Section 2
Development of 3X Market Share Scenarios and Technology Assumptions

Clearly, the impacts of 3X vehicles depend not only on engine technology and fuel choice, but also on how quickly and completely they penetrate the light-duty-vehicle market. If penetration is rapid and complete, there is little time to make the kinds of infrastructure adjustments needed to accommodate different propulsion systems and fuels. Conversely, if penetration is slower and appears more predictable, deliberate planning is possible. To explore a range of 3X impacts, three market penetration scenarios were postulated. The scenarios include a base or reference scenario depicting a future without 3X vehicles and two market share scenarios bracketing a range of 3X vehicle sales. Thirteen combinations of fuels and propulsion systems were examined in the context of the two market-share scenarios.

2.1 Sales of New Light-Duty Vehicles

The vehicle sales forecast used in all three scenarios was taken from the Energy Information Administration's 1997 forecast of transportation energy demand through the year 2015 and extrapolated to 2030 (EIA 1996a). This forecast assumes 1.9% per year growth in gross domestic product (GDP), relatively low world oil prices (rising from $17.26 in 1995 to only $20.98 per barrel by 2015 [all in 1995 dollars]), continued growth in the number of licensed drivers, and moderate increases in new light-duty-vehicle sales and fuel economy. Under this forecast, new car sales increase from 9.31 million with a rated fuel economy of 28.3 mpg in 1995 to 10.55 million rated at 34.3 mpg in 2030; new light-truck sales increase from 5.88 million rated at 20.4 mpg in 1995 to 7.76 million rated at 26.3 mpg in 2030.

2.2 Market Penetration of 3X Vehicles

The 3X vehicle market share scenarios retain the basic parameters of the reference scenario (e.g., energy prices, economic growth, overall vehicle sales) but allow such market factors as the level of technology maturity and consumer preferences to vary. Since each of these factors is subject to some uncertainty, two extreme sets of conditions could materialize. Under one set, every factor favorable to 3X vehicles' market success could occur, resulting in rapid consumer acceptance and high sales of new 3X vehicles. Alternatively, some factors may not be as favorable to market success, resulting in slower early acceptance and low-to-moderate sales of new 3X vehicles. Historical precedents can be found for extremely rapid market acceptance, relatively slow market acceptance, and for many intermediate levels between these two. For example, the market experience of front-wheel drives and downsizing (i.e., weight reduction) provide some insight into just how rapid market penetration could be. In the United States, the market share of front-wheel drives increased from virtually zero to 80% of new passenger cars between 1976 and 1992, a span of 16 years (Figure 2.1).

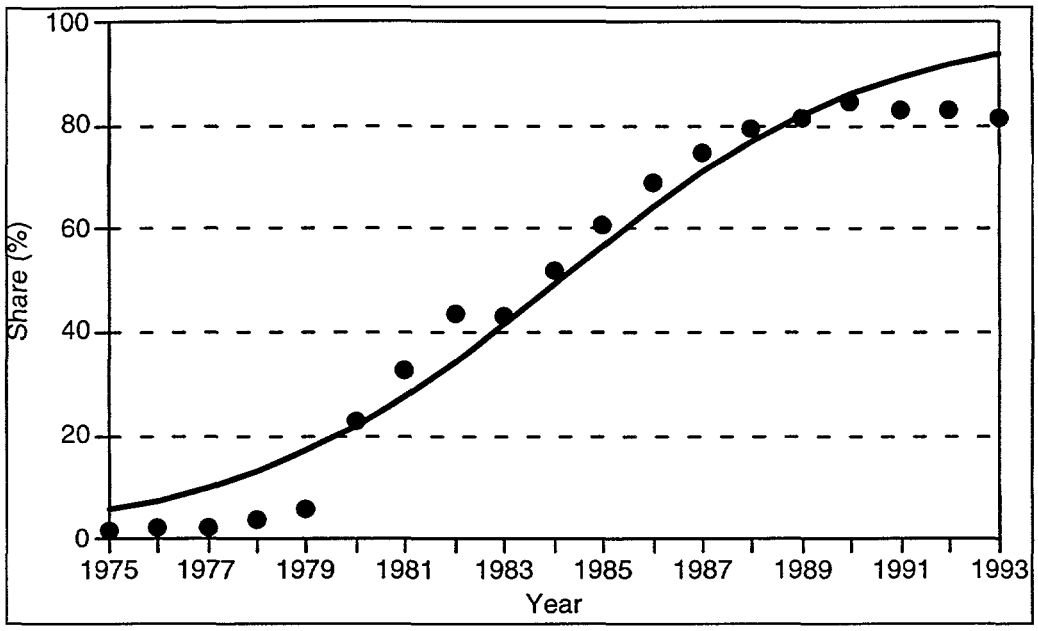

Figure 2.1 Market Share of Front-Wheel-Drive Autos in the United States (based on Murrell et al. 1993)

Light-duty-vehicle (LDV) weight reduction (and the many technologies incorporated therein) has been equally dramatic, with average inertia weight declining by more than 20% between 1976 and 1980 (Figure 2.2). Since a transition to 3X vehicles — involving changes in power systems, materials, and fuels, even as conventional vehicles are produced — is a more complex proposition than introducing either of these technologies, the penetration curves shown in Figures 2.1 and 2.2 provide an indication of the upper limits to market penetration of 3X vehicles.

