Section 4
Total Fuel-Cycle Analysis

Petroleum savings by a 3X technology come from two sources: tripling fuel economy and fuel substitution. Tripling fuel economy reduces energy consumption for vehicle operation by 67% and, if the replacement fuel is petroleum-based, results in comparable petroleum displacement (100% if the replacement fuel is not petroleum-based). However, if resource recovery, fuel production, and other upstream processes are highly energy- and/or petroleum-intensive, total energy and petroleum savings could be much less. This reduction in savings is particularly dramatic for nonpetroleum fuels, like hydrogen. Because energy-cycle analysis examines all the stages in the process of vehicle and fuel production and distribution, as well as end-use consumption, it permits a more definitive assessment of energy and petroleum savings (and emissions reductions) than standard end-use analysis, which, by definition, is limited to vehicle operation. For new fuel- and propulsion-system technologies with significantly different energy cycles, the two approaches could produce different conclusions.

Figure 4.1 illustrates the fuel cycle and vehicle cycle,[16] which, together, comprise the total energy cycle. 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. Fuel-cycle activities before vehicular fuel combustion are usually referred to as upstream activities (which result in upstream energy use and upstream emissions). Primary energy resources (e.g., crude oil, natural gas, and coal) are usually referred to as energy feedstocks, and fuels are referred to as, for example, gasoline, diesel, and electricity.

[16] A 3X vehicle is likely to differ from a conventional vehicle in more than just fuel economy. Lightweight materials, such as aluminum, magnesium, plastic, and composites, will probably be used extensively, thus requiring changes in production processes, manufacturing inputs, and suppliers. The powertrain, most likely a hybrid, will be very different from a conventional ICE powertrain, thus requiring additional production changes. All of these variables lead to significantly different energy use and emissions of the vehicle cycle, which includes material recovery and fabrication, vehicle assembly, and vehicle disposal/recycling (see Figure 4.1). The energy and emissions impacts of 3X vehicle manufacturing and material fabrication are addressed in other DOE-sponsored efforts. This study addresses only fuel-cycle (including vehicle operations) energy use and emissions.

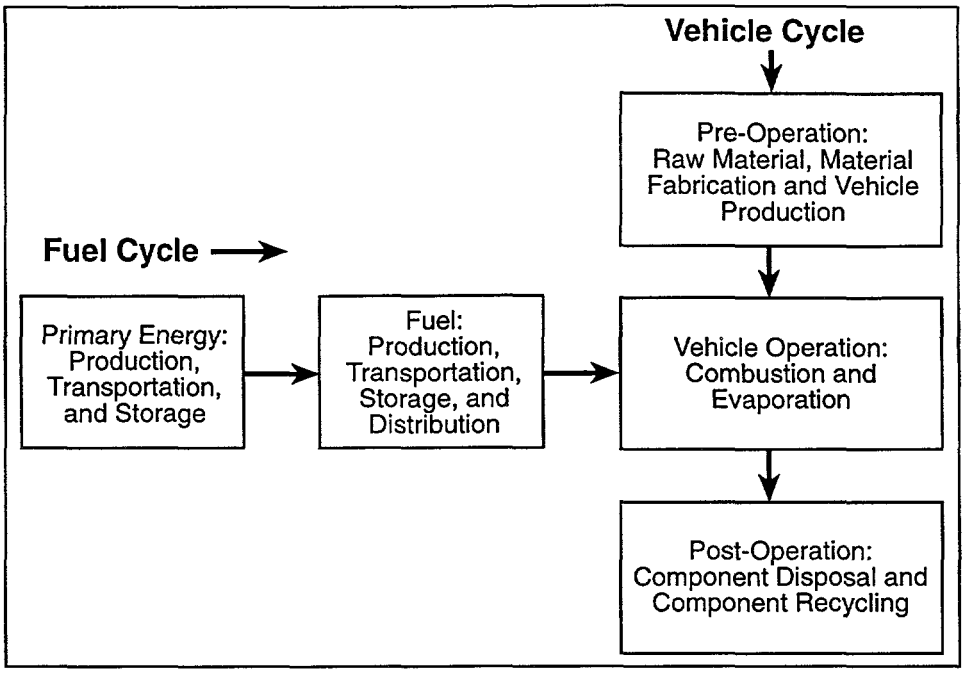


Figure 4.1 Fuel Cycles and Vehicle Cycles for Transportation Energy and Emissions Analysis

In this analysis (as well as in the prior Phase 1 effort), technology-specific rates of energy use and emissions produced were estimated by using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Wang 1996). Rates were then applied to forecasts of miles traveled and energy use by 3X and conventional vehicles in the reference, high-, and low-market-share scenarios as produced in the IMPACTT model. The resulting estimates of operational and upstream energy use were then combined to produce annual estimates of total energy (all energy sources), fossil energy (petroleum, natural gas [NG], and coal), and petroleum for each of the candidate 3X technologies. Similarly, estimates of operational and upstream emissions were combined to produce annual estimates of criteria pollutants and greenhouse gases for each of the 3X technologies.

4.1 GREET Analytical Approach

GREET calculates energy use and emissions associated with a variety of alternative transportation fuels and technologies. GREET includes both fuel and vehicle cycles and can calculate energy and emissions for either or both.

For this analysis, GREET was used to calculate energy and emission rates for the fuel cycle only. In this mode, GREET takes into account energy use for primary feedstock recovery and transportation, fuel production, and fuel transportation, storage and distribution. GREET includes emissions caused by process fuel combustion, fuel leakage, and fuel evaporation. Upstream energy use and emissions are calculated in Btu and g/mmBtu of fuel delivered at the pump.

GREET then calculates operational energy use (which is a member of both the vehicle and the fuel cycle, as shown in Figure 4.1) from vehicle fuel economy. Vehicular emissions for conventional ICE vehicles fueled with gasoline and diesel are estimated with EPA's Mobile model.[17] Vehicular emissions for other fuels and propulsion systems are calculated from baseline conventional vehicle emissions and anticipated changes between baseline vehicles (gasoline or diesel) and new technologies. Depending on the application, operational energy use may be assigned to either the vehicle or fuel cycle. In this analysis, it was included in the fuel cycle.

Within GREET, fuel-cycle and vehicle-cycle results are converted into per-mile rates, which may then be reported separately or combined into a total energy-cycle result. Fuel economy is used to convert fuel-cycle energy use and emissions from g/mmBtu to g/mi; lifetime vehicle utilization is used to convert vehicle-cycle energy use and emissions from g/vehicle to g/mi.

The key outputs from the GREET model are gram-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 smaller than 10 μm (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 then weighted by their global warming potentials to estimate CO_2-equivalent GHG emissions. In this study, the global warming potential factors recommended by the Inter-Governmental Panel on Climate Change (IPCC) were used to calculate CO_2-equivalent GHGs. Those factors are 1 for CO_2, 21 for CH_4, and 310 for N_2O.

Although GREET generates both upstream and operational energy use and emissions, only upstream results are fed into the IMPACTT model. Energy use during vehicle operation is calculated directly in IMPACTT. Emissions from vehicle operations are calculated in IMPACTT in a way similar to that in GREET. In fact, the two models share some of the same assumptions and equations used to calculate emissions from vehicle operations. The notable difference between GREET and IMPACTT is that GREET estimates emission rates, while IMPACTT estimates total emissions for a fleet of vehicles. Thus, while new-vehicle market penetration and stock are not used in GREET, they are crucial elements in IMPACTT (Mintz et al. 1994).

4.1.1 Upstream Calculations

As stated above, only the upstream energy and emission rates generated by GREET are fed into IMPACTT. Upstream calculations follow these steps. For a given stage in the fuel cycle, energy use (in Btu per million Btu of energy throughput) is calculated and allocated to different process fuels (e.g., NG, residual oil, diesel, coal, and electricity).

[17] The current version of EPA's Mobile model is Mobile5b. The next version – Mobile6 – is scheduled to be released in late 1998 or early 1999.

Fuel-specific energy use, together with fuel-specific emission factors (specific to a particular combination of fuel and combustion technology), is then used to calculate combustion emissions for the stage. GREET has an archive of combustion emission factors for various combustion technologies that use different fuels and are equipped with different emission control technologies. Combustion emission factors for VOC, CO, NO_x, PM_{10}, CH_4, and N_2O were derived primarily from data published by the EPA (EPA AP-42 document). For most fuels, emission factors for sulfur oxide are calculated from sulfur content, assuming that all sulfur contained in process fuels is converted into sulfur dioxide (SO_2). Similarly, carbon dioxide emission factors 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). The GREET calculation logic for upstream emissions is presented in Figure 4.2.

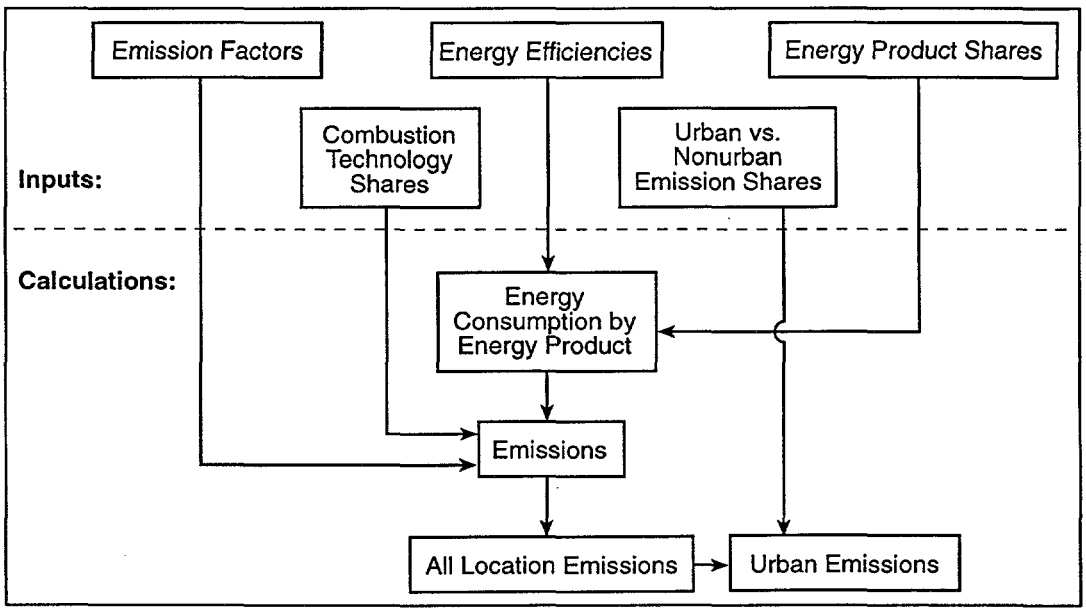


Figure 4.2 GREET Calculation Logic for Upstream Emissions

In the Phase 2 analysis, emissions of the five criteria pollutants were further separated into total emissions and urban emissions. The major concern with respect to emissions is the effect on human health of exposure to air pollution created by these pollutants. Clearly, emissions that occur in remote, sparsely populated areas pose far less of a health threat than those in densely populated urban areas. Although GREET is not a location-specific model, the issue of human exposure warrants some degree of spatial

analysis.[18] Thus, emissions are separated into total and urban emissions to provide a better indication of health effects from a given combination of 3X fuel and propulsion system technologies.

GREET uses information on facility locations to separate upstream emissions into the two categories. For facilities located inside urban areas, all emissions are considered urban; emissions from all other facilities are considered to be non-urban. In this analysis, "urban" was defined as the 125 metropolitan areas specified in the 1992 Energy Policy Act. On the basis of a general understanding of the geographic location of fuel production facilities (e.g., petroleum refineries, electric power plants, etc.), a set of ratios was approximated. Corresponding to the share of each facility type located in urban areas, the ratios were then used to allocate emissions from each facility type between urban and non-urban areas.

4.1.2 Fuel-Cycle Paths

To estimate upstream energy and emissions, a fuel-cycle path from primary energy recovery to delivery at the fuel pump must be specified for each technology option. The base case or benchmark fuel-cycle path was defined as petroleum to RFG for conventional vehicles. In this study, 13 fuel-cycle paths were analyzed (see Figure 2.7).

As Figure 2.7 indicates, hydrogen was assumed to be produced from either NG or solar energy, and ethanol was assumed to be produced from either corn or biomass. Prior to 2020, all hydrogen was assumed to be produced from NG via steam reforming; beginning in 2020, some production was assumed to come from solar energy (via water electrolysis). Similarly, all ethanol production was assumed to be from corn until 2016, when production from cellulosic biomass was assumed to begin. Over time, as more new plants begin producing hydrogen from solar energy and ethanol from cellulosic biomass, these technologies' respective shares of total hydrogen and total ethanol production were assumed to rise steadily.

Petroleum to RFG. This path includes crude oil recovery in oil fields; crude oil transportation and storage; crude oil refining; and gasoline (i.e., RFG) transportation, storage, and distribution. Among the upstream processes for this fuel cycle, crude oil refining consumes the most energy (with an energy efficiency of 82.5%, which is slightly below that of refining crude to conventional gasoline). As for GHG emissions, the venting of associated gas in oil fields is a significant source of CH_4 emissions.

