Section 6
Fuel-Cycle Energy Use and Emissions Results

This section presents results of energy use and emissions associated with individual alternative fuels and advanced vehicle technologies, as calculated by GREET 1.5. To generate the results presented in this section, we used default assumptions (presented in previous sections) about upstream fuel production activities and vehicle operations. As stated throughout this report, the default assumptions used in GREET are based on our research. Readers need to pay attention to the assumptions as much as to the results. It is preferable that, for their own analyses, users collect the necessary data, make changes to critical assumptions in GREET, and produce their own results. However, the results presented in this section do represent our best judgments, made on the basis of our research.

6.1 Near- and Long-Term Alternative Fuels and Vehicle Technologies

Among the fuels and vehicle technologies included in GREET, some are already available in the marketplace and being used, while others, still in the research and development stage, must overcome technological hurdles or are not marketable because of cost and infrastructure constraints. Economics and market readiness of these long-term technologies are beyond the scope of this study.

Thus, evaluation of fuel-cycle energy and emission impacts of alternative fuels and advanced technologies is conducted separately for near-term and long-term technologies. The separation is necessary because, over time, baseline conventional technologies will be improved, and the improved baseline conventional technologies should be used to analyze the impacts of long-term technologies. For our analysis, near-term technologies are those already available in the United States, and long-term technologies could become available around the year 2010 (see Tables 4.35, 4.45, and 4.46 for near- and long-term technologies).

To evaluate near-term technologies, we assumed that they would be applied to vehicles produced around 2001 (MY 2001) and that the baseline MY 2001 GVs would meet National Low-Emission Vehicle (NLEV) emission standards. The NLEV program, adopted by EPA in the spring of 1998, is a voluntary program in which 9 northeast U.S. states and 23 automakers participate. The program requires that NLEV vehicles begin to be introduced to the northeast United States in MY 1999 and to the rest of the United States (except California) in MY 2001 (EPA 1998a). The NLEV program allows manufacturers to certify vehicles fueled by gasolines like the federal Phase 2 RFG.

Table 6.1 presents NLEV emission standards and Tier 1 standards currently in place. Tier 1 emission standards were fully in effect beginning in MY 1996. Under the NLEV program, each automaker is subject to fleet average NMOG standards. In the Northeast United States, the fleet average NMOG standards are 0.148 g/mi for MY 1999 and 0.095 g/mi for

Table 6.1 Tier 1 and NLEV Emission Standards for Light-Duty Vehicles and Trucks (in g/mi)[a]

Vehicle		THC	NMHC	NMOG	CO	NO_x	PM[b]	HCHO[c]
				5 Years/50,000 Miles Useful Life				
Cars	Tier 1	NE[d]	0.25	NE	3.4	0.4	0.08	NE
	TLEV	NE	NE	0.125	3.4	0.4	NE	0.015
	LEV	NE	NE	0.075	3.4	0.2	NE	0.015
	ULEV	NE	NE	0.040	1.7	0.2	NE	0.008
LDT1[e]	Tier 1	NE	0.25	NE	3.4	0.4	0.08	NE
	TLEV	NE	NE	0.125	3.4	0.4	NE	0.015
	LEV	NE	NE	0.075	3.4	0.2	NE	0.015
	ULEV	NE	NE	0.040	1.7	0.2	NE	0.008
LDT2[e]	Tier 1	NE	0.32	NE	4.4	0.7	0.08	NE
	TLEV	NE	NE	0.160	4.4	0.7	NE	0.018
	LEV	NE	NE	0.100	4.4	0.4	NE	0.018
	ULEV	NE	NE	0.050	2.2	0.4	NE	0.009
LDT3[f]	Tier 1	NE	0.32	NE	4.4	0.7	NE	NE
LDT4[f]	Tier 1	NE	0.39	NE	5.0	1.1	NE	NE
				10 Years/100,000 Miles Useful Life				
Cars	Tier 1	NE	0.31	NE	4.2	0.6	0.10	NE
	TLEV	NE	NE	0.156	4.2	0.6	0.08	0.018
	LEV	NE	NE	0.090	4.2	0.3	0.08	0.018
	ULEV	NE	NE	0.055	2.1	0.3	0.04	0.011
LDT1[e]	Tier 1	0.80	0.31	NE	4.2	0.6	0.10	NE
	TLEV	NE	NE	0.156	4.2	0.6	0.08	0.018
	LEV	NE	NE	0.090	4.2	0.3	0.08	0.018
	ULEV	NE	NE	0.055	2.1	0.3	0.04	0.011
LDT2[e]	Tier 1	0.80	0.40	NE	5.5	0.97	0.10	NE
	TLEV	NE	NE	0.200	5.5	0.9	0.10	0.023
	LEV	NE	NE	0.130	5.5	0.5	0.10	0.023
	ULEV	NE	NE	0.070	2.8	0.5	0.05	0.013
LDT3[f]	Tier 1	0.80	0.46	NE	6.4	0.98	0.10	NE
LDT4[f]	Tier 1	0.80	0.56	NE	7.3	1.53	0.12	NE

[a] Source: EPA Office of Mobile Sources Internet Home Page.

[b] PM emission standards are applied to diesel vehicles only.

[c] HCHO = formaldehyde.

[d] NE = not established.

[e] Definitions of LDT1 and LDT2 are different between emission regulations and emission estimations in Mobile 5b. In emission regulations, LDT1 is defined as an LDT with a loaded vehicle weight of 0–3,750 lb and with a GVW below 6,000 lb; LDT2 is defined as an LDT with a loaded vehicle weight of 3,750–5,570 lb and with a GVW below 6,000 lb. For emission estimation in Mobile 5b, LDT1 is defined as an LDT with a GVW of less than 6,000 lb; LDT2 is defined as an LDT with a GVW of 6,000–8,500 lb.

[f] LDT3 and LDT4 for emission regulations are the LDT2 defined in Mobile 5b simulations. Both LDT3 and LDT4 have a GVW of 6,001–18,500 lb. LDT3 has a loaded vehicle weight of 0–3,750 lb, and LDT4 has a GVW of greater than 3,750 lb.

MY 2000 and beyond for cars and LDT1; and 0.190 g/mi for MY 1999 and 0.124 g/mi for MY 2000 and beyond for LDT2. Nationwide, the fleet average NMOG standards are 0.075 g/mi for cars and LDT1 and 0.100 g/mi for LDT2, both beginning in MY 2001. Nationwide, NLEV vehicles will be required to account for at least 25% of total vehicle sales in MY 2001, 50% in MY 2002, and 85% in MY 2003 and beyond.

To represent the average lifetime emissions of MY 2001 vehicles, we estimate, with Mobile 5b and Part 5, per-mile emissions of the MY 2001 baseline vehicles (i.e., gasoline and diesel vehicles) in calendar year 2006, when these vehicles will accumulate about half of their lifetime VMT. Consequently, GREET 1.5 was run for calendar year 2006 for near-term technologies.

The GREET 1 series is designed to estimate fuel-cycle energy use and emissions for passenger cars, light-duty trucks 1 (LDT1s, pickups, minivans, passenger vans, and sport utility vehicles with a GVW up to 6,000 lb), and light-duty trucks 2 (LDT2s with a GVW between 6,001 and 8,500 lb). Energy use and emissions are estimated for passenger cars, LDT1s, and LDT2s separately. Tables 4.45 and 4.46 indicate that changes in fuel economy and emissions of alternative-fuel transportation technologies are assumed to be the same for passenger cars and LDT1s, while changes for LDT2s are different. Consequently, relative changes in fuel-cycle energy use and emissions for passenger cars and LDT1s are the same. On the other hand, fuel economy (affecting per-mile upstream emissions) and per-mile vehicular emissions are distinctly different for the three vehicle classes. Thus, changes in absolute amount (i.e., Btu/mi and g/mi) for energy and emissions are also different for the three.

To run GREET 1.5 for calendar year 2006, where both current and future emission factors are applied to a given combustion technology, we assumed a split of 20%/80% between current emission factors and future emission factors to calculate average emission factors for the combustion technology. Table 6.2 summarizes key assumptions about upstream activities for evaluating near- and long-term technologies.

To estimate fuel-cycle energy and emission impacts of long-term technologies, GREET was run in calendar year 2015 for MY 2010 vehicle technologies. Besides changes in vehicle operations emissions, changes were also made in the assumptions about upstream activities. For the long-term technology evaluation, future emission factors alone were used for combustion technologies; current emission factors were zeroed out. For the four NG-based fuels (methanol, DME, FTD, and H_2), energy efficiencies in production plants were increased, or steam credit was assumed (see Table 6.2). Energy intensity for manufacturing fertilizers and pesticides was reduced by 15%. Farming energy use (in Btu/bu) and use of fertilizers and pesticides (in g/bu) were reduced by 10% for both corn and soybean farming. Energy use in ethanol plants and biodiesel plants was reduced by 10%. The share of NG as the process fuel in ethanol plants was increased, while the share of coal was decreased. Ethanol yield was increased from 2.6 to 2.7 gal/bu of corn for dry milling corn ethanol plants and from 2.5 to 2.6 gal/bu for wet milling ethanol plants. The electric generation mix projected in EIA’s *Annual Energy Outlook 1998* (EIA 1997d; see Table 4.34) for 2015 was used.

Table 6.2 Key Parametric Assumptions for Near- and Long-Term Technologies (in the exact forms accepted by GREET 1.5)

Item	Near-Term (2006)	Long-Term (2015)
Upstream fuel combustion: current emission factors	20%	0%
Upstream fuel combustion: future emission factors	80%	100%
Methanol plant efficiency: NG as feedstock	68%	65%[a]
Methanol plant efficiency: flared gas as feedstock	65%	65%
FTD plant efficiency: NG as feedstock	54%	53%[b]
FTD plant efficiency: flared gas as feedstock	52%	52%
DME plant efficiency: NG as feedstock	69%	68%[c]
DME plant efficiency: flared gas as feedstock	66%	66%
NG to H_2 plant efficiency: central plant	73%	67%[d]
NG to H_2 plant efficiency: refuel station production	65%	65%
Liquid H_2 liquefaction efficiency	82%	85%
Chemical manufacture energy intensity	Default values	85% of default values
Energy use intensity: corn and soybean farming	Default values	90% of default values
Chemical use intensity: corn and soybean farming	Default values	90% of default values
Energy use intensity: biodiesel production	Default values	90% of default values
Corn ethanol plants		
Ethanol yield: dry milling (gal/bu)	2.6	2.7
Ethanol yield: wet milling (gal/bu)	2.5	2.6
Dry milling production share	1/3	1/2
Wet milling production share	2/3	1/2
Ethanol plant energy use intensity	Default values	90% of default values
Share of coal as process fuel: dry milling plants	50%	20%
Share of coal as process fuel: wet milling plants	80%	50%
Electricity generation		
Electric generation mix (see Table 4.34)	2005 mix	2015 mix
NG combined cycle: % of NG capacity	30%	45%
Advanced coal technology: % of coal capacity[e]	5%	20%
Baseline GVs[f]		
Fuel economy (mpg): cars/LDT1/LDT2	22.4/16.8/14.4	24/18/15.4
Baseline Fuel	CG	FRFG2
Exhaust VOC emissions	NLEV emissions	Tier 2 emissions
Evaporative VOC emissions	NLEV emissions	Tier 2 emissions
Exhaust CO emissions	NLEV emissions	Tier 2 emissions
Exhaust NO_x emissions	NLEV emissions	Tier 2 emissions
Exhaust PM emissions	NLEV emissions	Tier 2 emissions
Baseline DVs[f]		
Exhaust VOC emissions	NLEV emissions	Tier 2 emissions
Exhaust CO emissions	NLEV emissions	Tier 2 emissions
Exhaust NO_x emissions	NLEV emissions	Tier 2 emissions
Exhaust PM emissions	NLEV emissions	Tier 2 emissions

[a] Plus 111,000 Btu of steam credit per million Btu of methanol produced.

[b] Plus 264,000 Btu of steam credit per million Btu of FTD produced.

[c] Plus 44,000 Btu of steam credit per million Btu of DME produced.

[d] Plus 269,000 Btu of steam credit per million Btu of H_2 produced.

[e] Advanced coal technologies for electric power plants include PFB/CC and IGCC, both of which have high energy conversion efficiency and low emissions.

[f] Fuel economy and emissions for baseline vehicles are for the 55/45 combined cycle. Fuel economy values are on-road-adjusted results. Emission estimates for baseline vehicles are presented in Section 6.2.

Corn ethanol is produced from both wet milling and dry milling facilities. At present, two-thirds of total U.S. ethanol is produced from wet milling plants and one-third from dry milling plants. For near-term corn ethanol, we used this split to combine the results of wet and dry milling plants. In the future, more dry milling plants will likely be built than wet milling plants, partly because capital requirements are lower for dry milling plants and because some states offer tax incentives for building small dry milling plants. Thus, for long-term corn ethanol production, we assumed 50% from wet milling plants and 50% from dry milling plants.

We assumed that long-term fuels and vehicle technologies would be applied to MY 2010 vehicles and that MY 2010 baseline GVs would meet the Tier 2 emission standards proposed by EPA (EPA 1999). Table 6.3 presents the proposed Tier 2 standards for cars, light LDTs (LLDTs), and heavy LDTs (HLDTs). In the Tier 2 proposal, EPA defined LLDTs as LDTs with a GVW of 0–6,000 lb and HLDTs as LTDs with a GVW of 6,000–8,500 lb. That is, the newly defined LLDTs are Mobile 5b-defined LDT1, and the newly defined HLDTs are Mobile 5b-defined LDT2. Note that beginning in MY 2009, all cars, LLDTs, and HLDTs will be subject to the same Tier 2 standards. For Tier 2, EPA proposed that evaporative emission standards be reduced by 50%.

6.2 Mobile 5b and Part 5 Runs

We used EPA’s Mobile 5b and Part 5 to generate per-mile emission rates for baseline GVs and DVs. For evaluation of near-term fuels and technologies, we used Mobile 5b and Part 5 to generate emissions estimates for LEVs that are six years old and have accumulated about 64,000 miles, which represents the mid-point of a vehicle’s lifetime. In accordance with EPA’s guidelines for estimating emission inventories, we estimated emissions of VOCs and NO_x for summer conditions and emissions of CO for winter conditions. PM emissions are not affected by ambient temperature, so we assumed summer conditions to generate PM emissions by using the Part 5 model.

In 1998, EPA developed an NLEV version of Mobile 5b to estimate emission impacts of the NLEV program (EPA 1998b). We used the Mobile 5 NLEV version to generate emissions of baseline GVs and DVs. Together with the NLEV program, the enhanced phase 2 on-board diagnosis system (OBDII) will be required for light-duty vehicles. In Mobile 5 NLEV runs, we included OBDII and an annual I/M program. However, our tests with Mobile 5 NLEV showed that OBDII overrode the I/M programs. That is, as long as OBDII is included, the I/M program does not offer any additional emission benefits for OBDII-equipped cars. We suspected that too many emission credits are assigned to OBDII in Mobile 5 NLEV. The new evaporative test procedure, which considers multiple diurnal tests, took effect in MY 1996. Cold CO emission standards were assumed for LEV vehicles. Beginning in 1998, an on-board refueling vapor recovery system was also assumed. We considered these requirements as well. Because of limitations of vehicle types in Mobile 5 NLEV, we had to make some adjustments outside of Mobile 5 NLEV. The footnotes in Table 6.4 describe these adjustments.

Vehicle emissions and fuel economy (especially emissions) are significantly affected by vehicle driving cycles. While emissions are regulated under the federal urban driving schedule (FUDS), corporate average fuel economy (CAFE) is regulated under the FUDS and the

Table 6.3 Proposed Tier 2 Vehicle Emissions Standards for Passenger Cars and Light-Duty Trucks[a,b]

Bin	NMOG	CO	NO_x	PM	HCHO
Tier 2 Light-Duty Vehicle Standards[c]					
7	0.125	4.2	0.20	0.02	0.018
6	0.090	4.2	0.15	0.02	0.018
5	0.090	4.2	0.07	0.01	0.018
4	0.055	2.1	0.07	0.01	0.011
3	0.070	2.1	0.04	0.01	0.011
2	0.010	2.1	0.02	0.01	0.004
1	0.000	0.0	0.00	0.00	0.000
Interim Standards for Non-Tier 2 Cars and LLDTs during Tier 2 Phase-In[d]					
5	0.156	4.2	0.60	0.06	0.018
4	0.090	4.2	0.30	0.06	0.018
3	0.055	2.1	0.30	0.04	0.011
2	0.090	4.2	0.07	0.01	0.018
1	0.000	0.0	0.00	0.00	0.000
Interim Standards for HLDTs during Tier 2 Phase-In[e]					
5	0.230	4.2	0.60	0.06	0.018
4	0.180	4.2	0.30	0.06	0.018
3	0.156	4.2	0.20	0.02	0.018
2	0.090	4.2	0.07	0.01	0.018
1	0.000	0.0	0.00	0.00	0.000

[a] Source: EPA (1999).

[b] The emission standards are in g/mi for a useful lifetime of 120,000 mi.

[c] For cars and LLDTs, the Tier 2 standards will be phased in beginning in MY 2004 and will be fully in effect in MY 2007. For HLDTs, the standards will be phased in beginning in MY 2008 and will be fully in effect in MY 2009. That is, beginning in MY 2009, cars, LLDTs, and HLDTs will be subject to the Tier 2 standards. The three vehicle groups together will be subject to a fleet average NO_x standard of 0.07 g/mi for each automaker.

For cars and LLDTs, the minimum Tier 2 vehicle sales percentages are 25% in MY 2004, 50% in MY 2005, 75% in MY 2006, and 100% in MY 2007 and beyond. For HLDTs, the minimum sales percentages are 50% in MY 2008 and 100% in MY 2009 and beyond.

[d] These standards will be applied to non-Tier 2 cars and LLDTs between MY 2004 and 2006. The non-Tier 2 vehicles together will be subject to a fleet average NO_x standard of 0.30 g/mi for each automaker. The maximum non-Tier 2 vehicle sales percentage will be 75% in MY 2004, 50% in MY 2005, 25% in MY 2006, and 0% in MY 2007 and beyond.

[e] These standards will be applied to HLDTs between MY 2004 and 2008. These vehicles together will be subject to a fleet average NO_x standard of 0.20 g/mi for each automaker. The minimum sales percentages of HLDTs subject to the interim standards are 25% in MY 2004, 50% in MY 2005, 75% in MY 2006, 100% in MY 2007, 50% (maximum) in MY 2008, and 0% in MY 2009 and beyond. The remainder of the new HLDT fleet between MY 2004 and 2007 will be subject to Tier 1 standards.

highway cycle. We ran Mobile 5b and Part 5 separately for the FUDS and the highway driving cycle, then averaged the results of the two cycles together with 55% mileage for the FUDS and 45% for the highway cycle. This “55/45 combined cycle” is used for the CAFE regulation. This cycle is more appropriate for estimating energy use and GHG emissions than for estimating criteria pollutant emissions. If the user’s main focus is on criteria pollutants, the FUDS and other urban driving cycles should be used.

Mobile 5b and Part 5 cannot be used to estimate emissions for the proposed Tier 2 vehicles, so we applied changes in emission standards from LEVs to Tier 2 to emissions of LEVs to estimate emissions of Tier 2 vehicles. As Tables 6.1 and 6.3 show, there are large reductions in emission standards between LEVs and Tier 2 vehicles. Table 6.5 lists these reductions, which are especially significant for NO_x and PM. Also note that reductions for HLDTs are much higher than those for cars and LLDTs. We used these reduction rates to estimate on-road emissions of Tier 2 vehicles from on-road emissions of LEVs. The footnotes in Table 6.4 describe our estimates.

Table 6.4 Fuel Economy and Emissions Rates of Baseline Gasoline and Diesel Vehicles[a]

Item	Gasoline Car	Gasoline LDT1[b]	Gasoline LDT2[b]	Diesel Car[c]	Diesel LDT1[c,d]	Diesel LDT2[c,d]
Near-Term Vehicles: LEVs Fueled with CG or CD[e]						
Economy (mpgeg)[f]	22.4	16.8	14.4	30.2	22.7	19.4
Emissions (g/mi)						
Exhaust VOC	0.080	0.091	0.629	0.080[g]	0.091[g]	0.540
Evaporative VOC	0.127	0.107	0.156	0.000	0.000	0.000
CO	5.517	8.247	16.846	1.070	1.139	1.208
NO_x	0.275	0.381	1.173	0.600[g]	0.600[g]	1.224
Exhaust PM_{10}	0.012	0.015	0.015	0.100	0.100	0.109
Brake and tire wear PM_{10}	0.021	0.021	0.021	0.021	0.021	0.021
CH_4[h]	0.084	0.090	0.090	0.011	0.014	0.017
N_2O[i]	0.028	0.033	0.040	0.016	0.024	0.032
Long-Term Vehicles: Tier 2 Vehicles Fueled with FRFG2 or RFD[j]						
Economy (mpgeg)[k]	24.0	18.0	15.4	36	27	23.1
Emissions (g/mi)						
Exhaust VOC	0.062	0.062	0.080	0.049	0.080	0.112
Evaporative VOC	0.063	0.063	0.078	0.000	0.000	0.000
CO	2.759	2.759	5.518	2.759	5.518	5.518
NO_x	0.036	0.036	0.135	0.063	0.135	0.180
Exhaust PM_{10}[l]	0.010	0.010	0.020	0.010	0.020	0.020
Brake and tire wear PM_{10}	0.021	0.021	0.021	0.021	0.021	0.021
CH_4[m]	0.065	0.065	0.091	0.011	0.014	0.017
N_2O[n]	0.028	0.033	0.040	0.016	0.024	0.032

[a] Fuel economy and emissions for baseline vehicles are for the 55/45 combined cycle.

[b] Mobile 5b defines light-duty gasoline truck 1 (LDGT1) as vehicles with a GVW of up to 6,000 lb and light-duty gasoline truck 2 (LDGT2) as vehicles with a GVW between 6,001 and 8,500 lb.

[c] For diesel vehicles, we assumed DI engines for both near-term and long vehicles.

[d] Mobile 5b does not estimate emissions for diesel LDT1. Instead, the model estimates emissions for LDTs, which include both LDT1 and LDT2. However, most diesel trucks are classified as LDT2. So we used Mobile 5b-estimated diesel LDT emissions as emissions for diesel LDT2. We estimated emissions of diesel LDT1 as the average emissions of diesel cars and diesel LDT2, except as noted.

[e] LEVs were assumed to be fueled with conventional gasoline or conventional diesel. PM emissions were estimated by using Part 5, and other emissions were estimated by using the NLEV version of Mobile 5b, except as noted.

[f] Fuel economies of LEVs are from EIA's 1998 Annual Energy Outlook (AEO98) projections for MY 2001 new vehicles (EIA 1997d) with supplemental data from EPA (Heavenrich and Hellman 1996). Near-term direct injection diesel vehicle fuel economy, presented in mpgeg, is estimated from GV fuel economy and the assumed 35% mpgeg improvement between GVs and DVs.

[g] The NLEV version of Mobile 5b does not estimate emissions of diesel cars and diesel LDT1 that are subject to NLEV standards. For exhaust VOC emissions, we assumed that emissions from diesel cars and LDT1 will be the same as those for GVs and LDT1, respectively. For exhaust NO_x emissions, we assumed that diesel cars and LDT1 will meet the TLEV NO_x standard (0.6 g/mi; see Table 6.1) under the NLEV program.

[h] CH_4 emissions were calculated as the difference between THC and NMHC, both of which were estimated by using Mobile 5b.

[i] N_2O emissions are from EPA (1998c).

Table 6.4 (Cont.)

[j] Emissions from Tier 2 GVs were estimated on the basis of emissions from gasoline-fueled LEVs and reductions in emission standards between gasoline-fueled LEVs and Tier 2 GVs (see Table 6.5), except as noted below.

Emissions from Tier 2 gasoline-fueled LDT1 were assumed to be the same as those for Tier 2 gasoline cars (except as noted), because both cars and LDT1 were assumed to be subject to Bin 3 of the Tier 2 proposal (see Table 6.5).

Emissions from Tier 2 gasoline-fueled LDT2 were estimated on the basis of emissions from Tier 2 gasoline cars and the difference in emission standards between Bin 3, to which Tier 2 gasoline cars are subject and Bin 6, to which LDT2 are subject (see Table 6.5), except as noted.

Emissions from Tier 2 diesel cars, diesel-fueled LDT1, and diesel-fueled LDT2 were estimated using a method similar to that used to calculate emissions from Tier 2 gasoline-fueled LDT2.

[k] We projected fuel economy of MY 2010 vehicles on the basis of MY 2000 vehicle fuel economy and mpg improvement between MY 2001 and 2010 for passenger cars, as predicted in EIA's AEO98 (7% improvement over the period) (EIA 1997d).

[l] PM emissions from Tier 2 vehicles were assumed to be at the applicable PM standard levels.

[m] CH_4 emissions from Tier 2 GVs were calculated on the basis of the differences in exhaust VOC emissions. CH_4 emissions from Tier 2 diesel vehicles were assumed to be the same as CH_4 emissions from diesel-fueled LEVs, because diesel-fueled LEVs already have low CH_4 emissions.

[n] N_2O emissions from Tier 2 vehicles were assumed to be the same as emissions from LEV vehicles, because no N_2O emission data are available for Tier 2 vehicles, and because only small improvements in N_2O emissions have been shown with further NO_x emission control (see EPA 1998c).

Table 6.5 Reductions in Emissions Standards for Tier 2 Vehicles Relative to LEVs[a]

Vehicle	Applicable Tier 2 Bin Assumed[b]	Exhaust VOC	Evaporative VOC	CO	NO_x	PM_{10}[c]
Gasoline cars	3	22%	50%	50%	87%	NA[d]
Gasoline LLDTs	3	36%	50%	57%	90%	NA
Gasoline HLDTs	6	82%	50%	39%	88%	NA
Diesel cars	4	39%	NA	50%	77%	88%
Diesel LLDTs	6	18%	NA	13%	63%	78%
Diesel HLDTs	7	75%	NA	39%	84%	82%

[a] Reductions in emission standards were calculated from standards presented in Tables 6.1 and 6.3. For LLDTs, the average of standards for LDT1 and LDT2 in Table 6.1 was used. For HLDTs, the average of standards for LDT3 and LDT4 in Table 6.1 was used.

[b] Under the Tier 2 proposal, an automaker can certify its vehicles to any of the seven bins, as long as its fleet average NO_x standard is below 0.07 g/mi. Consequently, many combinations of vehicle sales among the seven bins exist for automakers to select for meeting the average NO_x standard. The applicable Tier 2 bin that we selected for each vehicle group, one of the many possible combinations, represents our assessment of technological potentials.

[c] PM emission standards in Table 6.1 are applied to DVs only. For LEVs, PM emissions from GVs are not constrained by PM standards. Reductions for PM emission standards for GVs were therefore not calculated here.

[d] NA = not applicable.

Relative to GVs, DVs have inherently higher NO_x and PM emissions. The Tier 2 bins we have chosen for DVs are based on the assumption that automakers will certify DVs at higher emission levels for NO_x and PM. On the basis of this assumption, NO_x and PM emissions from DVs are about twice as high as those from GVs (except PM emissions from diesel cars).

Table 6.4 presents estimated fuel economy and vehicular emissions of baseline GVs and DVs for passenger cars, LDT1, and LDT2. As stated above, emissions of near-term baseline vehicles were estimated by using the Mobile 5 NLEV version and assuming that baseline passenger cars and LLDTs will meet NLEV standards and that HLDTs will meet Tier 1 standards. Because most of the United States will still use CG and because no RFD will be introduced in the near term, we assumed use of CG in baseline GVs and CD in baseline DVs.

The long-term baseline vehicles were assumed to meet the newly proposed Tier 2 standards. To help meet the standards, Tier 2 vehicles were assumed to be fueled with FRFG2 and RFD. Tier 2 vehicle emissions were estimated on the basis of LEV emissions and emission standard reductions between LEVs and Tier 2 vehicles (see Table 6.5).

In particular, for Tier 2 gasoline-fueled cars, emissions of exhaust VOCs, evaporative VOCs, CO, and NO_x were estimated from LEV emissions and emission standard reductions from NLEVs to Tier 2 vehicles (as presented in Table 6.5). Exhaust PM emissions for Tier 2 gasoline-fueled cars were assumed to be at the PM standard for Tier 2 Bin 3. Exhaust CH_4 emissions were estimated from LEV CH_4 emissions and exhaust VOC emission reductions between LEVs and Tier 2 Bin 3. There are no data on N_2O emissions from Tier 2 vehicles. Because NO_x emissions are significantly reduced for Tier 2 vehicles, we expect that N_2O emissions could increase, on the basis of nitrogen mass balance calculations. On the other hand, emission control technologies and clean gasoline and diesel will help reduce N_2O emissions. We assumed the same N_2O emissions for LEVs and Tier 2 vehicles.

We assumed that Tier 2 gasoline-fueled LDT1 (LLDTs, as defined in the Tier 2 proposal) would be subject to Tier 2 Bin 3, the same bin to which Tier 2 gasoline cars are subject. Emissions of the former were assumed to be the same as those of the latter, except for N_2O, for which emissions from Tier 2 LDT1 were assumed to be the same as those from LEV LDT1.

We estimated emissions from Tier 2 gasoline-fueled LDT2 on the basis of Tier 2 gasoline-fueled car emissions and emission standard differences between Tier 2 Bin 3 (to which gasoline-fueled cars are subject) and Bin 6 (to which gasoline-fueled LDT2 are subject), except as noted. VOC evaporative emissions from Tier 2 gasoline-fueled LDT2 are estimated on the basis of LEV gasoline LDT2 and emission standard differences between LEV LDT2 and Tier 2 LDT2.

Emissions from Tier 2 diesel-fueled cars, diesel-fueled LDT1, and diesel-fueled LDT2 were calculated using a method similar to that used to calculate emissions from Tier 2 gasoline-fueled LDT2, except as noted. Tier 2 CH_4 emissions from DVs were assumed to be the same as those for LEV diesel vehicles, because DVs in general have very low CH_4 emissions.

PM emissions for all Tier 2 vehicles were assumed to be at the applicable Tier 2 PM standard levels.

Table 6.4 shows the results of our emissions estimates for baseline GVs and DVs. For the near-term baseline vehicles, there are large increases in emissions from LDT1 to LDT2. This is because, while LDT1 will be subject to the NLEV standards, LDT2 will continue to be subject to the Tier 1 standards (see Table 6.1; the NLEV program does not cover Mobile 5-defined LDT2). From the near-term to the long-term baseline vehicles, substantial reductions in emissions result from Tier 2 standards. If Tier 2 standards are implemented, baseline vehicle emissions will be significantly reduced.

6.3 Contribution of Each Stage to Fuel-Cycle Energy Use and Emissions

The 21 figures that follow present shares of fuel-cycle energy use and emissions by fuel-cycle stage for each combination of fuels and vehicles. These figures, created automatically in GREET 1.5, are meant to help readers readily grasp the key stage for a given combination in terms of fuel-cycle results. For this purpose, fuel-cycle activities are grouped into three stages: feedstock-related, fuel-related, and vehicle operation stages. The feedstock-related stage includes feedstock recovery, transportation, and storage. The fuel-related stage includes fuel production, transportation, storage, and distribution. The vehicle operation stage includes vehicle refueling and operations.

The 21 figures described below are based on calculations for passenger cars. Among the three light-duty vehicle types (passenger cars, LDT1s, and LDT2s), stage contributions to total fuel-cycle energy use and emissions are similar.

6.3.1 Near-Term Technologies

Figure 6.1 shows stage contributions for conventional GVs. Three types of gasoline (CG, FRFG2, and CARFG2) are included in GREET, and the two RFG types can be produced with MTBE, ETBE, and ethanol. Stage contributions are similar for these options. The figure here presents the results for CG. As the figure shows, vehicle operations contribute the most to total fuel-cycle results, except for emissions of SO_x and CH_4. Petroleum refining accounts for the largest amount of SO_x emissions. Crude recovery in oil fields produces a large amount of CH_4 emissions.

Figure 6.2 shows stage contributions for DVs. Overall, the pattern for DVs is similar to that for GVs, except for PM_{10}, NO_x, and VOCs, for which DV operation accounts for most of the total emissions.

Figure 6.3 shows the results for dedicated CNG vehicles. As one might expect, vehicle operation involves no petroleum use and a very small amount of SO_x emissions. NG compression, which consumes a considerable amount of electricity and NG, produces most of the fuel-cycle SO_x emissions. NG recovery and processing produce a large amount of CH_4 emissions. For NO_x emissions, feedstock- and fuel-related activities account for more than half of the total fuel-cycle emissions. Upstream VOC emissions account for a large share of total

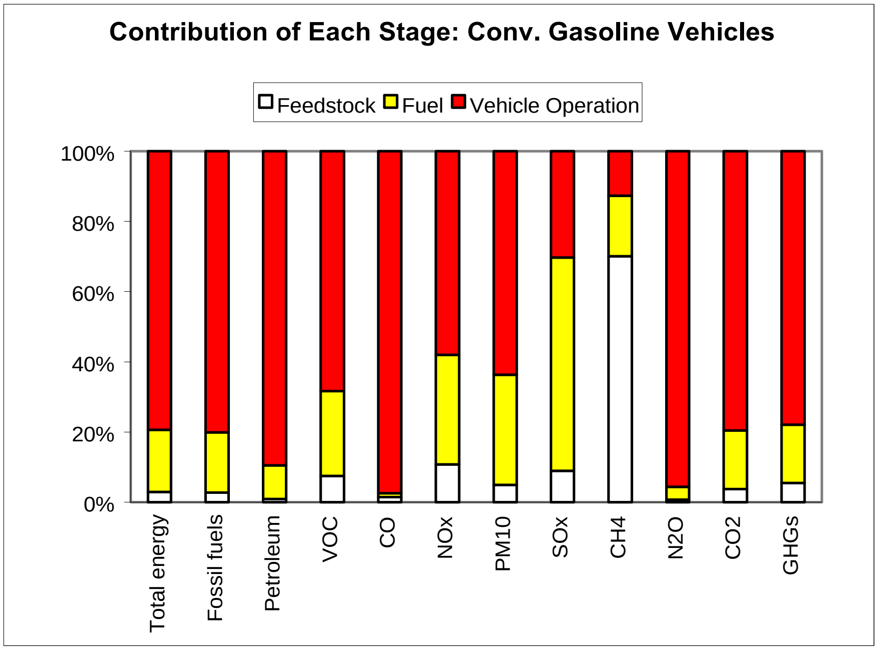

Figure 6.1 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Converted Gasoline Vehicles

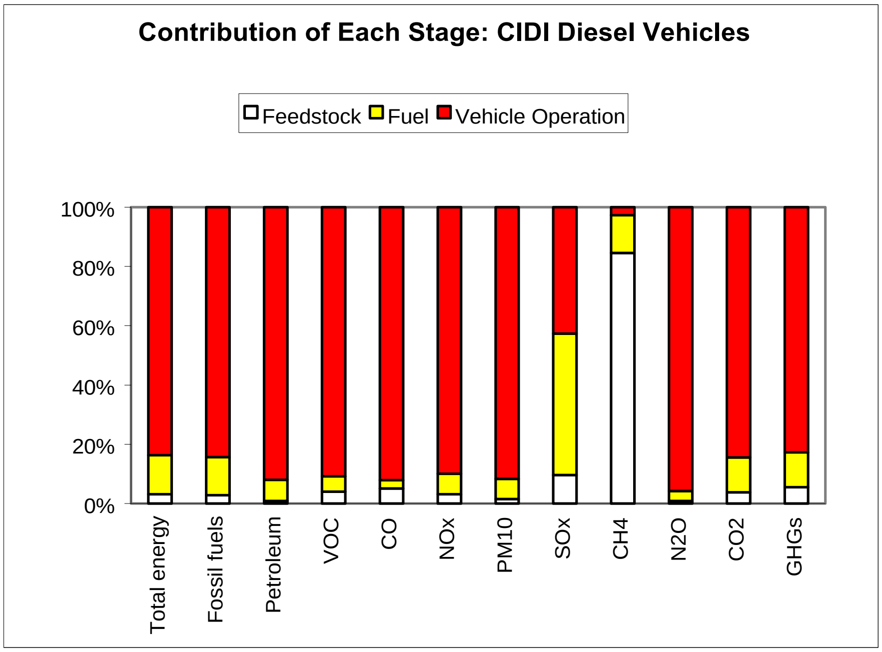

Figure 6.2 Shares of Fuel-Cycle Energy Use and Emissions by Stage: CIDI Diesel Vehicles

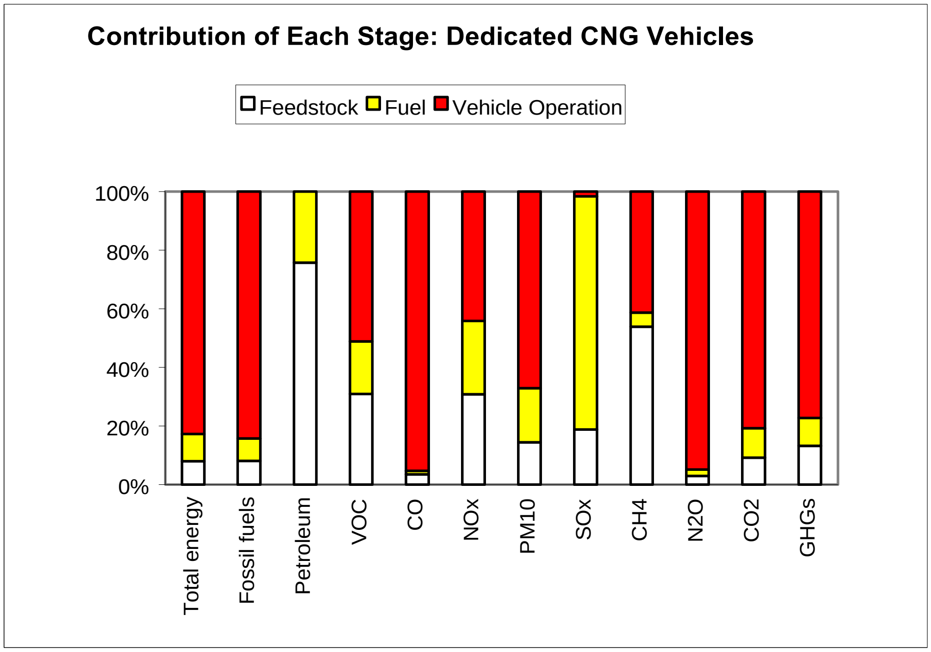

Figure 6.3 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Dedicated CNG Vehicles

VOC emissions. A similar pattern of stage contributions exists for bi-fuel CNG vehicles burning NG.

