree, but with increased vehicle cost. Natural gas parallel hybrid vehicles offer the greatest potential for reducing greenhouse gas emissions at low incremental production cost, followed by diesel parallel hybrids and direct hydrogen fuel cell vehicles (FCVs).

Based solely on the criterion of reducing greenhouse gas emissions, we conclude the following:

1. Natural gas is the preferred fuel, providing the lowest cost alternative vehicles in either conventional or hybrid mode.

2. The natural gas parallel hybrid vehicle provides the best combination of low additional vehicle cost and the lowest projected greenhouse gas emissions. Series hybrids are not as effective in all cases, adding cost and increasing greenhouse gas emissions relative to parallel hybrids.

3. Adding hydrogen to natural gas (hythane) is ***not*** an effective strategy for greenhouse gas reduction, since it adds cost and also increases greenhouse gases compared to neat natural gas.

4. Similarly, hydrogen hybrid vehicles are ***not*** an effective choice, since natural gas hybrids provide much lower greenhouse gas emissions at lower vehicle cost.

5. The direct hydrogen fuel cell vehicle (FCV) provides substantial greenhouse gas emission savings if the hydrogen is produced from natural gas, but is not as effective as either the natural gas or diesel parallel hybrid vehicles, both of which are projected to cost less and emit lower greenhouse gases.

6. Both methanol- and gasoline-powered FCVs are even less attractive, costing more and reducing greenhouse gases less than the direct hydrogen FCV. The most probable gasoline-FCV case would cost over $5,000 more than a conventional car and provide negligible greenhouse gas reductions compared to conventional gasoline ICEVs. The methanol FCV would most likely provide greater GHG reductions than the gasoline FCV at lower incremental cost.

7. Electrolysis of water to produce hydrogen is ***not*** a viable option from a greenhouse gas perspective, since the projected year 2000^+ utility generator mix in the U.S. would more than double greenhouse gases (to 936 g/mile -- not shown in Figure 15 -- far off scale to the right) relative to conventional ICEVs, even when used in a direct hydrogen fuel cell vehicle.[21]

Conclusions Based on Local and Greenhouse Gas Emissions

The cost of greenhouse gas emissions is even harder to quantify, but some analysts have estimated a cost of $24/tonne of CO_2 (compared to much higher costs for VOCs - $5,840/tonne, CO - $960/tonne, NOx - $7,150/tonne, and PM-10 - $4,410/tonne.) The combined costs of GHGs and local emissions are plotted in Figure 16. The direct hydrogen fuel cell vehicle has the lowest total emission and GHG cost with these parameters. But natural gas and hydrogen parallel hybrids and hythane ICEVs have only moderately higher environmental costs at somewhat lower incremental vehicle costs.

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[21]Hydrogen produced by electrolysis using intermittent renewable energy sources such as photovoltaics and wind would generate zero emissions and zero greenhouse gases in operation. However, until intermittent renewables achieve greater than 15% to 20% utility grid penetration, greenhouse gases would be reduced 1.8 times more by displacing grid electricity than by electrolyzing water to provide hydrogen for use in FCVs. When renewables supply 15% to 20% of the utility energy, then the grid could not absorb more renewable energy, and making hydrogen would be effective in reducing GHGs further. Since even the most optimistic renewable energy projections do not show renewables at 15% before 2020 to 2030, substantial use of renewable electrolytic hydrogen in the industrialized nations is probably two to three decades away.

Conclusions Based on Oil Import Costs

The societal costs of protecting our access to imported oil are even more subjective. However, all of the most promising fuel/vehicle combinations from the environmental viewpoint (Figure 16) derive their fuel from natural gas -- either natural gas itself or methanol or hydrogen derived from natural gas. Hence all of the front-runners from an environmental viewpoint would eliminate virtually all vehicle dependence on imported oil. Adding an oil import cost would merely shift the gasoline-FCV, ICEV and diesel hybrids to the right in Figure 16, farther out of contention, leaving the other vehicles unchanged.

For the two vehicles that rely on crude oil, the diesel parallel hybrid would cut crude oil consumption by 59%, while the gasoline-powered FCV would at best reduce oil consumption by 40%, and, in the probable case, would not reduce oil consumption at all.

Final Alternative Vehicle Conclusions

The key societal attributes of the major alternative vehicles[22] are summarized in Table 12. Each vehicle/fuel choice has at least one shaded box corresponding to an undesirable trait. There is no clear winner.

Both of the alternative vehicles that could utilize the existing gasoline or diesel fuel infrastructure have major hurdles to overcome:

The gasoline-powered FCV faces three major hurdles: the highest estimated vehicle incremental cost ($3,110 to $5,135) in mass production, the highest greenhouse gas emissions in the probable case (with the exception of electrolytic hydrogen in a FCV), and the likelihood of little or no reduction in oil imports. However, successful development of the gasoline-FCV could pave the way for FCVs with more environmentally friendly domestic fuels in the future. Hence development of the gasoline-FCV does have long term merit, if the cost and performance obstacles can be overcome so that market penetration could begin earlier than the other FCV options.

The diesel parallel hybrid has lower hurdles compared to the gasoline-FCV: lower but still substantial cost differential, one of the best greenhouse gas potentials (similar to the natural gas hybrid), and the diesel parallel hybrid would reduce oil imports by half. However, local emissions from the diesel hybrid could be a show-stopper, particularly if the new EPA regulations on smaller

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[22] In addition to the nine vehicles reported here, we also evaluated two variations on the fuel cell vehicle: a fuel cell range extender (see Section 2.4 of Thomas 1998b) and a FCV with a regenerative fuel cell that could be used at night as an electrolyzer to refill the hydrogen tanks (see Section 2.5 of Thomas 1998b).

particulates (below 2.5 microns) go into full force in five years as planned.

Of those vehicle that require new fuel infrastructure, the natural gas parallel hybrid has the best short-term attributes: lowest greenhouse gas emissions, lowest incremental cost, and moderately low local emissions of criteria pollutants. On the negative side, the natural gas hybrid does not provide a pathway to a sustainable energy transportation option. Natural gas itself is not readily manufactured from biomass or other renewable resources (although it can be generated by anaerobic digestion of municipal solid waste or collected from landfills), and development of the hybrid vehicle could preclude or delay mass market development of the fuel cell system that has higher fuel economy and potentially lower life cycle costs than the ICE hybrid.

The methanol-powered fuel cell vehicle does provide a sustainable energy pathway: methanol itself can be readily manufactured from biomass or municipal solid waste, and the fuel cell vehicle could be powered by renewable hydrogen in the future. But in a sense the methanol FCV could be considered the worst of both worlds: it eventually requires added fuel production capacity and a new fueling infrastructure while still having very high vehicle incremental costs and moderately high greenhouse gas emissions for the probable case.

Finally, the direct hydrogen FCV provides zero tailpipe and evaporative emissions (the only ZEV considered here), with moderately good greenhouse gas reductions and moderate vehicle cost increase of $2,176 per vehicle. Hydrogen-powered FCVs face three perceived challenges, however: onboard hydrogen storage, the need for a new hydrogen fueling infrastructure, and the general public perception of an unsafe fuel. Directed Technologies, Inc. (DTI) and the Ford Motor Company, working under contract to the U.S. Department of Energy, have previously shown the efficacy of onboard hydrogen storage using 5,000 psia carbon fiber wrapped composite tanks or liquid hydrogen tanks (James-1996), and, working with the hydrogen merchant gas suppliers, we have also laid out an economically plausible approach to provide a cost-effective, dispersed supply of hydrogen to match an evolving fuel cell vehicle market(Thomas 1997, Thomas 1998a). By producing hydrogen on-site at the dispensing station, either by water electrolysis with low cost off-peak electricity or by small scale steam methane reforming of natural gas, hydrogen could be produced and sold at a price comparable to the cost of gasoline per mile driven. This on-site hydrogen generation approach effectively utilizes the existing electrical grid and the existing natural gas pipeline system, obviating the need for installing a national hydrogen pipeline or liquid hydrogen tanker truck fleet.

