ANL/ESD/TM-140

Assessment of PNGV Fuels Infrastructure

Phase 1 Report: Additional Capital Needs and Fuel-Cycle Energy and Emissions Impacts

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Foreword

The purpose of this report is to document the methodologies and results of Argonne's assessment of additional capital needs and fuel-cycle energy and emissions impacts of using various fuels in vehicles having fuel economy three times as high as today's light-duty vehicles. These "3X vehicles" are being investigated by the Partnership for a New Generation of Vehicles (PNGV). In 1994, the National Research Council's Peer Review Committee on the PNGV program called for assessment of potential PNGV 3X-vehicle infrastructure impacts. Consequently, the U.S. Department of Energy (DOE) provided funding to Argonne National Laboratory and Oak Ridge National Laboratory for investigating such infrastructure issues. Argonne has been responsible for fuels-related infrastructure issues and Oak Ridge for lightweight-materials-related issues. In August 1995, the results of a preliminary analysis by the two laboratories were presented to the Peer Review Committee. In November 1996, the results of the phase 1 analysis by the two laboratories were presented to the committee. The phase 2 analysis, which is intended to include additional issues identified during the phase 1 analysis, is being undertaken at this time. This report documents the results of Argonne's phase 1 analysis on fuels infrastructure issues related to PNGV 3X vehicles.

Acknowledgments

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by

M. Wang, K. Stork, A. Vyas, M. Mintz, M. Singh, and L. Johnson

Abstract

This report presents the methodologies and results of Argonne's assessment of additional capital needs and the fuel-cycle energy and emissions impacts of using six different fuels in the vehicles with tripled fuel economy (3X vehicles) that the Partnership for a New Generation of Vehicles is currently investigating. The six fuels included in this study are reformulated gasoline, low-sulfur diesel, methanol, ethanol, dimethyl ether, and hydrogen. Reformulated gasoline, methanol, and ethanol are assumed to be burned in spark-ignition, direct-injection engines. Diesel and dimethyl ether are assumed to be burned in compression-ignition, direct-injection engines. Hydrogen and methanol are assumed to be used in fuel-cell vehicles. We have analyzed fuels infrastructure impacts under a 3X vehicle low market share scenario and a high market share scenario. Our assessment shows that if 3X vehicles are mass-introduced, a considerable amount of capital investment will be needed to build new fuel production plants and to establish distribution infrastructure for methanol, ethanol, dimethyl ether, and hydrogen. Capital needs for production facilities will far exceed those for distribution infrastructure. Among the four fuels, hydrogen will bear the largest capital needs. The fuel efficiency gain by 3X vehicles translates directly into reductions in total energy demand, fossil energy demand, and CO_2 emissions. The combination of fuel substitution and fuel efficiency results in substantial petroleum displacement and large reductions in emissions of nitrogen oxide, carbon monoxide, volatile organic compounds, sulfur oxide, and particulate matter of size smaller than 10 microns.

1 Introduction

1.1 Background

In September 1993, the U.S. government and the U.S. Council for Automotive Research (USCAR), which represents Chrysler, Ford, and General Motors, jointly initiated the Partnership for a New Generation of Vehicles (PNGV) with the goals of (1) significantly improving national competitiveness in automotive manufacturing; (2) implementing commercially viable innovations from ongoing research on conventional vehicles; and (3) developing vehicles that can achieve up to three times the fuel economy of today's comparable vehicles, which would be about 80 miles per gallon (mpg) for six-passenger automobiles. An additional constraint on the development of very-high-efficiency vehicles (goal three) is that the vehicles should not only meet the safety and emissions requirements expected to be in place when these vehicles are introduced, but also maintain the performance, size, utility, and cost of ownership/operation of the vehicles that they are intended to replace.

To develop vehicles that will be up to three times as efficient (often called 3X vehicles), the PNGV program is focusing on the development and use of advanced automotive technologies, new transportation fuels, and lightweight materials. These technologies could be incorporated into such propulsion systems as advanced diesel engines (with as-yet-undeveloped emission control devices), gas turbines, or fuel cells. To meet the emissions goals or to provide the optimum fuel for these new propulsion systems, new fuels (e.g., hydrogen, methanol, ethanol, or dimethyl ether) could be necessary. Capturing energy now lost in braking to further improve energy efficiency could require energy storage devices (high-power batteries, flywheels, or ultracapacitors) and sophisticated electronics for energy management on-board the vehicle. To achieve the weight reduction goals, conventional iron and steel materials in automobiles might be replaced with significant amounts of aluminum, magnesium, titanium, or polymer composites. If development of the 3X vehicles is successfully achieved, replacement of conventional vehicles, materials, and fuels would inevitably require changes in automotive manufacturing, materials production, and fuel production and distribution.

1.2 National Research Council Peer Review of the PNGV Research Program

The National Research Council (NRC), a part of the National Academy of Sciences, has created a standing committee to provide peer review of the research program of the PNGV. In their first review of the PNGV program, the NRC Peer Review Committee concluded that there was the potential for "substantial discontinuities" in vehicle manufacturing and the transportation system (NRC 1994). Consequently, the Committee observed that a need existed for in-depth assessment of changes that could occur in "infrastructure, capital requirements, shifts in employment, total environmental consequences, alternative safety strategies, and total cost of operation associated with each technology being explored in the PNGV program" (NRC 1994).

Argonne National Laboratory (ANL), together with Oak Ridge National Laboratory (ORNL), conducted a preliminary assessment for the Office of Advanced Automotive Technologies (OAAT) in the U.S. Department of Energy (DOE) to quantify the major impacts on the infrastructure, capital requirements, resource availability of new materials, and environmental consequences resulting from the commercialization of 3X vehicles. ANL analyzed fuel-related infrastructure issues, while ORNL was responsible for lightweight-materials-related infrastructure issues. Results of this preliminary assessment were presented to the NRC Committee. First-order effects for advanced automotive technologies were defined, potential alternative fuel demand was quantified, and the importance of the length of time for the transition period was discussed. The Argonne results were later published in the proceedings of the 29th International Symposium on Automotive Technology and Automation (ISATA) (Wang and Johnson 1996).

The Committee's subsequent report noted the need to continue the infrastructure analysis (NRC 1996). Responding to this request by the Review Committee, ANL conducted further research to provide more detailed analyses of the key issues identified in the preliminary assessment regarding infrastructure changes, capital requirements, and environmental consequences of using alternative fuels in 3X vehicles. This report documents Argonne's analysis of the fuel-related infrastructure impacts.

1.3 Study Scope and Approach

Argonne's analysis, sponsored by DOE/OAAT, included infrastructure issues related to fuel production and distribution, total energy, and environmental impacts of use of 3X vehicles. This study assumed as a point of departure that technological obstacles will be overcome; i.e., the PNGV's primary goal of tripling fuel economy will become an engineering reality. Key analysis issues in this study included changes in production processes and distribution systems for new transportation fuels, capital requirements for these changes, petroleum savings from using 3X vehicles, and reductions in emissions of air pollutants and greenhouse gases. In particular, we attempted to address three specific areas related to fuels infrastructure. First, we estimated additional capital investment needs of fuel production facilities for the fuels that we included in our analysis. Second, we estimated additional capital investment needs of fuel distribution systems for meeting the fuel volume demanded by 3X vehicles. Third, we estimated full fuel-cycle energy and emissions impacts of using several potential PNGV fuels in the 3X vehicles.

We estimated additional capital needs for fuel production and distribution on the basis of requirements for given fuel volumes, using our survey of existing studies and our projected 3X vehicle fuel demand. Fuel-cycle energy use and emissions were estimated by using models that were developed at Argonne and peer reviewed.

The analytic time frame of this study is between 2007 (three years after completion of the research and development for 3X vehicles) and 2030 (when a significant portion of the light-duty fleet could be expected to be composed of these highly efficient vehicles). The study therefore assumes that 3X vehicles will be introduced beginning in 2007 and that 3X vehicle sales will continuously increase to a defined maximum sales target.

2 Scenario Development and Technology Choices

2.1 Development of Reference and Market Share Scenarios for 3X Vehicles

A set of scenarios showing light-duty-vehicle sales, stock, travel, and energy consumption were needed to estimate the impacts that the 3X vehicles would have and the infrastructure they would require: (1) a reference scenario to depict the conditions that would exist without the 3X vehicles and (2) two market share scenarios bracketing a range of 3X vehicle sales to show the extent of impacts of these vehicles.

The Energy Information Administration (EIA) within DOE has projected statistics on energy demand and related attributes for all energy-consuming sectors through the year 2015 (EIA 1996). EIA's transportation sector projections are based on a 2.0% per year growth in the gross domestic product (GDP). The projections assume participation of the labor force declines after the year 2005. However, increased productivity and the gradually declining federal deficit support continued growth, although at a lower rate. The world oil price is projected to rise from $16.81 to $23.70 per barrel by 2010, and to $25.43 per barrel by 2015 (all in 1994 dollars). These projections are used by various agencies within DOE. The reference case projections from EIA's Annual Energy Outlook 1996, which takes these factors into account, were used as the reference scenario in our analysis.

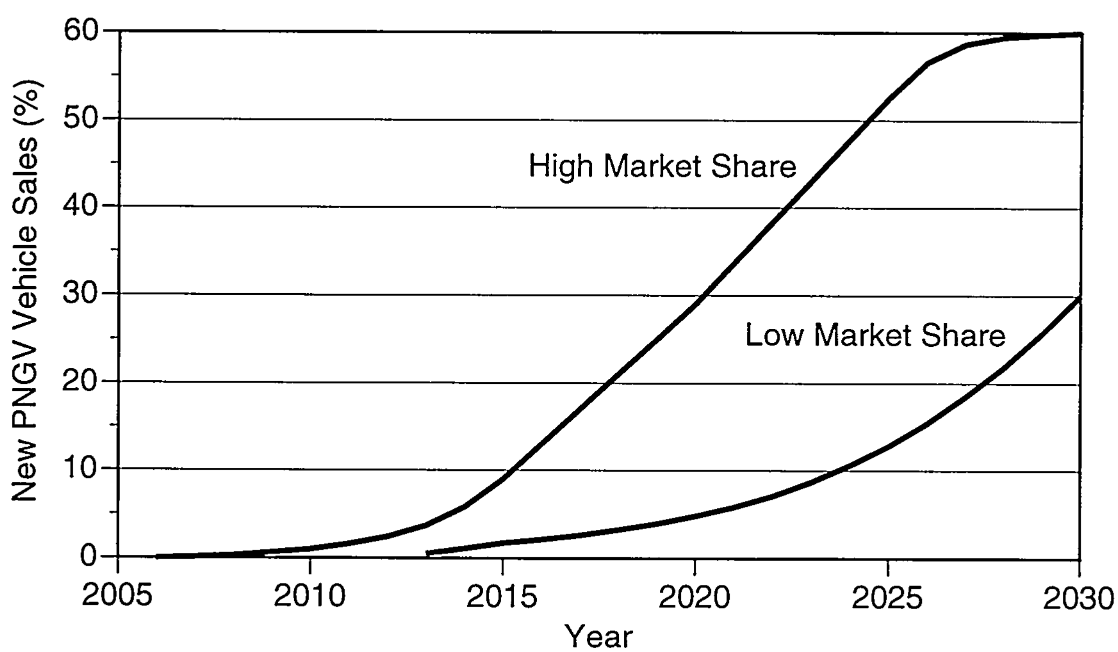
The EIA's reference scenario shows energy consumption by light-duty vehicles increasing by 0.8% per year between 1995 and 2015. The light-duty vehicles, which account for 57% of current transportation energy use, will continue to be the largest transportation-energy consumers at 53% in 2015. Their usage, measured as vehicle-miles traveled (VMT), will grow at an annual rate of 1.4%. Low fuel cost, rising incomes, and an increasing number of drivers will sustain the growth in light-duty-vehicle use. The rate of growth in VMT, however, will slow to 1.1% per year during the period 2010-2015 because of a sharp decline in the labor force caused by the retirement of the "baby boom" generation. The new-car fuel economy (rated) is projected to increase from 27.5 mpg in 1995 to 31.9 mpg in 2010 and to 33.1 mpg in 2015. The new-light-truck fuel economy will increase from 20.2 mpg in 1995 to 23.8 mpg in 2010 and to 25.1 mpg in 2015. Total new-car sales will increase from 8.92 million in 1995 to 9.66 million in 2010 and to 10.05 million in 2015, while new-light-truck sales will increase from 5.53 million in 1995 to 7.52 million in 2010 and to 7.89 million in 2015. The fuel economy and sales projections were extended to 2030 by using the respective growth rates between 2010 and 2015.

New 3X vehicle sales for a given future year can be estimated by using total new-vehicle-sales projections and market share of 3X vehicles. The future 3X vehicle market share depends on the level of technology maturity, vehicle costs, consumer preferences, and many other factors, each subject to some uncertainty. Two extreme sets of conditions may materialize. Under one set of conditions, every item favorable to the 3X vehicles would take place, resulting in rapid consumer acceptance and high sales of new 3X vehicles. Under the second set of conditions, some items may not turn out as favorable, resulting in slower early consumer acceptance and low to moderate sales of new 3X vehicles. To address the uncertainty, two market share scenarios for 3X vehicles — high market share and low market share — were established (Figure 1 and Table 1).

New-vehicle sales under the reference and the two market share scenarios were simulated by using the Integrated Market Penetration and Anticipated Cost of Transportation Technologies (IMPACTT) model developed at Argonne. The model uses vehicle survival and age-dependent usage relationships to project vehicle stock, VMT, and energy usage. Information about IMPACTT is provided in Section 4.1.

2.2 Market Penetration Analysis

To assess infrastructure impacts of the mass introduction of 3X vehicles, the total number of 3X vehicles in the fleet and the total volume of fuel consumed each year between 2007 and 2030 must be estimated. In the preliminary assessment conducted late 1995, the mid-case 3X vehicle sales scenario established by the DOE Policy Office for the Policy Dialogue Advisory Committee (the "Car Talk" Committee) was assumed for each potential 3X technology (Resolve, Inc. 1995). Each technology was assumed to have the same penetration scheme, and the technologies did not compete with one another. In this study, review of the Car Talk mid-case



High market share: Modified "Car Talk" mid-case scenario
Low market share: Similar to historical French diesel car sales

FIGURE 1 Market Share Scenarios for 3X Vehicles scenario suggested that the sales figures climb too rapidly for realization in terms of the adaptation of the vehicle manufacturing industry. Alternative market sales scenarios to the Car Talk mid-case scenario needed to be considered.

TABLE 1 Share of New 3X Vehicles under the High Market Share and Low Market Share Scenarios

	High Market Share	Low Market Share
Year	% Share	% Share
2006	0.0	-
2007	0.1	-
2008	0.3	-
2009	0.6	-
2010	1.0	-
2011	1.6	-
2012	2.4	0.0
2013	3.7	0.5
2014	5.8	1.1
2015	9.0	1.7
2016	13.0	2.1
2017	17.0	2.6
2018	21.0	3.2
2019	25.0	3.9
2020	29.0	4.8
2021	33.7	5.8
2022	38.4	7.1
2023	43.1	8.7
2024	47.8	10.6
2025	52.5	12.8
2026	56.6	15.4
2027	58.7	18.4
2028	59.5	21.8
2029	59.8	25.7
2030	60.0	30.0

Traditionally, 3X vehicle market sales scenarios should be based on historical technological transformations in the automotive industry. The Car Talk scenarios arose from a primary concern with greenhouse-gas reduction, with a secondary emphasis on the feasibility and infrastructure transition issues that are of explicit concern in the PNGV program.

In the scenarios we established for our study, we again assume the full penetration of a given technology into 3X vehicles, setting aside competing technologies for other scenarios. This assumption provides the basis for analyzing the maximum impact of each technology on the infrastructure. The following description provides a summary of vehicle sales and energy consumption under the high market share and the low market share scenarios.

The market penetration of 3X vehicles for the two market share scenarios was determined exogenously. The Resolve, Inc., report (1995) was used to develop the high market share scenario, while the historical rate of diesel market penetration in France (Automotive Industry Data, Ltd. 1995) was used to develop the low market share scenario. Under the high market share scenario, 3X vehicles enter the market in 2007. Their share increases to 60% of the new vehicle market by 2030. This scenario is a modified version of the mid-case scenario established for the Car Talk committee (Resolve, Inc. 1995). Compared with historical experience in the introduction of such radical new automotive technologies as front-wheel drivetrain and weight reductions, the high market share scenario is moderate. For example, in the United States, the market share of front-wheel drivetrain increased from virtually 0% to 80% of new passenger cars between 1976 and 1992, a span of 16 years (Figure 2). Also, light-duty-vehicle weight was reduced by more than 20% between 1976 and 1980, a period of just five years (Figure 3).

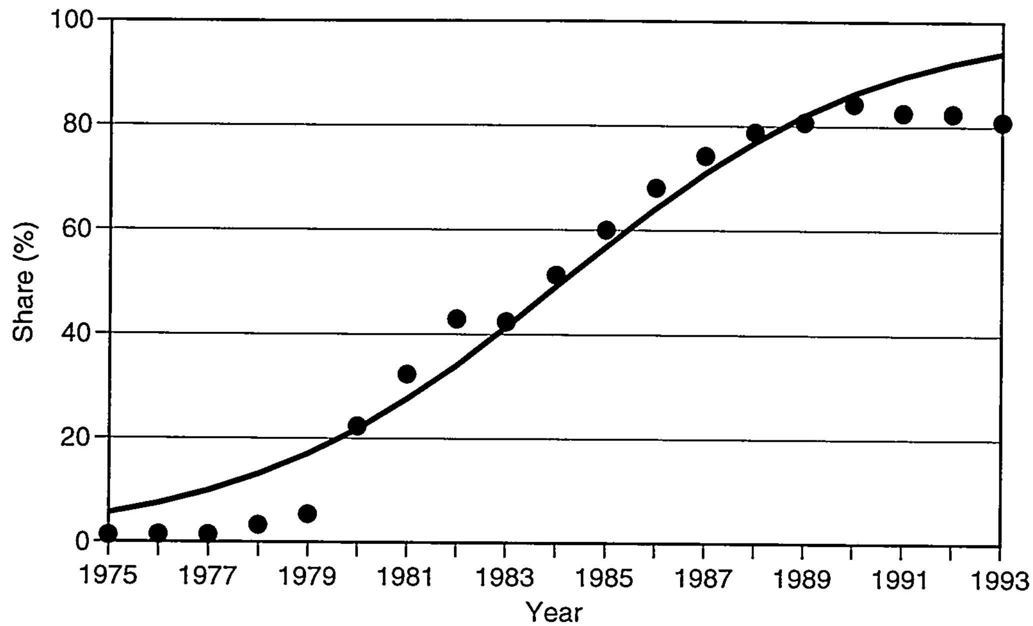


FIGURE 2 Market Share of Front-Wheel Drive Autos in the United States (based on Murrell et al. 1993)

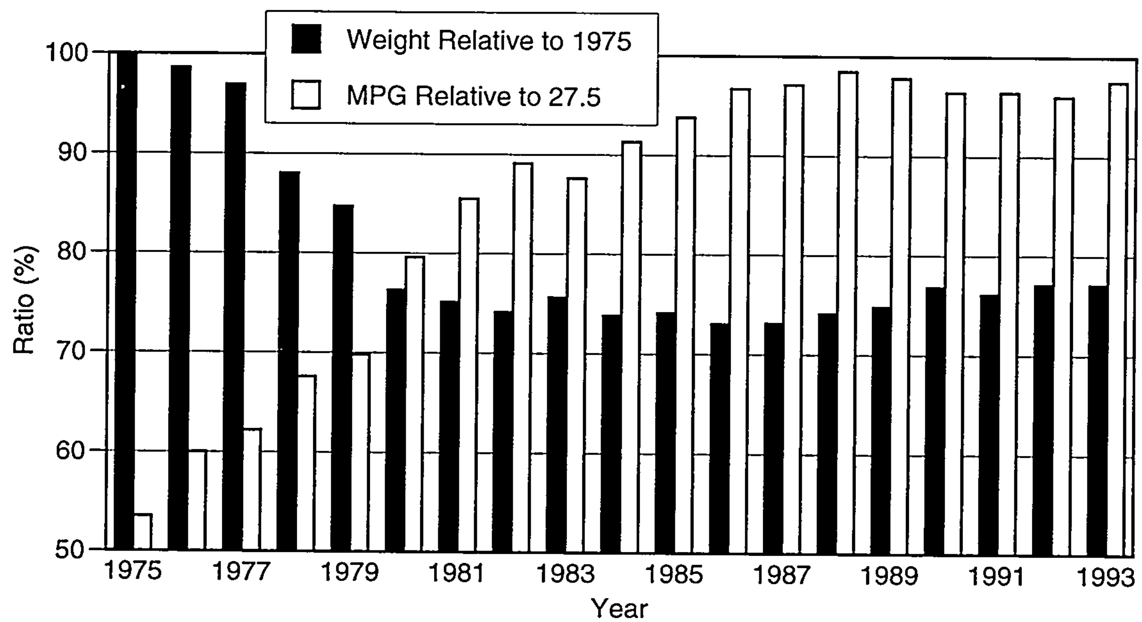


FIGURE 3 Weight Reduction and Fuel Economy Improvement of New Automobiles in the United States (fuel economy given on basis of 1995 standard of 27.5 mpg) (based on Murrell et al. 1993)

The low market share scenario assumes late introduction of 3X vehicles into the market and a low rate of increase in sales. Under this scenario, 3X vehicles enter the market in 2013, six years later than in the high market share scenario, and capture a 30% share of the new vehicle market by 2030. The low market share scenario is similar to the market share of diesel cars in France in the 16 years between 1973 and 1989 (Figure 4).