Petroleum to Diesel. This path includes crude oil recovery, transportation, and storage; diesel production in crude refineries; and diesel transportation, storage, and

[18] Ideally, results from GREET could be used in an emissions inventory model to generate an emissions distribution by geographic location. The location-specific inventory could then be fed into an air quality model, the results of which could be combined with a population exposure model to assess human health effects of air pollution.

distribution. Again, the largest energy requirement for this cycle occurs at petroleum refineries (with an energy efficiency of 90%).

Petroleum to LPG. This path includes crude oil recovery, transportation, and storage; LPG production in petroleum refineries; and LPG transportation, storage, and distribution. Despite an energy efficiency of 93.5%, LPG production at petroleum refineries consumes the most energy; transportation of imported LPG consumes the next largest share. For this analysis, a constant 40% of LPG supply was assumed to come via this pathway (i.e., from crude oil) under all scenarios. This assumption is based on current U.S. propane production shares (EIA 1997a; EIA 1997c).

NG to CNG. On this path, natural gas is produced in, and processed near, NG fields and transported through pipelines to service stations where it is compressed to about 300 psi. NG pipelines are powered by NG-fueled engines and turbines. Of the stages making up this path, NG compression (by means of electric compressors at dispersed refueling facilities) has the lowest energy efficiency (95%).

NG to LNG. On this path, natural gas is produced in and processed near NG fields, liquefied at LNG plants that are adjacent to NG processing plants, and then transported by rail and truck to LNG service stations. Of the stages making up this path, NG liquefaction uses the most energy (with an energy efficiency of 85%).

NG to LPG. For domestic supplies, this path includes natural gas recovery in NG fields, LPG production at NG processing plants near NG fields, and LPG transportation via rail or truck to LPG service stations. For imports, LPG is assumed to be transported to major U.S. ports via ocean tanker and then transported to LPG refueling stations via truck and pipeline. Though high relative to other fuels, the efficiency of LPG production (96.5%) is the lowest of all the stages in the pathway. In this analysis, NG was assumed to account for 60% of LPG supply under all scenarios.

NG to DME. On this path, natural gas is recovered in and processed near NG fields. DME is then produced at plants that are adjacent to NG processing plants. DME production has the lowest energy efficiency (70%) of these upstream activities. For this analysis, all DME was assumed to be produced overseas from inexpensive NG, shipped by ocean tanker to main U.S. ports, and transported to service stations via pipeline and truck.

NG to Methanol. The upstream stages of this path are similar to those of the NG-to-DME path except that methanol is produced instead of DME. For this analysis, all methanol was assumed to be imported, shipped to main U.S. ports via ocean tanker, and then transported to service stations via pipeline and truck. Methanol production has the lowest energy efficiency (65%) of all the upstream activities in this path.

NG to F-T Diesel. On this path, natural gas is recovered in and processed near NG fields. At F-T plants that are adjacent to NG processing plants, F-T diesel is produced and blended with conventional diesel. F-T diesel blends are then transported to service

stations in the same way as conventional diesel. Among the upstream activities of this cycle, F-T diesel production has the lowest energy efficiency (57%).

NG to H_2. Hydrogen can be produced in centralized facilities (like it is now) or in decentralized facilities (like refueling stations using NG). The advantage of decentralized production is its avoidance of expensive H_2 distribution infrastructure. For this analysis, centralized production was assumed because the technology is proven and economies of scale can be realized. Although both liquid and gaseous H_2 can be used for H_2-powered fuel-cell vehicles (FCVs), gaseous H_2 was assumed for this analysis because liquefaction poses additional energy losses and emissions, and the transportation and storage of liquid H_2 can be expensive.

Under this path, NG is recovered in and processed near NG fields, H_2 is produced at centralized plants adjacent to NG processing plants, and gaseous H_2 is transported to service stations via pipeline. In this analysis, H_2 was assumed to be compressed to about 6,000 psi at service stations. With an energy efficiency of 68%, H_2 production consumes the most energy of all the stages in this path. Because H_2 contains no carbon and no carbon sequestration was assumed, the conversion of NG to H_2 produces considerable CO_2 emissions.

Solar Energy to H_2. Production of H_2 from solar energy via water electrolysis offers significant energy and environmental benefits, as well as the possibility of a practically unlimited energy source. In this study, H_2 was assumed to be produced in centralized facilities in such regions as the Southwestern United States where solar energy is abundant. Hydrogen was then assumed to be compressed moderately (to about 100 psi) and transported via pipeline to H_2 refueling stations. There, gaseous H_2 was assumed to be compressed to about 6,000 psi for use by H_2-powered FCVs. Electricity was assumed to be used for compressing H_2 and powering pipeline motors, and parameters typical of U.S. average electric generation were used to estimate emissions of criteria pollutants and GHGs from the electricity used. Note that the same assumptions were applied to H_2 transportation and compression for the above NG-to-H_2 path. Energy efficiencies for gaseous H_2 transportation via pipeline and H_2 compression at service stations were assumed to be 94% and 90%, respectively.

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. Both wet- and dry-milling technology is currently used in the United States to produce ethanol. Wet-milling plants now account for about two-thirds of ethanol production capacity; dry-milling plants account for the remaining third. Because of tax incentives that are available in certain states and their generally lower capital requirement, most newer ethanol plants are small-scale, dry-milling plants. In this analysis, future corn-to-ethanol plant capacity was assumed to be evenly split between the two technologies (i.e., half wet-milling and the other half dry-milling). Note that this assumption implies that more

dry-milling plants will be built in the future than wet-milling plants. For a detailed discussion of the technical assumptions regarding this cycle, see Wang et al. (1997b).

Biomass to Ethanol. This path includes biomass production and transportation; ethanol production; and ethanol transportation, storage, and distribution. Biomass includes both woody and herbaceous feedstocks. In this analysis, the energy and emissions associated with biomass production were calculated in the same way as those for producing ethanol from corn. At cellulosic ethanol plants, the lignin portion of biomass was assumed to be burned to generate steam and electricity in co-generation systems. While combustion of biomass undoubtedly releases CO_2 emissions, this CO_2 came from the atmosphere through photosynthesis. Thus, CO_2 emissions from biomass combustion were treated as a transfer back into the atmosphere with a net effect of zero. For the same reason, CO_2 emissions from ethanol combustion by ethanol-powered vehicles were also assigned a net value of zero.

The electricity generated at ethanol plants was assumed to be exported to the power grid. Emissions credits for the generated electricity were calculated in GREET as a function of the amount of electricity generated and average emissions associated with electricity generation in U.S. electric utility systems.

Soybeans to Biodiesel. This path includes soybean farming; soybean transportation; soy oil extraction and transesterification; biodiesel blending; and biodiesel blend transportation, storage, and distribution. Among the upstream activities for this path, biodiesel production (including extraction and transesterification of soy oil) and soybean farming consume most of the energy and produce most of the emissions.

4.2 IMPACTT Analytical Approach

The IMPACTT model was used to estimate annual energy consumption and emissions production by conventional and 3X vehicles. IMPACTT is a spreadsheet model that simulates the movement of vehicles through the light-duty fleet. IMPACTT incorporates a vehicle stock model that adds new vehicles (3X or conventional) and retires old vehicles from an initial vehicle population profile to produce annual profiles of the auto and light-truck population by age and technology; a usage module to compute vehicle-miles-traveled (VMT), oil displacement, and fuel use by technology; and an emissions module to compute upstream and operational emissions of criteria pollutants and GHGs for autos and light trucks, again by technology. The usage module computes the petroleum that would have been consumed by conventional vehicles in the absence of 3X vehicles, the petroleum equivalent (i.e., GGEs) consumed by 3X vehicles, and the net savings due to the presence of 3X vehicles in the fleet.[19] Upstream energy use is computed post hoc, as a function of operational energy use and a series of GREET-developed rates, which are specific to each potential 3X fuel.

[19] Unlike GREET, IMPACTT's fuel-use module computes only downstream or operational energy use. Upstream energy use is then computed as the product of operational energy use and a GREET-supplied rate.

In IMPACTT, emissions of NO_x, CO, VOC, and PM_{10} are computed separately for autos and light trucks by using age-based tailpipe emission rates obtained from EPA's MOBILE5b and PART5 models for conventional SI and CI engines operating on gasoline and diesel fuel, respectively, and average operational emission rates for nonconventional engines and fuels estimated with assumptions presented in Section 4.2.1. Operational emissions of SO_x and CO_2 are computed as a function of fuel consumption and fuel specifications (see Table 2.5) by using assumptions from GREET. Upstream emission rates for all fuels (conventional as well as potential 3X fuels) are also obtained from GREET.

Version 5.0 of IMPACTT (IMPACTT5) was used for this analysis. Major changes in the emissions module account for most of the difference between this version and the one documented earlier (Mintz et al. 1994). On the emissions side, all emissions are now computed separately for autos and light trucks; emissions of greenhouse gases (CO_2, CH_4 and N_2O) have been added, along with an estimate of total greenhouse gases; and upstream emissions of criteria pollutants and GHGs have been added. On the energy side, operational energy use is now broken down into total energy, fossil fuel, and petroleum; upstream energy has been added (and is broken down into the same categories); and a procedure for estimating urban emissions of criteria pollutants has been developed.

Figure 4.3 illustrates IMPACTT5's structure. Outputs include estimates of the quantity of oil consumed and emissions produced by conventional vehicles, the quantity of alternative fuels consumed and emissions produced by advanced-technology vehicles, and the total quantity of fuel consumed and emissions produced by all vehicles expected to be on the road in a given year under a given scenario.

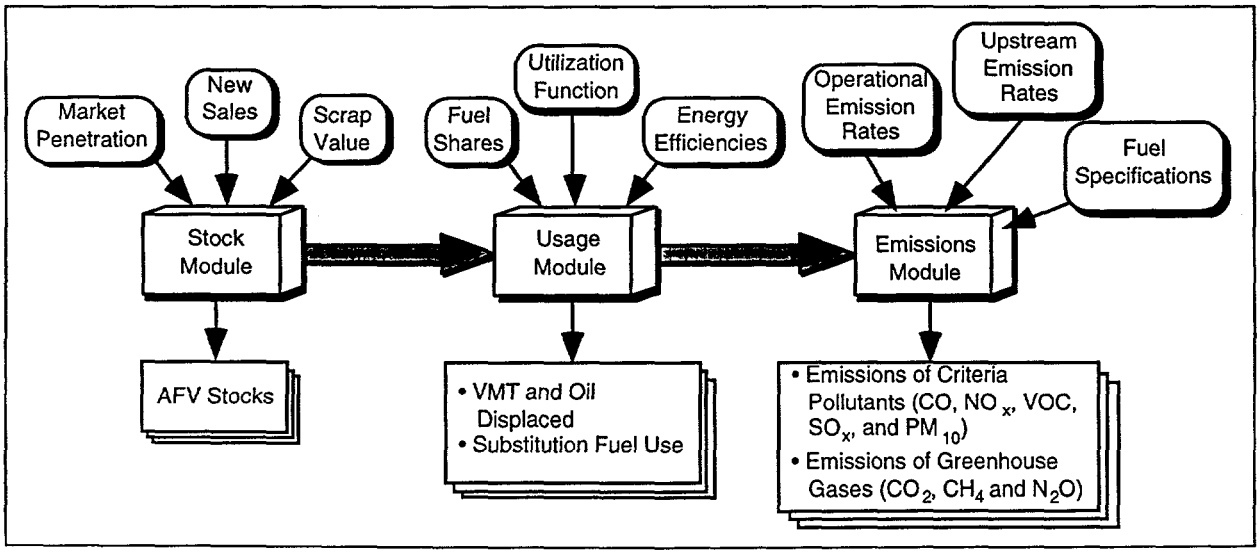


Figure 4.3 Structure of the IMPACTT5 Model

4.2.1 Emissions Calculations

Emission standards are an important reason for considering alternative propulsion systems in the PNGV program. Approximately 40% of model year 1994 (MY94) passenger cars met the Phase 1 (commonly called Tier 1) emission requirements of the Clean Air Act Amendments; by MY96, all passenger cars were required to be in compliance with Tier 1 standards. These standards — for carbon monoxide (CO), oxides of nitrogen (NO_X), non-methane hydrocarbons (NMHC), and particulate matter (PM) — are shown in Table 4.1. Note that the standard for particulate matter (PM) applies only to light-duty diesels. Tier 2 standards that require a further 50% reduction in emissions have been proposed but are not yet mandated. EPA is scheduled to rule on the need for these more stringent standards by December 1999.

