CHAPTER SIX
GREENHOUSE GASES AND OTHER ENVIRONMENTAL CONSIDERATIONS

INTRODUCTION

This chapter evaluates fuel-vehicle system options that could significantly lower U.S. transportation sector greenhouse gas (GHG) emissions for light-duty (LD), medium-duty (MD), and heavy-duty (HD) vehicles. GHG emissions in the transportation sector result from the interaction of four major factors: vehicle efficiency, transportation fuel carbon concentration, travel demand,[1] and travel efficiency.[2] This chapter discusses reductions in GHG emissions resulting from technology advances in conventional and alternative LD and HD fuel-vehicle systems as well as other GHG reduction strategies for the transportation sector.

GHG emissions for fuel-vehicle systems were analyzed to develop a perspective on GHG reduction potential for the transportation sector if technology and transition hurdles are overcome. This analysis used results from the LD and HD economic analyses of this study.[3] Additionally, criteria air pollutant emissions and water use characteristics for these fuel-vehicle systems were analyzed.

Broader sustainability issues such as biodiversity, land, and vehicle materials associated with the production of advanced vehicle technologies are beyond the scope of the study.

Because of the long time frame of the study analysis, the number of uncertainties surrounding many variables increases, which in turn affects the calculations and outputs. Uncertainty and variability associated with GHG calculations are described in this chapter.

Additional GHG reduction options were identified to supplement the vehicle and fuel technology options described in this study analysis. The GHG reduction strategies evaluated are a subset of all available options and include lower carbon intensity electric grid, reduced travel demand, improved travel efficiency, renewable natural gas, and LD vehicle ultra-lightweighting.

Studies that have assessed U.S. GHG reduction options conclude that GHG reduction opportunities are highly fragmented and spread across the economy. GHG reduction costs per ton of carbon dioxide (CO_2) abated are also highly variable across and within each sector of the U.S. economy. For example, many of the GHG reduction opportunities in the transportation sector that are covered in this study, such as fuel economy improvements and the use of biofuels, span a broad cost range.[4]

In response to the Secretary of Energy's supplemental question in the April 30, 2010, letter (see Appendix A for request letters), on ways to achieve an absolute 50% GHG reduction in the U.S. transportation sector, the following conclusions are noted:

- All individual LD, MD, and HD fuel-vehicle systems considered in this study have the potential

1 Travel demand is focused on ways to reduce GHG emissions from personal travel activity through consumer behavior, technology, and regulatory action. Examples include increasing the cost of driving, land use development that reduces trip lengths, worksite trip reduction, and public information campaigns.

2 Travel efficiency focuses on ways to improve transportation networks for on-road vehicles, air, rail, and marine by improving the efficiency of transportation operations. Examples include travel time reduction, travel flow improvements, decreased idling, and more efficient transportation of goods.

3 It should be noted that those analyses did not attempt to minimize GHG emissions from each fuel-vehicle system, but rather optimized vehicle designs for lowest cost of driving.

4 McKinsey & Company, *Reducing U.S. GHG Emissions, How Much at What Cost?*, December 2007.

to achieve at least a 40% emissions reduction by 2050 compared to 2005 average vehicle emissions on a per-mile basis. In the LD vehicle segment, internal combustion engine (ICE), hybrid ICE, and plug-in hybrid electric vehicles (PHEVs) using advanced biofuels (not considering emissions impacts from indirect land use change[5]) along with fuel cell electric vehicles (FCEVs) fueled by hydrogen from natural gas, can produce the lowest calculated 2050 GHG emissions per mile.[6]

- On a vehicle fleet basis, increased transportation demand offsets the per-mile GHG emissions reductions gained by each fuel-vehicle system and must be taken into account. Projected 2005–2050 demand growth was considered alongside potential LD, MD, and HD fuel-vehicle system GHG reduction improvements. The study identified certain compositions of LD vehicle fleets operating under very certain conditions that achieved a 50% GHG reduction in the LD vehicle segment. No MD or HD fleet composition or set of conditions was able to overcome the significant 2005–2050 demand growth and achieve a 50% GHG reduction in this fleet.[7]
- In addition to low-carbon fuels and efficient vehicles, supplemental strategies, such as reducing the carbon intensity of the electric grid (or other fuels such as hydrogen and natural gas), reducing transportation demand, improving transportation system operating efficiency and/or other options, can enable deeper GHG emissions reductions in the U.S. transportation sector.
- When compared to gasoline[8] and diesel vehicles, all alternative fuel and vehicle options provide improved urban criteria air pollutant emissions on a vehicle mile traveled (VMT) basis. For water consumption, generally the alternative fuel and vehicle options analyzed have similar or improved water consumption performance on a VMT basis, except for irrigated biomass used for biofuels.

5 Study analysis did not include biofuel GHG emissions with indirect land use change (ILUC) because of considerable ILUC emission uncertainty with current as well as future biofuel pathways. Biofuel ILUC GHG emissions are treated as an uncertainty in the study analysis.

6 Chapter Two, "Light-Duty Vehicles," discusses these vehicle technologies in more detail.

7 GHG emissions analysis was not performed for the marine, rail, and air sectors, which make up about 15% of transportation demand due to limited GHG reduction options relative to on-road transportation options and slower turnover of capital stock.

8 Gasoline is understood to always mean E10 gasoline (gasoline with 10% ethanol by volume) in this report.

BACKGROUND

GHG Emissions in the Transportation Sector

Greenhouse gases represent a category of gases and aerosols that have climatic impacts when released into the environment. The primary GHGs produced in the transportation sector are CO_2, methane (CH_4), and nitrous oxide (N_2O). Other GHG emissions that occur in the transportation sector include automotive air conditioner refrigerants, chlorofluorocarbons, and hydrofluorocarbons, which can be released during accidents or improper maintenance. These refrigerants do not contribute materially to overall transportation sector GHG emissions and are not included in the scope of GHG emissions for this study.

CO_2, a byproduct of carbon-based fuel combustion, accounts for about 94% of U.S. transportation GHG emissions as shown in Figure 6-1.[9] Historically, these GHG gas emission ratios change little from year to year.

Throughout this report, transportation GHG emissions are reported in terms of carbon dioxide equivalency (CO_2e) for CO_2, CH_4, and N_2O emissions, which describes the amount of CO_2 that would have the same global warming potential (GWP)[10] as a given mixture and amount of GHGs when measured over a specified timescale. For this study, the time scale is 100 years, which is consistent with the Intergovernmental Panel on Climate Change methodology.[11]

9 Energy Information Administration, "Table 3, Distribution of Total U.S. Greenhouse Gas Emissions by End-Use Sector," in *Emissions of Greenhouse Gases in the United States 2009,* March 2011.

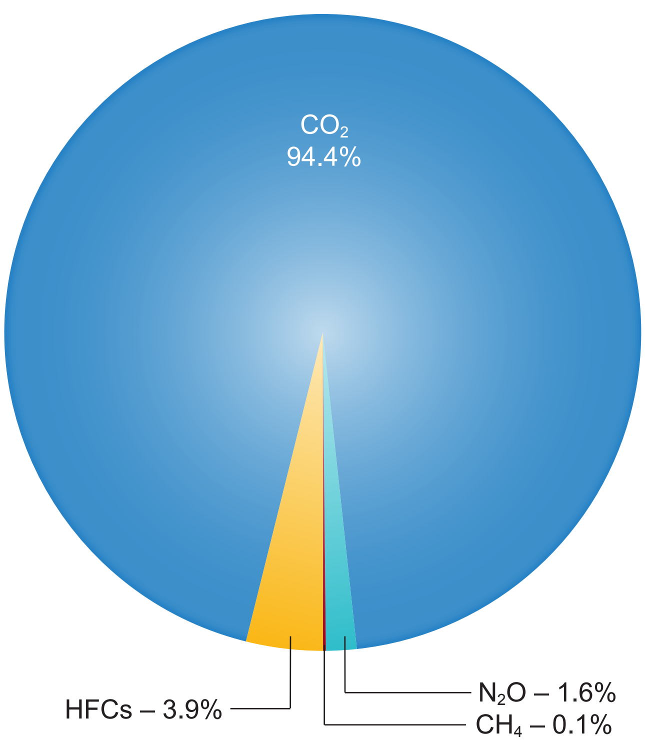
10 The GWP of a greenhouse gas is defined as the ratio of time-integrated radiative forcings from the release of one kilogram (kg) of the gas (or other substance) relative to that of a kg of CO_2. The GWP of CO_2 is always defined as 1, because it is the reference gas to which all others are referred. GWP provides a mechanism for converting all GHGs to an equivalent amount of CO_2. Additional details on GWP and radiative forcings can be found in the IPCC Fourth Assessment Report cited below.

11 Intergovernmental Panel on Climate Change (IPCC), "Changes in Atmospheric Constituents and in Radiative Forcing," in *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2007.

Global Warming Potential and Methane

The scientific community has long recognized that there are several methodologies available to calculate a measure of the power of different GHGs to effect a global climate change. The scientific community and policymakers evaluate tradeoffs between simplicity, complexity, accuracy, and transparency in order to assess an appropriate methodology. Policymakers at the United Nations Framework Convention on Climate Change have consistently chosen GWP and the associated 100-year time horizon as the most appropriate method for comparing the effects of GHGs.

The life-cycle emission estimates presented in this chapter and in the study employed a 100-year GWP for all GHGs, including methane. Most GHG regulations and policy discussions consider the 100-year time horizon. Considering a shorter time horizon can provide an alternate perspective of the near-term effects of shorter-lived species such as methane. For example, a 20-year GWP for methane would result in larger GHG emissions values than those used in this study for natural gas, gasoline, and diesel fuel pathways due to fugitive methane emissions. Emissions from natural gas are associated with plug-in electric, hydrogen fuel cell, compressed natural gas (CNG), and liquefied natural gas (LNG) vehicles because fugitive methane emissions can occur in natural gas production and distribution, as well as CNG/LNG storage and distribution. However, because methane emissions are significantly smaller than CO_2 emissions, and CO_2 will remain the dominant long-lived greenhouse gas in the transportation sector, this study uses the 100-year GWP time frame for all GHGs, including methane.



Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2009*, 2011.

Figure 6-1. *U.S. Transportation GHG Emissions by Gas, 2009*

The transportation sector is the second largest contributor to GHG emissions in the United States, as shown in Figure 6-2. In 2010, direct or tailpipe GHG emissions accounted for about 33% of total U.S. GHG emissions.[12] Historically, these GHG emission ratios by economic sector change little from year to year.

Transportation sector GHG emissions have been growing steadily in recent decades due to increasing transportation demand. From 1990 to 2006, direct GHG emissions from transportation grew more than any other U.S. sector, accounting for almost half (47%) of the increase in total U.S. GHG emissions for that period.[13] The VISION model,[14] using data from the Energy Information Administration's (EIA) Annual Energy Outlook 2010 (AEO2010) Reference Case, projects GHG emission growth rates of 0.4% and 0.7% per year between 2008–2035 and 2035–2050, respectively.

12 Energy Information Administration, "Table A18, Carbon Dioxide Emissions by Sector and Source," in *Annual Energy Outlook Early Release 2012*, 2012.

13 Cambridge Systematics, Inc., *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions*, published by Urban Land Institute, July 2009.

14 The VISION model has been developed by Argonne National Laboratory to provide estimates of the potential energy use, oil use, and carbon emission impacts of advanced light- and heavy-duty vehicle technologies and alternative fuels through the year 2050.

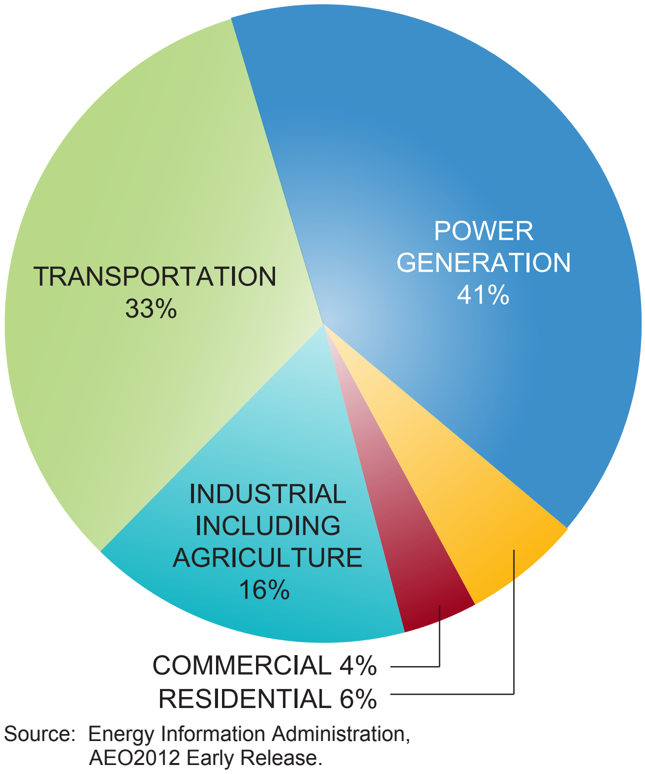


Figure 6-2. *U.S. GHG Emissions by Economic Sector for 2010*

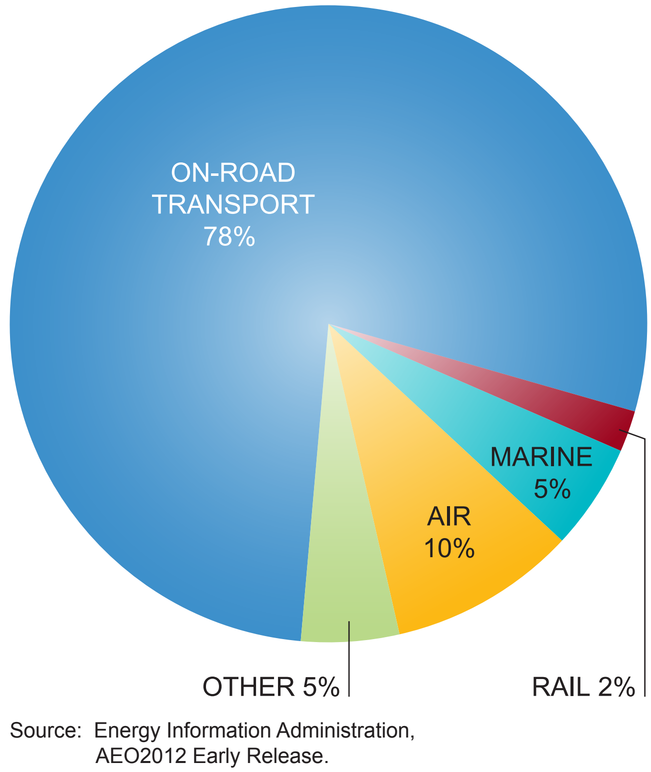


Figure 6-3. *Direct GHG Emissions from Transportation by End-Use Category for 2010*

Figure 6-3 shows that direct GHG emissions from on-road transportation represent the largest end-use category, making up almost 80% of U.S. transportation sector GHG emissions.[15]

Passenger transport includes LD vehicles, buses, aircraft, and some train and marine transport. Freight transport includes MD and HD trucks, a large majority of marine and rail transport, and a small percentage of air transport. GHG emissions from these various passenger and freight modes have different GHG emission intensity profiles. The "Additional GHG Reduction Strategies" section of this chapter outlines different approaches for more efficient modes of passenger and freight travel.

In passenger transport, domestic aircraft and passenger rail represent the most efficient travel modes when considered on a GHG emissions per passenger mile traveled basis, while LD vehicles are the least efficient.

15 Energy Information Administration, "Table A19, Energy-Related Carbon Dioxide Emissions by End-Use," in *Annual Energy Outlook Early Release 2012*, 2012.

Rail and marine freight have significantly lower GHG emissions per ton-mile[16] than truck or air freight due to carriage of bulk and containerized goods, coupled with low transit speeds and economies of scale. Trucking generates higher GHG emissions, reflecting the relatively higher inefficiencies of smaller vehicles transporting lighter cargo loads at higher speeds. Airfreight, which primarily transports higher-value, time-sensitive cargo represents the most inefficient freight mode on a GHG emissions per ton-mile basis.[17]

GHG METHODOLOGY

GHG Emissions Assessment Approach

This study employs well-to-wheels (WTW) accounting of total GHG emissions from vehicle use.

16 Ton-mile is the product of total weight (freight and transport) and total distance traveled.

17 U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006,* 2008; and U.S. Department of Transportation, Report to Congress, *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions, Volume 1: Synthesis Report,* April 2010.

Several fuel-vehicle systems, such as battery electric vehicles (BEVs)[18] and hydrogen FCEVs considered in the study, have no tailpipe GHG emissions; however, these systems still contribute to the GHG emissions from transportation. Their contribution to GHG emissions is associated with the production of the energy carrier[19] they use, in this case electricity and hydrogen. The "upstream" GHG emissions associated with electricity and hydrogen production account for the largest portion of the WTW GHG emissions for these alternate fuel-vehicle systems.

Figure 6-4 depicts the steps of several, but not all, fuel pathways where emissions are produced. Emissions generated in the fuel production and distribution process present the "well-to-tank" portion, and the "tank-to-wheels" portion represents emissions from the use of the fuel in the vehicle for transportation. This WTW characterization has to be extended slightly to represent electricity and hydrogen fuel production and their use as a transportation fuel.

18 Battery electric vehicles are fueled only by electricity.

19 Per IPCC: Energy carriers include electricity and heat as well as solid, liquid, and gaseous fuels. They occupy intermediate steps in the energy-supply chain between primary sources and end-user applications. By this definition, both electricity and hydrogen are defined as energy carriers in the study.

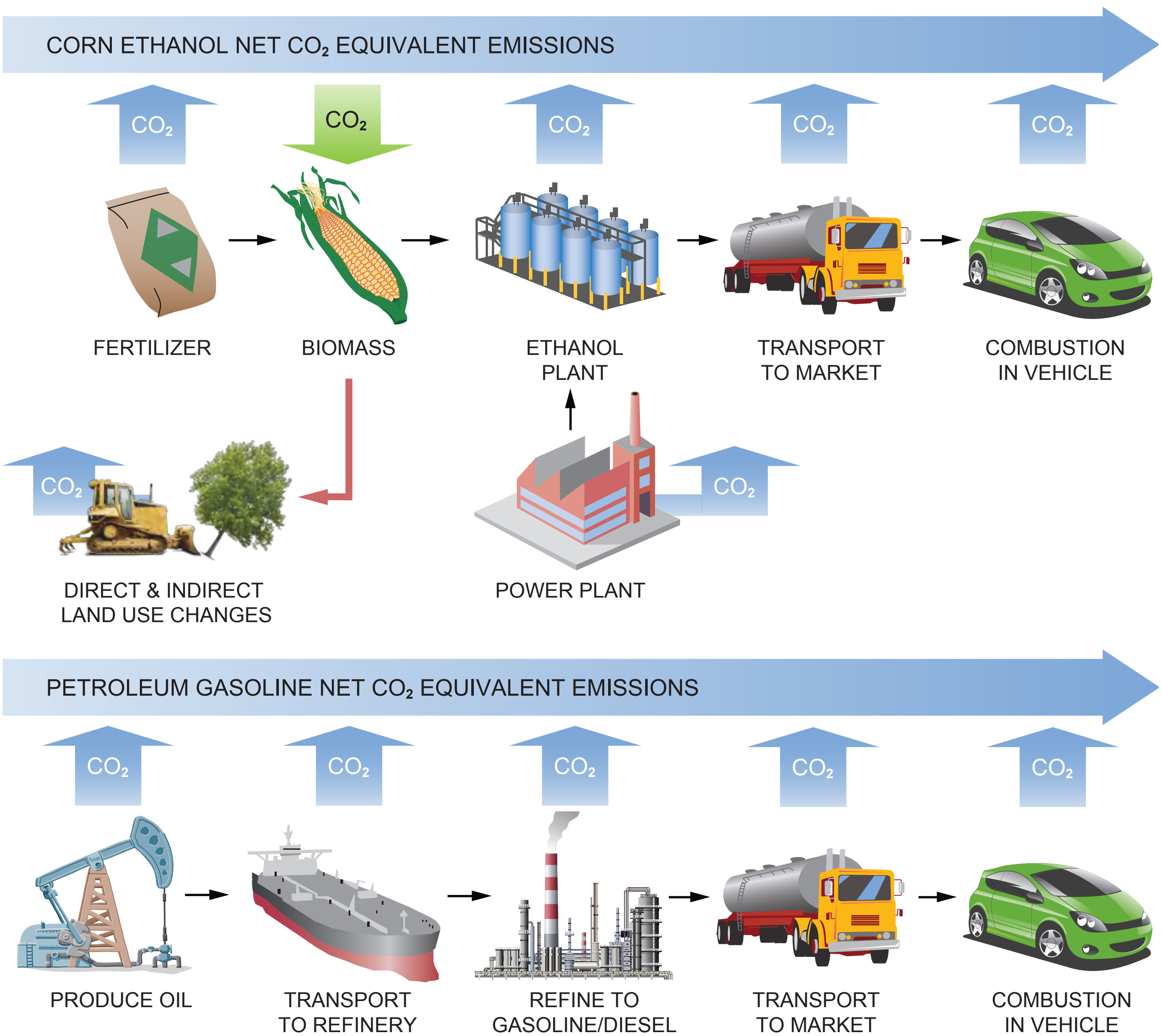


Figure 6-4. *Corn Ethanol and Petroleum Life-Cycle GHG Emissions*

GHG emissions from transportation are generated from two sources:

1. Well-to-wheels emissions:
   - emissions from the production (extraction or farming, transport, refining) and combustion of the fuel
   - emissions from the production of the energy carrier (such as electricity or hydrogen used in plug-in electric and hydrogen fuel cell vehicles)
2. Life-cycle emissions from the vehicle manufacturing through vehicle disposal and/or recycling.