2.2.1 Total New Light-Duty-Vehicle Sales

The technologies studied for the 3X vehicle can be applied to passenger cars, class 1 light-duty trucks, and class 2 light-duty trucks (which together compose light-duty vehicles). As described above, EIA projections of new light-duty-vehicle sales (EIA 1996) were extended to 2030 for this analysis. The new 3X vehicle sales were computed from total new light-duty-vehicle sales estimates and the two 3X vehicle demand scenarios. Estimated new 3X vehicle sales are presented in Table 2.

The light-duty-vehicle market is the largest automotive market, with new vehicle sales ranging between 13 million and 15 million vehicles per year over the past five years. EIA projects new light-duty-vehicle sales of 18 million in 2015 (EIA 1996). When we extended the projection horizon to 2030 by using the sales growth during 2010-2015, the projected sales of new light-duty vehicles in 2030 were 20 million. For this analysis we have assumed the market to be vehicles covered by the CAFE regulations (i.e., up to 8,500 lb). The light-duty-vehicle market has three major sectors: automobiles, light trucks up to 6,000-lb gross vehicle weight (GVW), and light trucks over 6,000 lb GVW. The automobile has been the largest sector historically, but its share of the light-duty-vehicle sales has been shrinking. Due to increased popularity of minivans and sports

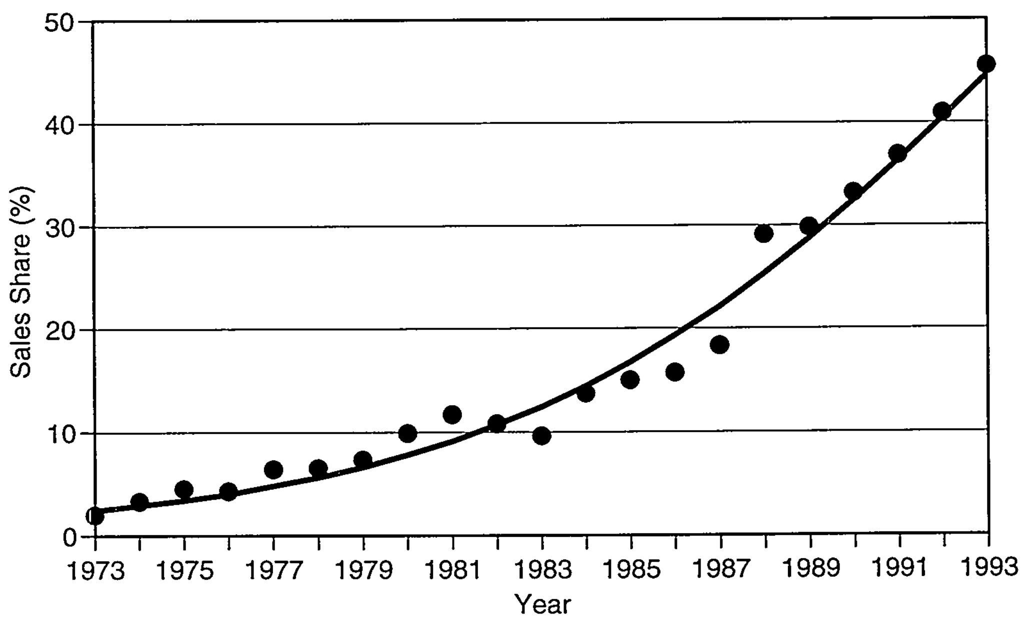


FIGURE 4 Sales Share of New Diesel Cars in France

TABLE 2 New 3X Vehicle Sales and Their Energy Consumption as Estimated by IMPACTT[a]

	New 3X Vehicle Sales (10^3)						Energy Consumption by 3X Vehicles (10^6 Gasoline Equivalent Gallons)					
	High Market Share Scenario			Low Market Share Scenario			High Market Share Scenario			Low Market Share Scenario		
Year	Auto	Light Truck	Total	Auto	Light Truck	Total	Auto	Light Truck	Total	Auto	Light Truck	Total
2007	9	7	17	–	–	–	2	2	4	–	–	–
2008	29	22	50	–	–	–	9	9	17	–	–	–
2009	58	45	102	–	–	–	22	22	43	–	–	–
2010	97	75	172	–	–	–	43	44	87	–	–	–
2011	151	118	269	–	–	–	76	78	154	–	–	–
2012	236	184	420	–	–	–	128	130	258	–	–	–
2013	370	290	659	49	39	88	209	213	421	12	12	23
2014	579	455	1,034	110	86	196	335	342	677	37	38	75
2015	904	709	1,613	169	133	302	531	544	1,076	75	77	152
2016	1,325	1,024	2,349	212	164	376	818	834	1,652	122	124	246
2017	1,760	1,338	3,098	266	202	467	1,195	1,207	2,402	179	181	360
2018	2,208	1,651	3,859	332	248	581	1,659	1,659	3,319	249	249	499
2019	2,669	1,964	4,633	415	305	720	2,210	2,186	4,397	336	332	669
2020	3,144	2,275	5,419	517	374	892	2,846	2,783	5,629	443	433	876
2021	3,710	2,641	6,351	644	458	1,102	3,583	3,460	7,043	574	554	1,128
2022	4,293	3,005	7,298	799	559	1,358	4,417	4,212	8,629	736	700	1,435
2023	4,893	3,368	8,261	989	680	1,669	5,346	5,031	10,377	933	875	1,809
2024	5,511	3,728	9,239	1,219	825	2,043	6,365	5,911	12,276	1,175	1,086	2,261
2025	6,146	4,087	10,233	1,496	995	2,491	7,471	6,842	14,314	1,469	1,337	2,806
2026	6,731	4,398	11,129	1,827	1,194	3,021	8,643	7,805	16,448	1,827	1,636	3,462
2027	7,086	4,550	11,636	2,218	1,424	3,642	9,816	8,742	18,559	2,257	1,989	4,246
2028	7,294	4,601	11,894	2,674	1,686	4,360	10,951	9,619	20,570	2,773	2,404	5,178
2029	7,444	4,611	12,056	3,198	1,981	5,179	12,029	10,420	22,449	3,387	2,887	6,274
2030	7,880	4,318	12,198	3,939	2,159	6,098	13,118	11,048	24,166	4,145	3,398	7,542

[a] The total columns may not reflect exact sums due to rounding.

utility vehicles, light trucks have increased their share from 16.5% of the new vehicle sales in 1980 to 40.4% in 1996. Most of the growth has been in class 1 light trucks, which became very popular after 1985. The class 1 light truck share increased from 6.1% in 1980 to 24.3% in 1996. The class 2 truck share has also increased, from 10.4% in 1980 to 16.1% in 1996. For this analysis, we assumed all standard pickups and large vans to have GVW over 6,000 lb. The average inertia weight of standard pickups has been between 4,200 and 4,400 lb. When cargo capacity is added, the GVW rating would be over 6,000 lb.

2.2.2 Fuel Consumption by 3X Vehicles

For any given future year, the existing 3X vehicle fleet consists of new 3X vehicles and 3X vehicles sold in previous years. Thus, existing vehicle fleet composition is determined by new vehicle sales (estimated above) and survival rates of existing vehicles. As the market share of 3X vehicles increases, usage of these vehicles will represent a greater share of travel, and their energy impacts will be greater over time.

Fuel consumption by the existing 3X vehicle fleet is determined by fuel economy and annual VMT. On the basis of 1993 new-vehicle fuel-economy data presented by the U.S. Environmental Protection Agency (EPA) (Murrell et al. 1993), we assumed that 3X cars will achieve a fuel economy of 81 mpg and 3X light trucks will achieve 63 mpg. Argonne's IMPACTT model was used to calculate annual energy consumption by the 3X vehicle fleet for each year from 2007 to 2030 by taking into consideration vehicle stock, age-dependent usage, and fuel economy. Table 2 presents the fuel consumption by 3X vehicles estimated by using IMPACTT.

2.2.3 Energy Savings Potential

Energy consumption by light-duty vehicles was estimated for the three scenarios: the reference scenario without 3X vehicles and the 3X vehicle low market share and the 3X vehicle high market share scenarios. For the reference scenario, we used EIA's light-duty-vehicle fuel economy projections to 2015. As described above, the growth rate in EIA's fuel economy between 2010 and 2015 was extended to estimate reference scenario fuel economy for vehicles produced after 2015. Under the reference scenario, fuel economy for new cars and for light trucks increased from 27.5 and 20.2 mpg in 1995 to 35.4 and 26.5 mpg in 2030, respectively. We used the IMPACTT model to simulate total energy consumption by light-duty vehicles under the three scenarios. The resulting energy consumption estimates are shown in Table 3.

Figure 5 shows energy consumption by light-duty vehicles. The figure shows the energy savings potential by introducing 3X vehicles, which is dramatic for the high market share scenario and more modest, but still substantial, for the low market share scenario. This reduction in petroleum use is due entirely to improved fuel efficiency and not the substitution of alternative

TABLE 3 Total Light-Duty-Vehicle Energy Consumption (in 10^6 gasoline-equivalent gallons) under the Three Scenarios

	Automobiles			Light Trucks			Total Light-Duty Vehicles		
Year	Reference Case	Low Market Share	High Market Share	Reference Case	Low Market Share	High Market Share	Reference Case	Low Market Share	High Market Share
1990	72,433	72,433	72,433	34,077	34,077	34,077	106,510	106,510	106,510
1991	70,668	70,668	70,668	34,107	34,107	34,107	104,774	104,774	104,774
1992	74,053	74,053	74,053	35,509	35,509	35,509	109,562	109,562	109,562
1993	75,050	75,050	75,050	37,019	37,019	37,019	112,069	112,069	112,069
1994	78,234	78,234	78,234	38,354	38,354	38,354	116,588	116,588	116,588
1995	75,771	75,771	75,771	45,624	45,624	45,624	121,395	121,395	121,395
1996	75,767	75,767	75,767	46,648	46,648	46,648	122,415	122,415	122,415
1997	75,590	75,590	75,590	48,176	48,176	48,176	123,766	123,766	123,766
1998	75,952	75,952	75,952	49,544	49,544	49,544	125,496	125,496	125,496
1999	76,481	76,481	76,481	50,800	50,800	50,800	127,281	127,281	127,281
2000	76,906	76,906	76,906	52,120	52,120	52,120	129,026	129,026	129,026
2001	77,332	77,332	77,332	53,304	53,304	53,304	130,636	130,636	130,636
2002	77,492	77,492	77,492	54,408	54,408	54,408	131,900	131,900	131,900
2003	77,813	77,813	77,813	55,448	55,448	55,448	133,261	133,261	133,261
2004	78,118	78,118	78,118	56,424	56,424	56,424	134,542	134,542	134,542
2005	78,551	78,551	78,551	57,488	57,488	57,488	136,039	136,039	136,039
2006	78,920	78,920	78,920	58,344	58,344	58,344	137,264	137,264	137,264
2007	79,298	79,298	79,293	59,080	59,080	59,076	138,378	138,378	138,369
2008	79,714	79,714	79,695	59,712	59,712	59,696	139,426	139,426	139,391
2009	79,939	79,939	79,892	60,144	60,144	60,105	140,083	140,083	139,997
2010	80,140	80,140	80,047	60,560	60,560	60,484	140,700	140,700	140,531
2011	80,244	80,244	80,080	60,920	60,920	60,789	141,164	141,164	140,868
2012	80,356	80,356	80,083	61,208	61,208	60,993	141,564	141,564	141,076
2013	80,405	80,380	79,966	61,440	61,422	61,096	141,845	141,802	141,062
2014	80,436	80,360	79,741	61,648	61,590	61,104	142,084	141,950	140,845
2015	80,613	80,453	79,513	61,848	61,736	61,001	142,461	142,189	140,514
2016	80,708	80,455	79,035	62,109	61,947	60,837	142,817	142,402	139,872
2017	80,803	80,437	78,390	62,371	62,165	60,564	143,174	142,602	138,955
2018	80,898	80,397	77,589	62,634	62,384	60,185	143,532	142,781	137,774
2019	80,993	80,328	76,642	62,898	62,600	59,705	143,891	142,928	136,347
2020	81,088	80,225	75,561	63,163	62,806	59,128	144,252	143,031	134,689
2021	81,184	80,082	74,325	63,430	62,996	58,433	144,614	143,078	132,759
2022	81,279	79,891	72,953	63,697	63,161	57,630	144,977	143,053	130,583
2023	81,375	79,644	71,460	63,966	63,294	56,723	145,341	142,938	128,183
2024	81,471	79,331	69,864	64,236	63,383	55,724	145,707	142,715	125,588
2025	81,567	78,941	68,184	64,507	63,418	54,642	146,074	142,359	122,826
2026	81,663	78,461	66,461	64,779	63,385	53,504	146,442	141,846	119,965
2027	81,759	77,880	64,809	65,052	63,269	52,400	146,811	141,149	117,209
2028	81,855	77,184	63,296	65,326	63,057	51,382	147,182	140,240	114,678
2029	81,952	76,361	61,946	65,602	62,733	50,474	147,554	139,094	112,420
2030	82,048	75,374	60,736	65,879	62,092	49,582	147,927	137,467	110,318

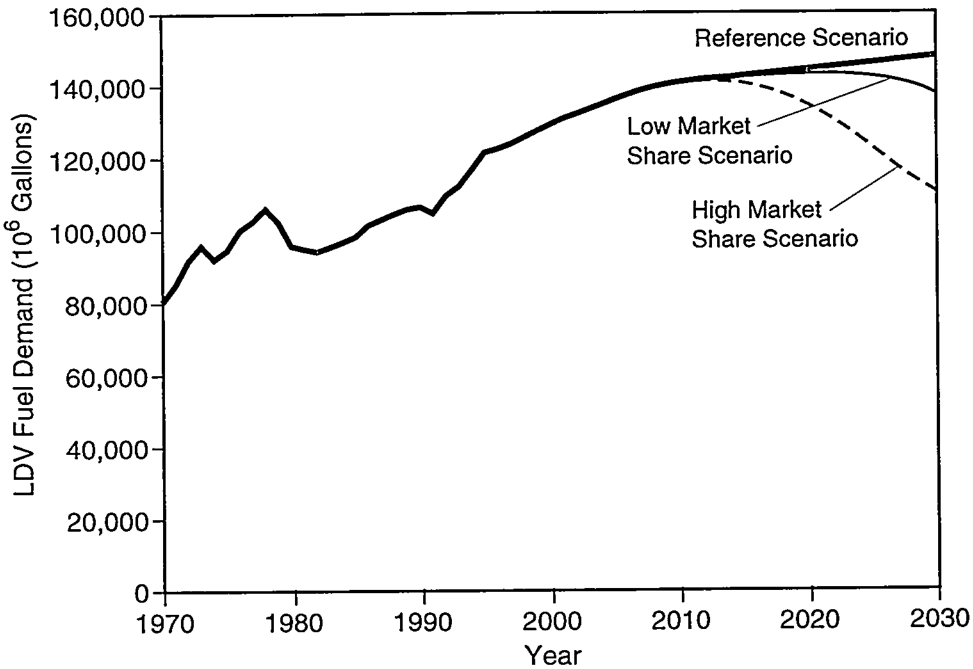


FIGURE 5 Impact of PNGV 3X Vehicles on Light-Duty-Vehicle (LDV) Energy Consumption

fuels. If alternative fuels (such as methanol, ethanol, hydrogen, and dimethyl ether) are used in 3X vehicles to replace gasoline, additional reduction in gasoline consumption is expected. The amount of gasoline reduction from fuel substitution is equal to the amount of energy consumed by 3X vehicles operating on fuels other than gasoline (as shown in Table 2). The effect of both efficiency gain and fuel substitution on petroleum use is shown in Figure 12.

Note that fuel use presented in Table 3 and Figure 5 is fuel consumption by vehicles only. Fuel consumption for upstream fuel production activities will be estimated in Section 4. There, fuel-cycle energy use and petroleum displacement due to both vehicle efficiency gains by 3X vehicles and fuel substitution will be presented.

2.3 Vehicle Technologies Analyzed

The PNGV has targeted three areas for achieving the goal of tripling fuel economy: converting fuel energy more efficiently, reducing the energy demands of the vehicle, and implementing regenerative braking to recapture braking energy (Automotive Engineering 1996). To convert energy more efficiently in vehicles, various types of on-board power units are being investigated. These technologies include direct-injection, spark-ignition (DISI) engine; direct-injection, compression-ignition (DICI) engine; gas turbine; and fuel cell. To reduce vehicle energy demand, the PNGV is investigating use of advanced lightweight materials, improvement of drag coefficient, lowering of rolling resistance, improvement of drivetrain efficiency, and lowering of accessories load. To recapture braking energy, the PNGV is investigating use of hybrid electric vehicles in which on-board power units can be designed to be operated in the energy efficient regime of the engine map and braking energy can be recaptured and stored in such energy storage systems as batteries, flywheels, or ultracapacitors.

In particular, the PNGV is considering these candidate propulsion technologies: 4-stroke DISI engines (stand-alone or hybrid-electric configuration), 4-stroke DICI engines (stand-alone or hybrid configuration), gas turbine/series-configured electric hybrid, and proton exchange membrane (PEM) fuel cells/hybrid configuration.

Because this study focused on fuels infrastructure and total energy and environmental effects of 3X vehicles, we aggregated the propulsion technologies into these groups: stand-alone spark ignition (SI) engines, hybrid SI engines, stand-alone compression ignition (CI) engines, hybrid CI engines, fuel cells, and hybrid gas turbines. We implicitly assumed that direct injection technologies are to be applied to both SI and CI engines. We included all these technologies except gas turbines in our analysis.

2.4 Fuels Analyzed

The fuels included in this analysis are not intended to represent a comprehensive picture of available and potential transportation fuels. The choice of fuels analyzed (and the vehicle technologies with which they were paired) was based in each case on a specific advantage of the fuel-vehicle system related to the PNGV program goals.

The following fuels were analyzed: reformulated gasoline (RFG), low-sulfur diesel (LSD), dimethyl ether (DME), methanol, ethanol, and hydrogen. Some fuels not analyzed include liquefied petroleum gas (LPG), compressed natural gas/liquefied natural gas (CNG/LNG), biodiesel, and Fischer-Tropsch diesel made from coal or natural gas. These fuels may offer other benefits and, although not analyzed in the phase 1 work, are being considered in the phase 2 analysis. The fuels analyzed are discussed below.

- Reformulated gasoline served as the reference scenario conventional fuel. Reformulated gasoline was assumed to be federal phase 2 RFG, available around the year 2000.

- Low-sulfur diesel was assumed to have sulfur content below 0.05% by weight (highway diesel as used now). We will attempt to determine the likely future specifications for reformulated diesel in phase 2 work as details of EPA's plans become available.

- Dimethyl ether was analyzed because several recent studies have indicated that this fuel, although expensive and requiring changes in fuel storage and injection systems, may offer significant environmental benefits while exploiting the high thermal efficiency of a CI engine system. Although diesel engine manufacturers plan to meet Tier 2 federal emission standards (and California ULEV standards) for diesel fuel, DME was analyzed because of the possibility that vehicles using petroleum-based diesel fuel may not satisfy future, as yet unspecified, particulate matter (PM) emission regulations.

- Methanol was considered in pure form (M100) for both internal combustion engines (in a hybrid electric vehicle [HEV] or stand-alone) and in fuel cells. It is most likely to be a hydrogen carrier for a fuel cell.

- Ethanol was included because it, alone among the fuels considered, is currently made from renewable resources. Ethanol would be assumed to be burned in internal combustion engines. Pure ethanol (E100) was considered.

- Finally, hydrogen, for use in fuel-cell vehicles, was analyzed. Hydrogen and methanol are the principal fuels considered for use in fuel cells.

A total of 12 fuel-vehicle combinations were evaluated in this analysis. Table 4 presents the technology matrix of these combinations.

As Table 4 shows, RFG, methanol, and ethanol are fuels for SI engines, while diesel and DME are fuels for CI engines. Methanol and ethanol have high octane numbers and are suitable for SI engines. DME has a high cetane number (55-60) and is a candidate fuel for CI engines. For methanol fuel-cell vehicles, we assume that methanol is reformed into hydrogen on board the vehicle, and the hydrogen produced is then fed to the fuel cell. Other fuels and vehicle technologies are under investigation by the PNGV. Due to time and resource limitations, we have not covered all potential fuels and technologies. In phase 2 of our analysis, we are including additional fuels and technologies.