Table 4.1 Five-Year or 50,000-mi Emission Standards for Light-Duty Vehicles: 49 States and California (g/mi)

Standard	First MY	NMHC	NMOG	CO	NO_X	PM	HCHO (formaldehyde)
			49 States (mandated)				
Tier 1	1994	0.25	N/A[a]	3.4	0.4	0.08[b]	N/A
Tier 2	2004[c]	0.125	N/A	1.7	0.2	0.08[b]	N/A
			California (mandated)				
TLEV	1994	N/A	0.125	3.4	0.4	0.08[d]	0.015
LEV	1997	N/A	0.075	3.4	0.2	0.08[d]	0.015
ULEV	1997	N/A	0.040	1.7	0.2	0.04[d]	0.008
ZEV	2003	0[e]	0[e]	0[e]	0[e]	0[e]	0[e]
			National LEV Program (voluntary)				
TLEV	2001	N/A	0.125	3.4	0.4	0.08[d]	0.015
LEV	2002	N/A	0.075	3.4	0.2	0.08[d]	0.015
ULEV	2003	N/A	0.040	1.7	0.2	0.04[d]	0.008

[a] Not applicable.

[b] Applies to all 49-state LDVs beginning in MY96.

[c] Need for these standards will be determined by EPA in 1999. They are not yet mandated. Definition of useful life increased to 10 yr or 100,00 mi.

[d] Applies to diesel vehicles only; standards are for 10 yr or 100,000 mi.

[e] Emissions from vehicle itself.

California has defined still stricter vehicle emission standards to be phased in over the next decade. The standards include formaldehyde and replace the non-methane hydrocarbon (NMHC) standard with a non-methane organic gas (NMOG) standard (which includes NMHC and several other organic gases). To meet a fleetwide standard for NMOG, vehicle manufacturers must certify each of their vehicles in one of four

emission categories: Transitional-Low-Emission Vehicles (TLEV), Low-Emission Vehicles (LEV), Ultra-Low-Emission Vehicles (ULEV), or Zero-Emission Vehicles (ZEV). A weighted average consisting of the emission standard for the category and the share of each manufacturer's California sales in that category will then be used to determine if manufacturers are meeting the fleetwide NMOG standard.

The California Air Resources Board recently proposed the so-called "LEV II" program (CARB 1997), which extends the already adopted TLEV, LEV, and ULEV standards to 120,000 mi; tightens PM emission standards to 0.04 g/mi for TLEV and 0.01 for LEV and ULEV (applicable at 120,000 mi); and adds a new vehicle category – super-ultra-low-emission vehicle (SULEV). Applicable for 120,000 mi, the proposed SULEV standards are 0.01 g/mi for NMOG, 1.0 for CO, 0.02 for NO_x, and 0.01 for PM.

Recently, EPA adopted a national low-emission-vehicle (NLEV) program to encourage the introduction of LEV types. Forty-five states and the District of Columbia will be covered under this program. The NLEV program is voluntary, and vehicle manufacturers can participate in lieu of complying with the individual requirements of any state except California.[20] The NLEV program begins in MY 2001 and is similar to the California LEV program with one major exception: Zero Emission Vehicles (ZEVs) are not required to be sold (EPA 1998).

It is generally believed that 3X vehicles will be subject to Tier 2 standards for VOC, CO, and NO_x and the ULEV standard for PM. For this analysis, it was assumed that RFG-fueled SIDI engines will meet Tier 2 standards, but no further emissions reductions (e.g., LEV II standards) will occur. All other SIDI engines (fueled with methanol, ethanol, CNG, LNG, and LPG) were assumed to at least meet Tier 2 standards. If an alternative fuel offers inherently lower emissions than RFG, emission reductions were assumed for that fuel. Table 4.2 presents the emission reductions assumed for the five alternative SIDI fuels.

Recently, it has been proposed that CIDI 3X vehicles should be subject to a PM standard of 0.01 g/mi, which is equivalent to the PM emission rate of conventional gasoline SI vehicles. For this analysis, it was assumed that 3X vehicles with CIDI engines will at least meet Tier 2 standards for NO_x, CO, and VOC and current ULEV standards (i.e., 0.04 g/mi) for PM. As with SIDI alternative fuels, CIDI alternative fuels that offer inherently lower emissions were assumed to achieve further reductions relative to RFD. Table 4.3 presents the emission standards that the four CIDI fuels were assumed to meet. Note that the four fuels were assumed to produce no evaporative emissions since all have very low Reid vapor pressure (RVP). RFD, B20, and F-T50 were assumed to

[20] Twenty-three automakers that comprise nearly all of the U.S. LDV market have agreed to participate in the NLEV program. New York, Massachusetts, Maine, and Vermont have decided to pursue ZEV requirements (i.e., the California model) instead of participating in NLEV.

Table 4.2 Relative Emissions of Alternative SIDI Fuels

	Percent Tier 2 RFG-Fueled SIDI Rate				
Pollutant	Methanol	Ethanol	CNG	LNG	LPG
VOC (exhaust)	55	55	15	15	75
VOC (evaporative)	100	100	0	0	0
CO	60	60	40	40	60
NO_x	80	80	60	60	90
PM (exhaust)	10	10	1	1	1
PM (brake and tire)	100	100	100	100	100
CH_4[a]	65	65	1000	1000	100
N_2O[b]	100	100	100	100	100

[a] Gasoline vehicle CH_4 emissions = 0.074 g/mi.

[b] *Gasoline vehicle N_2O emissions = 0.005 g/mi.*

Table 4.3 Emissions of Alternative CIDI Fuels

	Emissions (g/mi), by Fuel			
Pollutant	RFD[b]	DME	B20	F-T50
VOC (exhaust)	0.125	0.125	0.125	0.125
VOC (evaporative)	0	0	0	0
CO	1.7	1.7	1.7	1.7
NO_x	0.2	0.2	0.2	0.2
PM (exhaust)	0.04	0.01	0.04	0.04
CH_4[a]	0.008	0.008	0.008	0.008
N_2O[b]	0.005	0.005	0.005	0.005

[a] Based on GREET estimates for conventional diesel.

[b] Current California diesel has a sulfur content of about 150 ppm. RFD was assumed to have a sulfur content of 100 ppm in order to meet the 0.04 g/mi PM_{10} emission standard.

meet the current ULEV standard for PM. DME was assumed to meet the tighter LEV II ULEV Standard (0.01 g/mi), which is equivalent to that of an SIDI engine.

It is generally believed that FCVs (using H_2, methanol, or gasoline) will have substantially lower emissions than either SIDI or CIDI engines. Table 4.4 presents the emission assumptions used in this analysis. Note that entries are relative to Tier 2 RFG-fueled vehicles.

4.2.2 Fuel Specifications

In this analysis, diesel fuel specifications were modified to replace the low sulfur California diesel considered in Phase 1 with a lower sulfur, low aromatics

Table 4.4 Relative Emissions of Alternative FCV Fuels

Pollutant	Percent of Tier 2 RFG-Fueled SIDI Rate		
	Hydrogen	Methanol[a] (Partial Oxidation)	Gasoline[a] (Partial Oxidation)
VOC (exhaust)	0	0.5	0.5
VOC (evaporative)	0	20[b]	50[d]
CO	0	1	1
NO_x	0	1	1
PM (exhaust)	0	0	0
PM (brake and tire)	100	100	100
CH_4[c]	0	0	0
N_2O[d]	0	0	0

[a] Based on personal communication with Romesh Kumar of ANL.

[b] Smaller tank size for 3X vehicles helps reduce evaporative emissions.

[c] Gasoline vehicle CH_4 emissions = 0.074 g/mi.

[d] Gasoline vehicle N_2O emissions = 0.005 g/mi.

"reformulated" diesel (RFD). As with gasoline, all diesel was assumed to be reformulated beyond 2000. Specifications for RFD, as well as all other fuels considered in this study, are presented in Table 2.5.

As discussed in Section 2, several fuels that had not been included in the Phase 1 analysis were added to Phase 2. These fuels include a 20% blend of methyl soyate (biodiesel) and conventional diesel (designated as B20), a 50% blend of Fischer-Tropsch diesel and conventional diesel (designated as F-T50), CNG, LNG, and LPG.

4.2.3 Greenhouse Gas Emissions

Operational emissions. As stated above, gasoline-equivalent fuel use by 3X vehicles was calculated simply by assuming that all 3X vehicles meet the PNGV goal (i.e., gasoline-equivalent rated fuel economy of 81 mpg for passenger cars and 63 mpg for light trucks). CO_2 emissions from vehicle operations were then calculated by using a carbon-balance approach (i.e., as a function of the physical quantity of the candidate fuel consumed and its carbon content, less the carbon contained in combustion emissions of VOC, CH_4 and CO).

As part of the Phase 2 analysis, calculations of GHG emissions were expanded to include CH_4 and N_2O and to generate total GHG emissions (in CO_2 equivalents). As with all other pollutants, operational emission rates for CH_4 were assumed to be related to fuel and engine type — CIDI, SIDI, or fuel cell. Operational emission rates for CH_4 and N_2O for each propulsion system-fuel combination were presented in the previous three tables.

Upstream emissions. Upstream emission rates can vary over time as feedstock sources and production processes change. CO_2, CH_4, and N_2O upstream emission rates for each potential 3X fuel were obtained from GREET outputs for 2007 and 2030. Together with rates for the intervening years, estimated by straight-line interpolation, these values were applied to annual estimates of fuel use. For the most part, rates for 2030 are approximately 10% below 2007 values. Key exceptions are ethanol and hydrogen, for which production was assumed to shift from current processes to more advanced, and as yet unproved, processes (i.e., ethanol from biomass as opposed to corn and hydrogen from the electrolysis of water instead of from natural gas). For these fuels, emission rates were assumed constant until introduction of the new process. During the transition to the new process, emission rates were weighted by the share of total capacity represented by each process (see Section 4.3.4).

4.2.4 Urban Emissions

To evaluate the relative damage (in terms of population exposure to criteria pollutants) associated with alternative 3X power system/fuel technologies, the IMPACTT files created for the high- and low-market-share scenarios of Phase 2 were modified to estimate those portions of operational and upstream emissions likely to occur within urban areas. For the estimate, urban vehicle sales, survival and utilization, and urban upstream emission rates had to be estimated.

Both vehicles residing in urban areas ("urban vehicles") and non-resident vehicles being operated within urban areas ("non-urban vehicles") can contribute to urban operational emissions. According to the Nationwide Personal Transportation Survey (NPTS), trips of 75 mi or less account for 82% of total VMT, and trips of 200 mi or less account for 94% of total VMT (Hu 1993). Thus, it may be assumed that approximately 90% of the VMT (and associated emissions) in urban areas is attributable to urban vehicles.[21] Further, it may be assumed that the remaining VMT (and emissions) due to the operation of nonurban vehicles on urban roads is more or less offset by VMT due to the operation of urban vehicles in nonurban areas (or in other, nonresident urban areas). Urban emissions due to vehicle operations may then be estimated as a function of the share of new vehicle sales in urban areas and the survival, urban utilization, and urban emission rates of those vehicles.

For this analysis, "urban" was defined as a metropolitan statistical area (MSA) with a population of 250,000 or more, a definition consistent with the Energy Policy Act of 1992 (EPACT), and an "urban vehicle" was defined as a light-duty vehicle (LDV) residing in such an MSA. According to the 1990 NPTS, "urban vehicles" comprise

[21] Non-urban vehicles could further affect urban air quality if considerable numbers of them are operated near urban area boundaries or atmospheric conditions transport their emissions into urban areas. In the absence of detailed atmospheric modeling, however, it is assumed that this possibility accounts for a negligible share of urban emissions.

70.8% of the LDVs of all ages that households purchased new and 92.7% of the 1990–91 MY LDVs that households purchased new (FHWA 1992). Assuming that vehicles purchased by businesses and other nonhousehold entities follow a similar pattern, it may be assumed that approximately 70% of all the light-duty vehicles sold in the United States remain "urban vehicles".[22]

For this analysis, "urban" and "non-urban" vehicles were assumed to have the same survival and emission rates. Utilization is more problematic. Conventional wisdom suggests that "urban" vehicles may be driven fewer miles because travel destinations are less distant than in rural areas. However, according to the 1990 NPTS, the reverse may be true. "Urban" and "non-urban" automobiles have about the same annual utilization (10,756 mi/yr vs. 10,494 mi/yr), but urban light trucks may travel more miles than nonurban light trucks (11,637 mi/yr vs. 10,766 mi/yr). This surprising pattern was examined further by disaggregating NPTS data by vehicle age or vintage. As shown in Table 4.5, age differences between the urban and nonurban vehicle populations account for virtually all of the difference in light truck utilization (FHWA 1992). Only the newest vehicles continue to show differences in utilization, and these differences may be due to their use on longer trips. Thus, for this analysis, newer vehicles were assumed to travel a slightly higher fraction of miles outside urban areas (to account for their use on longer trips), a fraction that declines with vehicle age. For vehicles aged 0–4 yr, 10% of VMT was assumed to occur outside urban areas; for

Table 4.5 Annual Utilization by Vehicle Type, Location, and Age (VMT/vehicle)

Age (yr)	Automobiles		Light Trucks	
	Urban	Non-Urban	Non-Urban	Urban
0–1	8,294	8,396	8,938	9,885
2	13,517	13,575	14,256	15,237
3	13,312	13,527	14,586	14,285
4	12,634	12,670	12,197	11,975
5	11,692	12,063	13,661	13,103
6–10	10,953	10,964	12,314	12,498
11+	8,000	7,572	7,313	8,687

Source: FHWA 1992.