Figure 6.4 presents results from methanol FFVs fueled with M85. Upstream NG recovery and processing produce most of the total fuel-cycle CH_4 emissions. Methanol production at methanol plants accounts for the largest share of the total SO_x emissions. Methanol production accounts for a noticeable portion of the total energy use, fossil fuel use, and emissions of NO_x, PM_{10}, VOC, CO_2, and GHGs.

Figure 6.5 presents shares of stages for LPG vehicles. In GREET 1.5, production of LPG is simulated with two pathways: crude and NG to LPG. On average, the United States produces 60% of its LPG from NG and 40% from crude. The results in Figure 6.5 are for this combination of production. As the figure shows, upstream activities contribute to all the SO_x emissions. Crude recovery and NG recovery and processing contribute most to the total CH_4 emissions.

Figure 6.6 shows results for ethanol FFVs fueled with E85, where ethanol is produced from corn. Ethanol can be produced in either dry or wet milling plants. The results in this figure are for a combination of both, with two-thirds of the ethanol produced from wet milling plants and one-third from dry milling plants. Except for total energy use, petroleum use, and emissions of CO and VOC, upstream activities account for most of the total fossil energy use and

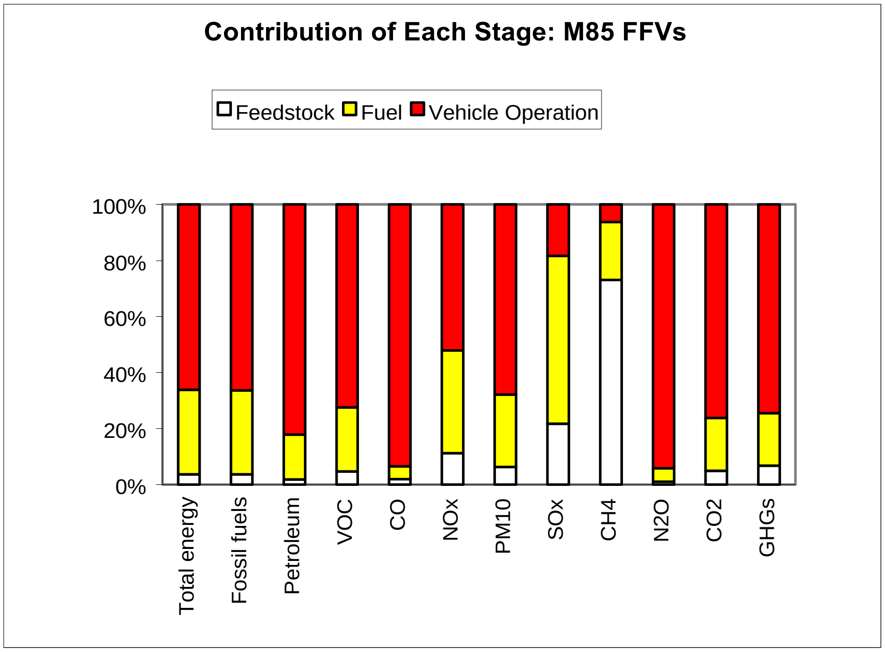

Figure 6.4 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Methanol FFVs Fueled with M85

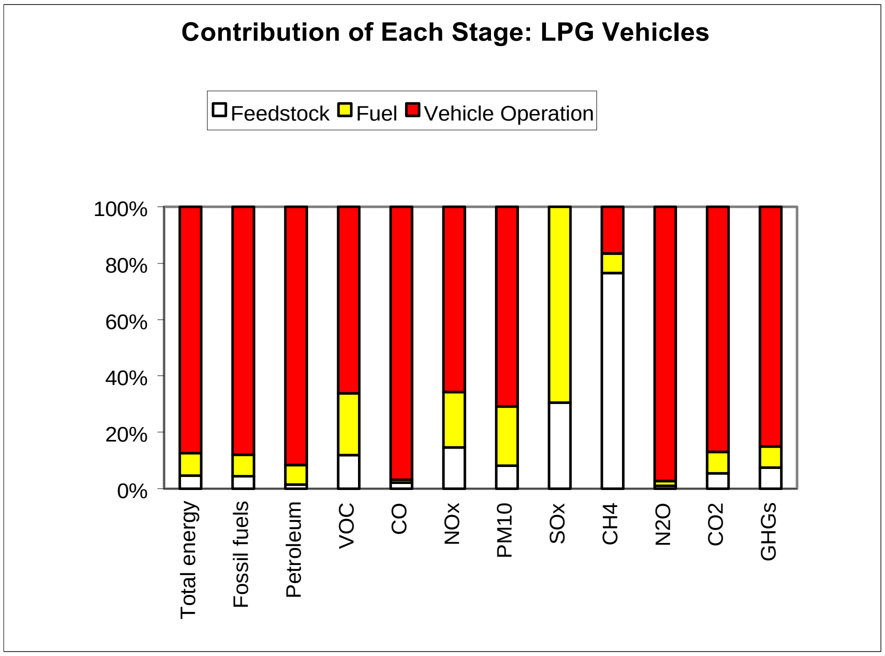

Figure 6.5 Shares of Fuel-Cycle Energy Use and Emissions by Stage: LPG Vehicles

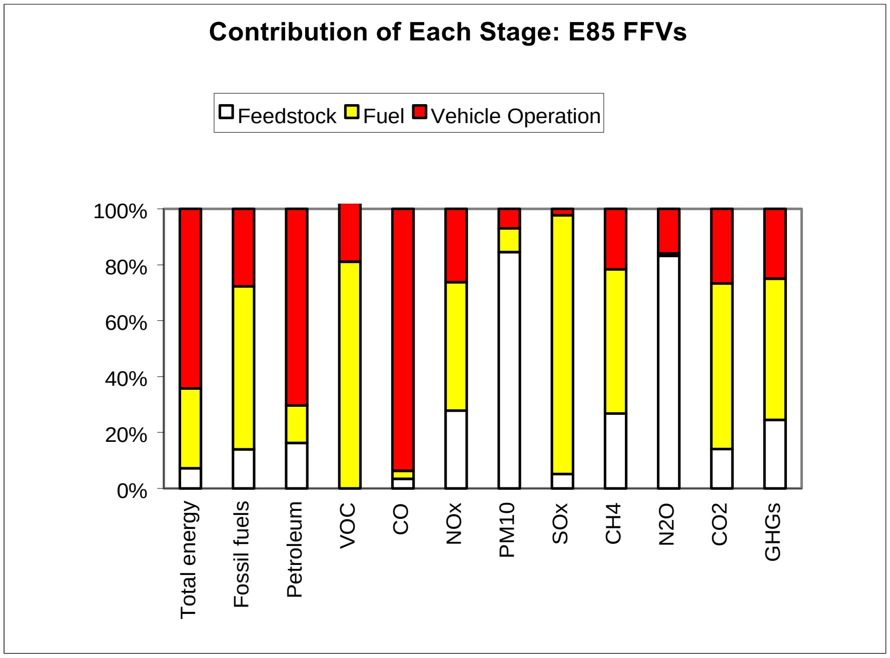

Figure 6.6 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Ethanol FFVs Fueled with E85 Produced from Corn

emissions. This indicates that assumptions about upstream activities have large effects on fuel-cycle results for ethanol FFVs. Because of nitrification and denitrification of nitrogen fertilizer, corn farming contributes the most to the total N_2O emissions. Ethanol production at corn ethanol plants consumes a large amount of fossil fuels and produces large amounts of PM_{10}, VOC, NO_x, SO_x, CH_4, CO_2, and GHG emissions. PM emissions from corn farming (mainly tillage emissions and farming tractor emissions) account for the largest share of fuel-cycle PM emissions.

Figure 6.7 shows the results for EVs. The results are for the U.S. generation mix, under which 54% of electricity is generated from coal. Energy use and emissions occur during upstream stages, except for PM_{10}, where EV brake- and tire-wear emissions are noticeable. Furthermore, among the upstream activities, energy use and emissions occur mostly during electricity generation. Methane emissions occur primarily during coal mining and NG recovery and processing. Also, a large amount of VOC and CO emissions and petroleum use occur during coal mining and NG recovery and processing.

Figure 6.8 presents the results for grid-connected HEVs, where ICEs are fueled with California RFG2. In our study, we assume that for grid-connected HEVs, grid electricity powers 30% of their VMT, with on-board ICEs providing energy for the remaining 70%. Except for petroleum use and emissions of VOC, CO and N_2O, energy use and emissions occur more during upstream stages (especially during fuel production stages) than during the vehicle operation stage.

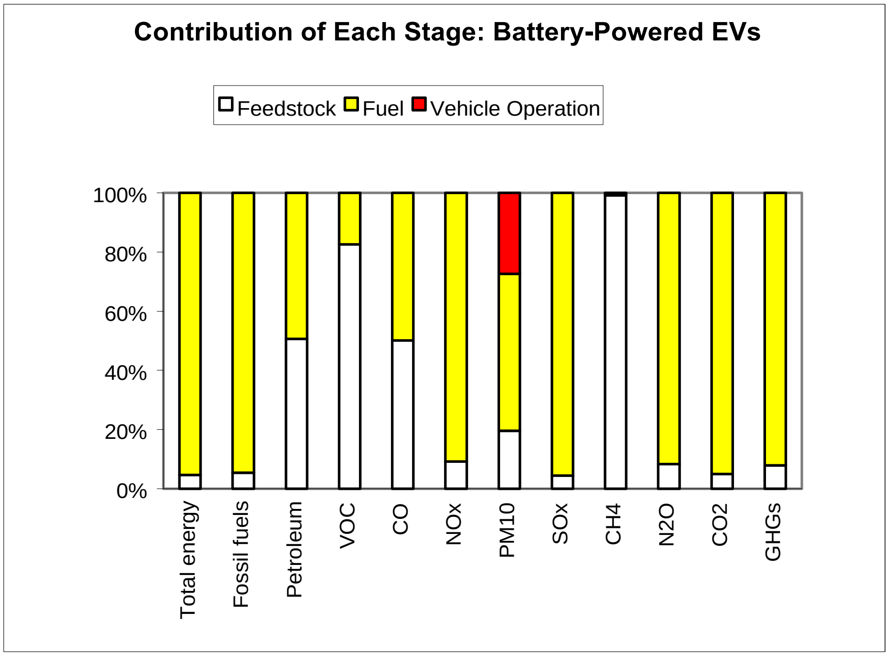

Figure 6.7 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Battery-Powered EVs

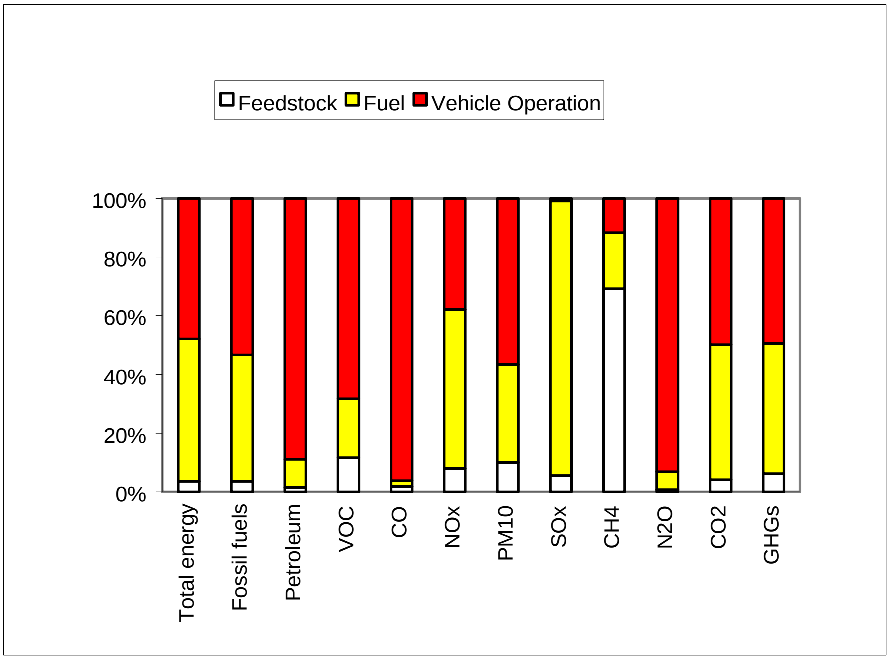

Figure 6.8 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Grid-Connected HEVs, ICEs Fueled with RFG

Figures 6.9 and 6.10 present stage contributions for grid-independent HEVs fueled with RFG and CD. Petroleum refining accounts for a large portion of the total SO_x emissions. Petroleum recovery accounts for a large portion of the total CH_4 emissions. Otherwise, vehicle operations contribute overwhelmingly to total energy use and emissions.

In the above ten figures, stage contributions for the five criteria pollutants are for total emissions. Stage contributions for urban emissions of the five pollutants are different from those for total emissions. Even though upstream contributions to total emissions are large for a given vehicle technology, the upstream contributions could be very small because most upstream activities (and upstream emissions) occur outside of an urban area.

6.3.2 Long-Term Technologies

This section presents the results for those long-term technology options that are very different from the near-term options. Technology options similar to the near-term options are presented in Section 6.3.1. In particular, stage contributions for ICE vehicles fueled with CNG and LNG are similar to those for near-term dedicated CNGVs (Figure 6.3), although as vehicle fuel economy increases among vehicle technologies, upstream contributions become smaller. Stage contributions for ICE vehicles fueled with M90 are similar to those for the near-term M85 FFVs (Figure 6.4). Stage contributions for ICE vehicles fueled with E90 are similar to those for the near-term E85 FFVs (Figure 6.6).

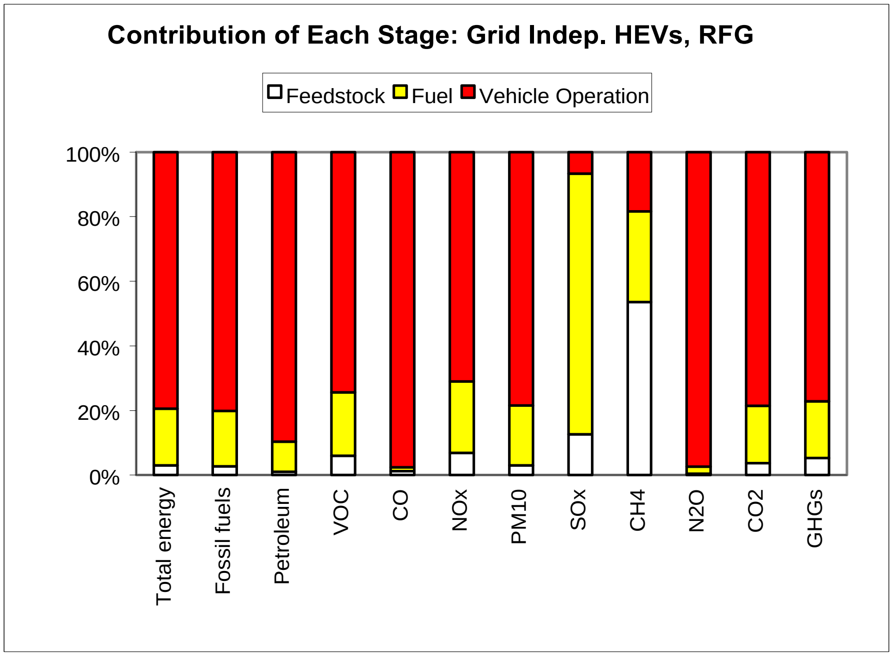

Figure 6.9 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Grid-Independent HEVs, ICEs Fueled with RFG

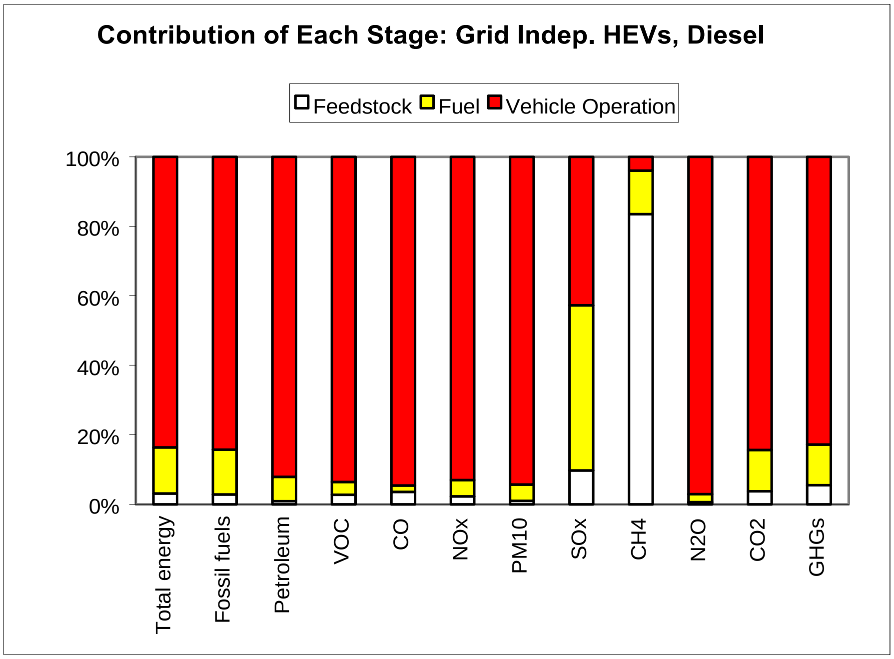

Figure 6.10 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Grid-Independent HEVs, ICEs Fueled with CD

Figures 6.11 and 6.12 show the results for CIDI vehicles fueled with FT50 and BD20. Because diesel is used in blending with both FTD (50%) and biodiesel (80%), the results for the two blends are similar. Except for emissions of SO_x, CH_4, and NO_x vehicle operations contribute mostly to the total energy use and emissions. For SO_x emissions, production of fuels (diesel, FTD, and biodiesel) contributes significantly to the total fuel-cycle emissions. Petroleum recovery and NG recovery and processing (for FTD) produce the greater portion of the total CH_4 emissions. Fuel production contributes to a large share of total NO_x emissions. With BD20, a large amount of VOC emissions are generated during biodiesel production (mainly because of n-hexane loss during soy oil extraction).

Figure 6.13 shows that for CIDI vehicles fueled with DME, upstream activities account for all the petroleum use and SO_x emissions as well as a greater portion of total CH_4 emissions. Furthermore, petroleum use emissions are primarily from DME production; CH_4 emissions are primarily from NG recovery and processing, and SO_x emissions are from both NG recovery and DME production. For other energy use and emissions, vehicle operations account for a large portion. Note that upstream activities contribute a significant portion to total energy use, fossil energy use, and emissions of NO_x, VOC, CO_2, and GHGs.

Figure 6.14 shows the results for grid-connected HEVs, where on-board ICEs are fueled with CNG. Except for CO emissions, energy use and emissions occur primarily during upstream stages. Furthermore, feedstock production accounts for the greater part of upstream

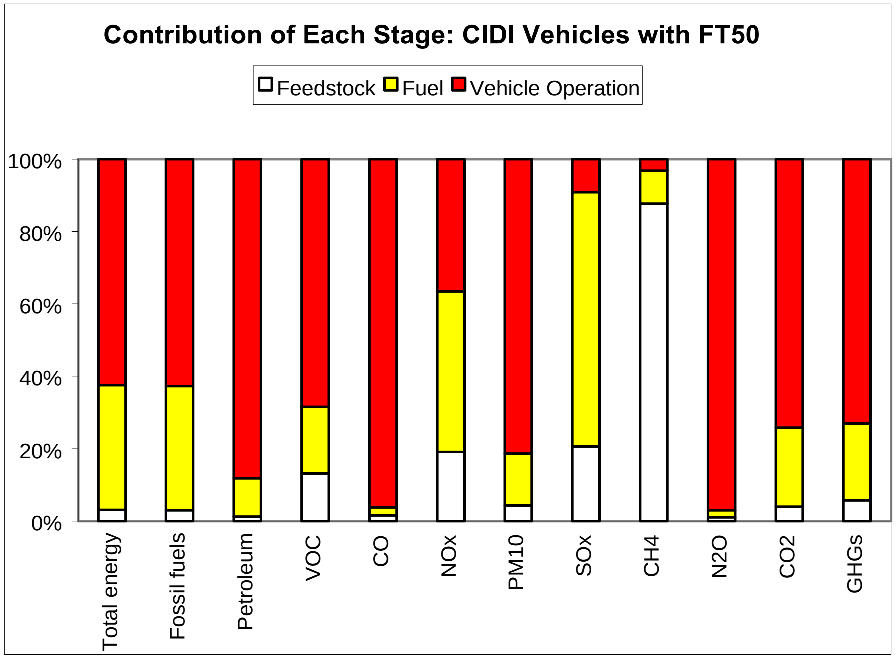

Figure 6.11 Shares of Fuel-Cycle Energy Use and Emissions by Stage: CIDI Vehicles Fueled with FT50

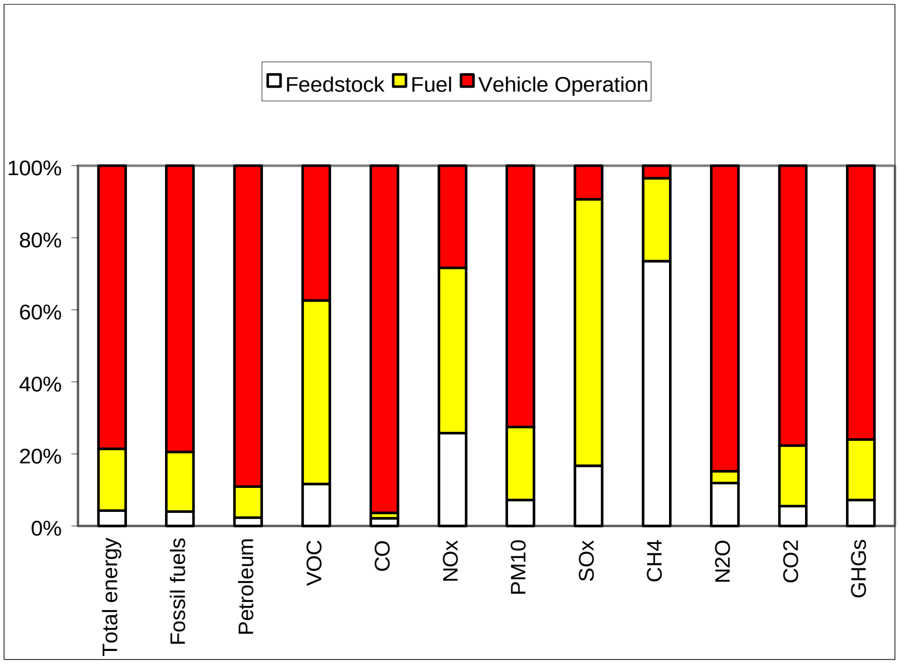

Figure 6.12 Shares of Fuel-Cycle Energy Use and Emissions by Stage: CIDI Vehicles Fueled with BD20

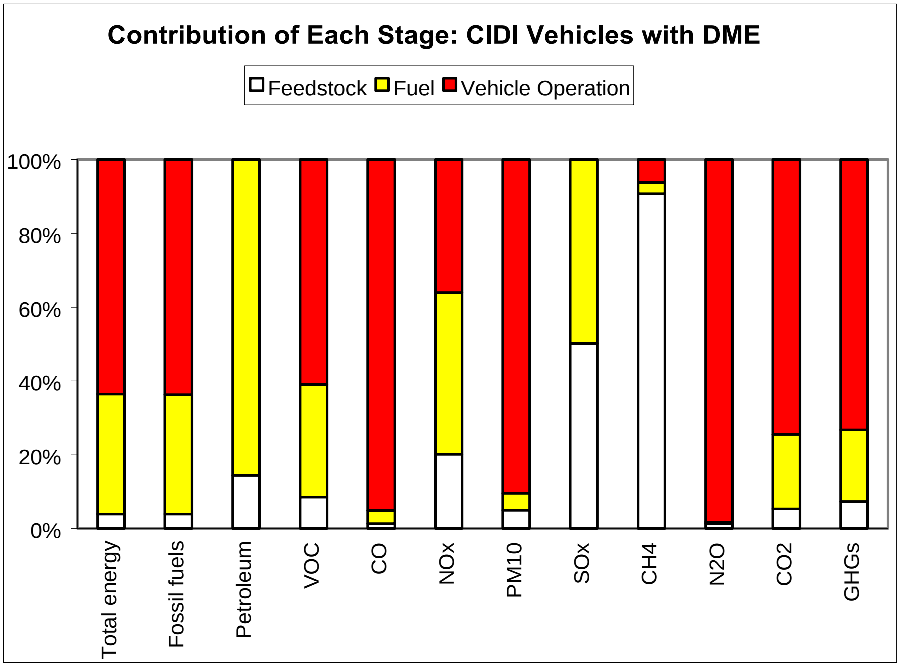

Figure 6.13 Shares of Fuel-Cycle Energy Use and Emissions by Stage: CIDI Vehicles Fueled with DME

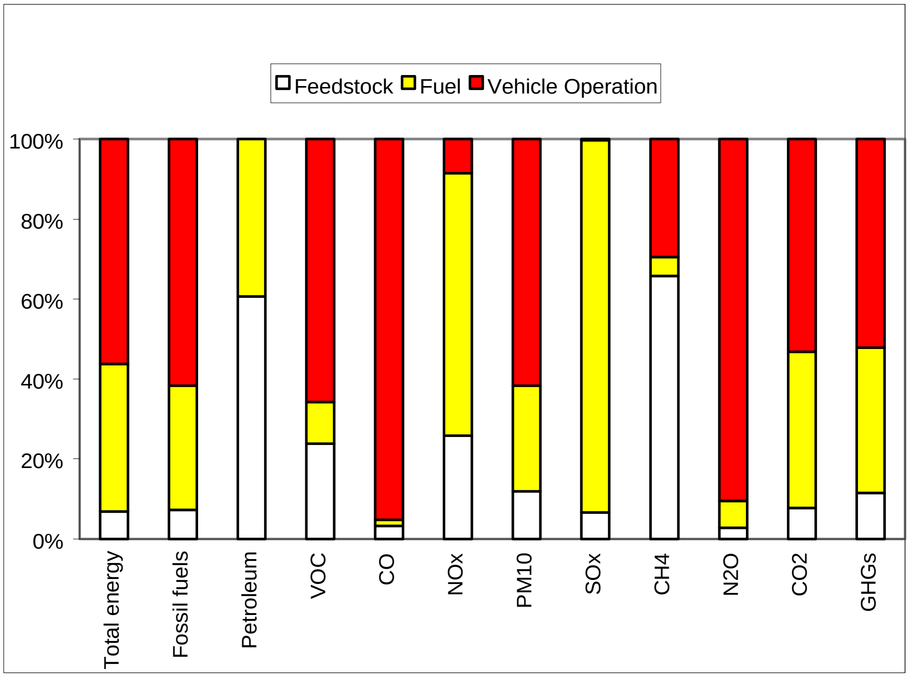

Figure 6.14 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Grid-Connected HEVs, ICEs Fueled with CNG

petroleum use and CH_4 emissions. For other energy use and emissions, fuel production (i.e., electricity generation and NG compression) contributes the most.

Figure 6.15 presents stage contributions for grid-independent HEVs fueled with NG. The general pattern for the HEVs is similar to that for the grid-connected HEV with ICE operation fueled with NG. With the former, however, the contribution from vehicle operations is increased.

Figure 6.16 presents the results for FCVs fueled with gaseous H_2 produced from NG. Except for total energy, fossil energy, and PM_{10} emissions, energy use and emissions occur during upstream stages. Vehicular PM_{10} emissions are from tire and brake wear. Most upstream petroleum use and emissions occur during H_2 production. The exception is CH_4 and petroleum use, where NG recovery and processing account for a large portion of the total CH_4 emissions and petroleum use.

As for FCVs fueled with H_2 produced from solar energy, Figure 6.17 shows that energy use and emissions are from transportation and compression of gaseous hydrogen, except for total energy use and PM_{10} emissions, where vehicle operations also contribute. As Figures 6.16 and 6.17 show, FCVs fueled by H_2, like EVs (Figure 6.7), generate no tailpipe emissions.

Figure 6.18 presents the results for FCVs fueled with NG-based methanol. NG recovery and processing accounts for the greater portion of the total CH_4 emissions. Methanol production at methanol plants consumes a large amount of petroleum and produces a large amount of NO_x and SO_x emissions. Vehicle operations contribute significantly to the total energy use, fossil energy use, and emissions of VOCs, CO, PM_{10} (from brake and tire wear), N_2O, CO_2, and GHGs.

Figure 6.19 shows that for FCVs fueled with RFG, crude recovery accounts for the greater portion of the total CH_4 emissions. Petroleum refining accounts for a large amount of the total emissions for NO_x and SO_x. Vehicle operations contribute most to the total energy use, fossil energy use, petroleum use, and emissions of VOCs, CO, PM_{10}, N_2O, $CO_{2,}$ and GHGs.

Figure 6.20 shows stage contributions for FCVs fueled with ethanol produced from corn. Except for total energy use and CO emissions, upstream stages contribute most of the energy use and emissions. Between corn farming and ethanol production, ethanol production contributes mainly to fossil energy use and emissions of VOCs, NO_x, SO_x, CH_4, CO_2, and GHGs. Corn farming contributes mainly to petroleum use and emissions of PM_{10} and N_2O.

Figure 6.21 presents the results for CNG-fueled FCVs. NG recovery, processing, and transmission contribute significantly to petroleum use and emissions of NO_x and CH_4. NG compression produces a large amount of emissions of NO_x and SO_x. Vehicle operations consume the greater portion of the total energy and fossil energy and produce most of the CO, N_2O, PM_{10}, CO_2, and GHG emissions.