TABLE 4 Vehicle and Fuel Technology Matrix for this Study

Fuel	Propulsion Technology
RFG	Stand-alone SI engines Hybrid SI engines
Diesel	Stand-alone CI engines Hybrid CI engines
DME	Stand-alone CI engines Hybrid CI engines
Methanol	Stand-alone SI engines Hybrid SI engines Fuel cells
Ethanol	Stand-alone SI engines Hybrid SI engines
Hydrogen	Fuel cells

2.5 Fuel Production Pathways

To estimate capital needs for fuel production and distribution and to assess fuel-cycle energy and emissions impacts, fuel production pathways must be specified for each of the six selected fuels. On the basis of Argonne's previous research in fuels areas, we specified the fuel pathways as presented in Figure 6. As the figure shows, RFG and LSD will be produced from petroleum. Methanol and DME will be produced from natural gas. We assume that before 2020, hydrogen will be produced from natural gas through steam reforming, and in 2020 and beyond, hydrogen will be produced from solar energy through water electrolysis. For ethanol, we assume that before 2020, ethanol will be produced from corn, and in 2020 and beyond, ethanol will be produced from biomass (both woody and herbaceous).

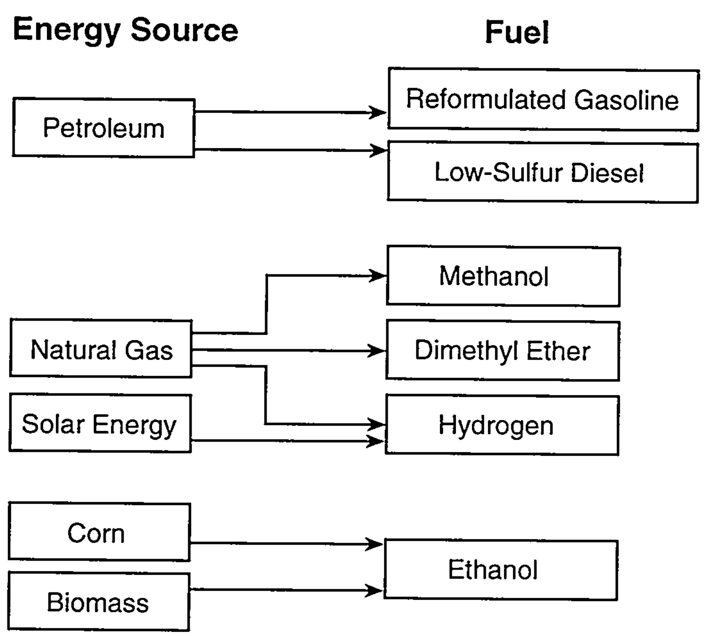


FIGURE 6 Fuel Pathways Considered in this Study

3 Capital Requirements of PNGV Fuel Infrastructure

The capital cost requirements of the candidate fuels were estimated from published data on production and distribution infrastructure costs. A target fuel requirement was specified that, depending on energy content, dictated the physical volume of fuel needed, which, in turn, dictated the size or capacity of facilities for which costs were estimated. The approach used to select the fuel requirement target is discussed in Section 3.1. Assumptions, calculations, and final estimates of production and distribution costs are presented in Sections 3.2 and 3.3. Six candidate fuels were analyzed: RFG, LSD, methanol, ethanol, hydrogen, and DME. For each of these fuels, a unique set of production and distribution facilities will be required to satisfy 3X vehicle fuel demand. Even for diesel-fueled 3X vehicles, diesel production and distribution will entail shifting from a gasoline-oriented product slate to a diesel-oriented slate at petroleum refineries. The new product balance at refineries, as well as the possibility of shortages of gasoline co-products, is discussed in Section 3.4. Along with 3X vehicles' increases in fuel economy, use of methanol, ethanol, hydrogen, or DME will result in reductions in gasoline demand, causing under-utilization or idling of some refineries and possible investment write-offs of idled refineries. These issues are also discussed in Section 3.4.

The cost estimates presented here were calculated for supplying a maximum level of anticipated fuel demand for each of the candidate fuels at two distinct points in time. In other words, capital costs were calculated for infrastructure with a capacity sufficient to supply the fuel requirements of 3X vehicles in 2015 and 2030 under the high market share scenario. The volumes (or production/distribution capacities) used in the cost analysis were 70×10^3 bbl/d (gasoline equivalent gallons) in 2015 and 1.6×10^6 bbl/d (gasoline equivalent gallons) in 2030. All costs were estimated in 1995 dollars. Because these point estimates are based on the capacity required to satisfy demand in the target year, they are discrete snapshots of accumulated capital investment through the target year rather than rates of capital spending in that year. Thus, all capital costs are cumulative.

3.1 Fuel Requirement Levels for Cost Estimation

To estimate the additional capital need for fuel production and distribution, the amount of fuel needed by 3X vehicles must first be estimated. To be precise, fuel volumes must be estimated for each year from 2007 to 2030 under the low and the high market share scenarios. Capital need can then be estimated for each year. Because of time and resource limitations, we did not estimate capital need on an annual basis. Instead, as discussed above, we selected two points of fuel demand under the high market share scenario within the period of analysis and estimated capital need for these two points. The years selected were 2015 and 2030.

Each fuel was considered to separately supply the entire energy demand of 3X vehicles. RFG and LSD were assumed to impose no incremental storage or distribution costs, and gasoline was assumed to impose no incremental production cost. For the alternative fuels — methanol, ethanol, DME, and hydrogen — the volume of fuel required at 2015 and 2030 was calculated from the fuel's energy content and 3X vehicle fuel use as estimated with IMPACTT. The quantities of fuel demanded by 3X vehicles and their production pathways in 2015 and 2030 are presented in Table 5.

3.2 Fuel Production

To estimate the additional capital needed for producing a specified fuel volume, we first estimated capital costs for a large-scale fuel production plant. We then calculated the number of plants required. In this way, capital requirement is calculated for the fuel volumes presented in Table 5. The results are presented in Table 6. Details of calculations for each fuel are presented below.

TABLE 5 Fuel Quantities Required and Production Pathways

Fuel Pathway	Volume or Mass of Fuel Required	
	2015	2030
Reformulated gasoline from petroleum	70×10^3 bbl/d	1.6×10^6 bbl/d
Diesel fuel from petroleum	62.9×10^3 bbl/d	1.4×10^6 bbl/d
DME from natural gas	123×10^3 bbl/d	2.8×10^6 bbl/d
Hydrogen		
From natural gas	1.3×10^9 SCF/d	–
From solar electrolysis of H_2O	–	28.3×10^9 SCF/d
Ethanol		
From corn	1.6×10^9 gal/yr	–
From cellulosic biomass	–	36.9×10^9 gal/yr
Methanol from natural gas[a]	6.6×10^6 t/yr	148.1×10^6 t/yr

[a] t = metric tons; also known as tonnes.

TABLE 6 Summary of Cumulative Capital Costs for Fuel Production

	High Market Share Scenario			
	Through 2015 Capacity = 70 x 10^3 bbl/d GEG[a]		Through 2030 Capacity = 1.6 x 10^6 bbl/d GEG	
Fuel	No. of Plants	Cost ($ billions)	No. of Plants	Cost ($ billions)
Methanol	2	3.2	50	84
Ethanol	40[b]	4.5[b]	737	81
Hydrogen	13	10	NA[c]	397
DME	3	3	66	66

[a] GEG = gasoline equivalent gallons

[b] Some ethanol may be diverted from current gasoline blending, which would reduce these values.

[c] No particular scale economies apply for solar hydrogen. Therefore, plant size and number of plants were not estimated for hydrogen in 2030.

3.2.1 Hydrogen

Hydrogen is produced from crude and natural gas at stand-alone hydrogen facilities for use primarily in the refining, chemical, and food industries. No hydrogen is currently used as a transportation fuel (except minor amounts used as rocket fuel). In the foreseeable future, hydrogen will probably continue to be produced primarily from natural gas.

Hydrogen is also produced within petroleum refineries as a by-product of crude processing. When additional hydrogen is needed in refineries, typically a hydrogen plant will supply hydrogen made from natural gas. The hydrogen plant can either be built as a unit of the refinery or constructed as an "across-the-fence," nominally independent plant with all or most of its product consumed by the parent refinery. Another option for producing hydrogen is to install natural gas reformers at refueling stations, so that hydrogen is produced at user sites. This option, however, will not be feasible until the cost of reformers goes down dramatically.

In the near term, we assumed that the likely production route for hydrogen is the currently common route of conversion of natural gas to hydrogen via steam methane reforming. Production will occur in central facilities near gas fields and the hydrogen will be transported to user sites. Starting in 2020, we have assumed a switch to solar electrolysis of water as the source of hydrogen to capture the environmental benefits. Interest in producing hydrogen from solar energy via water electrolysis has increased in the United States, and research and development (R&D) efforts have been undertaken so that in the long term, hydrogen can be produced from solar energy (Delucchi 1992). Because solar hydrogen is not subject to significant economies of scale, this assumed switch raises the long-run capital cost of hydrogen production substantially. In both 2015 and 2030, we assumed that hydrogen would be produced domestically.

In general, the direct production costs associated with fuels — including cumulative capital investment associated with transition to the alternative fuels and operating costs of providing fuels — are not prohibitive. The exception is producing hydrogen via electrolysis of water by using solar panels. This production route has been assumed for 2030 (i.e., the high production volume case) for hydrogen. As a result, the financial costs associated with hydrogen in this year are an order of magnitude larger than those for the other fuels in that year. Costs would be substantially lower if natural gas were the assumed feed, but the environmental benefits would be diminished.

Hydrogen has multiple potential production routes but only two storage and distribution options. Hydrogen can be stored as a cryogenic liquid or as a gas. Because a large-scale fuel system is needed in the 2030 case, this study assumed gaseous storage and distribution of hydrogen in 2030. To simplify, and for consistency with the long-term goal of a gaseous hydrogen system, hydrogen was assumed to be gaseous in 2015 as well, although in reality a mix of gaseous and liquid storage, or a transition from liquid to gaseous hydrogen, is likely. The choice of gaseous hydrogen necessitates the development of a hydrogen pipeline system. The pipelines in this system likely would be developed as grassroots projects, rather than converted from existing natural gas or petroleum product pipelines.

We estimate that 13 large hydrogen plants, costing \$10 billion, will be sufficient to supply the hydrogen required in the high market share scenario in 2015. These plants would produce 1.3×10^9 SCF of hydrogen per year from natural gas. Feedstock costs are estimated to be \$676 million per year for natural gas.

After switching to solar hydrogen in 2020, we estimate that in 2030 sufficient solar panels to produce the required 28.3×10^9 SCF hydrogen will cost \$397 billion.

3.2.2 Diesel

The U.S. petroleum refining system has been developed over a period of many decades to maximize the yield of gasoline, to some extent at the expense of diesel fuel. Impacts on petroleum refining are discussed explicitly in Section 3.4.

Both costs and benefits are associated with a move from gasoline to diesel fuel for light-duty vehicles. Because higher thermal efficiencies are possible with a CI system, crude-oil throughput may be marginally reduced by the switch. On the other hand, distillate fuel requires more hydrotreating to remove sulfur than does gasoline. Additionally, distillate desulfurization is conducted under significantly higher pressure than naphtha desulfurization. Therefore, new desulfurization reactors will be required for a large-scale transition to diesel fuel, and additional energy costs may be imposed to operate the hydrotreaters. Finally, a change in the demand structure for petroleum fuels may alter the relative values of today's light products and complicate the issues. With additional diesel demand, gasoline may not be the preferred product.

Given the relatively moderate rate of market penetration of 3X vehicles, however, there is unlikely to be a problem supplying sufficient diesel fuel. We have assumed that the incremental cost of diesel production will be comparable to that of gasoline under the reference scenario.

3.2.3 Ethanol

Ethanol was assumed to be domestically produced in this analysis. It is currently produced by fermentation of agricultural sugars, most often from corn. Research and development efforts are underway to produce ethanol from woody and herbaceous biomass. In the 2015 analysis, we assumed that corn will continue to be the dominant feedstock for the production of ethanol. We also assumed that the capacity of ethanol plants will be in the range of approximately 40 million gallons per year — fairly large by today's standards. Ethanol is currently used in the transportation sector ("fuel ethanol") in the form of oxygenated fuels (usually containing about 10% ethanol and 90% gasoline by volume). The volume of ethanol required for 3X vehicles in 2015 is about equal to the current volume of fuel ethanol used (about 7% of gasoline).

The production of ethanol from cellulosic biomass, the production route used for the 2030 analysis, was modeled for Argonne by the National Renewable Energy Laboratory. In the model runs, we assumed that each plant had a production capacity of 50 million gallons per year and consumed about 2,000 dry tons per day of cellulosic biomass. Such a plant is extremely large relative to most current thinking on cellulosic facilities because of the large demand for feedstock and high feedstock transport costs.

We estimate that 40 large, grain-based, ethanol production plants, using the wet-milling process, will supply 1.6 billion gallons of ethanol in 2015. Feedstock cost in that year is estimated to be $1.9 billion, and the assumed feedstock is corn (although other grains are also possible). The 40 plants, each of which produces 40 million gallons of ethanol annually, will cost $4.5 billion. We have not assumed any reduction from nameplate capacity, as these estimates are already gross.

In 2030, 737 large cellulosic ethanol production plants will supply 36.9 billion gallons of ethanol. These plants will consume 2,000 dry tons per day of cellulosic biomass each, which is extremely large relative to typical current projections. It is not clear that sufficient cellulosic feedstock will be available locally to supply these plants, but the assumption of large facilities was consistent with the other analytical scenarios, given the large total volume of ethanol required. It is not likely that transporting cellulosic biomass over great distances would be economic, and

2,000 dry tons per day was the largest plant size that seemed justified. The projected cost of feedstock in 2030 for the cellulosic plants is $16 billion.

3.2.4 Methanol

Production costs for methanol were estimated by assuming that it is supplied by massive methanol plants, each with a capacity of approximately 10,000 tonnes/d. This capacity is approximately four times that of a current typical, large domestic methanol plant. The use of a much larger plant would provide considerable economies of scale. Previous studies by DOE and others have generally assumed that methanol would be imported and that assumption was made for the present study as well. Moreover, current methanol import/export balances for the United States strongly suggest that we would be net methanol importers. In 1995, for example, the United States exported 202×10^3 tonnes of methanol and imported 1.8×10^6 tonnes, as compared to a demand of 7.3×10^6 tonnes. (Approximately 2.3×10^6 tonnes of this demand was used in transportation fuels, primarily tertiary methyl butyl ether [MTBE] or tertiary amyl methyl ether [TAME], but also, in small quantities, as M85 [85% methanol–15% gasoline by volume]).

Another reason for producing methanol in remote, and most likely foreign, plants is that the feedstock costs assumed in this study are low. Natural gas was assumed to be available at $0.80 per 10^6 Btu in 2015 and at $1.00 per 10^6 Btu in 2030. This price is reasonable only if use of foreign natural gas is assumed. The prototypical plant using these feedstock price assumptions was taken to be in Venezuela. For a plant in Saudi Arabia to remain competitive, it would need to produce gas more cheaply than a plant in Venezuela to compensate for the higher shipping costs.

Two additional large methanol plants could supply the entire needs of the PNGV program in 2015. These plants would consume about $210 million worth of natural gas feedstock. This analysis assumes that approximately 30% of the MTBE/TAME used in gasoline would become available due to displacement of gasoline vehicles by 3X vehicles and that other sources of methanol demand would remain the same as a portion of the economy (i.e., demand growth or contraction collinear with economic activity). Other sources of demand include, primarily, production of formaldehyde and acetic acid, and to a lesser extent, solvent methanol and methyl methacrylate.

Under similar assumptions updated to 2030, 50 additional methanol plants would be required, costing $84 billion in capital cost and consuming $5.7 billion worth of natural gas. In 2030, 60% of the MTBE/TAME is assumed to be available from gasoline due to displacement of gasoline vehicles.

3.2.5 Dimethyl Ether

The current worldwide DME production level is less than 40 million gal/yr, and virtually all DME is produced from methanol. We assumed that, as large-scale production occurs, DME will be produced directly from natural gas and that production cost will be reduced. Recent studies by Amoco and Haldor-Topsøe have promoted the use of DME made from natural gas as an economic alternative, with benign environmental properties compared to diesel fuel (Fleisch et al. 1995). If DME is used extensively in 3X vehicles, DME production capacity must be established from virtually zero today, and large investments will be inevitable. As was the case for methanol, DME from natural gas was assumed to be produced abroad and imported to the United States.

The production cost of DME was estimated by using data from the literature (Hansen et al. 1995). Key assumptions were (1) inexpensive natural gas ($0.80 per 10^6 Btu in 2015 and $1.00 per 10^6 Btu in 2030) and (2) very-large-scale plants (40,000 bbl/d). The current capital cost for such a plant has been estimated at approximately $1 billion. Three such plants would be required in 2015, and 66 would be required in 2030. Feedstock costs suggest that DME will be produced from remote gas sources, most likely outside the United States. A study by Amoco indicated that DME produced in Venezuela and transported by tanker to the U.S. Gulf Coast would have a break-even price 35% higher than diesel fuel. Approximately $254 million would be needed for feedstock in 2015 ($7.0 billion in 2030) under the high market share scenario.

3.3 Fuel Distribution, Storage, and Refueling

Existing literature was consulted to determine the storage requirements, extent of movement by various modes of transportation, and required number of refueling stations for the volume of fuel required. In some cases, existing fuel distribution systems could be used for the PNGV fuels (e.g., using some elements of gasoline infrastructure for methanol or ethanol). Finally, cumulative costs for production, storage, distribution, and refueling stations were estimated from the literature and consultation with industry experts.

Methanol is assumed to be imported in this analysis. Figure 7 shows methanol distribution infrastructure. The imported M100 will be stored in tanks at terminals until it is distributed. Trucks will distribute initial volumes of M100 (the first 1×10^6 bbl/d gasoline equivalent) to service stations or inland terminals within 100 miles of marine terminals. In this way 75% of the U.S. population can be easily reached. For larger volumes, pipelines will be constructed. Currently, no methanol pipeline distribution system is available. Because of the corrosiveness of methanol, existing steel pipeline systems will have to be modified to handle this fuel. Methanol refueling pumps will have to be added to existing stations. We have assumed that 50,000 gasoline equivalent gallons will be supplied per station.

Ethanol, all of which was assumed to come from domestic sources, will not be produced in evenly distributed regions (Figure 8). Initially, ethanol will be moved by truck, but eventually, as volumes increase, we assume it will be moved by pipeline (48%), barge (12%), and rail (40%) (agreeing with a study by EA Energy Technologies Group [1991]).

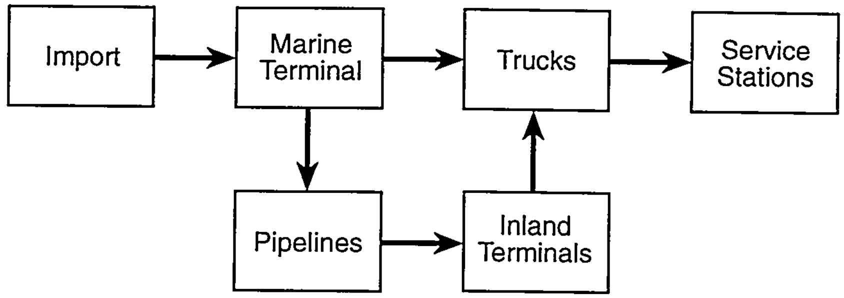


FIGURE 7 Methanol Distribution Infrastructure

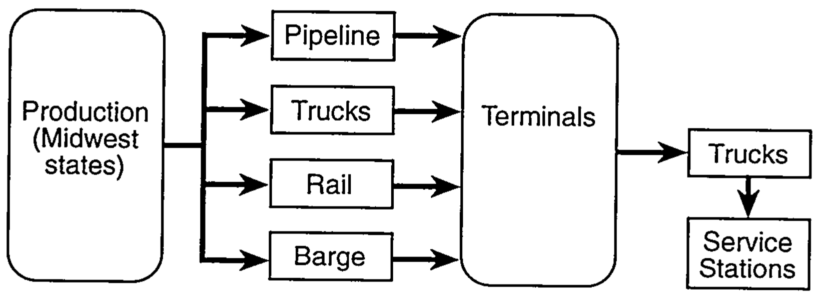


FIGURE 8 Ethanol Distribution Infrastructure

Dimethyl ether was also assumed to be imported in this analysis. Figure 9 shows DME distribution infrastructure. Like methanol, it will be stored at large marine terminals and transported to inland terminals and stations within 100 miles by truck for initial volumes and by pipeline for larger volumes. Dimethyl ether has physical properties similar to LPG and was assumed to be transported via LPG pipelines. However, LPG pipeline systems are not extensive, and LPG consumption will not be reduced as a result of DME use, so additional pipelines will have to be constructed for widespread use of DME. Gasoline pipelines, which will become available as DME replaces gasoline, might be converted for DME transportation and distribution. Gasoline refueling stations can be upgraded to handle DME refueling by adding DME pumps. Service station equipment and costs are based on those for LPG.

Extensive transportation and distribution systems for hydrogen in either gaseous or liquid form are not currently available. A dedicated pipeline system would have to be built for gaseous hydrogen because hydrogen can diffuse through metals. Liquid hydrogen must be maintained below its boiling point (–252.7°C) and is generally shipped by truck or rail. These modes of transport are expensive, but it is not feasible to ship cryogenic liquids via pipeline. For this reason, we have assumed that gaseous hydrogen transported through pipeline systems will be used in hydrogen fuel-cell vehicles (FCVs). Figure 10 shows hydrogen distribution infrastructure.