This study did not include emissions from vehicle manufacturing/recycling in the fuel-vehicle system emissions values because they are significantly smaller than emissions from the production and use of transportation fuel and energy carriers.[20] Also, there are relatively few studies of emissions from vehicle manufacturing. A detailed discussion on life-cycle analysis is included in Topic Paper #29, "Green House Gas Life Cycle Assessment/Analysis," on the NPC website. As vehicle manufacturers incorporate more lightweighting of vehicles in the future, vehicle production energy usage and emissions may become more material to overall life-cycle GHG emissions in the transportation sector. This topic is covered in additional detail in the "Additional GHG Reduction Strategies" section of this chapter.

GHG Life-Cycle Emissions Modeling

The WTW GHG emissions were calculated using the **G**reenhouse Gases, **R**egulated **E**missions, and **E**nergy Use in **T**ransportation (GREET) model developed at Argonne National Laboratory. This model evaluates energy and emission impacts of traditional and advanced vehicle technologies and numerous transportation fuels. This allows for comparisons among various vehicle and fuel combinations.

The GREET 1.8d version (hereafter referred to as GREET) GHG carbon intensity values are the basis for LD vehicle and MD/HD vehicle GHG emissions in the VISION model used for the study. GREET was selected due to its integrated use with other U.S. Department of Energy (DOE) models used in this study as well as transparent treatment of assumptions. Information on GREET and life-cycle assessment can be found in Topic Paper #29.

GREET includes estimates for CO_2, CH_4, and N_2O emissions, and reports GHG emissions on a CO_2e basis. GREET also estimates emissions of several U.S. criteria air pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter smaller than 10 and 2.5 microns in diameter (PM_{10} and $PM_{2.5}$). Criteria air pollutants generally have weak GWP values and are emitted in much lower quantities than CO_2, but can contribute to the formation of compounds that do have climatic effects, such as ozone and sulfate aerosols.[21] In general, GREET does not include criteria air pollutants in GHG equivalency values with the exception of CO oxidation. Additional information on criteria air pollutants associated with the fuel-vehicle systems analyzed in this study is provided later in this chapter.

GREET assesses electricity GHG emissions from the fuel used for power generation: coal, nuclear, natural gas, hydro, and other renewable sources of power generation. The version of GREET utilized for this study relied on the U.S. power generation fuel mix assumptions used in the VISION model, which is based on the AEO2010 Reference Case. The VISION model electricity fuel mix projected out to 2050 contains significant amounts of coal-fired power generation, a carbon intense fuel. There are varying views on the future carbon intensity of electricity generation. This study examines several different lower carbon intensity electric grid fuel mix scenarios and the resultant impact on plug-in electric vehicles' (PEVs)[22] GHG emissions in the "Additional GHG Reduction Strategies" section of this chapter. These lower carbon electricity scenarios were evaluated outside of this study's economically driven analysis because power generation and transmission cost information was not available in most cases.

20 Carnegie-Mellon study on plug-in hybrids, which looked at battery production and found GHGs associated with lithium-ion battery materials and production account for 2–5% of life-cycle emissions from PHEVs. See: C. Samaras and K. Meisterling, "Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy," *Environmental Science and Technology* 42, no. 9 (2008): pages 3170-3176.

21 M. Delucchi and T. Lipman, "Chapter 6" in *Sustainable Transportation Energy Pathways: A Research Summary for Decision Makers,* Institute of Transportation Studies, University of California–Davis, 2008.

22 PEVs includes battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Uncertainty

Given the long time frame of the study analysis, a number of uncertainties arise which are discussed in this chapter. Uncertainties associated with life-cycle GHG modeling and resulting WTW GHG emissions values are described in this chapter and further described in Topic Paper #30, "Data Variability and Uncertainty in Greenhouse Gas Life Cycle Assessment." Other uncertainties such as year 2050 VMT projections used to calculate GHG emissions/mile traveled, fuel pathway uncertainties associated with criteria air pollutant and water usage, or possible biases in GHG analyses are also noted in this chapter.

Total vehicle fleet GHG emissions are sensitive to year 2050 VMT projections. For example, the most recent LD and HD 2050 VMT projection based on AEO2012 Early Release are lower by ~10% and ~15%, respectively, than the 2050 VMT projections based on the AEO2010 Reference Case. VMT was extrapolated from 2035 to 2050 using a methodology consistent with that used in VISION.

Fugitive methane emission uncertainty in natural gas production and distribution,[23] as well as in the storage and distribution of compressed natural gas (CNG) and liquefied natural gas (LNG), creates WTW emissions uncertainty for natural gas pathways given methane's larger global warming potential relative to CO_2.

In all biofuels pathways, a key element of uncertainty in the GHG life-cycle assessment is indirect land use change (ILUC), associated with the production of biomass for use as fuel feedstock. ILUC refers to the incremental regional and global market-driven conversion of land for agricultural purposes to produce crops that previously were raised on land that is now being used to produce biomass for fuel.[24] GHG emissions associated with ILUC include the following and are developed through complex modeling:

- All above-ground carbon is initially released due to burning of the native vegetation to clear the land for cultivation. This activity represents a majority of overall GHG emissions to ILUC.
- Below-ground carbon is released over many years.
- Long-term carbon sequestration is forgone.

Uncertainty of Biofuels Emissions

GREET biofuel GHG emission values do not include potential indirect land use change (ILUC) considerations (with the exception of corn ethanol), which represent a material element of uncertainty. A preponderance of scientific reports agree that ILUC represents a potentially material component of life-cycle GHG emissions for biofuels; however, the science is uncertain and emerging on how to quantify its effects. Excluding ILUC from the study analysis creates a directional bias towards lower GHG emissions for biofuel-based pathways. As the science progresses, ILUC effects should be incorporated into any conclusions, plans, and policies drawn from this study. While accurately quantifying ILUC impacts will be challenging over time, technology improvements that improve crop yields on existing U.S. cropland will directionally reduce ILUC GHG impacts.

A preponderance of evidence suggests that ILUC is a component of life-cycle GHG emissions for biofuels; however, the science associated with quantifying ILUC for various biofuel pathways is relatively new and evolving. ILUC calculations now require econometric models predicting world economic and agricultural activity over several future decades or longer, plus many thousands of pieces of data, much of which is impossible to verify.

As a result, all LD and HD vehicle economic analyses performed in the study did not include ILUC emissions as part of WTW GHG emission values. However, because land use conversion can be a significant factor in GHG emissions, this chapter does address ILUC GHG emissions on a qualitative basis and provides ranges of GHG emissions that include potential ILUC impacts as reported in different GHG emissions data sets. ILUC emissions uncertainty is described in more detail in Topic Paper #30, "Data

23 Further information on methane emissions uncertainty can be found on pages 335-343 of the NPC's 2011 *Prudent Development* report.

24 Julie Witcover, Sonia Yeh, and Daniel Sperling, *Policy Options to Address Global Land Use Change from Biofuels,* Institute of Transportation Studies, University of California–Davis, 2012.

Variability and Uncertainty in Greenhouse Gas Life Cycle Assessment."

Definition of the 2050 GHG Reduction Metric

To measure the performance of technological advances in reducing GHG emissions from the U.S. transportation sector, the Argonne National Laboratory's VISION model was used to establish a WTW 2005 baseline of GHG emissions for the LD and MD/HD transportation segments. An alternate method was used to establish a baseline for buses and non-road transport. The 2005 WTW GHG emissions for buses, marine, rail, and air was estimated by taking 2005 AEO energy usage for these end-use categories and multiplying by GREET fuel-cycle GHG carbon coefficients[25] associated with the petroleum feedstocks most predominately used for these end-use categories. This approach was deemed to be sufficiently accurate since these segments contribute less than 20% of the energy consumed by the entire transportation sector.

Table 6-1 summarizes the transportation sector 2005 WTW GHG emissions baseline and compares it to the GHG emission levels representing a 50% reduction by 2050: 1,000 million metric tons (MMT) CO_2e for LD and HD vehicles and 250 MMT CO_2e for non-road end-use categories including rail, marine shipping, and air, but excluding the "other" category.[26] Further discussion explaining the basis for the numbers in this table is provided in Appendix 6A, "Calculation of 2005 GHG Emissions and 50% Reduction," at the end of this chapter.

Fuel Carbon Intensity

Carbon intensity is a measure of the WTW CO_2e emitted by a fuel for every BTU used. Future carbon intensities are uncertain because they are influenced by variations in numerous factors such as fuel production efficiency, impact of ILUC, and methods for fuel distribution. As technologies continue to advance, it is reasonable to expect future fuel production to become more efficient and associated carbon emissions to decrease.

The future GHG emissions for the fuels considered in this study were evaluated using the default GREET future carbon intensity values for each fuel,

25 Utilized GREET version 1.8d year 2005 GHG coefficients using a high heating value basis.

26 Calculated 50% GHG reduction levels for on-road and non-road categories are rounded up and kept at one and a half digit precision, which is consistent with the quantitative analysis and approach of this study.

U.S. Transportation Sector by End-Use Categories	2005 Energy Use (Quadrillion BTU) AEO2008 Table A7	Energy Contribution	2005 WTW Emissions (MMT CO_2e)‡ VISION values	50% Emissions Level (MMT CO_2e)
Light-Duty Vehicles*	16	59%	1,500	750
Heavy-Duty Vehicles†	5	18%	500	250
50% Reduction Level for On-Road Segment‡				*1,000*
Rail	<1	2%	100	50
Marine Shipping	1	4%	100	50
Air	3	10%	300	150
50% Reduction Level for Non-Road Segment‡				*250*
Other (excluded for 50% GHG calculation)	2	6%		
Total Transportation	**27**	**100%**		
Total Transportation (excluding "Other")	**25**		**2,500**	**1,250**

* Includes commercial light trucks.
† Includes buses and freight trucks.
‡ Value rounded up to nearest 50.

Table 6-1. *2005 Baseline Emissions and 50% Reduction Level* with the exception of hydrogen, and are shown in Table 6-2. The future carbon intensity value for hydrogen was calculated by adding emissions from distribution and dispensing processes[27] to the default GREET value, which resulted in a ~10% increase in carbon intensity.

To gain perspective on the uncertainty of carbon intensity values, it is helpful to consider carbon intensity values other than those provided by GREET. The variability resulting from different carbon coefficient values for similar fuels are also shown in Table 6-2.

The Renewable Fuel Standard (RFS) program defines "advanced biofuels" as any bio-derived fuel that reduces life-cycle GHG emissions by at least 50%, except corn starch derived ethanol. This analysis uses this definition to be consistent with the RFS program. The life-cycle GHG emissions for advanced biofuels are represented by the range of carbon intensity values for sugarcane and forest residue feedstocks. The Light-Duty Vehicles, Heavy-Duty Vehicles, and Biofuels chapters of this study (Chapters 2, 3, and 12) consider a number of cellulosic feedstocks for biofuels production (corn stover, woody biomass, forest residue, and switchgrass) and do not consider imported sugarcane. The use of corn stover, woody biomass, or switchgrass results in slightly lower fuel carbon intensity than that considered in this GHG analysis. The use of imported sugarcane results in slightly higher fuel carbon intensity than using only cellulosic feedstock. The distinction between advanced biofuels and cellulosic biofuels has been made for transparency; however, this distinction does not have a material impact on the GHG emissions calculated in this analysis.

The carbon coefficients in GREET may not correlate with current real-world performance data. Coefficients have not been modified to reflect potential future changes/advancements beyond those already assumed in GREET. Furthermore, the uncertainty inherent in GHG emissions calculations (discussed in detail in Topic Paper #30, "Data Variability and Uncertainty in Greenhouse Gas Life Cycle Assessment") is not considered in the study findings. The degree of uncertainty can vary significantly from fuel to fuel. Traditional fuels such as gasoline and diesel have GHG emission uncertainty

	GREET Default*	Uncertainty Range†	
		Low	High
Gasoline‡	88,353	86,306	108,851
Diesel	93,526	93,424	111,367
Corn Ethanol§	68,861	49,879	109,038
Advanced Biofuels¶	32,609–37,258	25,206	75,226
CNG	70,417	63,993	79,491
LNG	69,190	64,662	88,917
Electricity	205,333	204,607	206,352
Hydrogen#	104,801	85,758	124,916

* GREET default values for year 2020.

† Uncertainty range values may include impact of indirect land use change. A description of recognized North American and European GHG models used to develop the uncertainty ranges are described in Appendix 6B, "Third-Party Data Resources for Fuel Carbon Intensity Values," at the end of this chapter.

‡ 90% gasoline blended with 10% corn ethanol.

§ 85% corn ethanol blended with 15% gasoline.

¶ 85% ethanol from sugarcane or forest residue blended with 15% gasoline.

\# Not GREET default—see Chapter Fifteen, "Hydrogen," for calculation.

Table 6-2. *Future Fuel Cycle Carbon Intensity Values (Grams of CO_2e per Million BTU)*

of ~10%. Fuels that have not been demonstrated at a commercial scale would have greater uncertainty. If the impact of ILUC is considered, the uncertainty in GHG emissions from biofuels could result in higher GHG emissions.

This analysis assumes life-cycle carbon intensity values remain unchanged after 2020 because GREET does not provide carbon intensity values beyond 2020. However, it is reasonable to expect that process and technology improvements and efficiencies will continue to put downward pressure on the carbon intensity of fuels beyond 2020.

Electricity, natural gas, and hydrogen have the potential for lower carbon intensity in the future.[28] There are efforts under way to reduce grid carbon intensity through the increased use of wind, solar,

27 Based on Chapter Fifteen, "Hydrogen."

28 While natural gas has a favorable environmental profile compared to other fossil energy sources, an analysis of the GHG emissions associated with shale gas extraction has raised potential issues. The National Petroleum Council's 2011 *Prudent Development* report offers a comparative analysis of current life-cycle studies of natural gas.

Future Electricity Generation Carbon Intensity

Well-to-wheels GHG emissions from plug-in electric vehicles, especially all-electric battery electric vehicles, correlate with the carbon intensity of electricity generation. Consistent with study methodology, the study assumes the AEO2010 Reference Case extrapolated to 2050; however, the recently released AEO2012 Early Release projects a 7% lower grid carbon intensity for 2035 relative to the AEO2010 due to recent changes in the grid mix, such as displacement of coal by natural gas power generation.

The future mix of the electric grid is uncertain. For example, future grid emission characteristics can be affected by:

- potential new regulations on electricity generation emissions
- the displacement of coal power generation with natural gas
- the future of nuclear power generation influenced by the recent incident at the Fukushima Daiichi nuclear complex
- the economic slowdown or changes in fiscal benefits on renewable power generation such as solar and wind*
- the potential for carbon capture and sequestration implementation
- the response to the potential price increases on electricity from changes in the grid.

Examining the potential future of the grid emission characteristics and its uncertainties was beyond the scope of this study. However, there is great interest in the impact of lower grid GHG emission on electric vehicles. Therefore, in the figure below, we offer two studies as illustrations of possible lower electricity grid carbon intensity values. The Resources for the Future (RFF) study[†] and Stanford Energy Modeling Forum study[‡] (EMF-22) calculated significant emission reductions by increasing the use of nuclear and renewable power generation, adding carbon capture and sequestration to coal and natural gas power generation, and displacing coal with natural gas power generation. Additional details on these and other low carbon grid analyses are provided in the "Additional GHG Reduction Strategies – Reduced Carbon Intensity of the U.S. Electric Grid" section of this chapter.

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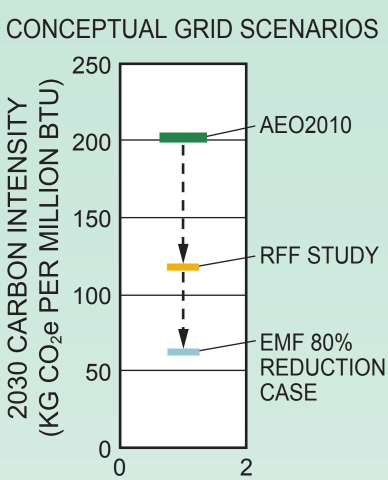
* Jesse Jenkins, Mark Muro, Ted Nordhaus, Michael Shellenberger, Letha Tawney, and Alex Trembath, *Beyond Boom and Bust: Putting Clean Tech on a Path to Subsidy Independence,* Brookings Institution, April 2012.

† Stephen P. A. Brown, Alan J. Krupnick, and Margaret A. Walls, *Natural Gas: A Bridge to a Low-Carbon Future?,* Resources for the Future, Issue Brief 09-11, December 2009.

‡ John P. Weyant, *Energy Modeling Forum 22: Climate Change Control Scenarios,* Stanford University, February 2010.



	Grid Carbon Intensity (kg CO_2e/ million BTU)	Grid Mix by Generation Source						
		Coal	Coal with CCS	Natural Gas	Natural Gas with CCS	Nuclear	Renewables	Other
AEO2010	202	48%	0%	16%	0%	20%	15%	1%
RFF Study	118	23%		28%		25%	23%	2%
EMF 80% Reduction Case	64	10%	3%	26%	4%	28%	29%	0%

nuclear, biomass, and other power generation alternatives. Similarly, the use of biomethane would reduce the carbon intensity of natural gas. Some options for reducing the carbon intensity of hydrogen production include the increased use of biomass/biogas feedstocks for fuel production, electrolysis using renewable electric power, and carbon capture and sequestration. These options are discussed in their respective chapters.

RESULTS AND DISCUSSION

Light-Duty Vehicles

U.S. Fleet Average Fuel Economy

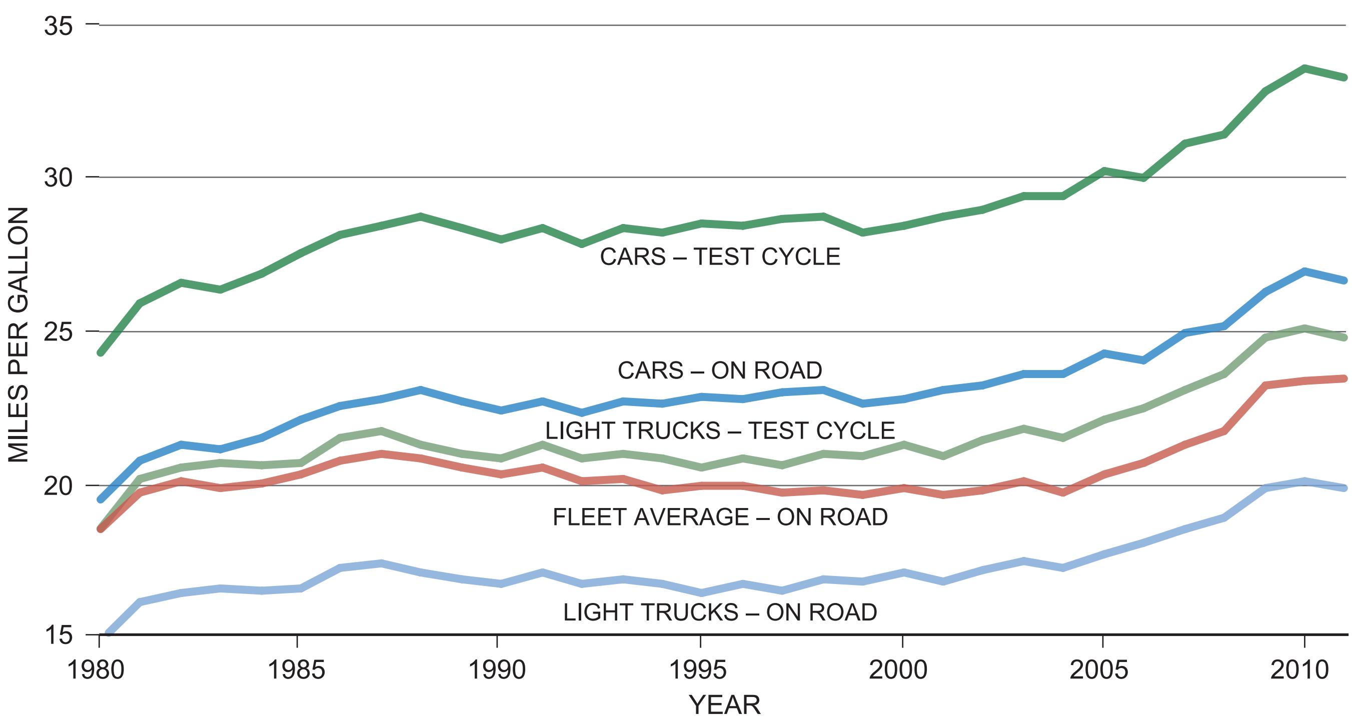
The 2010 average test cycle[29] fuel economy for new models of LD cars and trucks was 33.7 and 25.1 miles per gallon (mpg), respectively. Historically, "on-road" fuel economies have been approximately 80% of the test cycle values; therefore, the 2010 on-road average fuel economy for new models is approximated to be 27 mpg for LD cars and 20.1 mpg for LD trucks. The historical fuel economy for new LD cars and trucks is shown in Figure 6-5.

The market share of LD trucks (including pickups, vans, and SUVs) has grown steadily from 9.7% in 1979 to 47% in 2001 and has remained in the 50% range up to 2011, largely due to the popularity of SUVs.[30] This market shift toward LD trucks has resulted in a lower near-term weighted average fuel economy compared to historical averages, which were closer to LD car performance.

The average on-road fuel economy ranges for each vehicle type from several analyses are shown in Figure 6-6. NPC analysis fuel economy ranges are consistently higher than those reported in VISION. This is because VISION data are based on AEO2010, which does not consider the impact of technology hurdles being overcome, whereas the NPC study does.

29 Test cycle refers to fuel economy measured under controlled conditions in a laboratory using a standardized test procedure specified by federal law. Commonly referred to as EPA mileage.

30 U.S. Department of Transportation, National Highway Traffic Safety Administration, *Summary of Fuel Economy Performance,* NVS-220, April 2011, http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2011_Summary_Report.pdf.



Source: U.S. Department of Transportation, *Summary of Fuel Economy Performance*, April 2011.