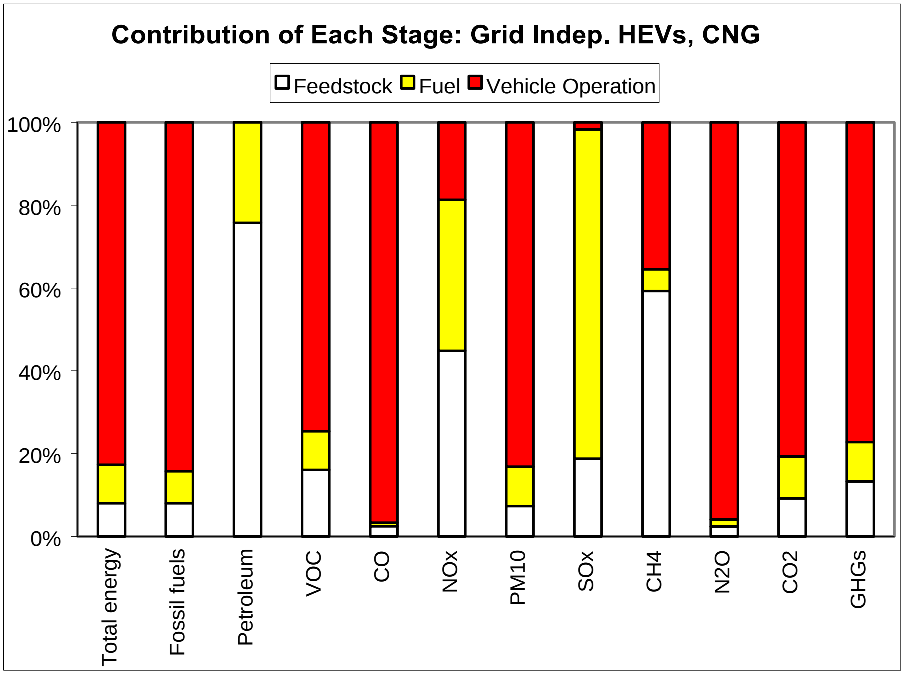

Figure 6.15 Shares of Fuel-Cycle Energy Use and Emissions by Stage: Grid-Independent HEVs, ICEs Fueled with NG

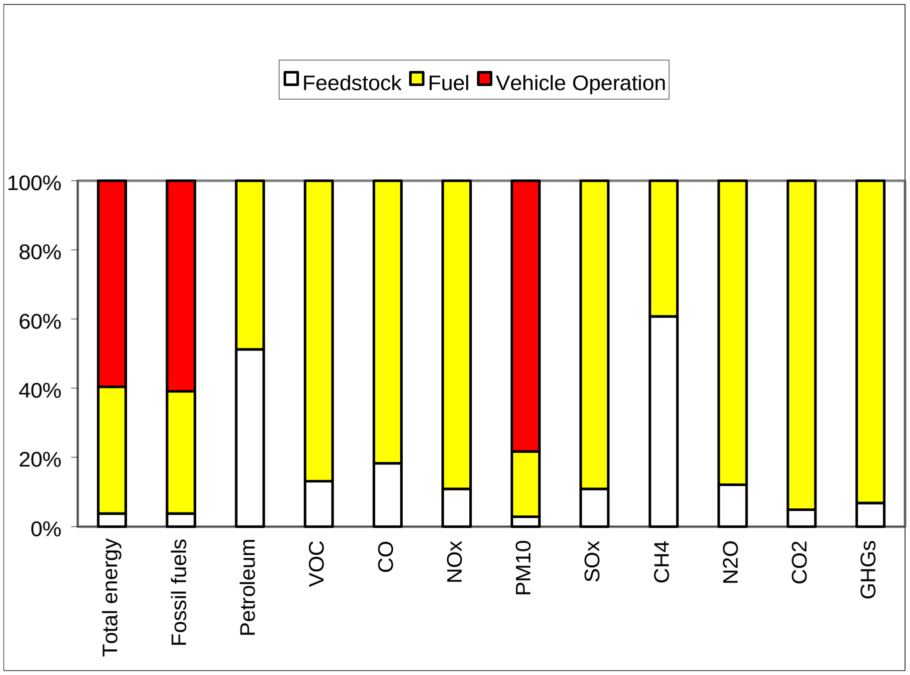

Figure 6.16 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with H_2 Produced from NG

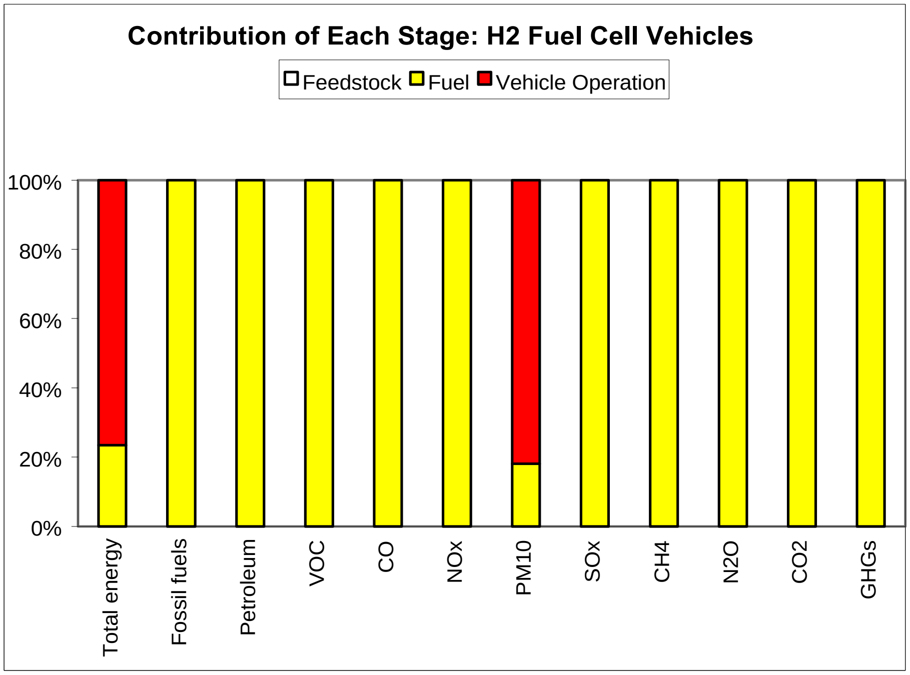

Figure 6.17 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with H_2 from Solar Energy

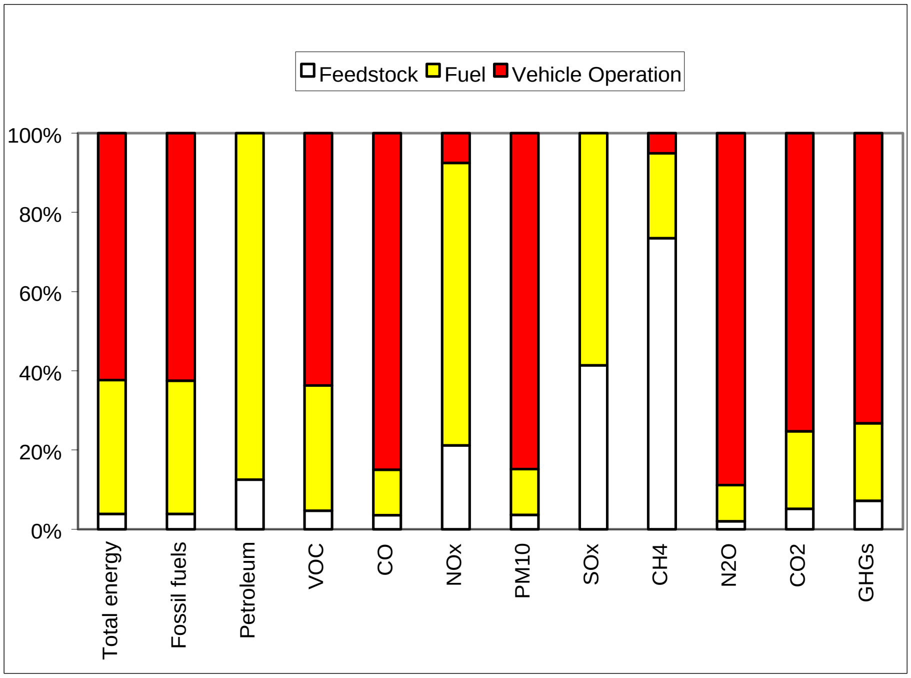

Figure 6.18 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with Methanol

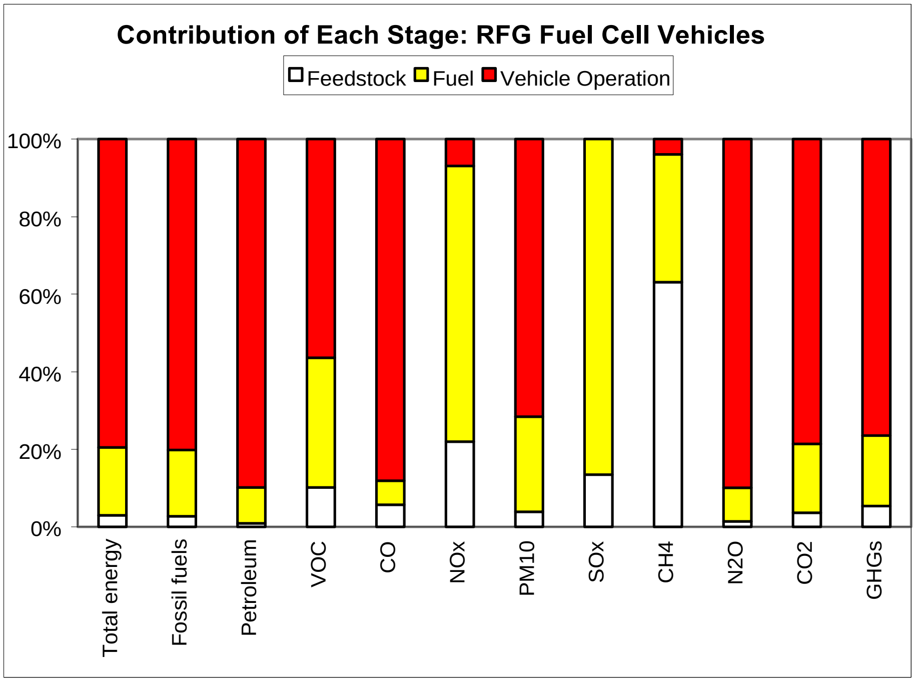

Figure 6.19 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with RFG

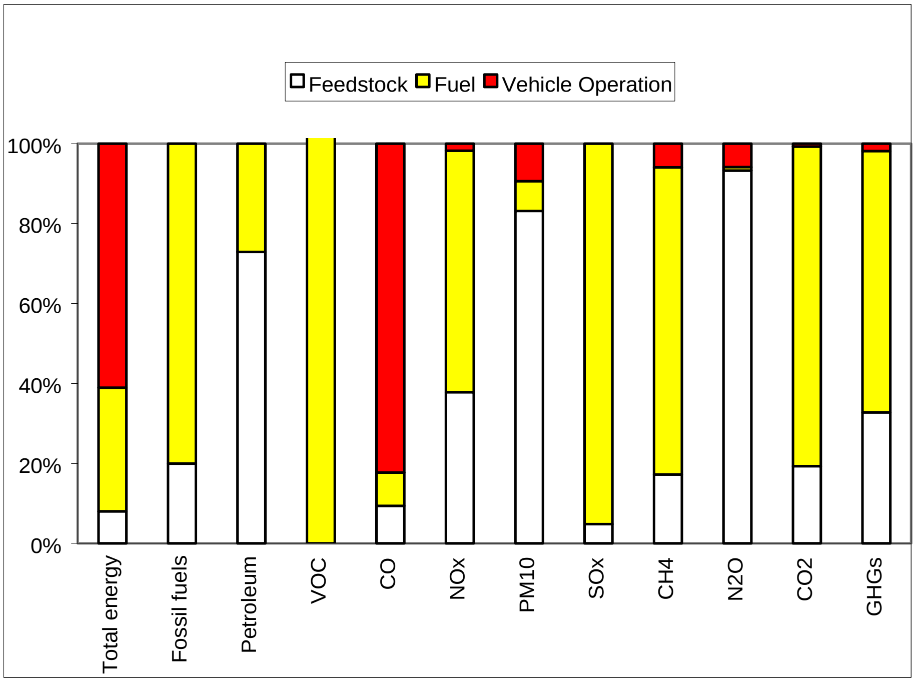

Figure 6.20 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with Ethanol

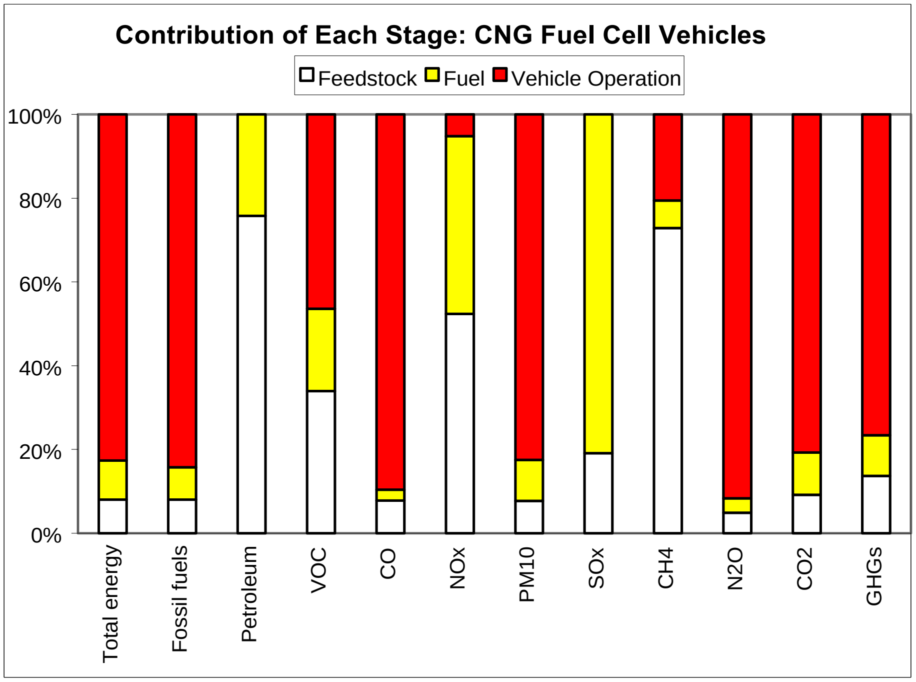

Figure 6.21 Shares of Fuel-Cycle Energy Use and Emissions by Stage: FCVs Fueled with CNG

Stage contribution results for cellulosic-ethanol-fueled vehicles (dedicated ethanol vehicles and FCVs) are not presented, because those results are distorted by energy and emission credits for the electricity generated at cellulosic ethanol plants. If energy and emission credits for the generated electricity were not considered, upstream biomass farming and cellulosic ethanol production would contribute significantly to total fuel-cycle energy use and emissions.

6.4 Per-Mile Energy Use and Emissions Results

In this section, we present per-mile, fuel-cycle energy use and emission results for the near- and long-term technologies included in GREET 1.5. Calculated per-mile energy use and emissions for three light-duty vehicle types — passenger cars, LDT1, and LDT2 — are presented in Appendix B. Changes in per-mile energy use and emissions associated with alternative fuels and advanced transportation technologies relative to baseline GVs are presented in this section.

Among the three light-duty vehicle types, the absolute amounts of fuel-cycle energy use (in Btu/mi) and emissions (in g/mi) increase in the following order: passenger cars, LDT1, and LDT2. For alternative transportation technologies, even if the relative changes in energy use and emissions are similar among the three types, the changes in absolute amounts will be different. In particular, application of a given technology to LDT2 will result in greater changes in per-mile energy use and emissions than its application to LDT1, and application to LDT1 will result in greater changes than its application to passenger cars. Users can employ the per-mile energy and emission results presented in Appendix B to determine the absolute energy and emission benefits per mile driven.

The relative changes by a given alternative fuel or an advanced transportation technology certainly differ among the three light-duty vehicle types, although the differences between passenger cars and LDT1 are generally smaller (because the same relative fuel economy and emission changes for vehicle operations are assumed for these two types; see Table 4.35). Our discussion of the relative changes in fuel-cycle energy use and emissions is based on the results for passenger cars, and the figures presented in the sections below are for passenger cars. Similar figures giving relative changes for LDT1 and LDT2 are presented in Appendix C. Numerical values of relative changes for passenger cars, LDT1, and LDT2 are presented in Appendix D.

6.4.1 Near-Term Technologies

The next nine figures show changes in fuel-cycle energy use and emissions of various near-term alternative fuels and transportation technologies relative to conventional GVs fueled with CG. Figure 6.22 shows changes in fuel-cycle total energy use. Use of ethanol, methanol, CNG, FRFG2, or CARFG2 in conventional SI engines causes increases in total energy use. The increases associated with M85 and E85 are above 15% and 20%, respectively. The increases are caused primarily by the significant amount of energy consumed during ethanol and methanol production. The increases associated with CNG are caused by CNGV fuel economy penalties. Use of EVs, HEVs, or CIDI engines fueled with diesel results in decreased fuel-cycle total energy use. The decreases are caused mainly by the high energy efficiencies of these vehicle technologies.

Figure 6.23 presents changes in fuel-cycle total fossil energy use for each fuel or vehicle type. Fossil fuels here include petroleum, NG, and coal. Use of M85 in methanol FFVs results in an increase of about 15% in per-mile fossil energy use, which is caused primarily by the large amount of NG used in methanol production at methanol plants. Use of CNG results in small increases in per-mile fossil energy use. Large fossil energy reductions occur with E85 and with diesel in CIDI engines, EVs, or HEVs. The large reduction with E85 occurs because ethanol is a nonfossil fuel; large reductions for CIDI vehicles, EVs, and HEVs are attributable to their high energy efficiencies. Use of LPG also results in reductions.

Figure 6.24 shows petroleum displacement by fuel and vehicle technology. As expected, use of non-petroleum-based fuels reduces petroleum use substantially. Among the vehicle technologies that use petroleum-based fuels, grid-connected and grid-independent HEVs and CIDI vehicles reduce petroleum use by more than 50% because of their efficiency gains. Use of RFG results in a small decrease in petroleum use because the MTBE and ETBE used in RFG are not petroleum based. The limited reduction by E10 occurs because 90% of the fuel blend is gasoline. The limited reduction by petroleum-based LPG occurs apparently because the fuel is petroleum based. The reduction by diesel CIDIs is attributable to vehicle efficiency gains.

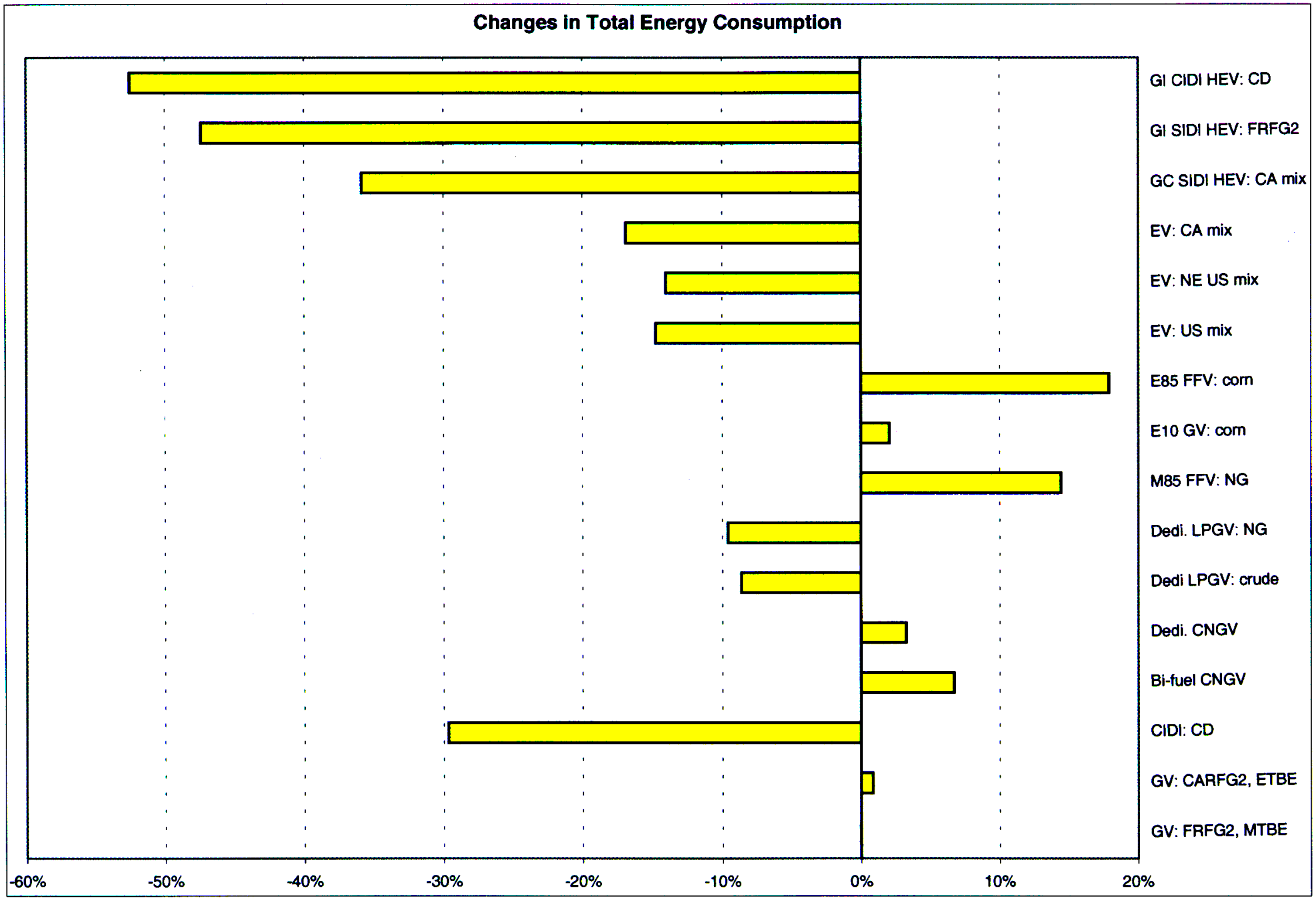

Figure 6.22 Changes in Fuel-Cycle Total Energy Use Relative to GVs Fueled with CG: Near-Term Technologies

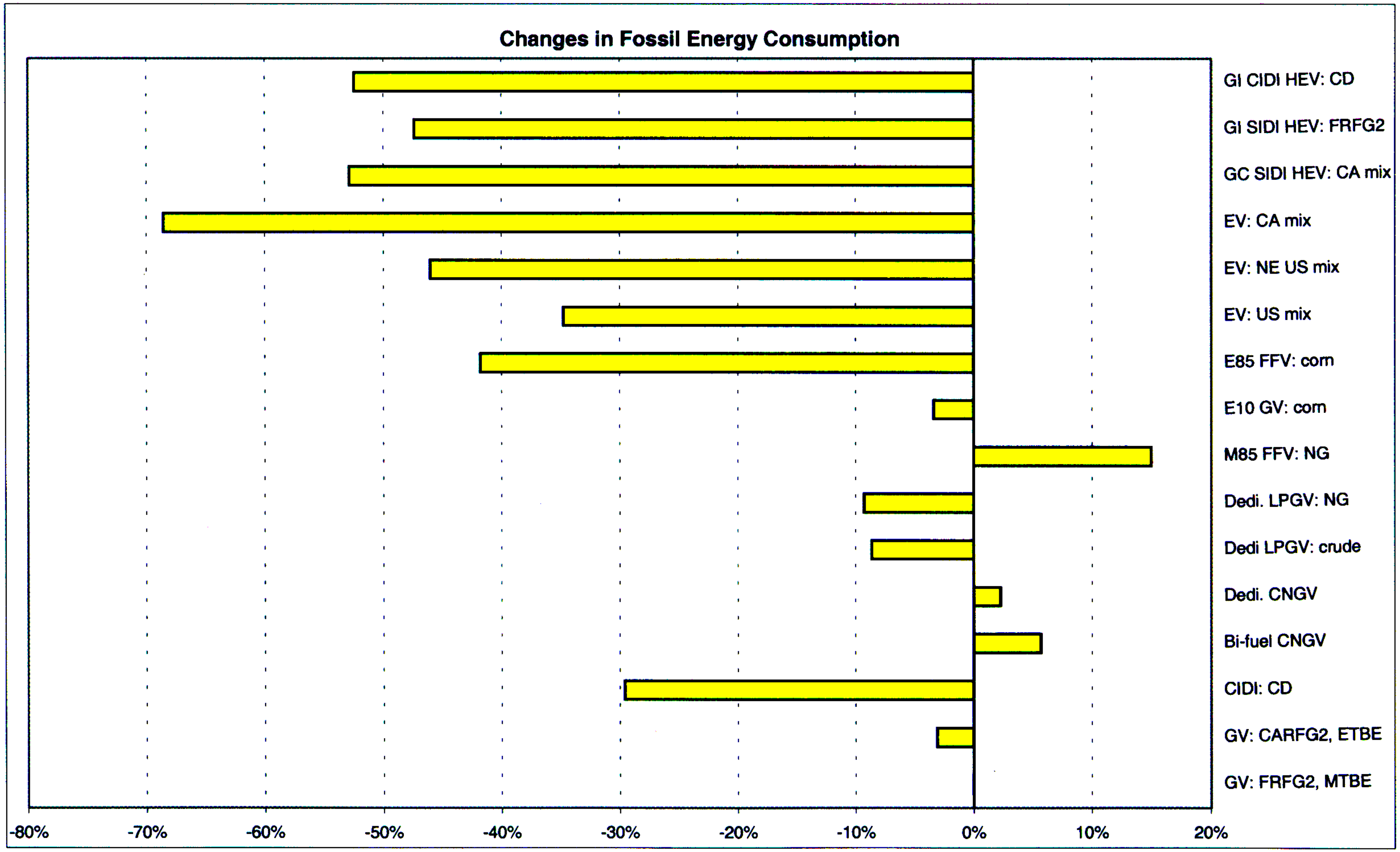

Figure 6.23 Changes in Fuel-Cycle Fossil Energy Use Relative to GVs Fueled with CG: Near-Term Technologies

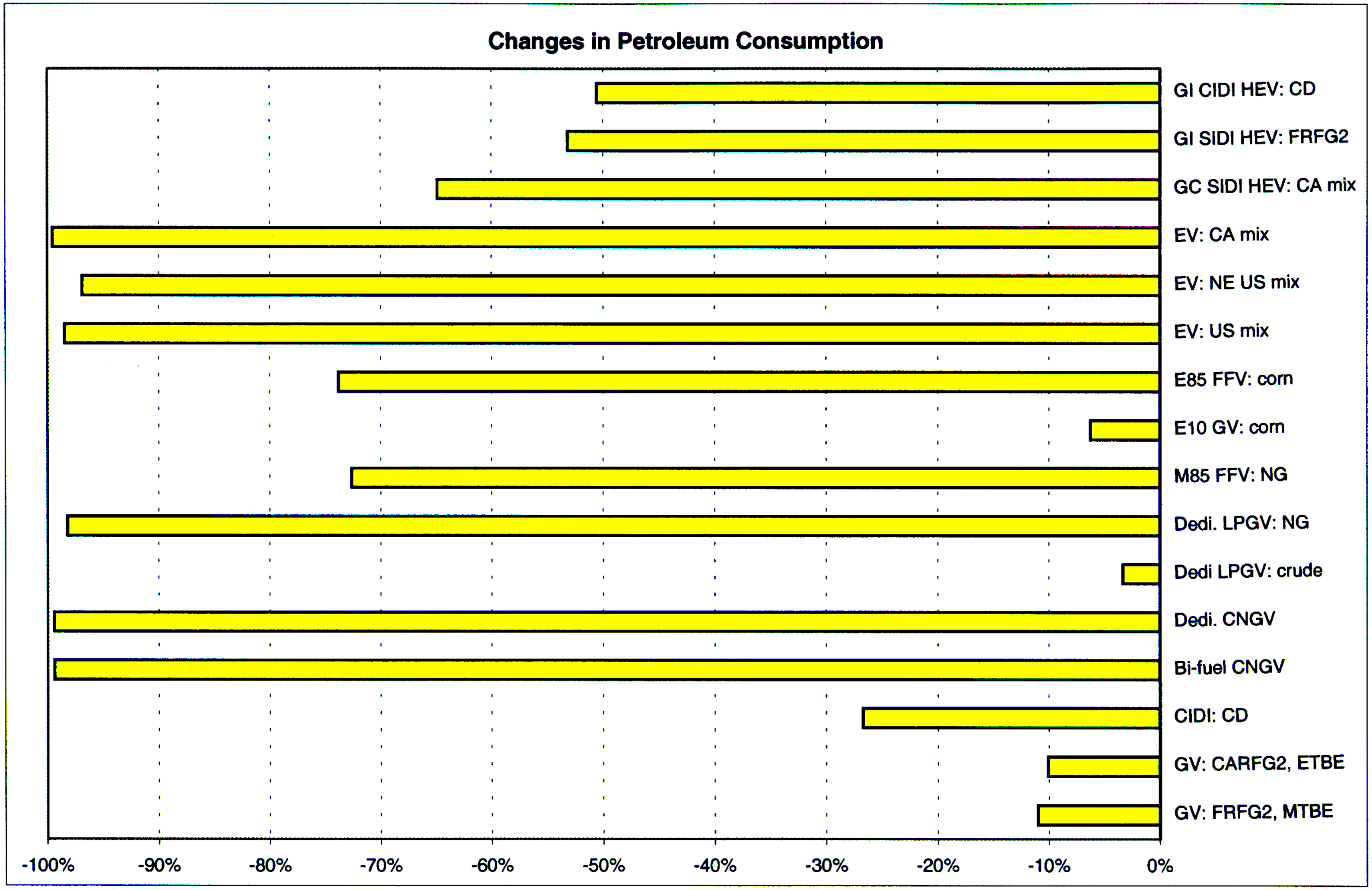

Figure 6.24 Changes in Fuel-Cycle Petroleum Use Relative to GVs Fueled with CG: Near-Term Technologies

Figure 6.25 shows changes in emissions of CO_2 and CO_2-equivalent GHGs. GHG emissions are the sum of emissions of CO_2, CH_4, and N_2O, weighted by their GWPs. Except for use of RFG, where a tiny increase in GHG emissions occurs, use of any fuel or vehicle technology helps reduce GHG emissions. The largest reductions occur for EVs with the California electric generation mix, under which 48% of electricity is produced from hydropower plants. In general, EVs and HEVs reduce GHG emissions by more than 40%, mainly because of their efficiency gains. Significant reductions are also achieved by use of CIDI vehicles and E85 FFVs. The CIDI reduction results from vehicle efficiency gains. The E85 reduction occurs because ethanol is produced from a renewable resource (corn). Even emissions from corn farming and ethanol production are taken into account. Use of LPG and CNG achieves moderate reductions. Use of E10 results in only a small reduction (a few percentage points) because gasoline still accounts for most of E10. The small reduction by M85 FFVs is attributable to methanol production emissions. Use of ETBE in RFG results in a smaller benefit than use of MTBE because ETBE is produced from ethanol.

The reductions in CO_2 and GHG emissions are similar for the combinations of fuels and vehicle technologies considered, except for CNG and E85, which resulted in smaller reductions in GHG emissions than in CO_2 emissions. The smaller GHG emissions reduction by CNGVs is attributable to a large amount of CH_4 emissions during upstream stages of the NG cycle. The smaller reduction by E85 is attributable to a large amount of N_2O emissions during corn farming.

Figure 6.26 presents changes in both total and urban VOC emissions. Use of any fuel or vehicle technology helps reduce fuel-cycle total and urban VOC emissions, except for E10 and E85, both of which produce small increases in VOC emissions (urban VOC emissions are reduced by use of E85). The increase in total VOC emissions with E85 is caused by significant VOC emissions released during ethanol production. High VOC emissions during ethanol production and high VOC evaporative emissions during vehicle operation cause the increases in both total and urban VOC emissions when E10 is used. Use of EVs achieves better than 90% reductions in both total and urban VOC emissions. In fact, use of EVs almost eliminates urban VOC emissions. Use of LPGVs, CNGVs, diesel CIDI, CNGVs, grid-connected HEVs, or diesel HEVs achieves greater-than-40% reductions. Use of RFG or M85 FFVs achieves reductions of about 20%.

Figure 6.27 shows that use of the subject fuels or vehicle technologies helps reduce both total and urban fuel-cycle CO emissions. Because the greater portion of fuel-cycle emissions occurs during vehicle operation for these fuels or technologies (except for EVs), urban CO emissions, where vehicular CO emissions occur, are very close to total CO emissions. Use of EVs and diesel fuels in HEVs or CIDI engines helps reduce CO emissions by more than 80%. Use of CNGVs, LPGVs, methanol FFVs, ethanol FFVs, E10 FFVs, and HEVs results in reductions in CO emissions of around 40%. Use of RFG reduces CO emissions by about 20%.

Figure 6.28 indicates that NO_x emissions can decrease or increase, depending on the fuels or vehicle technologies used. For urban NO_x emissions, diesel engines face the challenge of

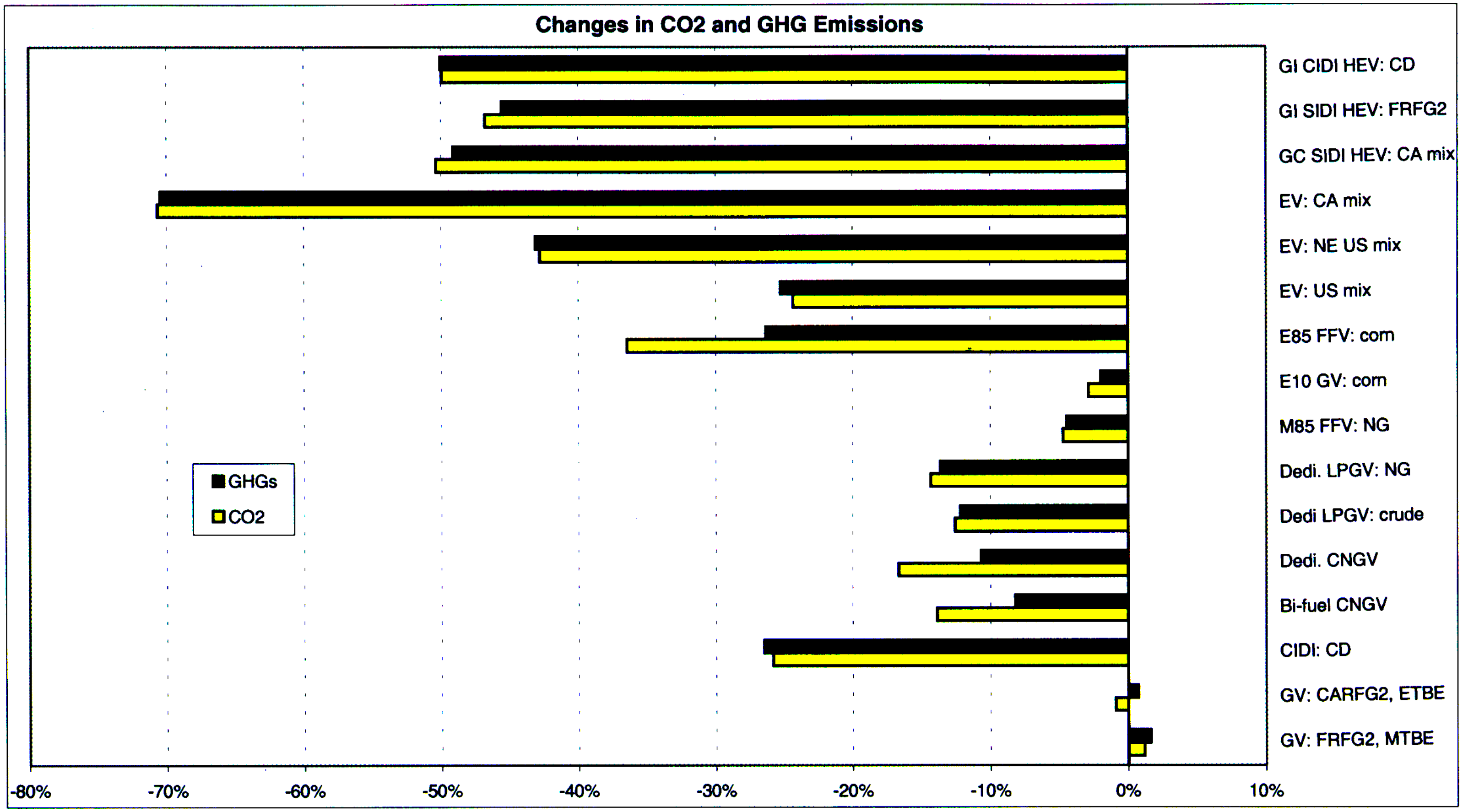

Figure 6.25 Changes in Fuel-Cycle GHG Emissions Relative to GVs Fueled with CG: Near-Term Technologies

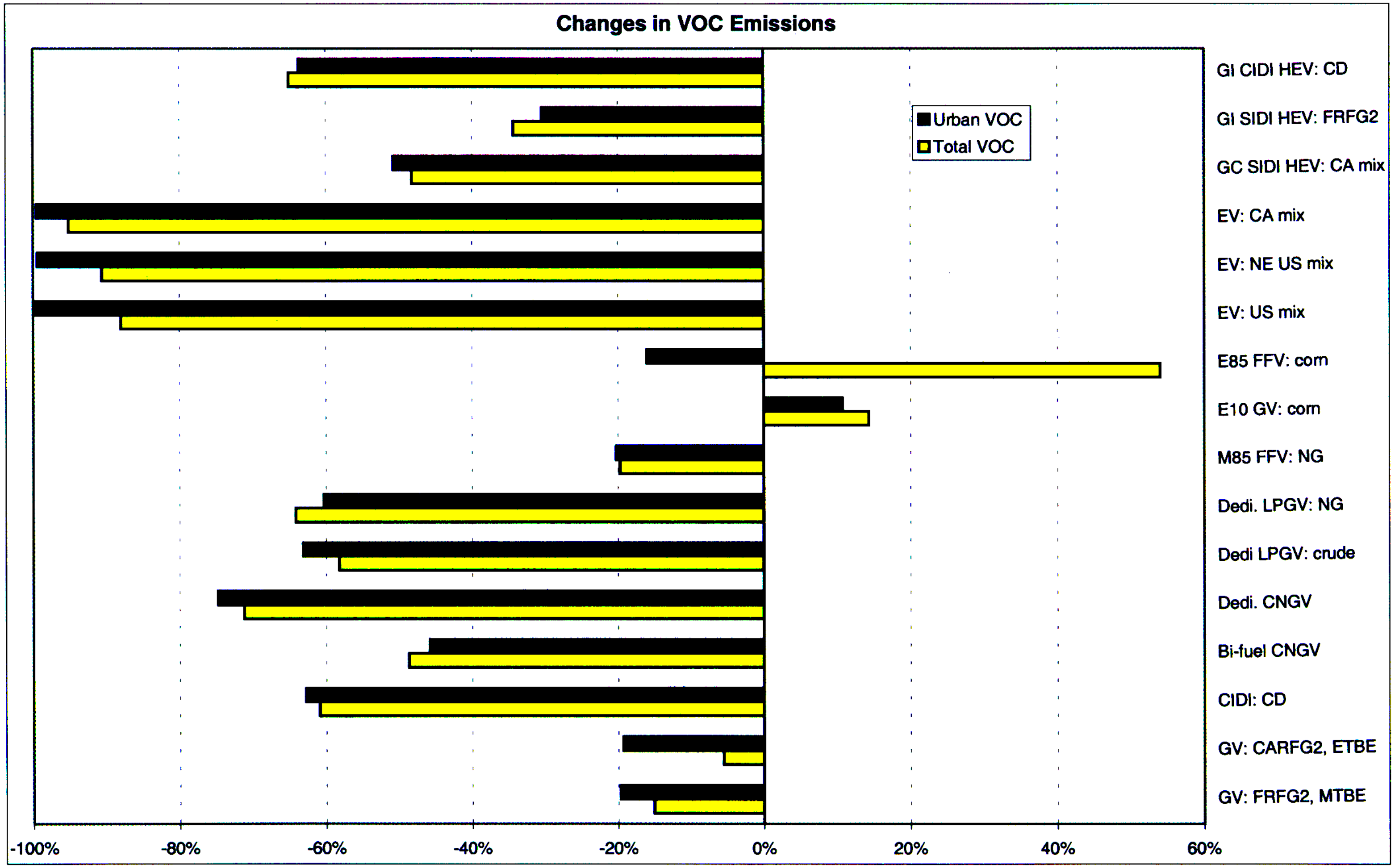

Figure 6.26 Changes in Fuel-Cycle VOC Emissions Relative to GVs Fueled with CG: Near-Term Technologies