The mid case for 3X vehicle sales developed by DOE's Policy Office for the Policy Dialogue Advisory Committee (the "Car Talk" Committee) (Resolve, Inc. 1995) is another example of relatively rapid penetration. Under that case, 3X sales achieve a lower ultimate share than front-wheel-drive vehicles or the technologies used to achieve a 20% weight reduction, but penetration is still relatively rapid in terms of the ability of the vehicle manufacturing industry to adapt to such a production shift. For this reason, the mid case was modified slightly for this analysis, extending the timeframe over which the market penetration target is achieved. Thus, the "Car Talk" mid case was modified to produce the high-market-share scenario in which 3X vehicles enter the new light-duty-vehicle market in 2007 and take over 20 years to achieve a 60% market share.

As compared with the high-market-share scenario, the low-market-share scenario assumes a later introduction of 3X vehicles and a slower rate of increase in their sales. Under this scenario, 3X vehicles are assumed to enter the market in 2013, six years later than in the high-market-share scenario, and to capture a 30% share of the new LDV market by 2030. The low-market-share scenario is similar to the market penetration of diesel cars in France in the 16 years between 1973 and 1989 (Figure 2.3). Table 2.1 and

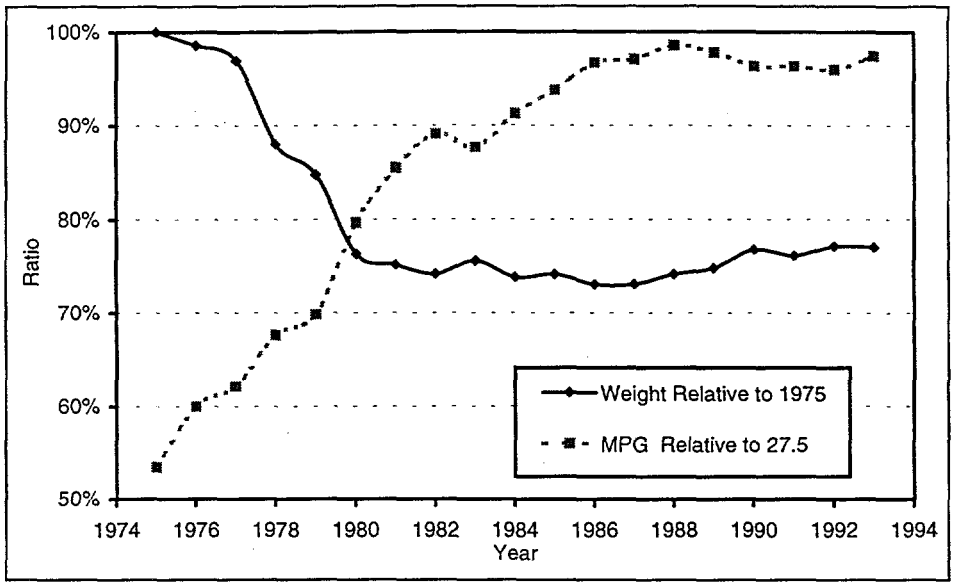

Figure 2.2 Weight Reduction and Fuel Economy Improvement of New Automobiles in the United States (fuel economy relative to 1995 standard of 27.5 mpg) (based on Murrell et al. 1993)

Figure 2.4 illustrate the share of new vehicle sales represented by 3X vehicles under the two scenarios.

For both market share scenarios, each PNGV fuel/engine combination is assumed to have the same market penetration, to compete solely with conventional vehicles (not with one another), and therefore to account for all of the impacts identified. Because competing technologies are set aside for separate fuel/engine comparisons, this assumption provides the basis for analyzing the maximum impact of each technology.

2.3 Sales and Stocks of 3X Vehicles

As stated above, EIA's 1997 forecasts of new car and light-duty-truck (LDT) sales were used to represent total light-duty-vehicle (LDV) sales in the reference scenario and in each of the two market share scenarios. Sales of new 3X vehicles were then estimated as the product of sales and sales shares for cars and LDTs. Note that this implicitly assumes that 3X technologies achieve the same penetration of car and LDT markets, and that 3X LDTs (vans, sport utility vehicles, and pick-ups) achieve the same share of the 3X LDV market as conventional LDTs achieve of the conventional LDV market.

Because of several revisions in input parameters (some of which were offsetting), the number of 3X vehicles expected to be on the road and their fuel use and emissions differ somewhat between Phases 1 and 2 of this study. In Phase 1, total auto and LDT sales were based on EIA's 1996 forecast (Chien 1996, EIA 1996b). For Phase 2, these assumptions were updated with EIA's 1997 forecast (Chien 1997, EIA 1996a), which assumes slightly higher LDV sales in the short term, considerably lower sales in the long term (between 2010 and 2015), and lower conventional vehicle fuel economy. Since new