A summary of the distribution and refueling capital equipment needs and costs appears in Tables 7-10 for each of the alternative fuels for the years 2015 and 2030. Figure 11 shows the distribution infrastructure costs.

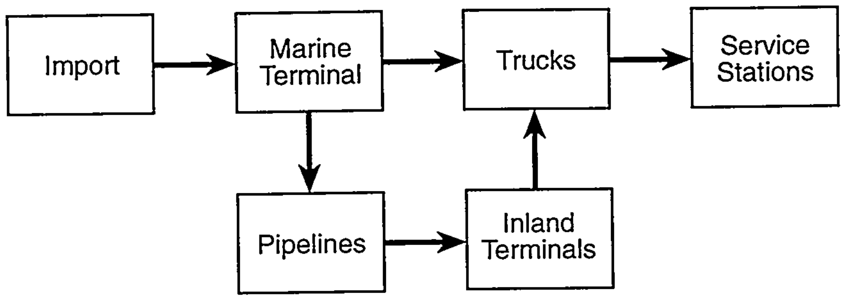


FIGURE 9 Dimethyl Ether Distribution Infrastructure

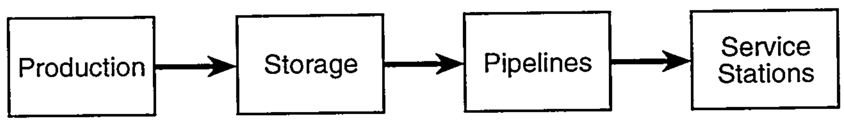


FIGURE 10 Hydrogen Distribution Infrastructure

TABLE 7 Distribution Infrastructure Requirements and Costs for M100

Infrastructure Element	Physical Requirements (Number)	Costs ($\$10^6$)
Through 2015: 70,000 bbl/d GEG[a] Capacity		
Total barrels (terminal tanks)	2.90×10^6	28
Terminal truck racks	8	10
Total trucks	218	16
Pipelines	0	0
Service stations	1,793	308
Total		363
Through 2030: 1.6×10^6 bbl/d GEG Capacity		
Total barrels (terminal tanks)	8.91×10^7	873
Terminal truck racks	184	238
Total trucks	5,118	500
Pipelines	5	549
Service stations	40,277	6,928
Total		9,088

[a] GEG = gasoline equivalent gallons.

TABLE 8 Distribution Infrastructure Requirements and Costs for E100

Infrastructure Element	Physical Requirements (Number)	Costs ($\$10^6$)
Through 2015: 70,000 bbl/d GEG[a] Capacity		
Total barrels (terminal tanks)	2.17×10^6	16
Terminal truck racks	6	8
Total trucks	241	12
Pipelines	0	0
Rail cars	143	9
Barges	4	0.4
Service stations	1,793	289
Total		334
Through 2030: 1.6×10^6 bbl/d GEG Capacity		
Total barrels (terminal tanks)	4.87×10^7	366
Terminal truck racks	138	178
Total trucks	3,656	260
Pipelines	5	375
Rail cars	3,216	209
Barges	84	9
Service stations	40,277	6,485
Total		7,882

[a] GEG = gasoline equivalent gallons.

3.4 Impacts on Existing Petroleum Refineries

The potential impact of the PNGV program on the U.S. petroleum refining industry is an issue that arose during the August 1995 PNGV program review. This issue was analyzed in some detail in the phase 1 study to determine the impact of reduced refinery crude throughput due to efficiency improvements under the PNGV program and a possible switch to a nonpetroleum fuel.

Considerable amounts of gasoline will be saved as a result of using 3X vehicles. The gasoline saving is due to two factors — fuel efficiency gains by 3X vehicles and substitution of gasoline by other fuels. Figure 12 reveals the effects of fuel economy efficiency and fuel substitution of 3X vehicles on U.S. gasoline consumption. Although both effects are significant, the efficiency effect is about twice as large as the substitution effect. As the figure shows, even

TABLE 9 Distribution Infrastructure Requirements and Costs for DME

Infrastructure Element	Physical Requirements (Number)	Costs ($\$10^6$)
Through 2015: 70,000 bbl/d GEG[a] Capacity		
Total barrels (terminal tanks)	2.50×10^6	85
Terminal truck racks	8	10
Total trucks	187	26
Pipelines	0	0
Service stations	1,793	441
Total		563
Through 2030: 1.6×10^6 bbl/d GEG Capacity		
Total barrels (terminal tanks)	7.66×10^7	2,605
Terminal truck racks	182	235
Total trucks	4,400	843
Pipelines	5	1,259
Service stations	40,277	9,908
Total		14,850

[a] GEG = gasoline equivalent gallons.

TABLE 10 Distribution Infrastructure Requirements and Costs for H_2

Infrastructure Element	Physical Requirements (Number)	Costs ($\$10^6$)
Through 2015: 70,000 bbl/d GEG[a] Capacity		
Pipeline mileage	7,533	5,273
Service stations	1,793	2,510
Total		7,783
Through 2030: 1.6×10^6 bbl/d GEG Capacity		
Pipeline mileage	167,000	116,900
Service stations	40,277	56,388
Total		173,288

[a] GEG = gasoline equivalent gallons.

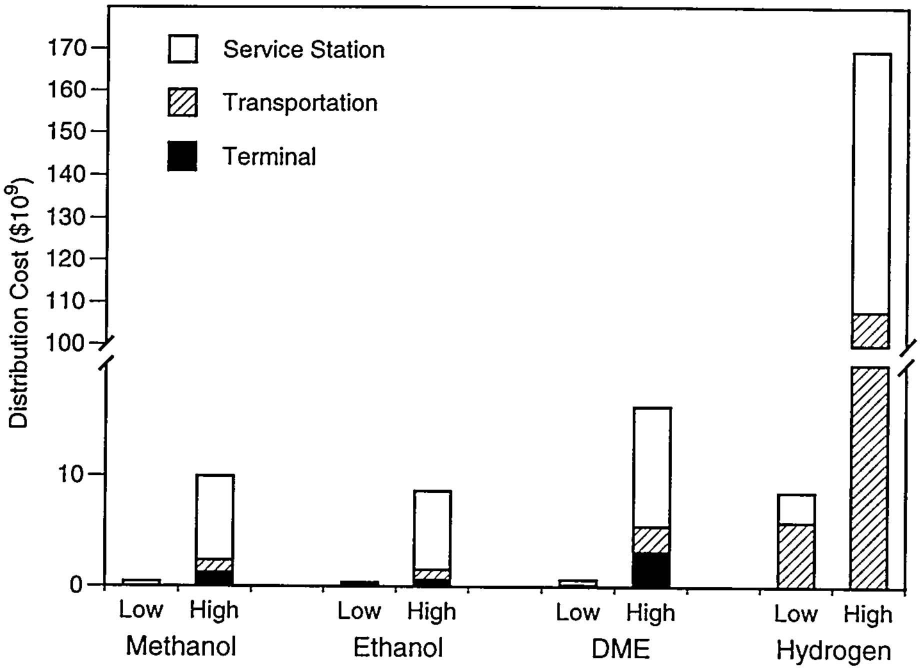


FIGURE 11 Capital Requirements of Fuel Distribution Infrastructure

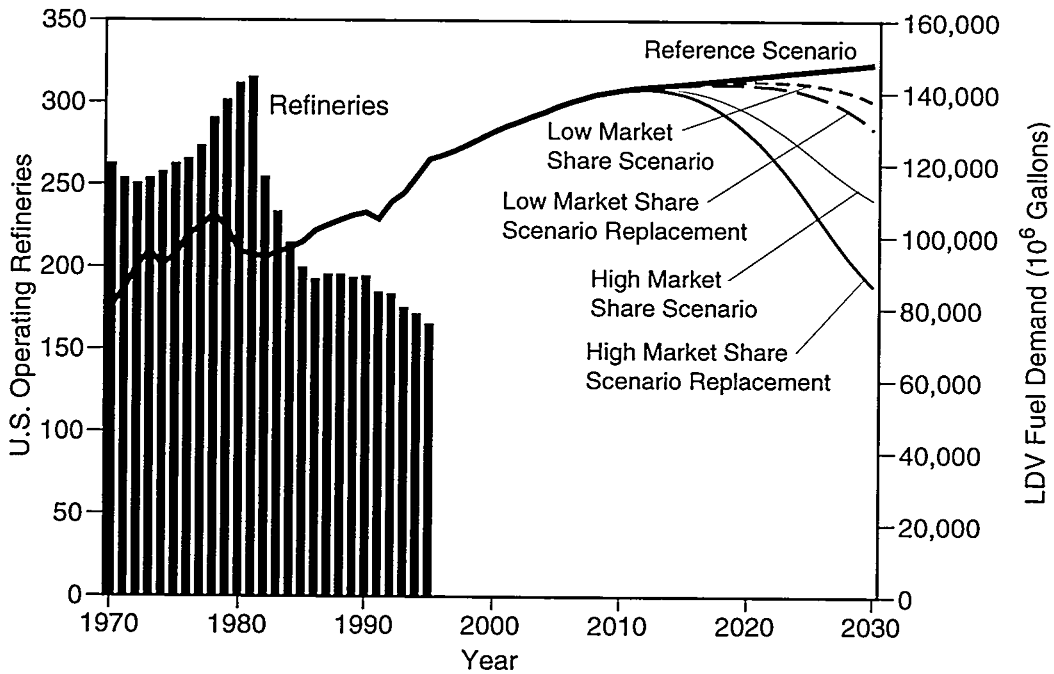


FIGURE 12 Light-Duty-Vehicle Fuel Consumption under the PNGV Scenarios and Historical Data on U.S. Refineries

though vehicle usage will continue to rise from now until 2030, the commercialization of 3X vehicles, even those using gasoline, in high volume will bring light-duty-vehicle gasoline consumption below the 1990 level beginning around 2020.

Since diesel fuel is produced at the same refineries and from the same feedstock (petroleum) as gasoline, production of an increased amount of diesel fuel for 3X vehicles will not pose a major infrastructure problem. However, the U.S. petroleum refining industry has had a long history of maximizing gasoline production, so an increase in demand for diesel fuel would require refiners to modify the product balance. The flexibility of refineries with respect to product slate varies considerably among individual refineries, but there are some fundamental differences between producing diesel fuel and gasoline that could have a major impact on the industry as a whole. Such a change in the industry average product slate would not be as easily accommodated as a marginal change. Also, to reduce emissions from diesel combustion, clean diesel fuel will have to be produced for use in 3X vehicles; additional distillate desulfurization capacity will have to be installed at refineries. In summary, although new refineries may not need to be built for diesel, investments in existing refineries will be necessary for increased diesel fuel production.

The impact on the refining industry will not be as dramatic as had been feared in August 1995 under the market penetration assumptions employed in this study. First, foreknowledge of the program will be unprecedented and ample in terms of lead time and technical details. Reductions in projected fuel demand will not begin to be evident for about 10 years and then will occur only gradually. Demand for light-duty transportation fuel will be reduced significantly by introducing 3X vehicles. In 2030, light-duty transportation fuel demand under the low market share scenario will be reduced to the reference scenario level for 2005. Demand will be reduced to the reference scenario level for 1990 under the high market share scenario. This estimate only pertains to efficiency improvements due to the use of 3X vehicles. The impact on refineries will be greater if a nonpetroleum fuel is dominant among 3X vehicles.

The refining industry has survived more dramatic downturns over a shorter period of time in the past. In the period from the mid-1980s through the early 1990s, a large number of refineries were closed. The change in refining capacity was less dramatic than what we might see under PNGV, however, largely because the older and simpler (i.e., smaller) refineries were the ones that closed and the larger, more complex, newer refineries survived.

The rationalization of the refining industry during that period suggests that there is no longer much slack in the system. Currently, refineries have higher capacity utilization rates than was the case prior to the rationalization (capacity factor was near 70% in the early 1980s and is over 90% now). These higher rates are necessary, in large part, for the refineries to run profitably. The usual retirement of refining equipment should be sufficient to avoid massive refinery closures of an economically unrecoverable nature, if the reduction in capacity is planned.

The U.S. refining industry continues to move abroad due to the high cost of environmental regulations in the United States. We expect this trend will continue and will not be greatly influenced by the PNGV program. What influence there is, however, will tend to accelerate the movement of fuel production abroad. Still, the long lead time for the transition to the PNGV program provides some relief for the concerns of many refiners. The relatively modest shifts in fuel-product slate envisioned if diesel is used as the PNGV fuel (instead of gasoline) would probably put U.S. refiners at a disadvantage relative to foreign refiners. Certainly, this statement would hold as refineries are configured today. However, with a 10-20 year average life cycle for refinery equipment, these gasoline-maximized refineries could be retooled to produce more diesel over time.

The increased use of diesel fuel in the United States may upset the world balance of crude oil demand, increasing the value of waxier crude oils. European countries currently buy some U.S. distillate and sell gasoline to the United States. Gasoline is also imported from Canada and the Caribbean. Changing the relative values of petroleum fuels would have an impact on such trade, although the precise effects may be difficult or impossible to predict accurately.

More dramatic impact would presumably be felt by shifting to nonpetroleum fuels. The impact on distribution, storage, and retailing systems would certainly be greater. In short, there is currently no significant national infrastructure for the distribution of any fuels other than gasoline, No. 2 and No. 6 diesel fuels, and natural gas. Alcohols present hydrophilic and materials-compatibility problems with pipelines (and fuel distribution pumps and some vehicles), and transport by trucks is expensive. Here, again, the long lead time available will make adaptation feasible but will not necessarily make an inexpensive or simple transition.

4 Total Fuel Cycle Analysis

4.1 Fuel-Cycle Energy and Emissions Modeling

For a given 3X technology, powered with a given fuel, per-mile fuel-cycle energy use and emissions are first estimated with the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Wang 1996). The per-mile energy and emissions results are then fed into the IMPACTT model to estimate energy use and emissions per year under the two 3X vehicle sales scenarios (Mintz, Tompkins, and Camp 1994). In the end, petroleum savings and emissions reductions of the given technology are estimated for the complete fuel cycle, including both vehicle operations and upstream fuel production processes. Petroleum savings by a 3X technology comes from two sources — tripling fuel economy and fuel substitution. The fuel-cycle analysis includes both effects in estimating petroleum savings.

For a given transportation fuel, a fuel cycle includes the following chain of processes: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion (see Figure 13). Fuel-cycle activities before vehicular fuel combustion are usually referred to as upstream activities (which account for upstream energy and upstream emissions). In this report, primary energy resources (e.g., crude oil, natural gas, and coal) are referred to as energy feedstocks; fuels are referred to as gasoline, diesel, electricity, etc.

4.1.1 GREET

Energy is consumed and emissions are generated during upstream fuel-cycle activities, as well as during vehicular activities. In each upstream activity, fossil energy is burned and emissions are generated. Also, fuel leakage and evaporation that ultimately generate emissions are associated with upstream activities. The GREET model calculates fuel-cycle energy use and emissions by taking into account all these sources (Wang 1996).

The GREET model calculates grams-per-mile (g/mi) emissions and Btu-per-mile (Btu/mi) energy use for various fuel cycles. GREET includes emissions of volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with size smaller than 10 microns (PM_{10}), sulfur oxides (SO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The three greenhouse gases (GHGs) (CH_4, N_2O, and CO_2) are further combined with their global warming potentials as CO_2-equivalent GHG emissions. GREET calculates energy consumption for three types of energy: total energy (all energy sources), fossil energy (petroleum, natural gas, and coal), and petroleum only. For a given fuel-cycle stage, energy use (in Btu per million Btu of energy throughput) is calculated. The calculated total energy use for the particular stage is allocated into different process fuels (e.g., natural gas, residual oil, diesel,

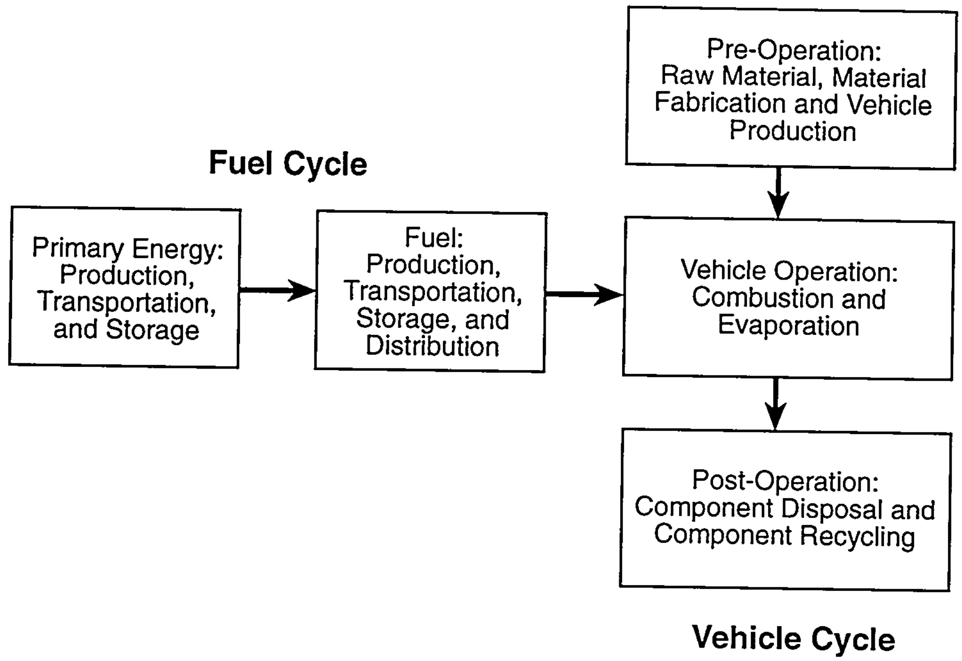


FIGURE 13 Fuel Cycles and Vehicle Cycles for Transportation Energy and Emissions Analysis

coal, and electricity). Fuel-specific energy use, together with emission factors of the combustion technology for a specific fuel, is then used to calculate combustion emissions for the stage. GREET has an archive of combustion emission factors for various combustion technologies fueled with different fuels and equipped with different emission-control technologies. Combustion emission factors for VOC, CO, NO_x, PM_{10}, CH_4, and N_2O are derived primarily from data published by the EPA (EPA AP-42). Sulfur oxides emission factors for most fuels are calculated from sulfur content, assuming that all sulfur contained in process fuels is converted into sulfur dioxide (SO_2). Carbon dioxide emissions are calculated by a carbon balance approach; i.e., the carbon contained in the fuel burned, minus the carbon contained in combustion emissions of VOC, CO, and CH_4, is assumed to be converted to CO_2. GREET calculation logic for upstream emissions is presented in Figure 14.

Emissions of VOC, CO, and NO_x from vehicle operations for gasoline vehicles (GVs) and diesel vehicles (DVs) are calculated with EPA's Mobile5a model, which calculates on-road per-mile emissions of motor vehicles for the three pollutants. Emissions of PM_{10} for GVs and DVs are calculated with EPA's Part5 model, EPA's Mobile5a-equivalent model for calculating particulate matter and SO_x emissions. Gasoline vehicles are treated in this study as benchmark vehicles. Vehicular emissions from alternative-fueled vehicles (AFVs) are calculated within GREET by using benchmark GV emissions and emission reduction rates by AFVs relative to benchmark GVs.

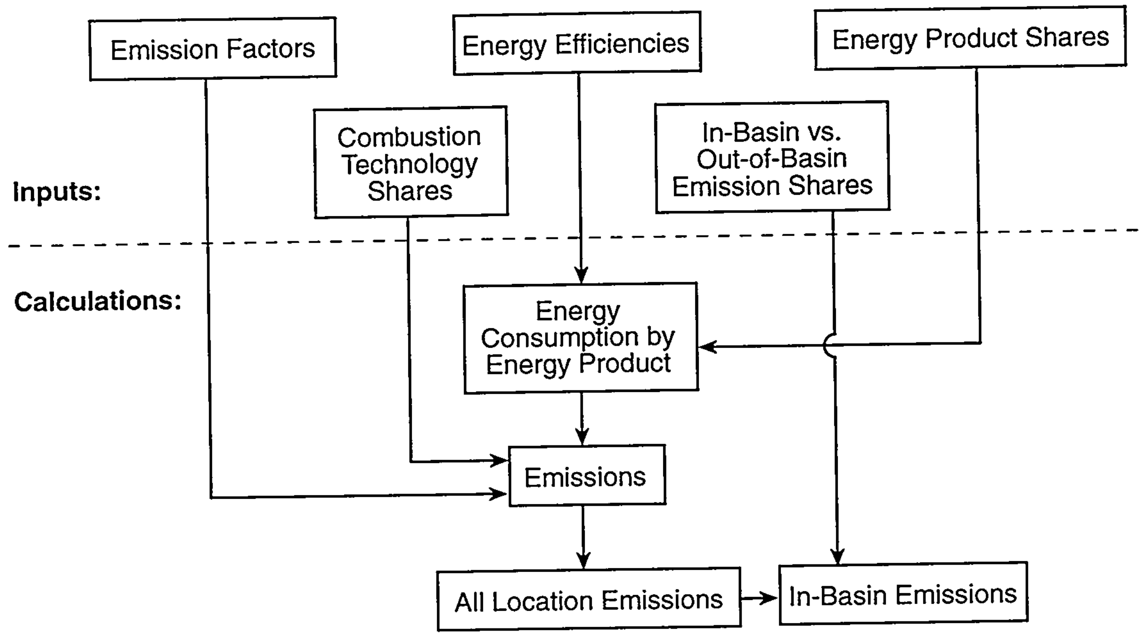


FIGURE 14 GREET Calculation Logic for Upstream Emissions

4.1.2 IMPACTT

The IMPACTT model was used to estimate annual energy and emissions impacts associated with 3X vehicles (Mintz, Tompkins, and Camp 1994). IMPACTT is a model that calculates the effect of advanced-technology vehicle characteristics and market penetration assumptions on baseline fuel use and emissions. IMPACTT incorporates a vehicle stock model that adds new vehicles and retires old vehicles from an initial population profile to produce annual profiles of the auto and light-truck population by age or vintage; a usage module to compute VMT, oil displacement and fuel use; and an emissions module to compute upstream and downstream emissions of criteria pollutants and GHGs for autos and light trucks. The usage module computes the petroleum that would have been consumed by conventional vehicles in the absence of the new technology, the energy consumed by new-technology vehicles, and the net savings due to the presence of new-technology vehicles in the fleet.[1] Figure 15 illustrates the model's structure. Outputs include estimates of the quantity and value of oil displaced and emissions reduced, the quantity of alternative fuels consumed by the advanced-technology vehicles, and the marginal costs borne by purchasers of advanced-technology vehicles.