[22] A higher proportion of late-model LDVs may be "urban." However, because some of these vehicles are eventually resold to non-urban owners, a lower estimate of urban vehicle sales was used in this analysis. Thus, results may be considered conservative estimates of urban vehicle emissions. (For additional discussion, see Section 4.3.3.)

those aged 5–9 yr, 5% of VMT was assumed to occur in non-urban areas; for those 10 yr and older, all VMT was assumed to be urban.[23]

By using these factors, the IMPACTT files created for the high- and low-market-share scenarios were modified to create estimates of the urban vehicle population and the VMT, energy use, and operational emissions of those vehicles under each of the two scenarios. Urban upstream emissions were then added to these values. Urban upstream emissions were calculated as a function of the GREET-estimated upstream urban emissions rate for each pollutant and the IMPACTT estimate of total fuel use (urban and non-urban) under each scenario.

4.3 Key Issues

4.3.1 Utilization and Efficiency of 3X Vehicles

Both conventional and 3X vehicles were assumed to have the same utilization. Because 3X vehicles have triple the fuel economy of conventional vehicles, their per-mile operating cost will be considerably less than that of conventional vehicles operating on the same fuel. This lower operating cost could increase vehicle utilization (as well as energy use and emissions), much like the "rebound effect" that has been documented as a result of CAFE-induced increases in fuel economy (Greene 1992). This analysis does not address the effect of tripled fuel economy on operating cost because it is unclear whether any reduction should be assumed. The PNGV goal is for "comparable" costs. On a lifecycle basis, "comparable" may be achieved in many ways. Alternative fuels with triple the GGE cost of gasoline could result in "comparable" fuel costs. Or, lower fuel costs could offset higher vehicle costs, resulting in "comparable" lifecycle costs. Even more likely is a combination of somewhat higher vehicle costs and GGE equivalent fuel cost. Thus, tripling fuel economy does not necessarily suggest a reduction in operating cost, which might then translate into increased vehicle utilization.

Both 3X and conventional vehicles were assumed to have the same percentage gap between rated and on-road fuel economy. Because the PNGV goal is to triple the fuel economy of conventional vehicles, it was assumed that the appropriate base should be actual, not rated, values. Thus, 81 mpg was reduced to approximately 65 mpg for cars ($27 \times 3 = 81 \times 0.8 = 64.8$), and 63 mpg was reduced to approximately 50 mpg for light trucks ($21 \times 3 = 63 \times 0.8 = 50.4$).

4.3.2 Emission Standards and In-Use Emissions

For this analysis, all vehicles were assumed to achieve at least Tier 2 emission standards by model year 2004. Thus, conventional vehicles meet Tier 2 standards, while 3X vehicles, depending on fuel and technology, achieve either Tier 2 or ULEV

[23] These factors were applied to annual utilization which also declines with vehicle age.

standards. Tables 4.1–4.4 contain the emission standards assumed for 3X vehicles using SIDI and CIDI engines and fuel cells (by fuel type), as well as the emission rates (relative to Tier 2 gasoline vehicles) for 3X vehicles using fuel cells and alternative fuels. Note that the four CIDI engine fuels were assumed to meet the Tier 2 gasoline standards of 0.2 g/mi NO_x and 0.04 g/mi PM. Some type of aftertreatment will be required to meet these standards, and deterioration in the performance of that technology may be anticipated. Thus, it is assumed that NO_x emissions from CIDI engines will be comparable with those of SI engines over all vehicle ages, despite the (uncontrolled) CI engine's historically lower emissions deterioration.[24]

Because many of these vehicles have not been built, let alone been subject to certification testing, assumptions about emission rates are speculative. Clearly, achieving Tier 2 and ULEV standards will be a challenge for vehicle manufacturers. Because one of the goals of the PNGV is to achieve emission levels comparable with those of the conventional vehicles that are being replaced, 3X vehicles were assumed to also achieve Tier 2 and ULEV standards. Unless noted to the contrary, emissions of criteria pollutants by SIDI and CIDI engines were assumed to deteriorate over time at their respective historical deterioration rates as predicted by EPA's MOBILE5b model. Even this is somewhat speculative, however, because EPA is revising the MOBILE model. On the basis of unofficial statements, it appears that the rates at which gasoline vehicles will deteriorate will be considerably lower in the next version of the model. If such is the case, this lower rate of deterioration would reduce the emission benefits of 3X vehicles, particularly those operating on fuel cells or using fuels other than gasoline.

4.3.3 Urban Emissions

A number of simplifying assumptions were needed to permit estimation of the operational portion of urban emissions. Several of these are subject to uncertainty. First, are 70% of all household vehicles sold to urban households, or is it over 90%? According to NPTS, 93% of the model year 1990–91 vehicles that were bought new by households during the timeframe in which NPTS was administered went to urban households (FHWA 1992). Because some of these vehicles may ultimately be resold to nonurban households, it is safe to assume that 93% is a high estimate of vehicles that spend their entire lifetime within urban areas. But, the question is, how high? This analysis used 70%, since it is the share of all vehicles (of all vintages) originally bought new that are currently in urban households. However, if urban households have a lower propensity to retain vehicles purchased new, 70% may be a low estimate.

Second, it is unclear whether the approximately 30% of vehicles assumed to be nonurban generate a significant amount of urban VMT. By using data from NPTS, it appears that approximately 17% of total VMT comes from trips to MSAs with a population of 1,000,000 or more by vehicles from outside MSAs or from MSAs with a

[24] If historical CI emissions deterioration rates were assumed, diesel-like fuels would emit less NO_x than gasoline over a vehicle's lifetime.

population less than 1,000,000 (Hu 1993). Because this study's definition of urban includes MSAs with a population of 250,000 or more, 17% is probably a high estimate of urban VMT by nonurban vehicles. But zero is probably a low estimate.

Third, urban vehicles may contribute more nonurban VMT than assumed. If trips of 75 mi or more account for 18% of total VMT (Hu 1993), one might reasonably assume that no more than 82% of urban vehicle VMT should occur within urban areas. For this analysis, a considerably larger share (90% for newer vehicles, increasing to 100% for vehicles 10 years or older) is assumed. Presumably, the higher share assumed for urban vehicles offsets the lower share assumed for nonurban vehicles.

Fourth, the urban share of upstream emissions is uncertain. Shares were estimated by using the ratio of fuel production to fuel consumption within an urban area. High ratios corresponded to net exporters of energy; low ratios corresponded to net importers. Upstream emissions (and energy use) were then allocated between urban and nonurban areas. In many cases, sparse data necessitated the use of default values that are subject to some uncertainty.

Section 4.5 focuses on urban emission results for the various 3X propulsion system/fuel alternatives. Urban emissions of criteria pollutants are clearly more damaging and of greater interest from a nonattainment perspective. Total emissions of greenhouse gases are also presented in Section 4.5.

4.3.4 Transition in Upstream Production Processes

In the Phase 1 analysis, the transitions from corn to biomass ethanol and from natural gas to solar hydrogen were each assumed to occur over a five-year period, from 2015 to 2020 for ethanol and from 2020 to 2025 for hydrogen. A straight-line interpolation procedure was used to weight the upstream energy and emissions rates associated with each production process in order to estimate total upstream energy and emissions. For the Phase 2 analysis, the 5-yr weighting procedure was replaced with annual estimates of production shares from each process, beginning in the year when the new process was introduced and continuing through 2030. The revised procedure is consistent with the capital cost analysis, which incorporates revised assumptions about investment decisions and plant turnover. Although the cost analysis still assumes a five-year interval for the transition, added capacity, not total production, is assumed to shift to the new production process over that five-year interval. Table 4.6 shows the distribution of both added capacity and production shares by production process for each year from 2007 to 2030. Clearly, the most significant change from the Phase 1 analysis is that solar hydrogen falls far short of full market penetration, achieving only 61% penetration under the high-market-share scenario vs. 76% penetration under the low-market-share scenario by 2030.

Table 4.6 Transition from Natural Gas to Solar Hydrogen and from Corn to Biomass Ethanol

	Hydrogen				Ethanol			
	Added Capacity (%)		Total Production (% solar)		Added Capacity (%)		Total Production (% cellulosic)	
Year	NG	Solar	High Mkt Share	Low Mkt Share	Corn	Cellulosic	High Mkt Share	Low Mkt Share
2007	100	0	0		100	0	0	0
2008	100	0	0		100	0	0	0
2009	100	0	0		100	0	0	0
2010	100	0	0		100	0	0	0
2011	100	0	0		100	0	0	0
2012	100	0	0		100	0	0	0
2013	100	0	0	0	100	0	0	0
2014	100	0	0	0	100	0	0	0
2015	100	0	0	0	100	0	0	0
2016	100	0	0	0	80	20	0	0
2017	100	0	0	0	60	40	0	0
2018	100	0	0	0	40	60	27	6
2019	100	0	0	0	20	80	58	48
2020	100	0	0	0	0	100	74	68
2021	80	20	4	3	0	100	79	75
2022	60	40	10	10	0	100	83	80
2023	40	60	17	16	0	100	86	84
2024	20	80	26	26	0	100	88	87
2025	0	100	35	38	0	100	90	90
2026	0	100	44	49	0	100	91	92
2027	0	100	50	59	0	100	92	93
2028	0	100	55	66	0	100	93	94
2029	0	100	58	72	0	100	93	95
2030	0	100	61	76	0	100	94	96

4.4 Energy and Emissions Estimates

The IMPACTT setup used for this analysis included reference scenario vehicles and 3X vehicles with any of 13 combinations of future propulsion system/fuel technologies. Reference scenario vehicles incorporated RFG-fueled conventional SI engines; 3X vehicles could be powered by the following:

- RFG-fueled SIDI engines,
- Methanol-fueled SIDI engines,

- Ethanol-fueled SIDI engines,
- CNG-fueled SIDI engines,
- LNG-fueled SIDI engines,
- LPG-fueled SIDI engines,
- RFD-fueled CIDI engines,
- F-T50-fueled CIDI engines,
- B20-fueled CIDI engines,
- DME-fueled CIDI engines,
- RFG fuel cells,
- Methanol fuel cells, or
- Hydrogen fuel cells.

For each of these propulsion system/fuel technologies, IMPACTT calculations proceeded in three steps. First, using the reference scenario forecasts of vehicle sales and 3X vehicle market share assumptions described in Sections 2.1 and 2.2, stocks of 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. (Shares of 3X vehicles [out of total LDV stocks]) under the two market penetration scenarios are shown in Figure 2.5). Second, energy use (in gasoline gallon equivalents, or GGEs) was calculated for conventional and 3X vehicles by scenario, year, and vehicle type (auto vs. light truck). Differences in total fuel use between the reference and market share scenarios were then 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}, and SO_x) and greenhouse gases (GHGs) were computed by scenario, year, and vehicle type as a function of either fuel use or a combination of VMT and age-based emission factors.[25] Emissions were calculated for conventional vehicles and each of the 13 propulsion system/fuel alternatives under the two market-share scenarios.

[25] Operational emissions of NO_x, CO, VOC, and PM_{10} were computed as a function of VMT and emission rates by vehicle type (auto or light truck) and age (0 to over 20 years), which varied by calendar year; upstream emissions of all pollutants and operational emissions of SO_x and CO_2 were computed as a function of the quantity of fuel used and its composition (i.e., sulfur or carbon content for SO_x and CO_2, which varied by calendar year or as the result of switching from one fuel type to another [e.g., from RFG to methanol]). Fuel specifications are provided in Table 2.5.

As compared with the low-market-share scenario, the high-market-share scenario has nearly three times as many 3X vehicles on the road by 2030. These vehicles produce similar increases in 3X VMT and fuel use.