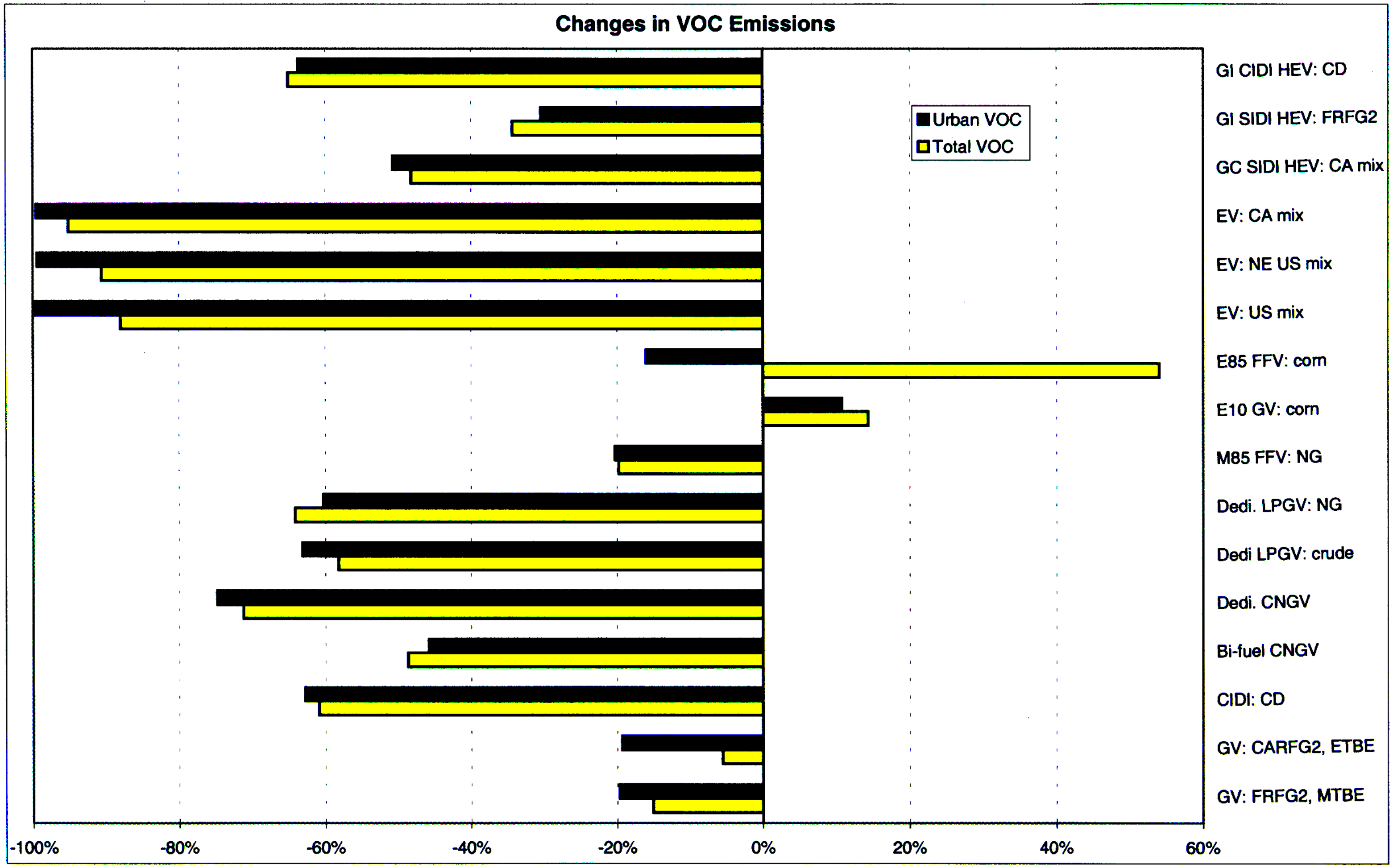

Figure 6.27 Changes in Fuel-Cycle CO Emissions Relative to GVs Fueled with CG: Near-Term Technologies

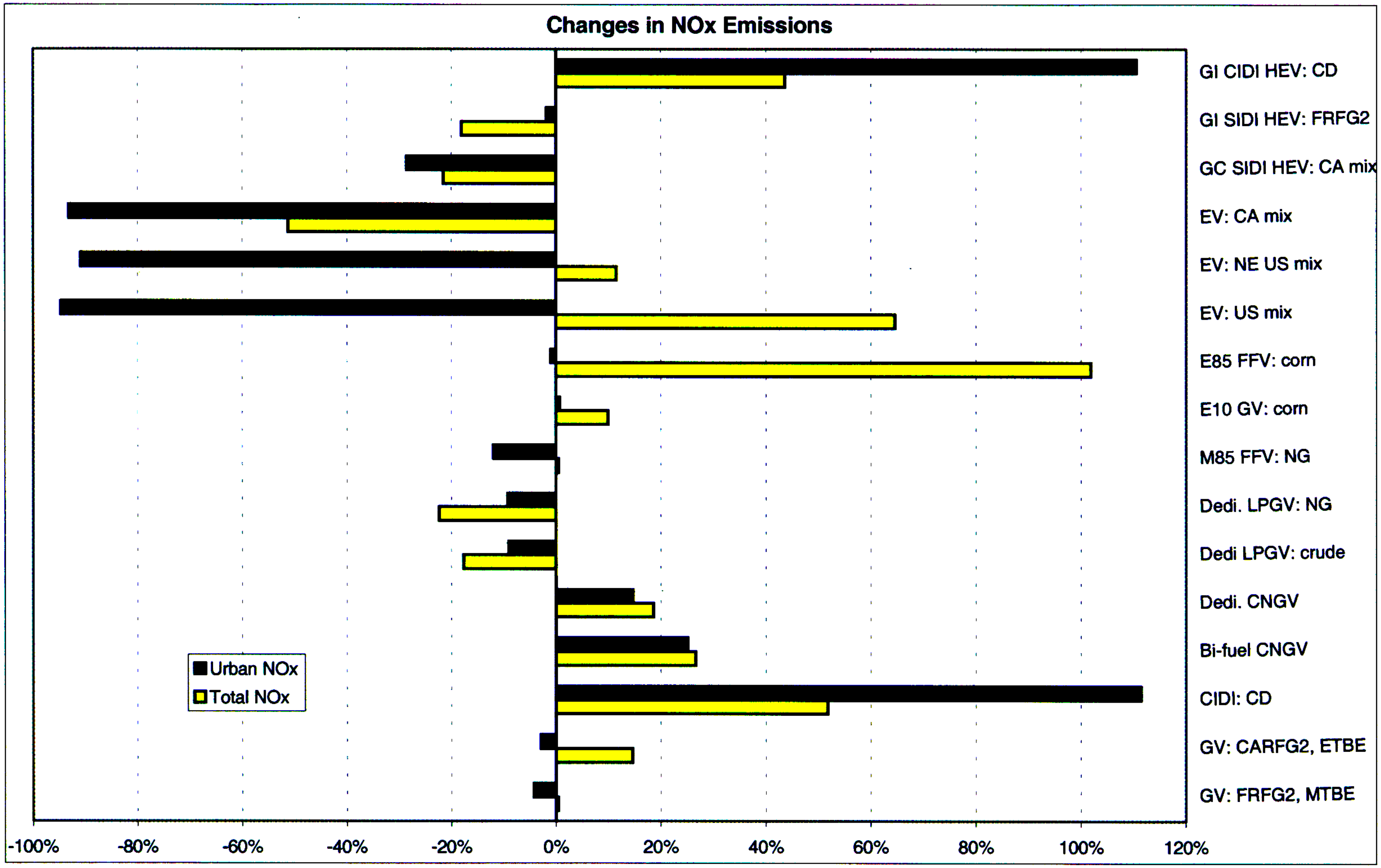

Figure 6.28 Changes in Fuel-Cycle NO_x Emissions Relative to GVs Fueled with CG: Near-Term Technologies

reducing NO_x emissions. Use of diesel fuels in HEVs and CIDI engines may cause over 100% increases in urban NO_x emissions. Use of RFG, M85, LPG, or E10 has little or no effect on NO_x emissions. Use of CNGVs increases both urban and total NO_x emissions, primarily because of the NO_x emissions generated by the compressors used for NG compression. Use of E85 FFVs or LPGVs achieves small reductions in NO_x emissions. Use of EVs reduces urban NO_x emissions by more than 95%. Use of ethanol FFVs and EVs could increase total NO_x emissions.

The increases in total NO_x emissions for E85 and E10 result from the large amount of NO_x emissions released during production of ethanol. The increases in total NO_x emissions from diesel fuels are smaller than the increases in urban NO_x emissions.

Figure 6.29 shows large variations in fuel-cycle PM_{10} emissions. Use of diesel fuels causes increases of about 250% in urban PM_{10} emissions. Use of RFG or E10 has little effect on urban PM_{10} emissions. Use of CNGVs, LPGVs, or EVs achieves moderate reductions (near 40%). The relatively smaller reductions in urban PM_{10} emissions are partly attributable to tire- and brake-wear PM_{10} emissions, which are borne by each vehicle type, diluting the emission reduction effects of fuels and vehicle technologies.

Use of diesel fuels increases total PM_{10} emissions by about 160%. Use of E85 FFVs increases such emissions by six times, because of high upstream PM_{10} emissions during corn farming and ethanol production. Use of E10 or EVs with the U.S. and the U.S. Northeast generation mix results in moderate increases in total PM_{10} emissions. Use of CNGVs, M85 FFVs, LPGVs, EVs, or HEVs with the California generation mix, or of grid-independent HEVs fueled with RFG achieves moderate reductions in total PM_{10} emissions.

Figure 6.30 shows that total SO_x emissions increase with the use of EVs (except with the California generation mix) or ethanol (both E85 and E10). The increase in SO_x emissions by EVs with the U.S. generation mix is 4.5 times. The increases are caused by high SO_x emissions during electricity generation and ethanol production at ethanol plants. Use of other fuels and vehicles results in reductions in total SO_x emissions.

Use of any fuel or vehicle technology reduces urban SO_x emissions, although these reductions are smaller for diesel fuels and E10. For RFG, CNGVs, LPGVs, methanol FFVs, ethanol FFVs, EVs, and HEVs, reductions in urban SO_x emissions are above 80%.

6.4.2 Long-Term Technologies

The next 36 figures show changes in fuel-cycle energy use and emissions for various long-term transportation fuels and advanced technologies relative to conventional GVs fueled with federal RFG2. The long-term technologies are divided into four groups: (1) vehicles equipped with conventional SI engines and SIDI engines fueled with various SI engine fuels; (2) grid-independent (GI) and grid-connected (GC) HEVs equipped with SI engines and SIDI engines powered by various SI engine fuels; (3) vehicles equipped with CIDI engines (including CIDI standalone vehicles), GI HEVs, and GC HEVs; and 4) EVs and FCVs. Because there are over 75 combinations of fuels and vehicle technologies for the long-term options, we created a chart

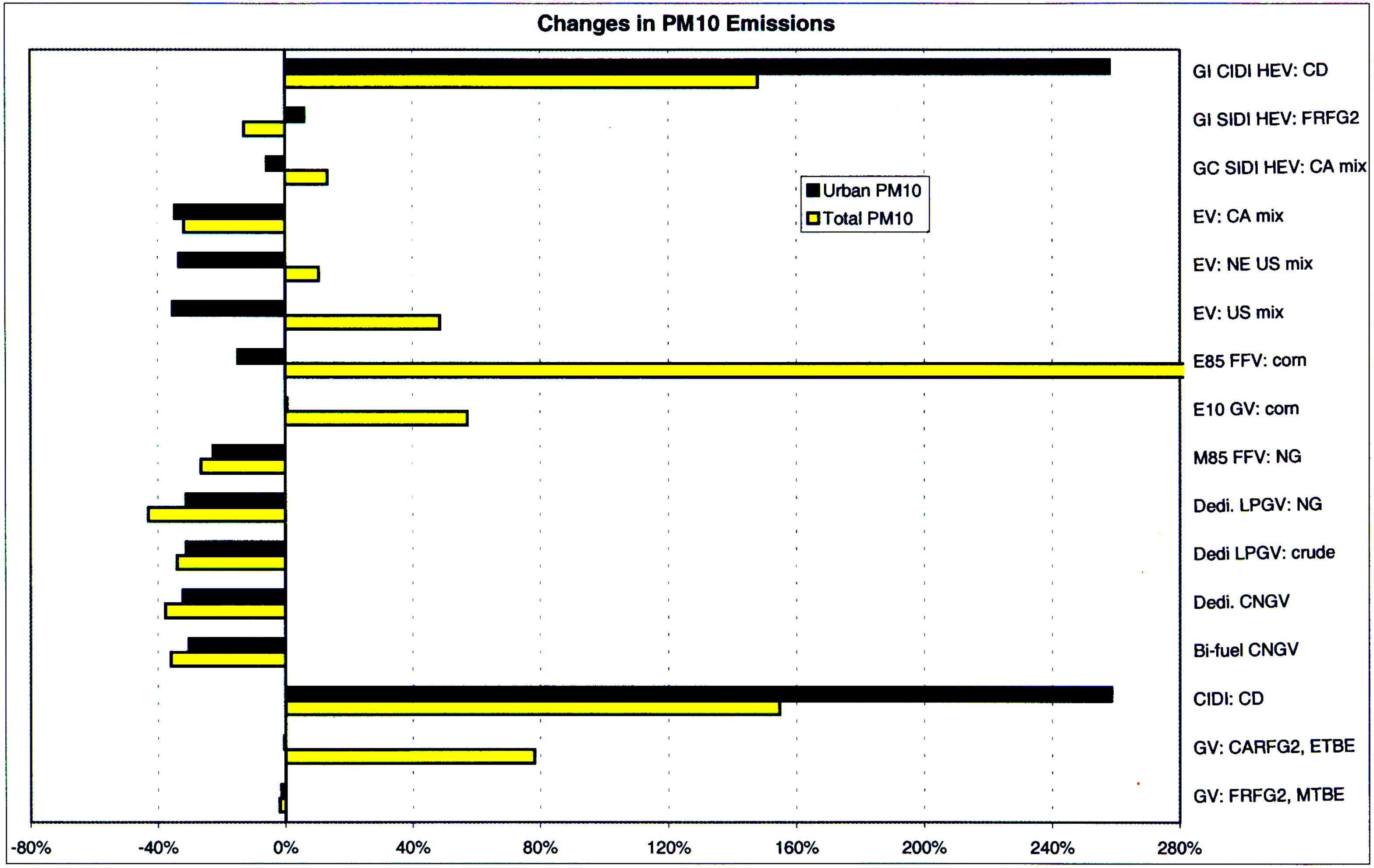

Figure 6.29 Changes in Fuel-Cycle PM_{10} Emissions Relative to GVs Fueled with CG: Near-Term Technologies

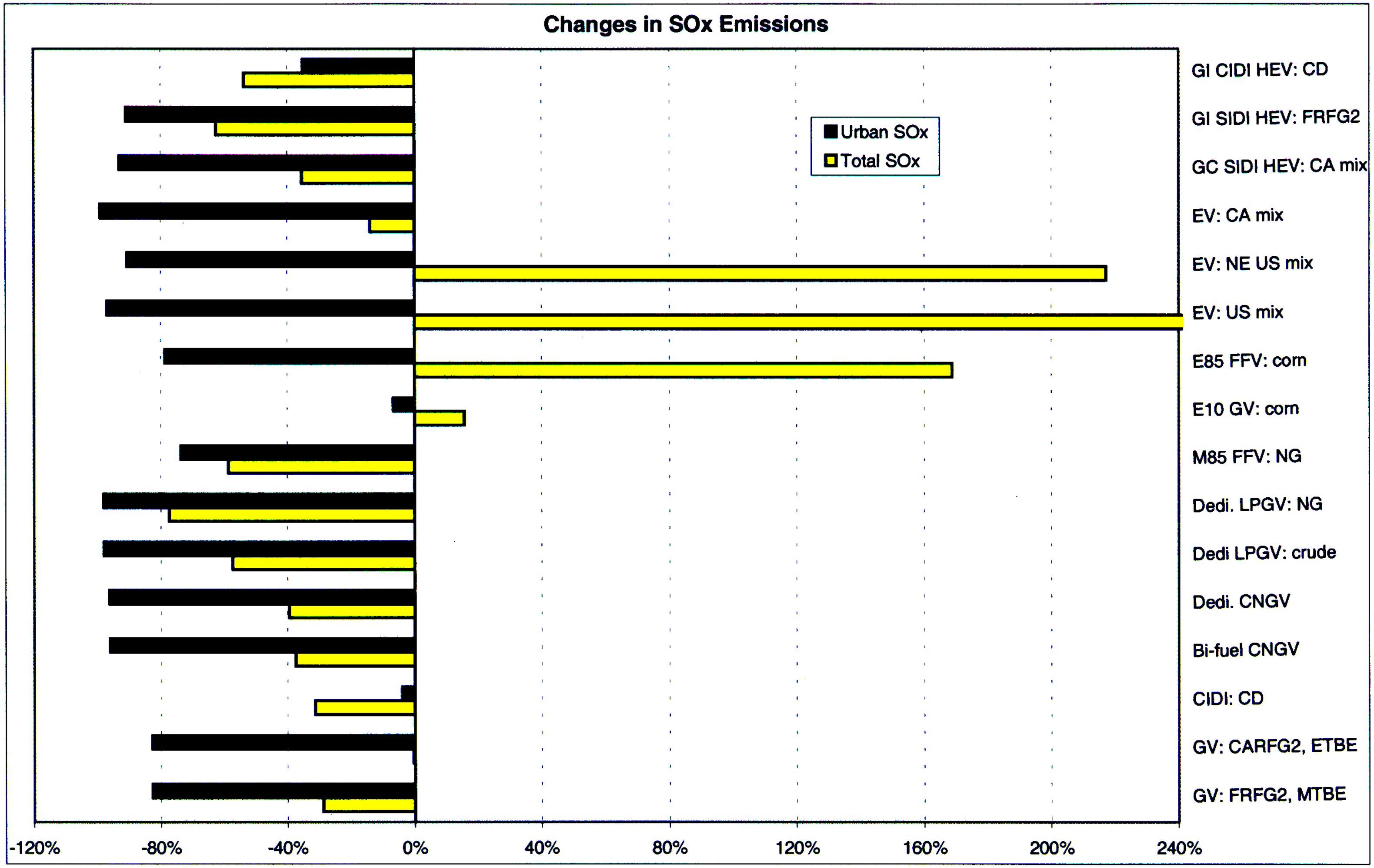

Figure 6.30 Changes in Fuel-Cycle SO_x Emissions Relative to GVs Fueled with CG: Near-Term Technologies

for each of the four groups and for each energy or pollutant to show fuel-cycle energy and emission effects.

Figures 6.31 through 6.34 show changes in fuel-cycle total energy use. Figure 6.31 shows total energy changes for SI and SIDI vehicles. Use of methanol from commercial natural gas or flared gas or ethanol from corn, woody biomass, or herbaceous biomass results in increased total energy use (note that total energy use includes the energy contained in corn and biomass that eventually comes from solar energy through the photosynthesis process). These increases are caused by the large amount of energy consumed during methanol or ethanol production. Use of LPGVs and SIDI vehicles fueled with RFG and methanol from landfill gases results in 15–20% reductions in total energy. The reduction by LPGVs is primarily because only a small amount of energy is consumed during LPG fractionating in petroleum refineries or in NG processing plants. The reductions by SIDI vehicles in general are attributable to their increased fuel economy.

Figure 6.32 shows reductions in total energy use by SI and SIDI HEVs. Technology options here include GI and GC HEVs. Conventional SI engines rather than SIDI engines were assumed for LPG, CNG, and LNG, because no significant fuel economy benefits are offered by replacing SI engines with SIDI engines for these fuels. On the other hand, SIDI engines were assumed for RFG, methanol, and ethanol. Large reductions (35–45%) are achieved for these vehicle types except for HEVs fueled with ethanol produced from woody and herbaceous biomass, for which reductions are 10–20%. The lower reductions for these options are caused by the large amount of energy consumed in cellulosic ethanol plants.

Figure 6.33 shows reductions in total energy use by CIDI standalone vehicles and CIDI HEVs. The former achieves 10–30% reductions, and the latter achieves over 40% reductions. Use of DME and FT50 results in lower reductions than use of other CI engine fuels because production of DME and FTD consumes a significant amount of energy.

Figure 6.34 presents reductions in total energy use by EVs and FCVs. Except for FCVs fueled with cellulosic ethanol (reductions of 10–20%), all the vehicles reduce total energy use by 40–60%. The smaller reductions by cellulosic ethanol are caused (again) by the large amount of energy consumed in cellulosic ethanol plants.

The four figures together show that SIDI HEVs, CIDI HEVs, and FCVs achieve large reductions in total energy use because of their significant improvements in vehicle fuel economy relative to gasoline SI engine technology.

Figures 6.35 through 6.38 present changes in fuel-cycle fossil energy use for the four technology groups. Figure 6.35 shows that, among the SI and SIDI vehicles, use of methanol produced from NG results in about a 10% increase in fossil energy use because of the large amount of NG consumed in methanol plants. On the other hand, use of flared gas- or landfill gas-based methanol results in 50–70% reductions in fossil energy because the energy contained in landfill gas or flared gas is otherwise wasted, and therefore it is not accounted for in GREET’s fossil energy calculations. Use of CNG, LNG, and LPG achieves less than 20% reductions in fossil energy use. Use of ethanol reduces fossil energy use by 50% to over 80%

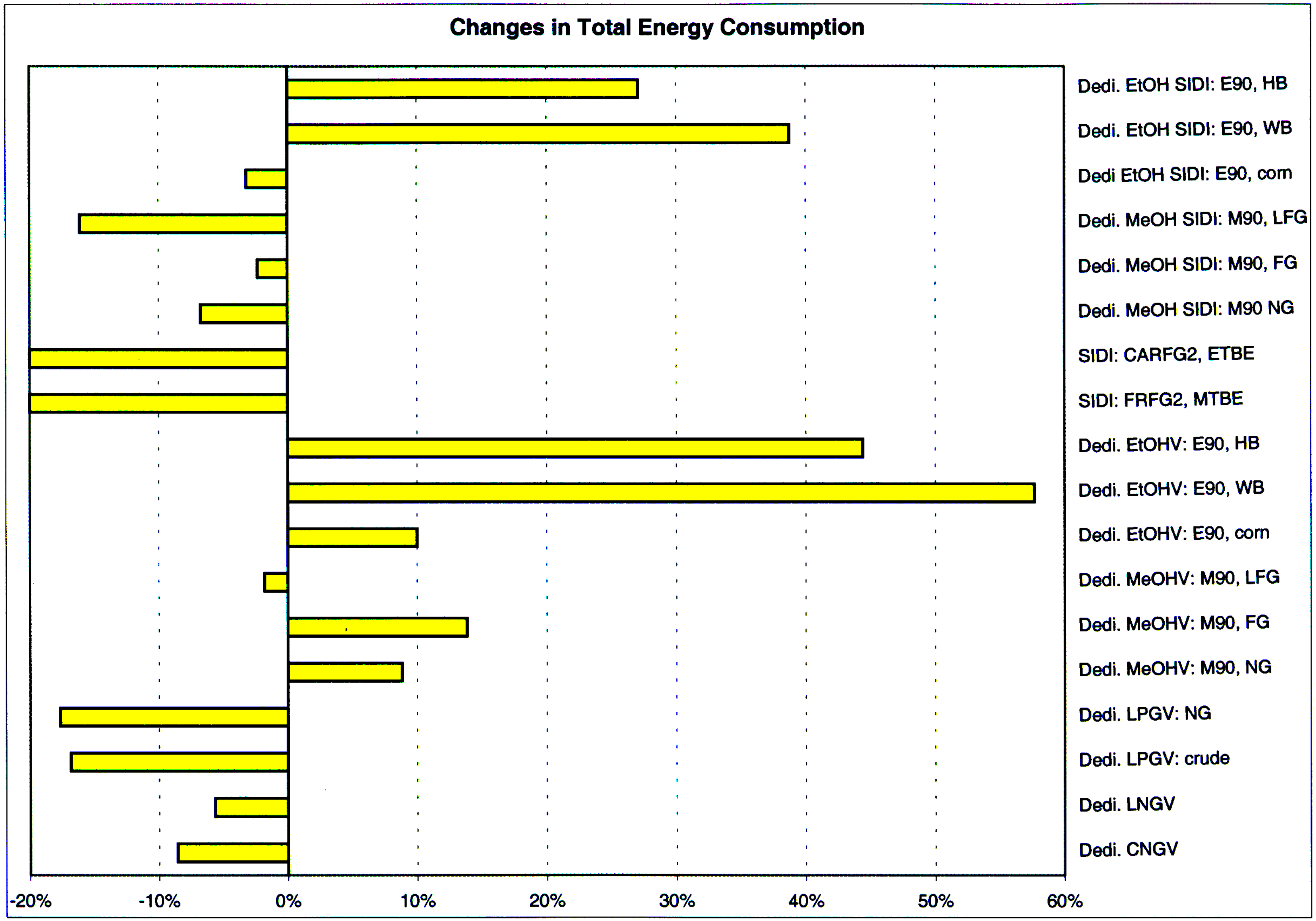

Figure 6.31 Changes in Fuel-Cycle Total Energy Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

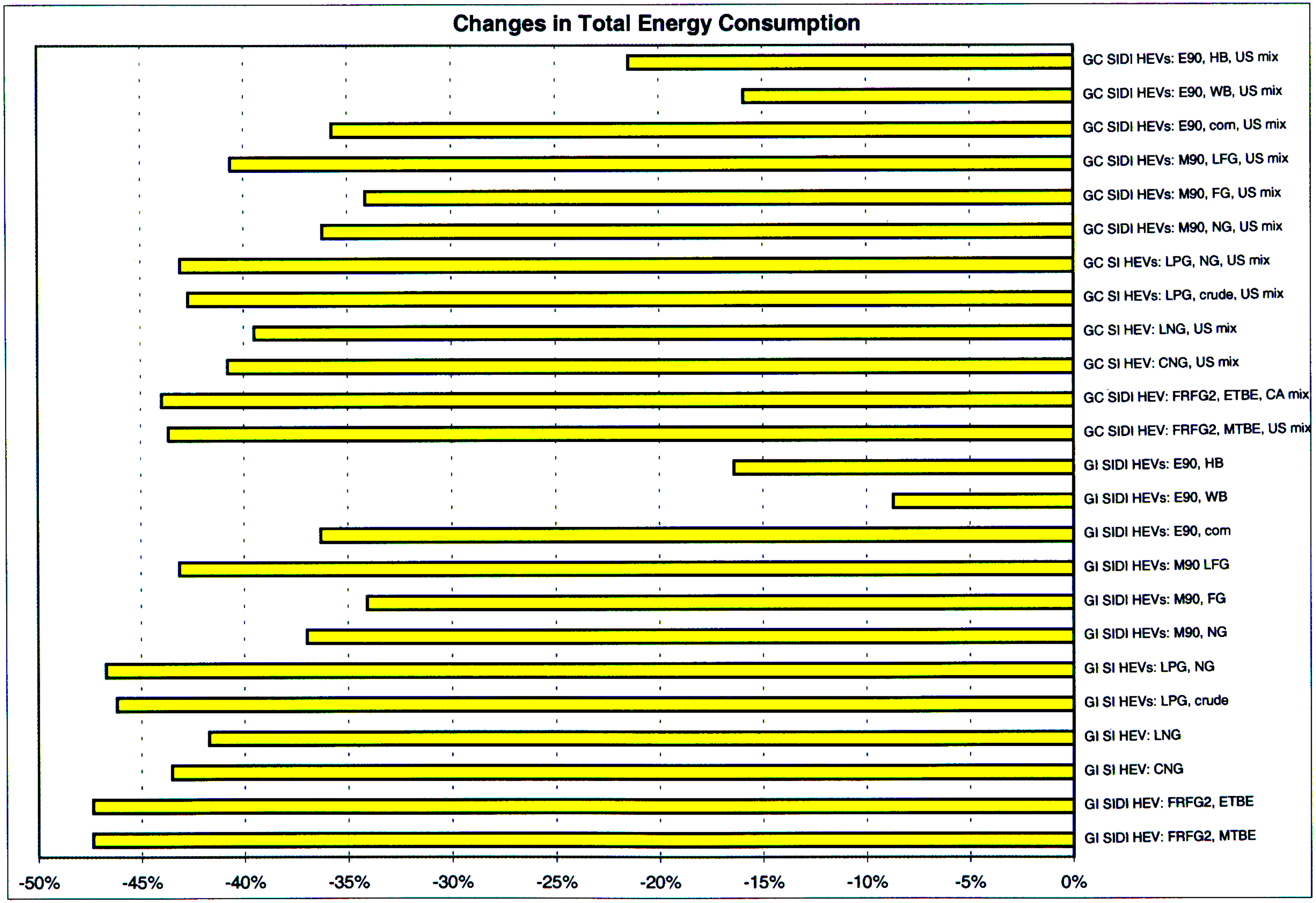

Figure 6.32 Changes in Fuel-Cycle Total Energy Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

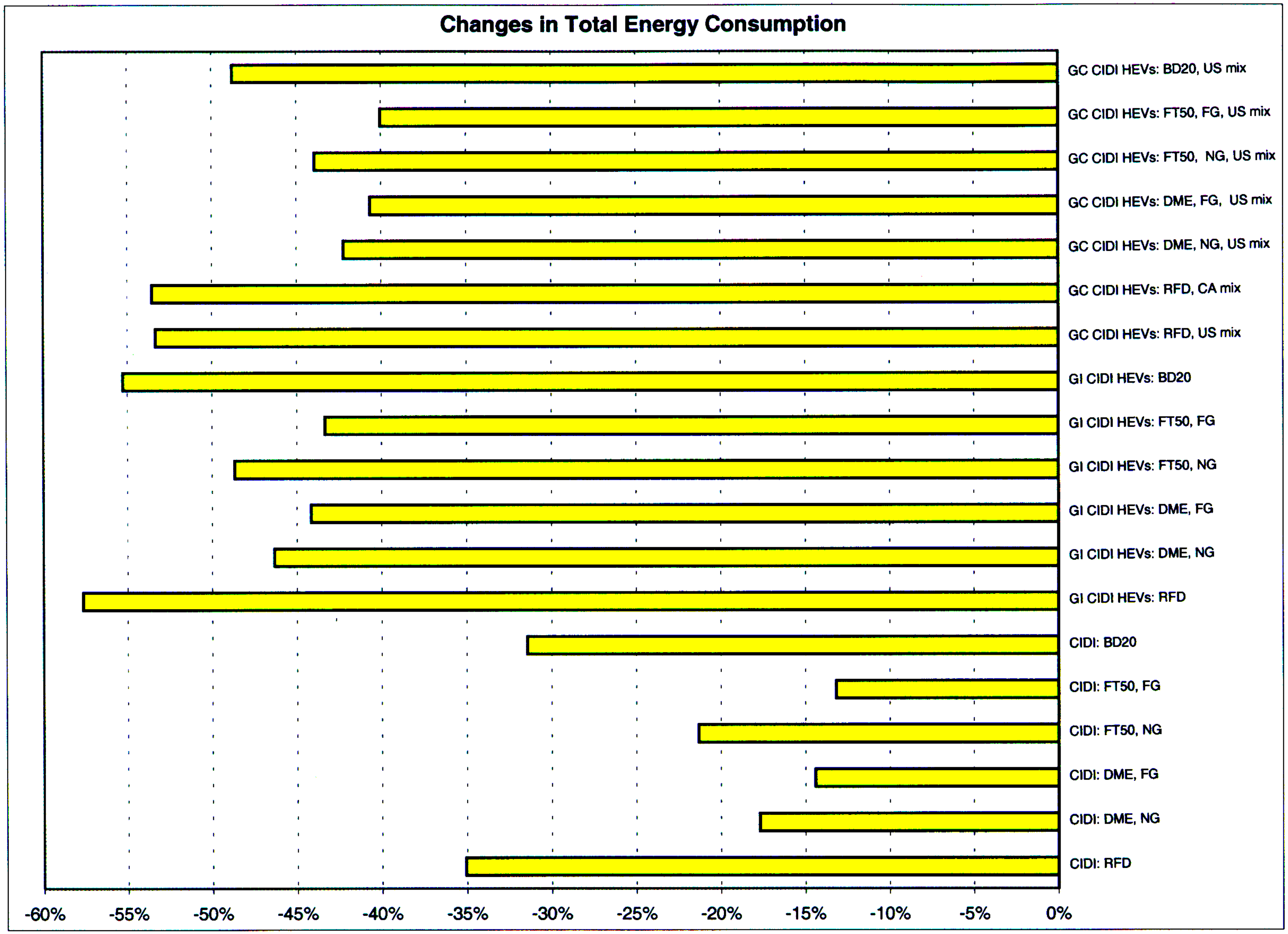

Figure 6.33 Changes in Fuel-Cycle Total Energy Use Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

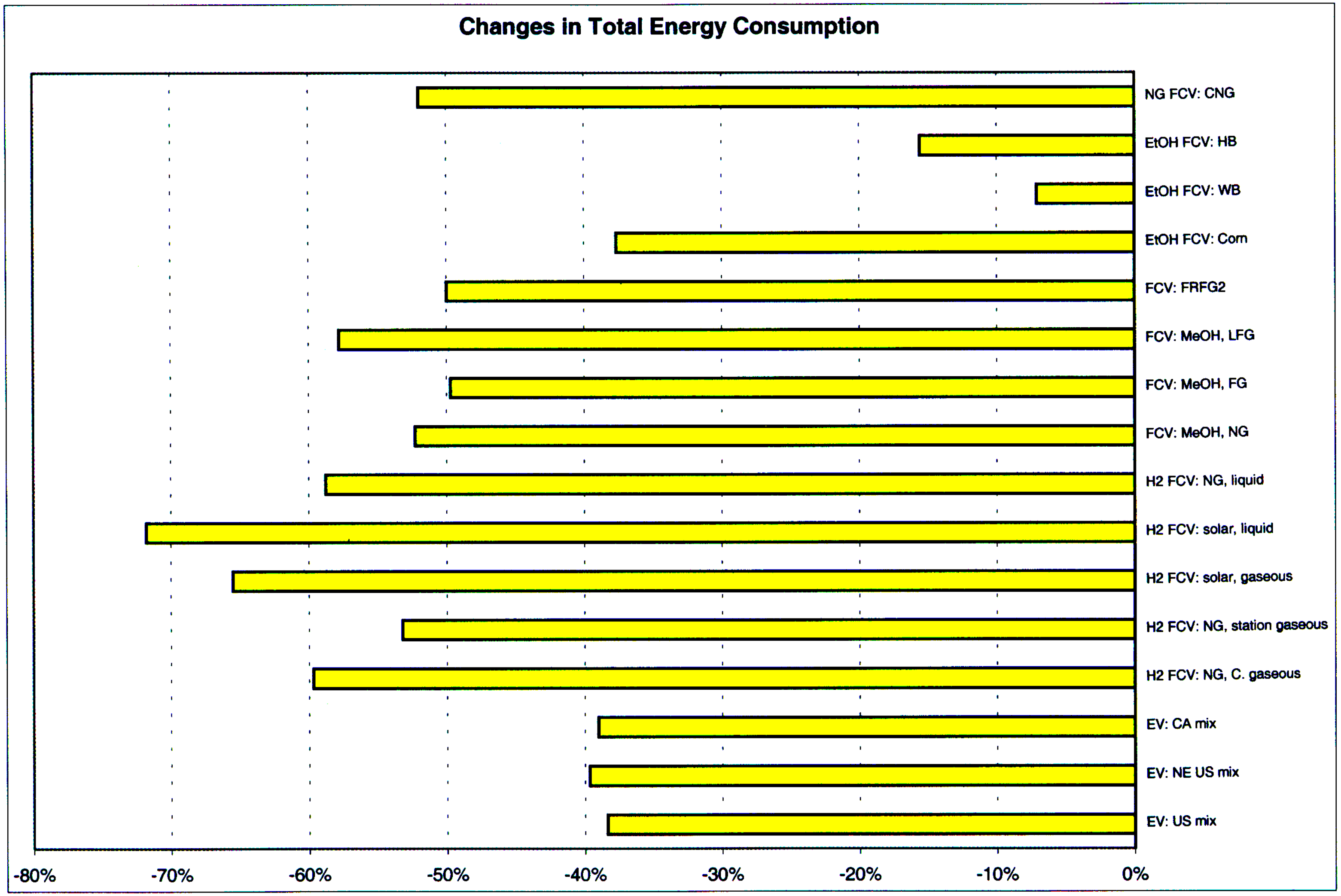

Figure 6.34 Changes in Fuel-Cycle Total Energy Use Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