Figure 6-5. *Historical Average Fuel Economy*

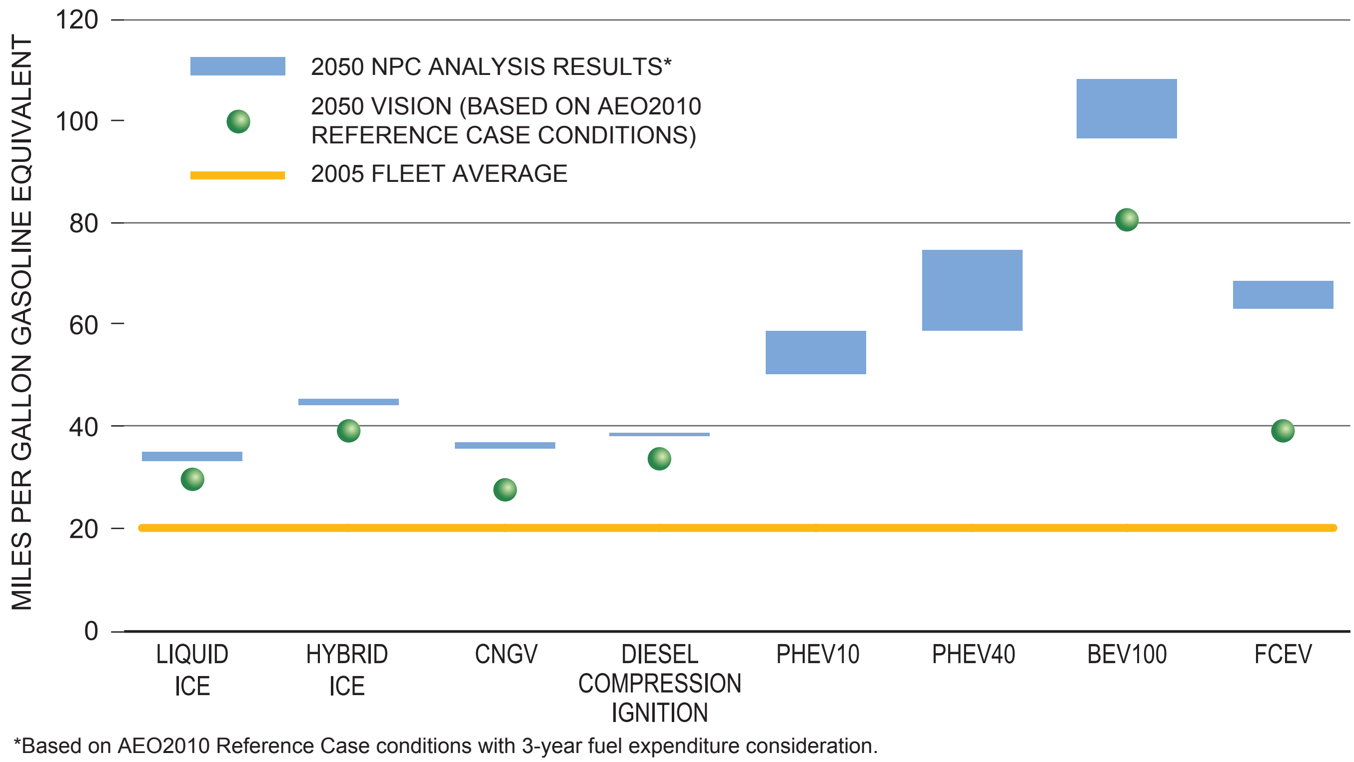


Figure 6-6. *Future On-Road Fuel Economy*

The NPC analysis shows that the consideration of longer-term economics would increase the fuel economy of all vehicles considered in this study and would have the greatest impact on improving the fuel economy of ICE vehicles. EIA data suggest that consumers typically purchase vehicles with fuel economy investments that provide for the lowest cost of driving (vehicle price and fuel costs) over a short time horizon (~3 years). If vehicles are instead designed with fuel economy investments that achieve the lowest cost of driving over the longer term (up to the life of a vehicle, ~17 years), the fuel economy for each system would increase. This in turn results in reduced GHG emissions.

LD Fuel-Vehicle Systems Emissions Comparison

GHG emissions from LD vehicles vary with each fuel-vehicle system. The LD vehicle fuel-vehicle combinations evaluated in the study are shown in Table 6-3.

The source of GHG emissions for fuel-vehicle systems can vary, particularly for PEVs and FCEVs where emissions are shifted upstream of vehicle use. Combining the data on the future carbon intensity of fuels (which includes WTW emissions) and future weighted average fuel economy ranges (weighted averages are based on the assumption that there is no change from current vehicle class mix) yields a comparison of per-mile emissions for the fuel-vehicle systems evaluated in this study, as shown in Figure 6-7.

Other recognized American and European GHG models provide a range of different carbon intensity values than GREET values. These alternate values include considerations, such as ILUC, that are not included in the GREET values. These differing carbon intensity values are represented in the GHG emissions ranges in Figure 6-7 as vertical green lines and show the variability and uncertainty in the actual range of GHG emissions.

Comparing the calculated GHG emissions for all of the 2050 LD fuel-vehicle systems to the average 2005 LD vehicle (~550 gCO_2e/mile) reveals that all LD fuel-vehicle systems can have significant

		Vehicle Options							
		Liquid ICE	Hybrid ICE	Diesel Compression Ignition	PHEV 10	PHEV 40	CNGV	BEV 100	FCEV
Fuel Options	Gasoline	☑	☑		☑	☑			
	Diesel			☑					
	Corn Ethanol	☑	☑		☑	☑			
	Advanced Biofuels	☑	☑		☑	☑			
	Natural Gas						☑		
	Electricity				☑	☑		☑	
	Hydrogen								☑

Table 6-3. *Light-Duty Vehicle Fuel-Vehicle Systems Evaluated*

improvements that result in greater than 40% GHG reduction on a per-mile-traveled basis.

Comparing the GHG emissions ranges for 2050 LD fuel-vehicle systems to each other suggests ICEs, hybrids, and PHEV10/40[31] running on advanced biofuels have the lowest GHG emissions on a per-mile-traveled basis if uncertainties such as ILUC are not considered. However, a U.S. LD vehicle fleet that is fueled exclusively with advanced biofuels is not feasible. The expected supply of advanced biofuels is insufficient to meet the entire expected LD demand due to limited biomass availability. Furthermore, when economic competitiveness and/or energy security are considered, vehicles fueled solely with advanced biofuels may not be preferred. Therefore, alternate fuel-vehicle systems need to be considered. FCEVs fueled by hydrogen produced from natural gas have the next lowest GHG emission on a per-mile-traveled basis after vehicles fuel by advanced biofuels. Hybrid gasoline vehicles, compressed natural gas vehicles (CNGVs), PHEVs, and BEVs have comparable GHG emissions to each other and lower emissions than ICE gasoline and compression ignition diesel vehicles.

If uncertainties in the calculation of WTW GHG emissions (e.g., ILUC) are not considered, it could be concluded that a significant utilization of corn ethanol and advanced biofuels may significantly reduce on-road GHG emissions. Although they were not used in this analysis, ILUC values for corn ethanol are available in GREET. These values increase the GHG emissions of corn ethanol from the values presented in Figure 6-7, and should be included when considering real-world GHG impacts from corn ethanol. For this reason, corn ethanol is not considered as a viable option for reducing GHG emissions to 50% of 2005 levels. As advanced biofuels technologies improve over time, costs are expected to decline. When these costs reach levels comparable to or lower than those of competing fuels, advanced biofuels utilization could increase. If advanced biofuels compete primarily with gasoline and diesel, the price of crude oil would impact the economic competitiveness of advanced biofuels. In 2011, crude oil price accounted for about 68% of the retail price of gasoline.[32] Higher crude oil prices or other factors that put upward pressure on gasoline and diesel prices could in turn accelerate advanced biofuels' competitiveness.

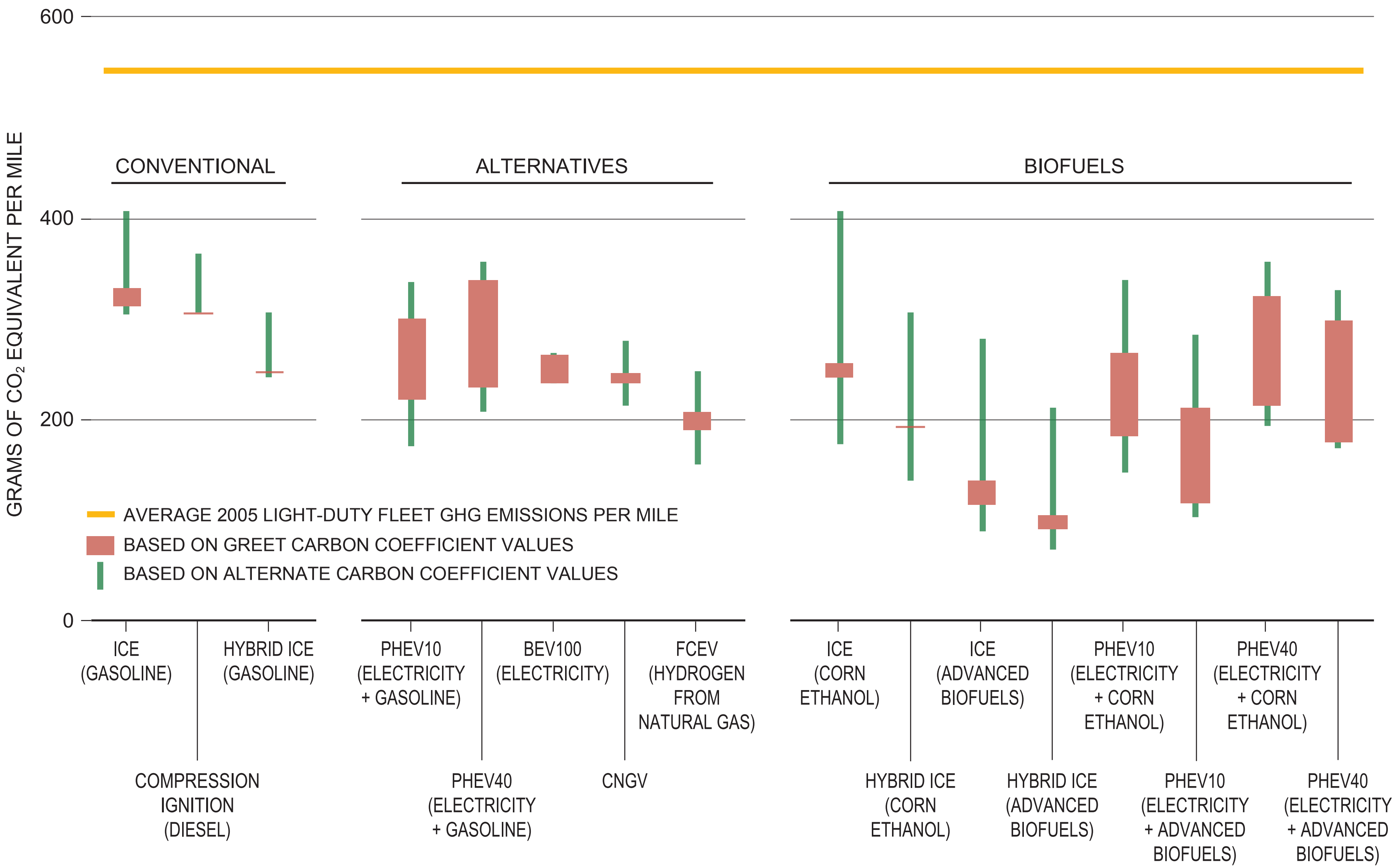
2050 Light-Duty Vehicle Fleet GHG Emissions

Achieving total fleet-level emissions reductions is dependent on the following:

- Future vehicle fuel economy (discussed previously in this chapter)
- Future fuel carbon intensity (discussed previously in this chapter)

31 PHEV10 means plug-in hybrid electric vehicle that is able to drive up to 10 miles in all-electric mode, and PHEV40 means plug-in hybrid electric vehicle that is able to drive up to 40 miles in all-electric mode.

32 Based on an average gasoline retail price of $3.52 and average of gasoline components as reported by EIA. See American Petroleum Institute's "What's Up with Fuel Prices," http://www.api.org/~/media/Files/Oil-and-Natural-Gas/Gasoline/FuelPriceFacts.ashx.



Notes:
- Gasoline assumed to contain 10% corn ethanol.
- Based on NPC analysis new vehicle fuel economy in 2050 under AEO2010 Reference Case conditions and assumes technology hurdles are overcome.
- 2020 GREET fuel cycle carbon intensity used (GREET does not go beyond 2020).
- Advanced Biofuels carbon intensity based on 15% gasoline blended with 85% biofuels from forest residue or sugarcane feedstock.
- Biofuels uncertainty range values may include impact of indirect land use change (ILUC).
- Green vertical lines represent uncertainty based on alternate fuel cycle carbon intensity assumptions and may include impact of ILUC.

Figure 6-7. *2050 Fuel-Vehicle System GHG Emissions*

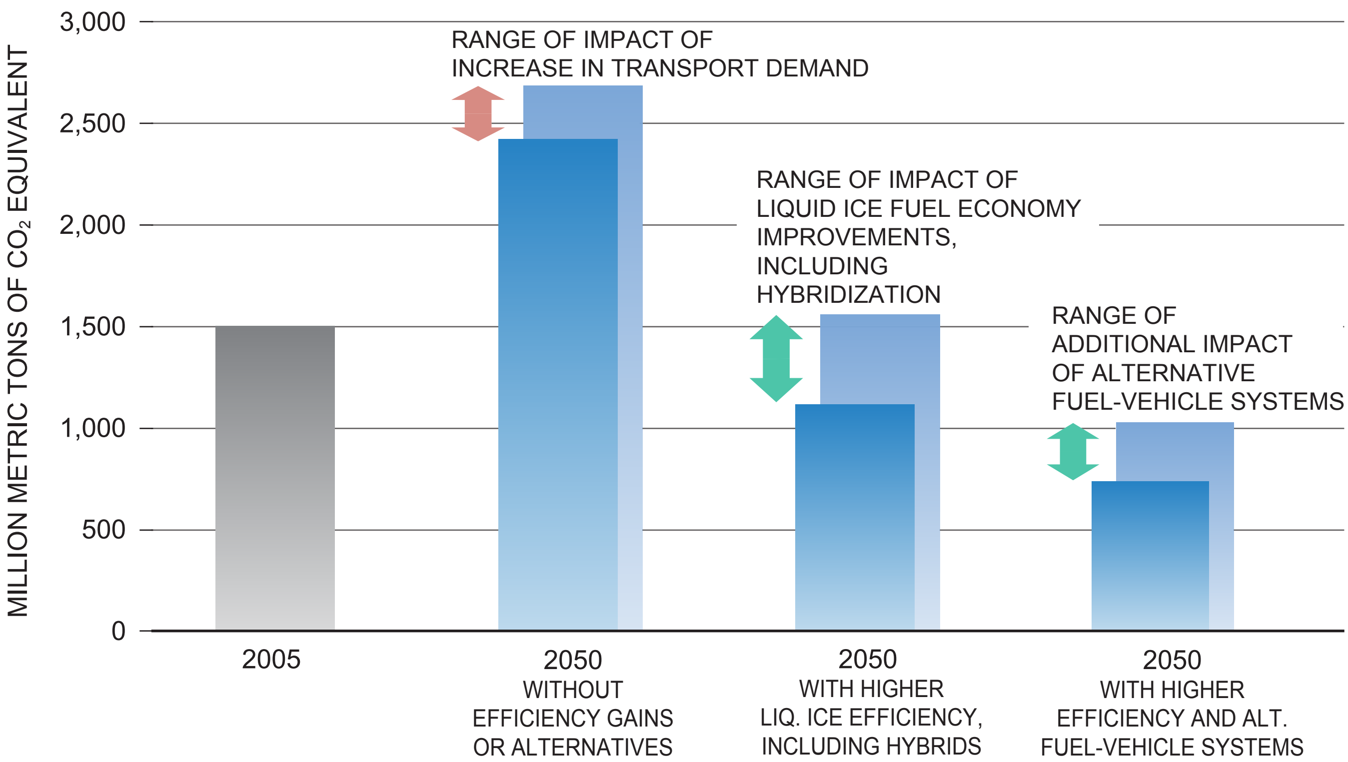
- Future portfolio of fuel-vehicle systems in the fleet (discussed in Chapter Two, "Light-Duty Vehicles")
- Future demand for on-road transportation, which is often quantified as VMT demand (LD vehicle VMT is projected to increase by 62–79% from 2005 levels in 2050[33]).

Future VMT is uncertain and can have material impact; therefore, a range of VMT has been considered in this analysis.

Figure 6-8 shows the potential 2050 impact of LD VMT growth and changing LD fuel-vehicle system portfolios. The total LD vehicle fleet GHG emissions in 2005 were ~1,500 MMT CO_2e. This measure of 2005 GHG emissions provides a benchmark for future GHG emissions estimates under the following three conditions taking into account increased VMT:

- If no vehicle fuel economy improvements and no changes in fuel carbon intensity are assumed from 2005 to 2050, total LD fleet emissions would rise to ~2,400–2,700 MMT CO_2e due to increasing VMT.
- If fuel economy improvements in liquid ICE vehicles and changes to the carbon intensity of gasoline are assumed (only gasoline ICE vehicles are in the 2050 fleet), total LD fleet GHG emissions would drop back to near 2005 levels (~1,200–1,600 MMT CO_2e) even with increased VMT.
- If all fuel-vehicle systems evaluated in this study advance and are commercialized, total LD fleet GHG emissions would further reduce to ~700–1,000 MMT CO_2e.

33 VMT increase is based on AEO2010 Reference Case and AEO2012 Early Release extrapolated to 2050.



Assumptions:
- Based on AEO2010 Reference Case conditions with 3-year and 17-year fuel expenditure considerations.
- VMT range based on AEO2010 Reference Case and AEO2012 Early Release, extrapolated to 2050.
- Carbon intensity (grams CO_2e/megajoule) values for fuels are from GREET in 2020.
- For cases including alternative fuel-vehicle systems, technology and transition hurdles are assumed overcome.
- Biofuels, where included, do not consider the impact of indirect land use change.

Figure 6-8. *Projected Range of Impact of Demand, Fuel Economy Improvements, and Alternative Fuel-Vehicle Systems on 2050 Light-Duty Vehicle Fleet GHG Emissions*

Reducing GHG emissions in the LD fleet to 50% of 2005 LD vehicle segment levels requires limiting LD vehicle GHG emissions to ≤750 MMT CO_2e. If technology and transition hurdles are overcome and advanced fuel-vehicle systems are commercialized, the lower end of the range of LD vehicle fleet GHG emissions achieves this level. Only a very limited number (<3%) of study analysis fleet portfolios achieved ≤750 MMT CO_2e and required the following conditions: high fuel economy, low VMT, and significant economic volumes of cellulosic biofuels (not considering the impact of ILUC). In the study modeling, this was achieved under Reference and High Oil Price Case conditions (2050 oil prices of ~$155–215/barrel in 2008 dollars) with the availability of up to ~70 billion gallons of cellulosic ethanol equivalent plus >20 billion gallons of corn-based ethanol per year. Vehicles in these low emission cases are designed considering fuel expenditures over the long term (up to 17 years—the life of the vehicle). Additionally, these low GHG emissions vehicle portfolios were typically characterized by significant shares of FCEVs and limited availability of CNGVs.

The calculations in this analysis were developed based on economic criteria, specifically, minimizing the cost of driving under varying conditions and assumptions. Fuel-vehicle systems with higher GHG emissions could have an economic advantage over fuel-vehicle systems with lower emissions. For example, the vehicles fueled with natural gas could be economically advantaged over vehicles running on advanced biofuels when crude oil prices are higher than the AEO2010 study Reference Case price projections (because natural gas price per BTU increases at only 25–33% the rate crude oil price increases in AEO2010). In this case, natural gas market penetration is advantaged, which results in greater market penetration of CNGVs and greater GHG emissions than if advanced biofuels utilization increases. Therefore, it is important to note that crude oil prices and GHG emissions are not always inversely related.

Medium- and Heavy-Duty Vehicles

Segment Characteristics

MD and HD vehicles are used in every sector of our economy. For the purposes of this discussion, MD and HD vehicles are grouped as Class 3-6 and Class 7&8, respectively.

The MD/HD vehicle segment uses nearly 20% of the total annual energy required by the U.S. transportation sector and produces nearly 20% of total transportation sector GHG emissions (including LD vehicle, marine, rail, and aviation). Vehicle distribution and fuel usage within the MD/HD vehicle classes vary significantly and are shown in Table 6-4.

HD vehicles contribute to over 80% of the total fuel consumption (and resulting emissions) in the MD/HD segment, as shown in Figure 6-9.

The emissions impact of fuel efficiency technologies in MD/HD vehicles can vary significantly due to application and duty cycle. For example, vehicles that consume significant amounts of fuel and have duty cycles with frequent start/stop events can realize far greater reductions in GHG emissions from hybrid solutions than vehicles with limited start/stop duty cycles. Because fuel consumption and emissions in the MD sector are dwarfed by the HD sector (specifically Class 8 vehicles),

	Medium Duty	Heavy Duty		
	Class 3-6	Class 7	Class 8a	Class 8b (long haul)
Number of Vehicles in Use in 2010	4 million	4.5 million		
Number of Vehicles Projected by 2050	11 million	7 million		
Annual Fuel Consumption*	1–7,000 gge/ vehicle	6–8,000 dge/ vehicle	9–12,000 dge/ vehicle	17–24,000 dge/vehicle

* gge = gasoline gallon equivalent; dge = diesel gallon equivalent.
Source: VISION model, based on AEO2010.