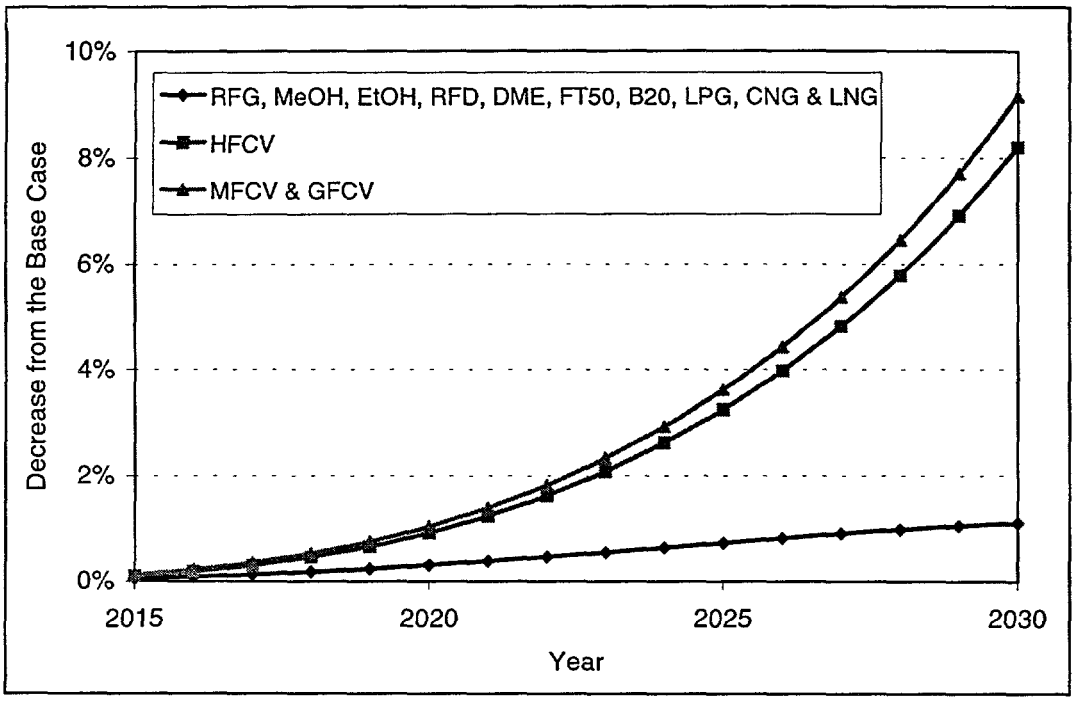
4.4.1 Emissions of Criteria Pollutants

Figures 4.4–4.9 display percent changes in urban emissions of the five criteria pollutants for each of the above propulsion system/fuel combinations. Each figure depicts results for a single pollutant as a series of curves showing annual percentage increases or decreases from the reference scenario forecast for each technology/fuel combination. Curves that are all but indistinguishable are combined to aid interpretation. Upstream and operational emissions are not shown separately (as they were in the Phase 1 report) because virtually all urban emissions are due to vehicle operation. Readers interested in further detail are urged to consult Appendixes A and B, which contain estimates of upstream, operational, and total emissions by propulsion system/fuel combination and scenario.

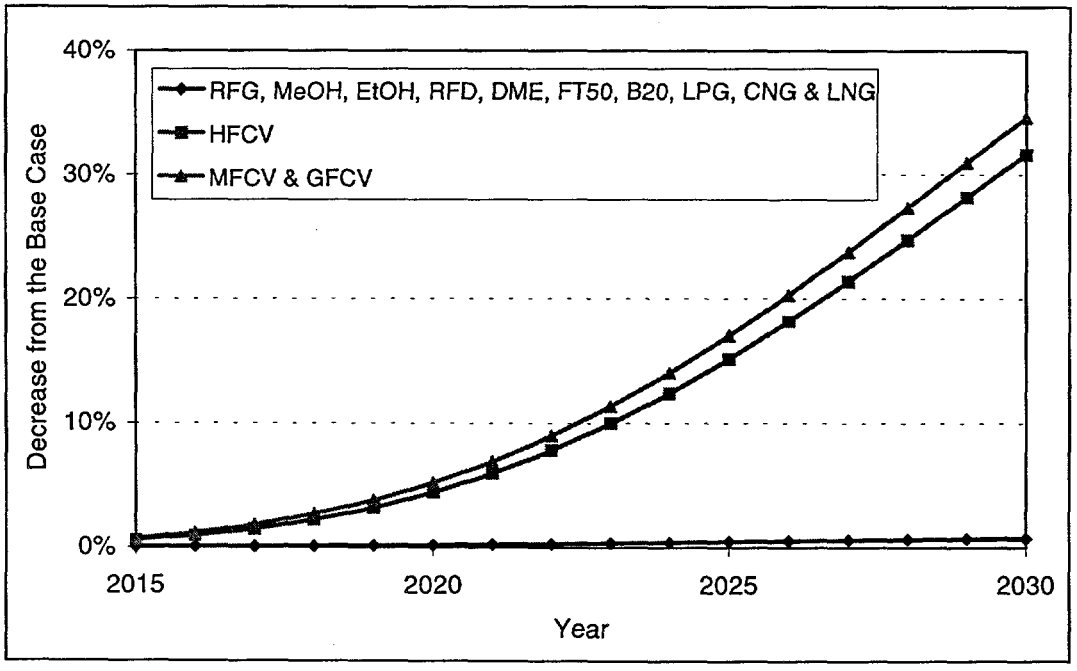
As in the Phase 1 analysis, emissions estimates under both market share scenarios show similar results. However, the patterns are much more striking under the high-market-share scenario (note the different y-axis scales), which, by definition, is a more extreme example of possible market penetration. Thus, the following discussion tends to focus on results from that scenario. Each technology/fuel alternative considered in the analysis was examined in the context of a scenario that contains a significant portion of conventional, as well as 3X, vehicles. Thus, emissions were computed for a combination of conventional and 3X technologies, and results are less striking than would be the case for 3X technologies alone.

Nitrogen Oxides (NO_x). Figure 4.4 illustrates the impact of alternative 3X propulsion system/fuel combinations on urban NO_x emissions under the two scenarios. Because it was assumed that the four CIDI fuels would meet equivalent Tier 2 emission standards, RFD, DME, F-T50, and B20 all fall within a narrow band and are essentially equivalent to RFG, MeOH, EtOH, LPG, and the gaseous-fueled alternatives. Methanol and gasoline fuel cells offer the largest reduction in urban NO_x emissions — 9% under the low-market-share scenario and 35% under the high-market-share scenario. Hydrogen fuel cells achieve somewhat lower NO_x reduction (approximately 8% in the low-market-share scenario vs. 32% in the high-market-share scenario) because of their relatively higher upstream emissions.

Carbon Monoxide (CO). Figure 4.5 shows reductions in CO emissions under the high- and low-market-share scenarios. Again, reductions range up to about 8% under the low-market-share scenario and 35% under the high-market-share scenario, with fuel cells achieving the highest reductions and SIDI engines on any of six fuels achieving the lowest. Between these two clusters, however, the position of the other propulsion system/fuel alternatives differs markedly from NO_x results. Given the CI engine's proven record of relatively low CO emissions, it is not surprising that diesel-like fuels (RFD, DME, F-T50, B20) have the second-best CO reduction.

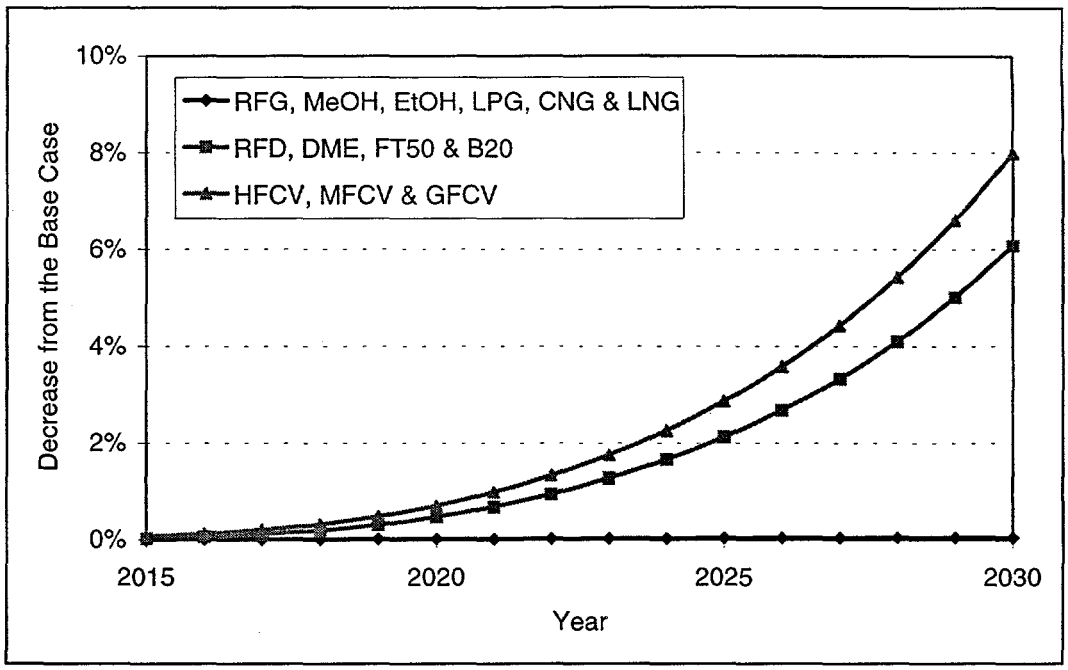


(a) Low-Market-Share Scenario

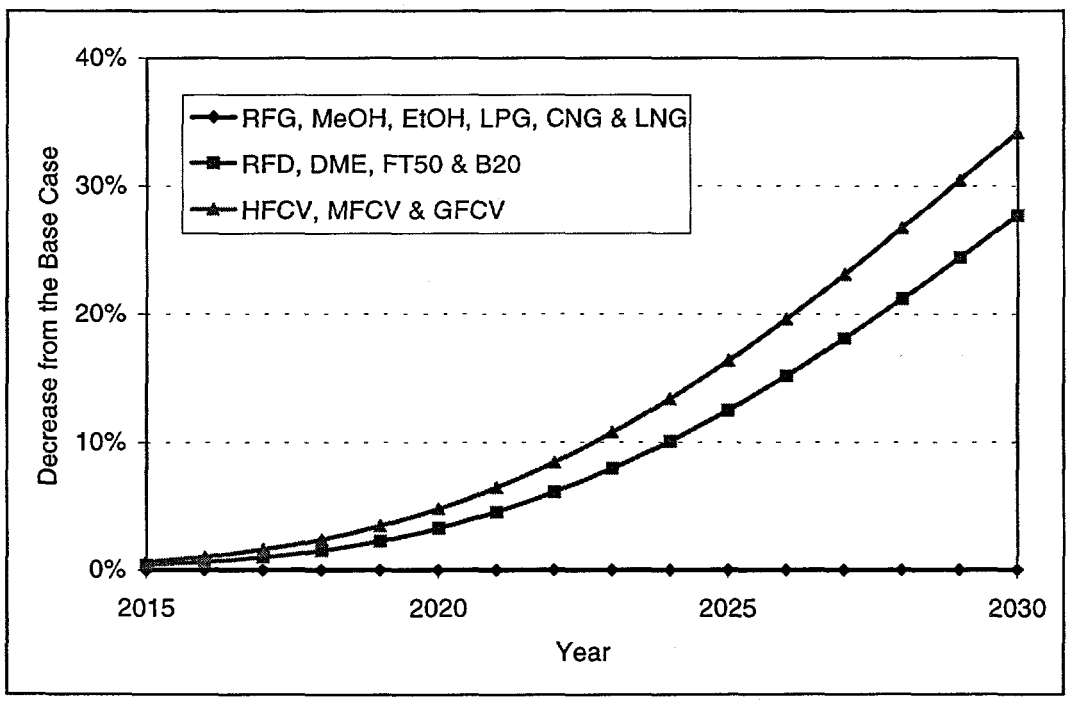


(b) High-Market-Share Scenario

Figure 4.4 Changes in Fuel-Cycle Urban NO_x Emissions by 3X Technology/Fuel Alternative