Table 12. Summary Vehicle Attribute Comparison Chart

		Incremental Vehicle Cost ($)	Greenhouse Gas Emissions (g/mile)	Local Pollution Costs ($/yr)	Oil Imports (Barrels/y)	New Fuel Infrastructure Required?
Direct Hydrogen Fuel Cell Vehicle	(H_2 from NG)	2,178	245	0	0	Yes
	(H_2 by electrolysis)	2,178	939	0	0	Yes
Range Extender FCV	(H_2 from NG)	2,273	313	0	0	Yes
Gasoline Fuel Cell Vehicle	Probable	5,135	398	27	7.9	No
	Best Case	3,110	275	19	5.6	No
Methanol Fuel Cell Vehicle	Probable	3,074	311	2	0	Yes
	Best Case	2,353	278	2	0	Yes
Parallel Hybrid Vehicles	Hydrogen	1,890	322	3	0	Yes
	Natural Gas	1,292	199	42	0	Yes
	Diesel Fuel	1,606	203	140	4.1	No
NGV		363	336	65	0	Yes
Hythane ICEV		467	381	7	0	Yes
Gasoline ICEV		0	415	200	7.6	No

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Figure 1 Series Hybrid ICE Vehicle Energy Flow Diagram (Thermostat Mode)

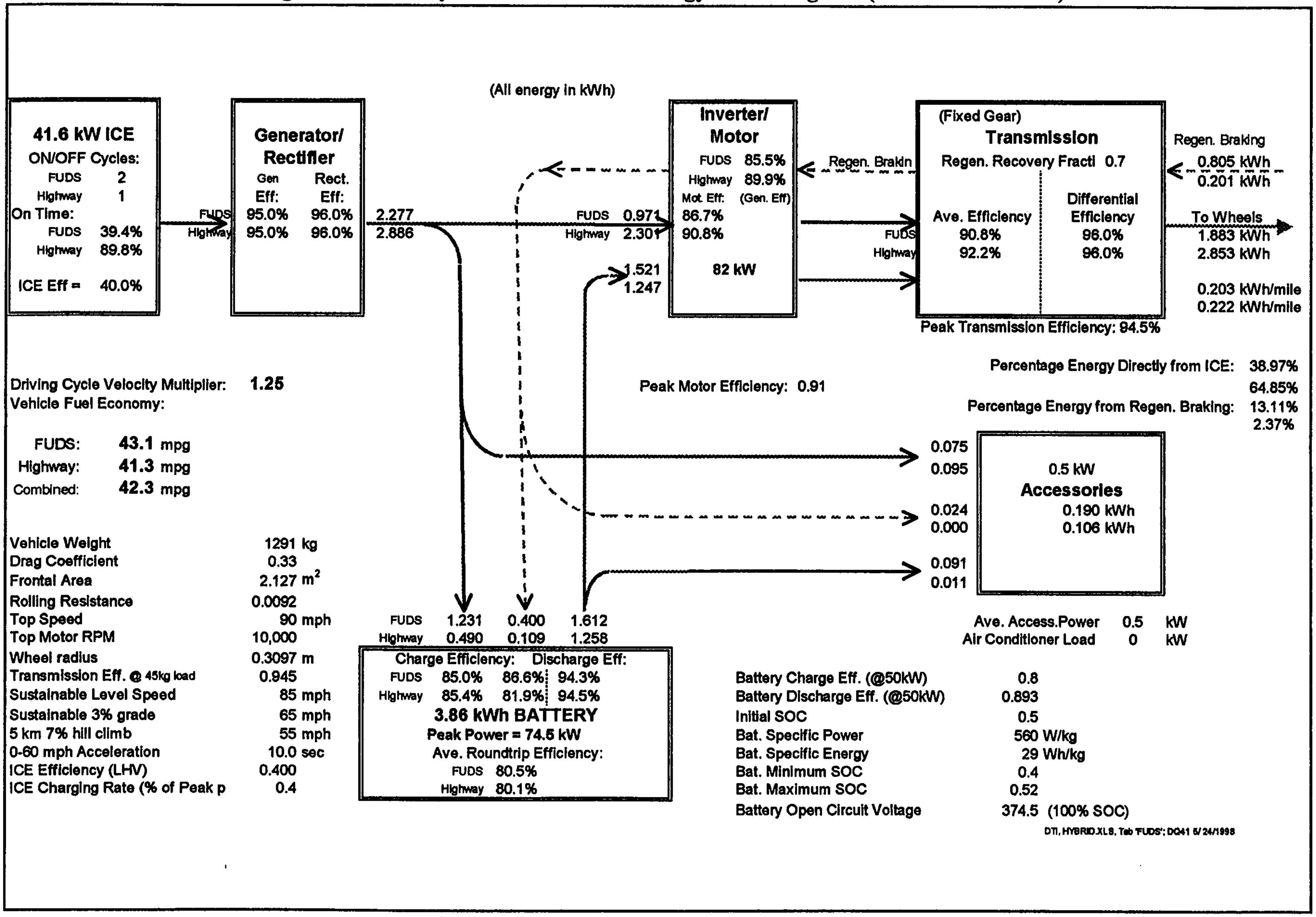


Figure 2 Series Hybrid ICE Vehicle Energy Flow Diagram (Load-Following Mode)