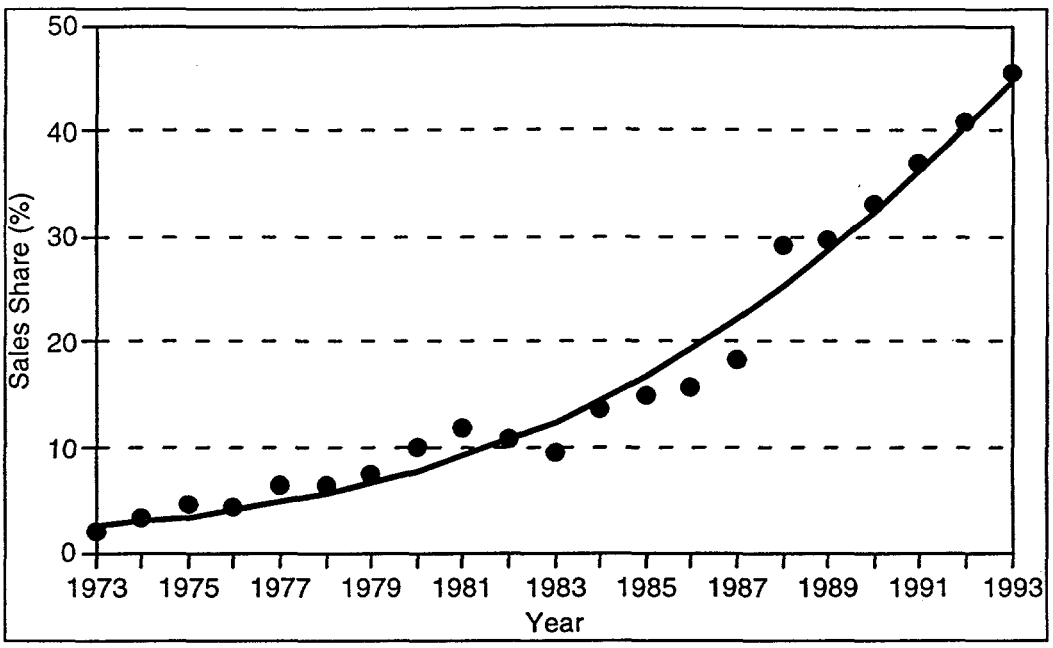

Figure 2.3 Sales Share of New Diesel Cars in France

Table 2.1 3X Share of New Light-Duty Vehicle Sales by Scenario

	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

vehicle sales in the outyears of the EIA forecast were extrapolated to 2030 for this study, the lower long-term sales resulted in approximately 10% fewer 3X vehicle sales in 2030 and approximately 7% fewer 3X sales over the entire forecast period (See Table 2.2).

The procedure used to forecast the fleet of 3X and conventional vehicles expected to be on the road in future years was essentially unchanged in Phase 2. As in the Phase 1 analysis, annual forecasts of 3X market penetration, new LDV sales, and an assumed split between auto and light truck sales were key inputs to the IMPACTT model, which was used to calculate 3X and conventional vehicle stocks and operational energy consumption for each year from 2007 to 2030 (Mintz et al. 1994). Within IMPACTT, a vintaging procedure adjusted a base year vehicle population — adding new vehicles, scrapping or aging others — to produce forecasts of the future light-duty-vehicle fleet by type (auto or light truck), age, and technology (3X or conventional). The resulting estimates of 3X vehicle stocks, expressed as percentages of

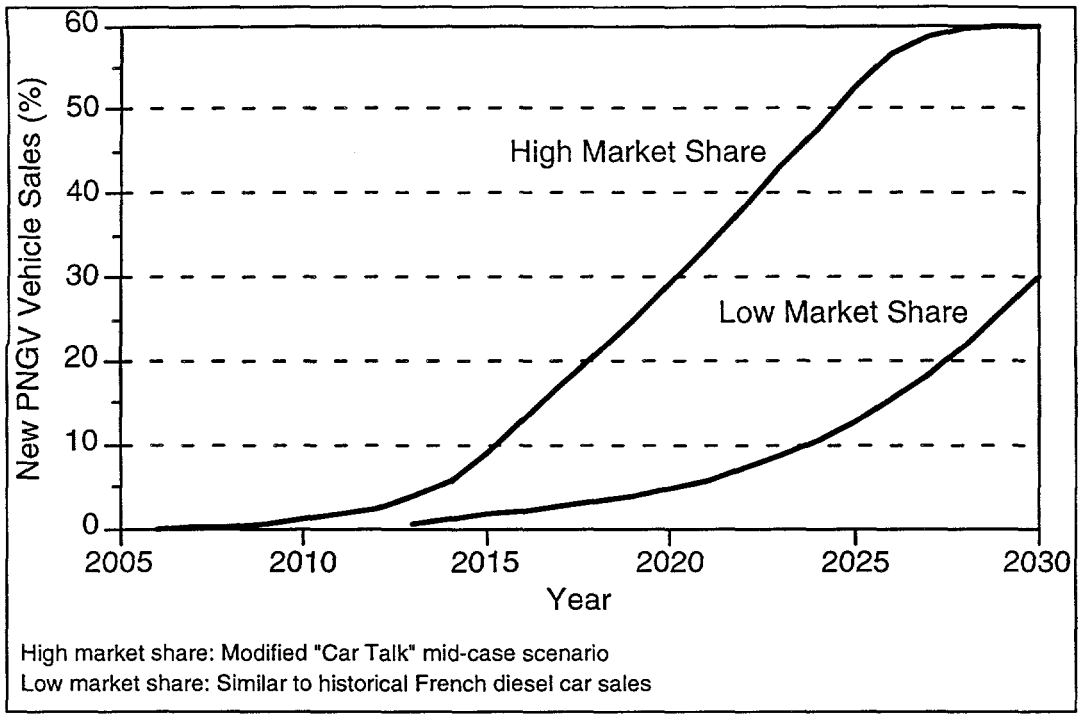

Figure 2.4 Market Share Scenarios for 3X Vehicles

total LDV stocks, are shown in Figure 2.5. Note that even under the high-penetration scenario, 3X vehicles still account for only a little over 40% of total LDV stocks in 2030. This occurs because the turnover of the LDV fleet, which consists of long-lived durable goods (i.e., vehicles), is very slow, typically requiring many years for the characteristics of the vehicle stock to reflect those of new additions to the fleet.