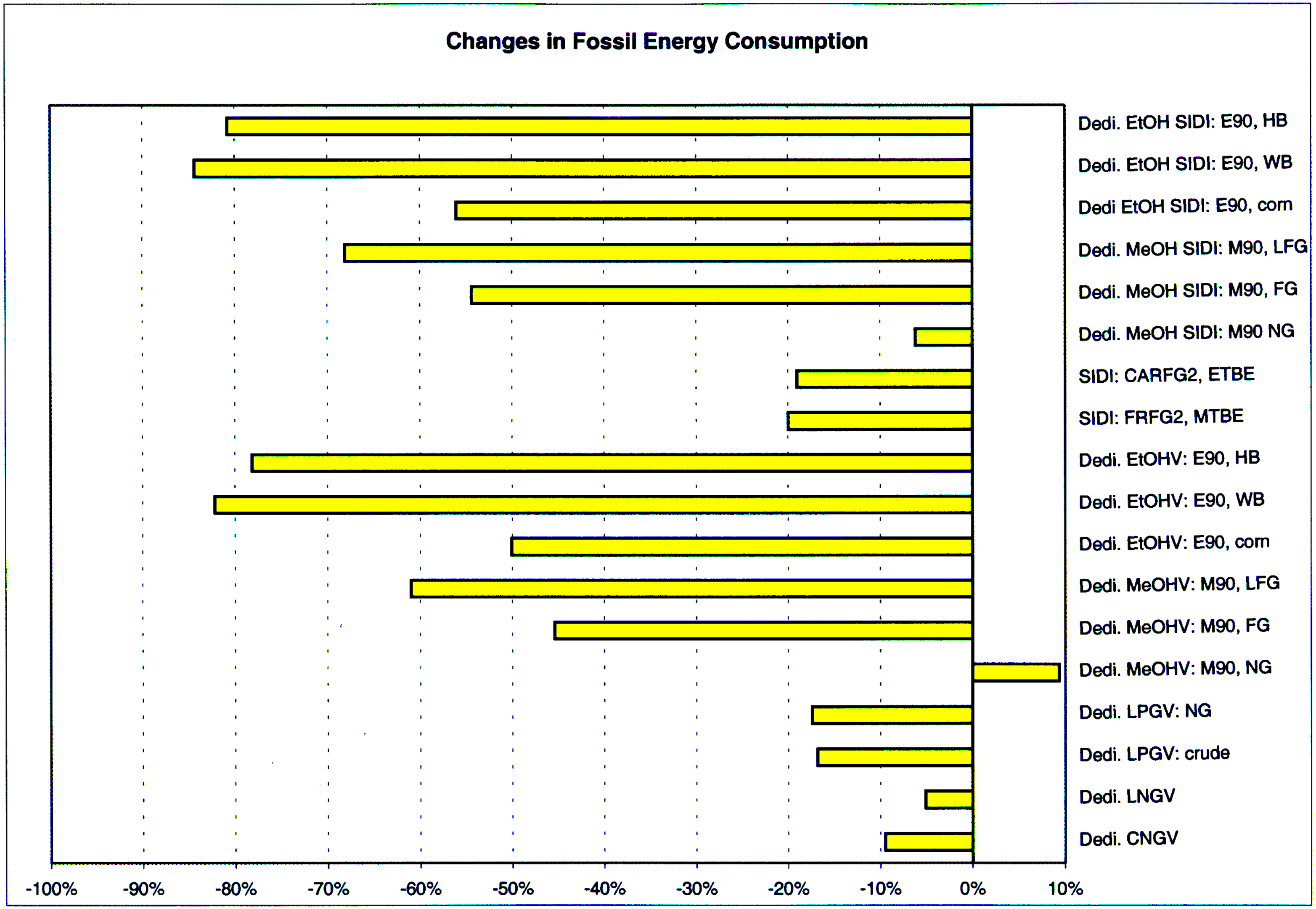

Figure 6.35 Changes in Fuel-Cycle Fossil Energy Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

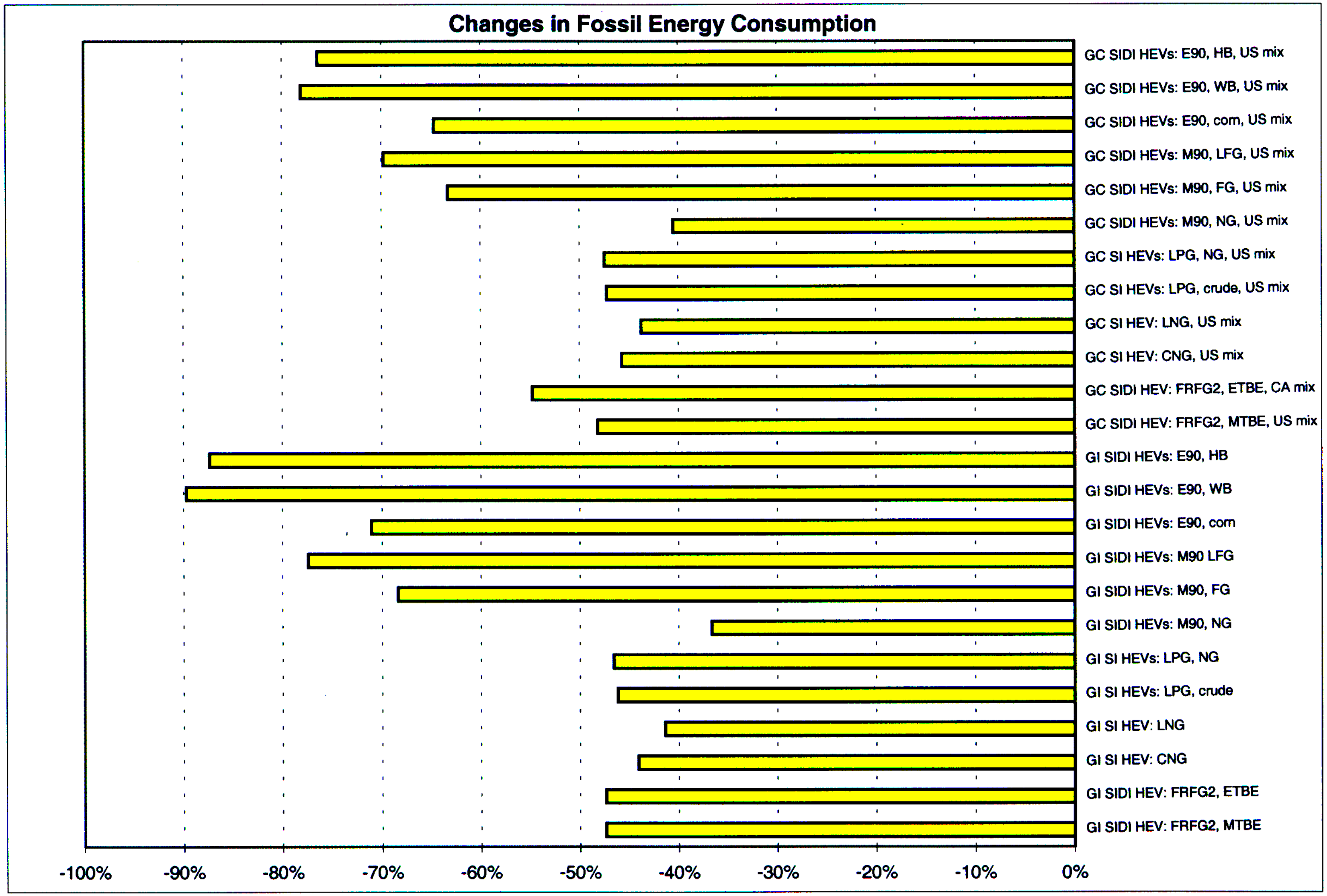

Figure 6.36 Changes in Fuel-Cycle Fossil Energy Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

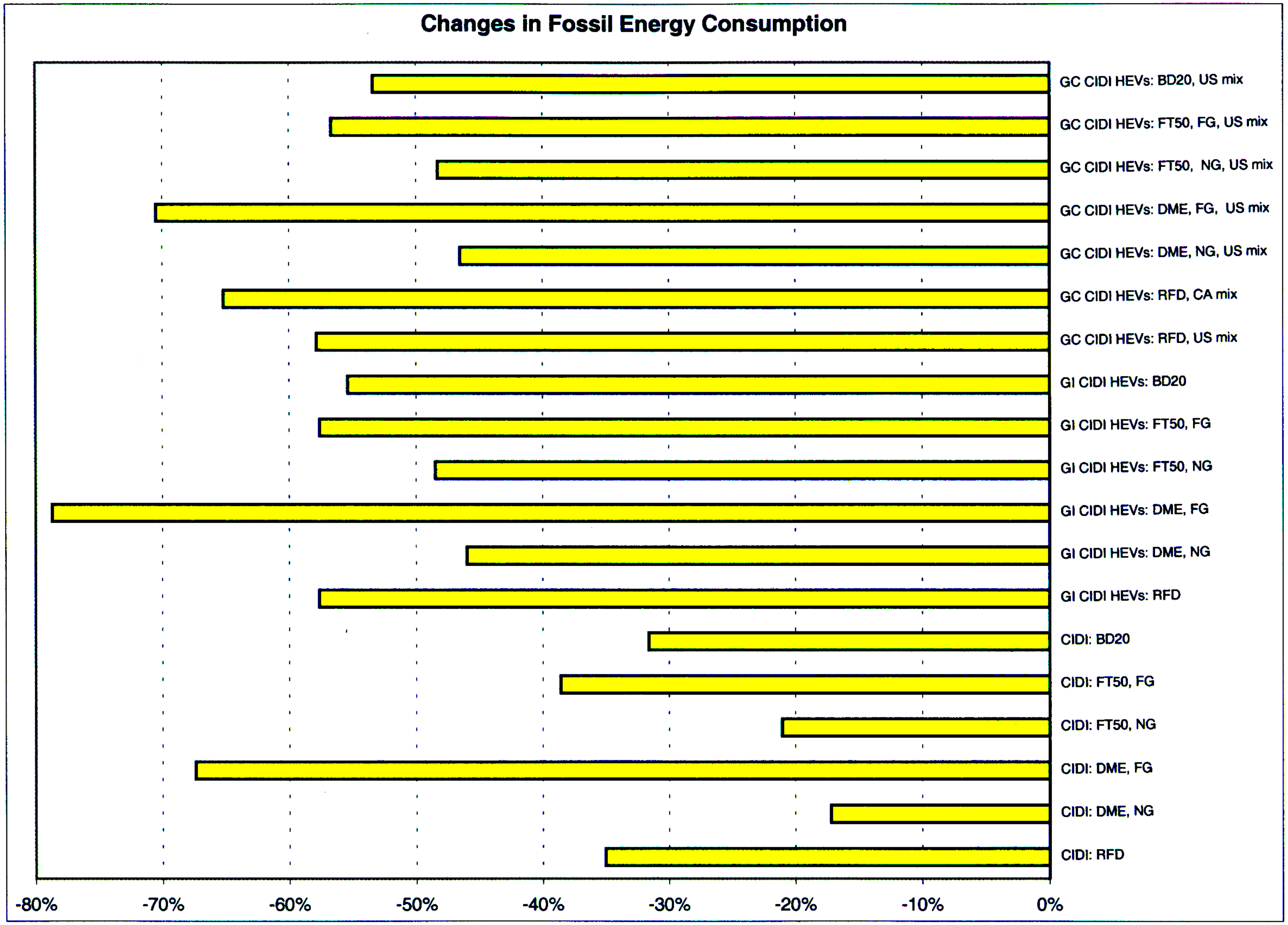

Figure 6.37 Changes in Fuel-Cycle Fossil Energy Use Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

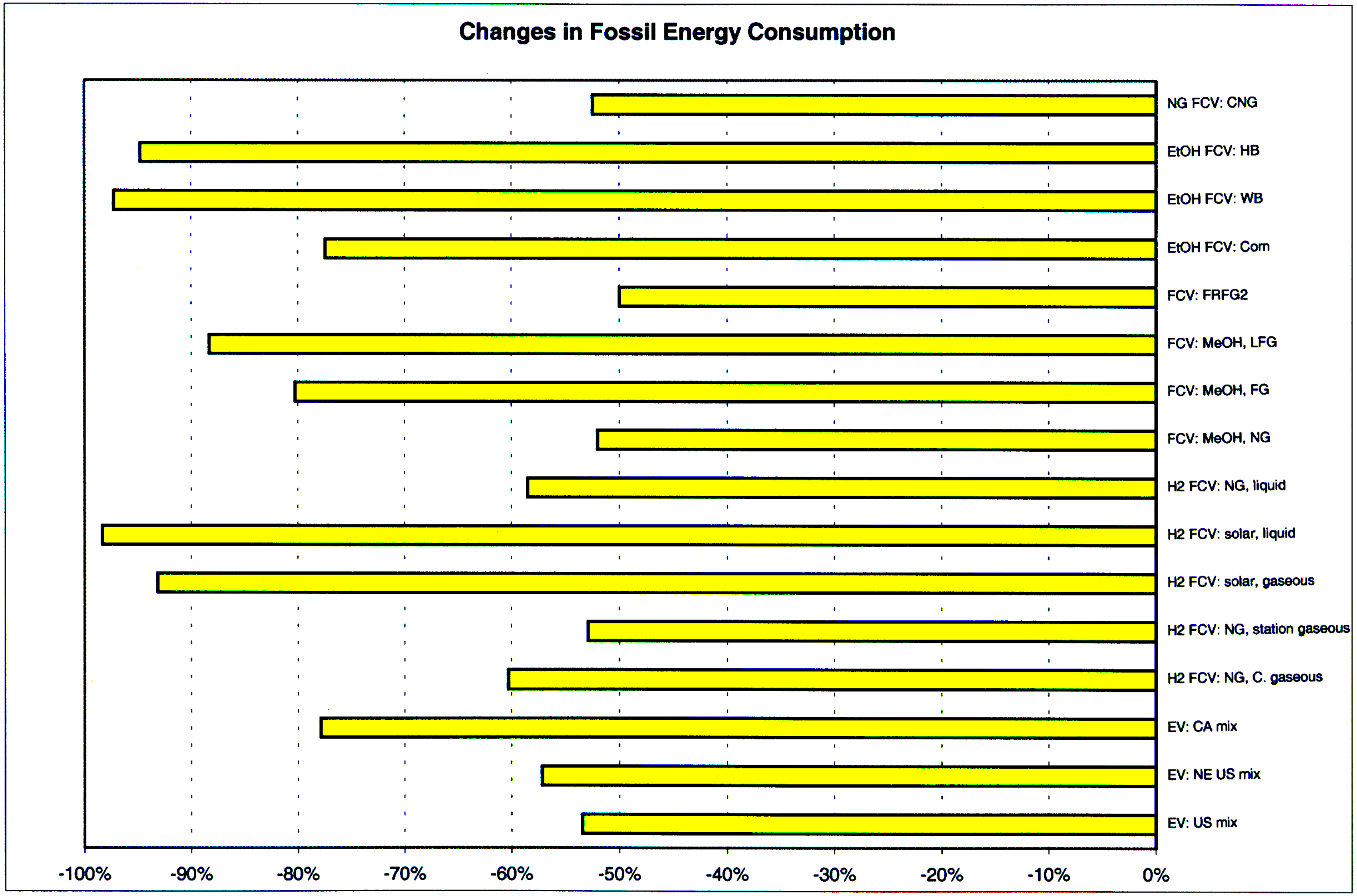

Figure 6.38 Changes in Fuel-Cycle Fossil Energy Use Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

because the energy in ethanol eventually comes from solar energy during the photosynthesis process. Overall, advanced SIDI engines achieve greater fossil energy reductions than conventional SI engines.

Figure 6.36 shows reductions in fossil energy use by SI and SIDI HEVs. The magnitude of reductions can be separated into two distinct levels. At the first level, reductions range from 35% to 50%. Fuels include those produced from fossil energy sources (i.e., petroleum and natural gas). The reductions here are attributable to fuel economy improvements of the vehicle technologies. At the second level, reductions in fossil energy use reach 70–90%. Fuels include those produced from renewable sources (corn and biomass for ethanol) and waste energy sources (landfill gas and flared gas for methanol). The reductions here are attributable to vehicle fuel economy improvements and use of non-fossil energy sources.

Figure 6.37 presents fossil energy reductions by CIDI vehicles and CIDI HEVs. Use of DME and FT50 in CIDI vehicles achieves about 20% reductions. The small reductions are caused by inefficiencies in DME and FTD production. Use of all the CI engine fuels in HEVs achieves greater-than-50% reductions in fossil energy use because of the significant increases in fuel economy by these vehicles.

Figure 6.38 shows reductions in fossil energy use by EVs and FCVs. Again, the reductions are at two distinct levels. At the first level, reductions between 50–60% are achieved. Vehicles at this level include EVs with the U.S. and Northeast U.S. electric generation mix and FCVs fueled with NG-based H_2, NG-based methanol, RFG, and CNG. Reductions by these vehicles are caused by improved vehicle fuel economy. The second level shows fossil energy reductions of 80–95%. Vehicles at this level include EVs with the California electric generation mix and FCVs fueled with H_2 from solar energy, landfill gas- and flared gas-based methanol, and ethanol. The additional reductions by these vehicles are attributable to use of renewable energy sources or waste energy sources.

Overall, the four figures show increased fossil energy reductions in the following order: SI, SIDI, CIDI, HEVs, EVs, and FCVs. Reductions are from two sources: improved vehicle fuel economy and substitution of fossil fuels (petroleum and natural gas) with non-fossil fuels (renewable and waste energy sources).

Figures 6.39 through 6.42 present petroleum use reductions by the long-term technology options. Figure 6.39 shows reductions by SI and SIDI vehicles. Use of petroleum-based LPG in SI vehicles has little effect on petroleum use. Use of RFG in SIDI vehicles achieves about a 20% reduction because of SIDI efficiency gains. Use of non-petroleum fuels achieves 80% to almost 100% reductions. The reductions of around 80% by M90 and E90 are attributable to the fact that 10% gasoline is used in these fuel blends. Figure 6.40 indicates petroleum use reductions by SI and SIDI HEVs. Introduction of HEVs helps increase petroleum reductions (compare with Figure 6.39). For example, use of M90 and E90 in HEVs can now achieve over 90% reductions. Figure 6.41 shows reductions by CIDI engines in standalone and hybrid applications. While improved fuel economy helps reduce petroleum use for all of the cases, use of non-petroleum fuels achieves further reductions. Note that the reductions with FT50 and BD20 are smaller because petroleum-based diesel is used in both blends. Figure 6.42 presents

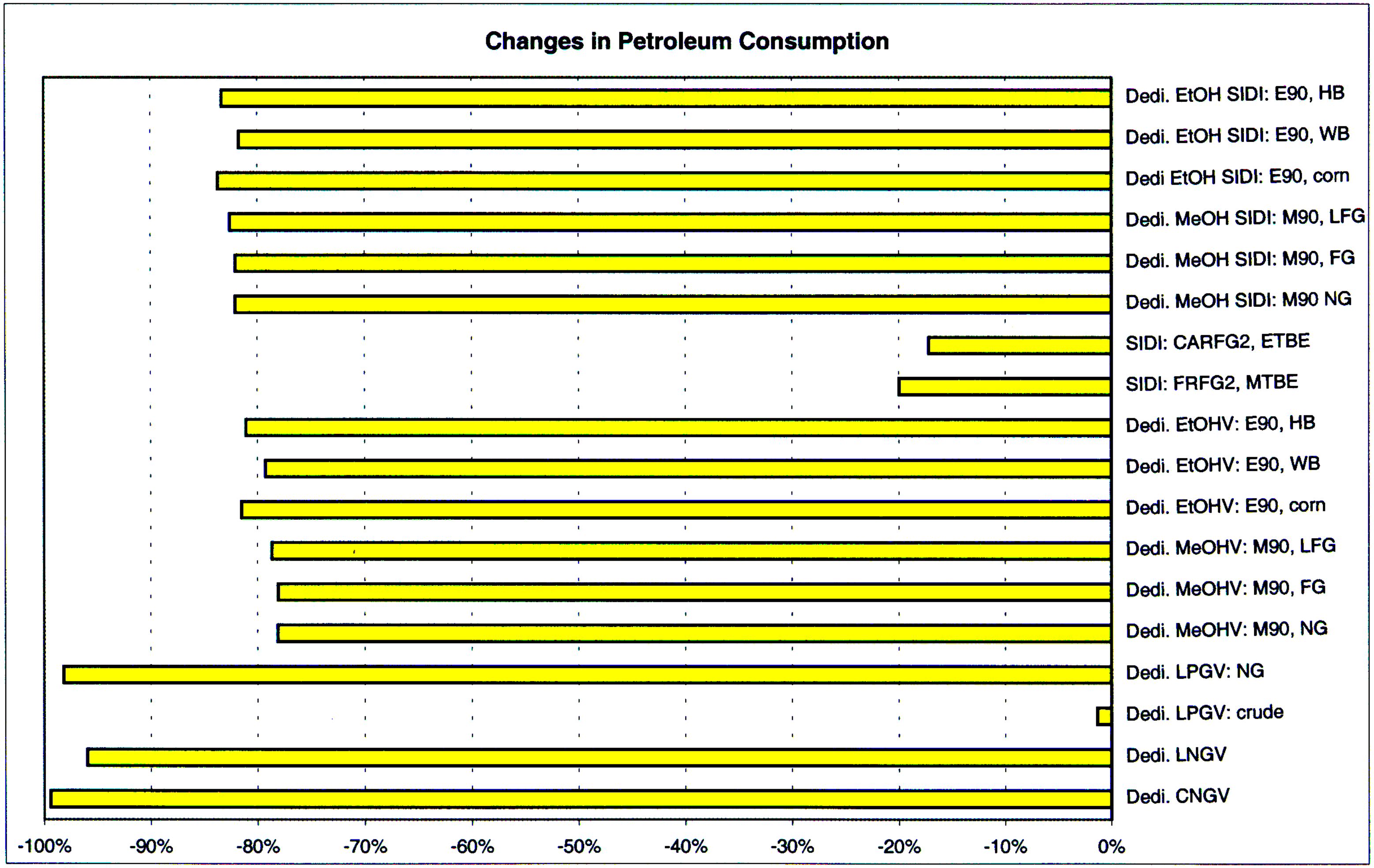

Figure 6.39 Changes in Fuel-Cycle Petroleum Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

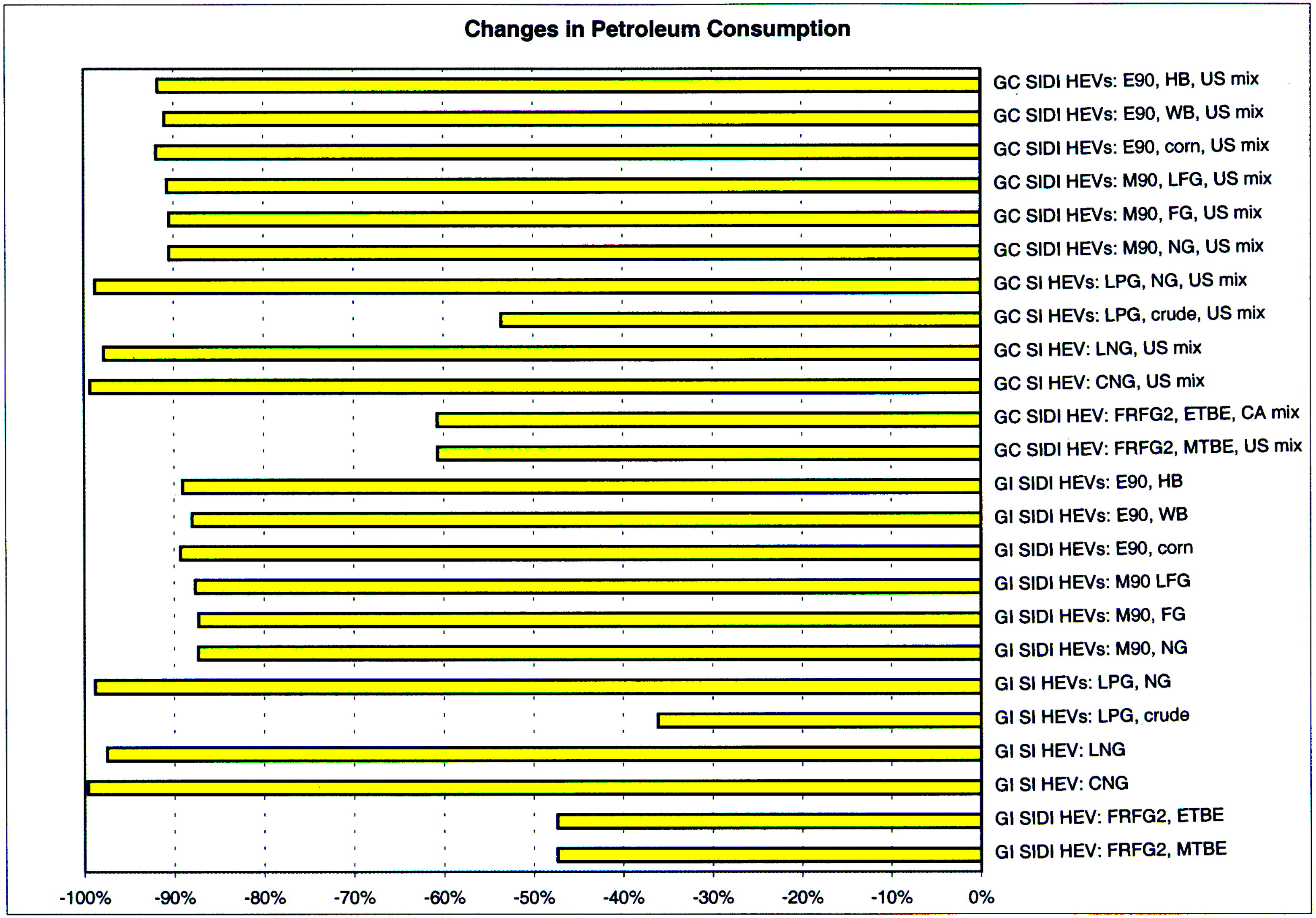

Figure 6.40 Changes in Fuel-Cycle Petroleum Use Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

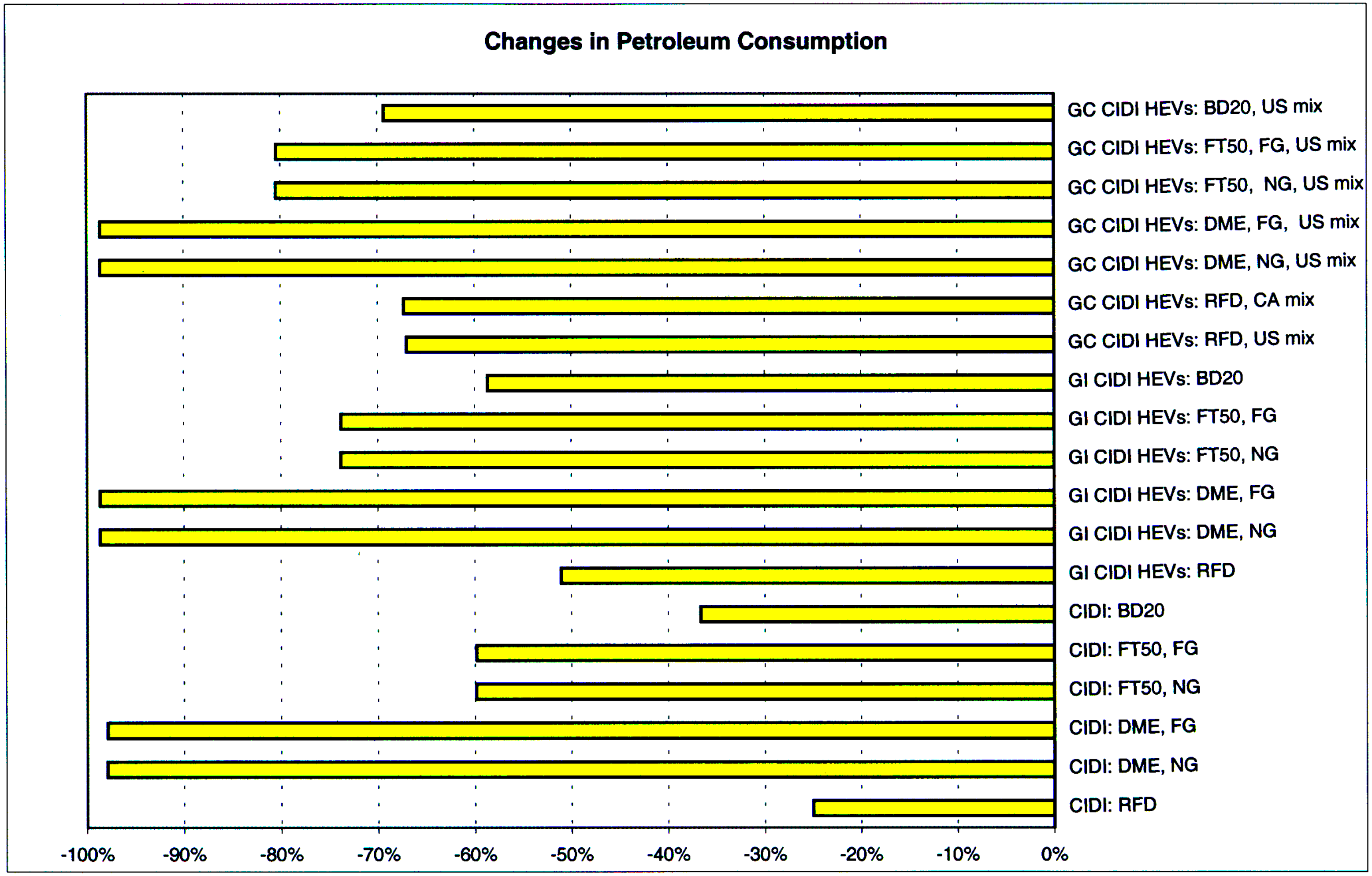

Figure 6.41 Changes in Fuel-Cycle Petroleum Use Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

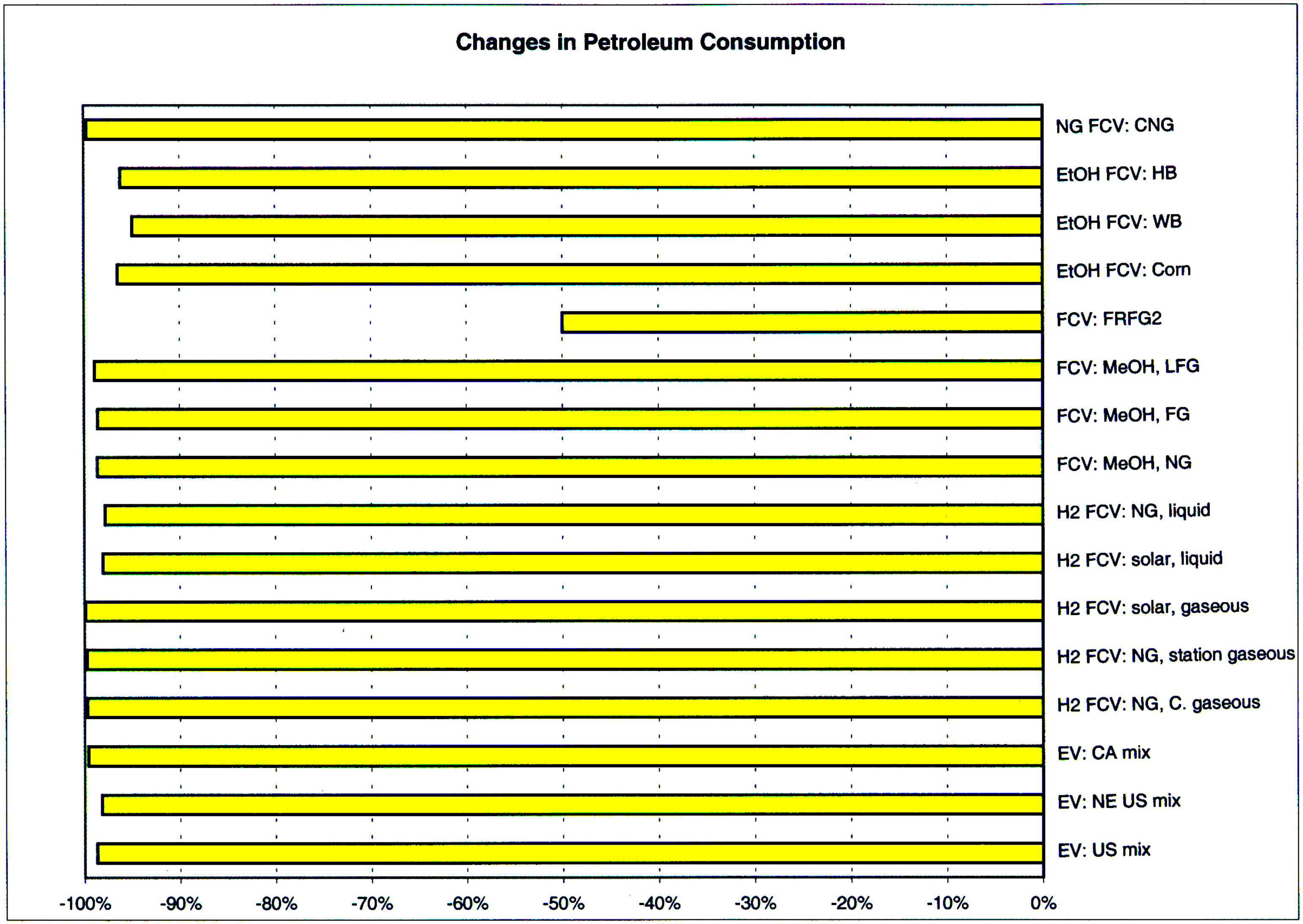

Figure 6.42 Changes in Fuel-Cycle Petroleum Use Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

results for EVs and FCVs. Except for FCVs fueled with RFG, all of these cases nearly eliminate petroleum use.

Again, the four figures show the increased benefits in petroleum reductions from SI engines to SIDI engines, to CIDI engines, to HEVs, to EVs, and to FCVs and the benefits of switching from petroleum-based to non-petroleum-based fuels.

Figures 6.43 through 6.46 present reductions in CO_2-equivalent GHG emissions by the long-term technologies. GHG emissions here include emissions of CO_2, CH_4, and N_2O. These emissions were converted into CO_2-equivalent emissions by using IPCC-adopted GWPs (1 for CO_2, 21 for CH_4, and 310 for N_2O). Figure 6.43 shows GHG emission reductions by SI and SIDI vehicles. Use of CNG, LNG and LPG in SI engines and RFG and M90 in SIDI engines achieves 20–25% reductions. Use of M90 in SI engines achieves about a 10% reduction. Use of ethanol made from corn reduces GHG emissions by 40–45%. Use of cellulosic ethanol and flared gas-based methanol results in 80–100% reductions. Use of landfill gas-based methanol reduces GHG emissions by over 140%. The large reductions by cellulosic ethanol are attributable to CO_2 sequestration during the photosynthesis process and to the GHG emission credits for the extra electricity generated in cellulosic ethanol plants. The large reductions by flared gas- and landfill gas-based methanol are attributable to elimination of CH_4 venting and CO_2 combustion emissions associated with gas flaring.