Table 6-4. *Medium- and Heavy-Duty Vehicle Distribution and Fuel Usage by Class*

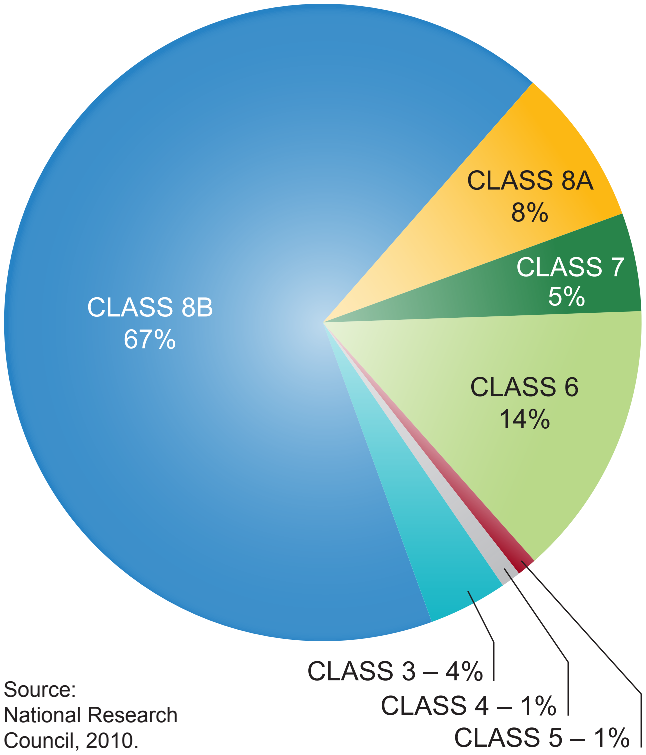


***Figure 6-9.** Medium-Duty Vehicle (Class 3-6) and Heavy-Duty Vehicle (Class 7&8) Fuel Consumption by Class*

technologies that reduce emissions in the HD sector will be needed to materially impact emission in the overall MD/HD sector.

Vehicle Miles Traveled Considerations

Annual VMT in the trucking sector has grown more quickly than in the LD sector; therefore, the MD/HD segment's share of total transportation sector fuel consumption and GHG emissions has increased.[34] The energy efficiency of freight movements is lower for trucks than for rail or marine transport; however, trucking is often preferred or required because of its ability to deliver goods from point of origin to point of use.[35] Over 80% of all communities in the United States are supplied with commercial goods delivered exclusively by trucks.

34 National Research Council of the National Academies, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles,* 2010.

35 Anthony Greszler, "Heavy Duty Vehicle Fleet Technologies for Reducing Carbon Dioxide: An Industry Perspective," Chapter Six in *Reducing Climate Impacts in the Transportation Sector,* Daniel Sperling and James Cannon (eds.) Springer Science and Business Media, December 2009, page 103.

The AEO2010 study Reference Case projects MD/HD VMT will increase more than twofold between 2010 and 2050. Significant vehicle efficiency improvements and/or lower carbon intensity fuels will be needed to offset the GHG emissions resulting from the projected MD/HD VMT growth.

With freight transport growth averaging over 5% annually, improvements in fuel economy alone may not be sufficient to materially reduce total fleet GHG emissions. The mitigation of GHG emissions from the MD/HD transportation segment may ultimately require the use of lower carbon fuels.[36]

Fuel Economy Regulations

Past environmental regulations for MD/HD vehicles have focused on the reduction of criteria air pollutant emissions. Significant improvements have been achieved in the reduction of criteria air pollutants, but with negative impacts to vehicle fuel economy. Looking forward, future requirements focus on reducing GHG emissions through improved fuel economy. In the development of fuel efficiency standards for MD/HD vehicles, the familiar "miles per gallon" metric associated with LD vehicles can present a challenge. Miles per gallon does not acknowledge the work performed by a vehicle. The metrics of "ton-miles per gallon" (developed by the Environmental Protection Agency [EPA]) to measure GHG emissions, and similarly "gallons per 1,000 ton-miles" (developed by National Highway Transportation Safety Administration [NHTSA]) to measure fuel consumption, were established to account for the work element (hauling freight or "tons") of commercial vehicle operations. While these new regulatory metrics do not perfectly match all of the diverse applications that commercial vehicles serve, the metrics do strike a balance between influencing desired market behaviors and regulatory simplicity.

GHG regulations for MD/HD vehicles were finalized by the EPA in July 2011 and corresponding standards for fuel economy were developed by NHTSA. These standards will phase in to the 2017 HD vehicle (Class 7&8) fuel economy and emissions requirements shown in Table 6-5.

Emissions regulations allow for compliance in one of two ways: by certifying engine emissions at

36 Ibid., page 112.

	EPA GHG Emissions Standard (grams CO_2 per ton-mile)			NHTSA Fuel Consumption Standard (gallons per 1,000 ton-miles)		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Class 7 Day Cab	104	115	120	10.2	11.3	11.8
Class 8 Day Cab	80	86	89	7.8	8.4	8.7
Class 8 Sleeper Cab	66	73	71	6.5	7.2	7.1

Table 6-5. *Newly Implemented GHG and Fuel Economy Regulations for Class 7&8 Tractor-Trailers in the 2017 Time Frame*

or below the applicable standards for each of the three regulated GHG constituents (CO_2, CH_4, and N_2O) individually; or by measuring total CO_2, CH_4, and N_2O emissions on a CO_2 equivalency basis.

Similar regulations went into effect for heavy-vocational vehicles (e.g., refuse haulers, construction trucks, etc.) and for Class 3-6 vehicles. While standards vary by vehicle class and segment, a minimum of 7% emissions reduction is cited for all classes by the EPA, with emission reductions for some classes reaching as high as 20%, relative to 2010 levels. According to the EPA's Regulatory Impact Analysis, the new rule will lead to a GHG reduction of 72 MMT of CO_2e and a fuel savings of 5.8 billion gallons in the year 2030, compared to a baseline case without the new rule.

Natural gas engines are subject to the same rules as diesel engines; however, because their WTW emission profile is quite different, their path for meeting the standard is different than that of diesel engines. Natural gas engines generate lower CO_2 emissions than diesel engines, but higher CH_4 emissions. The CH_4 limit of 0.1 grams per brake horsepower hour within the regulation is lower than the typical CH_4 emissions of a natural gas engine. The alternate compliance path, based on CO_2 equivalent emission levels, allows for engines (such as natural gas engines) with CO_2 emissions below the applicable standard to generate emissions credits that can be used to offset higher CH_4 and/or N_2O emissions.

Natural gas engines are expected to comply via the CO_2-equivalent methodology using CO_2 credits to offset CH_4 emissions. The use of natural gas engines is expected to generate a surplus of CO_2 credits even after allowance for CH_4 emissions. It is expected that diesel engines will comply with the regulation by emissions reductions that bring CO_2, CH_4, and N_2O emissions below applicable standards.

MD/HD Fuel Economy

EIA considers future EPA and NHTSA requirements (in gCO_2/ton-mile and gallon/1,000 ton-miles) to develop future MD/HD fuel economy projections. Historical and future new vehicle fuel economies from EIA for the MD/HD segment are shown in Figure 6-10.

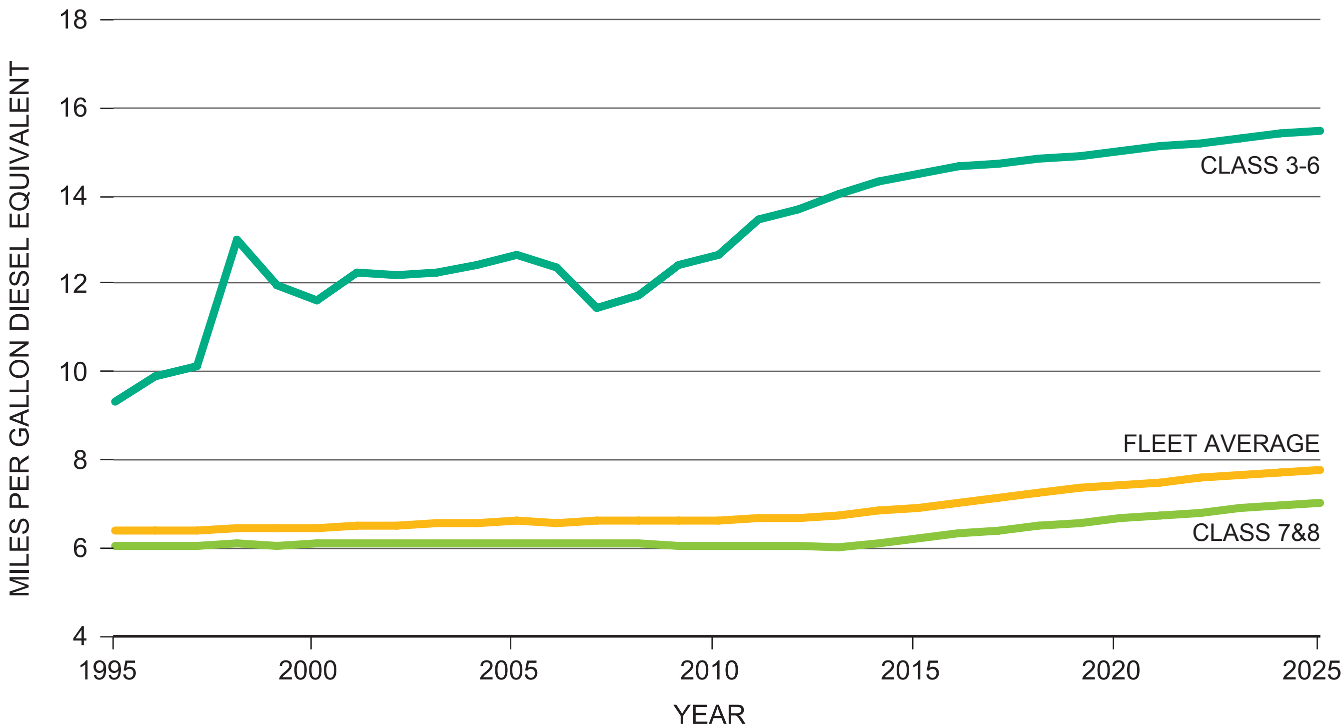
The potential 2050 average on-road fuel economy ranges for the MD/HD fuel-vehicle systems considered in this analysis are shown in Figure 6-11.

MD/HD Fuel-Vehicle Systems Emissions Comparison

The MD/HD vehicle fuels and vehicle combinations evaluated in this study are shown in Table 6-6.

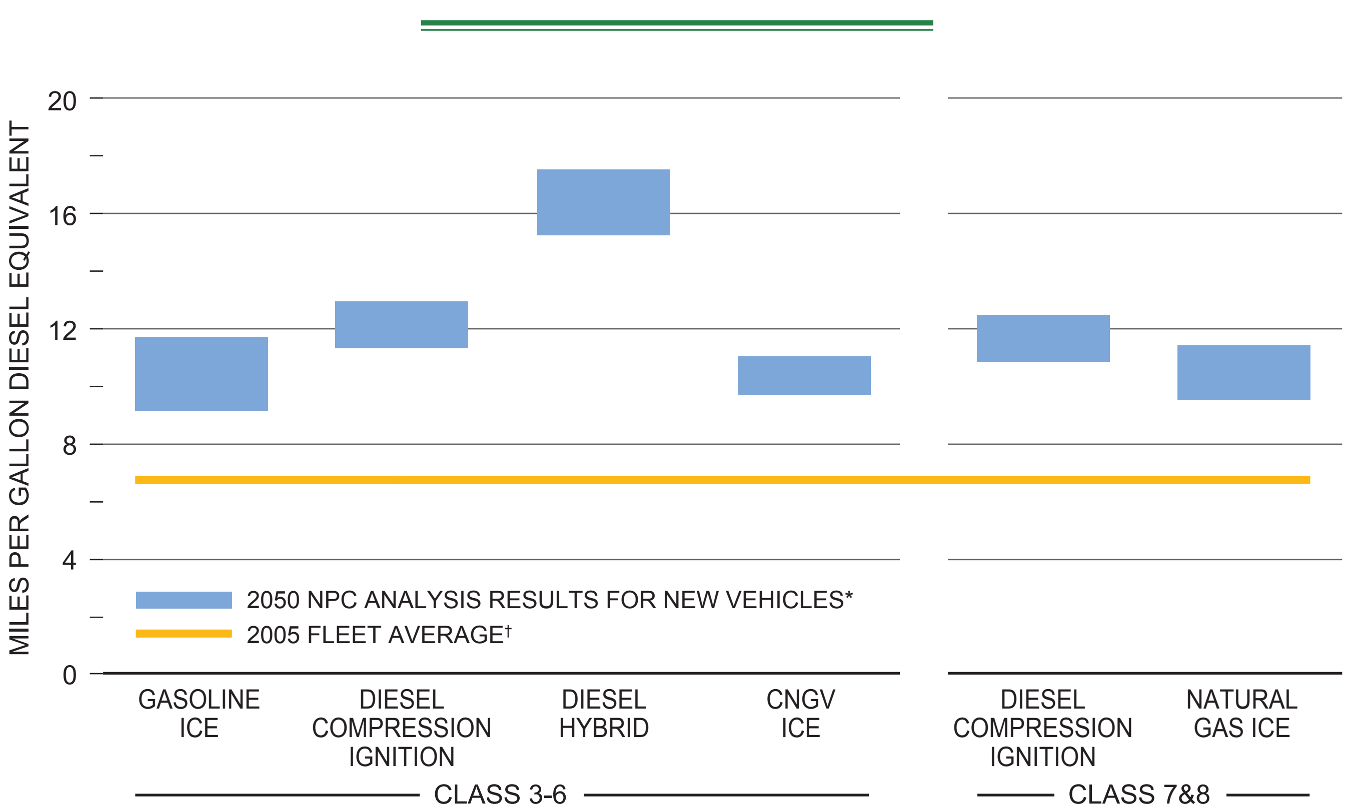
MD/HD vehicle GHG emissions were evaluated on a WTW basis. Figure 6-12 shows 2050 GHG emissions per mile for the MD/HD fuel-vehicle systems considered in this analysis. These results are calculated using the NPC analysis fuel economy ranges and GREET carbon intensity coefficient for each fuel presented previously. Alternate GHG models and data sets, used in the LD vehicle GHG emissions analysis are also used in this MD/HD analysis to establish ranges of uncertainty and variability and are represented by vertical green lines.

Comparing the calculated GHG emissions for all of the 2050 MD/HD fuel-vehicle systems



Source: Energy Information Administration, AEO2012 Early Release.

Figure 6-10. *Medium- and Heavy-Duty Vehicle New Model Year Average Fuel Economy*

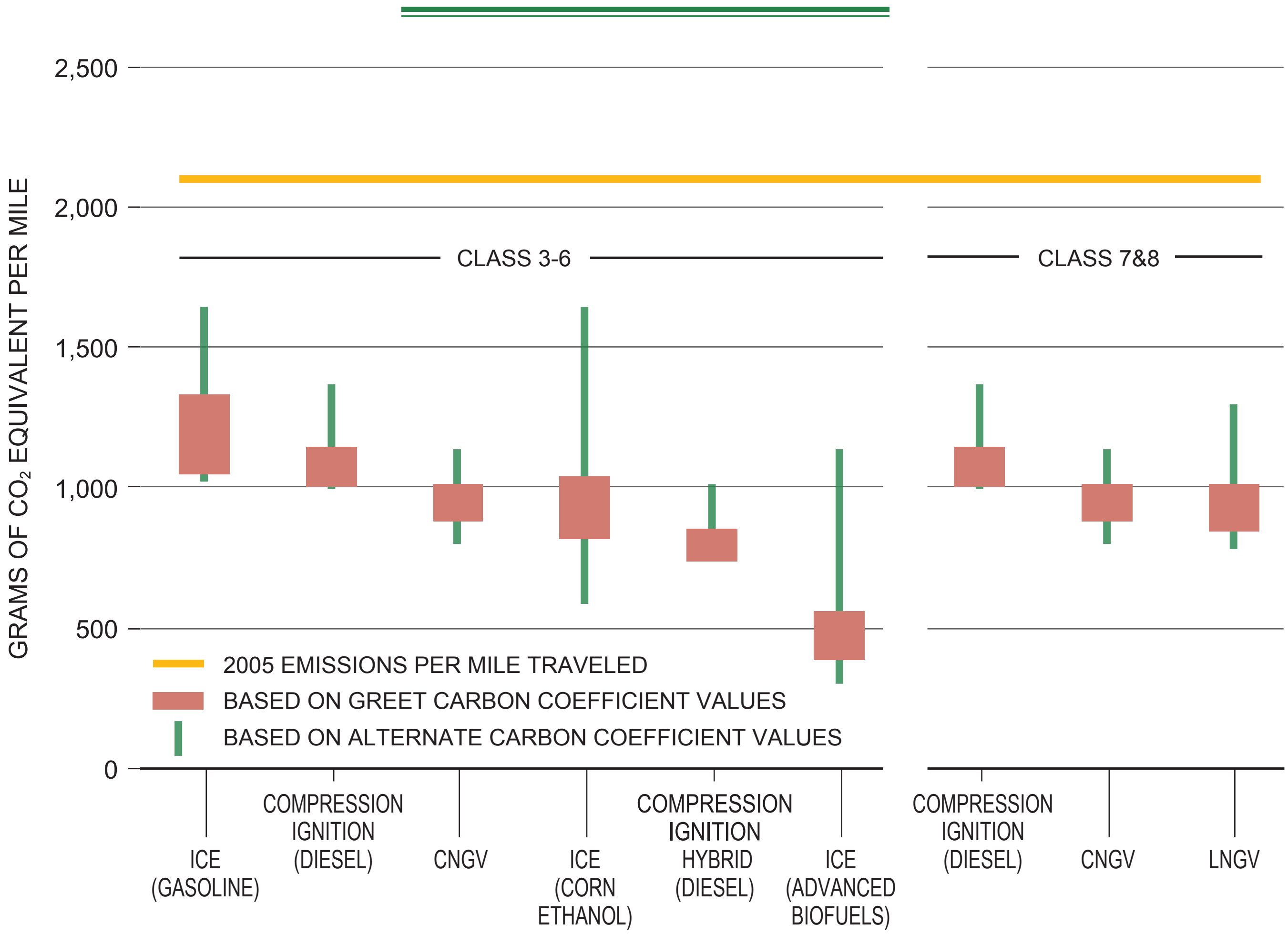


* AEO2010 Reference Case conditions.
† Based on AEO2012 Early Release.

Figure 6-11. *Potential Future On-Road Fuel Economy*

		Vehicle Options					
		Class 3-6				Class 7&8	
		Gasoline ICE	Diesel	Diesel Hybrid	CNGV ICE	Diesel Compression Ignition	Natural Gas ICE
Fuel Options	Gasoline	☑					
	Diesel		☑	☑		☑	
	Corn Ethanol	☑					
	Advanced Biofuels	☑					
	CNG				☑		☑
	LNG						☑

Table 6-6. *Medium- and Heavy-Duty Fuel-Vehicle Systems Evaluated*



Notes:
- Gasoline assumed to contain 10% corn ethanol.
- Based on NPC analysis new vehicle fuel economy in 2050 under AEO2010 Reference Case conditions and assumes technology hurdles are overcome.
- 2020 GREET fuel cycle carbon intensity used (GREET does not go beyond 2020).
- Advanced Biofuels carbon intensity based on 15% gasoline blended with 85% biofuels from forest residue or sugarcane feedstock.
- Biofuels uncertainty range values may include impact of indirect land use change.

Figure 6-12. *2050 CO_2 Emissions per Mile by Medium- and Heavy-Duty Fuel-Vehicle Systems* to those for the average 2005 MD/HD vehicle (~2,000 gCO_2e/mile) shows that all MD/HD fuel-vehicle systems can have significant fuel economy improvements that result in a GHG reduction of 40% or greater on a per-mile-traveled basis.

In Class 3-6 vehicles, liquid ICE vehicles using primarily advanced biofuel have the lowest GHG emissions on a per-mile-traveled basis if uncertainties such as ILUC are not considered. The next lowest GHG emissions are from diesel hybrid vehicles and ICE vehicles fueled by natural gas or ethanol.

Approximately 80% of GHG emissions from the MD/HD sector are from Class 7&8 vehicles. Therefore, reducing GHG emissions in these vehicle classes is especially important. In Class 7&8 vehicles, vehicles fueled by natural gas, either compressed or liquid, have lower GHG emissions than diesel fueled vehicles.

2050 MD/HD Vehicle Fleet GHG Emissions

When considering GHG emissions on a fleet basis, similar to the LD vehicle analysis, the potential future fuel economy improvements of MD/HD fuel-vehicle systems (discussed previously), future fuel carbon intensity (discussed previously), future portfolios for fuel-vehicle systems in the fleet (discussed in Chapter Three, "Heavy-Duty Vehicles"), and future MD/HD VMT must be evaluated simultaneously. MD/HD vehicle VMT is projected to increase by 77–105% from 2005 levels in 2050.[37] Future VMT is uncertain and can have material impact; therefore, a range of VMT has been considered in this analysis.

Figure 6-13 shows the potential 2050 impact of MD/HD VMT growth and changing MD/HD fuel-vehicle system portfolios. The total MD/HD vehicle fleet GHG emissions in 2005 were ~500 MMT CO_2e.

- If no vehicle fuel economy improvements, fuel carbon intensity reductions or changes of the U.S. fuel-vehicle systems portfolio are assumed from 2005 to 2050, total MD/HD fleet emissions would rise to ~800–900 MMT CO_2e due to increasing VMT.
- If all MD/HD fuel-vehicle systems evaluated in this study advance and are commercialized, total MD/HD fleet GHG emissions would fall to ~350–500 MMT CO_2e.

Given the significant increase in MD/HD VMT, MD/HD fuel-vehicle systems improvements are not expected to result in a 50% reduction in GHG emissions of 2005 MD/HD segment levels (~250 MMT CO_2e). Further GHG emissions reductions beyond those calculated in this analysis are possible through supplemental efforts such as the use of bio-based diesel, advanced biofuels, renewable natural gas, and/or improved freight efficiency on a ton-mile basis.