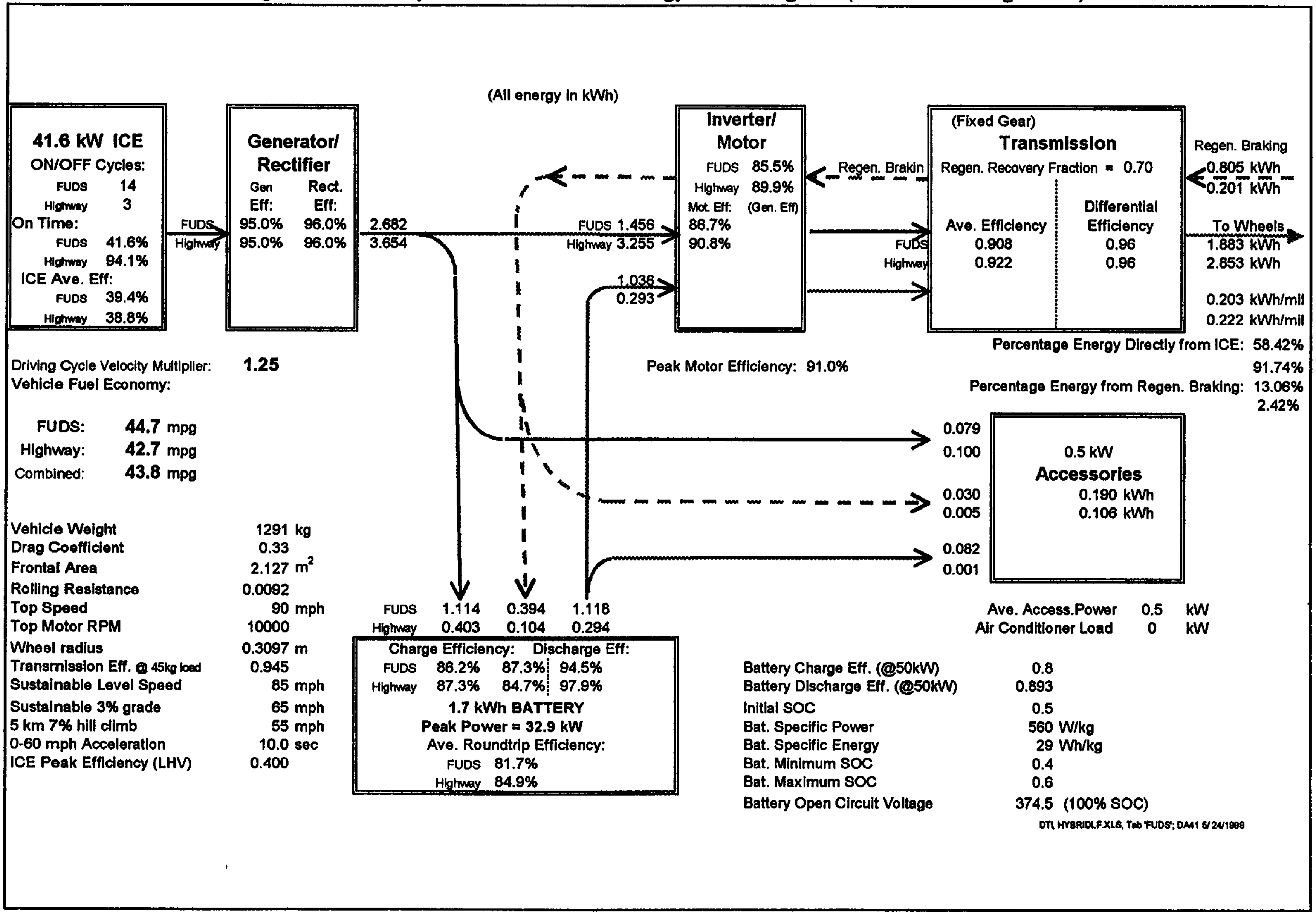


Figure 3. Parallel ICE Hybrid Vehicle Energy Flow Diagram

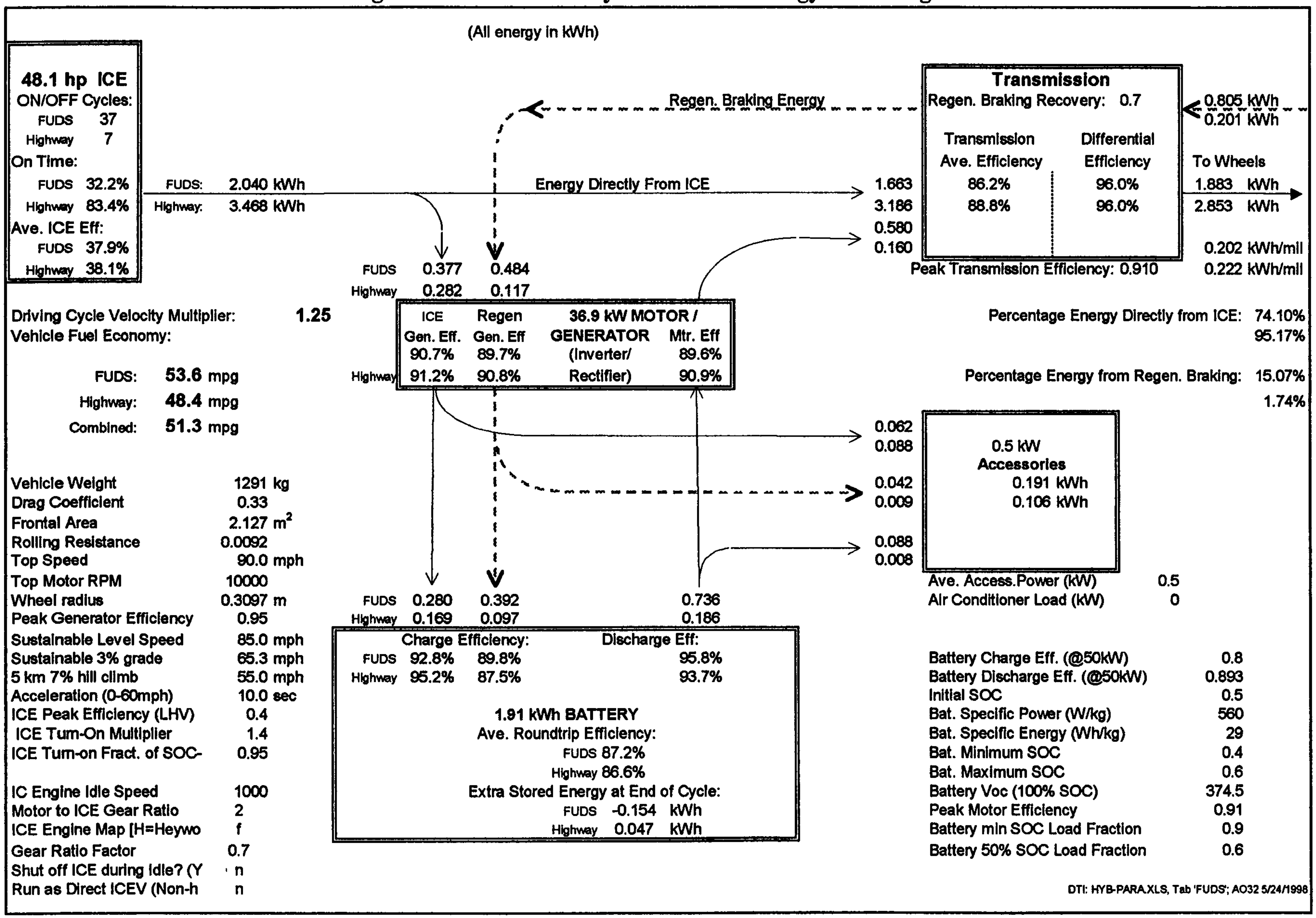


Figure 4. Estimated Fuel Economy for Conventional, Fuel Cell and Hybrid Vehicles

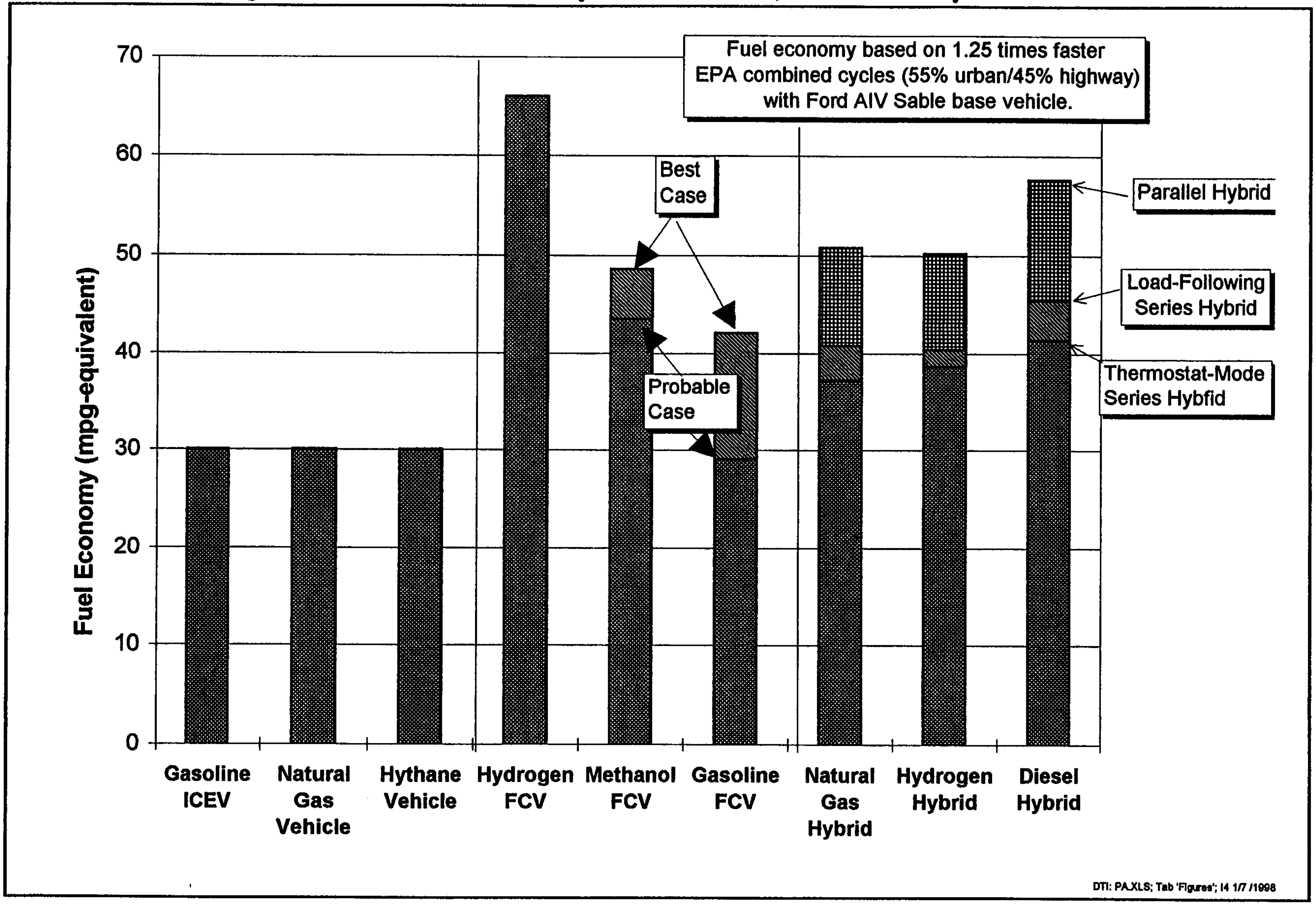


Figure 5. Comparison of NREL and DTI Fuel Economy Estimates