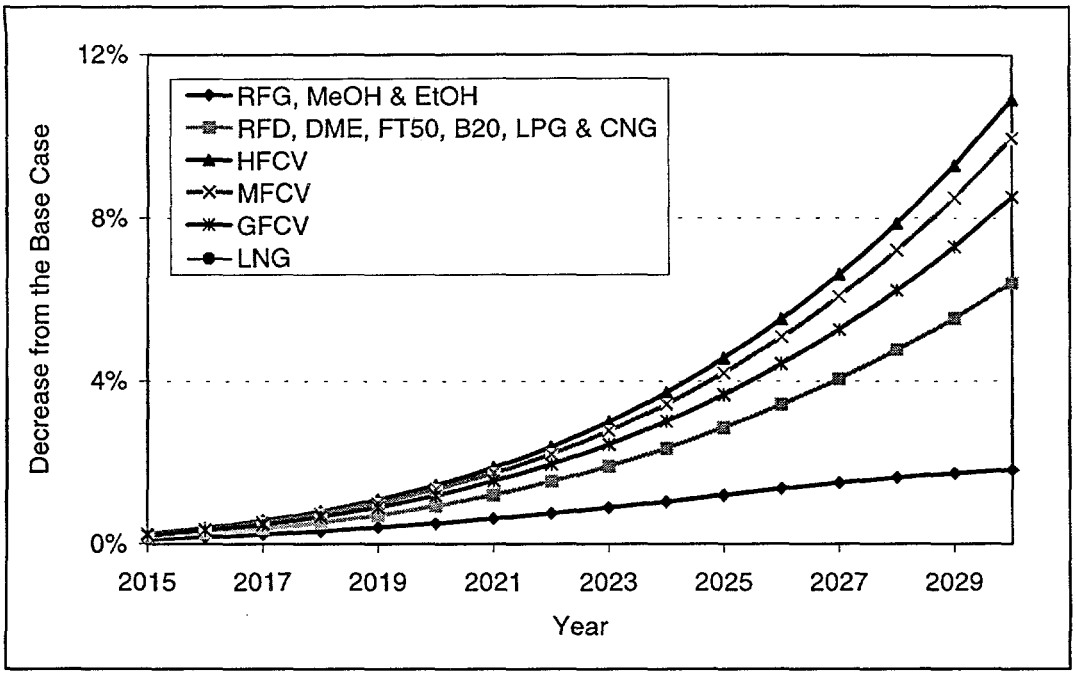


(a) Low-Market-Share Scenario

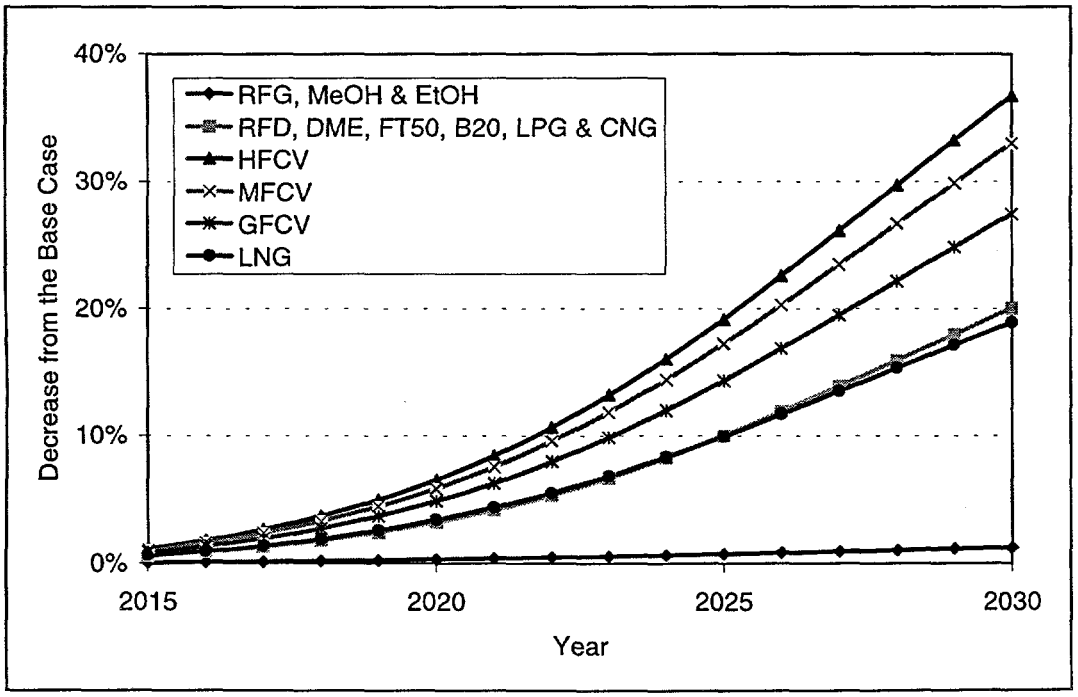


(b) High-Market-Share Scenario

Figure 4.5 Changes in Fuel-Cycle Urban CO Emissions by 3X Technology/Fuel Alternative

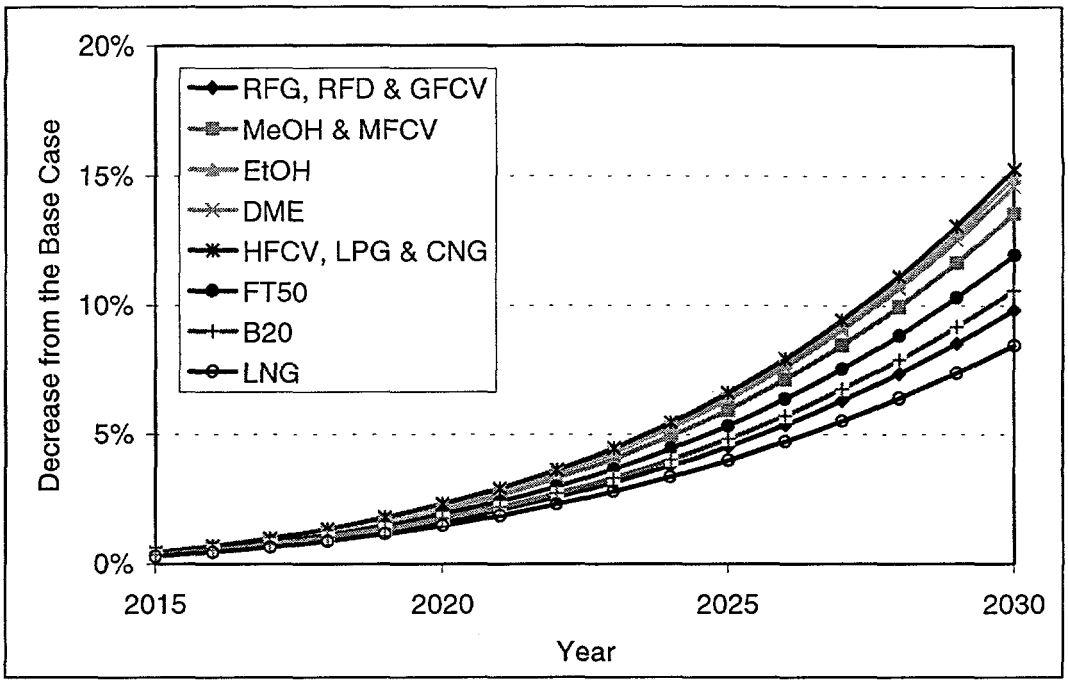


(a) Low-Market-Share Scenario

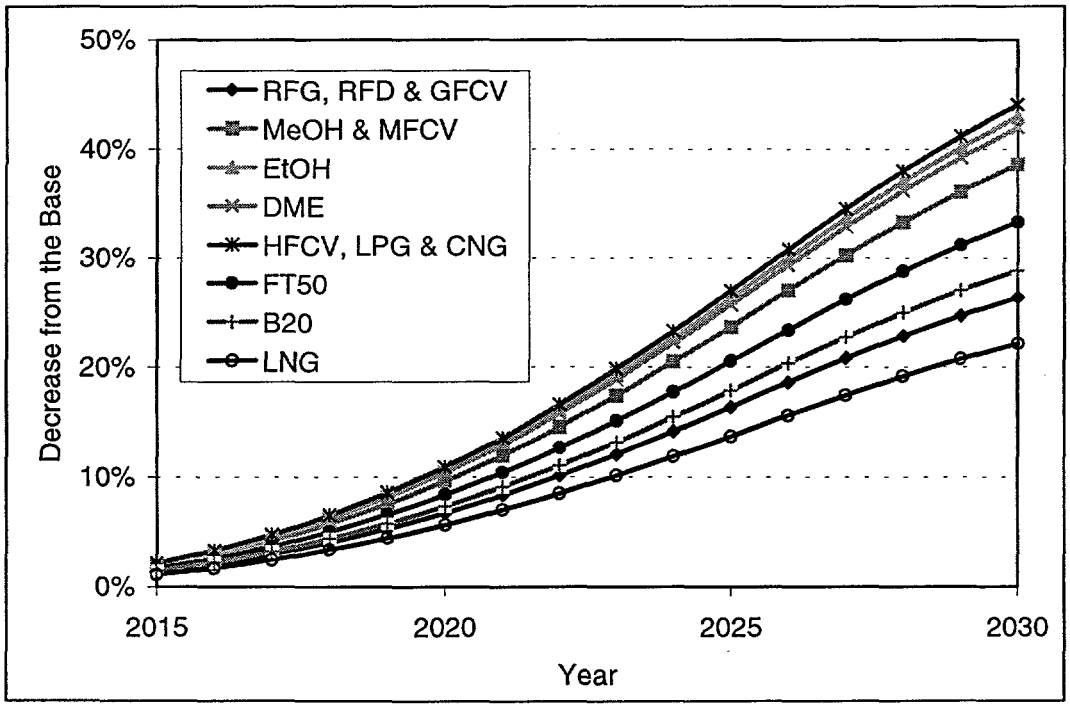


(b) High-Market-Share Scenario

Figure 4.6 Changes in Fuel-Cycle Urban VOC Emissions by 3X Technology/Fuel Alternative

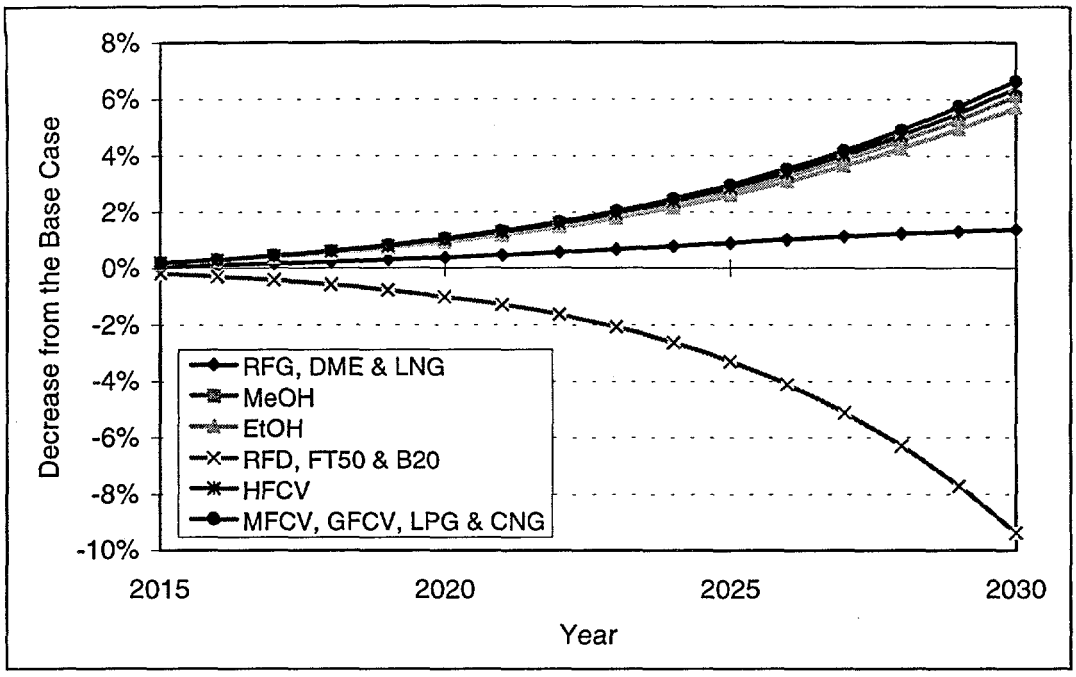


(a) Low-Market-Share Scenario

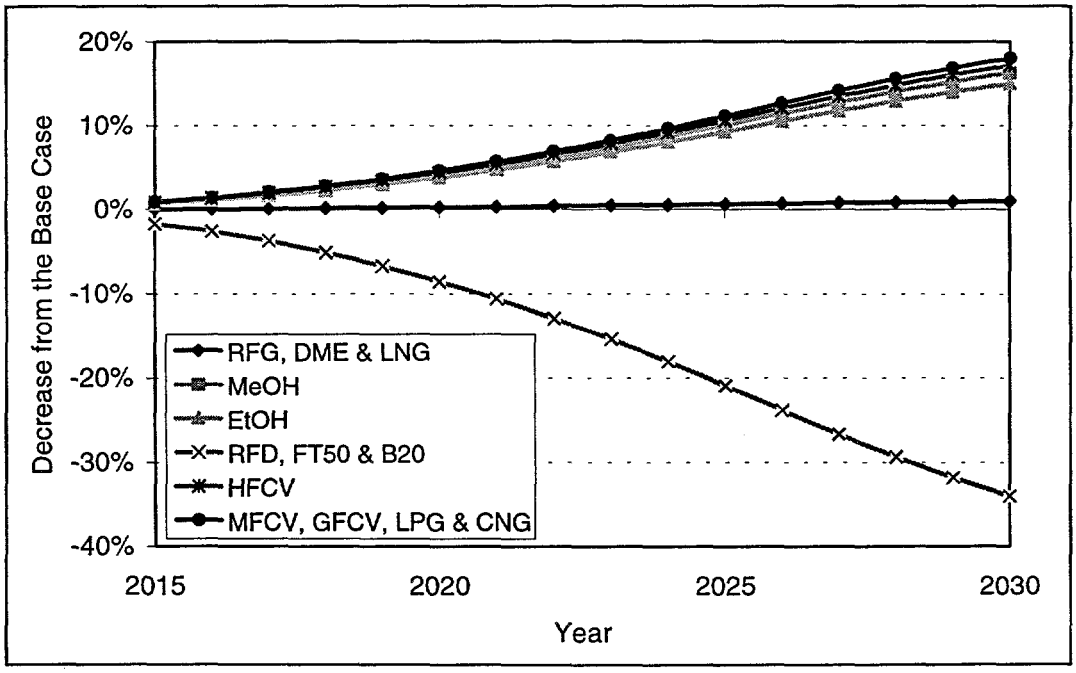


(b) High-Market-Share Scenario

Figure 4.7 Changes in Fuel-Cycle Urban SO_X Emissions by 3X Technology/Fuel Alternative



(a) Low-Market-Share Scenario



(b) High-Market-Share Scenario

Figure 4.8 Changes in Fuel-Cycle Urban PM_{10} Emissions by 3X Technology/Fuel Alternative

Volatile Organic Compounds (VOCs). For VOC, reductions from reference scenario emissions range up to approximately 11% in the low-market-share scenario and 37% in the high-market-share scenario (see Figure 4.6). Hydrogen fuel cells are the clear leader from a VOC reduction standpoint, with methanol fuel cells a close second and gasoline fuel cells third. CIDI engines on RFD, DME F-T50, or B20 and SIDI engines on LPG, CNG, or LNG achieve almost half the reduction of hydrogen fuel cells.