2.4 Fuel Savings Potential

Energy used in the operation of light-duty vehicles was estimated for three scenarios: the reference scenario (without 3X vehicles), the low 3X-market-share scenario, and the high 3X-market-share scenario. As described above, EIA's projections of new LDV fuel economy were used for 1996–2015 and were extrapolated to 2030 using EIA's growth rate between 2010 and 2015. Under the reference scenario, fuel economy for new cars and light trucks thus increases from 27.5 and 20.2 mpg in 1995 to 34.3 and 26.3, respectively, in 2030 (as compared to 35.4 and 26.5 mpg in the earlier EIA forecast used in Phase 1). Because there is no comparable reduction in 3X fuel economy, the percent of operational energy savings attributable to 3X vehicles is thus slightly greater in Phase 2, even though the quantity consumed is less. Estimates of energy use by 3X vehicles, in Phases 1 and 2, are shown in Table 2.3.

Note that energy consumed in the operation of the 3X vehicle fleet is determined not only by the number of 3X autos and light trucks on the road and their fuel economy, but also by annual utilization. Although utilization rates and survival probabilities are assumed to decline with vehicle age, within a particular age range both 3X and

Table 2.2 New 3X Vehicle Sales by Market Share Scenario, Phases 1 and 2 (10^3)

	Phase 1						Phase 2					
	High Market Share			Low Market Share			High Market Share			Low Market Share		
Year	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]
2007	9	7	17				10	8	18			
2008	29	22	50				30	23	52			
2009	58	45	102				59	45	104			
2010	97	75	172				99	75	174			
2011	151	118	269				159	120	279			
2012	236	184	420				240	181	420			
2013	370	290	659	49	39	88	372	279	651	50	38	88
2014	579	455	1,034	110	86	196	587	439	1,026	111	83	195
2015	904	709	1,613	169	133	302	908	677	1,585	172	128	299
2016	1,325	1,024	2,349	212	164	376	1,316	979	2,295	213	158	371
2017	1,760	1,338	3,098	266	202	467	1,727	1,283	3,009	264	196	460
2018	2,208	1,651	3,859	332	248	581	2,140	1,587	3,727	326	242	568
2019	2,669	1,964	4,633	415	305	720	2,556	1,892	4,448	399	295	694
2020	3,144	2,275	5,419	517	374	892	2,975	2,198	5,173	492	364	856
2021	3,710	2,641	6,351	644	458	1,102	3,467	2,560	6,027	597	441	1,037
2022	4,293	3,005	7,298	799	559	1,358	3,962	2,923	6,885	733	540	1,273
2023	4,893	3,368	8,261	989	680	1,669	4,460	3,288	7,748	900	664	1,564
2024	5,511	3,728	9,239	1,219	825	2,043	4,961	3,654	8,615	1,100	810	1,910
2025	6,146	4,087	10,233	1,496	995	2,491	5,464	4,022	9,486	1,332	981	2,313
2026	6,731	4,398	11,129	1,827	1,194	3,021	5,907	4,346	10,253	1,607	1,183	2,790
2027	7,086	4,550	11,636	2,218	1,424	3,642	6,142	4,519	10,661	1,925	1,416	3,342
2028	7,294	4,601	11,894	2,674	1,686	4,360	6,242	4,592	10,834	2,287	1,682	3,969
2029	7,444	4,611	12,056	3,198	1,981	5,179	6,290	4,626	10,916	2,703	1,988	4,691
2030	7,880	4,318	12,198	3,939	2,159	6,098	6,328	4,653	10,981	2,164	2,327	5,490

[a] The total columns may not reflect exact sums because of rounding.

conventional vehicles are assumed to have the same utilization and survival. As in the Phase 1 analysis, 3X cars are assumed to achieve 81 mpg on the EPA test (3X light trucks are assumed to achieve 63 mpg), and utilization is assumed to decline exponentially with vehicle age. In both phases, in-use fuel economy is assumed to be approximately 20% below EPA-test fuel economy for all vehicles.[4] The light-truck share of LDV sales rises from 35% in EIA's 1996 forecast to 42% in EIA's 1997 forecast. As a

[4] A correction factor of 0.814 was applied to correct for the observed discrepancy or gap between fuel economy as measured on the EPA test cycle and actual or in-use fuel economy. Several studies have confirmed the existence of such a gap and its relative magnitude (McNutt et al. 1978, Westbrook and Patterson 1989, Maples 1992, Mintz et al. 1993). The gap is believed to be due to changes in actual travel conditions since the design of the test cycle and development of averaging procedures, especially increases in the share of travel under urban conditions and increased traffic congestion. Because it is unclear how the fuel economy of 3X vehicles will be affected by these changes, the same correction factor was applied to all vehicle, fuel, and technology types.