1 Unlike GREET, IMPACTT's fuel use module computes only downstream or operational energy use.

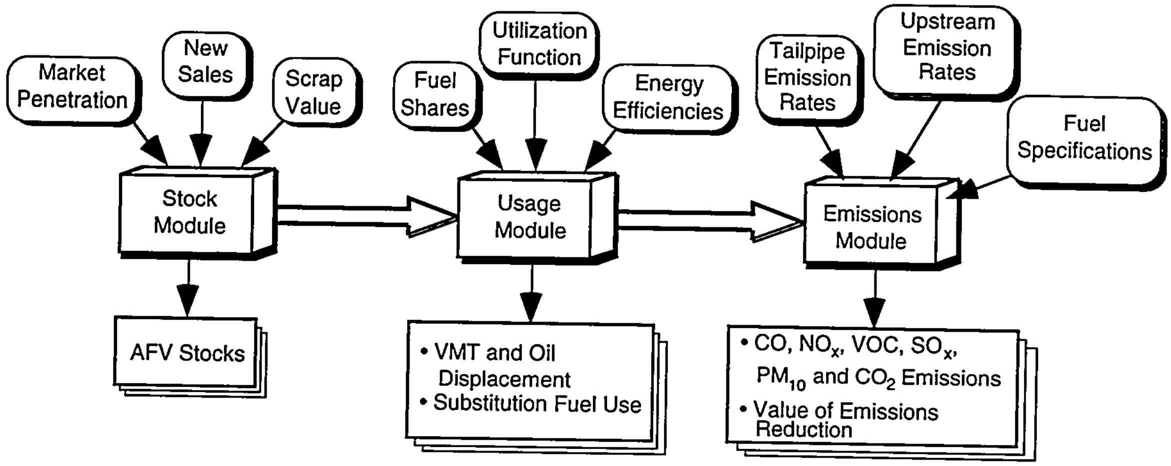


FIGURE 15 Structure of the IMPACTT Model

Version 5.0 of IMPACTT was used for this analysis. Major changes in the emissions module account for most of the difference between this version and the version documented earlier (Mintz, Tompkins, and Camp 1994). Emissions of NO_x, CO, VOC, and PM_{10} are now computed separately for autos and light trucks by using age-based tailpipe emission rates obtained from EPA's Mobile5a model (see Sec. 4.4) for conventional SI and CI engines operating on gasoline and diesel fuel and average tailpipe and upstream emissions rates for nonconventional engines and fuels obtained from GREET Version 1.3.

4.2 Analysis of Upstream Energy Use and Emissions Rates

In order to estimate upstream energy and emissions, a fuel cycle path from primary energy recovery to fuel combustion in vehicles must be specified for each technology option. The base case or benchmark fuel-cycle path is petroleum to gasoline for conventional vehicles. In this study, eight fuel cycle paths were analyzed (see Figure 6).

As Figure 6 indicates, hydrogen is produced either from natural gas or solar energy, and ethanol is produced either from corn or biomass. Prior to 2020, hydrogen is assumed to be produced from natural gas and ethanol from corn. Beginning in 2020, hydrogen is assumed to be produced from solar energy and ethanol from biomass.

Petroleum to RFG. This path includes crude oil recovery in oil fields; crude oil transportation and storage; crude oil refining; gasoline transportation, storage, and distribution; and gasoline combustion. Energy efficiency for each upstream stage is presented in Table 11. By using these energy-efficiency percentages, energy use and emissions from fuel combustion are calculated with GREET.

TABLE 11 Energy Efficiencies of Upstream Fuel-Cycle Activities (percent)

Activity	Petroleum to RFG	Petroleum to Diesel	Natural Gas to DME	Natural Gas to methanol	Natural Gas to H_2
Primary energy recovery	98.0	98.0	94.6[a]	94.6[a]	94.6[a]
Primary energy transportation and storage	99.5	99.5	N/A[b]	N/A[b]	N/A[b]
Fuel production	82.5	93.0	70.0	65.0	68.0
Fuel transportation, storage, and distribution	98.5	98.7	98.0	97.0	84.6[c]

Source: Wang (1996).

[a] Includes natural gas recovery efficiency (97%) and natural gas processing efficiency (97.5%).

[b] Not applicable. It is assumed that DME, methanol, and hydrogen are produced near natural gas fields.

[c] Includes gaseous hydrogen transportation (via pipeline) efficiency (94%) and compression efficiency (90%).

Petroleum to Diesel. This path includes crude oil recovery, transportation, and storage; diesel production in crude refineries; and diesel transportation, storage, and distribution. Energy efficiencies for these stages are presented in Table 11.

Natural Gas to DME. This path includes natural gas recovery and processing; DME production; and DME transportation, storage, and distribution. Energy efficiencies of these stages are presented in Table 11. Because the carbon ratio of DME is higher than that of natural gas, the process of converting 1 gram of natural gas to 1 gram of DME results in a net carbon absorption. The carbon absorption rate of the DME conversion process is estimated to be 17,724 grams of CO_2 per 10^6 Btu of DME produced. This CO_2 value is subtracted from the CO_2 emission value calculated for natural gas combustion in DME plants.

Natural Gas to Methanol. This path includes natural gas recovery and processing; methanol production; and methanol transportation, storage, and distribution. Energy efficiencies for these stages are presented in Table 11. Because the carbon ratio of methanol is higher than that of natural gas, the process of converting 1 gram of natural gas to 1 gram of methanol results in a net carbon absorption. The carbon absorption rate of the methanol conversion process is estimated to be 18,081 grams of CO_2 per 10^6 Btu of methanol produced. This CO_2 value is subtracted from the CO_2 emission value calculated for natural gas combustion in methanol plants.

Natural Gas to H_2. Although both liquid and gaseous H_2 can be used for H_2-powered fuel-cell vehicles (FCVs), gaseous H_2 is assumed here. Liquefaction of H_2 poses additional energy loss and emissions issues, and transportation and storage of liquid H_2 can be expensive. For gaseous H_2, the path from natural gas to H_2 includes natural gas recovery, and processing; H_2 production, transportation via pipeline, and storage; and H_2 compression at service stations. Energy efficiencies for these stages are presented in Table 11. Because H_2 contains no carbon, the conversion of natural gas to H_2 produces excess CO_2 emissions. We estimated that the conversion process produces CO_2 at a rate of 48,376 grams per 10^6 Btu of H_2 produced. No CO_2 sequestration in hydrogen plants is assumed here.

Solar Energy to H_2. Production of H_2 from solar energy via water electrolysis offers great energy and environmental benefits. This use of solar energy enables the transportation sector to use a practically unlimited energy source. It has been argued that, in the long run, H_2 from solar energy is the ultimate energy source for the transportation sector (Delucchi 1992), although much needs to be done to reduce the cost of solar H_2 technologies. We assumed in our study that H_2 is produced in centralized facilities in such regions as the Southwestern United States, where solar energy is abundant. The produced H_2 is compressed moderately (to about 100 psi) and then transported to H_2 service stations via pipelines. In service stations, gaseous H_2 is compressed to 5,000-6,000 psi and refueled to H_2-powered FCVs. We also assumed that electricity is used for H_2 compression and transportation. The U.S. average electricity generation is assumed for estimating GHG emissions from the electricity used for H_2 transportation and compression. We estimated that the energy efficiency of gaseous H_2 transportation via pipeline is 94% and that the energy efficiency of H_2 compression in service stations is 90%. Fossil energy use for H_2 production from solar energy is negligible and is ignored here.

Corn to Ethanol. This path includes corn production and transportation; ethanol production; and ethanol transportation, storage, and distribution. GHG emissions from corn production come from fuels used for farming, harvesting, and corn drying, together with the amount from fertilizers and herbicides used during corn farming. Agricultural inputs for corn production are presented in Table 12. To calculate GHG emissions for the amount of fertilizer and herbicide used for corn production, we assumed that 43.9, 8.3, 2.5, and 272 Btu are needed to produce a gram of nitrogen fertilizer, phosphorus fertilizer, potassium fertilizer, and herbicide, respectively.

Wet-milling technology is assumed for corn-to-ethanol production. In the United States, wet-milling ethanol plants now account for about two-thirds of total ethanol production capacity; the remaining one-third is produced in dry-milling plants. For wet-milling plants, we assumed that a bushel of corn produces 2.5 gallons of ethanol.

TABLE 12 Agricultural Inputs and Energy Efficiencies of Ethanol Paths

Path/Value	Corn (per bushel)	Woody Biomass (per dry ton)	Herbaceous Biomass (per dry ton)
Fuels for farming (Btu)	20,620	248,510	234,040
Nitrogen fertilizer (grams)	464	7,787	5,457
Phosphorus fertilizer (grams)	217	813	3,873
Potassium fertilizer (grams)	197	813	6,004
Herbicide (grams)	14.6	13.5	11.3
Transportation (Btu)	3,150	162,600	59,700
Ethanol production efficiency (%)	57,214[a]	55.0[b]	57.1[b]
Ethanol transportation, storage, and distribution efficiency (%)	97.8	97.8	97.8

Source: Wang (1996) with recent revisions.

[a] Btu of fuel input to corn-to-ethanol plants per gallon of ethanol produced.

[b] This does not include the electricity credit in ethanol plants. The electricity credit is taken into account separately.

Wet-milling ethanol plants produce by-products that can be used for animal feed or other purposes. Thus, total emissions from ethanol plants and from upstream corn production must be allocated between ethanol and other by-products. Allocation ratios can be calculated in several ways: by weight, by energy content, by market value, and by replacement (Shapouri et al. 1995).[2] For wet-milling ethanol plants, an ethanol co-product credit of 52% is estimated with the weight approach, 43% with the energy content approach, 30% with the market value approach, and 19% with the replacement approach. Although the market value approach is subject to the fluctuation of market prices of ethanol and co-products, it is the approach used in our analysis as it seems most reasonable for estimating corn-to-ethanol energy use and emissions. Currently, most corn-to-ethanol plants use coal as the process fuel.

Biomass to Ethanol. This path includes biomass production and transportation; ethanol production; and ethanol transportation, storage, and distribution. Biomass in our analysis includes both woody and herbaceous materials. Energy and emissions for biomass production are calculated in the same way as those for corn production. Agricultural inputs for biomass production are presented in Table 12. In this study, we assumed that biomass is burned in biomass-to-ethanol plants to provide heat. While combustion of biomass undoubtedly produces CO_2 emissions, these emissions come from the atmosphere through the process of photosynthesis during biomass

2 The weight approach allocates emissions on the basis of relative weights of ethanol and co-products; the energy content approach on the energy content of ethanol and co-products; the market value approach on the values of ethanol and co-products; and the replacement approach on the amount of animal feed replaced by ethanol co-products that otherwise would have been produced from soybeans.

growth. Thus, CO_2 emissions from biomass combustion are treated as being zero. For the same reason, CO_2 emissions from ethanol combustion by ethanol-powered vehicles also are treated as being zero.

Combustion of biomass in biomass-to-ethanol plants through cogeneration facilities generates electricity and also provides the heat required for ethanol production. Credits amounting to 1.11 and 0.67 kwh of electricity per gallon of ethanol produced are estimated for woody and herbaceous biomass ethanol plants, respectively (Wang 1996). The electricity generated is assumed to be exported to the electricity grid. Emissions credits for the generated electricity are calculated in GREET by taking into account the amount of electricity generated and the average emissions associated with electricity generation in electric utility systems.

4.3 Analysis of Downstream Energy Use and Emissions Rates

4.3.1 Energy and CO_2 Emissions Rates

Energy use by 3X vehicles is calculated simply by assuming that all 3X vehicles meet the PNGV goal; i.e., 3X passenger cars will have gasoline equivalent fuel economy of 81 mpg and 3X light trucks will have 63 mpg. CO_2 emissions are calculated by a carbon-balance approach: the amount of carbon contained in the fuel consumed minus the amount contained in VOC, CO, and CH_4 is assumed to be converted into CO_2.

4.3.2 Emissions Rates for Criteria Pollutants

Downstream emission rates are calculated by combining the in-use emission rates estimated by EPA's Mobile5a and Part5 (for PM_{10}) models for conventional SI and CI engines operating on gasoline and diesel fuels with the 3X efficiency goal and GREET-developed ratios of the relative in-use emissions-generating potential of the candidate PNGV engine/fuel combinations. Emission rates of passenger cars and light trucks are estimated separately. Since Mobile5a and Part5 estimate separate emission rates for class 1 and class 2 light trucks, a weighting procedure (assuming a split of 91% for class 1 and 9% for class 2) was used to compute average rates for all light trucks. Downstream VOC emissions (i.e., those related to vehicle operation) include both exhaust and evaporative components. Evaporative emissions, in turn, include diurnal, hot-soak, refueling, running loss, and resting loss emissions. PM_{10} emissions include exhaust, tire-wear, and brake-wear emissions. CO, NO_x, and SO_x emissions are all exhaust emissions. SO_x emissions are calculated by assuming that all the sulfur contained in a given fuel is converted into SO_2 emissions.

Mobile5a and Part5 estimate emissions for gasoline and diesel vehicles meeting federal Tier 1 emission standards. Emissions of gasoline vehicles from Mobile5a and Part5 are assumed to be those for SI engines fueled with RFG, and emissions of diesel vehicles are assumed to be those for CI engines fueled with diesel. It is generally assumed that 3X vehicles will be able to meet proposed federal Tier 2 emission standards. Between Tier 1 and Tier 2, exhaust standards for VOC, CO, and NO_x are lowered by 50%. To estimate 3X vehicle emissions from the emissions of Tier 1 vehicles estimated with Mobile5a, exhaust emissions of VOC, CO, and NO_x are assumed to be reduced by 50% for 3X vehicles relative to emissions of Tier 1 vehicles.

We anticipate that stand-alone engines for 3X vehicles generally will be larger than hybrid engines for 3X vehicles. Hybrid engines will be operated at the energy-efficient region of the engine map. Emission performance of stand-alone and hybrid engines fueled with the same fuel may be different as well. However, both engines will be subject to the same vehicle emission standards. Thus, manufacturers may design both engines for operation to meet applicable emission standards. For this reason, we assume that a same-type engine (e.g., SI or CI engine) fueled with the same fuel has the same emissions performance in stand-alone and in hybrid applications.

We assume that M100 and E100 will be used in SI engines. These two fuels have inherently low evaporative emissions. We assume evaporative emissions from SI engines fueled with M100 and E100 are 60% lower than those from SI engines fueled with RFG. Emissions of other pollutants or sources from RFG, M100, and E100 are assumed to be identical because the same standards will be applied to the three fuels.

For diesel 3X vehicles, Tier 2 equivalent emissions are estimated by assuming a 50% reduction in the exhaust emissions of VOC, CO, NO_x that were estimated for Tier 1 diesel vehicles. We assume that diesel vehicles will meet the current 0.08 g/mi PM standard. DME-fueled CI engines have inherently lower PM_{10} emissions. We assume that PM_{10} exhaust emissions are reduced by 90% for DME relative to diesel.

For hydrogen FCVs, we assume zero emissions for all pollutants and all sources except for PM_{10} tire-wear and brake-wear emissions, which we assume are the same as for other vehicles. On-board methanol reformers for methanol FCVs generate emissions. We assume a 90% reduction in exhaust emissions for VOC, CO, and NO_x; 60% reduction in VOC evaporative emissions; and 100% reduction in PM_{10} exhaust emissions for methanol FCVs relative to gasoline Tier 2 vehicles.

4.4 Energy and Emissions Estimates

In the IMPACTT setup used for this analysis, reference scenario vehicles and seven combinations of future fuel/engine technologies were modeled. Reference scenario vehicles incorporated RFG-fueled conventional SI engines. Alternative PNGV fuel/engine technologies were

- RFG-fueled SI or hybrid engines,
- Methanol-fueled SI or hybrid engines,

- Ethanol-fueled SI or hybrid engines,
- Diesel-fueled CI or hybrid engines,
- DME-fueled CI or hybrid engines,
- Hydrogen fuel cells, and
- Methanol fuel cells.

For each of these fuel/engine technologies, IMPACTT calculations proceeded in three steps. First, using the reference-scenario vehicle sales and 3X vehicle market share assumptions described in Section 2.1, vehicle stock for conventional and 3X vehicles were determined for each year between market introduction (2007 in the high market share scenario and 2013 in the low market share scenario) and 2030. These values are shown in Figure 16. Second, differences in total fuel use by U.S. light-duty vehicles between reference and alternative market share scenarios were used to calculate fuel savings attributable to fuel efficiency and fuel substitution by 3X vehicles. Third, emissions of criteria pollutants (i.e., CO, VOC, NO_x, PM_{10}, SO_x, and CO_2) were computed as functions of either fuel use or a combination of VMT and age-based emission factors.[3] Age-based emission degradation curves for CI and SI engines were derived from EPA's MOBILE5a model.

As compared to the low market share scenario, the high market share scenario has nearly three times as many PNGVs on the road by 2030. These vehicles produce similar increases in VMT and fuel savings.

4.4.1 Emissions of Criteria Pollutants

Figures 17-21 display emissions of the five criteria pollutants arising from upstream activity and vehicle operation (i.e., downstream activity) for the reference scenario and each of the fuel/technology combinations under the two PNGV 3X vehicle market share scenarios. For all figures, the reference scenario is shown as the first member of a series of bars, each of which represents an alternative fuel/technology combination. Upstream and downstream emissions are shown separately to more clearly illustrate how the alternative differs from the reference scenario

[3] Operational emissions of NO_x, CO, VOC, and PM_{10} are computed as functions of VMT and emissions rates by vehicle type (auto or light truck) and age (0 to over 20 years), which can vary by calendar year; upstream emissions of all pollutants and downstream emissions of SO_x and CO_2 are computed as functions of the quantity of fuel used and its composition (i.e., carbon and sulfur content, which can vary by calendar year or by switching from one fuel type to another [e.g., from RFG to methanol]). Fuel specifications are included in the Appendix.