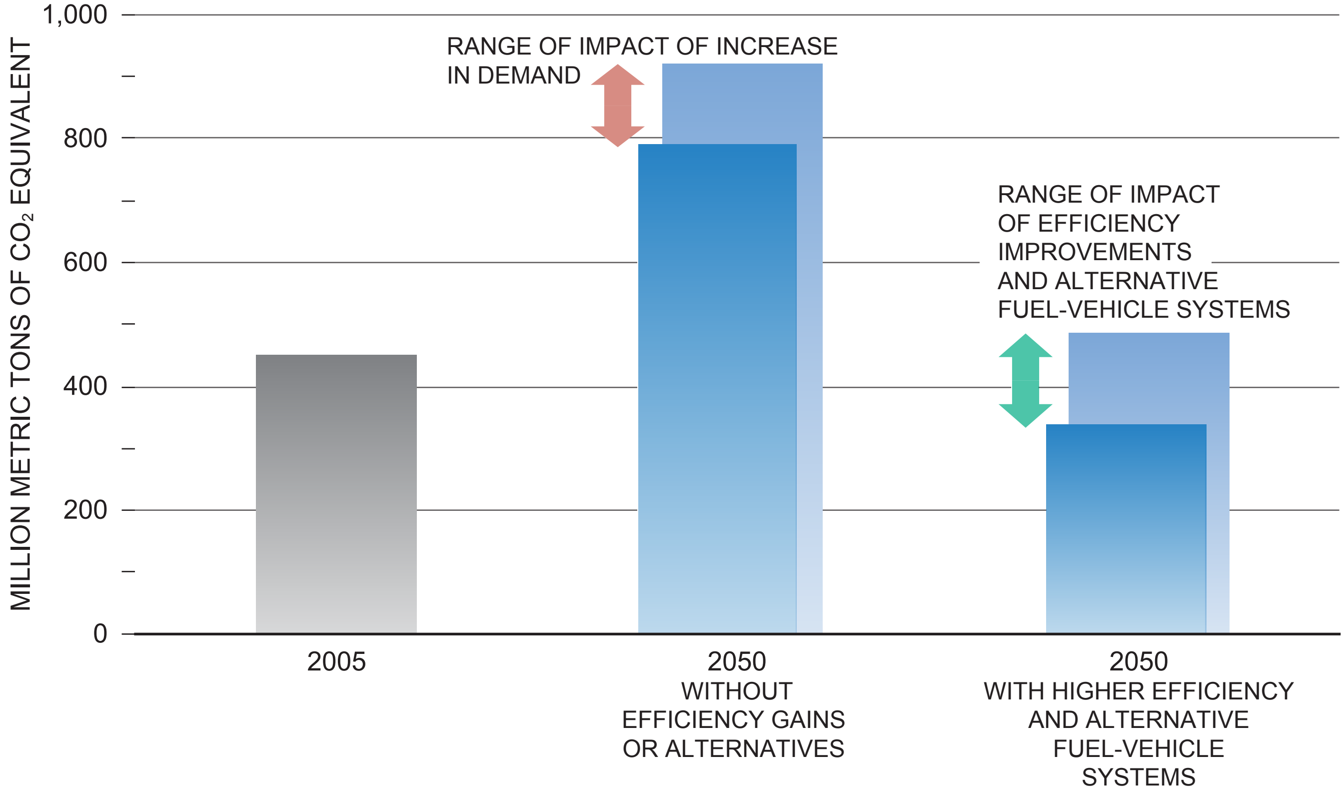
The following conditions are necessary to achieve the lower end of the range presented in the 2050 "Higher Efficiency and Alternative Fuel-Vehicle Systems" case in Figure 6-13: nearly twofold fuel economy improvement for Class 7&8, significant penetration of natural gas into Class 7&8 vehicles, availability of advanced biofuels for Class 3-6 (not considering the impact of ILUC), and VMT projections lower than those in AEO2010 (e.g., AEO2012 Early Release).

If gasoline and diesel prices are low, then fuel economy improvement technologies would be less economical because fuel expenditure reductions (needed to offset the expense of fuel economy technologies) would decrease. Additionally, the economic competitiveness of natural gas fueled vehicles relative to gasoline and diesel fueled vehicles would decrease. Both of these considerations suggest that lower gasoline and diesel prices relative to natural gas prices can have a negative impact in GHG emission reduction.

Air, Marine, and Rail Transportation Emissions

No quantitative GHG analysis was performed on the air, marine, and rail segments, which make up about 15% of total transportation sector demand. This was primarily due to a smaller set of GHG reduction options compared with on-road transportation. As a result of comparisons to the MD/HD fuel-vehicle systems, the study saw a low probability of the air, marine, and rail segments achieving an absolute 50% GHG emissions

37 VMT increase is based on AEO2010 Reference Case and AEO2012 Early Release extrapolated to 2050.



Assumptions:

- Based on AEO2010 Reference Case conditions with 3-year and 17-year fuel expenditure considerations.
- VMT range based on AEO2010 Reference Case and AEO2012 Early Release, extrapolated to 2050.
- Carbon intensity (grams CO_2e/megajoule) values for fuels are from GREET in 2020.
- For cases including alternative fuel-vehicle systems, technology and transition hurdles are assumed overcome.
- Biofuels, where included, do not consider the impact of indirect land use change.

Figure 6-13. *Projected Range of Impact of Demand, Fuel Economy Improvements, and Alternative Fuel-Vehicle Systems*

reduction in 2050 relative to 2005 for the following reasons:

- Transportation demand growth in the air, marine, and rail segments is similar to the MD/HD segment.
- New and more efficient engine technologies will be integrated in this segment more slowly compared to the MD/HD segment due to relatively slower turnover of capital stock. For example, airlines typically refresh their fleets on a 20–25 year cycle.[38]
- Like the HD vehicle segment, advanced biofuels compatible with diesel, jet, and bunker fuels for this segment was assumed to be limited due to relatively higher biofuel production cost compared with advanced biofuels for gasoline.

38 Data provided by this study's Air Travel Demand Subgroup.

Overall Transportation Sector GHG Emissions

In summary, as described in Table 6-7, advanced biofuels and efficient vehicles are necessary but probably not sufficient to achieve an absolute 50% reduction in the 2050 U.S. transportation sector GHG emissions relative to a 2005 baseline.

The probability of achieving an absolute 50% GHG emissions reduction for the overall transportation sector can be enhanced through additional GHG reduction strategies such as, but not limited to, those described in the next section.

Given the broad range of GHG reduction costs within and across each U.S. economic sector, it will be important to consider full life-cycle environmental impacts and cost effectiveness across all

Transportation Segment	Approximate Demand* Contribution from Segment	Year 2050 50% GHG Emissions Reduction Achieved?
Light-Duty	60%	Yes, under limited conditions
Medium-/Heavy-Duty	20%	No
Air, Marine, Rail, and Other	20%	Not likely

* Demand and corresponding GHG emissions from each segment is provided in Table 6-1.

Table 6-7. *Emissions Reduction from the Transportation Sector*

Strategic Use of Our Nation's Biomass Supply

Technologies are being developed for the economical and large-scale production of bio-based fuels. Biomass can also be used as a feedstock to produce lower carbon intensity electricity that can be used in plug-in electric vehicles and reduce stationary power emissions. Biomass can also be used as feedstock to produce hydrogen, for use in FCEVs, as well as in niche industrial chemical applications. In some cases, such as the HD truck or aviation segments, biofuels represent one of a limited number of GHG reduction options.

Federal renewable fuel and state renewable power standards, as well as other domestic and international demands, are placing increased pressure on current supplies of this resource. With a growing world population and rising standards of living, competing demands for biomass for food, fiber, and energy will likely increase even more. Questions about cost, benefit, and other tradeoffs for biomass conversion need to be better understood so that their use provides societal benefits.

- To what extent are alternative options to biomass available for GHG reductions in power generation, transportation, and other industry sectors?
- Should biomass be utilized in the power generation or transportation sectors to reduce GHG emissions?
- Within the transportation sector, should biomass be used to produces fuels for air, marine, or on-road sectors?
- Within the on-road segment, should biomass-based fuels be targeted towards LD or HD vehicles?
- Is it more beneficial for society to direct biomass usage through renewable fuel standards or through other mechanisms, if at all?

Under favorable market, technology, and production conditions, the future feedstock resources identified in DOE's *U.S. Billion-Ton Update* could be used to meet up to 30% of the nation's current demand for transportation fuels.* Determining whether to, or how to, properly distribute and allocate biomass for use in transportation, power generation, and other industrial sectors is outside the scope of this study.

It will also be necessary to better understand the long-term impacts from the increase in biomass production on marginal lands necessary to support the demands for biomass in power, fuels and chemicals. Increased agricultural inputs such as water, fertilizer, and fuel consumption should be compared against the anticipated benefits. In addition, conversion of marginal or otherwise fallow lands may have long-range impacts on wildlife diversity and water quality. However, improved yields of biomass supply, enabled by technology, will help mitigate the impacts from future biomass production on arable and marginal lands. Sustainability of the environment must be a key consideration for increased production of biomass-derived fuels, electricity and chemicals.

* U.S. Department of Energy, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry,* ORNL/TM-2011/224, prepared by Oak Ridge National Laboratory, August 2011.

sectors when evaluating GHG emission reduction options in the transportation sector.

Additional GHG Reduction Strategies

This section describes five GHG reduction strategies that supplement the GHG reductions from the fuel-vehicle systems described earlier. These strategies are not evaluated with respect to cost, which would impact their viability and consumer acceptance over time. Furthermore, these are not the only additional strategies available that could further reduce GHG emissions—other options are available and could be pursued. Additional strategies implemented alone or in combination, along with vehicle efficiency improvements and advanced biofuels, may be necessary to drive absolute GHG emissions reductions in the U.S. transportation sector. The five GHG reduction strategies that this section describes are:

- Reduced carbon intensity of the U.S. electric grid
- Reduced travel activity
- Improved operational efficiency of travel
- Increased use of renewable natural gas
- Use of ultra-lightweighting of LD vehicles.

The five strategies vary considerably in terms of the amount of reductions achieved, the cost of these reductions, and the time frame in which they achieve results. Some of the strategies can have synergistic effects and can have a greater impact on GHGs when implemented in combinations. In addition, transportation system improvements often have other benefits beyond just GHG reduction, such as criteria air pollutant reduction, society productivity enhancement from reduced congestion and increased mobility, energy security, or improved safety. The overall transportation sector emissions reductions achieved through these five strategies would be less if emissions are also reduced through technology changes that improve vehicle efficiency and/or lower the carbon content of fuel.

Although there are obvious GHG reductions that can be achieved from these strategies, there are also several key challenges: electric utilities must build new generation capability, vehicle manufacturers must increase the use of new lightweight materials, and concerns over increases in "induced travel" resulting from GHG reduction strategies must be addressed. Induced travel describes the additional demand for travel that occurs as a result of a decrease in the generalized cost of travel, including both travel-time and out-of-pocket costs.[39] This relationship is complex and difficult to measure but should be considered.

Lastly, a majority of these additional strategies apply to on-road transportation, which makes up approximately 80% of total transportation sector demand. Only a small number of the strategies identified, primarily improved operating efficiency of travel, provide GHG reduction strategies for air, marine, and rail.

Reduced Carbon Intensity of U.S. Electric Power Generation

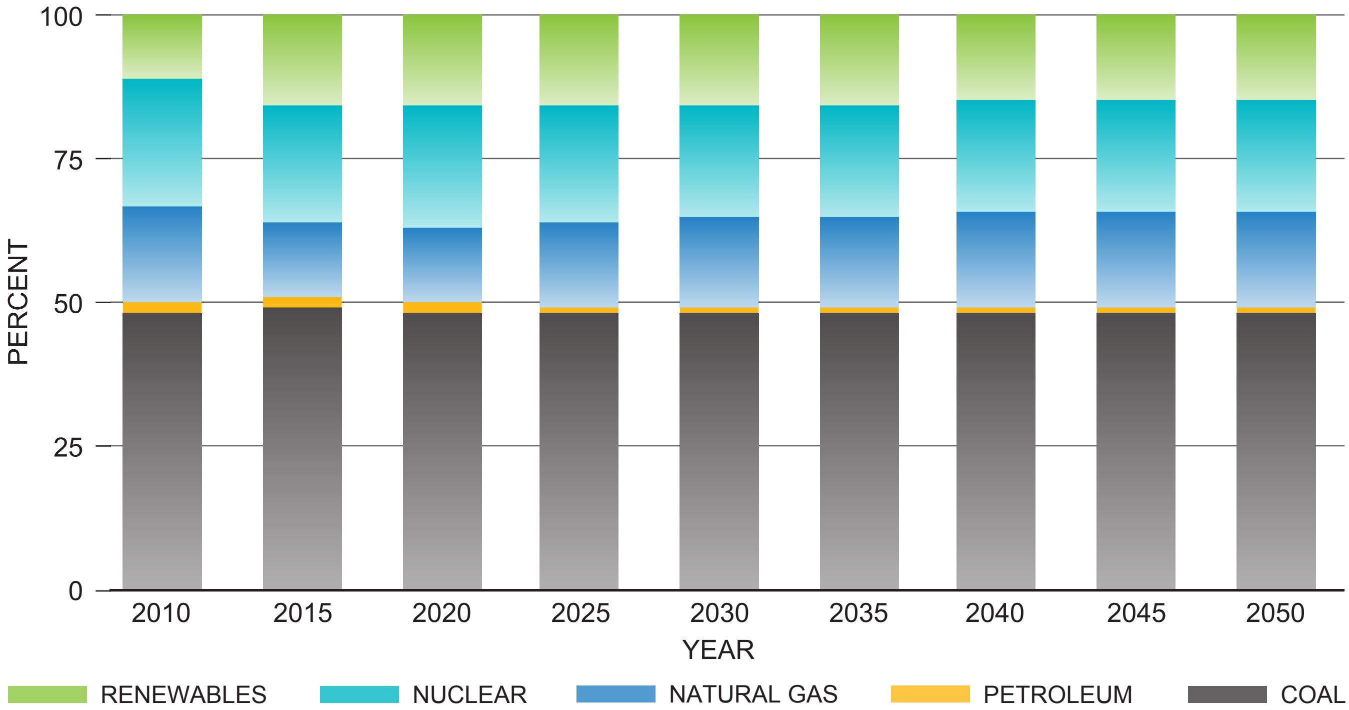
Well-to-wheels GHG emissions attributable to PHEVs and BEVs are dependent upon the electric power generation fuel mix. In regions where much of the power is generated from low GHG emission sources such as nuclear, wind, or hydroelectric power, the resulting GHG emissions/mile for PHEVs and BEVs can be relatively low. Conversely, in regions that are dominated by the higher emitting methods such as older coal-fired power plants, the emissions per mile for PHEVs and BEVs is significantly higher.

The study utilized the AEO2010 Reference Case assumptions as the basis for carbon intensity values used for all calculations.[40] For electricity, the default carbon intensity is based on the average emissions profile of the U.S. power generation system. As shown in Figure 6-14, using the AEO2010 Reference Case, the electricity generation fuels mix does not change substantially over the next several decades.

There are many variables that can influence future electric power generation, and there are a number of forecasts of future power generation demand, fuel mix, and calculated emissions profiles. This section summarizes several alternate, lower carbon electric power generation mixes, in

39 U.S. Department of Transportation, Federal Highway Administration (website), "Induced Travel: Frequently Asked Questions," http://www.fhwa.dot.gov/planning/itfaq.htm#q1.

40 U.S. Energy Information Administration, *Annual Energy Outlook 2010: With Projections to 2035,* 2010.



Source: VISION model (based on AEO2010 Reference Case conditions).

Figure 6-14. *U.S. Electricity Generation Fuel Mix*

order to further evaluate the potential to reduce GHG emissions from the power sector, which in turn would reduce WTW emissions from PHEVs and BEVs. Changes to the electric power generation fuel mix will be costly. The cost to the consumer for lower carbon intensity in the electric power sector is an important and complex topic; however, it is not addressed here and should be considered in future analyses.

Carbon Capture and Sequestration

One of the important and promising technologies for reducing carbon intensity from fossil fuels on a significant scale is carbon capture and sequestration (CCS). The greatest long-term opportunity for CCS is available in the power sector, and there are a number of technological, legal, institutional, regulatory, and other barriers that need to be overcome to realize significant GHG emission reductions.[41] These challenges include incomplete regulatory frameworks; high initial investment cost and extensive infrastructure; climate policy uncertainty; first-of-a-kind technology risks; and public acceptance. Some of the important issues currently under review include the legal and regulatory framework for CCS, the establishment of clear authorities, and provisions for long-term CO_2 storage liability.

There are a number of research, development, and demonstration projects underway to address the technological barriers for CCS. The DOE has placed significant emphasis on the development of next generation CCS technologies such as advanced CO_2 capture, CO_2 enhanced oil recovery, saline aquifer storage, turbo machinery, and large-scale testing.

Published estimates on the cost of CCS contain considerable variation. Some of this variation is inherent uncertainty in an emerging technology that is largely undemonstrated. Variation comes from regional differences, fuel types, or estimates provided for specific projects. Currently, cost is a significant impediment to large-scale deployment of CCS.

Implementation challenges should be kept in mind when considering the following summary

41 See Topic Paper #27, "Carbon Capture & Storage (CCS)," on NPC website.

because one of the important assumptions in forecasting reduced grid carbon intensity is wide-scale CCS adoption. The following carbon constrained scenarios often assume that the above challenges are overcome and that CCS eventually becomes an economic option for power generators to reduce GHG emissions as the price of carbon increases.

Power Sector Emissions Studies under Carbon Constrained Scenarios

The 2011 NPC study titled *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources* includes a comparison of several studies that address GHG emissions from the power sector. The first case is the AEO2011 side case titled *GHG Price Economywide,* which describes a carbon constrained future based on policy and a price on carbon. A second case is the Stanford Energy Modeling Forum 22 (EMF 22)[42] in which the participants modeled pathways to reach 50% and 80% reductions in GHG emissions from the power sector by 2050 (relative to 1990). The third case chosen for comparison is the Resources for the Future (RFF) study titled *Natural Gas: A Bridge to a Low-Carbon Future.*[43]

AEO2011 – GHG Price Economywide Scenario

In the GHG Price Economywide case, a price on CO_2 emissions is assumed which rises from $25 per metric ton in 2013 to $77 per metric ton in 2035 (2009 dollars). Other significant assumptions include the following:

- Breakthroughs are achieved in the cost of CCS.
- Natural gas combined-cycle plants with CCS are cheaper to build than advanced coal plants with CCS.
- The use of CO_2 for enhanced oil recovery will increase significantly.

These changes result in higher electricity prices and lower demand when compared to the AEO2010 Study Reference Case. A price on carbon drives a reduction in the use of coal and an increase in the use of natural gas, nuclear, and renewables for power generation. Figure 6-15 shows the electricity generation fuel mix by percentage under this scenario.

EMF 22: Climate Change Control Scenarios

The Stanford Energy Modeling Forums bring together global modeling experts to address specific questions of common interest. As part of the EMF 22 study, six different models analyzed the U.S. power sector emissions profile with goals of 50% GHG reduction (EMF 50%) and 80% GHG reduction (EMF 80%) relative to 1990 levels. The modelers independently created scenarios to reach those goals and described carbon prices and fuel mixes for their respective scenarios. Table 6-8 shows part of the outcome of the modeling work indicating what the price on carbon would have to be to drive GHG reductions to those levels. The table shows the minimum and maximum range of outcomes from the six different models.

Year	50% Reduction	80% Reduction
2030	$40 to $110	$90 to $180
2050	$95 to $300	$230 to $490

Table 6-8. *EMF 22 – Range of Carbon Prices per Metric Ton to Reach GHG Reduction Targets*

Although the six scenarios had varying fuel mix profiles, they are generally characterized by the reduced use of coal and the increased use of natural gas, nuclear, and renewables. In five of the six scenarios, the only way to reach 80% reduction levels is with nuclear and renewables, and with CCS on a high percentage of (>95%) of coal- and gas-fired power plants. Reaching 50% reduction by 2050 also required the significant utilization of CCS. The EMF lines on Figure 6-16 were derived by averaging the results of the six different models over time to 2030 for both targets.

RFF: Natural Gas: A Bridge to a Low-Carbon Future[44]

The Resources for the Future study assessed the role of natural gas as a bridge fuel to a low-carbon future. The scenarios included forecasts with and without the once-proposed American Clean

42 John P. Weyant, *Energy Modeling Forum 22: Climate Change Control Scenarios,* Stanford University, February 2010.

43 Stephen P. A. Brown, Alan J. Krupnick, and Margaret A. Walls, *Natural Gas: A Bridge to a Low-Carbon Future?,* Resources for the Future, Issue Brief 09-11, December 2009.