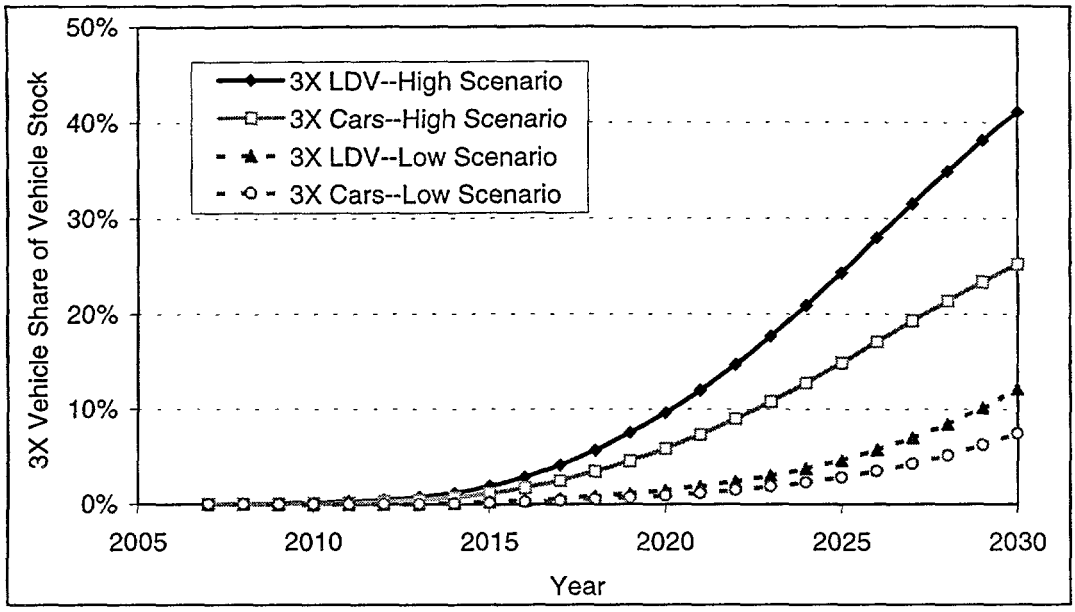

Figure 2.5 3X Cars and Light Trucks as Shares of Total LDV Stocks by Scenario

result, overall fuel use by the 3X fleet drops by 7% in Phase 2 as compared with Phase 1 (tripling the fuel economy of less efficient vehicles saves more fuel).

Figure 2.6 shows the Phase 2 forecast of energy consumption by light-duty vehicles. The figure shows the operational energy savings from 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 energy use is due entirely to improved fuel efficiency. If alternative fuels (such as methanol, ethanol, hydrogen, and DME) are used in 3X vehicles to replace gasoline, additional reductions in petroleum consumption may be expected. The total amount of petroleum reduction from fuel substitution is equal to the amount of energy consumed by 3X vehicles operating on fuels other than gasoline (including the non-gasoline component of blended fuels), plus reductions (if any) in the amount of petroleum consumed in upstream processes.[5] Thus, the effect of both efficiency gain and fuel substitution varies by fuel.

2.5 Candidate 3X Vehicle Technologies

To achieve the goal of tripling fuel economy, the PNGV program has targeted three general areas: converting and using fuel energy more efficiently by eliminating idling at stops and during deceleration; reducing the tractive energy demand of the vehicle by reducing mass, drag, and/or tire rolling resistance; reducing accessory loads of the vehicle; and recapturing some kinetic energy via regenerative braking. To convert and use energy more efficiently in vehicles, two on-board power generation systems have

[5] Note that data presented in Table 2.3 and Figure 2.6 pertain to energy use in vehicle operation only. Fuel consumption for upstream fuel production activities is discussed in Section 4.

Table 2.3 3X Vehicle Operational Energy Use by Market Share Scenario, Phases 1 and 2 (10^6 GGE)

	Phase 1						Phase 2					
	High Market Share			Low Market Share			High Market Share			Low Market Share		
Year	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]	Auto	Light Truck	Total[a]
2007	2	2	4				2	2	5			
2008	9	9	17				9	9	18			
2009	22	22	43				22	22	45			
2010	43	44	87				44	44	88			
2011	76	78	154				78	77	156			
2012	128	130	258				131	129	260			
2013	209	213	421	12	12	23	213	210	423	12	12	23
2014	335	342	677	37	38	75	340	335	675	37	37	74
2015	531	544	1,076	75	77	152	538	527	1,065	76	74	150
2016	818	834	1,652	122	124	246	822	804	1,626	122	119	241
2017	1,195	1,207	2,402	179	181	360	1,191	1,161	2,352	178	173	351
2018	1,659	1,659	3,319	249	249	499	1,639	1,596	3,235	246	239	486
2019	2,210	2,186	4,397	336	332	669	2,164	2,103	4,267	329	319	648
2020	2,846	2,783	5,629	443	433	876	2,762	2,680	5,441	429	416	846
2021	3,583	3,460	7,043	574	554	1,128	3,444	3,337	6,781	551	534	1,085
2022	4,417	4,212	8,629	736	700	1,435	4,205	4,070	8,275	699	676	1,375
2023	5,346	5,031	10,377	933	875	1,809	5,040	4,872	9,912	877	848	1,725
2024	6,365	5,911	12,276	1,175	1,086	2,261	5,941	5,738	11,679	1,092	1,055	2,147
2025	7,471	6,842	14,314	1,469	1,337	2,806	6,903	6,660	13,563	1,351	1,303	2,653
2026	8,643	7,805	16,448	1,827	1,636	3,462	7,904	7,620	15,523	1,660	1,600	3,259
2027	9,816	8,742	18,559	2,257	1,989	4,246	8,886	8,561	17,447	2,027	1,952	3,979
2028	10,951	9,619	20,570	2,773	2,404	5,178	9,815	9,449	19,264	2,461	2,369	4,830
2029	12,029	10,420	22,449	3,387	2,887	6,274	10,674	10,270	20,945	2,970	2,857	5,827
2030	13,118	11,048	24,166	4,145	3,398	7,542	11,461	11,022	22,483	3,560	3,424	6,984

[a] The total columns may not reflect exact sums because of rounding.

been selected by the PNGV program: direct-injection (DI) internal combustion engines and fuel cells. DI engines can be compression ignition (so-called CIDI engines) and be powered with such fuels as diesel, DME, biodiesel, and F-T diesel, all of which have high cetane number. DI engines can also be spark ignition (so-called SIDI engines) and be powered with such fuels as gasoline, methanol, ethanol, natural gas, and LPG, all of which have high octane numbers. Relative to conventional CI engines (diesel engines), CIDI engines can achieve a 30–40% improvement in fuel economy. Relative to conventional SI engines (gasoline engines), SIDI engines can achieve a 20–30% improvement in fuel economy. Fuel cells, which generate electricity from fuels through chemical reactions, are anticipated to achieve twice the fuel economy of conventional SI engines.