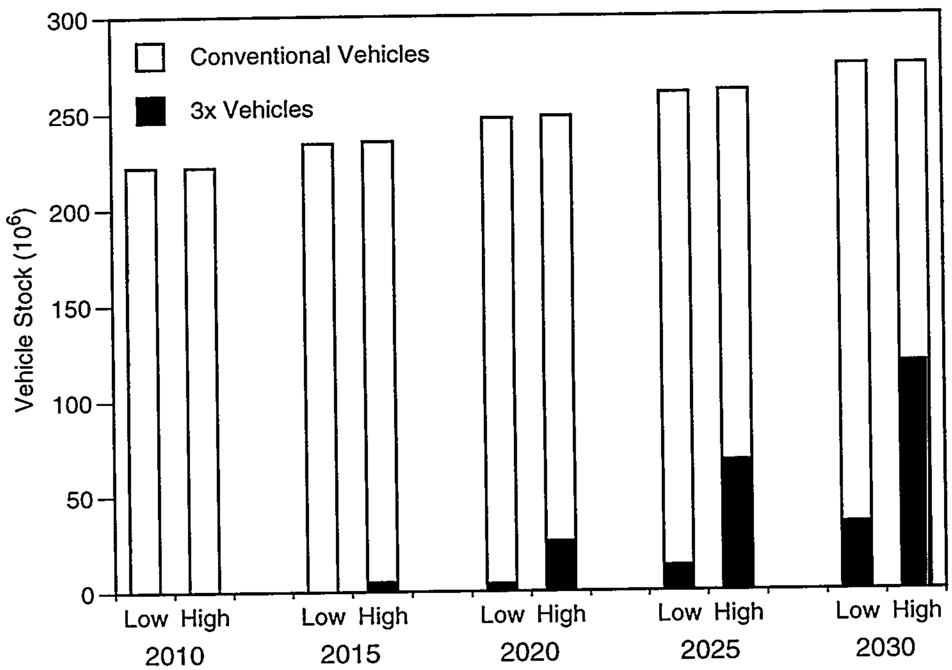
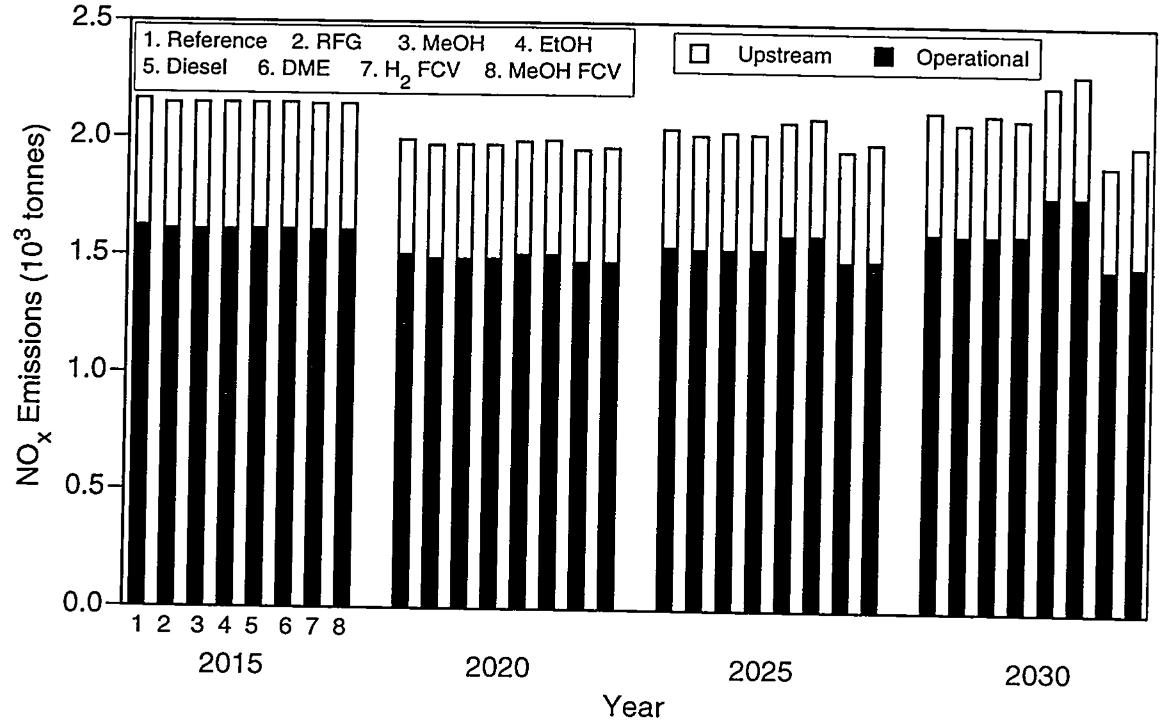


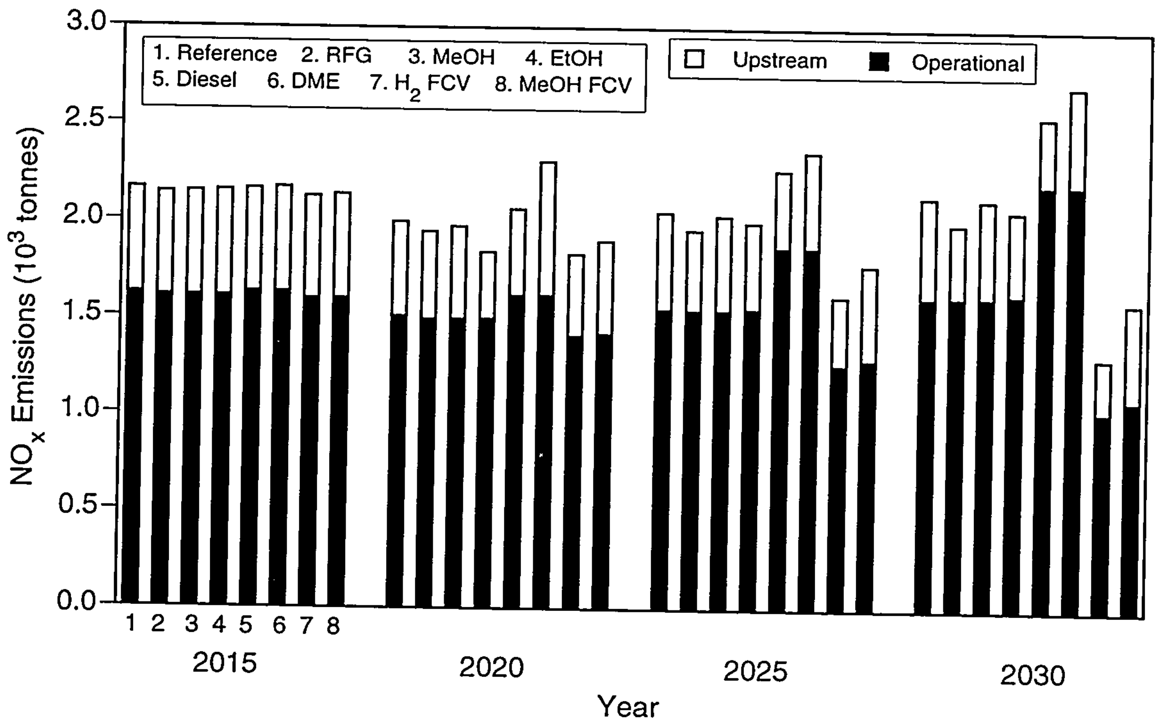
FIGURE 16 Conventional and PNGV Light-Duty-Vehicle Stock under the High and Low Market Share Scenarios

distribution of upstream vs. downstream emissions, as well as to indicate where impacts are likely to occur. Since upstream and downstream emissions often have very different spatial locations, the breakout also provides additional policy guidance for considering the impacts of the several alternatives. Generally speaking, most of the changes in NO_X, CO, and VOC impacts occur downstream, while SO_X and PM_{10} impacts occur both upstream and downstream. Although both market share scenarios show similar results, the patterns are much more striking under the high market share scenario, which by definition, is a more extreme example of possible market penetration. Thus, the following discussion tends to focus on results from the high market share scenario. Also note that each of the technology/fuel alternatives considered in the analysis was examined in the context of a market penetration scenario that contains a significant portion of conventional vehicles as well as PNGVs. Thus, emissions are computed for a combination of conventional and PNGV technologies, and the results are less striking than those of the PNGV technologies.

Nitrogen Oxides. Figure 17 illustrates NO_X emissions under the two scenarios. Because of the assumption of Tier 2 emissions controls, reference scenario NO_X emissions hold relatively steady over the forecast period. Fuel cell vehicles (especially those using hydrogen fuel) show the greatest potential for reducing NO_X emissions (primarily downstream), with RFG- and ethanol-fueled vehicles distant third and fourth place alternatives as a result of upstream emissions reduction. Both diesel- and DME-fueled alternatives are likely to increase downstream NO_X relative to the reference scenario. These results illustrate the need for implementing NO_X control technologies for CI engines.

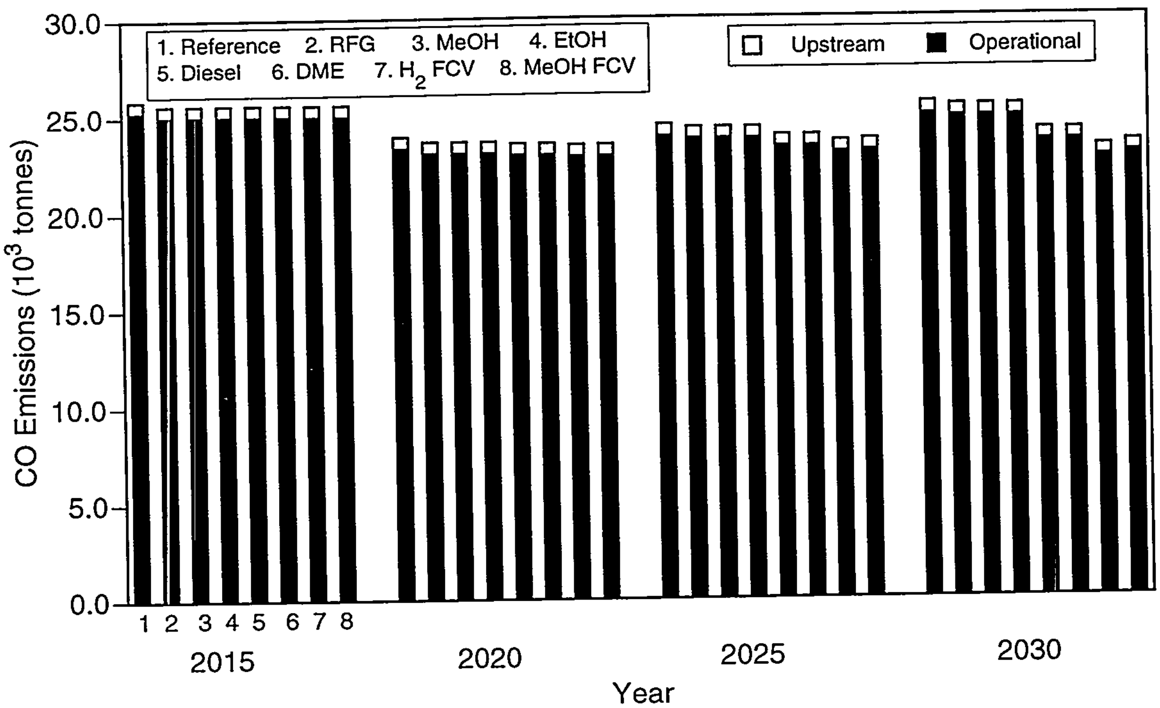


(a) Low Market Share Scenario

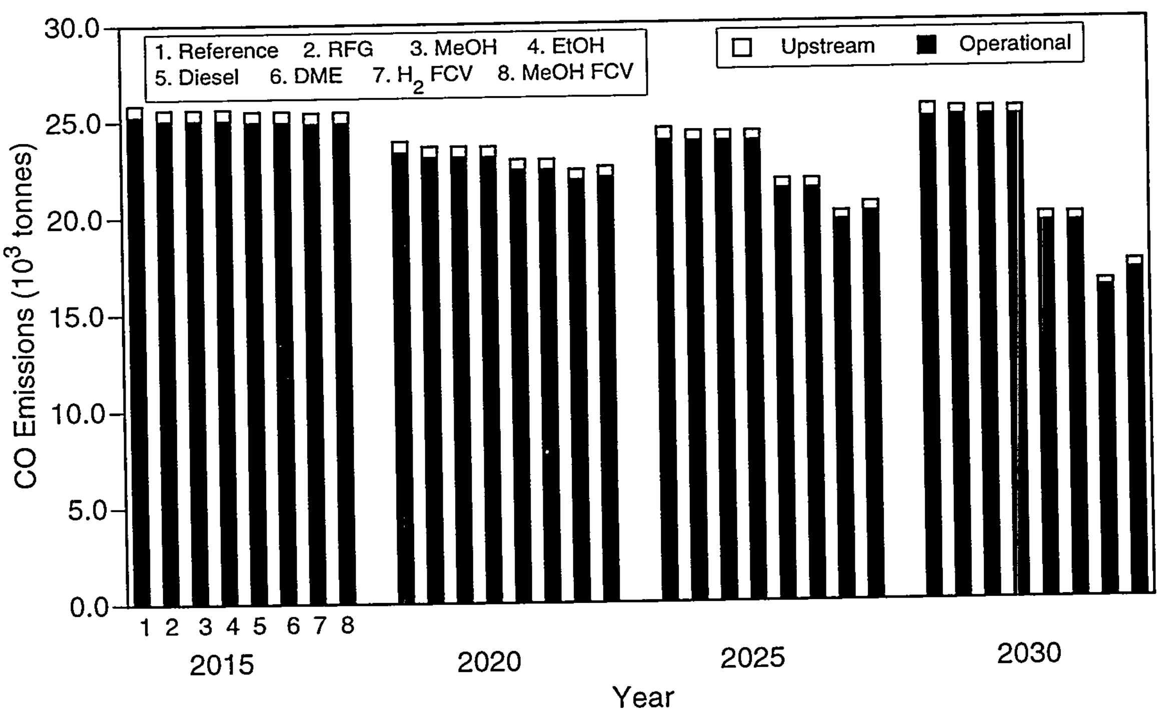


(b) High Market Share Scenario

FIGURE 17 Fuel-Cycle NO_x Emissions of U.S. Light-Duty-Vehicle Fleet (10^3 tonnes/yr)

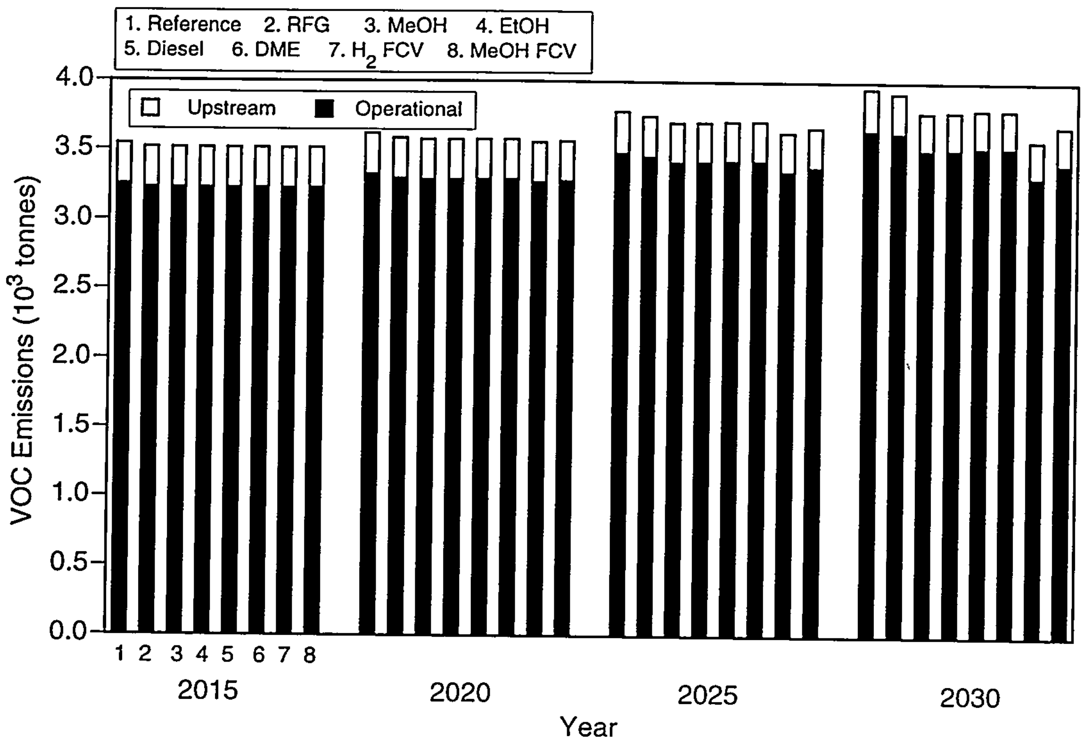


(a) Low Market Share Scenario

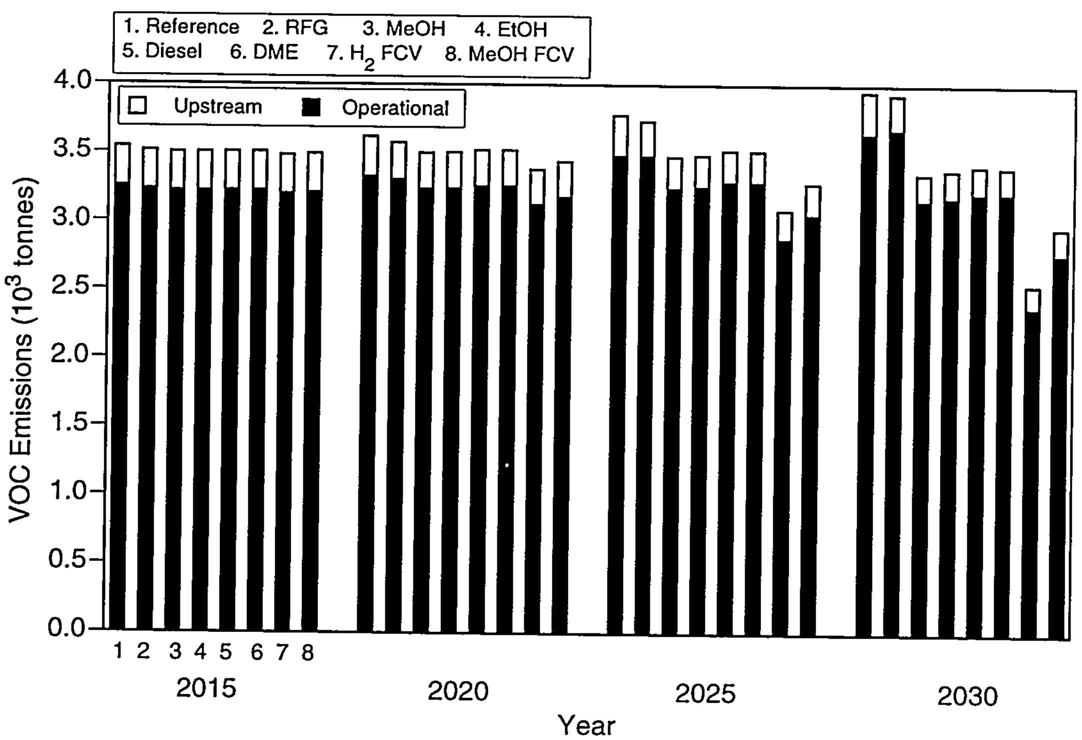


(b) High Market Share Scenario

FIGURE 18 Fuel-Cycle CO Emissions of U.S. Light-Duty-Vehicle Fleet (10^3 tonnes/yr)

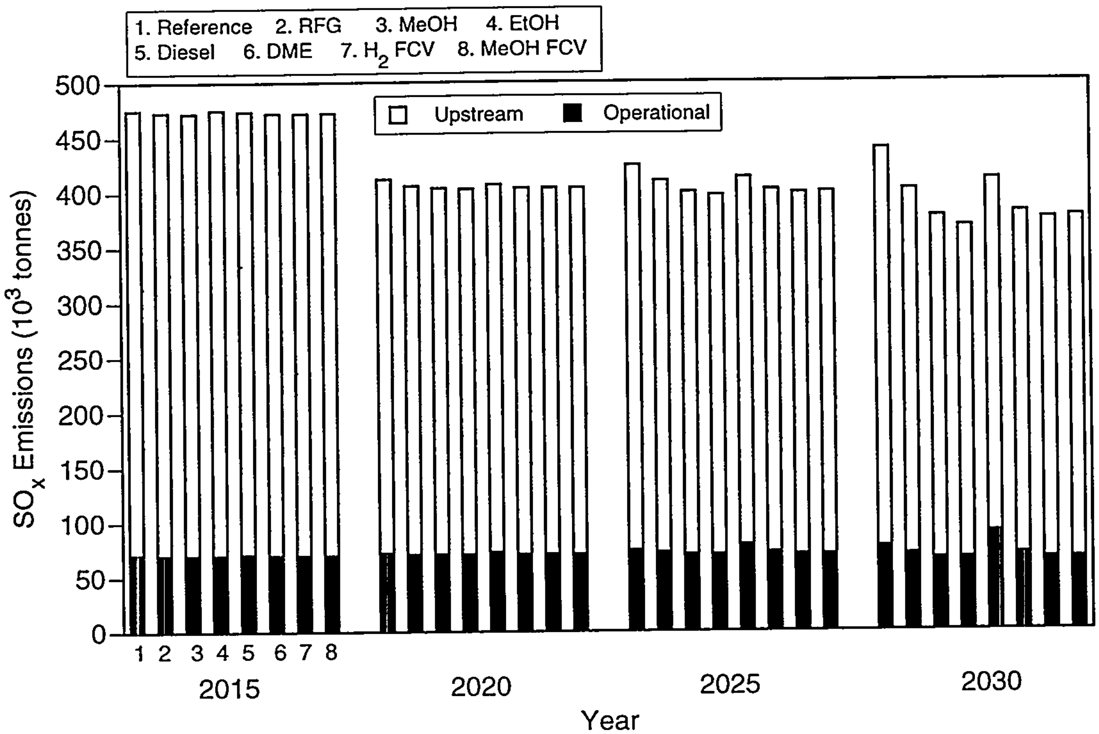


(a) Low Market Share Scenario

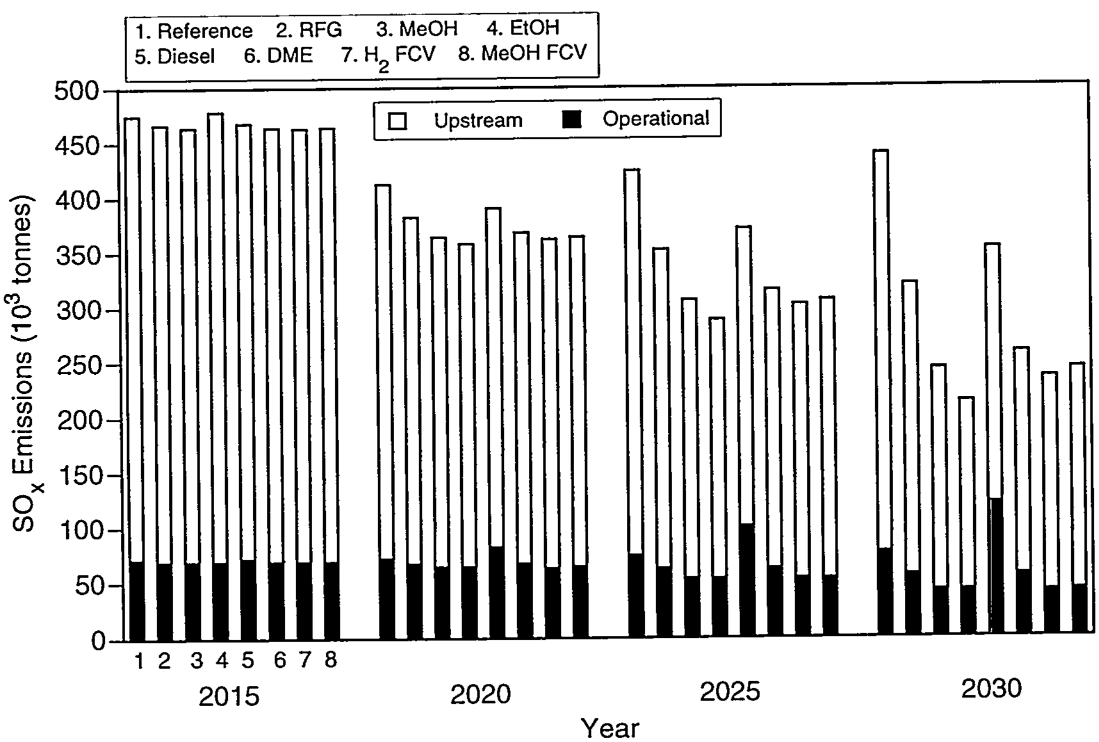


(b) High Market Share Scenario

FIGURE 19 Fuel-Cycle VOC Emissions of U.S. Light-Duty-Vehicle Fleet (10^3 tonnes/yr)