44 Ibid.

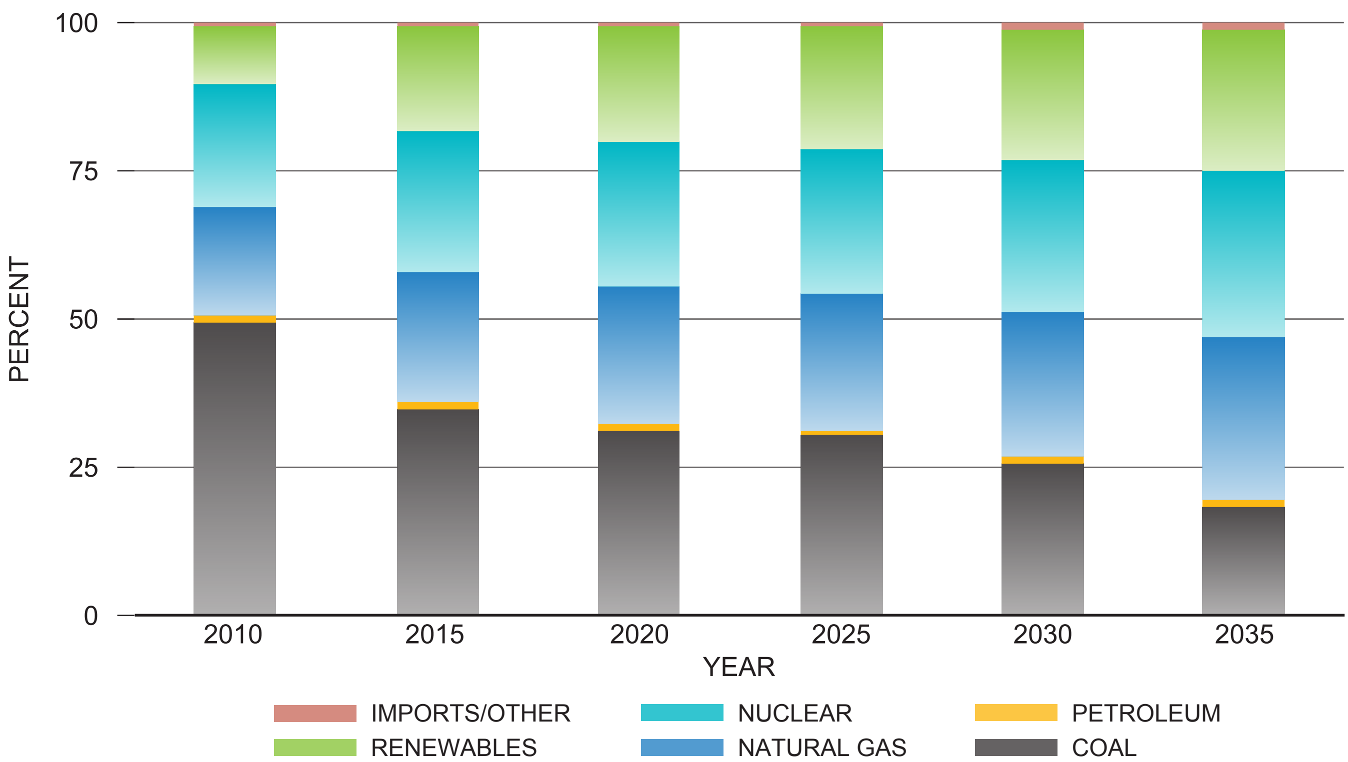


Figure 6-15. *U.S. Electricity Generation Fuel Mix, AEO2011 GHG Price Economywide Case*

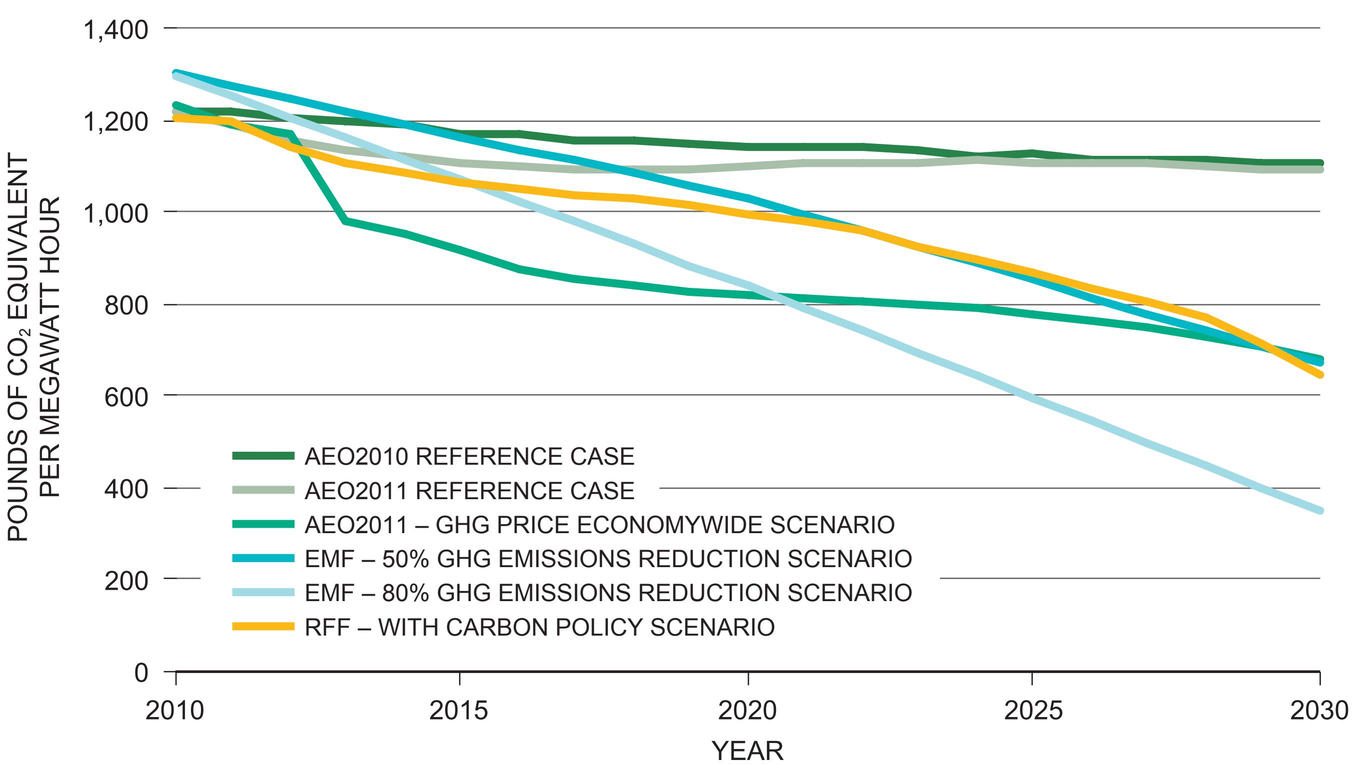


Figure 6-16. *Power Sector Emissions Intensity – Carbon Constrained Scenarios*

Energy and Security Act (Waxman-Markey) carbon policy in place, and with low and high estimates of U.S. natural gas resource development. Without a carbon policy in place, the increased use of natural gas at relatively low price may not necessarily reduce GHG emissions due to a likely increase in energy consumption along with a reduction of renewables and nuclear due to economics. With a price of carbon rising from $18.49 per metric ton in 2012 to $66.83 in 2030, the fuel mix for power generation evolves over time to less carbon intensive fuels as shown in Figure 6-17.

The fuel mix in 2030 is characterized by less coal and more gas, nuclear, and renewables, as well as increased CCS for both coal and gas. The RFF line on Figure 6-16 shows the carbon policy emissions intensity profile reaching a 42% reduction by 2030.

The Power Sector Emission Intensity, expressed in pounds of CO_2e per megawatt hour (MWh), for the above studies is shown in Figure 6-16. Three of the four carbon constrained studies converge on close to the same emissions intensity by 2030, although their profiles are quite different over the next decade.

Electric Power Research Institute published a 2009 update to their Prism/MERGE Analysis, which analyzed a variety of CO_2 reduction technologies and modeled economically optimum portfolios in response to a given CO_2 constraint.[45] Similar to three of the models above, they concluded there is technical potential for a 41% reduction in CO_2 emissions by 2030 relative to 2005 levels. The technologies needed to reach this level include end-use energy efficiency improvements (reduced demand); transmission and distribution loss improvements; increased use of renewables for power (wind, biomass, solar, other); increased nuclear power; improved efficiency of fossil fuel power; and significant development and utilization of carbon capture and sequestration.

45 Electric Power Research Institute, "Prism/MERGE Analyses: 2009 Update," July 2009, http://my.epri.com/portal/server.pt?Abstract_id=000000000001019563.

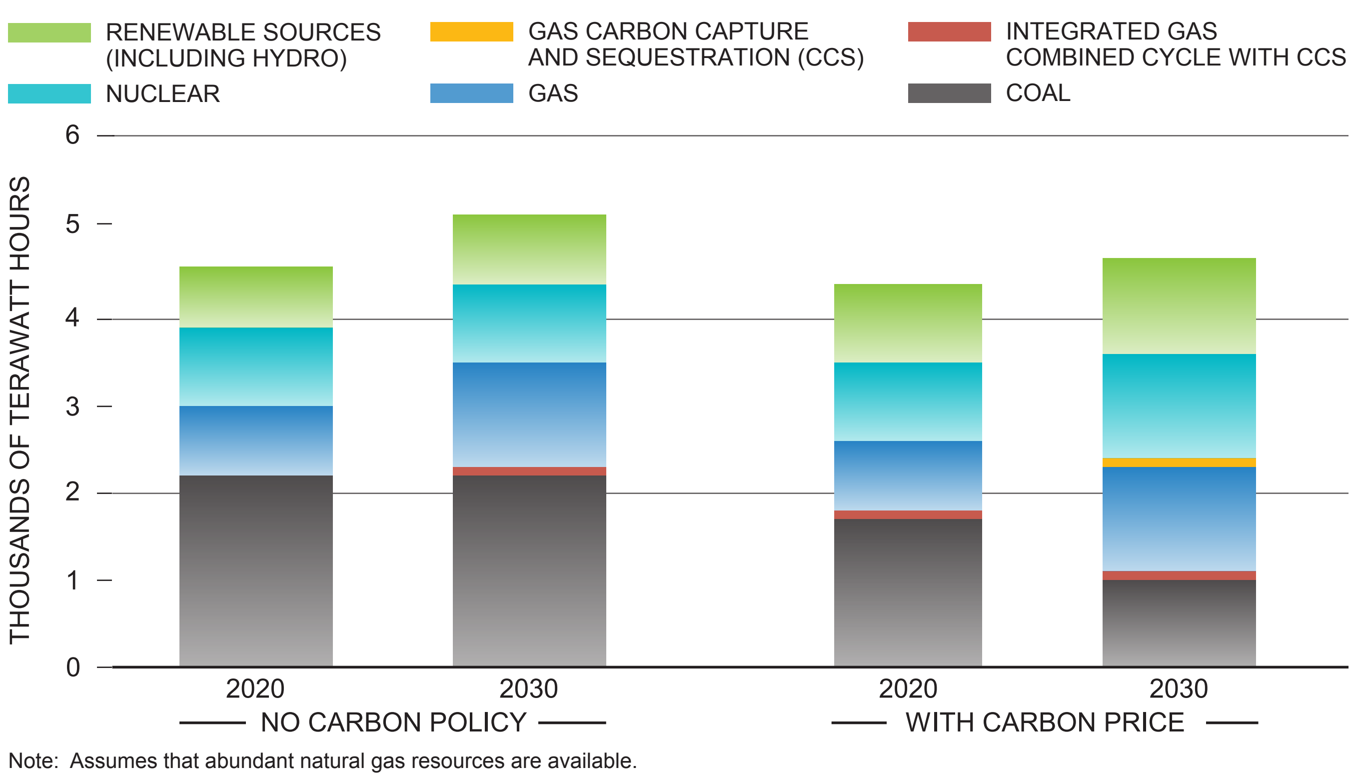
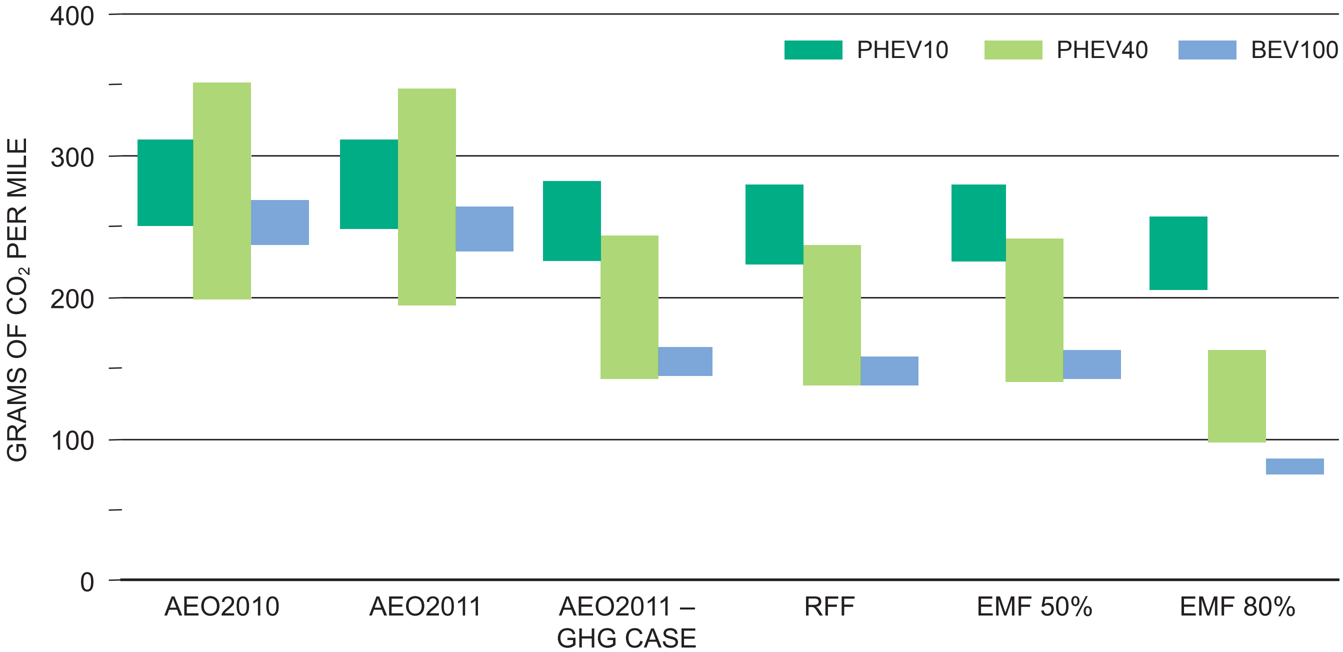


Figure 6-17. RFF Electricity Generation Fuel Mix Under Carbon Policy



Notes: Gasoline assumed to contain 10% corn-based ethanol.
Fuel economy ranges based on 2050 NPC analysis values under AEO2010 Reference Case conditions with 3-year fuel expenditure consideration.

Figure 6-18. *Electricity Generation Emissions Impact on 2030 Weighted Average Emissions*

Well-to-Wheels GHG Emissions per Mile for PHEVs and BEVs with a Low-Carbon Intensity Grid

Electricity grid GHG emissions reductions in the power generation sector directly reduce the emissions attributable to PHEVs and BEVs. Figure 6-18 shows the comparison of WTW GHG emissions/mile for PHEVs and BEVs for the AEO2010 Reference Case and the reduced-grid emissions scenarios discussed above. The three scenarios that project a reduction in electricity carbon intensity of approximately 40% by 2030 show the BEVs achieving the GHG emissions reduction of greater than 60% on a per-mile-traveled basis, relative to the average 2005 LD fleet of 550 gCO_2e/mile.

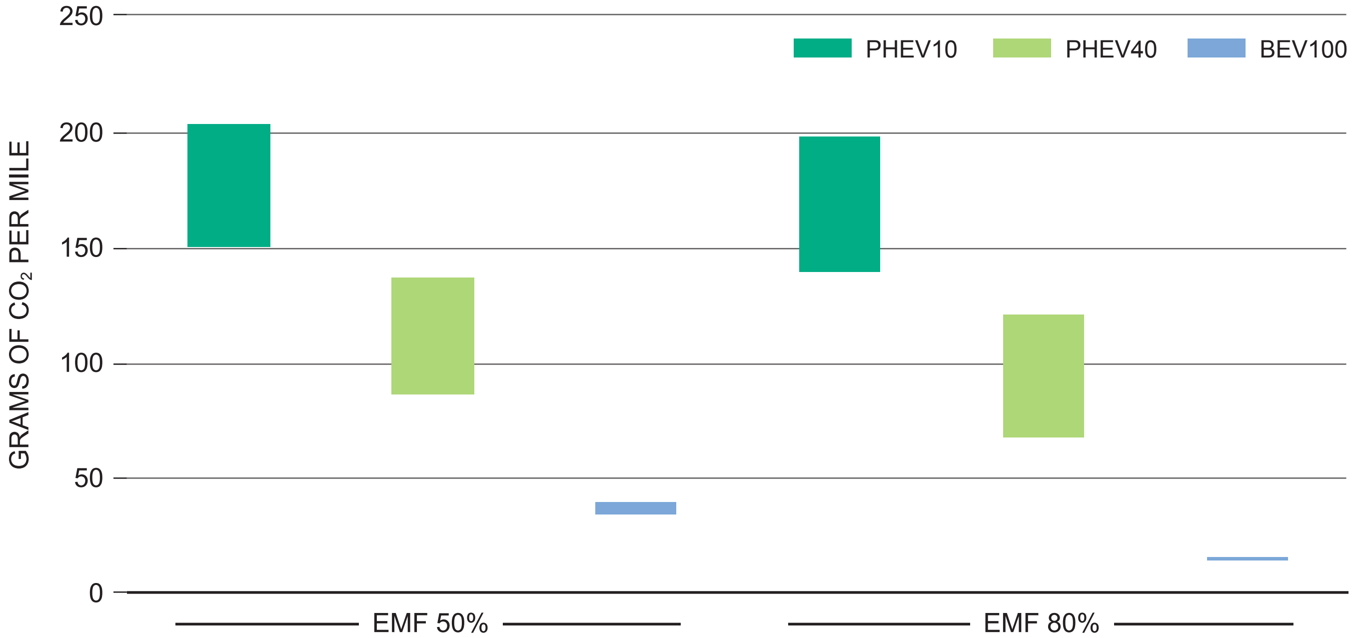
The EMF 22 scenarios were the only ones that continued to 2050. The carbon intensity of electricity generation in those scenarios continued to decrease dramatically resulting in (averaged) grid intensities of 164 pounds CO_2e/MWh for EMF 50% and 65 pounds CO_2e/MWh for EMF 80% by 2050. Using those intensities along with the vehicle efficiency improvements used in the NPC study, the calculated gCO_2/mile for the PHEVs and BEVs in 2050 for the EMF scenarios is shown in Figure 6-19.

GHG emissions per mile traveled from PHEVs and BEVs can be materially reduced with a lower carbon intensity grid. GHG emissions in the U.S. economy associated with a lower carbon electricity grid will be realized in both the power generation and the transportation sectors, the two largest economic sectors of the economy.

Reduced Travel Activity

Strategies to reduce GHG emissions from personal travel activity include changes to consumer behavior or regulatory action. These methods involve shifting travel to more efficient modes, reducing the need for travel or otherwise taking actions that reduce energy use and GHG emissions associated with personal travel.[46]

46 Strategies to shift freight to more efficient modes is discussed in the transportation system efficiency section.



Notes: Gasoline assumed to contain 10% corn-based ethanol.
Fuel economy ranges based on 2050 NPC analysis values under AEO2010 Reference Case conditions with 3-year fuel expenditure consideration.

Figure 6-19. *Emissions per Mile for PHEVs and BEVs Using EMF 22 Scenario Electricity Generation in 2050*

The demand reduction strategies presented here vary considerably in terms of the amount of reductions achieved, the cost of these reductions, and the time frame in which they achieve results. The strategies can have a greater impact on GHG emissions when combined. The GHG reduction benefits of demand reduction strategies will likely not be as high as technology changes that improve vehicle efficiency and/or lower the carbon content of fuel. Five main categories for reducing travel demand activity are summarized below that describe seven impactful GHG reduction strategies.

- Pricing strategies that increase the cost per mile of driving. Pricing strategies will result in a variety of effects including fewer trips, shorter trips, greater use of alternative travel modes, and a shift in travel to periods of lower congestion. Three examples of pricing strategies include:
  - VMT fees charge drivers a fee per mile of travel and are similar to economy-wide measures such as a cap and trade system or a carbon tax.
  - Pay-as-you-drive insurance converts a significant part of the fixed cost portion of insurance to a variable cost based on miles traveled. The logic of pay-as-you-drive insurance is that crash risk, which represents a large portion of the insurance costs, is directly related to distance driven, and therefore people who drive less should have lower premiums.
  - Congestion pricing charges for the use of roadway facilities in order to reduce traffic (typically at high traffic times) for an improved level of service.
- Improvements to transit, nonmotorized, and intermodal travel, including urban transit, intercity bus and rail, nonmotorized infrastructure, and intermodal facilities and information to encourage mode-shifting and increase the energy efficiency of travel per person-mile traveled. The example highlighted is:
  - Transit expansion, promotion, and service improvements have a goal of increasing the energy efficiency of travel per person-mile traveled.

- Land use and parking management strategies to create more compact development patterns that reduce trip lengths and support the use of alternative travel modes through walkable and transit-oriented communities. The example highlighted is:
  - Land use planning, in comparison, indirectly affects the demand for transportation. The physical arrangement of homes, businesses, and other activity locations, as well as the design of the built environment affect the total amount of travel and the most efficient means of travel.
- Commuter and worksite trip reduction programs to encourage alternatives to single-person transport through ridesharing, vanpooling, transit, non-motorized travel, alternative work schedules, and telecommuting, such as employer requirements to reduce single-occupancy employee trips, employer-facilitated work week alternatives and incentives. The example highlighted is:
  - Worksite trip reduction programs may include either requirements by employers to reduce single occupancy vehicle trips by their employees, or outreach, assistance, and incentive programs to encourage employees to do so.
- Other public information programs to educate people about the various choices available regarding travel options, vehicle purchase, driving habits and other issues. The example highlighted is:
  - Public information campaigns, such as eco-driving, are aimed at increasing vehicle fuel efficiency by affecting both driver behavior and vehicle maintenance.

Many of these travel reduction strategies could be implemented in the near term. Examples of several near-term activities include VMT fees, congestion prices, and pay-as-you-drive insurance. Longer-term activities include land use changes and transportation infrastructure investments. One of the more comprehensive studies of travel demand reduction, summarized in an April 2010 DOT Report to Congress, estimates that combining the aggregated impacts from the various programs within the five broad travel reduction categories above could result in a 5–17% GHG emissions reduction in 2030 and a 6–21% reduction by 2050.[47] The April 2010 DOT Report to Congress provides additional background on the above demand reduction strategies, along with eleven additional strategies.