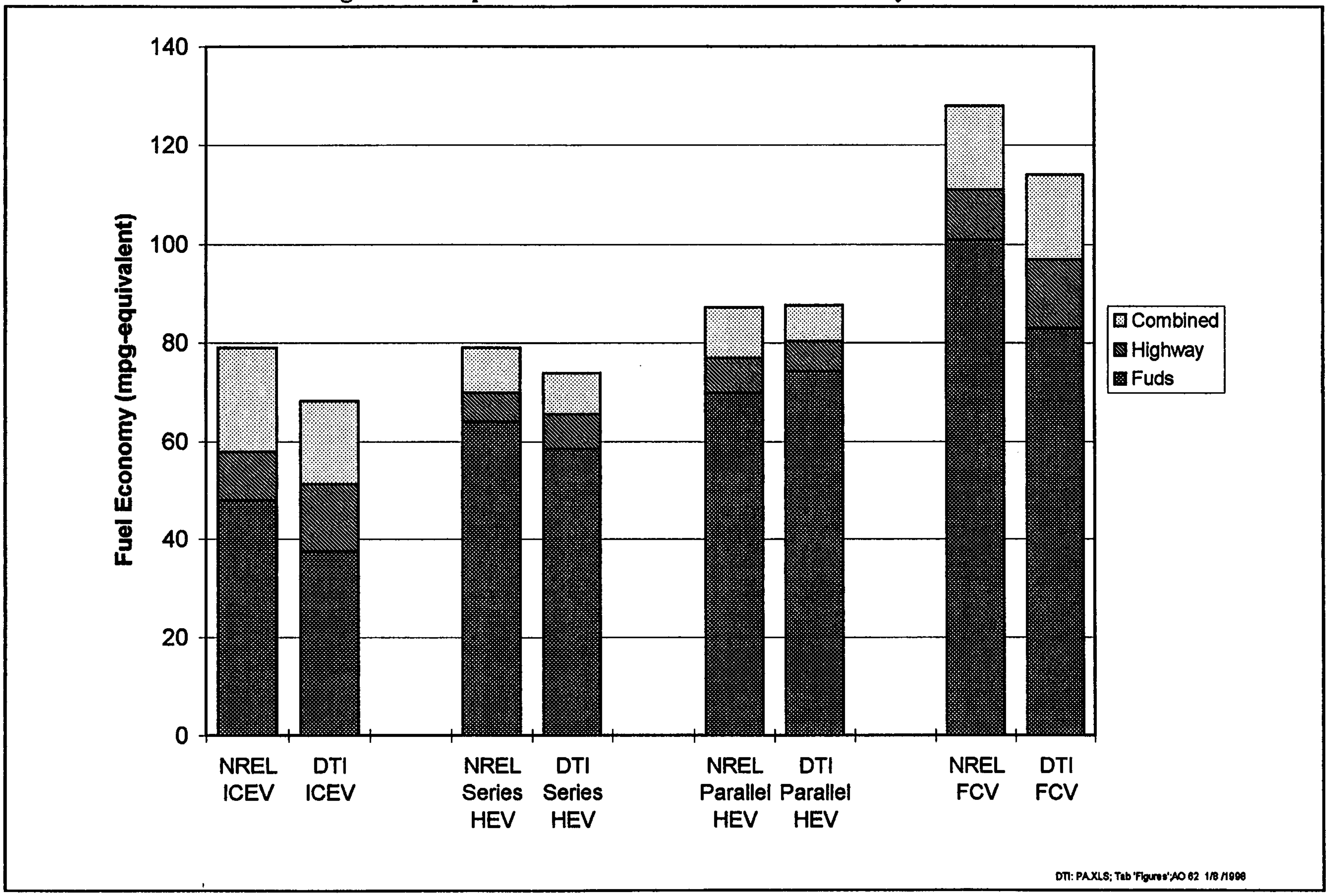


Figure 6. Fuel Economy Comparison Between LLNL and DTI ICEVs and Hybrid Vehicles

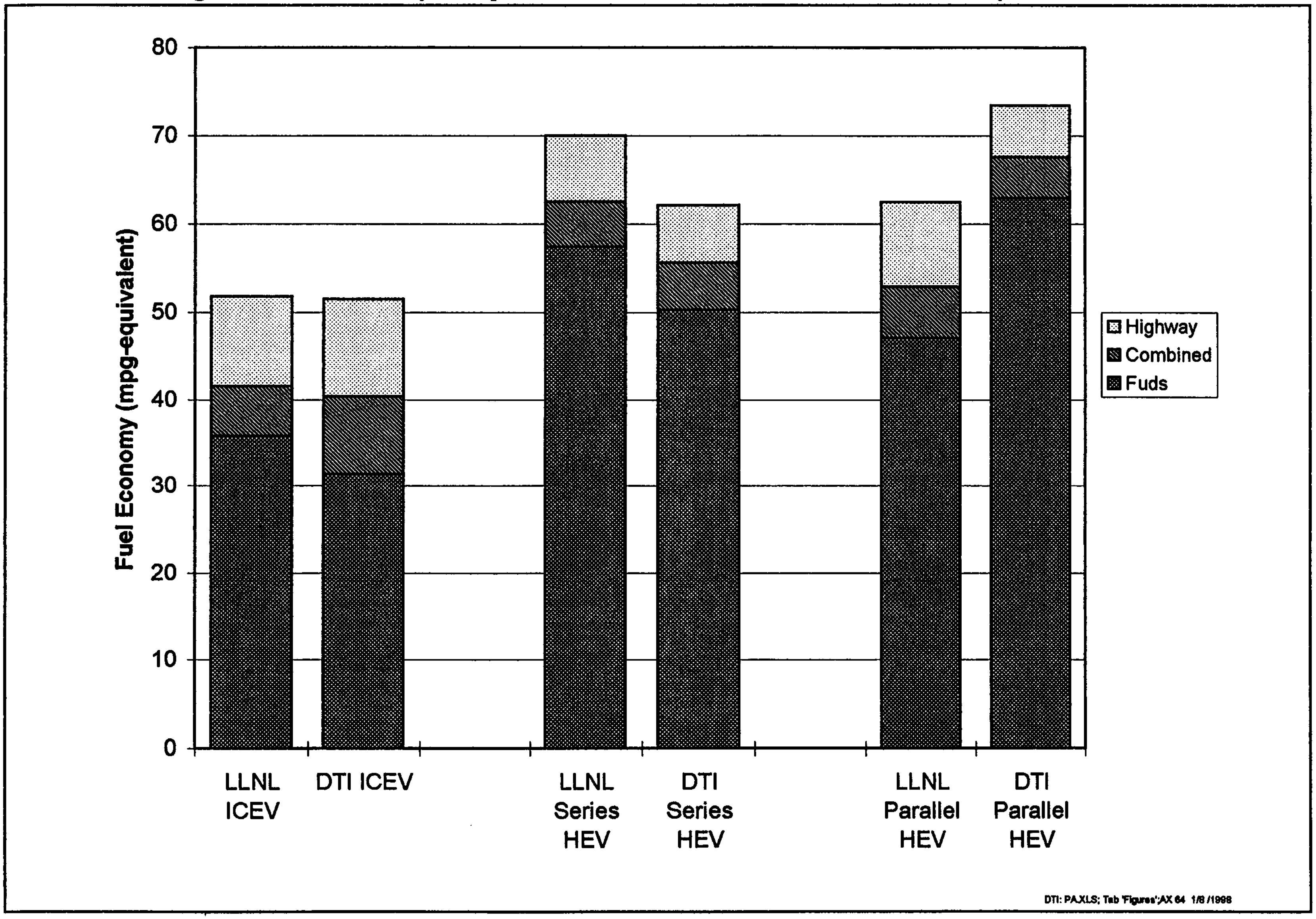


Figure 7. Vehicle Greenhouse Gas Emissions in 2000
(Hydrogen Produced by Steam Reforming of Natural Gas)