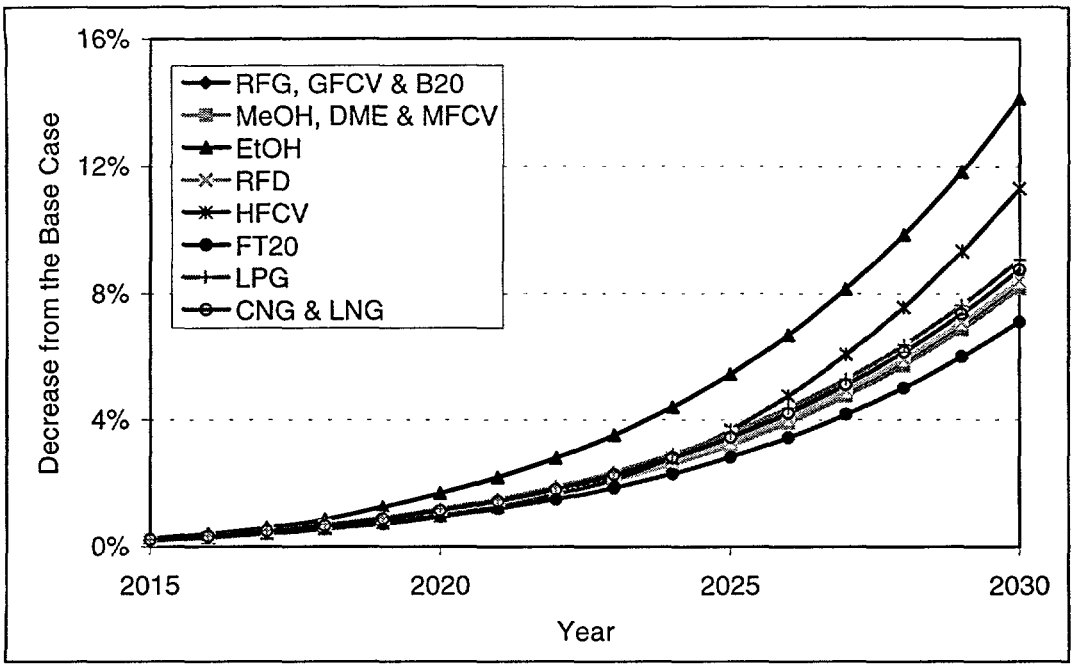
Sulfur Oxides (SO_x). Unlike the other criteria pollutants, urban SO_x emissions are closely related to the volume of fuel used. Thus, relative to the reference scenario, all propulsion system/fuel alternatives reduce urban SO_x emissions because of their tripled fuel efficiency (Figure 4.7). Hydrogen fuel cells, LPG, CNG, ethanol, and DME achieve the biggest reductions, but urban SO_x represents a very small share (on the order of 7–13%) of the total SO_x attributable to light-duty vehicles. Most SO_x emissions come from upstream fuel processing, which tends to be outside urban areas.

Particulate Matter (PM_{10}). Unlike total PM_{10} emissions, nearly half of which occur upstream, urban PM_{10} emissions are dominated by vehicle operations. Thus, with the exception of DME, diesel-like fuels increase PM_{10} emissions (Figure 4.8). Excluding RFG, DME, and LNG, which have little effect on PM, all the other alternatives decrease PM_{10} emissions by approximately 15% under the high-market-share scenario (6% under the low scenario). Note that the increase for diesel-like fuels occurs despite the assumption of a "Tier 2 equivalent" exhaust emission standard of 0.04 g/mi (as compared with the current standard of 0.08 g/mi at 50,000 mi). DME, which produces virtually no particulate matter from fuel combustion, was assumed to achieve the proposed LEV II ULEV standard (including 0.01g/mi PM_{10}). Given that assumption, it comes as no surprise that DME and RFG have comparable urban PM_{10} emissions. For LNG, which produces similar urban PM emissions, upstream processes account for much of urban PM.

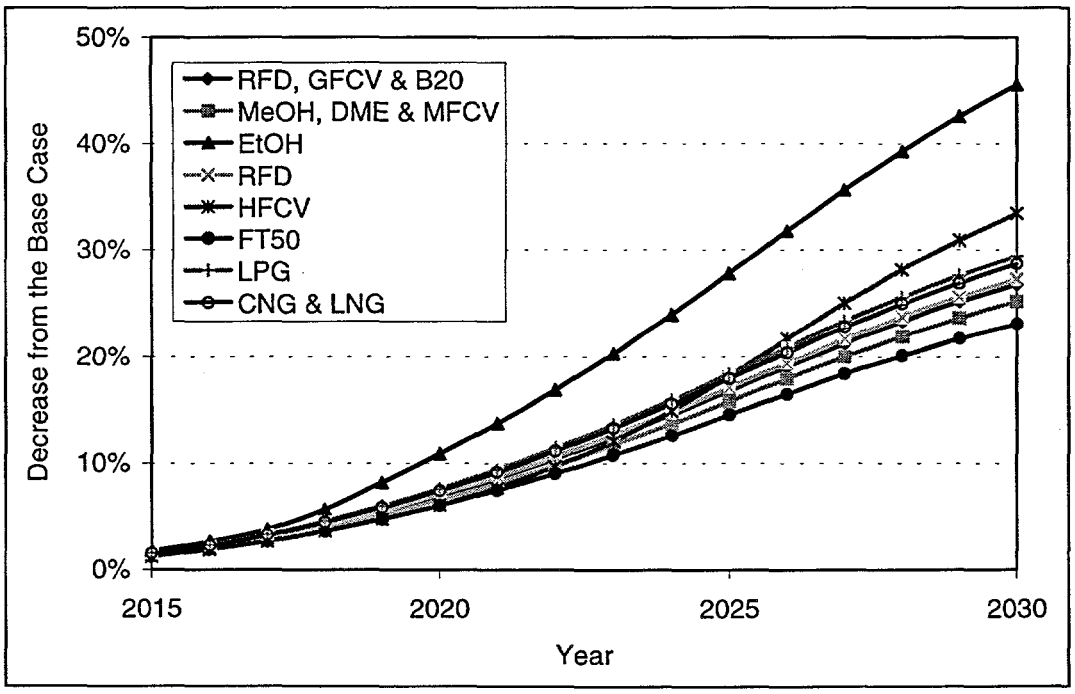
Note also that ethanol is not markedly different from the other SIDI fuel alternatives insofar as urban PM_{10} emissions are concerned. In Phase 1, however, ethanol accounted for the largest increase in total PM_{10} emissions. Virtually all of that increase was due to agricultural processes, making ethanol relatively benign from an urban perspective.

4.4.2 Greenhouse Gas Emissions

Figure 4.12 displays changes in total greenhouse gas (GHG) emissions in the same format as that used for the criteria pollutant graphs. Note that because CO_2 comprises the bulk of GHGs and all propulsion system/fuel alternatives share the same fuel efficiency, emission reductions from non-renewable fuels are clustered. Under the low-market-share scenario, GHG reductions range from 7 to 14%; under the high-market-share scenario, the range is from 23 to 45%. Chief among the low-GHG alternatives are ethanol-fueled SIDI engines and hydrogen fuel cells, both of which generate no CO_2 from vehicle operations. Hydrogen fuel-cell vehicles generate no CO_2 because no carbon is contained in the fuel. Ethanol-fueled SIDI engines are assumed to generate no CO_2 because the carbon in ethanol comes from carbon in the atmosphere via photosynthesis. When



(a) Low-Market-Share Scenario



(b) High-Market-Share Scenario

Figure 4.9 Changes in Fuel-Cycle GHG Emissions by 3X Technology/Fuel Alternative

combined with the conventional vehicles (and their GHG emissions) in the high-market-share scenario, these low-GHG alternatives achieve overall reductions (from all light-duty vehicles, both 3X and conventional) of 46% (for ethanol) and 33% (for hydrogen).

Note also that shifts from current to advanced production technologies cause some GHG reduction curves to shift position relative to the others. Specifically, hydrogen shifts from a position at or near the bottom of the pack to second place by 2025. Ethanol, which is also assumed to shift to a more advanced production technology, has a change in slope, but it is less obvious relative to the other alternatives. After ethanol and hydrogen, the only two renewable fuels examined, LPG and the gaseous fuels, achieve the next-best reduction in GHGs. However, they are only marginally better than the other alternatives.

As compared with Phase 1, Phase 2 estimates of CO_2 emissions reduction are somewhat lower. This result is primarily due to a reduction in projected fuel demand under the reference scenario[26] and a longer transition period from natural gas to solar hydrogen and from corn to cellulosic ethanol.

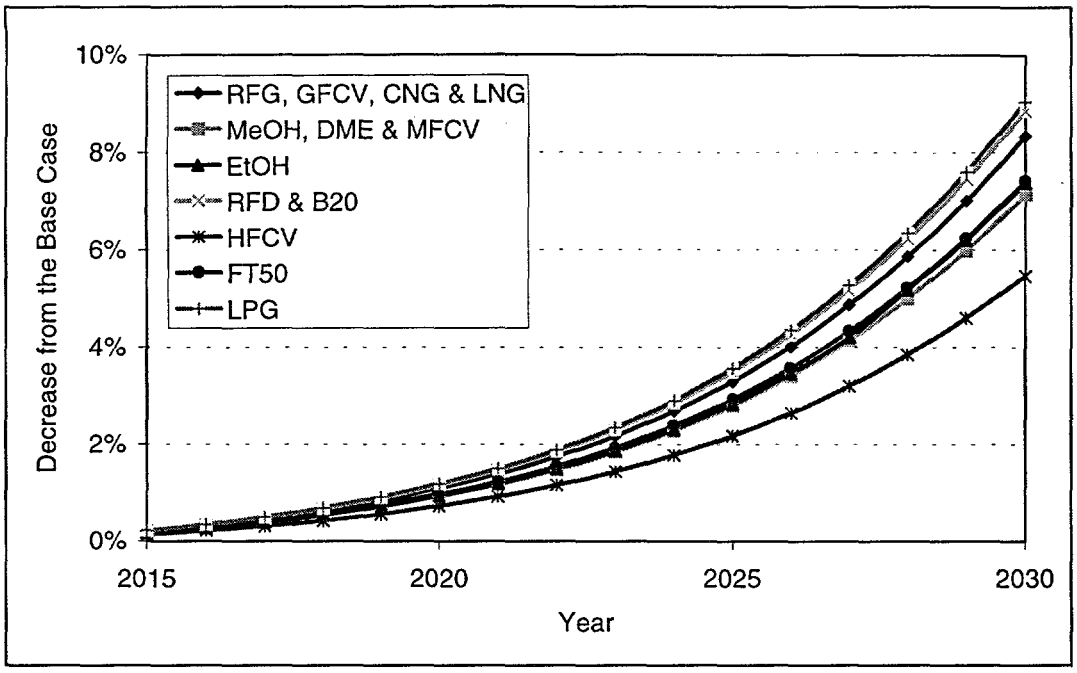
4.4.3 Energy Estimates

Figures 4.10–12 provide estimates of changes in total energy, fossil energy, and petroleum use for the low- and high-market-share scenarios relative to the reference scenario. Again, formats are identical to the above graphs.

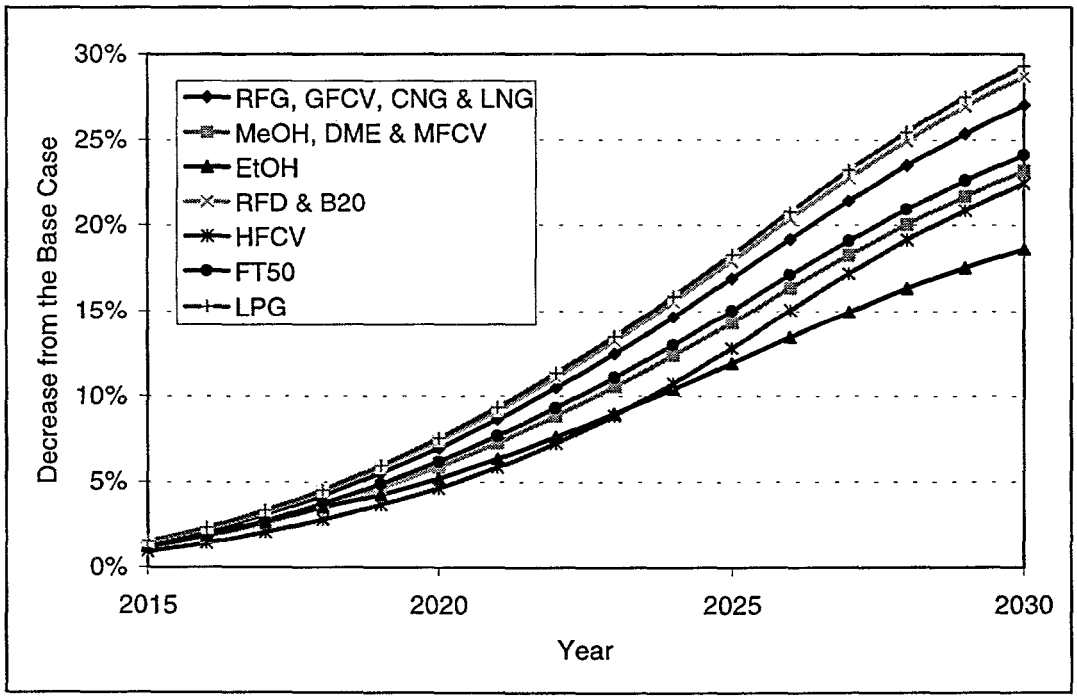
Total Energy. As shown in Figure 4.10, total energy use by light-duty vehicles declines by 18–29% under the high-market-share scenario (5–9% under the low-market-share scenario). By definition, all fuel/technology alternatives achieve 3X fuel economy. Thus, operational energy use declines by 27% in 2030 for all alternatives under the high-market-share scenario (15% 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 alternatives.