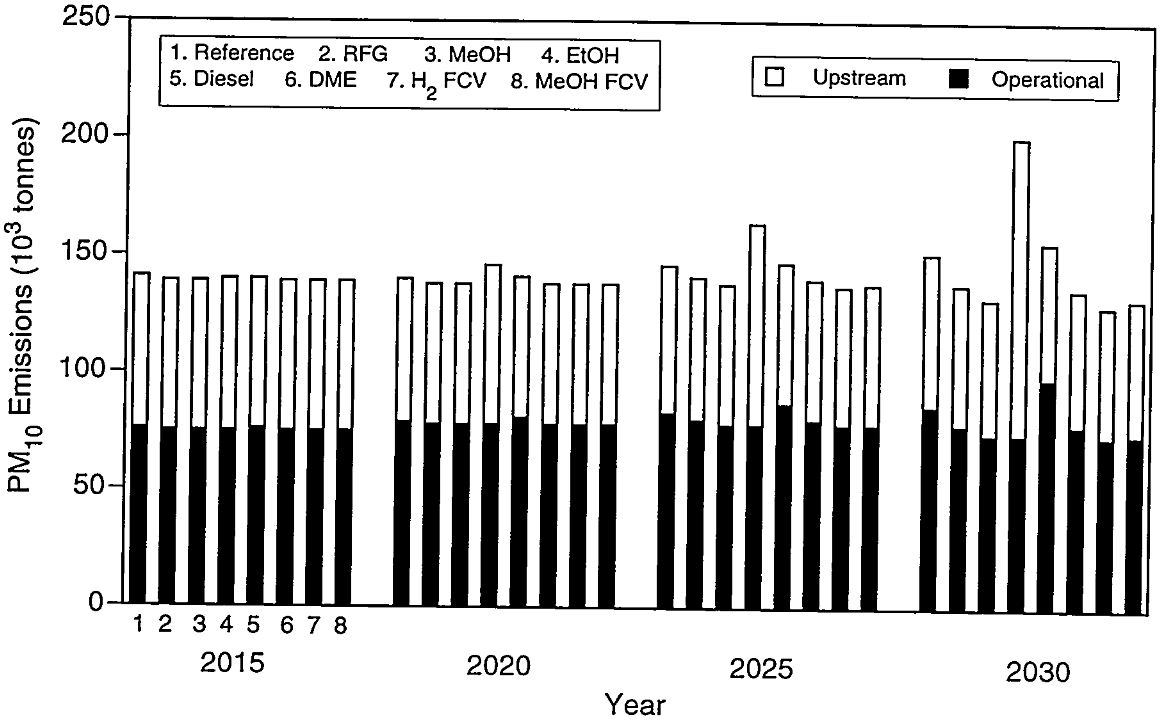


(a) Low Market Share Scenario

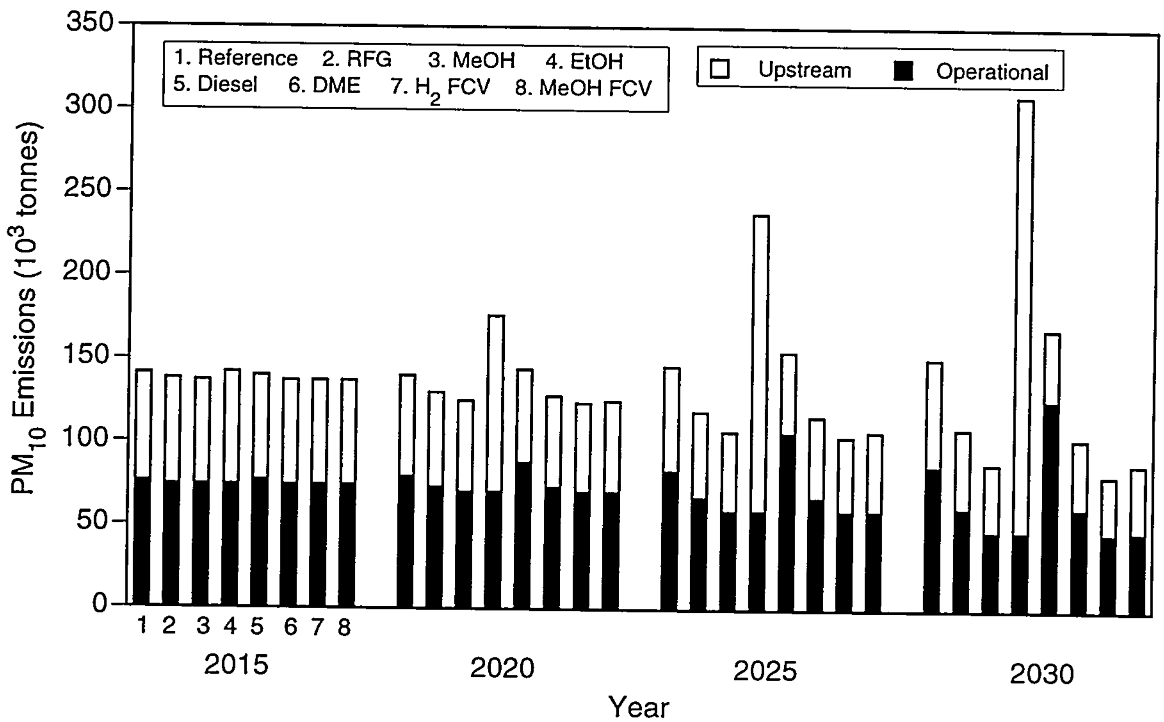


(b) High Market Share Scenario

FIGURE 20 Fuel-Cycle SO_x Emissions of U.S. Light-Duty-Vehicle Fleet (10^3 tonnes/yr)



(a) Low Market Share Scenario



(b) High Market Share Scenario

FIGURE 21 Fuel-Cycle PM_{10} Emissions of U.S. Light-Duty-Vehicle Fleet (10^3 tonnes/yr)

Carbon Monoxide. Figure 18 displays CO emissions under the high and low market share scenarios. Again, the assumption of Tier 2 emission standards constrains CO emissions, which drop between 2015 and 2020 and then rise slowly under the reference scenario. (The rise is due to the gradual increase in VMT.) Fuel cell vehicles again show the greatest potential for downstream emission reduction, followed by diesel- and DME-fueled alternatives. Given the CI engine's proven record of relatively low CO emissions, this result is not unexpected.

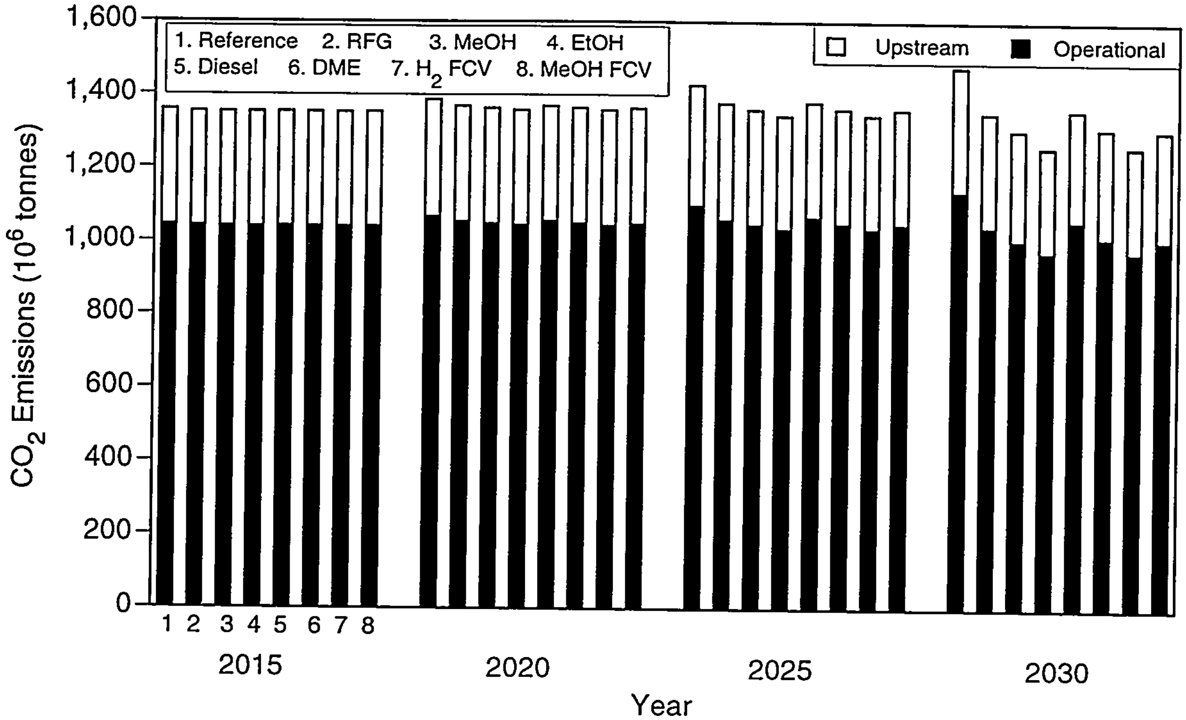
Volatile Organic Compounds. Unlike NO_x and CO, reference scenario emissions of VOCs continue to rise throughout the forecast period (see Figure 19). This rise is a result of increasing travel coupled with Tier 2 controls that apply to only a portion of VOC emissions (i.e., VOC emissions from engine exhaust). Again, fuel cells (especially hydrogen-fueled) are the clear leader from a VOC emissions reduction standpoint. Fuel cells produce substantial reductions in downstream VOC emissions relative to the other alternatives. With the exception of RFG, all technology/fuel alternatives produce significant reductions in upstream and downstream VOC emissions, primarily because of their fuel properties (see the Appendix).

Sulfur Oxides. Because most SO_x emissions occur upstream in the fuel pathway, SO_x emissions are closely related to the volume of fuel used. Improvements in upstream fuel production activities cause reference scenario SO_x emissions to drop between 2015 and 2020, and then to begin rising slowly (with VMT growth) over the forecast period (see Figure 20). Relative to the reference scenario, all technology/fuel alternatives produce a decline in SO_x emissions because of their 3X efficiency improvement. Ethanol-, methanol-, DME-, and hydrogen-fueled alternatives achieve the biggest declines because of the inherently low sulfur content of these fuels. Conversely, diesel shows the least reduction in SO_x emissions relative to the reference scenario, because diesel CI engines produce high tailpipe SO_x emissions.

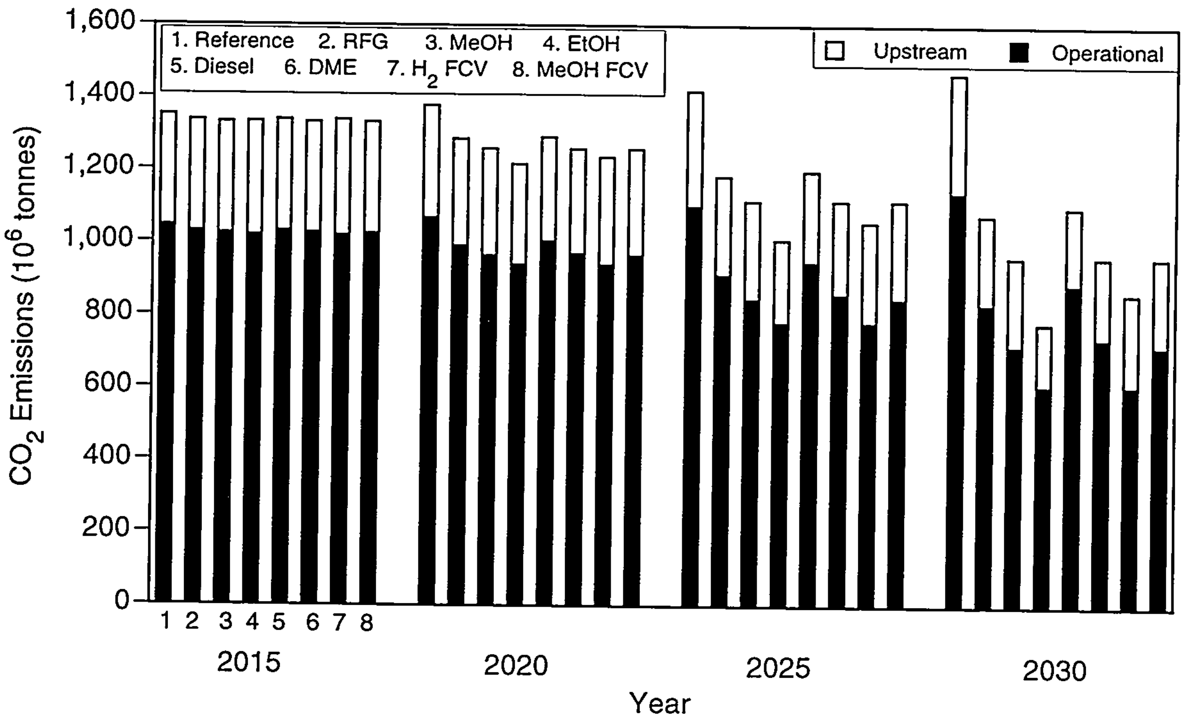
Particulate Matter. Nearly half of all PM_{10} emissions occur upstream. PM_{10} emissions rise slowly under the reference scenario due to growth in VMT (see Figure 21). Ethanol- and, to a lesser extent, diesel-fueled alternatives increase PM_{10} emissions, while hydrogen-, methanol-, DME-, and RFG-fueled alternatives reduce PM emissions. Note that the sharp increase in PM_{10} emissions for the ethanol-fueled alternative occurs upstream, from agricultural operations as well as ethanol production. The increase for the diesel-fueled alternative, which is expected, occurs downstream, from diesel engine exhaust, since we assume that diesel vehicles will meet the current 0.08 g/mi PM standard. If stringent PM standards are to be adopted and to be met by diesel vehicles, diesel PM emissions will be certainly lower than what we estimate here.

4.4.2 Carbon Dioxide Emissions

Figure 22 displays emissions of CO_2 for the reference scenario and PNGV market share scenarios in the same format as used for the criteria pollutant graphs. As shown in Figure 22, reference scenario emissions of CO_2 rise steadily over the forecast period. Since the reference scenario assumes no significant use of alternative fuels, the CO_2 generated by increased vehicular



(a) Low Market Share Scenario



(b) High Market Share Scenario

FIGURE 22 Fuel-Cycle CO_2 Emissions of U.S. Light-Duty-Vehicle Fleet (10^6 tonnes/yr) travel (by conventional vehicles) is moderated only by relatively modest fuel economy improvements (new autos achieve 27.5 mpg in 1995 vs. 35.4 mpg in 2030; light trucks rise from 20.2 mpg in 1995 to 26.5 mpg in 2030). Because of their 3X efficiency improvement, all technology/fuel combinations under the two market share scenarios achieve significant reductions in CO_2 emissions relative to the reference scenario. Even for the low market share scenario, with its relatively modest PNGV market shares, CO_2 emissions hold steady relative to the reference scenario for RFG- and diesel-fueled alternatives, while declining for all other technology/fuel combinations.

Under the high market share scenario, several of the alternatives produce dramatic reductions in CO_2 emissions. Chief among these low-CO_2 alternatives are ethanol-fueled IC engines and hydrogen fuel cells, both of which generate no CO_2 from vehicle operation. Hydrogen-fuel-cell vehicles generate no CO_2 emissions because no carbon is contained in the hydrogen fuel. Ethanol-fueled SI engines are assumed to generate zero CO_2 emissions because the carbon in ethanol comes from carbon in the atmosphere via photosynthesis. When combined with the conventional vehicles (and their CO_2 emissions) in the high market share scenario, these low-CO_2 alternatives achieve an overall reduction in total downstream CO_2 emissions (from all light-duty vehicles, both PNGV and conventional) of nearly 50%. Due to higher upstream emissions, the hydrogen scenario achieves somewhat less overall reduction; however, it is still far superior to the next best alternatives, DME- and methanol-fueled IC engines and methanol-fuel-cell vehicles.

4.4.3 Energy Estimates

Figures 23-25 provide estimates of total energy, fossil energy, and petroleum use for the reference and low and high market share scenarios. Again, totals are disaggregated by upstream vs. downstream component, and formats are identical to the above graphs.

Total Energy. As shown in Figure 23, total energy use by light-duty vehicles rises to 20.2 quads in 2030 under the reference scenario. Vehicle operations (downstream energy) account for 78% of this total (approximately 15.7 quads). (See Figure 12 for additional detail on downstream energy savings). By definition, all fuel/technology alternatives achieve 3X fuel economy. Thus, downstream energy use declines by 26% in 2030 for all alternatives under the high market share scenario (2% in the low market share scenario), and the upstream energy requirements of the various fuels account for all the variation in total energy use among the fuel/technology alternatives.