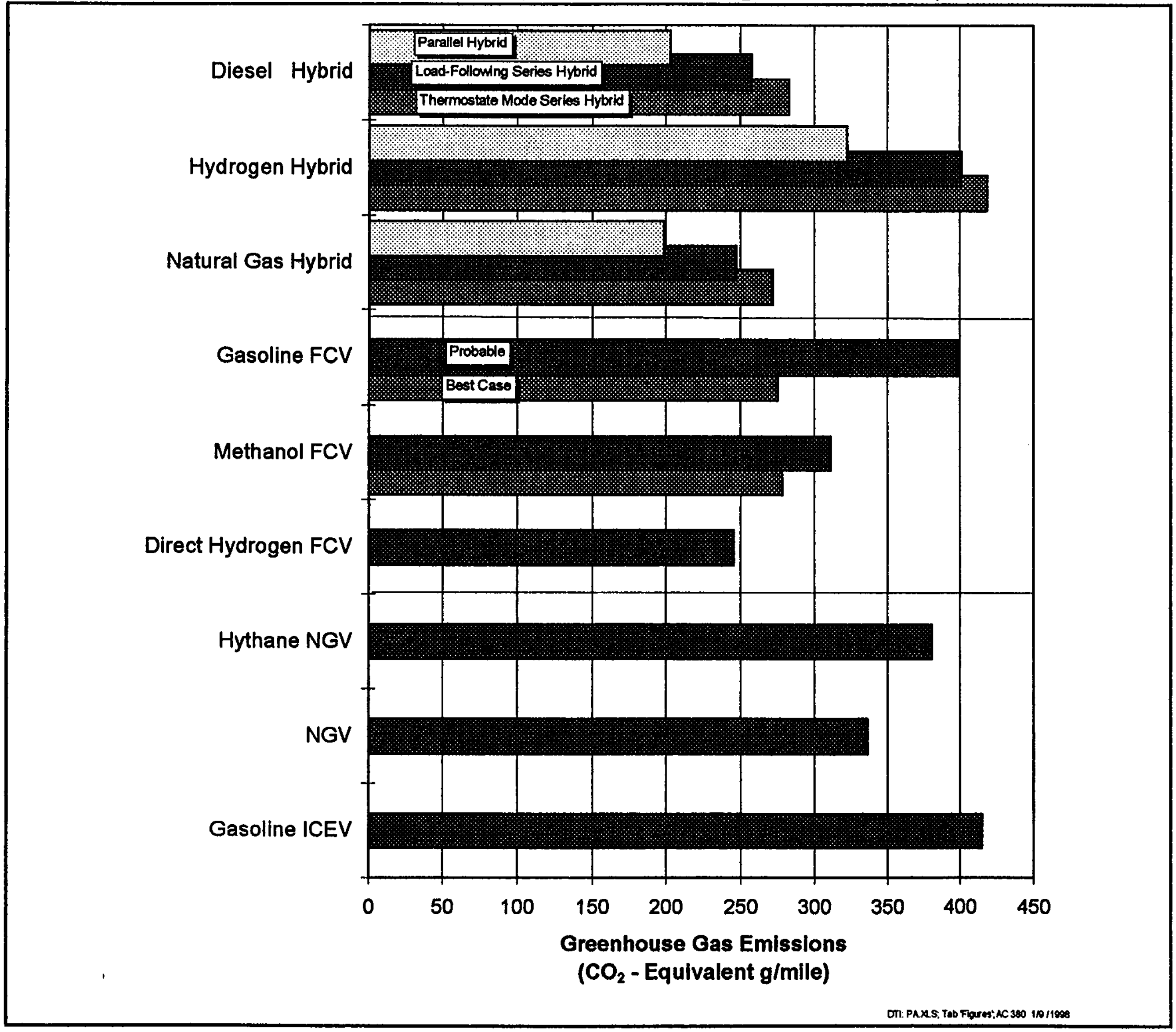


Figure 8. Vehicle Greenhouse Gas Emissions (Hydrogen Derived by Electrolysis with Grid Electricity)