Reduced Travel Demand Summary

The seven travel demand reduction programs are summarized in Figure 6-20 to highlight GHG reduction potential for 2030, against how quickly the GHG reduction programs can make an impact.[48]

Direct and indirect costs, as well as overall net social costs that include savings, associated with these travel demand programs described above are challenging to estimate. Complexities such as the level of induced demand, consumer response to increased driving costs, welfare losses associated with decreased mobility, and the assessment of the net economic benefit from various co-benefits of reduced travel represent some of the key assumptions that need to be factored into net social costs.

While the focus of this section has been on GHG reduction, there are numerous co-benefits from reduced travel such as:

- Improved safety with reduced crashes and associated costs and human impacts.
- Reduced congestion and increased mobility. Mobility benefits are particularly beneficial for low income people where the cost of driving is a financial hardship or seniors/disabled people where driving is difficult or impossible.

47 U.S. Department of Transportation (DOT), Report to Congress, *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions, Volume 1: Synthesis Report,* April 2010. The DOT studied 18 different travel demand reduction strategies. For the purposes of aggregating cumulative GHG emission reductions, it was infeasible to aggregate all 18 programs since some programs create similar impacts. The aggregate reduction range cited includes the following programs: pay-as-you-go insurance, congestion pricing, urban and intercity transit, non-motorized travel, land use, parking management, commuter/worksite trip reduction, telecommuting and compressed work week, individualized marketing, and eco-driving.

48 General positioning of these seven programs is taken from information presented in the DOT Report to Congress, which is previously cited. Definitions of 2030 GHG emission potential are: low = <0.5% of GHG emission reductions in 2030 (<12 MMT CO_2e); moderate = 0.5–2.5% GHG reduction (12–60 MMT CO_2e); and high = >2.5% GHG reduction (>60 MMT CO_2e). Timing of GHG reduction potential is defined as: short-term = most GHG benefits can be achieved within 5 years of program implementation; mid-term = most GHG benefits achieved within 5 to 20 years; and long-term = most GHG benefits achieved after 20 years. The projected 2030 GHG emissions baseline, derived from EIA's AEO2009 report uses 2,171 MMT CO_2e as the 2030 baseline.

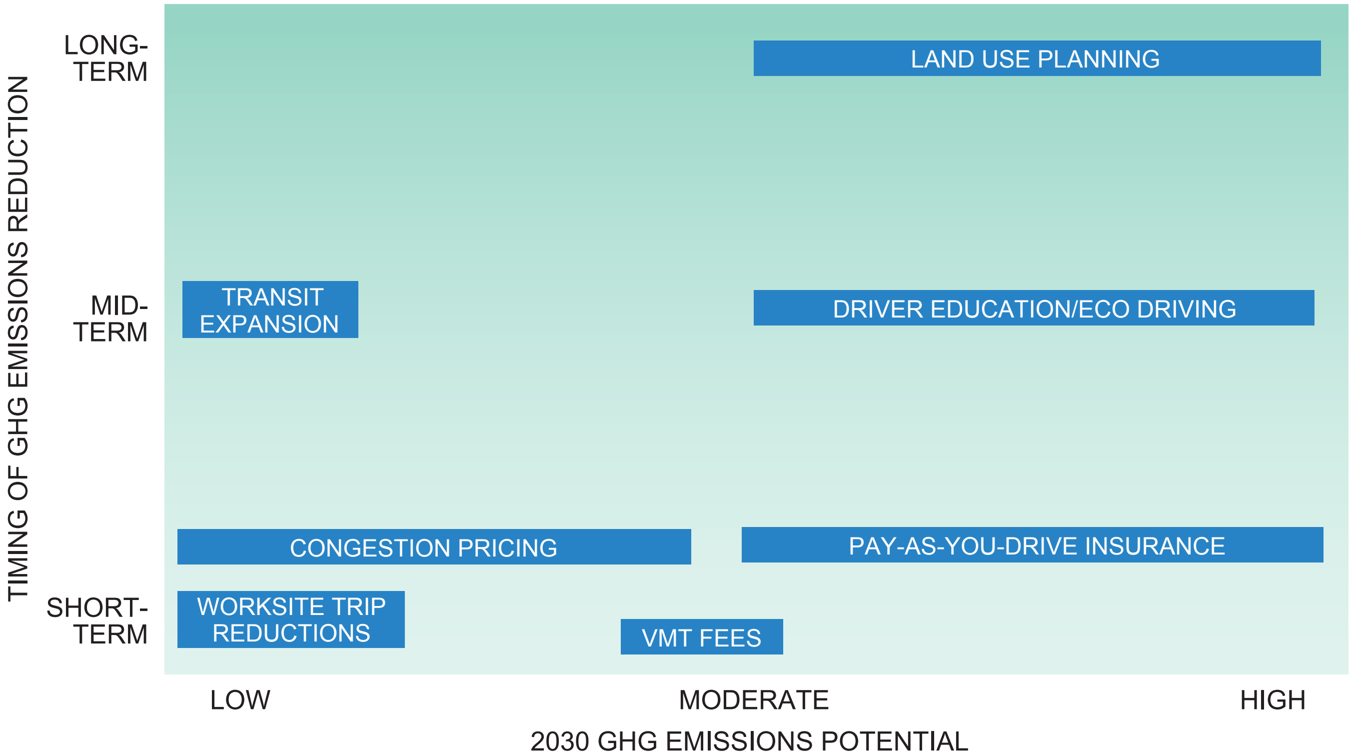


Figure 6-20. *GHG Emissions Timing, and Potential for Various Travel Demand Reduction Strategies*

- Improved environmental stewardship. Reduced travel reduces transportation fuel consumption with accompanying reductions in air pollution, reduced waste production, and water usage associated with fuel production, transport and combustion, as well as other environmental benefits.
- Improved energy security through more efficient use of energy.

Improved Operational Efficiency of Travel

Improving the operational efficiency of travel represents a diverse set of strategies that focus on ways to optimize the use of the transportation network by improving the efficiency of transportation operations. Four categories of transportation operations and efficiency improvements are summarized below. The strategies, outlined within these four categories, seek to improve the operation of the transportation systems through reduced vehicle travel time, improved traffic flow, decreased idling, and other efficiency of operations. Improvements in transportation systems offer GHG reduction opportunities in all transport modes (LD, HD, rail, marine, and air) as more operations may occur in optimal conditions. System improvements may generate benefits other than GHG reductions, such as fewer criteria air pollutant emissions, productivity enhancements, energy security, or public safety.

Highway Operations and Management

On-road transportation system efficiency improvements generally seek to optimize the use of the transportation network by enhancing transportation operations and reducing energy use and GHG emissions associated with a given unit of passenger or freight travel. These tactics seek to reduce congestion and keep vehicles moving at their most energy-efficient speeds such as Intelligent Traffic Systems, technology enabled rapid incident response, signal control management, road weather management systems, and traveler information systems with integration through Traffic Management Centers. They also include the identification and correction of chronic bottlenecks and capacity expansion. These transportation system improvements require more planning and investment, so benefits will take longer to capture. They have the common effect of reducing congestion and hence travel time, which could result in increased travel due to the improved conditions. This counteracting effect is often referred to as "induced demand." Several studies also identify setting maximum speed limits at 55–60 mph as a low-cost near-term step to reduce fuel consumption and reduce GHG emissions by 1–2% of total 2030 transportation sector emissions.[49]

Truck Operations and Management

System efficiency improvement opportunities seek to reduce the emissions per unit of goods moved per mile by HD truck (measured as CO_2e/ton-mile). Adding a second or a third trailer to Class 8 trucks is common in some states and is a simple way to deliver more goods per trip. Because many trucks in the United States are loaded to capacity in volume but not in weight, adding a second trailer allows more freight to be carried. Long combination vehicles are defined as multi-trailer combination vehicles operating on the U.S. "National Network" and weighing more than 80,000 pounds gross vehicle weight rating. Today, all 50 states allow double 28-foot trailers, and 22 states allow trucks to weigh more than 80,000 pounds, the U.S. federal maximum. By harmonizing laws to permit higher weights and longer vehicles, U.S. truck fleets could deliver more freight per trip, using less fuel per ton-mile delivered.

Other opportunities include various idle reduction techniques, improved logistics to maximize back-hauls, routing and scheduling software to reduce distances traveled, and freight inter-modal optimization.

Air Traffic Operations[50]

Airlines typically refresh their aircraft fleets on a 20- to 25-year cycle. Historically each new generation of aircraft, with current airframe and engine technology, has generated an approximate 15% improvement in fuel efficiency over the previous generation. As such, to the extent that airlines' financial stability is restored and maintained in coming years, airlines can expect to gradually improve the average fuel efficiency of their fleet at an average annual rate of 0.6–0.75% as older aircraft are replaced with new models.

The Federal Aviation Administration (FAA) has initiated a program known as NextGen, which is an umbrella term for the ongoing, wide-ranging transformation of the National Airspace System. NextGen encompasses a number of improvements in ground and airspace operations, including transforming the current ground-based system of air traffic control into a satellite-based system of air traffic management. It will include the development of aviation-specific applications for existing, widely used technologies, such as the Global Positioning System and technological innovation in areas such as weather forecasting, data networking and digital communications. NextGen is expected to yield many benefits, including improved safety, increased capacity and enhanced efficiency, as well as superior environmental performance, by allowing more aircraft to safely fly closer together on more direct routes. Airspace redesign and performance based navigation procedures are already saving fuel and reducing emissions in demonstrations with various air carriers. The FAA expects NextGen to cumulatively save over 1.4 billion gallons of jet fuel from air traffic operations between 2009 and 2018, representing about 0.8% of projected fuel consumption.

Freight Rail and Marine Operations

Efficiency improvements to rail and marine freight systems seek to reduce energy use per unit of goods moved by these modes or shift freight movements from truck to these more efficient modes. Potential rail system improvements include eliminating chokepoints, expanding reach of the rail network, development of "logistics parks," and container standardization. Idle reduction strategies similar to trucks can be applied to switcher engines where 75% of their time is spent idling consuming 27% of their fuel. Extending gate hours at ports can reduce wait times and congestion. The addition of shore-side power at the dock can allow ships to receive utility power rather than using on-board diesel generators. Marine routing optimization can reduce delays at ports, allow

49 DOT Report to Congress, April 2010.

50 Commentary and data provided by this study's Air Travel Demand Subgroup. The subgroup prepared Topic Paper #1, "Air Transportation Demand," which can be found on the NPC website.

ships to operate at more efficient cruise speeds, and reduce diversion to other ports that often involve circuitous routes. The "Transportation Efficiency" topic paper prepared for the NPC *Hard Truths* study indicates that system improvements in the marine sector such as "slow steaming" and "just-in-time" delivery strategies could reduce GHG emissions by 5–10%.[51]

Summary of Improved Operational Efficiency of Travel

One of the more comprehensive studies of travel efficiency is summarized in the April 2010 DOT Report to Congress. The GHG impacts of 13 individual strategies across all transportation modes presented in the DOT report were generally independent of each other, and therefore added together to provide a rough estimate of cumulative savings from these strategies. Combined benefits of all strategies are estimated to range from 2.9 to 5.7% of 2030 total transportation emissions, with the majority of the benefits from highway operations. Separate GHG benefit estimates for 2050 are not presented, as these strategies can generally be fully implemented by 2030.[52]

Six of the 13 strategies summarized in the DOT report, shown in Figure 6-21, highlight GHG reduction potential in 2030 against how quickly the GHG reduction programs can be realized.[53] Direct and indirect costs of these travel efficiency programs are challenging to estimate, and therefore no attempt has been make to quantify their respective cost.

51 Topic Paper #28, "Transportation Efficiency," for National Petroleum Council, *Hard Truths: Facing the Hard Truths About Energy,* 2007.

52 DOT Report to Congress, April 2010.

53 General positioning of these six programs is taken from information presented in the April 2010 DOT Report to Congress, which is previously cited. Definitions of 2030 GHG emission potential are: low = <0.5% of GHG emission reductions in 2030 (<12 MMT CO_2e); moderate = 0.5–2.5% GHG reduction (12–60 MMT CO_2e); and high = >2.5% GHG reduction (>60 MMT CO_2e). Timing of GHG reduction potential is defined as: short-term = most GHG benefits can be achieved within 5 years of program implementation; mid-term = most GHG benefits achieved within 5–20 years; and long-term = most GHG benefits achieved after 20 years. The projected 2030 GHG emissions baseline, derived from EIA's AEO2009 report, uses 2,171 MMT CO_2e as the 2030 baseline.

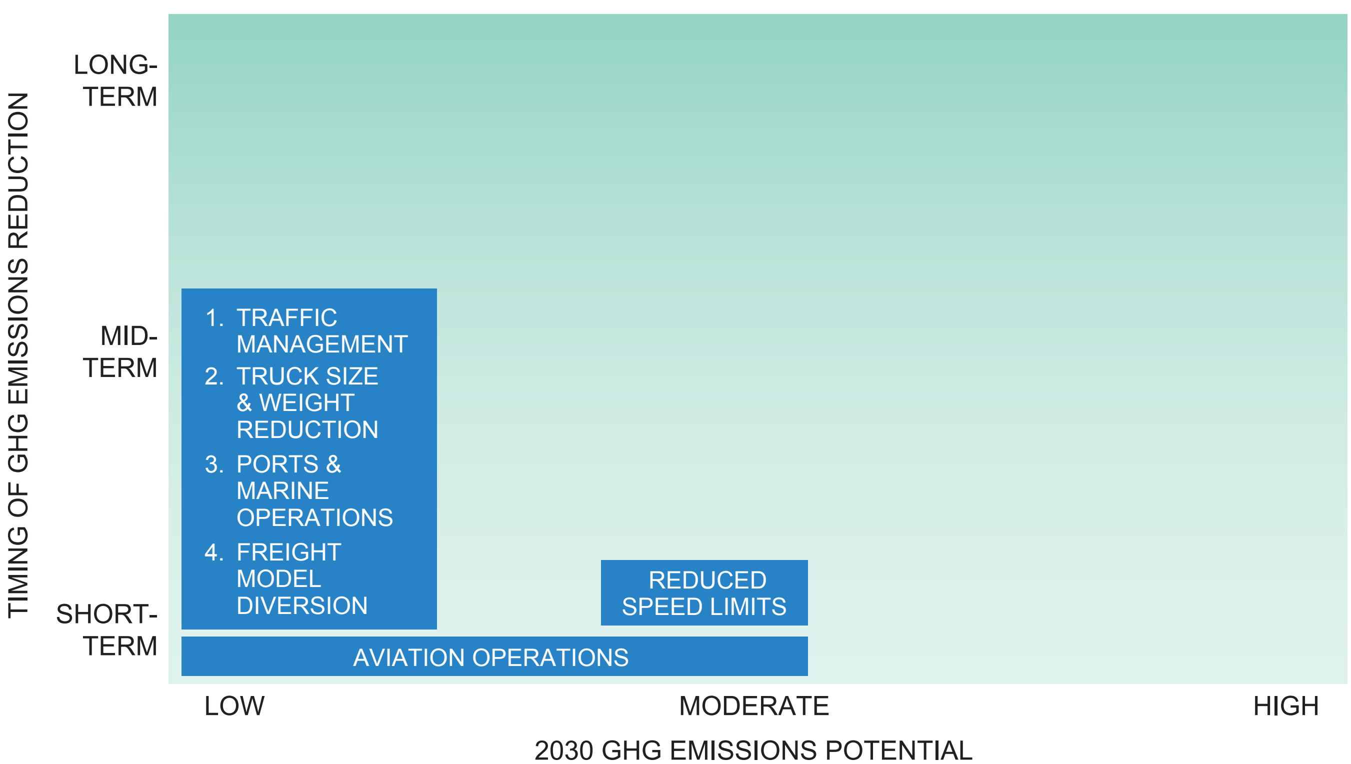


Figure 6-21. *Travel Efficiency Programs Timing and GHG Emissions Reduction Potential*

Increased Use of Renewable Natural Gas

Renewable natural gas (RNG) is pipeline quality gas that is fully interchangeable with fossil natural gas and can be used as a 100% substitute for, or blended with, conventional gas streams for use in vehicle engines. RNG is produced from a variety of biomass and/or biogas sources including landfill gas, solid waste, municipal wastewater, and agricultural manure via purpose-built anaerobic digesters. It can also be produced from lignocellulosic sources such as forestry and agricultural waste through the process of thermal gasification combined with methanation. Once biogas is purified to meet natural gas pipeline and/or fuel specifications, RNG can leverage the existing natural gas distribution network and limited fuel dispensing infrastructure to distribute and deliver a renewable transportation fuel.

RNG as a transport fuel is utilized in several European natural gas fleets such as in Sweden, Germany, Italy, and England.[54,55] RNG as a U.S. transport fuel is currently represented by a number of landfill projects with captive refuse fleets such as the Altamont Landfill near Livermore, California, and the Frank R. Bowerman Landfill in Irvine, California.[56] At present, the most significant demand for RNG is from power producers in Renewable Portfolio Standard (RPS) states that use the fuel in combined cycle plants to generate renewable electricity to satisfy RPS compliance requirements. A comprehensive discussion on RNG production technologies, available RNG feedstock inventory, RNG production economics, and barriers to commercialize RNG as a transport fuel is available in a topic paper commissioned as part of this study: Topic Paper #22, "Renewable Natural Gas for Transportation."

Compared to diesel, gasoline, fossil natural gas, and certain biofuels, RNG can offer significant greenhouse gas reductions.[57,58] There is the potential for emission reductions upstream or well-to-tank from the capture of methane emissions from landfills or dairies and tank-to-wheel via the use of RNG as a petroleum substitute or in blended mixtures with fossil natural gas.[59] The GHG benefits of RNG derived from landfill gas, dairy digester biogas, and manure have been well documented.[60] For example, RNG from landfill gas liquefied into LNG for heavy-duty transport applications has a WTW GHG savings of approximately 72–97% compared to diesel fuel pathways.[61]

The Gas Technology Institute's (GTI) 2011 report for the American Gas Foundation, *The Potential for Renewable Gas,* estimated the total potential impact of RNG in terms of production of energy, capital investment required, on-going operating costs, and the reduction of greenhouse gases.[62] The GTI report does not address competing demands or alternate pathways for either biogas or biomass resources. Under the non-aggressive and aggressive scenarios that were considered for the GTI study, the market potential of RNG ranges from 1.0 to 2.5 quadrillion BTU per year.[63] Ultimately, feedstock available for

54 Marianne Mintz and Jim Wegrzyn, *Renewable Natural Gas: Current Status, Challenges, and Issues: A Discussion Paper for Clean Cities Coalitions and Stakeholders to Develop Strategies for the Future,* U.S. Department of Energy, September 2009, http://www1.eere.energy.gov/cleancities/pdfs/renewable_natural_gas.pdf.

55 Max Ahman, "Biomethane in the Transport Sector – An Appraisal of the Forgotten Option," *Energy Policy* 38, no. 1 (January 2010): pages 208-217, http://www.sciencedirect.com/science/article/pii/S0301421509006909.

56 Operated by Waste Management–Linde, the Altamont Landfill has a daily capacity of 13,000 LNG gallons and fuels 400 refuse haulers powered by a Cummins Westport ISL G engine. The Frank R. Bowerman Landfill is the second largest commercial-scale landfill gas to RNG plant, generating nearly 5,000 gallons of LNG per day to fuel Orange County Transit Authority's fleet of LNG-powered buses and refuse trucks.

57 Argonne National Laboratory, *Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model,* Report ANL/ESD/10-3, May 2010, http://www.transportation.anl.gov/pdfs/TA/632.PDF.

58 Pal Borjesson and Bo Mattiasson, "Biogas as a Resource Efficient Vehicle Fuel," *Trends in Biotechnology* 26, no. 1 (January 2008): pages 7-13, http://www.globalbioenergy.org/uploads/media/0711_Boerjesson_Mathiasson_-_Biogas_as_a_resource-efficient_vehicle_fuel.pdf.

59 The GHG emissions reduction benefit is dependent on the feedstock and is not inherent in the fuel itself. A more comprehensive discussion on the life-cycle emissions of RNG is available in Topic Paper #22 (on the NPC website): "Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and Emission Reduction Benefits of RNG as a Low-Carbon Fuel."

60 Argonne National Laboratory has published models derived from GREET for CNG and LNG from landfill gas for a range of cases including different electricity sources, on-site compression or liquefaction, and off-site compression or liquefaction. CARB has carbon intensities for CNG and LNG from landfill gas and dairy digester biogas with differing cases of liquefaction efficiency.

61 Argonne National Laboratory, *Well-to-Wheels Analysis.*

62 American Gas Foundation, *The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality,* September 2011, http://www.gasfoundation.org/ResearchStudies/renewable-gas-2011.htm.