Figure 4.44 shows GHG emission reductions by SI and SIDI HEVs. Use of fossil energy-based fuels (RFG, CNG, LNG, LPG, and NG-based methanol) achieves around 50% reductions, mainly because of improved vehicle fuel economy. Use of fuels produced from renewable or waste energy sources results in much higher reductions. GC HEVs with the California electric generation mix achieve greater reductions than GI HEVs.

Figure 4.45 presents GHG emission reductions by CIDI vehicles and CIDI HEVs. Use of RFD, FT50, and BD20 in CIDI standalone vehicles reduces GHG emissions by 30–40%. Hybridization of CIDI engines helps increase GHG emission reductions to above 50%. Use of DME and FTD produced from flared gas reduces GHG emissions even further.

Figure 4.46 shows GHG emission reductions by EVs and FCVs. EVs with the U.S. electric generation mix and FCVs powered by RFG achieve about 50% reductions. EVs with the Northeast U.S. and California generation mixes achieve additional reductions. FCVs fueled with NG-based H_2, NG-based methanol, corn-based ethanol, and CNG achieve 60–70% reductions. Use of solar H_2, flare gas- and landfill gas-based methanol, and cellulosic ethanol in FCVs results in over-90% reductions.

Overall, large GHG emission reductions are achieved by using advanced engine and vehicle technologies that have much higher fuel economy than baseline GVs and by switching from fossil energy-based fuels to renewable fuels. The results here quantitatively show the effects of fuel economy improvements and alternative fuels on motor vehicle GHG emissions. The four figures also show the differences in CO_2 and GHG emission reductions. If CH_4 and N_2O emissions are not included (as for CO_2 emission changes only), GHG emission reductions by NG-based fuels and ethanol would be overestimated. This is because a significant amount of

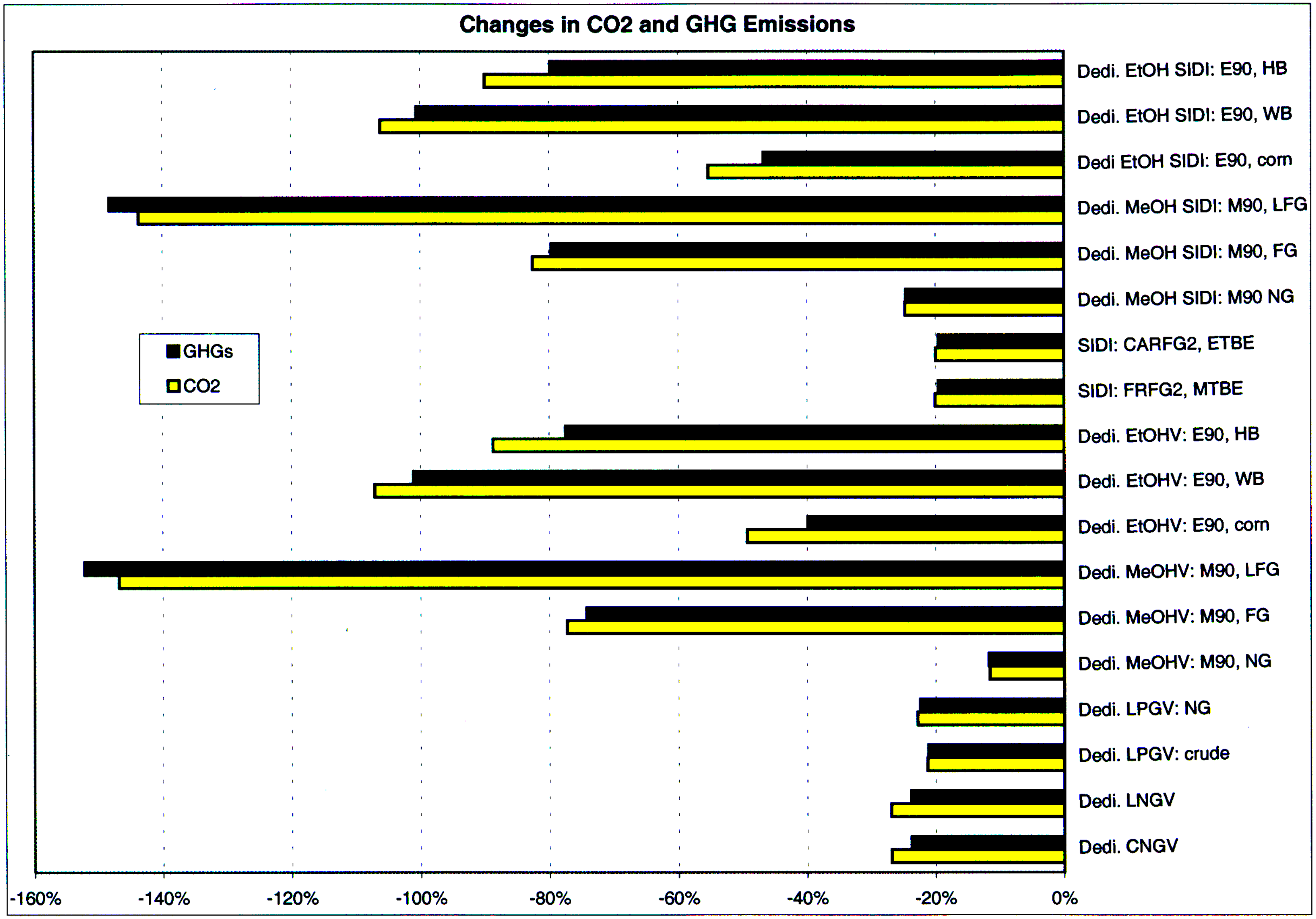

Figure 6.43 Changes in Fuel-Cycle CO_2-Equivalent GHG Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

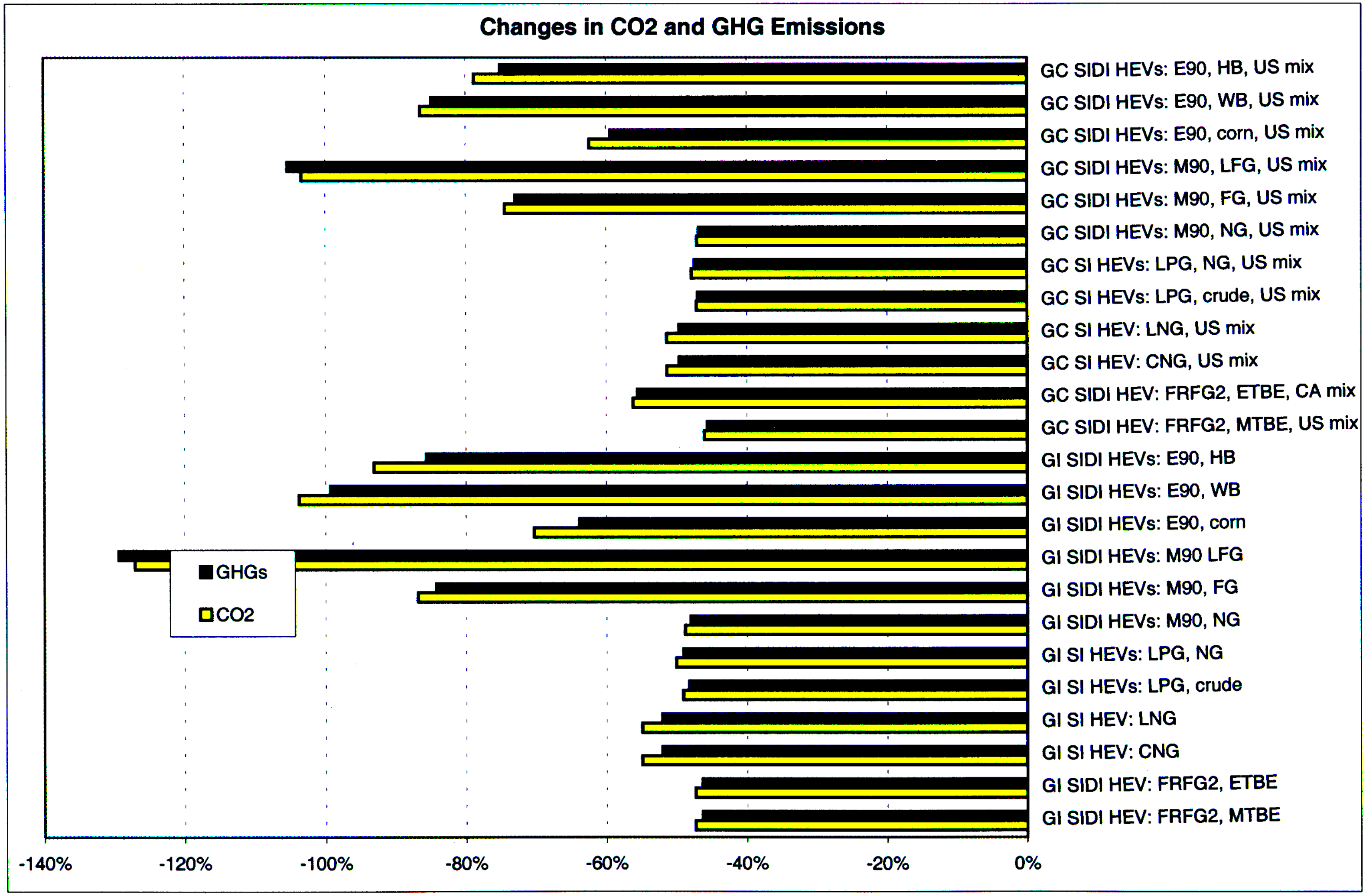

Figure 6.44 Changes in Fuel-Cycle CO_2-Equivalent GHG Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

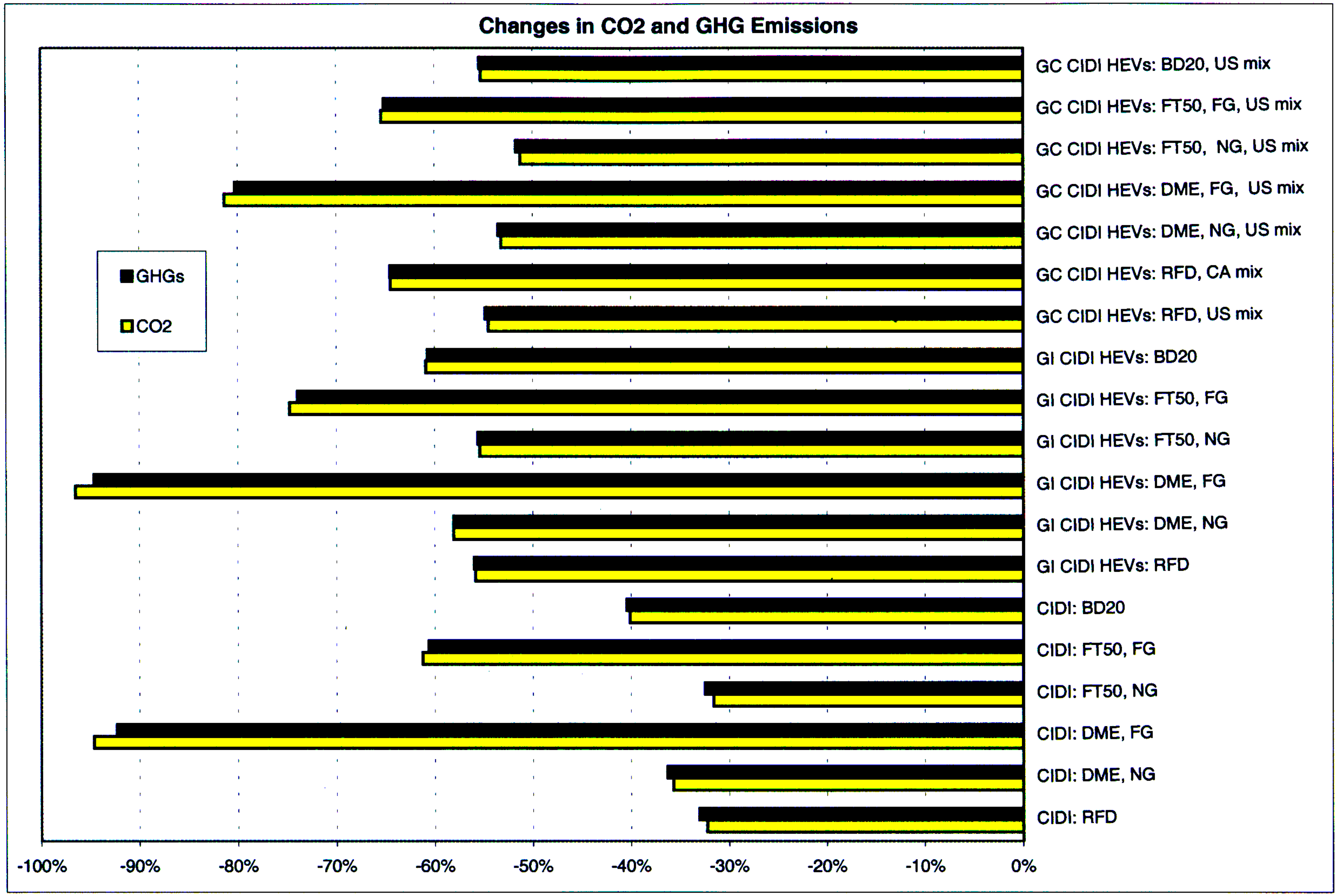

Figure 6.45 Changes in Fuel-Cycle CO_2-Equivalent GHG Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

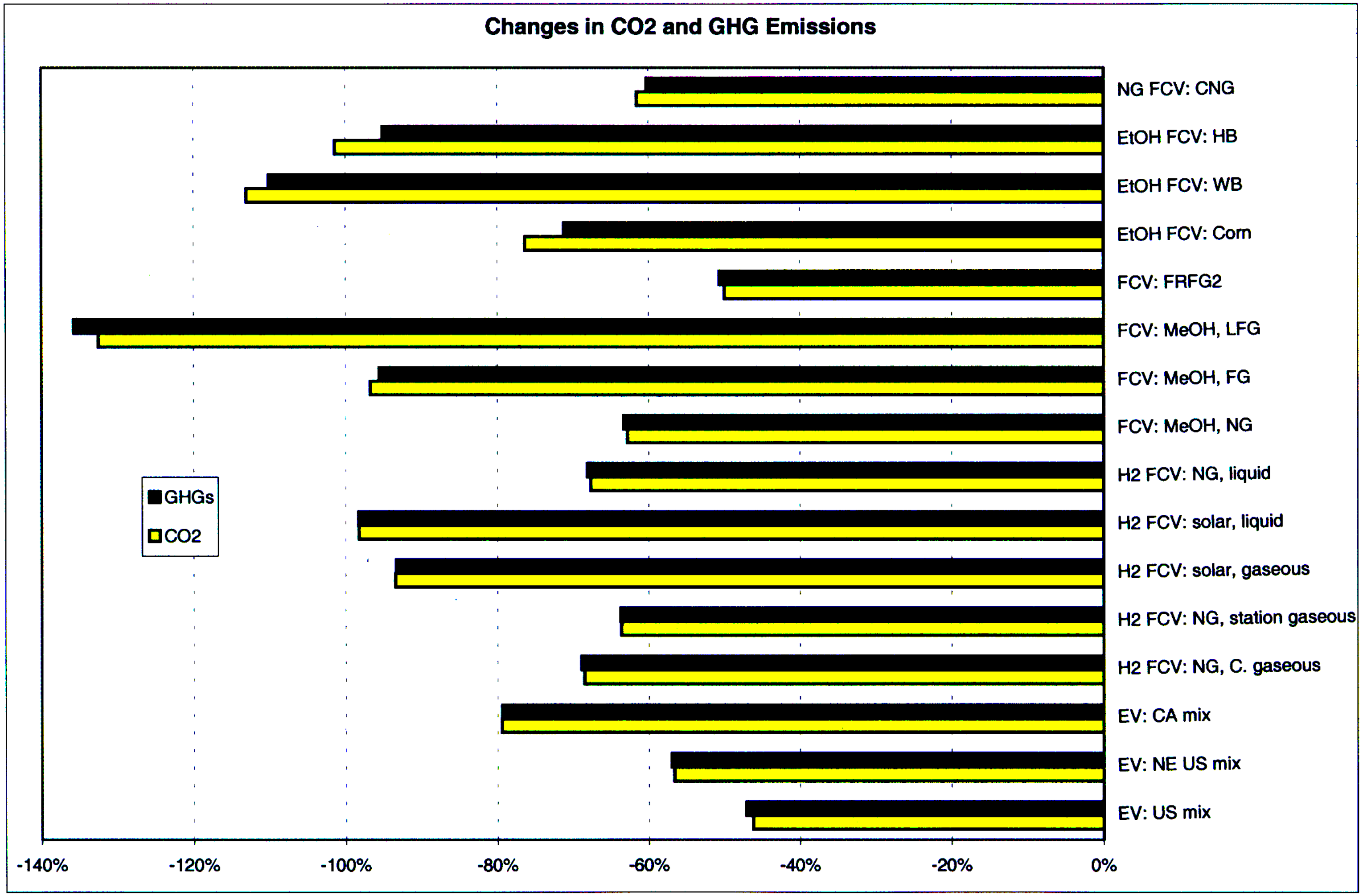

Figure 6.46 Changes in Fuel-Cycle CO_2-Equivalent GHG Emissions Relative to GVs Fueled with RFG: Long-Term EVs and HEVs

CH_4 emissions are associated with NG-based fuel pathways, and a significant amount of N_2O emissions results from nitrification and denitrification of nitrogen fertilizers in cornfields and biomass farms.

Figures 6.47 through 6.50 present changes in total and urban VOC emissions by the long-term technologies. For the five criteria pollutants, total emissions include emissions from fuel-cycle activities occurring everywhere, while urban emissions include emissions that occur only within urban areas; upstream emissions occurring outside of urban areas are excluded. Figure 6.47 shows VOC emission changes by SI and SIDI vehicles. Total VOC emissions are increased substantially by corn-based ethanol because of the VOC emissions from tractors used for corn farming and from ethanol production in ethanol plants. On the other hand, total VOC emissions are reduced by nearly 150% for flared gas-based methanol, which eliminates the VOC emissions associated with gas flaring during methanol production. Use of CNG, LNG, and LPG achieves 40–60% reductions in VOC emissions, primarily because VOC evaporative emissions from baseline gasoline vehicles are eliminated. VOC emission reductions by M90 and E90 vehicles are limited because these fuels still produce evaporative emissions.

Figure 6.48 presents VOC emission changes for SI and SIDI HEVs. Again, total VOC emissions are increased for corn-based ethanol, although the increase is much smaller. Total VOC emissions are significantly reduced by using flared gas-based methanol, which eliminates VOC emissions from gas flaring. Use of CNG, LNG, and LPG achieves about 50% reductions for GI HEVs and about 70% reductions for GC HEVs. In general, use of HEVs reduces both total and urban VOC emissions because of the vehicles' improved fuel economy, which helps reduce both upstream and vehicle evaporative emissions.

Figure 6.49 shows that use of CIDI standalone vehicles and CIDI HEVs achieves VOC emission reductions ranging from 40% to 80%, relative to use of GVs. The reductions result from elimination of GV evaporative emissions by CI fuels. Note that use of flared gas-based DME and FTD achieves huge reductions in total VOC emissions.

As Figure 6.50 shows, EVs and FCVs achieve uniform VOC emission reductions. Reductions by EVs and H_2- and CNG-fueled FCVs are almost 100% because these vehicles generate no tailpipe or evaporative VOC emissions. Reductions by FCVs fueled with methanol, ethanol, and gasoline are smaller because these fuels produce evaporative emissions, despite zero exhaust emissions.

Overall, the magnitude of VOC emission reductions is in the following order (from small to large): SI and SIDI standalone vehicles, SI and SIDI HEVs, CIDI vehicles and CIDI HEVs, and FCVs.

Figures 6.51 through 6.54 show changes in total and urban CO emissions by the long-term technology options. In Figure 6.51, use of CNG, LNG, and LPG reduces CO emissions by about 20%. Use of ethanol results in increased total CO emissions because of the high CO emissions associated with tractors used during farming and with ethanol production. Use of landfill gas-based methanol helps reduce both total and urban CO emissions by eliminating CO emissions from landfill gas burning. Other fuel options have little effect on CO emissions.

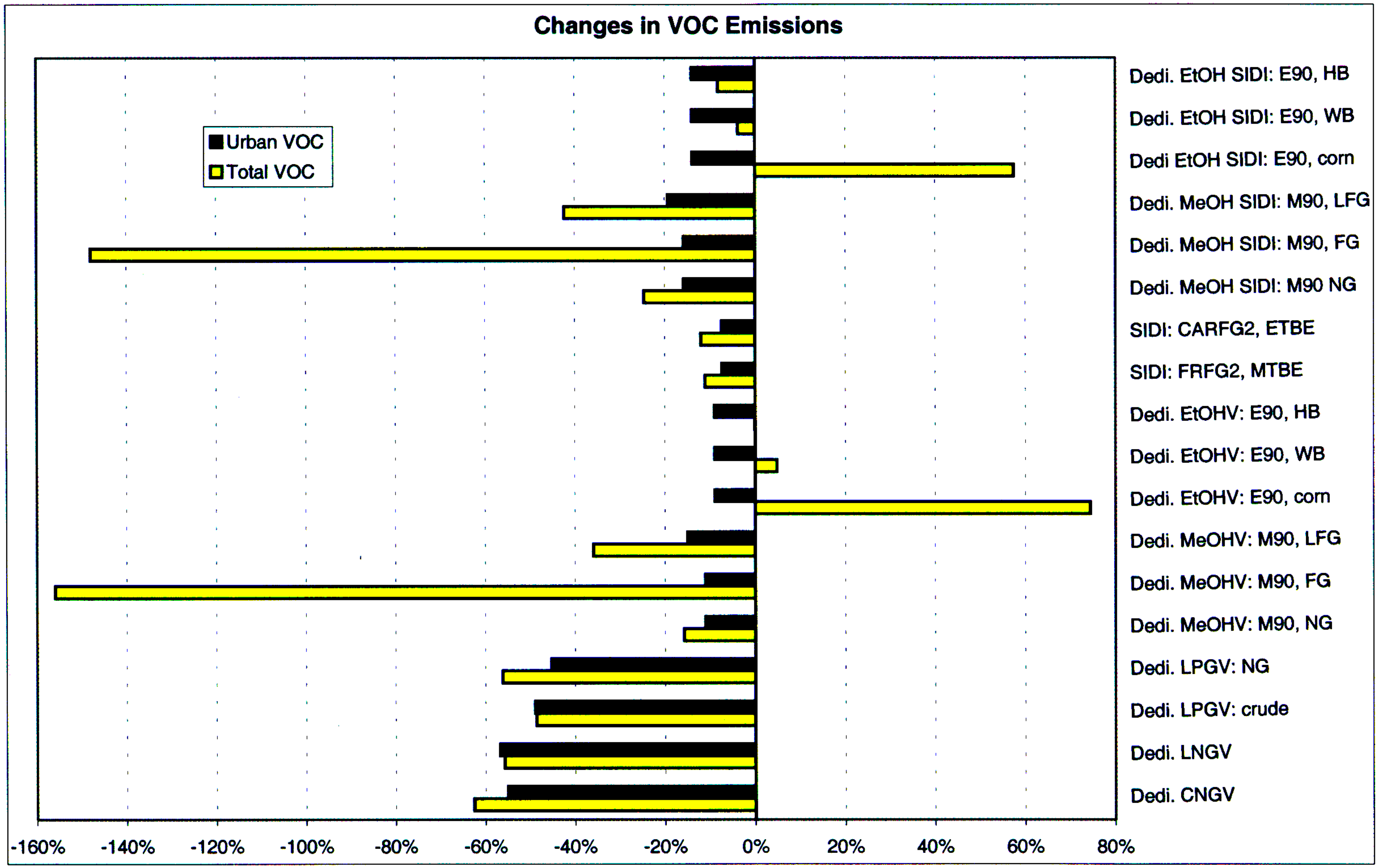

Figure 6.47 Changes in Fuel-Cycle Total and Urban VOC Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

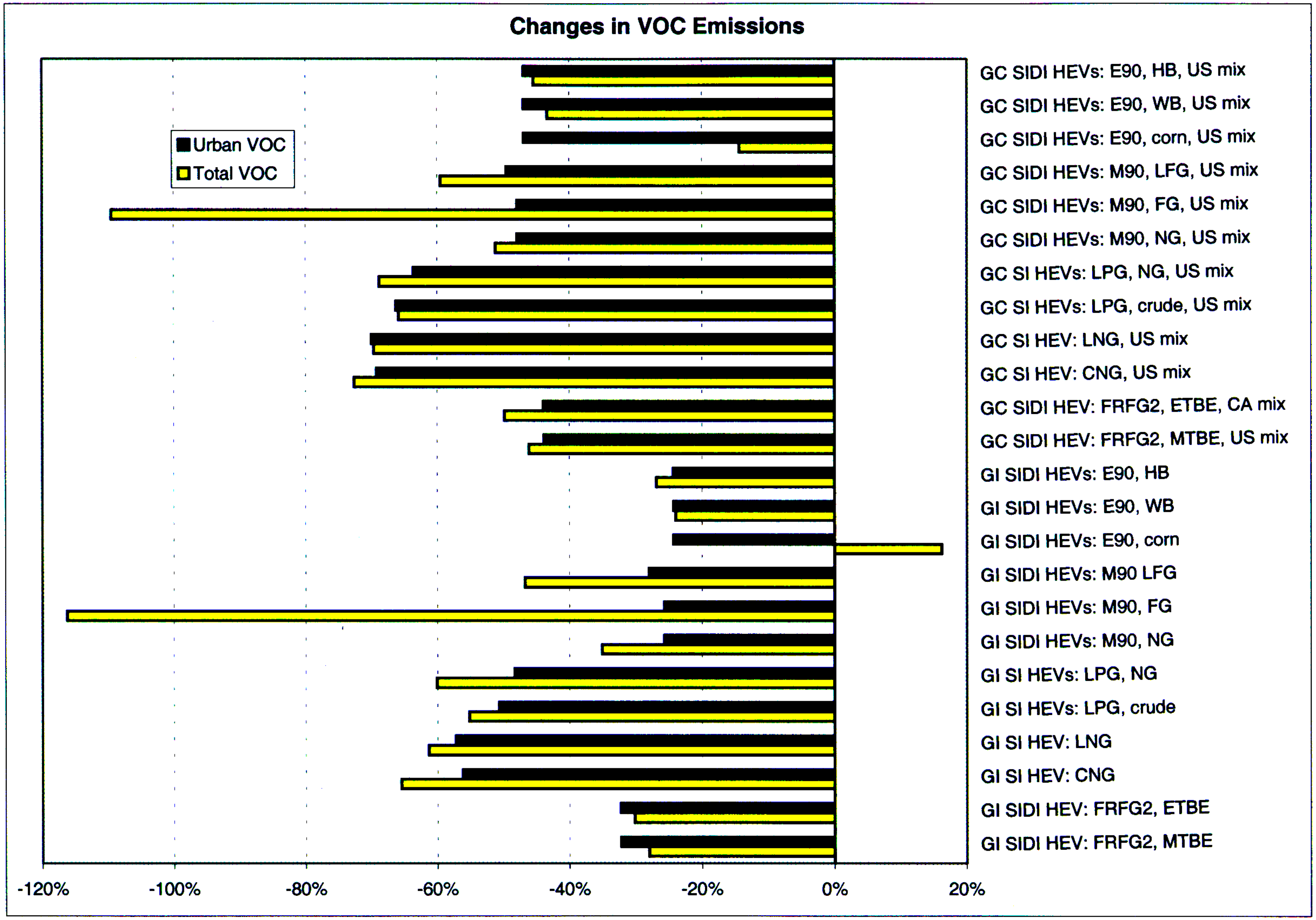

Figure 6.48 Changes in Fuel-Cycle Total and Urban VOC Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

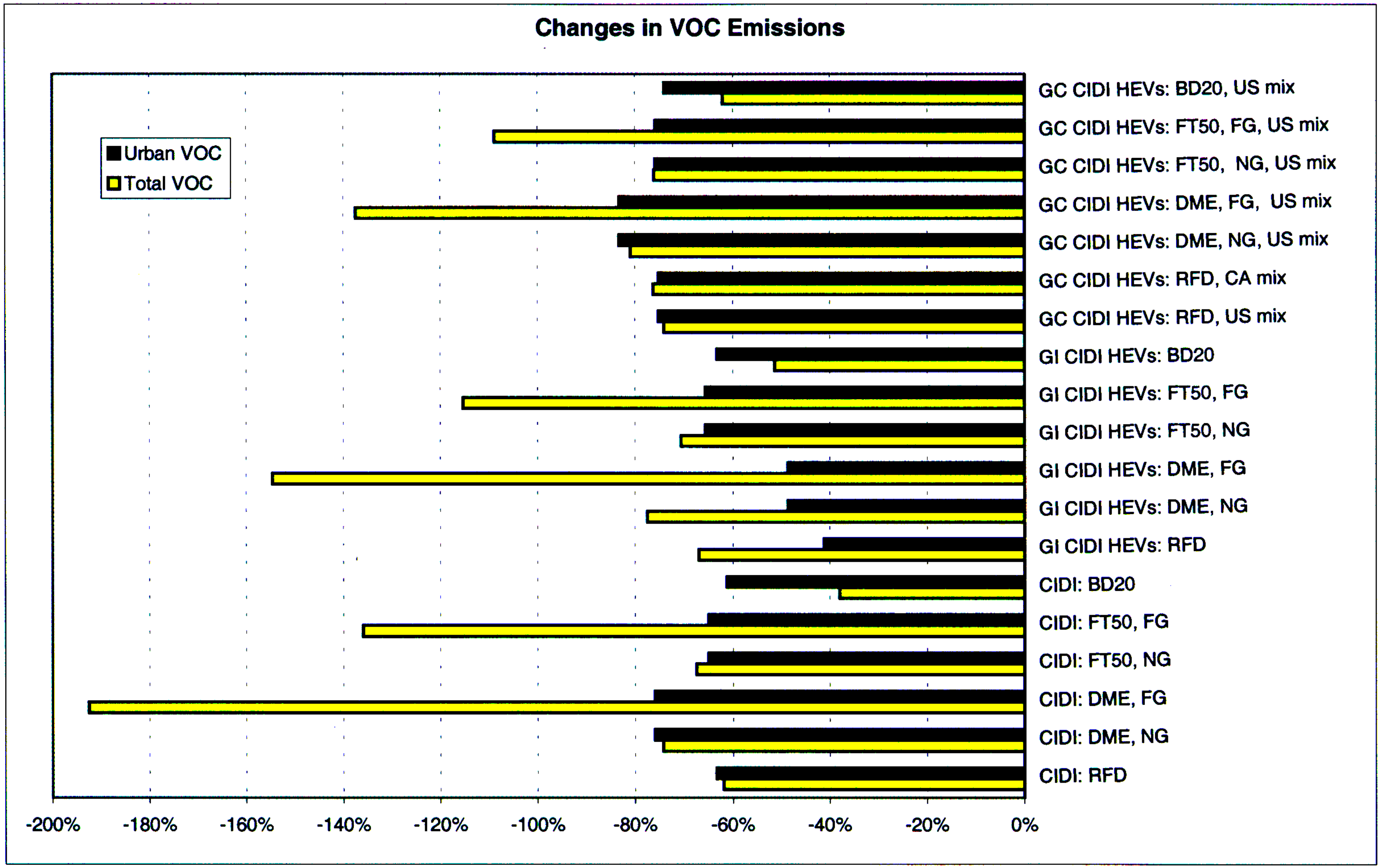

Figure 6.49 Changes in Fuel-Cycle Total and Urban VOC Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

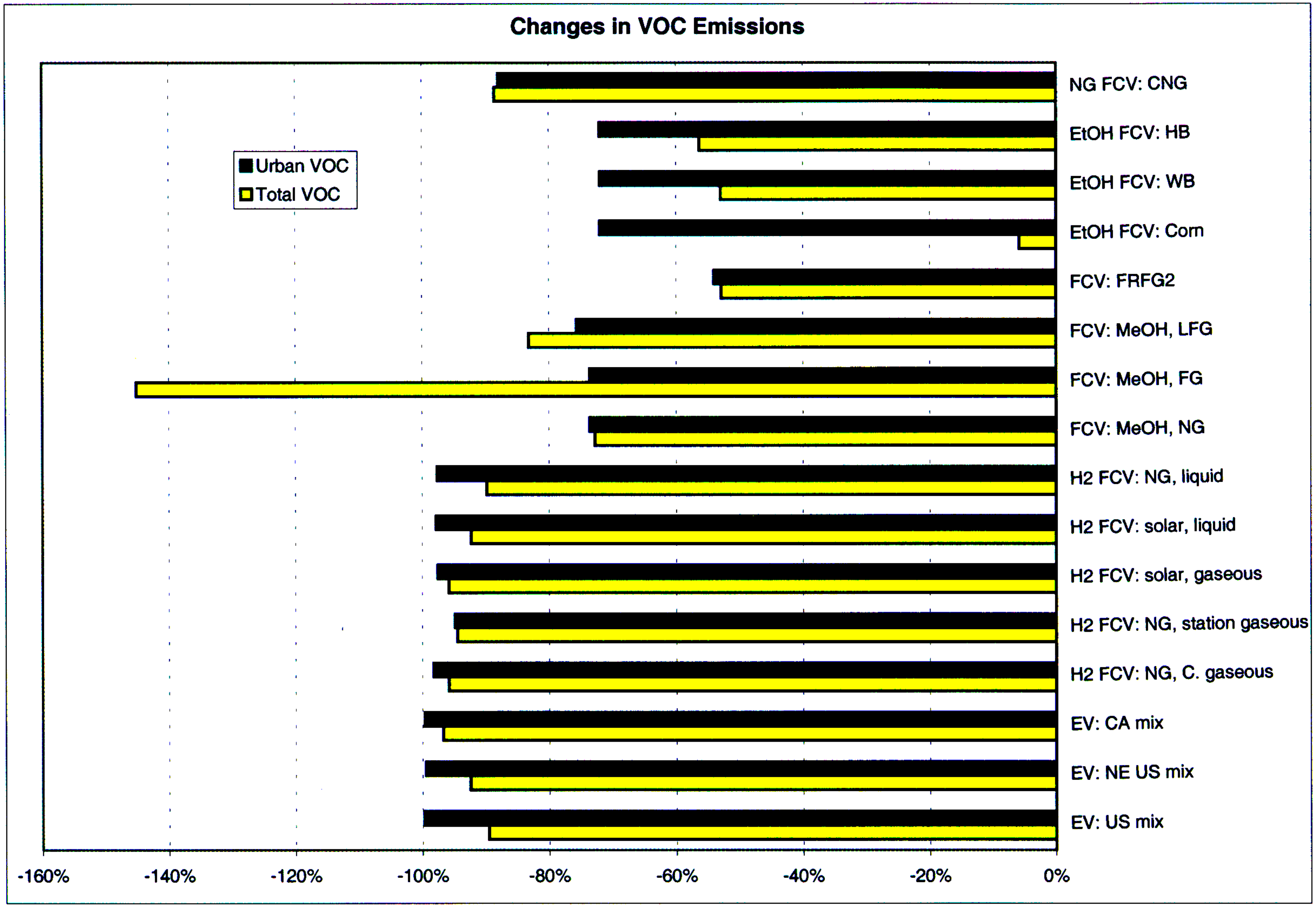

Figure 6.50 Changes in Fuel-Cycle Total and Urban VOC Emissions Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