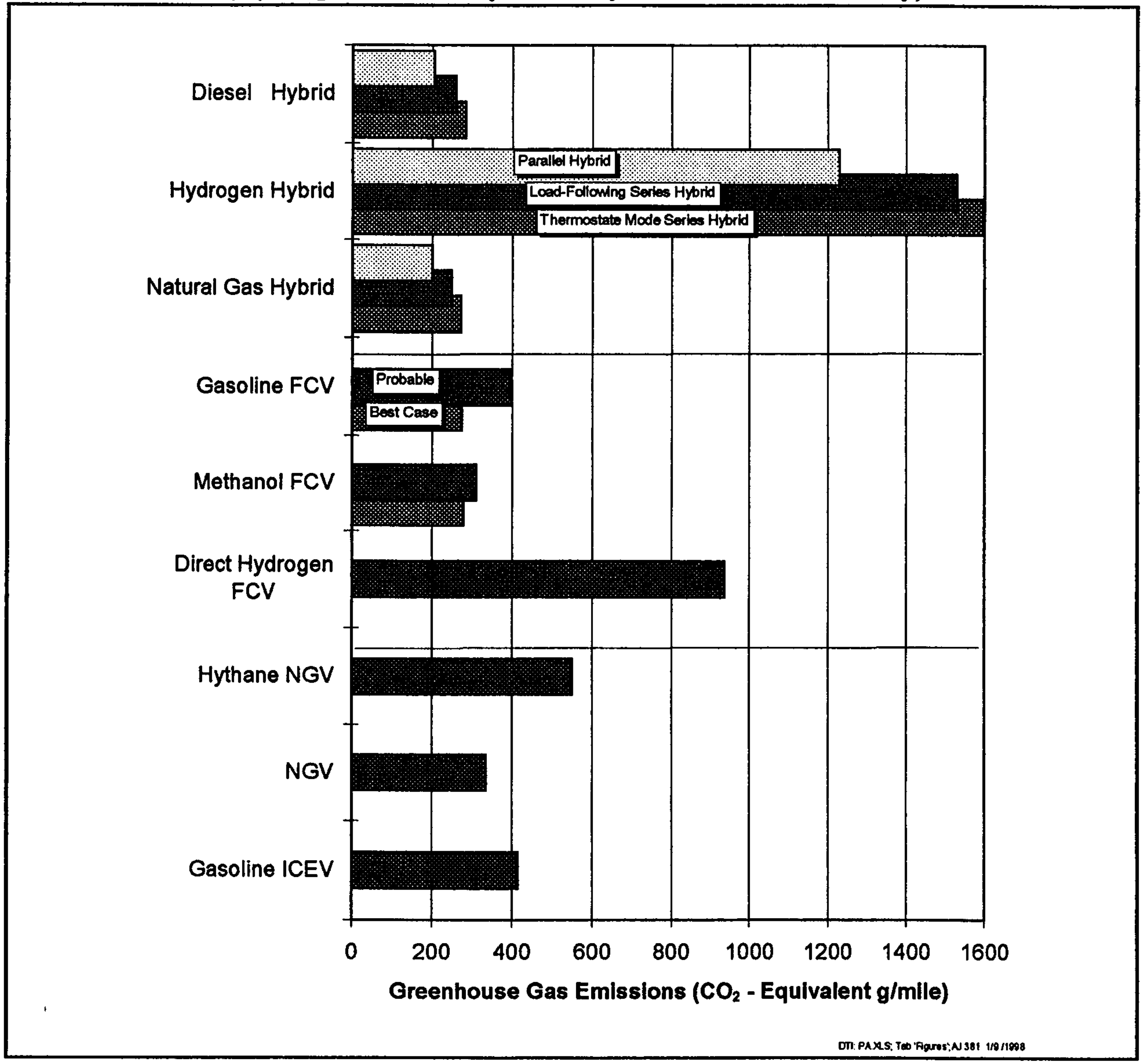


Figure 9. "Real World" Volatile Organic Compound Emissions in 2000

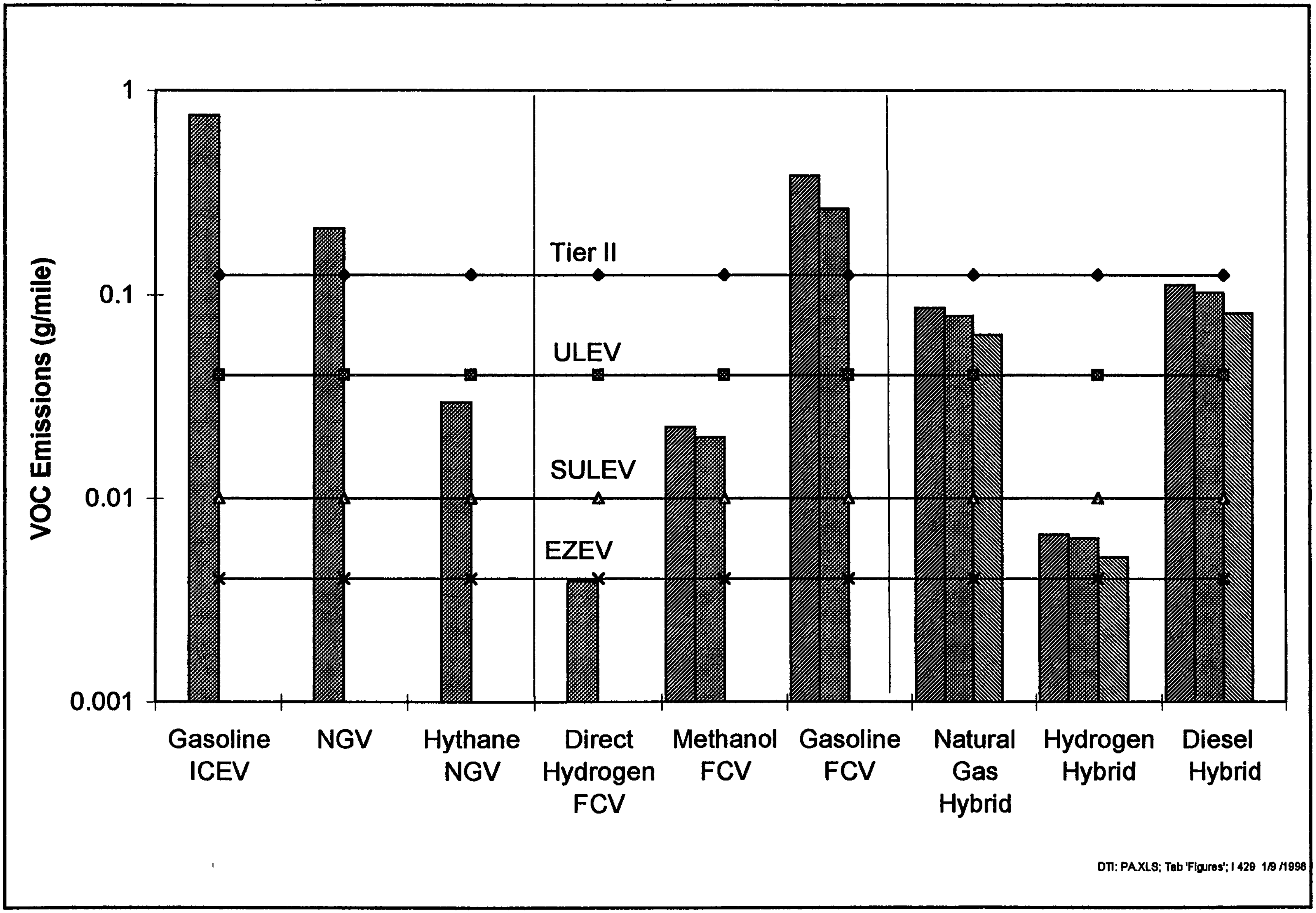


Figure 10. "Real World" Carbon Monoxide Emissions in 2000

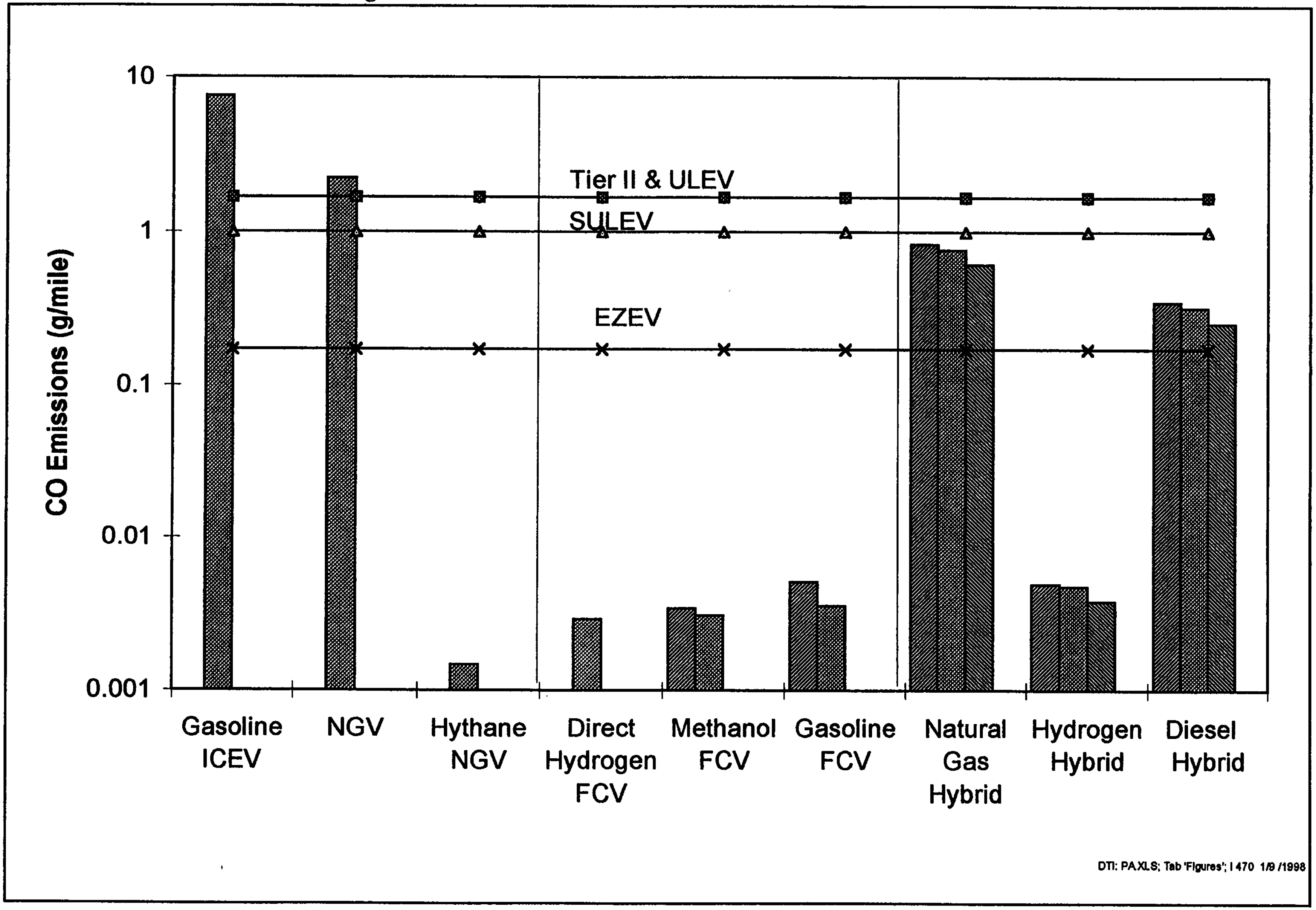