Fossil Fuels. Reductions in fossil energy use by the 13 fuel/technology alternatives under the reference scenario and the high- and low-market-share scenarios are shown in Figure 4.11. The ethanol- and hydrogen-fueled alternatives, both largely nonfossil fuels in 2030, achieve the largest reductions in fossil fuel use in that year (approximately 45% and 38%, respectively, under the high-market-share scenario vs. 11% and 12% under the low-market-share scenario), followed by the biodiesel blend (B20) and RFD, LPG, and CNG, which achieve reductions of nearly 30% under the high-market-share scenario vs. 9% under the low-market-share scenario. The transition from fossil to nonfossil feedstocks is particularly evident in the hydrogen curve, as is a flattening out in all

[26] The lower vehicle sales and fuel economy estimates in AEO-97 result in a 7% reduction in fuel use under the reference scenario as compared with the Phase 1 estimate, which was based on AEO-96 inputs.

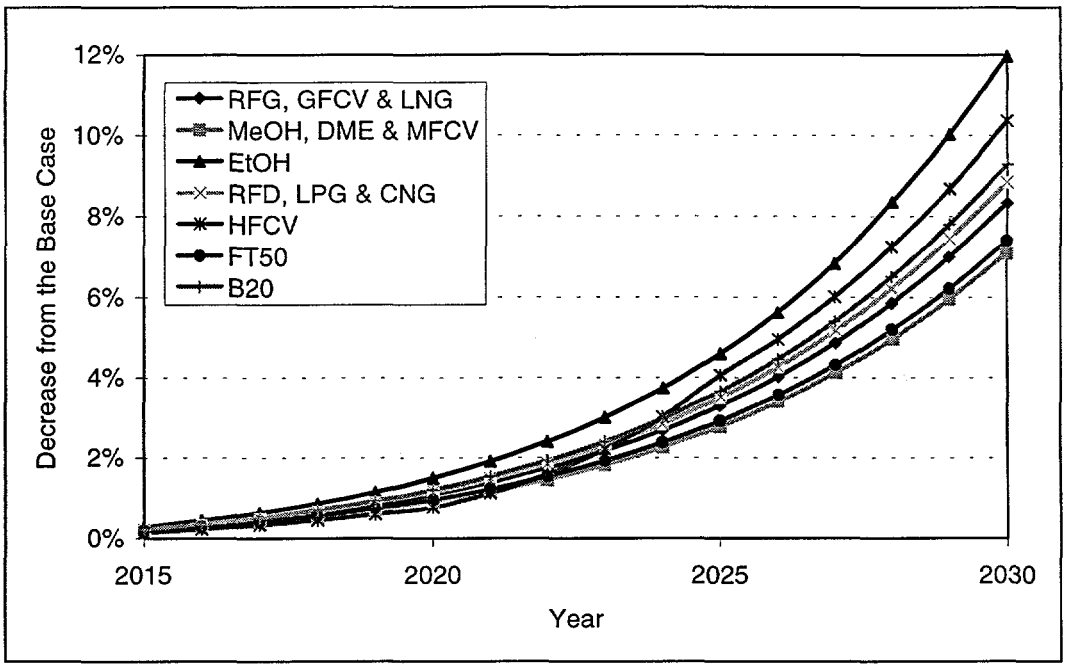


(a) Low-Market-Share Scenario

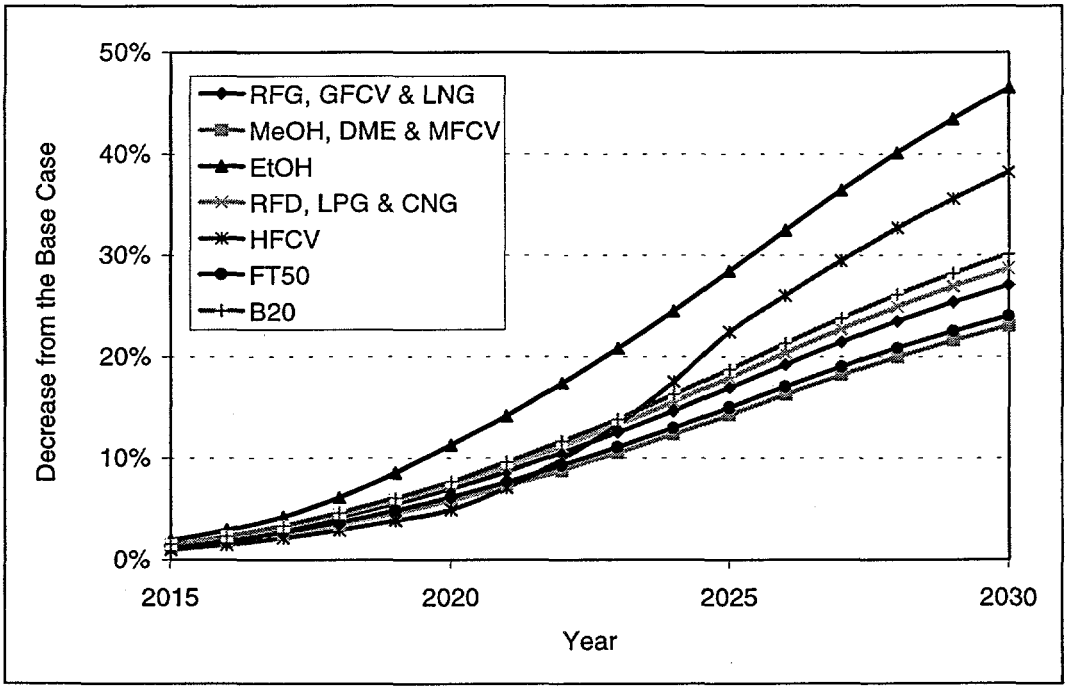


(b) High-Market-Share Scenario

Figure 4.10 Changes in Fuel-Cycle Total Energy Use by 3X Technology/Fuel Alternative

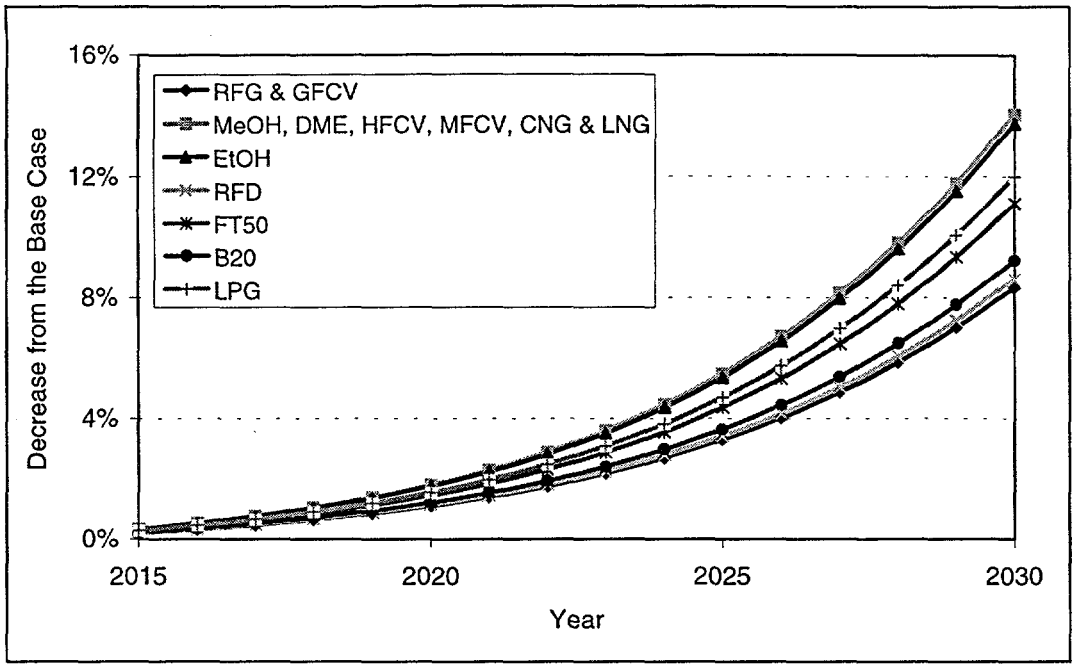


(a) Low-Market-Share Scenario

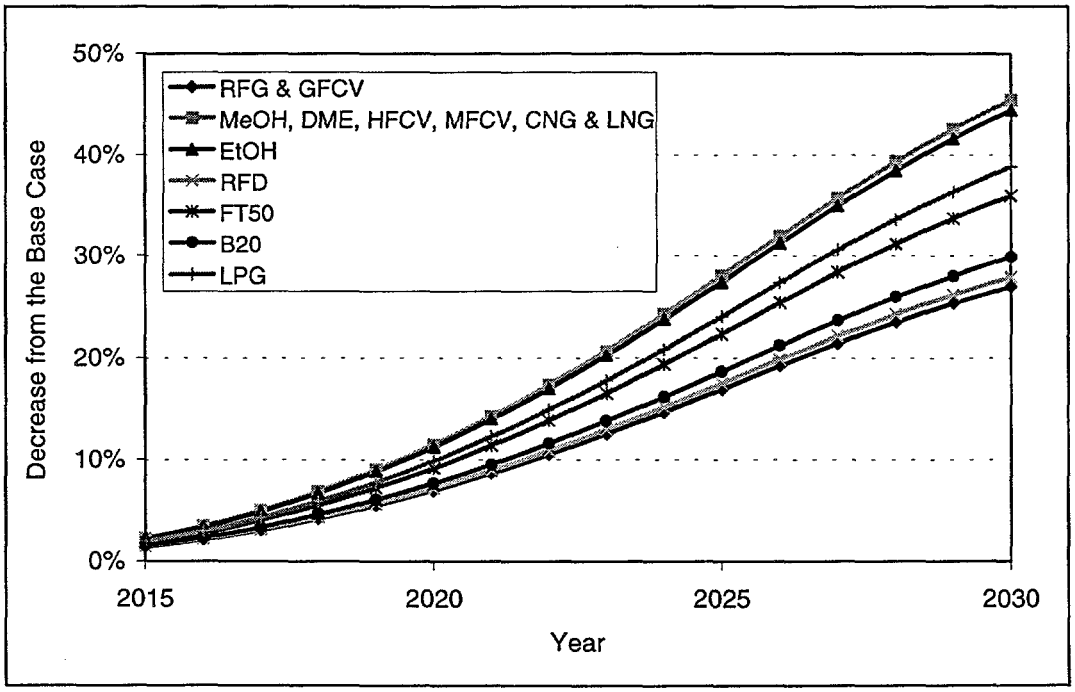


(b) High-Market-Share Scenario

Figure 4.11 Changes in Fuel-Cycle Fossil Energy Use by 3X Technology/Fuel Alternative



(a) Low-Market-Share Scenario



(b) High-Market-Share Scenario

Figure 4.12 Changes in Fuel-Cycle Petroleum Use by 3X Technology/Fuel Alternative

curves for the high-market-share scenario as compared with the low-market-share scenario.

All (completely) fossil-fueled alternatives consume 11.1 quads of fossil fuels because of vehicle *operation* in 2030 under the high-market-share scenario vs. 10.8 quads for B20, 20% of which is nonfossil, and 8.2 quads for the 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.

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 4.12 displays petroleum use by technology/fuel alternative for the reference and low- and high-market-share scenarios. Clearly, the alternatives cluster into three groups: largely petroleum fuels (i.e., RFG, RFD and B20), "part petroleum" fuels (i.e., F-T50 and LPG), and largely nonpetroleum fuels (i.e., hydrogen, methanol, ethanol, DME, CNG, and LNG). By 2030, the nonpetroleum alternatives achieve an approximately 45% reduction in total petroleum use under the high scenario (14% under the low-market-share scenario) relative to the reference scenario. The "part petroleum" alternatives (i.e., LPG and F-T50) achieve the next-best reduction — approximately 35% under the high-market-share scenario and 11% under the low-market-share scenario.