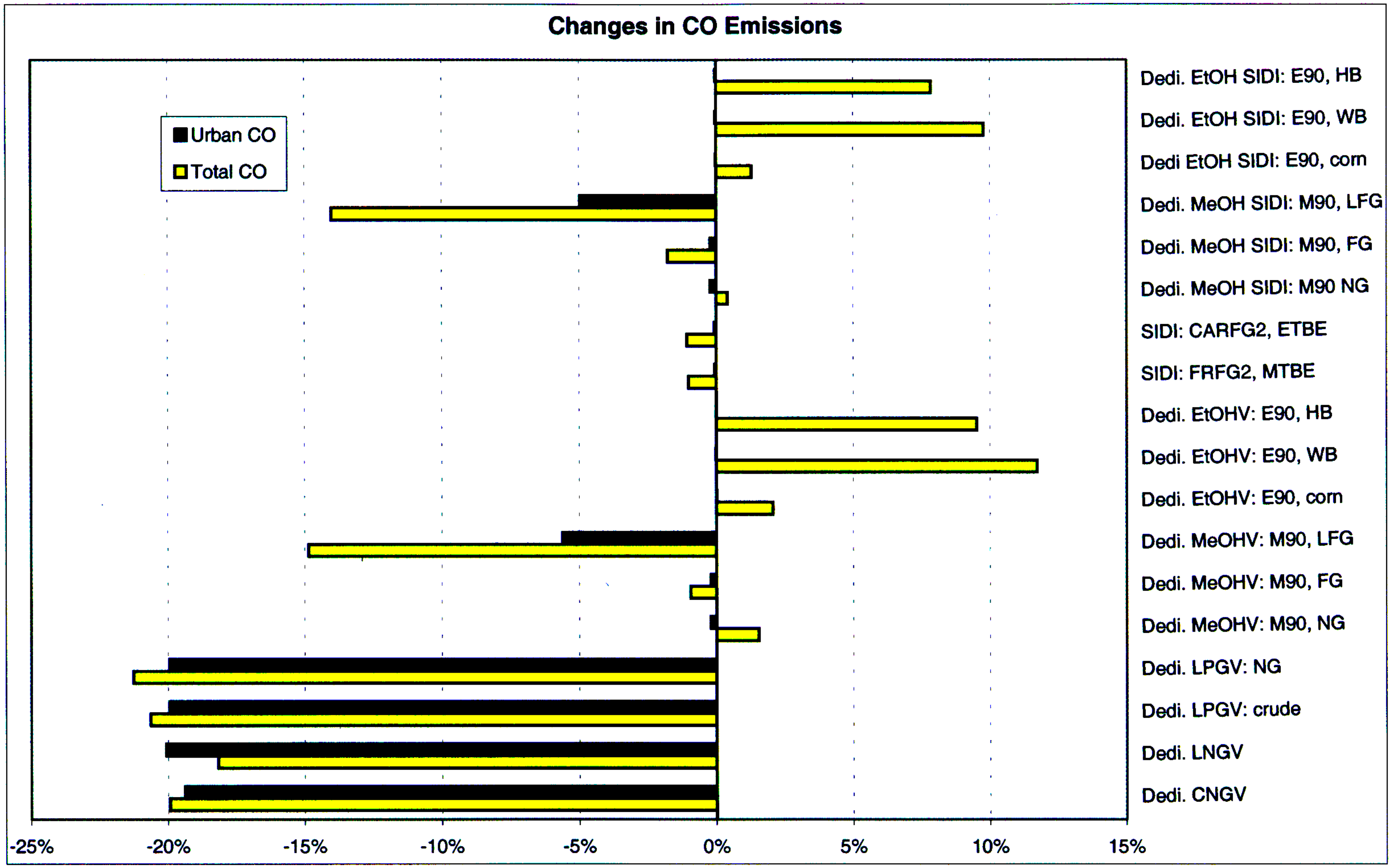

Figure 6.51 Changes in Fuel-Cycle Total and Urban CO Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

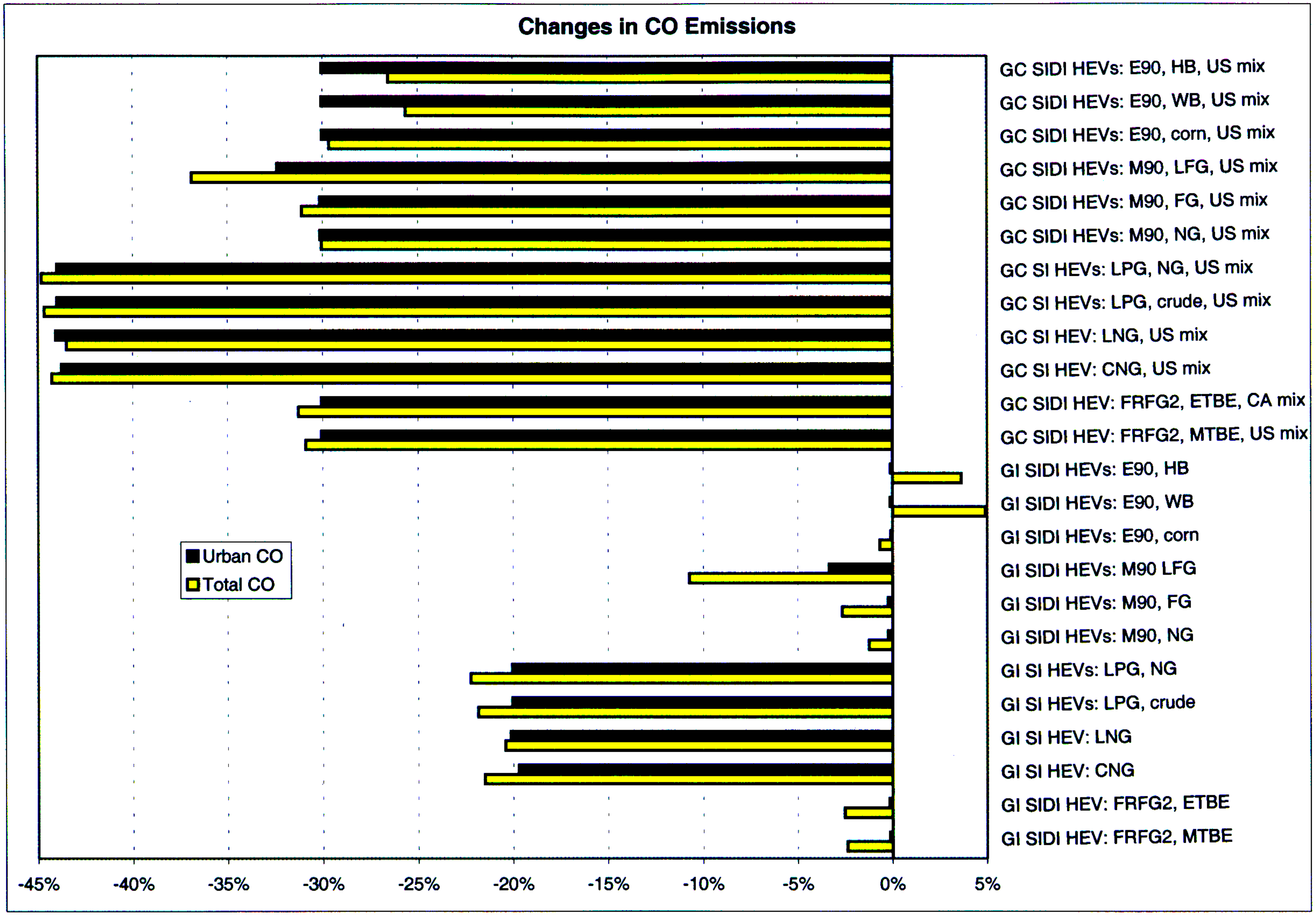

Figure 6.52 Changes in Fuel-Cycle Total and Urban CO Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

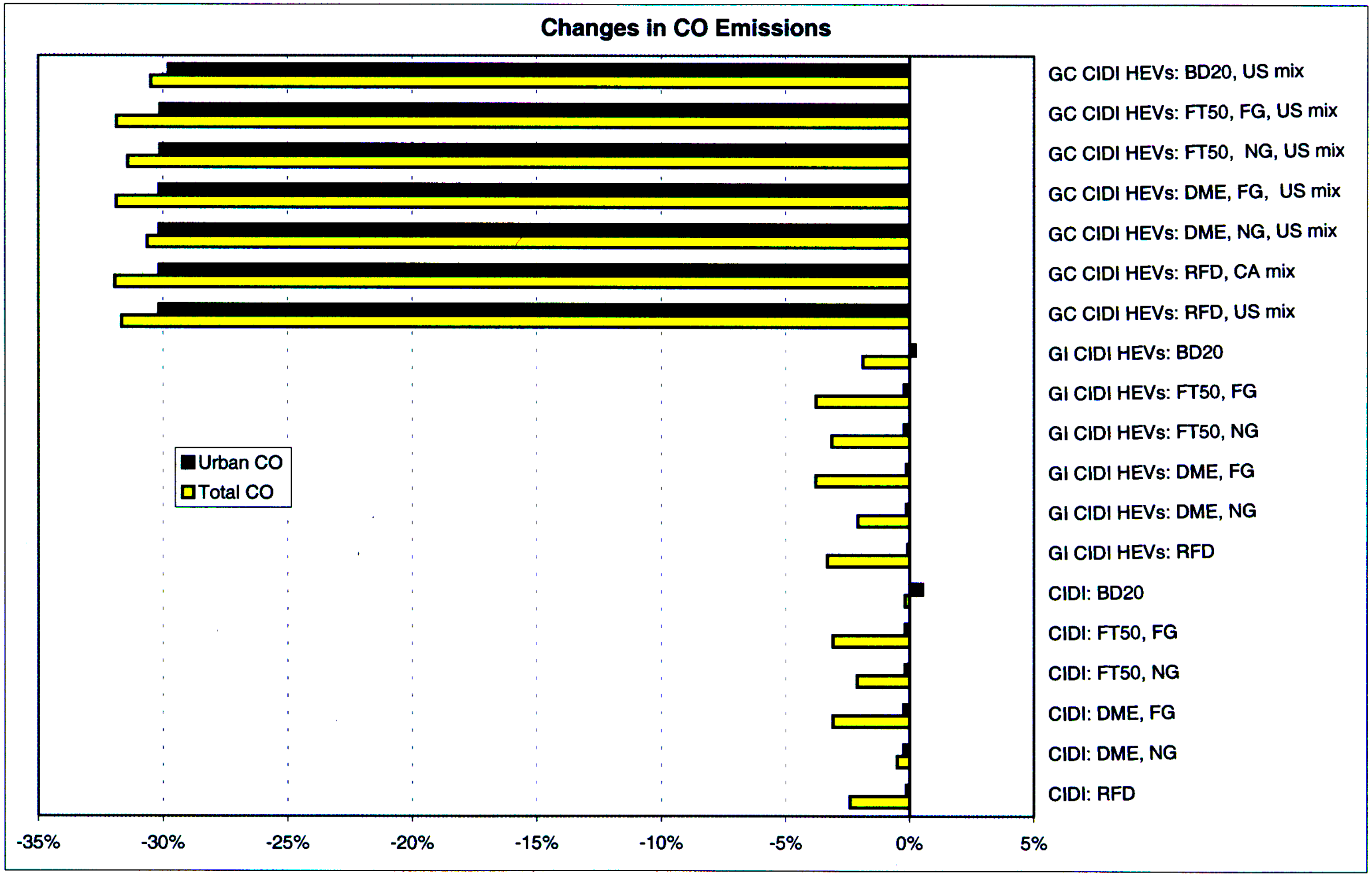

Figure 6.53 Changes in Fuel-Cycle Total and Urban CO Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

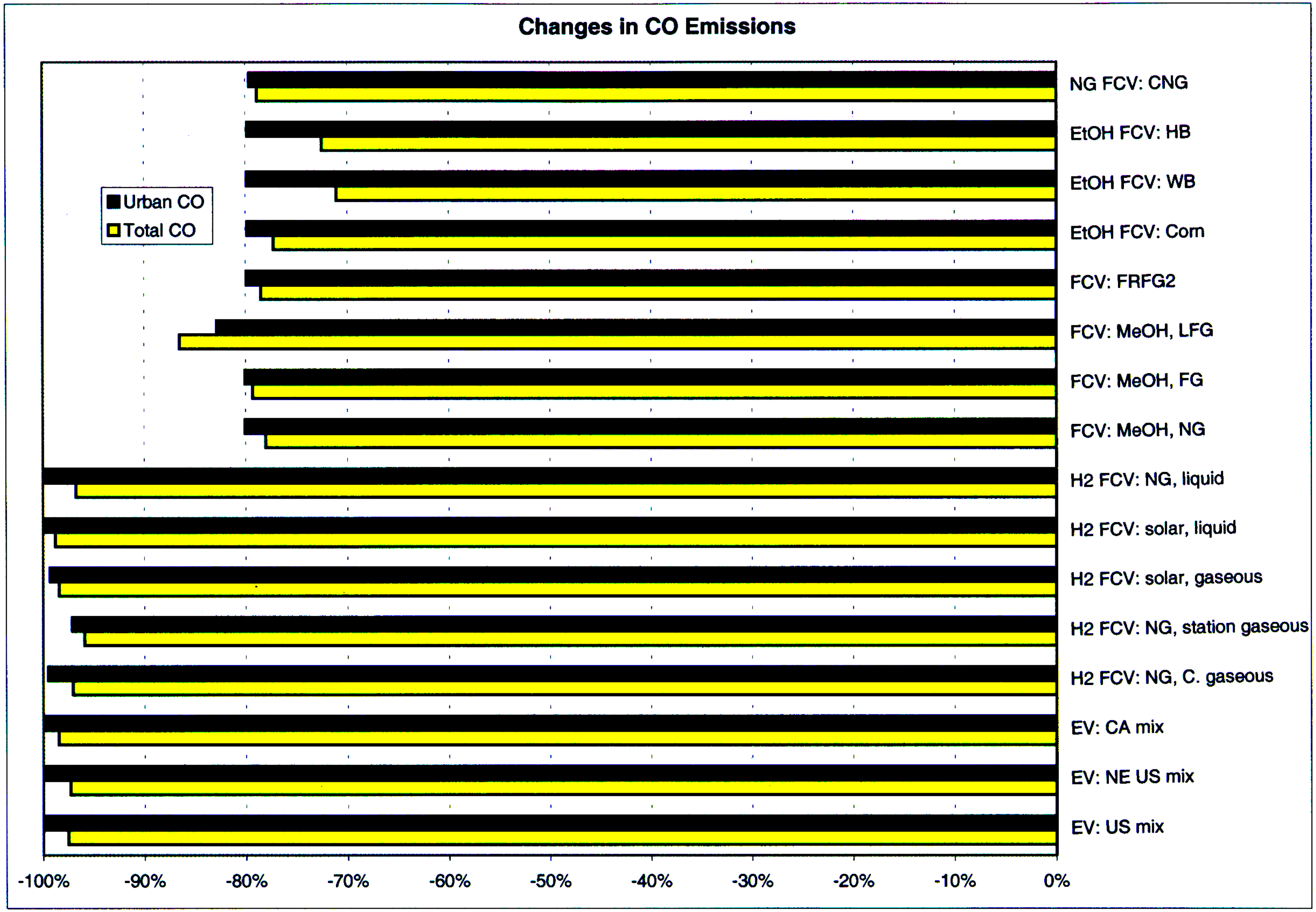

Figure 6.54 Changes in Fuel-Cycle Total and Urban CO Emissions Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

Figure 6.52 shows that use of CNG, LNG, and LPG in SI HEVs achieves 20–40% reductions in total and urban CO emissions. Use of methanol and ethanol has little effect on CO emissions. The figure shows that GC HEVs achieve consistently higher CO emission reductions than GI HEVs.

Figure 6.53 presents CO emission changes for CIDI standalone and hybrid vehicles. Use of CIDI standalone vehicles and CIDI GI HEVs has little effect on CO emissions, especially urban CO emissions. GC HEVs achieve about 30% reductions in CO emissions. The reductions are from the miles traveled on grid electricity for these HEVs. Note that in our GREET simulations (see Section 5), we assume that 30% of the total VMT for GC HEVs are powered by grid electricity.

Figure 6.54 shows CO emission reductions by EVs and FCVs. EVs and H_2-fueled FCVs almost eliminate CO emissions; they are true zero-emission vehicles. FCVs powered with methanol, ethanol, gasoline, and CNG achieve about 80% reductions in CO emissions. The CO emission reductions by these fuels are lower because of emissions associated with on-board fuel processing.

Figures 6.55 through 6.58 present changes in total and urban NO_x emissions for the long-term technology options. Figure 6.55 shows that NO_x emissions for some of the SI and SIDI vehicle options may increase significantly. For example, total NO_x emissions from use of ethanol increase 100–200% because of emissions during farming (tractors and nitrification and denitrification of nitrogen fertilizer) and emissions associated with diesel locomotives and trucks for ethanol transportation and distribution. Use of CNG can result in increased total and urban NO_x emissions caused by emissions from NG compressors in CNG refueling stations (we assumed that one half of the compressors used are electric and the remainder are powered by NG). Use of LNG increases total NO_x emissions, primarily because of emissions from diesel locomotives and diesel trucks used for LNG transportation and distribution. Use of LPG and methanol reduces NO_x emissions slightly. Use of landfill gas-based methanol achieves large reductions because landfill gas burning is eliminated.

Figure 6.56 presents changes in NO_x emissions by SI and SIDI HEVs. The general patterns in NO_x emissions for these vehicle options are similar to those for SI and SIDI vehicles (as shown in Figure 6.55). That is, use of ethanol could increase total NO_x emissions and use of CNG could lead to increased urban NO_x emissions. For other fuels such as LPG, methanol, and RFG, use of HEVs results in moderate reductions in NO_x emissions. Large reductions are achieved with use of flared gas- and landfill gas-based methanol. Use of GC HEVs achieves greater NO_x emission reductions than use of GI HEVs.

Figure 6.57 shows changes in NO_x emissions by CIDI vehicles and CIDI HEVs. In general, these vehicle options have higher urban NO_x emissions than baseline GVs, except GC HEVs, which generate NO_x emissions at levels similar to those of baseline GVs. Most vehicle options reduce total NO_x emissions because the amount of emissions from petroleum refining is larger than the amount from producing these CI fuels.

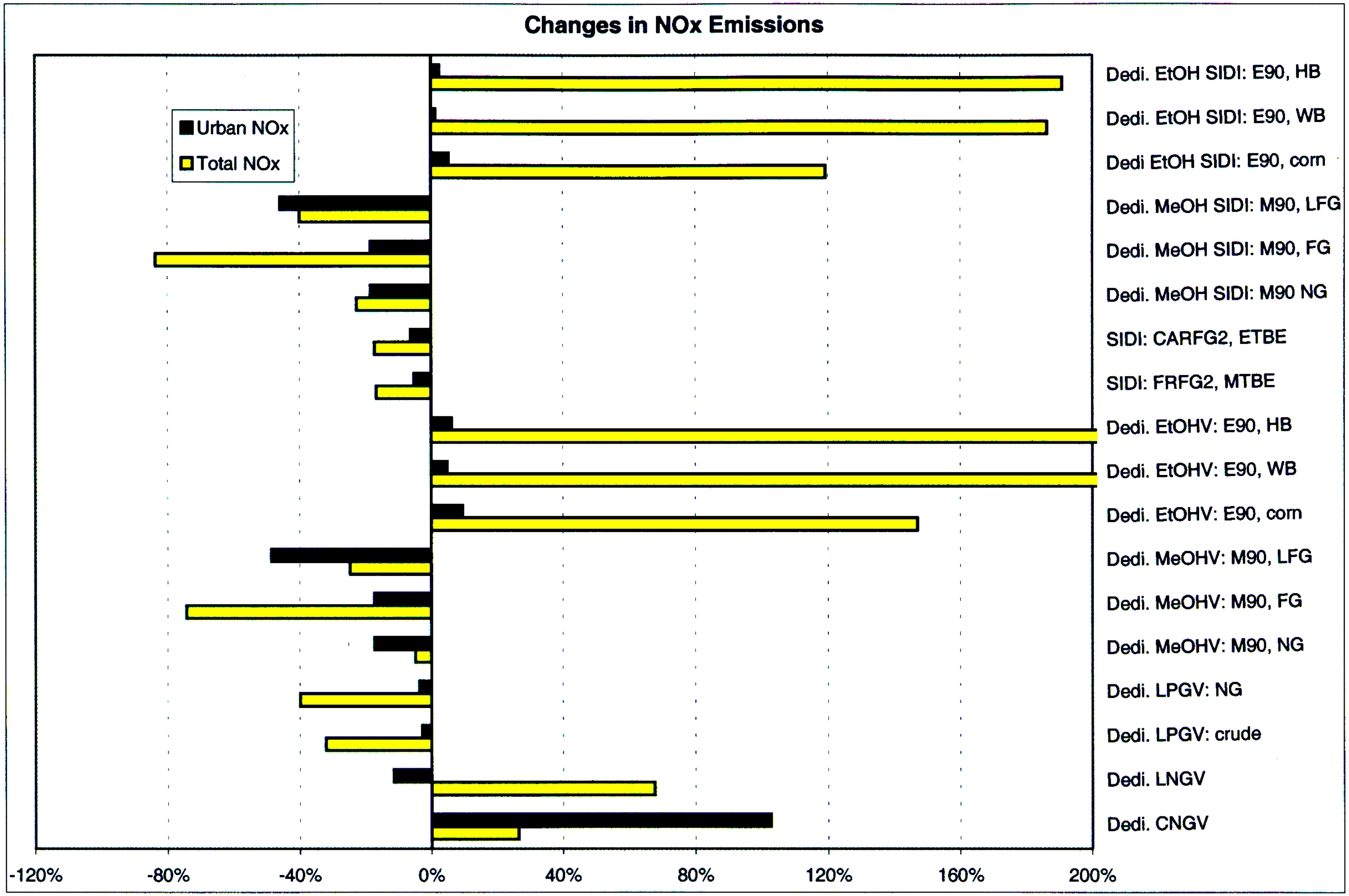

Figure 6.55 Changes in Fuel-Cycle Total and Urban NO_x Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

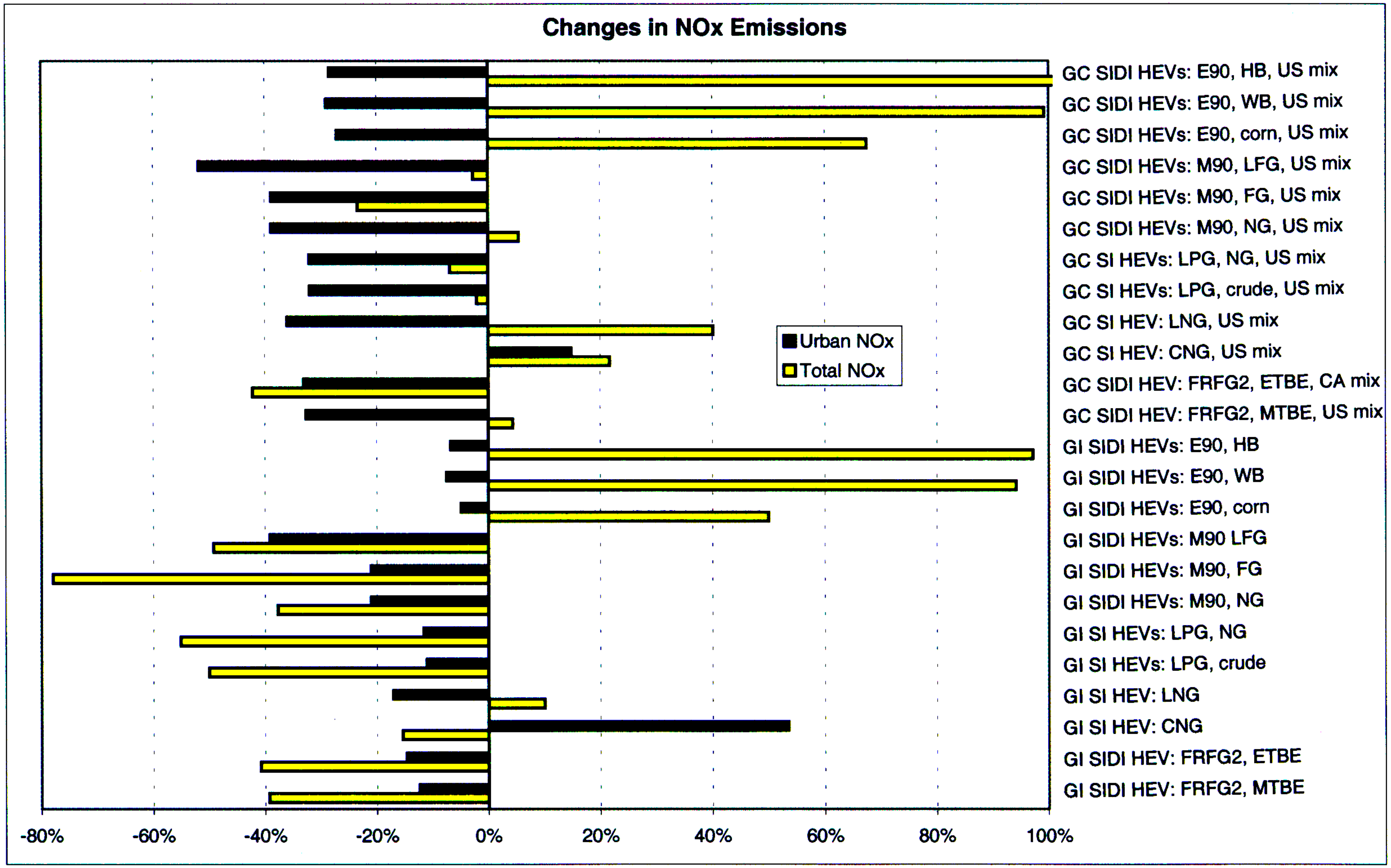

Figure 6.56 Changes in Fuel-Cycle Total and Urban NO_x Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

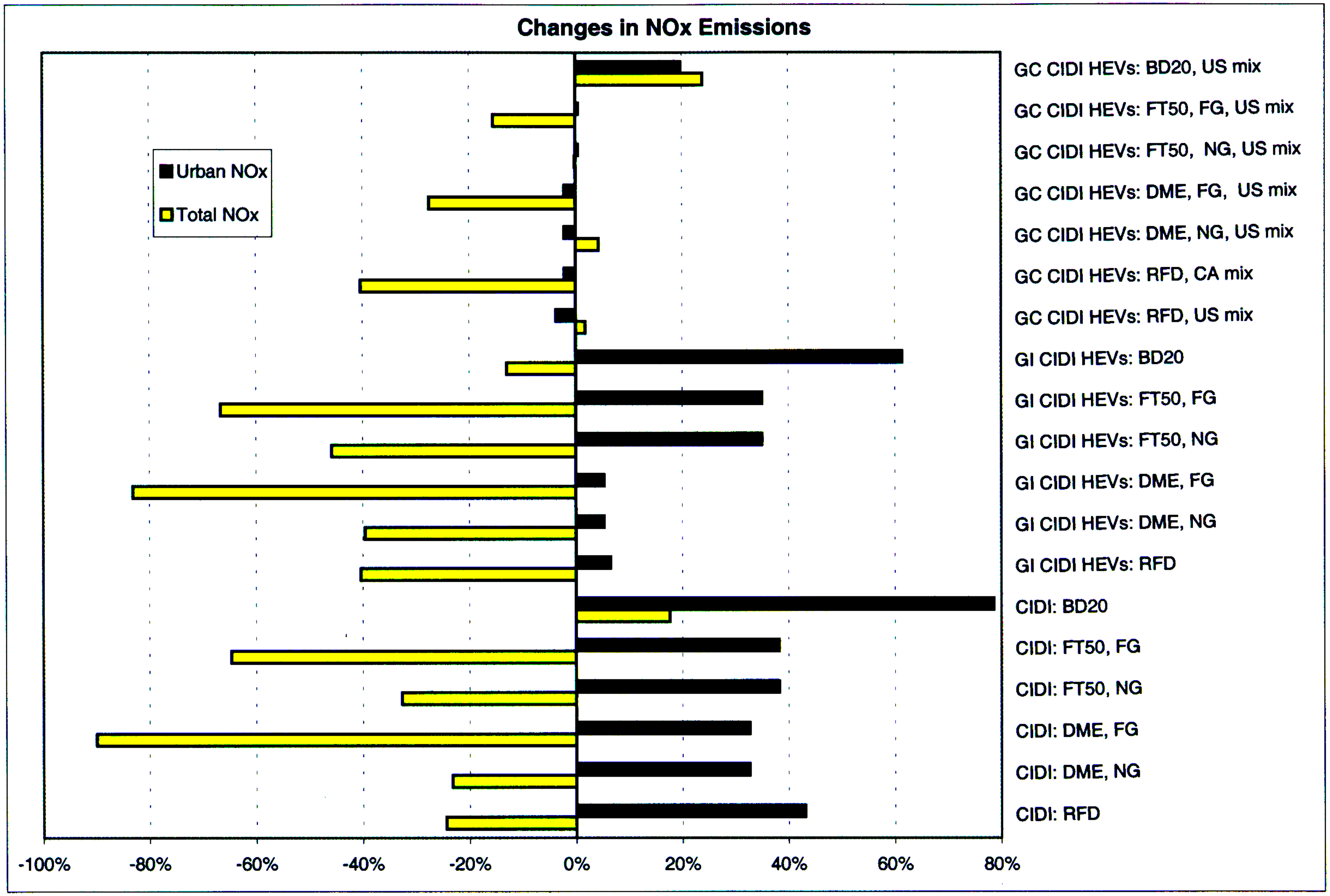

Figure 6.57 Changes in Fuel-Cycle Total and Urban NO$_x$ Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

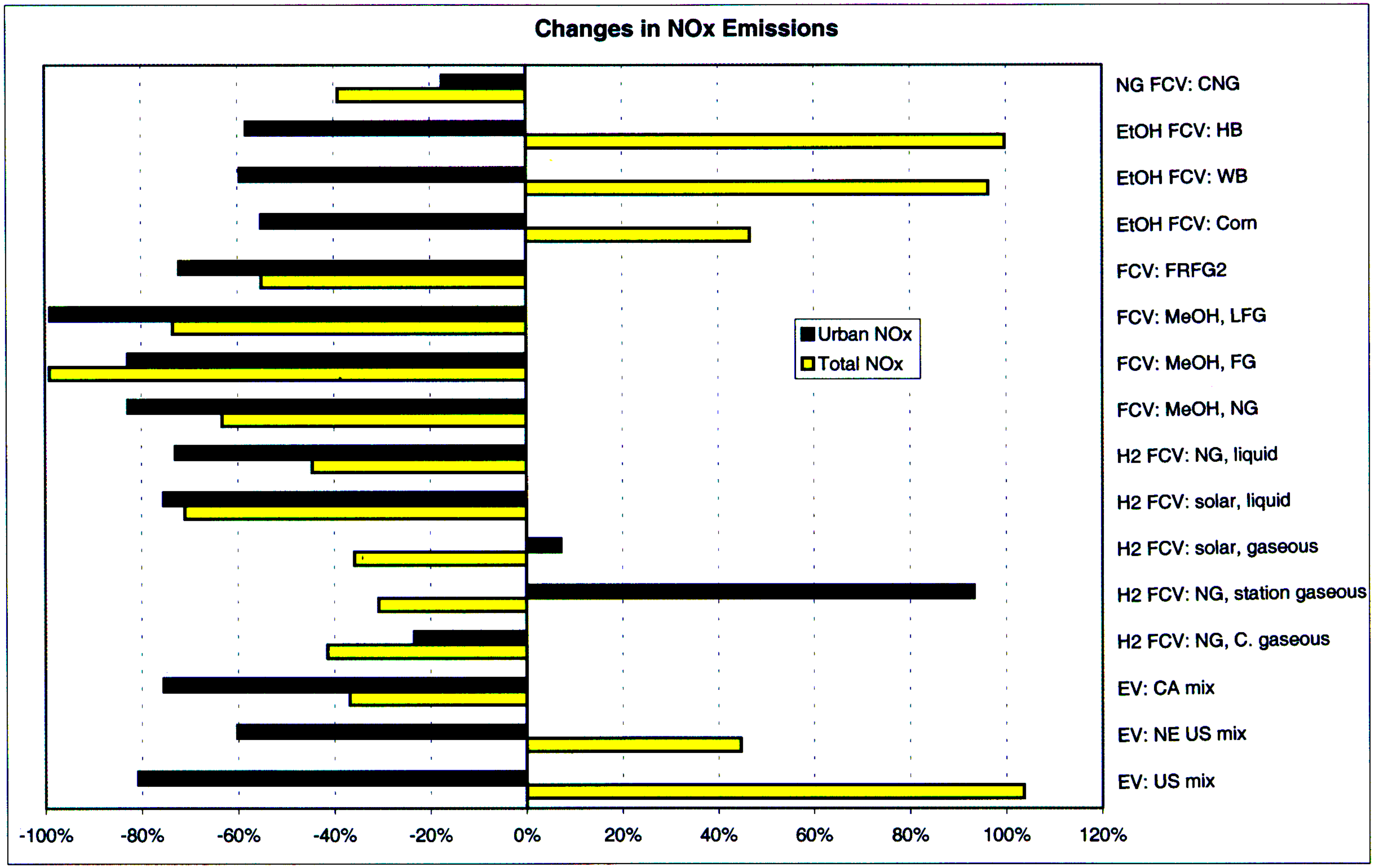

Figure 6.58 Changes in Fuel-Cycle Total and Urban NO$_x$ Emissions Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

Figure 6.58 presents changes in NO_x emissions for EVs and FCVs. With the U.S. and Northeast U.S. electric generation mix, use of EVs results in increases in total NO_x emissions, but decreases in urban NO_x emissions. With the California generation mix, EVs reduce both total and urban NO_x emissions. Of the FCV options, use of H_2 produced from NG at refueling stations (decentralized H_2 production) results in increases in urban emissions, because NO_x emissions from H_2 production at refueling stations occurs within urban areas. Use of ethanol increases total NO_x emissions because of high NO_x emissions during farming and ethanol production. Use of other fuels can achieve 60–80% reductions in urban NO_x emissions.

The results of changes in NO_x emissions demonstrate the increased importance of upstream emissions as regulations for vehicle tailpipe emissions are tightened. Even for clean vehicle technologies, such as CNGVs and H_2-fueled FCVs, urban NO_x emissions can be increased if the fuel used is produced within urban areas. Readers need to keep in mind that NO_x emissions from fuel production and compression calculated in GREET are estimated on the basis of current information, assumptions of the split between electric and gas compressors, and estimated emissions from gas compressors. When new information becomes available, the NO_x emission results could be different.

Figures 6.59 through 6.62 present changes in total and urban PM_{10} emissions for the long-term options. Note that vehicular PM_{10} emissions include tire- and brake-wear emissions as well as exhaust emissions. In fact, as tailpipe PM_{10} emissions are reduced (as more stringent PM standards for vehicles take effect), tire- and brake-wear emissions will account for a large share of total vehicle PM_{10} emissions. As Figure 6.59 shows, use of landfill gas-based methanol in SI and SIDI engines results in huge reductions in total and urban PM_{10} emissions because production of methanol from landfill gas eliminates PM_{10} emissions from landfill gas burning. On the other hand, use of corn-based ethanol causes large increases in total PM_{10} emissions (although urban PM_{10} emissions are reduced). The large increases are primarily caused by PM_{10} emissions during tillage for corn farming. Also, total PM_{10} emissions are increased to some extent by use of cellulosic ethanol. Use of CNG, LNG, LPG, and methanol from natural gas and flared gas results in moderate reductions in both total and urban PM_{10} emissions.

Figure 6.60 shows changes in PM_{10} emissions for SI and SIDI HEVs. The change patterns with these vehicles types are similar to those for SI and SIDI stand-alone applications (Figure 6.59).