Figure 11. "Real World" Oxides of Nitrogen Emissions in 2000

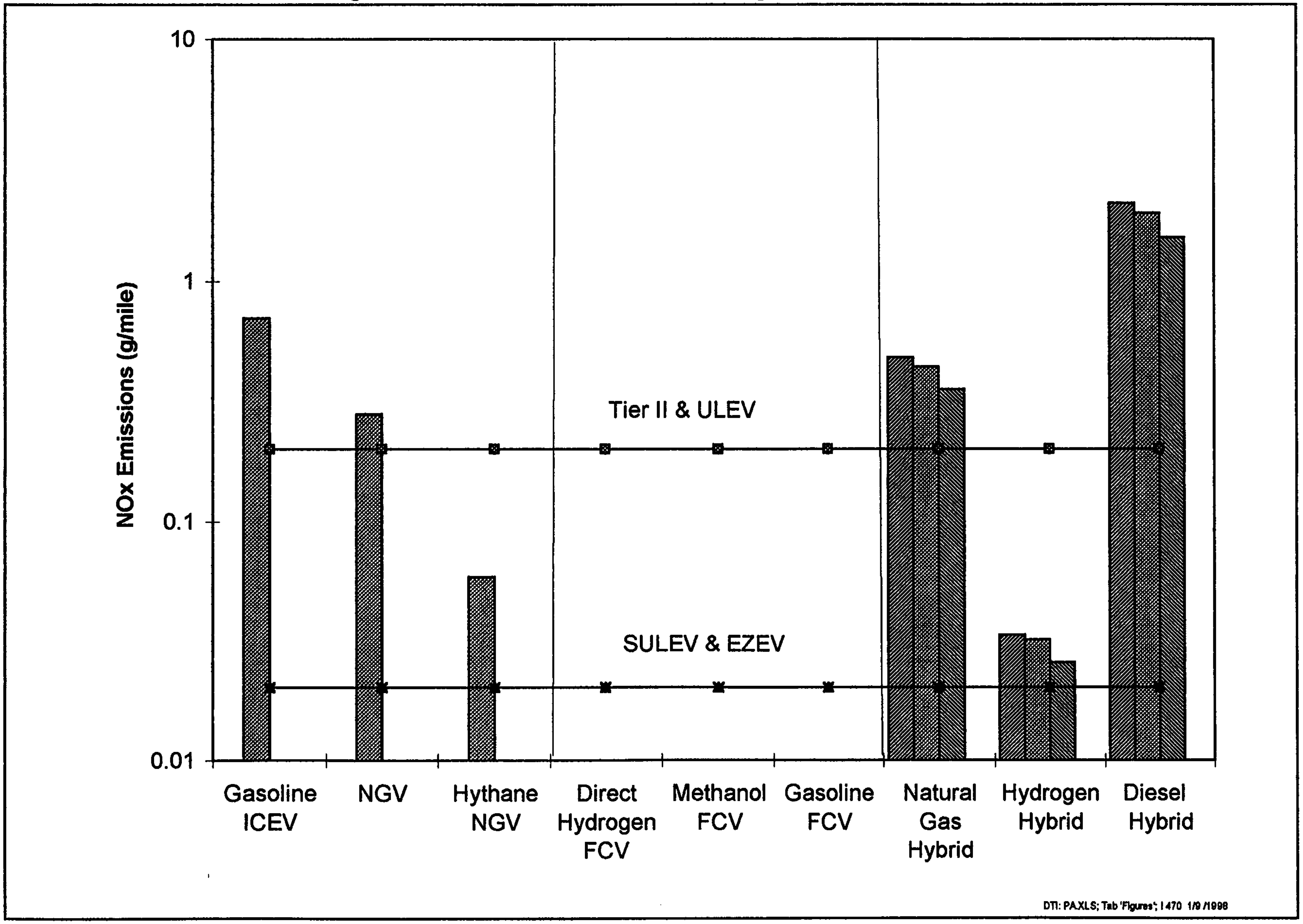


Figure 12. Incremental Mass Production Cost of Alternative Vehicles

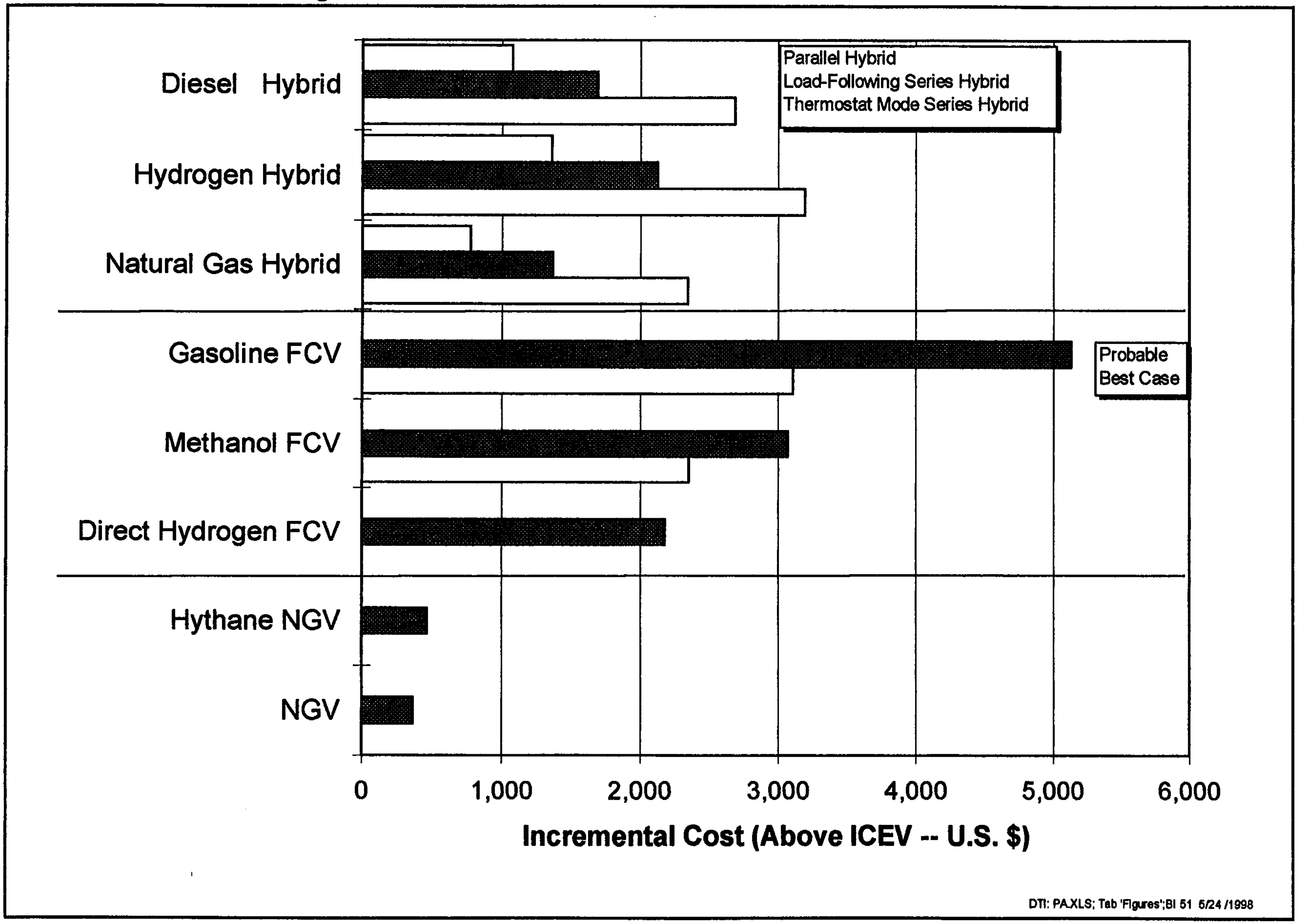
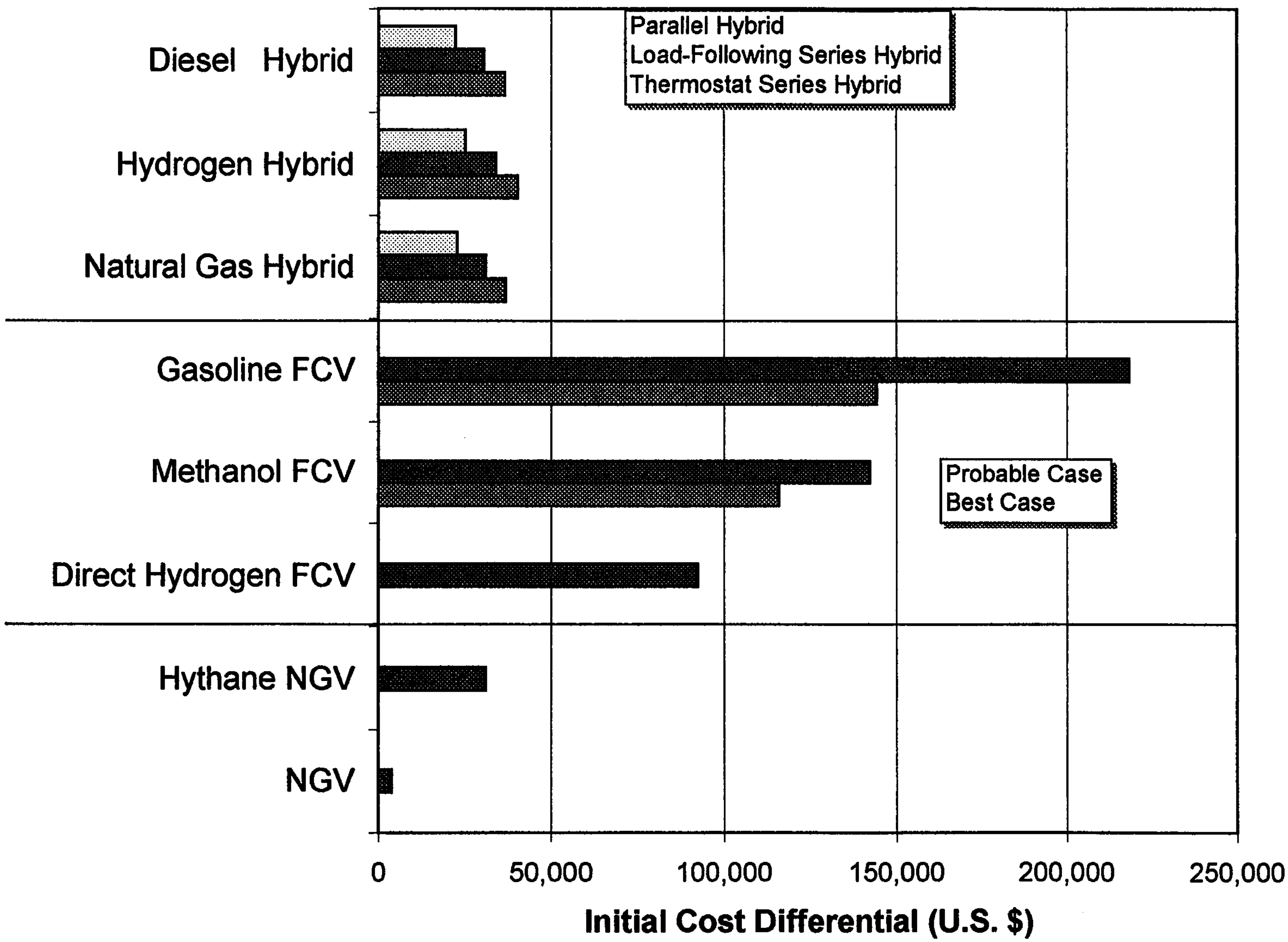