SIDI and CIDI engines can be used alone (the engines are the only power source on board the vehicle) or in hybrid configuration. Hybrid configuration achieves additional improvement in fuel economy by eliminating idling and fuel flow during deceleration and by operating engines in a more efficient regime of the engine map. In addition, a

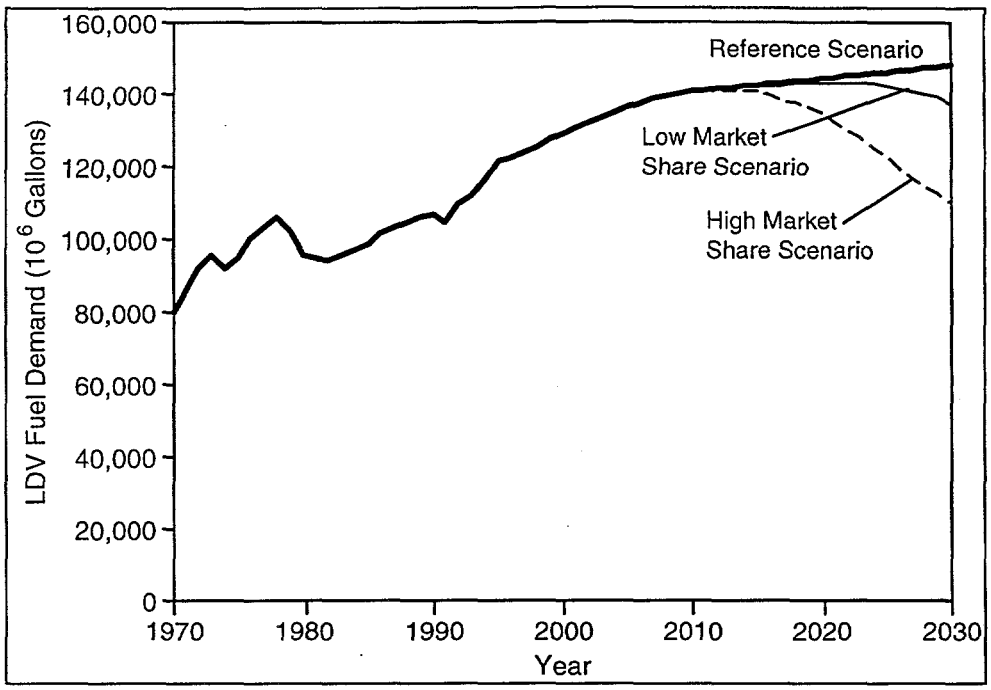

Figure 2.6 Impact of 3X Vehicles on Energy Use by LDVs, Phase 2 Results

hybrid configuration enables use of regenerative braking to recover some of the kinetic energy built up during accelerations, which is otherwise lost. SIDI and CIDI engines in hybrid configuration and fuel cells are presently regarded as reasonable candidates to meet the 3X goal.

However, changes in on-board power units will not be enough. Additional efficiency improvements will be needed to meet the 3X goal. These include reducing vehicle mass (by replacing steel with such lightweight materials as aluminum, magnesium, plastic, and composites); improving drivetrain efficiency, drag coefficients and rolling resistance; and lowering accessory loads. This analysis implicitly assumes that all technical means needed to achieve 3X fuel economy will be utilized. However, it does not address the impacts of developing and deploying the non-fuel technologies. With the exception of the infrastructure impacts of producing and using lightweight materials (which are being analyzed by Oak Ridge National Laboratory), impacts of other unnamed technologies are not addressed in the infrastructure analysis.

To summarize, this analysis includes SIDI engines, CIDI engines, and fuel cells, all in hybrid configuration. Fuel cells are assumed to be proton-exchange membrane (PEM), which is the most promising near-term fuel cell technology for motor vehicle applications. Throughout the analysis, each of the technologies was assumed to meet the 3X goal. However, among the three, SIDI engines currently achieve the least fuel economy improvement, CIDI engines the next, and fuel cells the most. This implies that if all technologies meet the 3X goal, vehicles equipped with SIDI engines will require the most additional effort (in improving drivetrain efficiency and/or reducing mass, drag,

accessory loads, or rolling resistance) to reduce vehicle energy demand, vehicles with CIDI engines will require moderate effort, and vehicles with fuel cells will require the least effort. Investigation of the integrated design of each vehicle type to meet the 3X goal is beyond the scope of this study.

2.6 Candidate 3X Fuels

In Phase 2 of this analysis, 11 different PNGV fuels were examined in the context of three propulsion systems. These fuels were selected not only because their properties make them technically feasible candidates, but also because of the broad range of infrastructure impacts that they might produce, the quantification of which could provide important input to the PNGV program for use in its selection of candidate 3X fuels. The fuels are reformulated gasoline, reformulated diesel, dimethyl ether, methanol, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, biodiesel, Fischer-Tropsch diesel, and hydrogen.