In 2030, upstream energy (for resource extraction/production and fuel production and distribution) accounts for 22% of total energy use by light-duty vehicles under the reference scenario vs. 27% of the total for methanol-fueled and 29% for ethanol-fueled alternatives under the high market share scenario. As a result, methanol- and ethanol-fueled alternatives achieve slightly less total energy reduction than either RFG- or diesel-fueled alternatives. The diesel-fueled

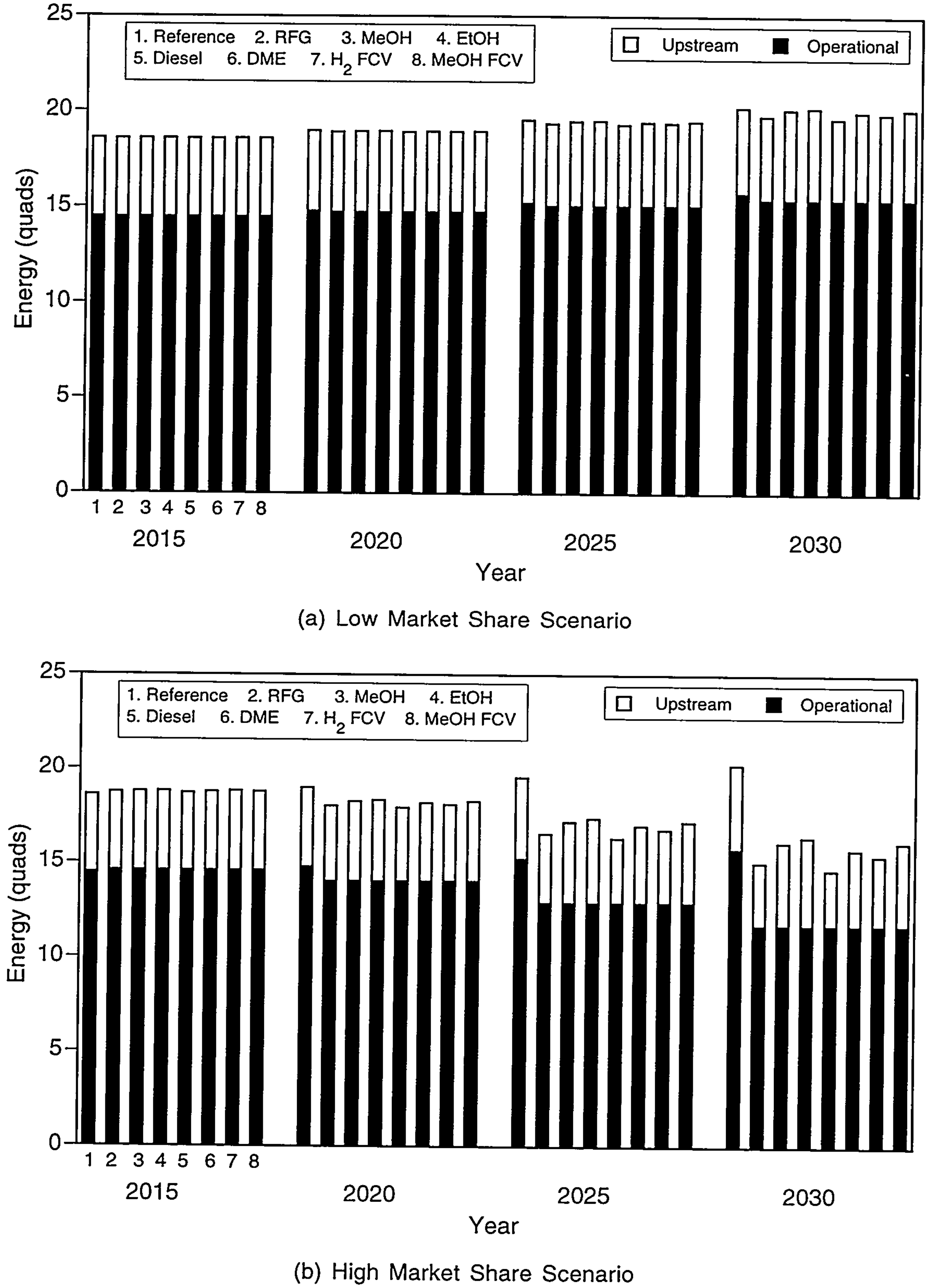
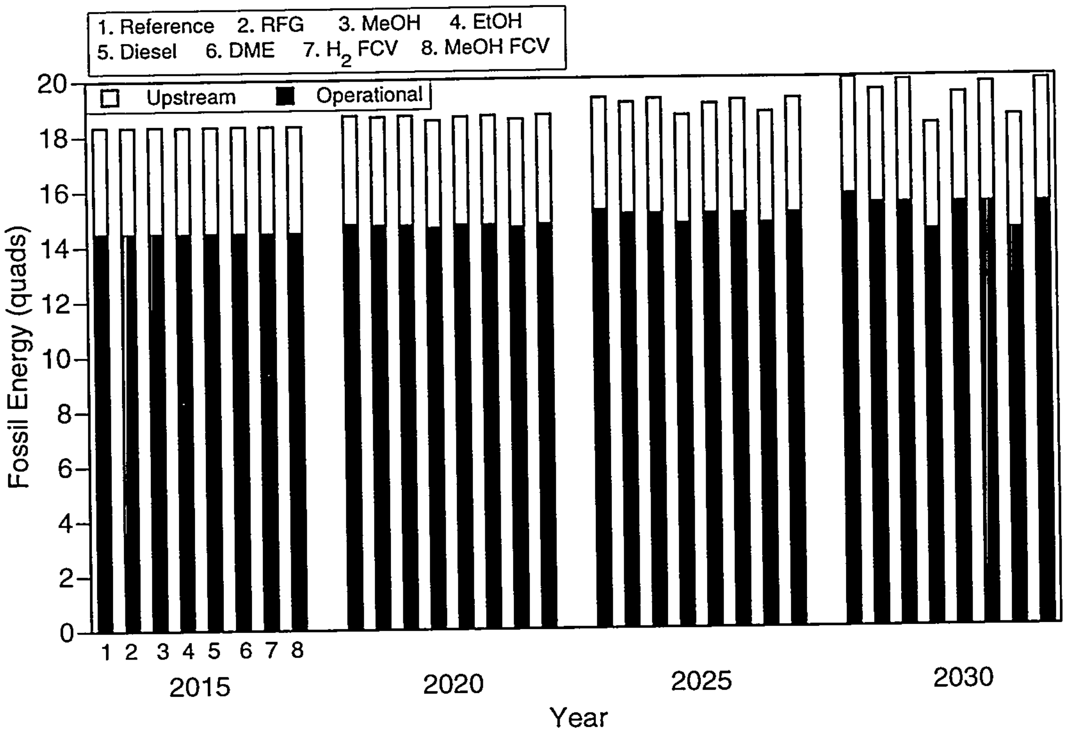
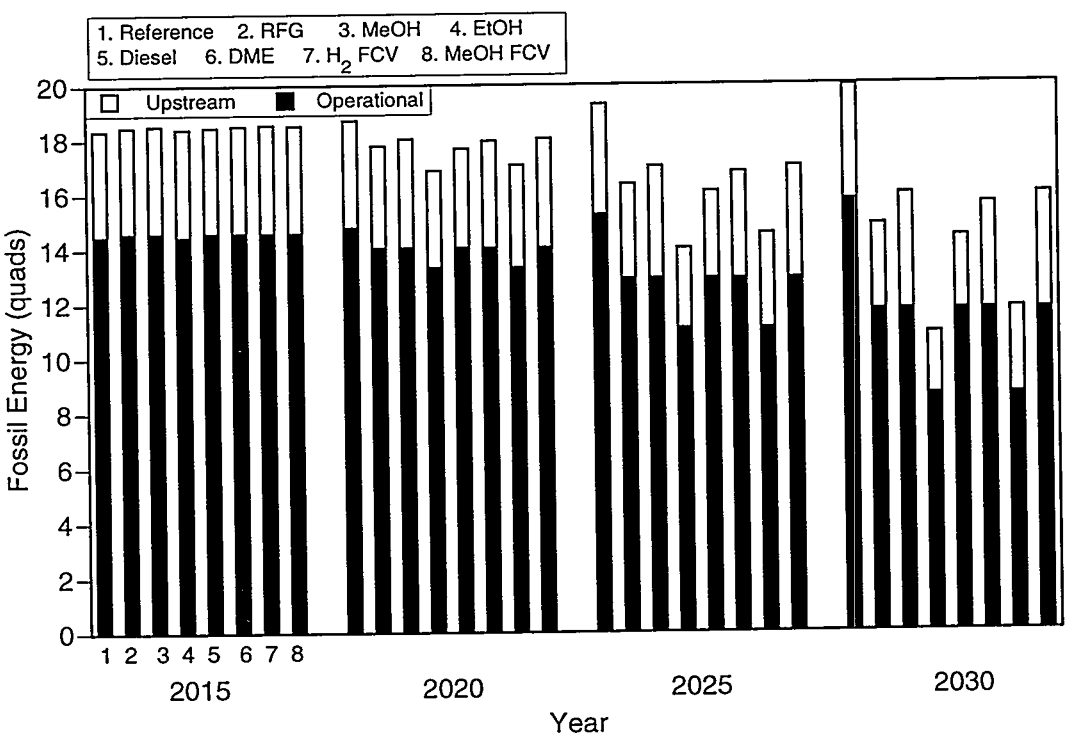


FIGURE 23 Fuel-Cycle Total Energy Use of U.S. Light-Duty-Vehicle Fleet (quads/yr)

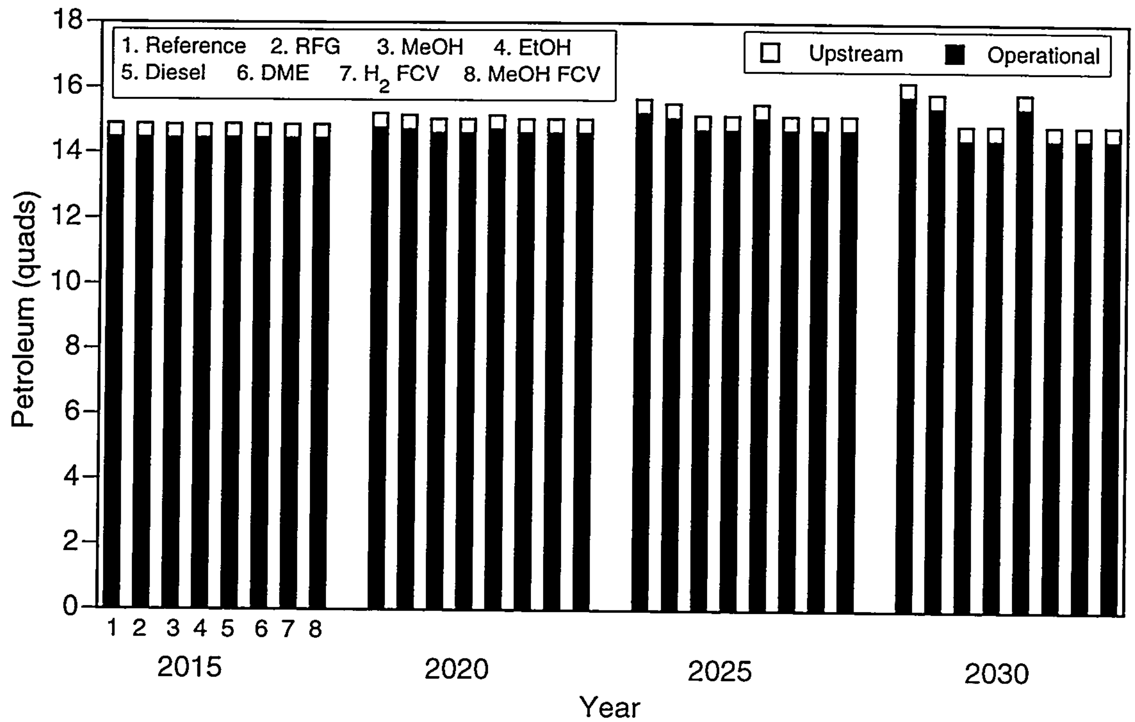


(a) Low Market Share Scenario

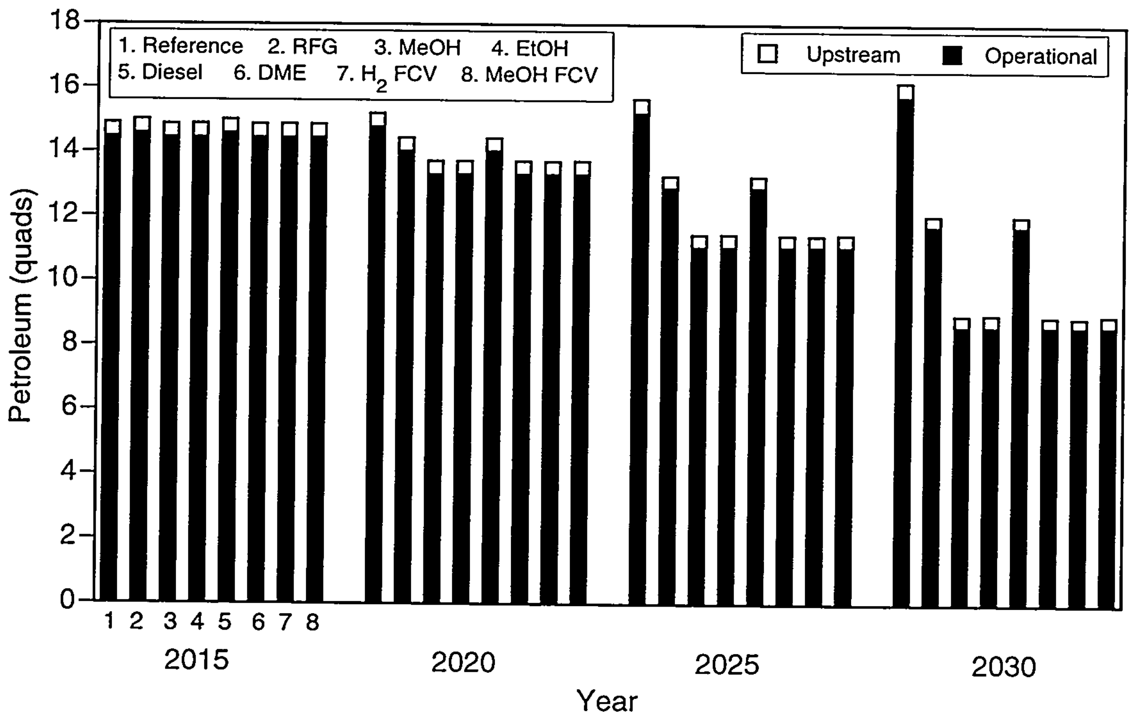


(b) High Market Share Scenario

FIGURE 24 Fuel-Cycle Fossil Energy Use of U.S. Light-Duty-Vehicle Fleet (quads/yr)



(a) Low Market Share Scenario



(b) High Market Share Scenario

FIGURE 25 Fuel-Cycle Petroleum Use of U.S. Light-Duty-Vehicle Fleet (quads/yr) alternative, for which the upstream portion accounts for only 20% of total energy use under the high market share scenario, uses the least total energy (14.7 quads or approximately 27% less than the reference scenario) in 2030.

Fossil Fuels. Fossil energy use by the seven fuel/technology alternatives under the reference scenario and the high and low market share scenarios is shown in Figure 24. Since virtually all (98.5%) the energy consumed by light-duty vehicles under the reference scenario (as well as for most of the technology/fuel alternatives) comes from fossil fuels, most of the bars are nearly identical to those shown in Figure 23. Only the ethanol- and hydrogen-fueled alternatives, both nonfossil fuels, change this pattern. In 2030 under the high market share scenario, fossil fuels drop to approximately two-thirds of total fuel-cycle energy for the ethanol-fueled alternative vs. three-quarters for the hydrogen-fueled alternative. By definition, all fuel/technology alternatives achieve the same gasoline equivalent fuel economy. Thus, all fossil-fueled alternatives consume 11.7 quads of fossil fuels due to vehicle *operation* in 2030 under the high market share scenario vs. 8.6 quads for the two nonfossil alternatives. Again, upstream energy use accounts for the variation in fossil energy use (for the entire fuel cycle) within the two groups of fossil- vs. nonfossil-fueled alternatives.

As expected, the two nonfossil-fueled alternatives also produce the largest reductions in CO_2 emissions (see Figure 22).

Petroleum. Several of the fuel/technology alternatives consume nonpetroleum fuels. To the extent that such fuels are derived from fossil sources (e.g., DME or methanol from natural gas), they offer little reduction in greenhouse gas emissions despite potentially dramatic reductions in petroleum use. Figure 25 displays petroleum use by technology/fuel alternative for the reference and low and high market share scenarios. By 2030 each of the nonpetroleum alternatives (i.e., hydrogen, methanol, ethanol, and DME) achieve an approximate 45% reduction in total petroleum use relative to the reference scenario.

5 Conclusions

In this study, we have evaluated six potential PNGV fuels (RFG, diesel, dimethyl ether [DME], methanol, ethanol, and hydrogen) for three power system applications (SI engine, CI engine, and fuel cell). We have established two 3X vehicle market share scenarios and estimated the capital cost of establishing a fuel production and distribution infrastructure with sufficient capacity to supply gasoline-equivalent fuel volumes of 70,000 bbl/d and 1.6 million bbl/d. We have estimated the full fuel-cycle energy and emissions impacts of using the six potential PNGV fuels.

Cumulative capital needs vary by fuel type. Supplying a gasoline-equivalent capacity of 70,000 bbl/d requires relatively modest capital investment, which is much lower than a gasoline-equivalent capacity of 1.6 million bbl/d. Facilities capable of producing 1.6 million bbl/d will require a cumulative capital investment of $66 billion to $84 billion for DME, methanol, or ethanol versus about $400 billion for hydrogen. Distribution facilities will cost $8 billion to $15 billion for ethanol, methanol, or DME versus nearly $175 billion for hydrogen. These hefty capital requirements pose a challenge to the widespread introduction of 3X vehicles. However, these investments will be spread over many years.

The impacts of vehicle efficiency gains and fuel substitution on petroleum displacement are substantial and their adverse impacts on refineries are inevitable. However, the commitment of time and resources to 3X technology development should provide ample economic signals and sufficient lead time for refinery operators to adjust their business to accommodate different fuel demands, including, perhaps, lower gasoline demand.

Energy and emissions impacts of 3X vehicles are highly dependent on market penetration and thus differ dramatically between the two scenarios examined in this study. Because impacts are relatively small under the low market share scenario, most of the discussion presented here focuses on the more significant results obtained for the high market share scenario. For all PNGV fuel/engine technologies, total energy use and fossil fuel use by U.S. light-duty vehicles decline significantly under the high market share scenario relative to reference scenario estimates for 2030. Fuel savings occur as a result of fuel efficiency improvements, which apply to all 3X technologies and which reduce transportation petroleum use by more than a quarter; fuel savings also result from fuel substitution, which applies to the nonpetroleum-fueled alternatives studied. Together, the two effects reduce transportation petroleum use in 2030 by nearly half relative to the reference scenario. CO_2 emissions follow a similar pattern. Total CO_2 emissions decline by almost one-third from 3X vehicles. With renewable fuels (i.e., ethanol and hydrogen from solar energy), CO_2 emissions decline to almost half the level estimated for the reference scenario.

Among the five criteria pollutants, NO_x emissions are increased from CI engines fueled with diesel and DME but are reduced from fuel-cell vehicles (FCVs). CO emissions from CI engines and FCVs are significantly lower than from SI engines. FCVs reduce VOC emissions significantly. All the PNGV alternatives reduce SO_x emissions. Diesel offers the least SO_x emission reductions, while methanol, ethanol, and hydrogen have the largest reductions. Ethanol and diesel dramatically increase PM_{10} emissions. The increase by ethanol is due to upstream agricultural operations and ethanol production, while the increase by diesel is due to high tailpipe PM_{10} emissions. (Note that CI engines using diesel fuel were assumed to meet the *current* PM emission standards.) Other PNGV alternatives help reduce PM_{10} emissions.

Table 13 qualitatively summarizes impacts of the PNGV alternatives on capital requirements and on energy use and emissions relative to the reference scenario. The table clearly shows the trade-off between costs and benefits. For example, while hydrogen FCVs have the greatest incremental capital needs, they offer the largest energy and emissions benefits. On the basis of the costs and benefits changes shown, methanol FCVs have a particularly promising benefits-to-costs ratio. As stated in the beginning of this report, we have assumed that 3X technologies become an engineering reality. This is speculative, particularly for some less mature technologies, such as fuel cells and DME fuel. Thus, the assumption of technological readiness should be a subject of continued reexamination.

The air quality implications of these emissions results should be interpreted cautiously. Changes in emissions of the five criteria pollutants (as presented in Table 13) do not necessarily translate into similar changes in air quality, simply because emissions from different fuels and upstream fuel-production activities occur in different locations and at different times. Generally speaking, upstream emissions occur outside urban areas, while vehicular emissions occur within

TABLE 13 Impacts of PNGV Fuels Relative to the Reference Scenario

	RFG	Diesel	DME	MeOH	EtOH	H_2 FCV	MeOH FCV
Costs for fuel production	0	0	-	-	-	---	-
Costs for fuel distribution	0	0	--	-	-	---	-
Total energy use	+++	+++	++	++	++	+++	++
Fossil energy use	++	++	++	++	+++	+++	++
Petroleum use	++	++	+++	+++	+++	+++	+++
CO_2 emissions	+	+	++	++	+++	+++	++
VOC emissions	0	+	+	+	+	+++	++
CO emissions	0	++	++	0	0	+++	+++
NO_x emissions	+	--	--	0	+	+++	++
PM_{10} emissions	++	-	++	+++	---	+++	+++
SO_x emissions	++	++	+++	+++	+++	+++	+++

0: no change
-: a little worse
--: worse
---: worst
+: a little better
++: better
+++: best

urban areas. Because of high population exposure (especially where mortality effects exist), emissions in urban areas generate far greater damage than those outside urban areas. Because we assume that methanol and DME are produced in foreign countries, emissions from methanol and DME production occur outside the United States. The damage from these emissions may be more of a concern to the producing countries than to the United States. As Table 13 shows, ethanol has far worse fuel-cycle PM_{10} emissions than does diesel. However, ethanol PM_{10} emissions occur upstream (during farming and ethanol production), while diesel PM_{10} emissions occur during vehicle operation. Because of population exposure and toxicity, diesel PM_{10} emissions, much of which is fine particulate matter of 2.5 microns or less ($PM_{2.5}$), may have much greater damage per unit than ethanol PM_{10} emissions, which tend to be in the 2.5 to 10 micron range. Full assessment of the damage caused by emissions from each fuel requires air quality modeling and risk assessment beyond the scope of this analysis.

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Appendix:

Specifications of Fuels

Appendix:

Specifications of Fuels

Liquid Fuels	LHV[a] (Btu/gal)	HHV[a] (Btu/gal)	Density (g/gal)	C Ratio (wt)	S Ratio (wt)
Conventional gasoline	115,000	125,000	2,791	0.855	0.000300
Reformed gasoline	113,000	122,000	2,749	0.830	0.000100
Diesel	128,500	138,700	3,240	0.870	0.000450
Methanol	57,000	65,000	2,996	0.375	0.000007
Ethanol	76,000	84,500	2,996	0.522	0.000007
Dimethyl ether (DME)	68,200	–	2,528	0.522	0.000000

Gaseous Fuels	LHV (Btu/SCF)	HHV (Btu/SCF)	Density (g/SCF)	C Ratio (wt)	S Ratio (wt)
Natural gas	928	1,031	20.5	0.738	0.000007
Gaseous H_2	274	324	2.4	0	–

[a] LHV = lower heating value; HHV = higher heating value.