Figure 13. Initial Cost Differential Between Alternative and Conventional Vehicles



DTI: PA.XLS; Tab 'Figures';BV 55 5/24/1998

Figure 14. Incremental Mass Production Vehicle Cost vs. Annual Local Emissions Cost

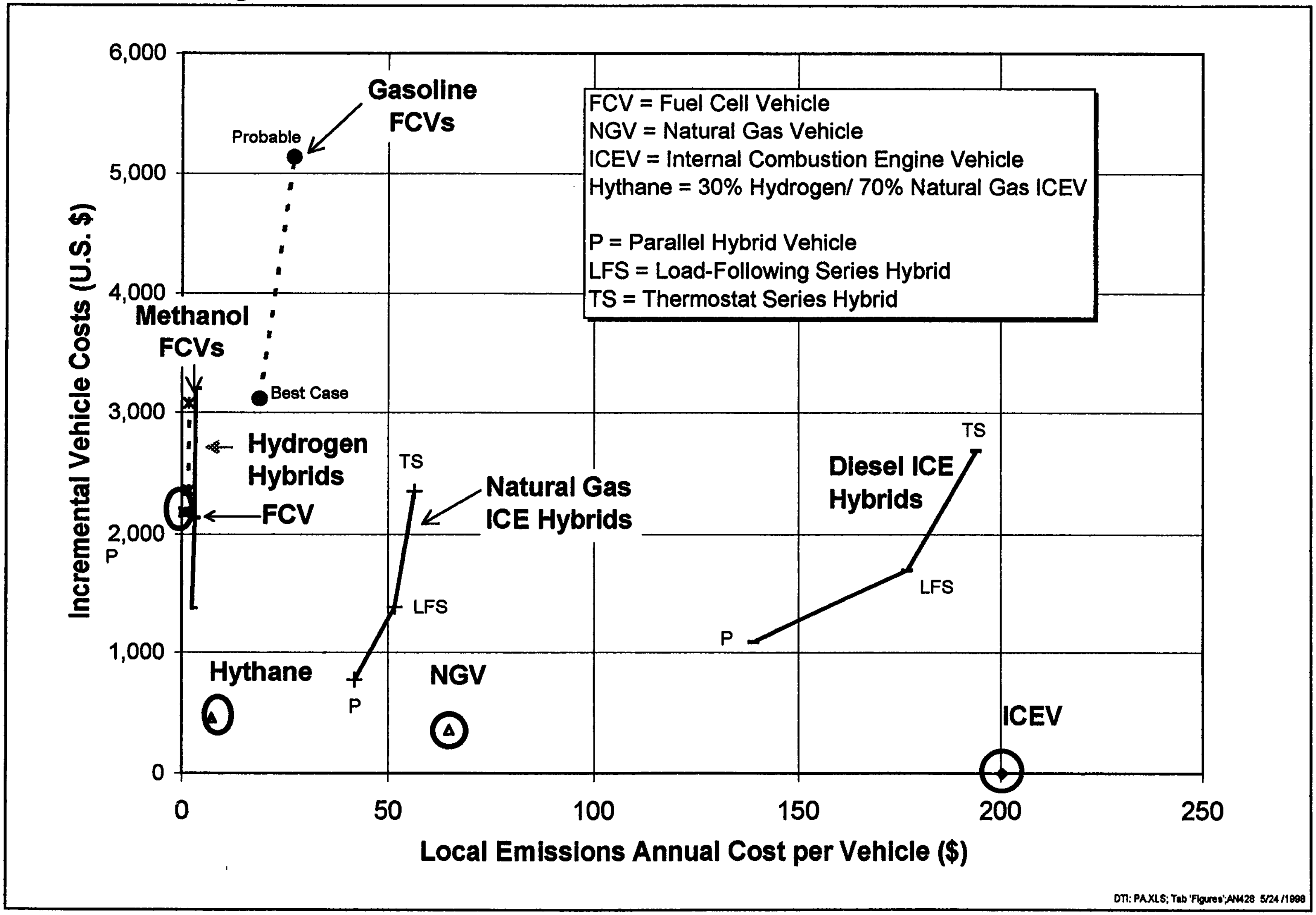


Figure 15. Incremental Mass Production Vehicle Cost vs. Greenhouse Gas Emissions

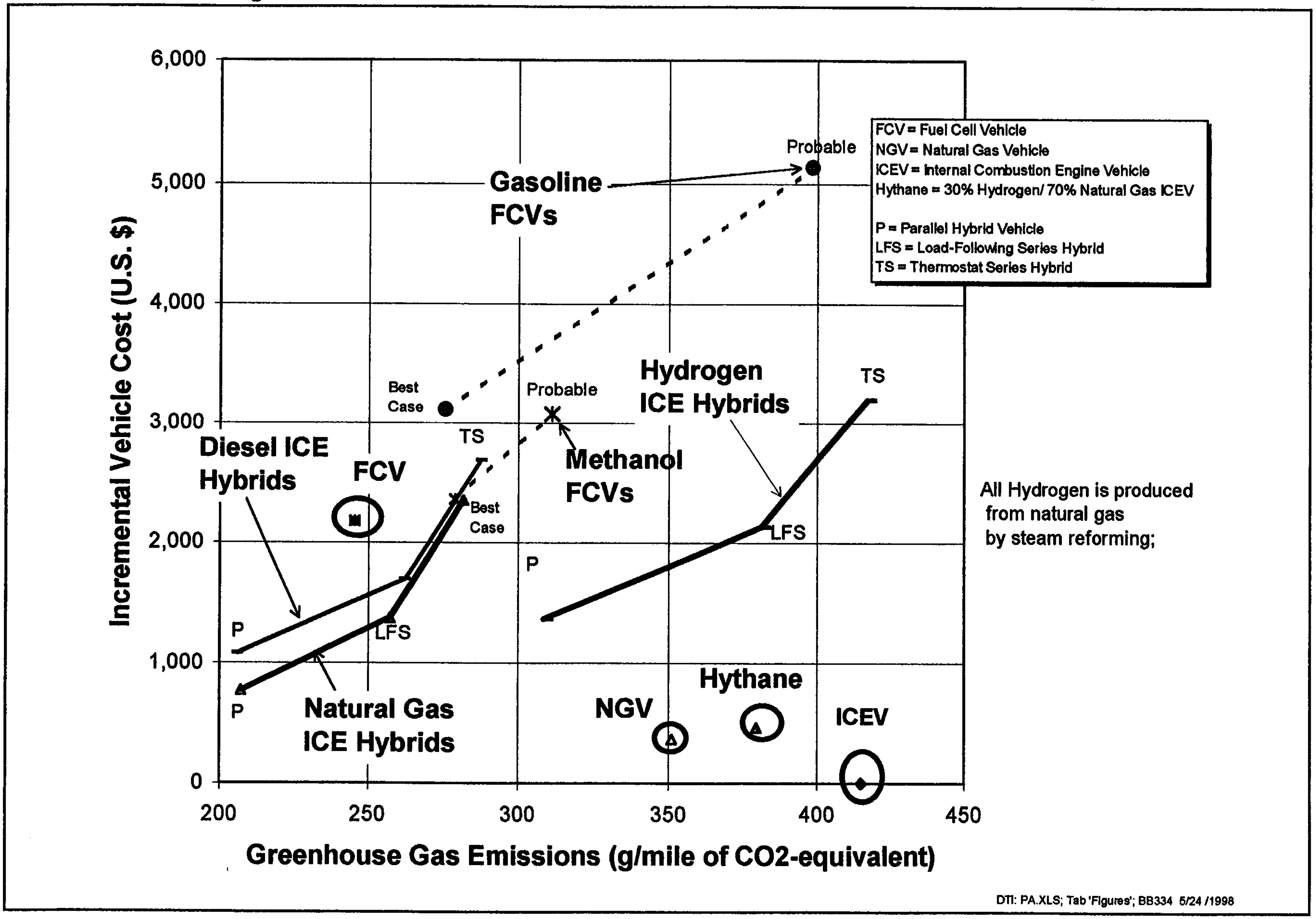


Figure 16. Incremental Mass Production Vehicle Cost vs. Combined Annual Local and Greenhouse Gas Emissions