Reformulated gasoline (RFG). RFG is mandated in the nine most severe ozone nonattainment areas of the United States. In California, a more stringent California-specified RFG is required. In addition, many other states that are not required to use RFG under the 1990 Clean Air Act Amendments have opted into the federal program, in effect mandating the use of RFG within their borders. Thus, a sizable portion of the U.S. light-duty-vehicle fleet may be using RFG by the time 3X vehicles are introduced. Phase 1 RFG was introduced in 1995. Phase 2 RFG is required to replace the Phase 1 formulation beginning in 2000. In this analysis, federal Phase 2 RFG was assumed to be used by all conventional LDVs in the reference scenario and by conventional vehicles and 3X SIDI and fuel-cell-powered vehicles in the high- and low-market-share scenarios. The use of light hydrocarbons in fuel-cell-powered vehicles is a relatively recent proposal with its share of technical hurdles. Research is currently under way to develop an efficient, quick-responding reformer to produce hydrogen from light hydrocarbons on board a fuel-cell vehicle using the partial oxidation process. In this study, RFG was assumed to be the hydrocarbon of choice for on-board reforming because it could be readily accommodated by the existing gasoline supply infrastructure.

Reformulated diesel (RFD). The diesel fuel examined in Phase 1 of this analysis was a low-sulfur diesel introduced nationwide in 1993. In the past year, emission targets for CIDI engines have been made more stringent, so stringent in fact that it is debatable whether they can be met with today's low-sulfur diesel fuel. More likely than not, a so-called reformulated diesel (RFD) with low sulfur and aromatic content will be needed. For this analysis, it was assumed that this new diesel fuel will have a sulfur content of 100 ppm by weight. At present, no information on potential aromatic content is available.

Dimethyl ether (DME). DME was included 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 CIDI engine. DME's high cetane number (55–60) and inherently low PM emissions make it a particularly attractive replacement for diesel.

Methanol (MeOH). Methanol was considered in pure form (M100) for both *SIDI* engines and fuel-cell vehicles. Methanol has been promoted for LDV applications because it has potentially low VOC and CO emissions while being produced from a non-petroleum source (i.e., natural gas). Methanol fuel cells were assumed to be of the partial oxidation type with on-board reformers.[6]

Ethanol (EtOH). Ethanol was included because it alone, among the fuels considered, is currently made from renewable resources. Ethanol was assumed to be burned in SIDI engines in pure form (E100). Although ethanol in different blend percentages with gasoline (such as 85% ethanol and 15% gasoline [E85] and 10% ethanol and 90% gasoline [E10]) has been used or promoted for LDV applications, pure ethanol better illustrates the fuel's potential impact. Use of ethanol reduces both GHG emissions and fossil fuel use.

Compressed natural gas (CNG) and liquefied natural gas (LNG). CNG and LNG were assumed to be used in SIDI engines. Since they are made from natural gas, which is relatively abundant in the United States and worldwide, CNG and LNG can reduce petroleum use and criteria pollutant emissions.

Liquefied petroleum gas (LPG). LPG was assumed to be used in SIDI engines primarily for its environmental benefits. LPG also offers some petroleum reduction, since approximately 50–60% of the LPG fraction appropriate for motor fuel use (i.e., propane) currently comes from natural gas (EIA 1997a; EIA 1997c). LPG is currently the most widely used alternative fuel in the United States. Consumers are relatively familiar with LPG as a transportation fuel.

Biodiesel. Biodiesel was included because it is produced from renewable sources and has a large potential for reducing transportation GHG emissions and petroleum use. It was assumed to be used in CIDI engines. Because of its high production cost and the desire to use the existing diesel distribution system, it is generally suggested that biodiesel be blended with conventional diesel. Most researchers in the field anticipate that a blend of 20% biodiesel and 80% conventional diesel (B20) will exploit the benefits of biodiesel at a reasonable cost premium. This blend percentage (with RFD as the diesel component) was selected for 3X vehicle applications.

Fischer-Tropsch diesel (F-T diesel). F-T diesel, produced from natural gas, was included because of its zero sulfur content, low aromatic content, and high cetane number. To better utilize F-T diesel's inherent advantages, some suggest that F-T diesel be blended with conventional diesel. In this analysis, a blend of 50% F-T diesel and 50% RFD (F-T50) was assumed for CIDI applications.

Hydrogen (H_2). Gaseous hydrogen was considered for use in fuel-cell vehicles, along with methanol and gasoline.

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[6] Because of on-board reforming, methanol was assumed to be lower quality, which is more or less comparable with the methanol burned by SIDI engines.

The three vehicle technologies and 11 fuels produced a total of 13 vehicle/fuel combinations, which were evaluated in this analysis. Table 2.4 shows the 13 combinations.