Figure 6.61 presents changes in total and urban PM_{10} emissions for CIDI standalone and hybrid applications. As presented in Table 6.5, we assumed that passenger cars fueled with RFD will meet the PM standard of 0.01 g/mi for Tier 2 Bin 4, the same standard to which Tier 2 gasoline cars will be subject under Tier 2 Bin 3. Consequently, tailpipe PM_{10} emissions for gasoline engines and diesel engines are the same (see Table 6.4). Automakers are currently conducting intensive research and development to reduce diesel engine PM_{10} emissions. While it is conceivable for diesel cars to achieve PM_{10} emissions comparable to those of gasoline cars, diesel engines will face a tough challenge to reduce PM_{10} emissions to that level. On the other hand, we assumed that diesel LDT1 and LDT2 will meet the PM_{10} standard of 0.02 g/mi. Thus, diesel LDT1 and LDT2 will have PM_{10} emissions higher than those of gasoline LDT1 and

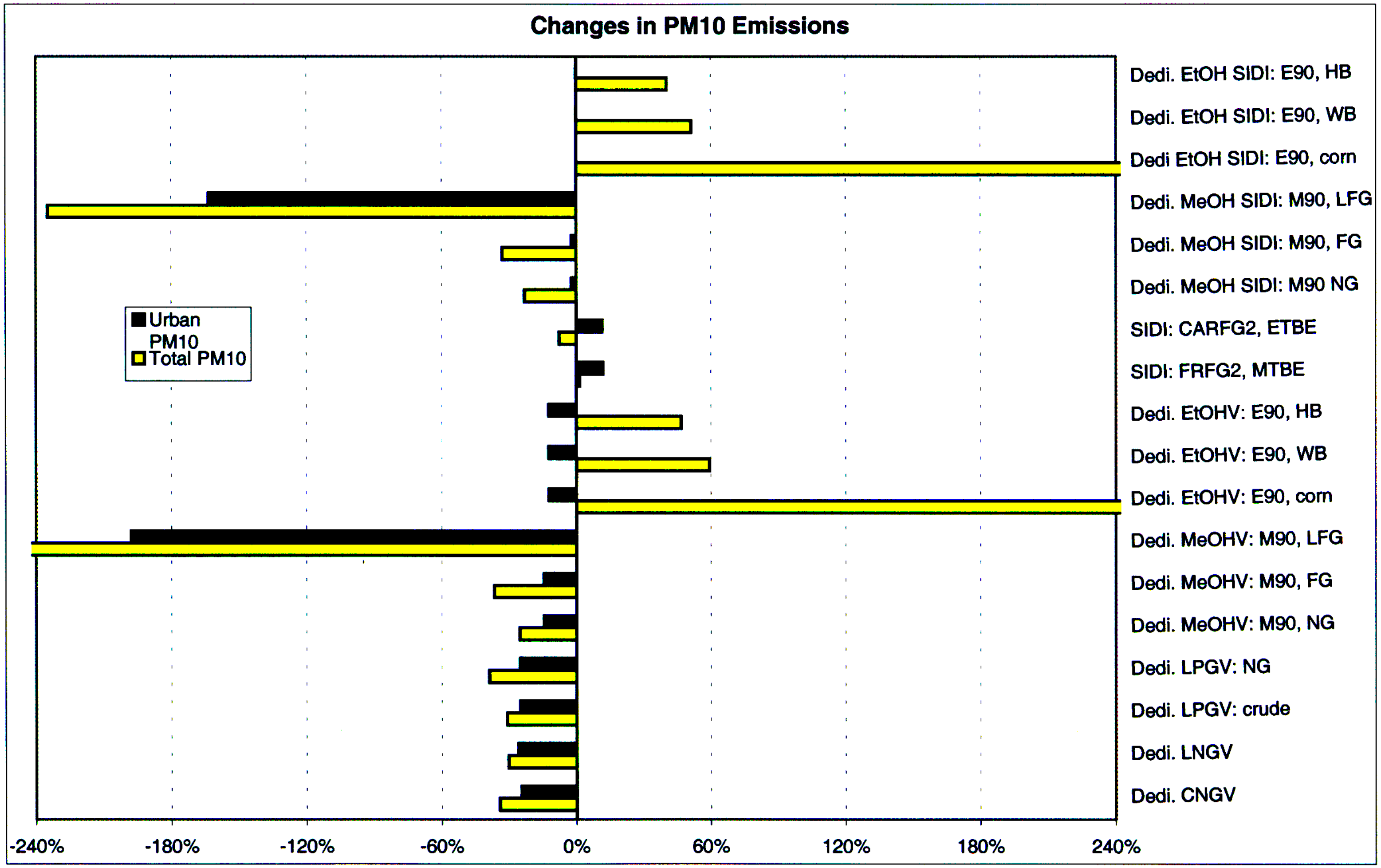

Figure 6.59 Changes in Fuel-Cycle Total and Urban PM_{10} Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

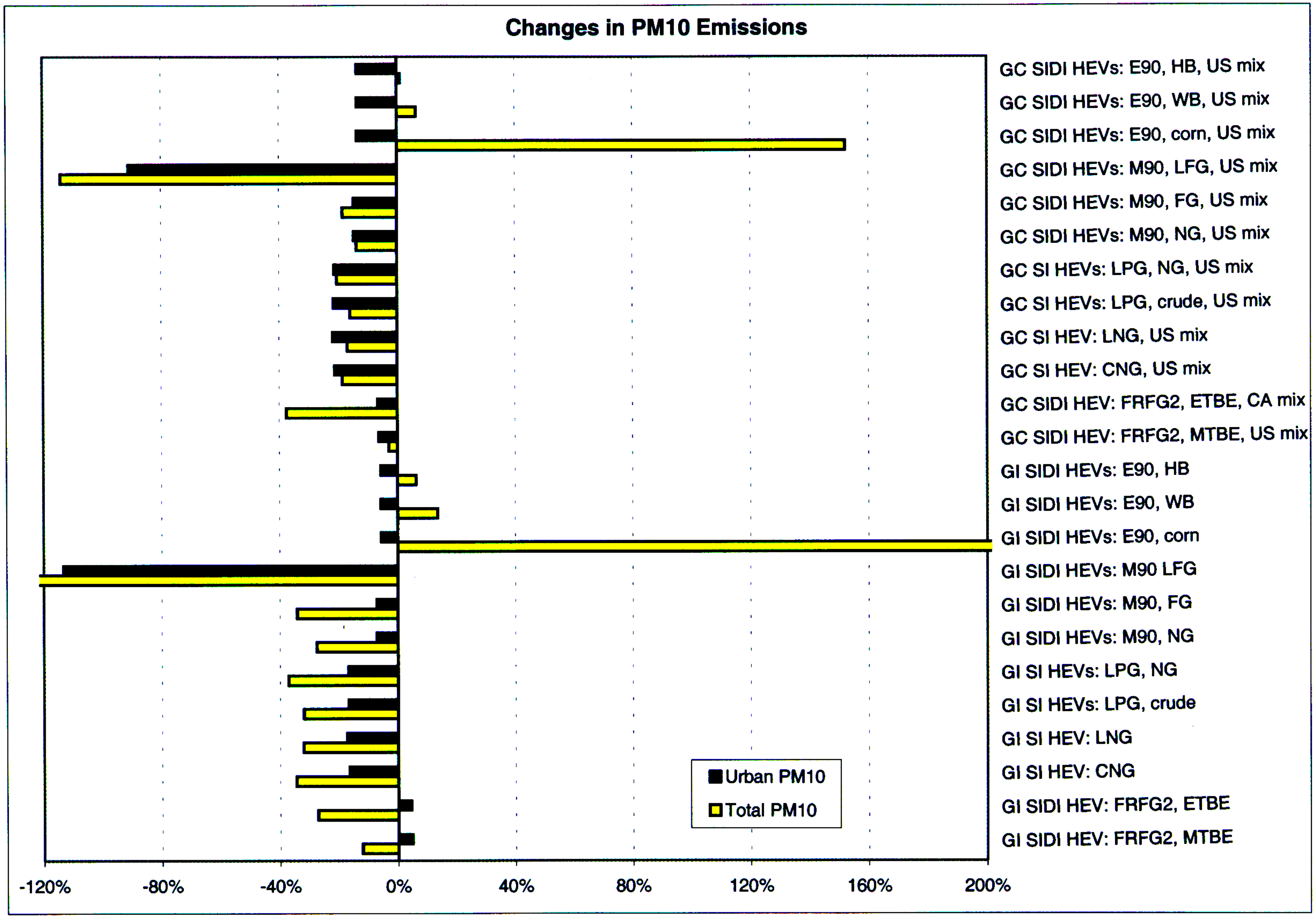

Figure 6.60 Changes in Fuel-Cycle Total and Urban PM_{10} Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

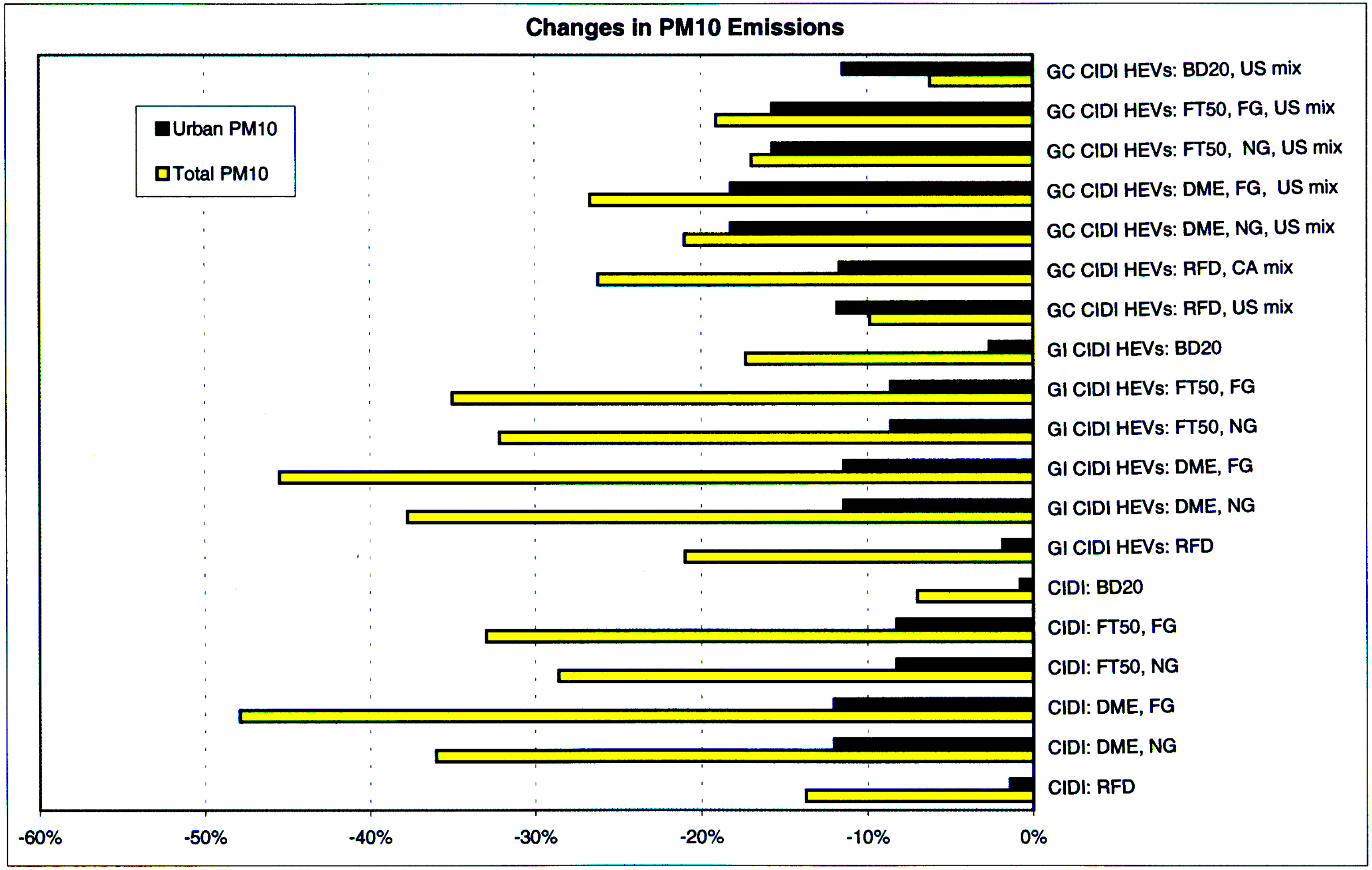

Figure 6.61 Changes in Fuel-Cycle Total and Urban PM_{10} Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

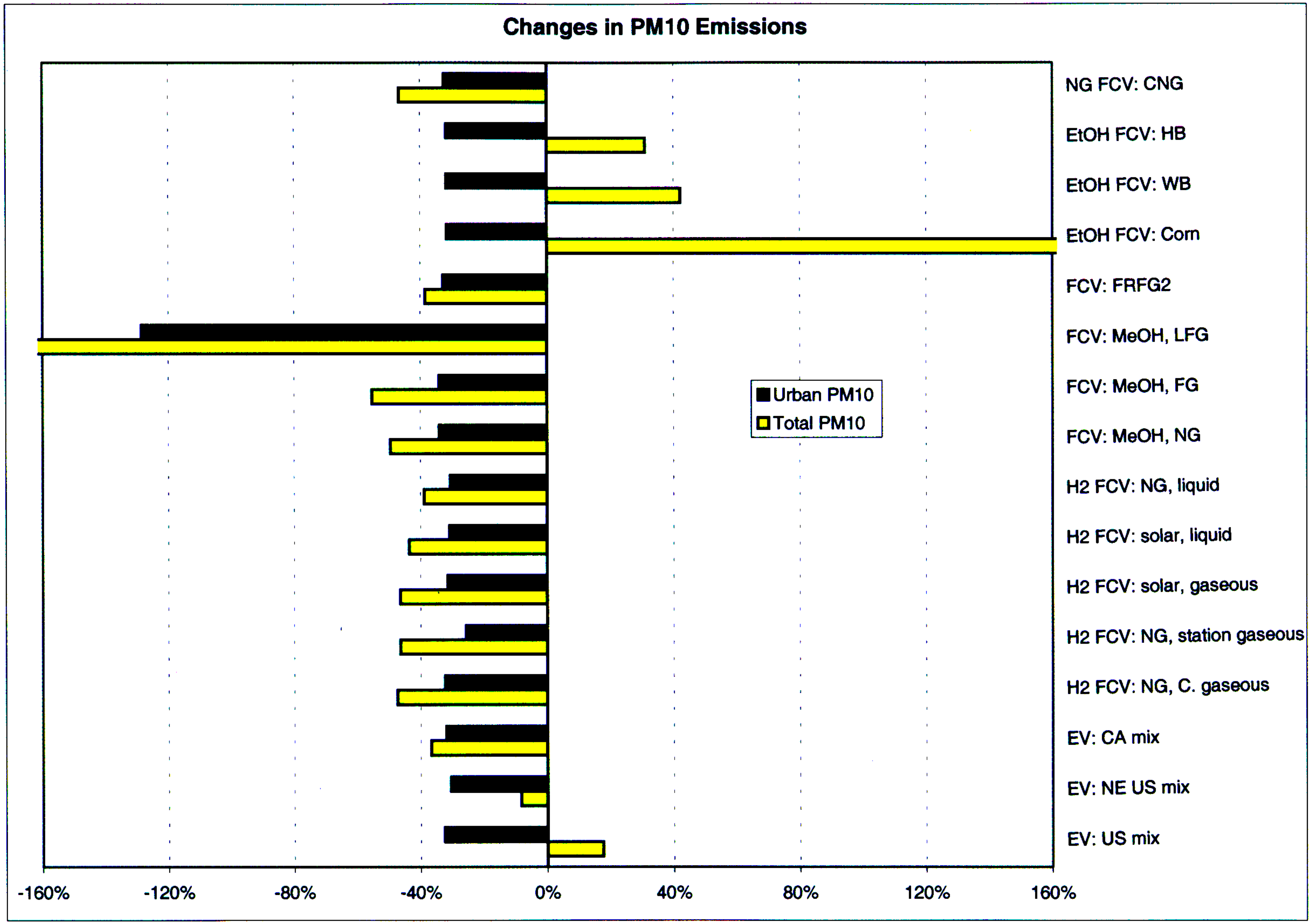

Figure 6.62 Changes in Fuel-Cycle Total and Urban PM_{10} Emissions Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

LDT2, respectively. As Figure 6.61 shows, the CIDI vehicle technologies fueled by RFD, DME, FT50, and BD20 reduce both total and urban PM_{10} emissions. Urban PM_{10} emission reductions are 10–20% for most options.

Figure 6.62 shows PM_{10} emission reductions by EVs and FCVs. Total PM_{10} emissions are increased by use of EVs with the U.S. average electric generation mix and by use of ethanol-fueled FCVs. The increases are caused by high PM_{10} emissions in coal-fired power plants (over 50% of electricity is generated from coal in the United States) and from tillage during corn farming for ethanol. On the other hand, use of landfill gas-based methanol in FCVs results in huge PM_{10} emission reductions because PM_{10} emissions generated by landfill gas burning are eliminated. Other fuel options achieve 30–40% reductions in PM_{10} emissions.

Overall, reductions in PM_{10} emissions by new fuels and advanced vehicle technologies are smaller than researchers might expect, primarily because vehicle tire- and brake-wear PM emissions are included in GREET calculations. Vehicles within the same class have similar tire- and brake-wear emissions, which dilutes the effects of the fuels and vehicle technologies.

Figures 6.63 through 6.66 present total and urban SO_x emission changes for the long-term technologies. Figure 6.63 shows the results for SI and SIDI vehicles. Total SO_x emissions are noticeably increased by use of landfill gas-based methanol and corn-based ethanol. The increase for methanol is caused by the significant amount of electricity used for landfill gas-to-methanol production. Electricity generation produces SO_x emissions outside of urban areas, which is why landfill gas-based methanol still achieves a huge reduction in urban SO_x emissions. For corn-based ethanol, the increased SO_x emissions are the result of coal combustion in ethanol plants. Use of other fuel options generally results in over-80% reductions in urban SO_x emissions, except for RFG used in SIDI engines, where a moderate 20% reduction results from SIDI’s improved fuel economy.

Figure 6.64 presents changes in SO_x emissions for SI and SIDI HEVs. For total SO_x emissions, GC HEVs with the U.S. electric generation mix produce higher emissions than GI HEVs because of high SO_x emissions from coal-fired electric power plants. On the other hand, all the fuel and vehicle options achieve over-80% reductions in urban SO_x emissions, except for RFG, which achieves moderate reductions of 40–60%.

Figure 6.65 shows SO_x emission changes for CIDI vehicles and CIDI HEVs. GC HEVs have higher total SO_x emissions than GI HEVs or CIDI vehicles. Urban SO_x emissions from RFD-fueled CIDI vehicles are a little higher than those from baseline GVs. For urban SO_x emissions, use of DME achieves the largest reduction because DME does not contain sulfur. On the other hand, FT50 and BD20, which contain RFD, account for some SO_x emissions.

As Figure 6.66 shows, EVs and FCVs reduce urban SO_x emissions by over 90%. Total SO_x emissions are increased by EVs with the U.S. and Northeast U.S. electric generation mix because of SO_x emissions from coal and oil-fired electric power plants. Total SO_x emissions are increased by corn-based ethanol in FCVs because of SO_x emissions associated with coal combustion in ethanol plants.

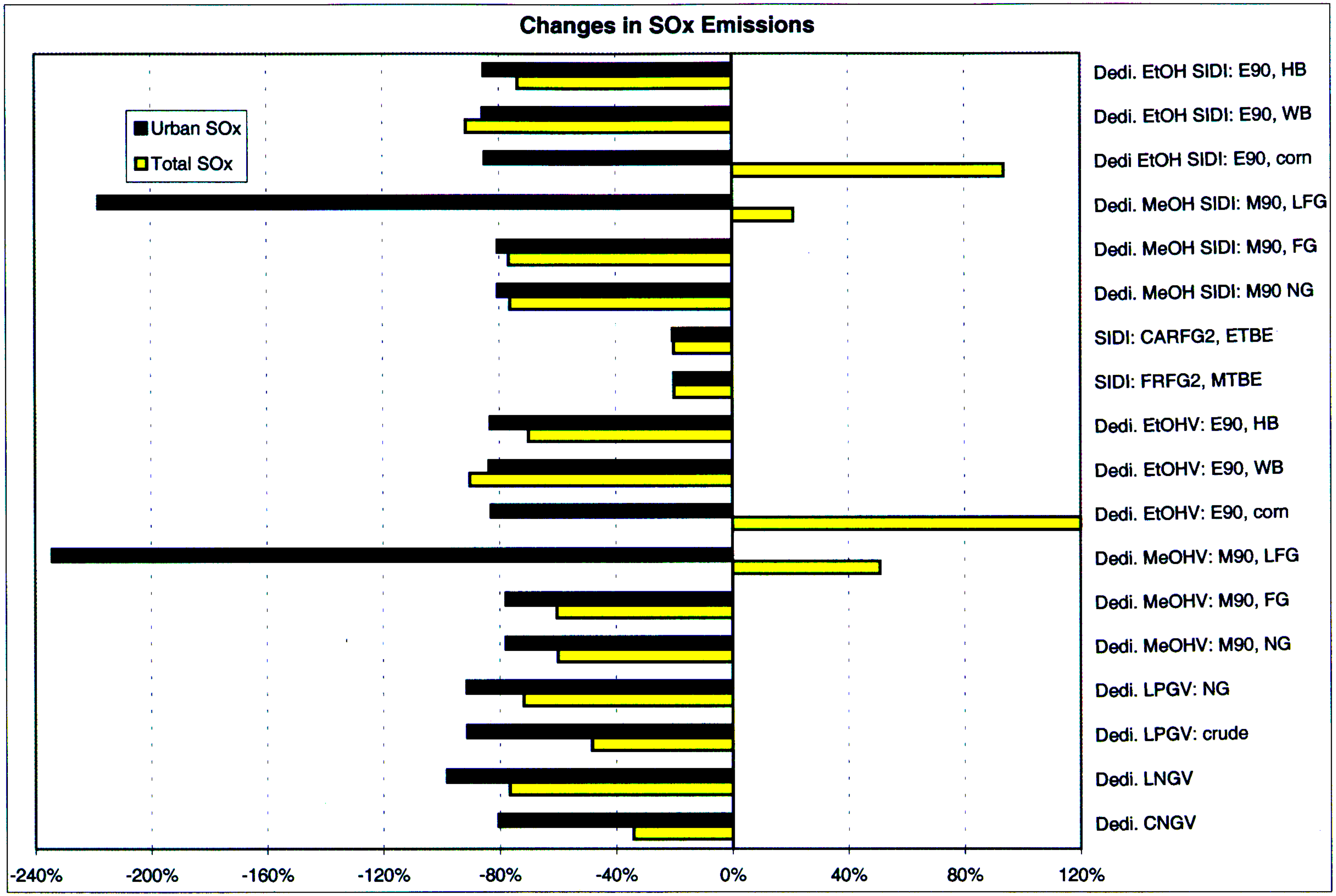

Figure 6.63 Changes in Fuel-Cycle Total and Urban SO_x Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI Vehicles

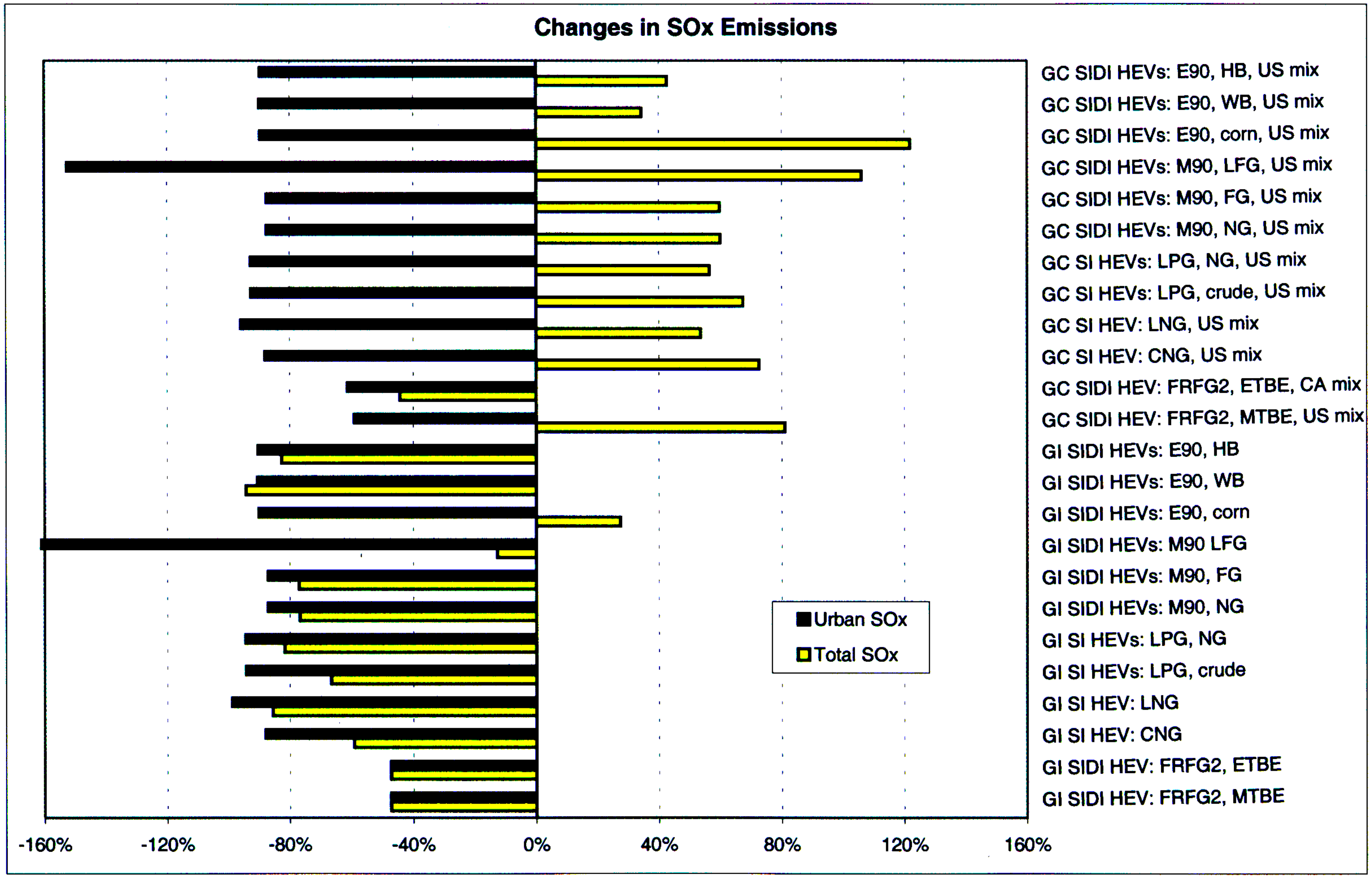

Figure 6.64 Changes in Fuel-Cycle Total and Urban SO_x Emissions Relative to GVs Fueled with RFG: Long-Term SI and SIDI HEVs

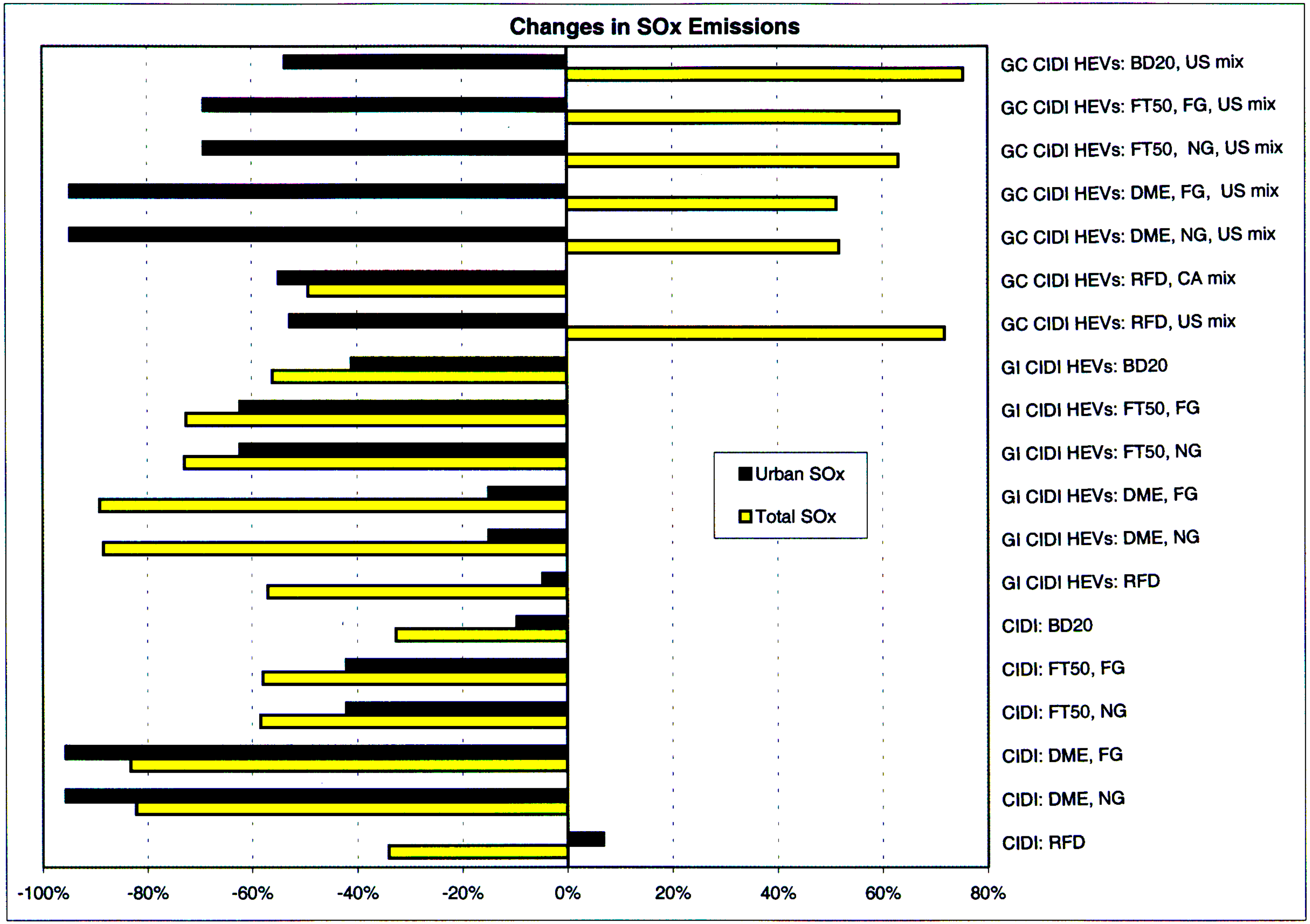

Figure 6.65 Changes in Fuel-Cycle Total and Urban SO_x Emissions Relative to GVs Fueled with RFG: Long-Term CIDI Vehicles and CIDI HEVs

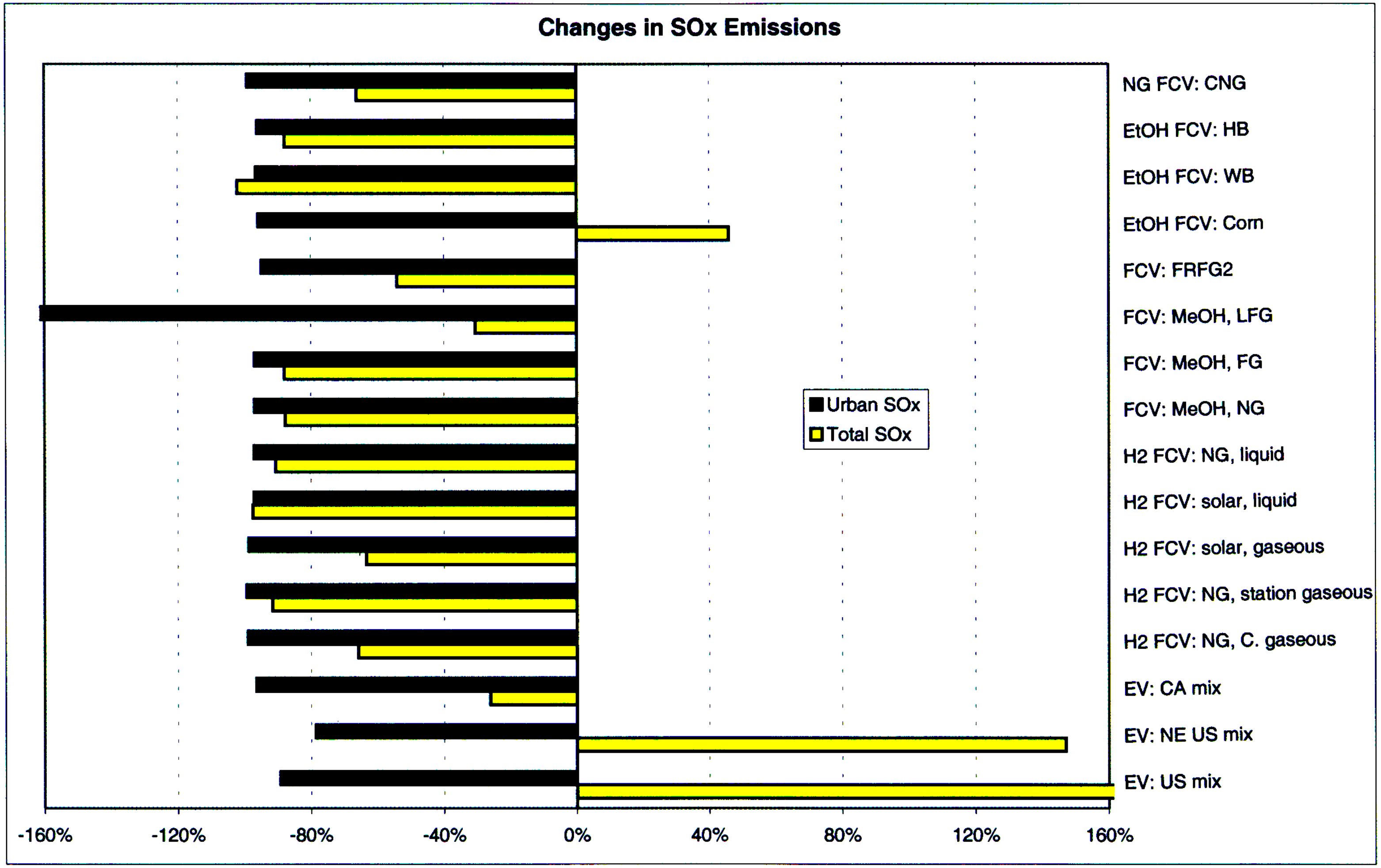

Figure 6.66 Changes in Fuel-Cycle Total and Urban SO_x Emissions Relative to GVs Fueled with RFG: Long-Term EVs and FCVs

6.5 Summary

Of the near- and long-term fuels and vehicle technologies evaluated in this study, the near-term technologies offer smaller energy and emission benefits than do the long-term technologies, especially with respect to energy use and GHG emissions. For emissions of criteria pollutants, the baseline GVs for the long-term technologies were assumed to meet the proposed federal Tier 2 vehicle emission standards. Although emission reductions by long-term alternative fuels and advanced technologies are relatively large in percentages, per-mile emission reductions achieved by long-term technologies are smaller than those achieved by near-term technologies.

Long-term technologies offer great energy and emission benefits, but most of them are not ready for commercial use. The market viability of these technologies will depend very much on the success of research and development efforts to overcome their technological hurdles. Evaluating the market readiness of these technologies is beyond the scope of this study.

Most of the technology options analyzed in this report have tradeoffs among energy use, emissions of GHGs, and emissions of criteria pollutants. That is, there is no single technology or technology/fuel combination — no “silver bullet” — that solves energy, GHG emissions, and urban pollution problems. One technology may have positive energy and GHG emission impacts but adverse urban air pollution impacts. Considering the tradeoffs and uncertainties in market viability of these technologies, it may be necessary to pursue multiple technology pathways to achieve energy, GHG emissions, and urban air pollution benefits for the transportation sector.

GREET is a fuel-cycle model based on conventional fuel-cycle analysis methodologies and approaches. The model addresses technological potentials of energy and emission impacts of given transportation fuels and technologies. As a new transportation technology is introduced into the marketplace, it could affect the use of existing technologies through some market mechanisms. That is, while energy and emission changes, as calculated in GREET, are based on mile-for-mile displacement between a new technology and the existing technology, the displacement in the real world may not be on a mile-for-mile ratio. Although the market effects of a few issues (such as land use changes from increased production of corn ethanol, coproducts of corn ethanol, and electricity credits of cellulosic ethanol) are addressed in GREET, the effects are generally beyond GREET’s modeling capability.

The results of our study represent our estimates of fuel-cycle energy and emission impacts of new technologies based on our own best judgments of technology advances over time. By nature, the evaluated technology options, especially the more speculative long-term technology options, are subject to uncertainties. These uncertainties will undoubtedly affect the outcomes of fuel-cycle assessments. For a given technology, we could have run the GREET model using different sets of assumptions to provide a range of estimates. However, because of the large number of technology options involved in this study and because our resources are limited, we were unable to conduct such a series of simulations using the GREET model. The results presented here provide a “snapshot” of potential technology effects based on our current understanding of technology advancements. As more information becomes available for new technologies, we will revise key assumptions in the GREET model regularly, and the results will change. Preferably, readers will study the assumptions used in this study, develop their own assumptions, and use those assumptions in the GREET model to generate their own results.