Table 2.4 Propulsion Technologies and Fuels Examined in the Phase 2 Analysis

Fuel	Propulsion Technology
RFG	SIDI engines Fuel cells
CNG	SIDI engines
LNG	SIDI engines
LPG	SIDI engines
Methanol	SIDI engines Fuel cells
Ethanol	SIDI engines
RFD	CIDI engines
DME	CIDI engines
Biodiesel	CIDI engines
F-T diesel	CIDI engines
Hydrogen	Fuel cells

Table 2.5 lists the physical and chemical properties of the 11 different fuels. It should be noted that heating value or energy content (Btu/gal) is a particularly important consideration. Though beyond the scope of this analysis, heating value will affect vehicle design and the mix of enabling technologies needed to achieve 3X fuel economy. Vehicles using fuels with heating values lower than RFG will have to provide more on-board fuel storage in order to achieve the PNGV target of a 380-mi driving range, unless some of the difference is compensated by improved efficiencies. Since methanol's heating value is approximately half that of gasoline, methanol tanks will have to be about twice as large as gasoline tanks. Similarly, ethanol tanks will be about one-third larger than gasoline tanks. For other fuels, on-board storage must accommodate both differences in heating value and in the conditions needed to maintain the fuel in a particular (generally liquid) state. LPG tanks will be larger and heavier than gasoline tanks in order to store the fuel at a pressure of about 100 psi; DME tanks will be similar. CNG will be stored in cylinders at about 3000 psi, while LNG will be stored in cryogenic tanks. Gaseous hydrogen (liquid hydrogen was excluded from this analysis) will be stored at approximately 6000 psi. Among the eleven fuels, CNG, LNG, and gaseous hydrogen will incur the most severe weight penalties, which then must be compensated by further mass reductions or efficiency improvements. By contrast, RFD, biodiesel, and F-T diesel have higher energy content than gasoline. On-board storage of these fuels will produce a small weight benefit.

2.7 Fuel Production Pathways

Fuel production pathways for each of the 11 different fuels must be specified in order to estimate capital needs for establishing fuel production and distribution infrastructure and to analyze fuel-cycle energy and emissions impacts. The fuel pathways presented in Figure 2.7 are based on ANL's previous research in this area.

As the figure shows, RFG and RFD are produced from petroleum. LPG is produced from both petroleum and natural gas (NG). CNG, LNG, DME, methanol, and F-T diesel

Table 2.5 Properties of 11 Potential 3X Fuels

Fuel	LHV[a] (Btu/gal)	HHV[a] (Btu/gal)	Density (g/gal)	C ratio[a] (wt)	S ratio[a] (wt)
Reformulated gasoline (RFG)	113,000	122,000	2,749	0.830	0.000100
Reformulated diesel (RFD)	128,500	138,700	3,240	0.870	0.000100
Methanol (MeOH)	57,000	65,000	2,996	0.375	0.000007
Ethanol (EtOH)	76,000	84,500	2,996	0.522	0.000007
Liquefied petroleum gas (LPG)[b]	84,000	91,300	2,000	0.820	0.000000
Liquefied natural gas (LNG)[b]	72,900	80,900	1,589	0.740	0.000000
Dimethyl ether (DME)[b]	68,200	73,600	2,528	0.522	0.000000
Methyl soyate (biodiesel)	117,100	128,500	3,346	0.780	0.000010
Fischer-Tropsch diesel	118,800	128,500	2,915	0.860	0.000010
Natural gas (per SCF)	928	1,031	20.5	0.738	0.000007
Hydrogen (H_2, per SCF)	274	324	2.4	0.000	0.000000

[a] LHV= lower heating value; HHV = higher value; C ratio = carbon ratio; S ratio = sulfur ratio.

[b] Under pressure.

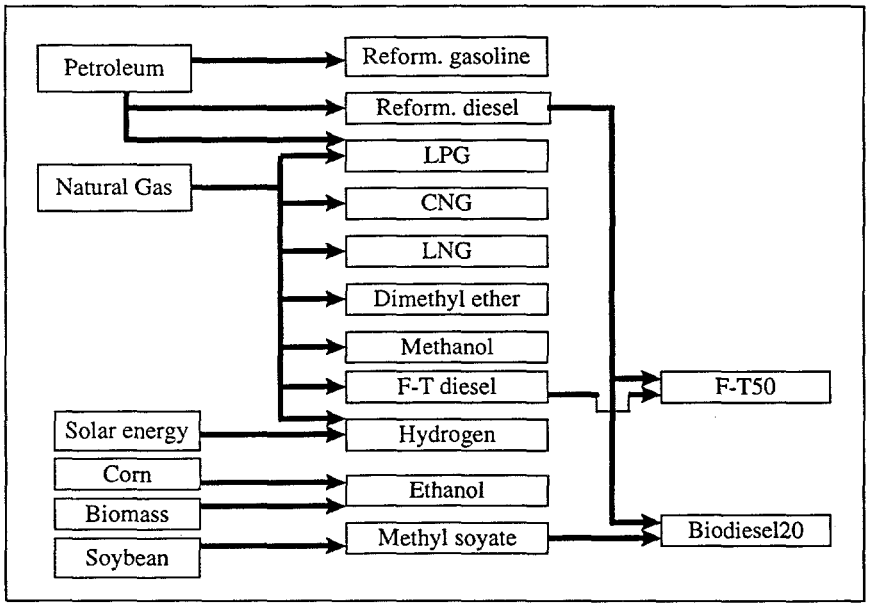

Figure 2.7 Fuel Pathways Considered in this Study

are produced from natural gas. Prior to 2020, all hydrogen was assumed to be produced from NG through steam reforming; beginning in 2020, new hydrogen capacity was assumed to come from solar sources through water electrolysis. Between 2020 and 2030, solar energy thus accounted for an increasing share of hydrogen production. Likewise, ethanol production (initially corn-based) was assumed to shift to cellulosic ethanol plants (using both woody and herbaceous biomass) beginning in 2016. Methyl ester (or soyate) is the oil produced from soy oil through the transesterification process and has properties similar to those of diesel fuel.