63 The non-aggressive and aggressive scenarios have the potential to meet between 4 and 10% of 2010 natural gas usage in the United States. This assumes a national usage of approximately 24 trillion cubic feet of natural gas or 24 quadrillion BTU as per http://www.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

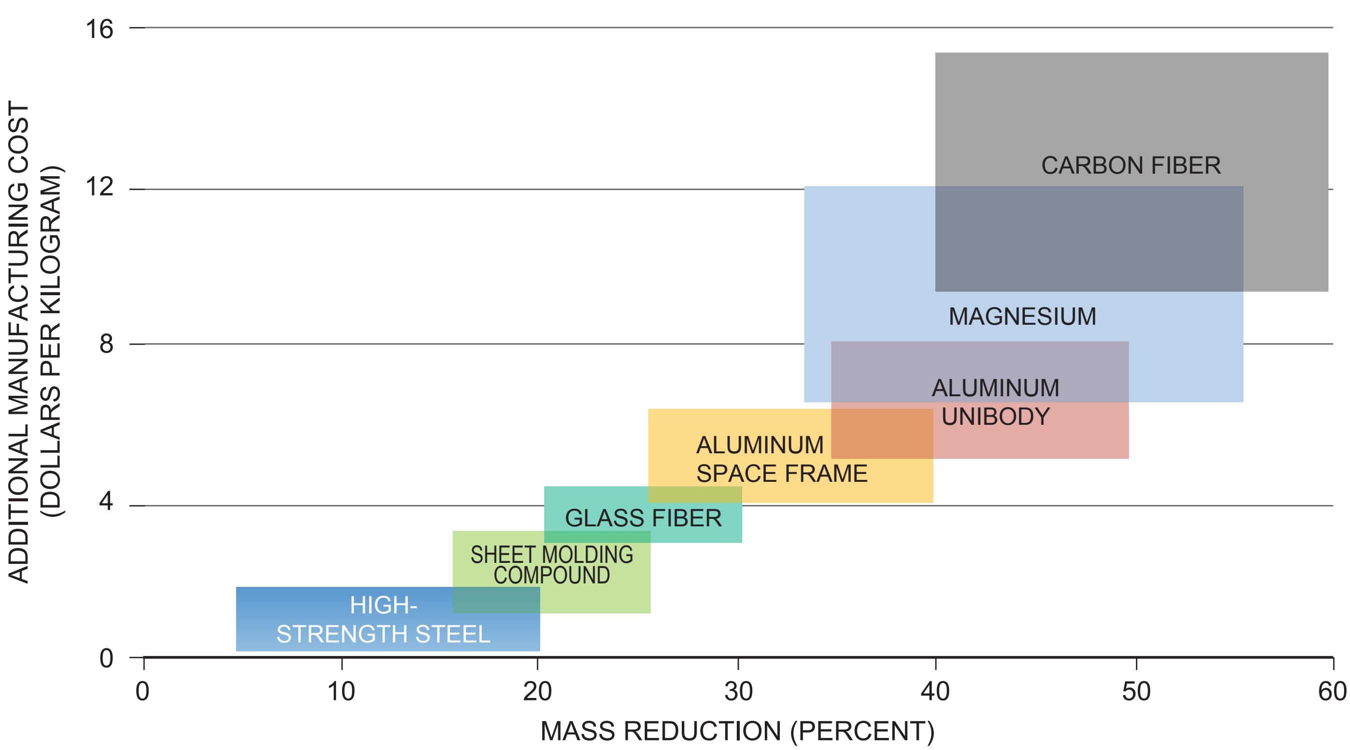
RNG production and the percentage of RNG directed towards CNG and LNG vehicle fueling will drive GHG reduction potential in the U.S. transportation sector associated with RNG use.

Use of Ultra-Lightweighting of Light-Duty Vehicles

A desire for greater fuel efficiency has driven an increased interest in lightweighting and ultra-lightweighting of light-duty vehicles where ultra-lightweighting is generally considered to be a 50–70% reduction in vehicle mass. Since lightweighting typically costs more than conventional vehicle production, economics have tended to restrict the use of lightweighting options to highly priced, high performance vehicles, where the extra costs of lightweighting can be covered by the higher vehicle price. Lightweighting may also be used in alternative fuel vehicles such as battery electric cars and fuel cell vehicles, in which lower vehicle weight can reduce the battery size or hydrogen storage system costs. Table 6-9 lists the

Lightweight Material	Material Replaced	Mass Reduction (%)
Magnesium	Steel, Cast Iron	60–75
Carbon Fiber Composites	Steel	50–60
Aluminum Matrix Composites	Steel, Cast Iron	40–60
Aluminum	Steel, Cast Iron	40–60
Titanium	Alloy Steel	40–55
Glass Fiber Composites	Steel	25–35
Advanced High Strength Steel	Mild Steel, Carbon Steel	15–25
High Strength Steel	Mild Steel	10–15
Source: U.S. Department of Energy.		

***Table 6-9.** Lightweight Material Replacement and Mass Reduction*



Note: Values estimated and based on a collection of MSL vehicle cost analyses and other sources.

Source: Charles Fine and Richard Roth, *Lightweight Materials for Transport: Developing a Vehicle Technology Roadmap for the Use of Lightweight Materials,* MIT Roundtable: The Future of Manufacturing Innovation, March 29, 2010, http://www.alum.mit.edu/sites/default/files/IC_assets/news/images/alumninews/Fine_Roth.pdf.

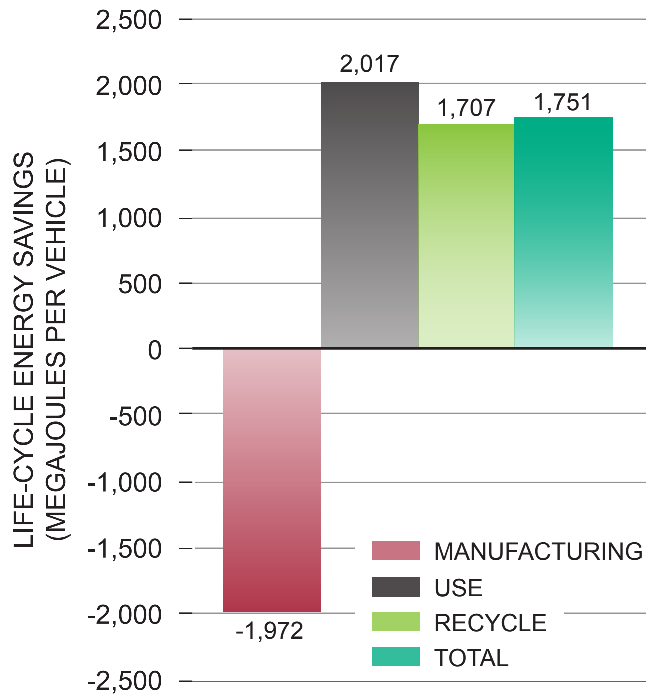
***Figure 6-22.** Lightweight Materials and Cost* lightweighting materials currently being assessed, the conventional materials each is likely to replace, and the potential weight reduction benefit from replacement.

Figure 6-22 shows the relationship between lighter materials (carbon fiber, magnesium, aluminum, glass fiber, sheet molding compound, and high-strength steel) and conventional steel in terms of potential weight reduction and cost.

Beyond production costs, there are other economic challenges to lightweighting. Vehicle manufacturers would need to make large investments in infrastructure, and the entire vehicle supply chain would need to be redesigned to incorporate the new lightweight materials. It is estimated that a 10% reduction in vehicle weight can improve fuel economy by 6 to 8%, with a corresponding 6 to 8% reduction in GHG emissions. DOE estimates that a 33% reduction in vehicle weight can achieve a 23% reduction in fuel consumption in 2020 vehicles with a corresponding 23% reduction in GHG emissions. NPC analysis assumes that a 10% vehicle weight reduction improves vehicle fuel economy by 6%, and regenerative braking improves fuel economy by 4%.

Any full energy life-cycle assessment must account for the production and end-of-life recycling energy of a component and vehicle subsystem in order to provide a complete picture. In some, but not all, cases the full energy life-cycle assessment for lightweight material provides energy saving which result in GHG emissions reductions when compared to convention materials. Figure 6-23 demonstrates the energy life-cycle assessment comparisons between aluminum casting lightweighting and conventional steel stamping of a liftgate inner. Oak Ridge National Laboratory estimates that it takes between 4 and 10 years of vehicle operation for the use of aluminum to achieve energy equivalence with the use of conventional steel in a single vehicle.

Quantifying the costs and benefits of specific lightweighting technologies on a life-cycle basis is difficult because most lightweighting technologies in use today are not in mass production. Therefore, the extrapolation of these processes to mass production has to be modeled and estimated which can introduce additional variability and uncertainty. The lack of solid lightweighting GHG data must be remedied if robust lightweighting vehicle designs are to be pursued in the future.



Source: Oak Ridge National Laboratory, Center for Transportation Analysis.

Figure 6-23. *Life-Cycle Energy Impacts of Stamped Steel Versus Cast Aluminum Liftgate Inner for Light-Duty Vehicles*

Argonne National Laboratory has developed an extension of the GREET model, GREET 2.7, that models the vehicle life-cycle process, to include production, maintenance, and recycling. GREET 2.7 was used to assess the GHG life-cycle impacts of producing conventional ICE vehicles, hybrid electric vehicles (HEVs), FCEVs, and lightweight versions of each of these.

The majority of the weight reduction was achieved by replacing steel and cast iron with carbon fiber- and glass fiber-reinforced plastics along with the use of wrought and cast aluminum. Table 6-10 shows the estimated fuel economy and weight changes for the three lightweighted vehicle types.

Figure 6-24 shows the GHG emission estimates for the vehicle life-cycle and Figure 6-25 shows the total fuel and vehicle life-cycle GHG estimates for these six vehicles.

The lightweight versions of the ICE and HEV had vehicle life-cycle GHG emissions very similar to the conventional versions of these vehicles. The

Parameter	ICE	Hybrid ICE	FCEV	Lightweight ICE	Lightweight Hybrid ICE	Lightweight FCEV
Fuel Economy (miles per gallon gasoline equivalent)	24.8	36.7	57.5	32.7	47.2	67.7
Lightweighting Weight Change (%)				41	29	25
Lightweighting Fuel Economy Change (%)				32	29	18

Table 6-10. *On-Road Adjusted Combined Fuel Economy Values*

same was true for FCEVs, but both FCEVs had significantly higher vehicle life-cycle GHG emissions than the ICEs and HEVs. As demonstrated in Figure 6-25, however, on a total energy-cycle (fuel plus vehicle) basis, FCEVs had the lowest overall GHG emissions, and each of the lightweighted versions had lower total GHG emissions than its conventional version.

Most lightweight materials require more energy to produce than current vehicle components, but can save energy through the improved fuel economy of the vehicle. Since GHG emissions track with energy usage, there is concern about whether the production of lighter weight vehicles will or will not produce more GHG emissions than the GHG emission reductions gained from the weight reduction. Based on the assumptions in the Argonne study, it appears possible that lightweighting can have overall life-cycle analysis GHG reduction benefits. However, most of the lightweighting and ultra-lightweighting concepts described in the study are

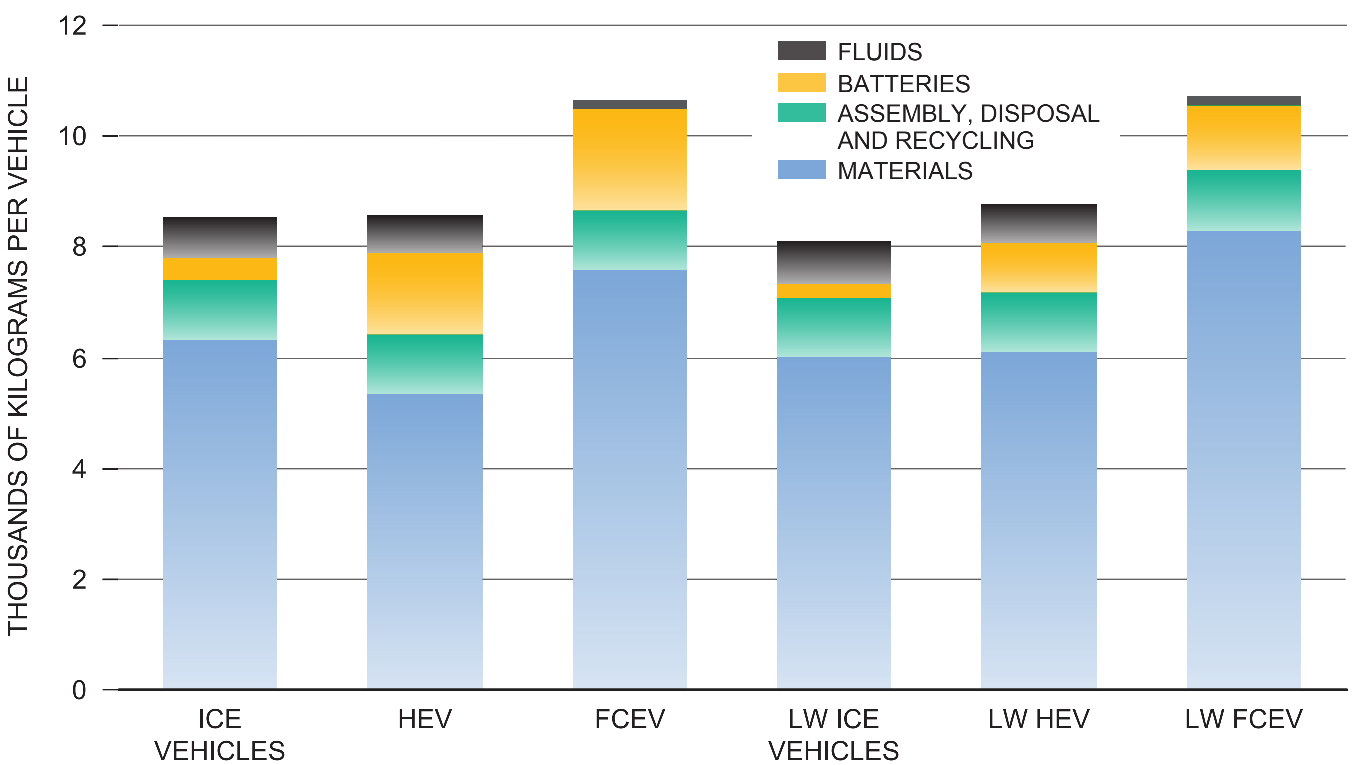


Figure 6-24. *Vehicle Life-Cycle Results: GHG Emissions per Vehicle*

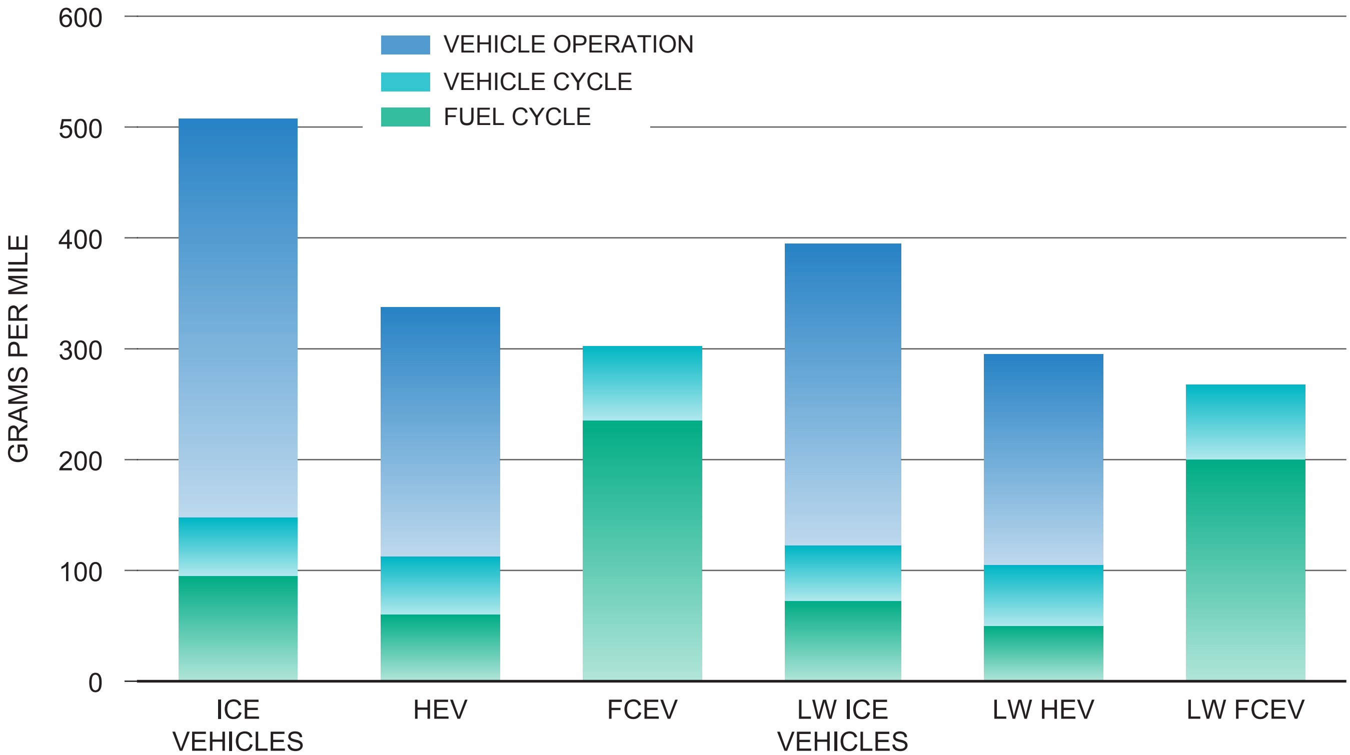


Figure 6-25. *Total Energy-Cycle Results: GHG Emissions*

not yet used in high-volume production applications, and therefore, future studies of real world lightweight material changes will be needed to quantify the GHG impacts of the production and recycling of lightweight vehicle components.

Full Life-Cycle Environmental Analysis – Criteria Air Pollutants and Water

The study analyzed criteria air pollutant (CAP) emissions and water usage for alternative pathways and conventional gasoline and diesel ICEs. This environmental analysis is based on the study's future fuel economy ranges from the LD vehicle and HD vehicle analyses, CAP emissions data from GREET, and water use ranges from a variety of published studies. CAP emissions and water usage for various fuel-vehicle systems was provided on a per vehicle mile traveled basis to ensure a consistent evaluation. Other environmental issues such as biodiversity, water quality impacts, and land impacts were beyond the scope of this study.

Criteria Air Pollutants from the Transportation Sector

The EPA has identified six criteria air pollutants that present a risk to the environment and human health, listed in Table 6-11. The EPA sets the National Ambient Air Quality Standards (NAAQS) for criteria air pollutants. On-road vehicles, marine engines, rail locomotives, and aircraft are sources of CAP emissions that affect air quality and impact human health.[64] Transportation is also a significant contributor to volatile organic compound (VOC) emissions, which is not classified as a CAP but reacts with NOx to produce ozone.[65]

64 While CAP emissions can have environmental impacts such as acid rain, the reduction of agricultural crop yields, forest decline, and restricting natural visibility, this analysis will focus primarily on human health effects.

65 Nitrogen dioxide (NO_2) is one of a group of highly reactive gases known as oxides of nitrogen or nitrogen oxides. Other nitrogen oxides include nitrous acid and nitric acid. While the EPA's National Ambient Air Quality Standards cover the entire group of nitrogen oxides, NO_2 is the component of greatest interest and the indicator for the larger group of nitrogen oxides. U.S. Environmental Protection Agency (website), Air & Radiation: Six Common Pollutants: Nitrogen Dioxide, http://www.epa.gov/air/nitrogenoxides/.

Pollutant	Contribution from Transportation	Regulation
Carbon Monoxide (CO)	Nationally and, particularly in urban areas, the majority of CO emissions come from transportation.*	Exhaust emissions are regulated under EPA Tier 2; the Clean Air Act requires winter oxygenated gasoline in CO nonattainment areas where mobile sources are a significant source of CO emissions.†
Lead	The switch to unleaded gasoline has reduced lead emissions from transportation by 95%.‡	Amendments to the Clean Air Act banned lead from gasoline.§
Nitrogen Oxides (NOx)	Emissions occur throughout the fuel cycle. NO_2 is formed from emissions from vehicles, power plants, and off-road equipment.	Exhaust emissions are regulated under EPA Tier 2.
Particulate Matter (PM)	Urban PM emissions are dominated by vehicle operation. Diesel engines are the main source of $PM_{2.5}$ emissions.	Exhaust emissions are regulated under EPA Tier 2 for light-duty vehicles, and under EPA emissions standards for heavy-duty vehicles and non-road engines.
Ozone (O_3)	Ground-level ozone is created by chemical reactions between NOx and volatile organic compounds (VOCs) in the presence of sunlight. On-road and off-road vehicles are contributors to VOC emissions.	EPA Tier 2 regulates vehicle emissions for NOx and VOCs (as non-methane organic gases) and EPA also regulates evaporative emissions.¶
Sulfur Dioxide (SO_2)	Most sulfur oxide (SOx) emissions are generated in the fuel production and upstream feedstock stages of the fuel life cycle.	EPA Tier 2 defines restrictions for the amount of sulfur content allowed in gasoline and diesel fuel.

* U.S. Environmental Protection Agency (website), Air & Radiation: Six Common Pollutants: Carbon Monoxide, http://www.epa.gov/airquality/carbonmonoxide/.

† EPA, Office of Mobile Sources, EPA 400-F-92-005, "Automobiles and Carbon Monoxide," January 1993, http://www.epa.gov/otaq/consumer/03-co.pdf.

‡ EPA (website), Air & Radiation: Six Common Pollutants: Lead in Air, http://www.epa.gov/air/lead/.

§ Science Progress (website), "A Brief History of Lead Regulation," October 2008, http://scienceprogress.org/2008/10/a-brief-history-of-lead-regulation/.

¶ The volatility (Reid Vapor Pressure, or RVP) of gasoline is regulated during the summer ozone season. Reformulated gasoline (RFG) is mandated in urban areas with high ozone levels. EPA (website), Transportation & Air Quality: Fuels & Fuel Additives: Gasoline, http://www.epa.gov/otaq/fuels/gasolinefuels/index.htm.

Table 6-11. *A Summary of Criteria Air Pollutants from Transportation*

Because population exposure can be an important factor in assessing the health effects of criteria pollutants, a distinction should be made between total emissions and urban emissions. Total emissions refer to those occurring everywhere within a set geographic area while urban emissions are a subset of the total that occur within designated urban areas.

The primary CAPs of concern associated with this study are ozone and particulate matter.[66] Figure 6-26 illustrates the counties designated as nonattainment for ozone and particulate matter standards.[67] Almost 40% of the population lives in areas where 8-hour ozone EPA NAAQS is not attained, such as California and metropolitan and industrial centers in the Northeast, Texas, and the Great Lakes.

CAPs are emitted from resource extraction through fuel production, storage, distribution, dispensing, and vehicle operation. The analysis of CAPs emissions for various fuel-vehicle systems

66 Lead, CO, SOx exposure levels are within NAAQS levels. EPA (website), "Air Trends: Our Nation's Air – Status and Trends through 2010," http://www.epa.gov/airtrends/2011/.

67 U.S. Environmental Protection Agency (website), Air & Radiation: Six Common Air Pollutants: Designations, http://www.epa.gov/oaqps001/urbanair/designations.html.

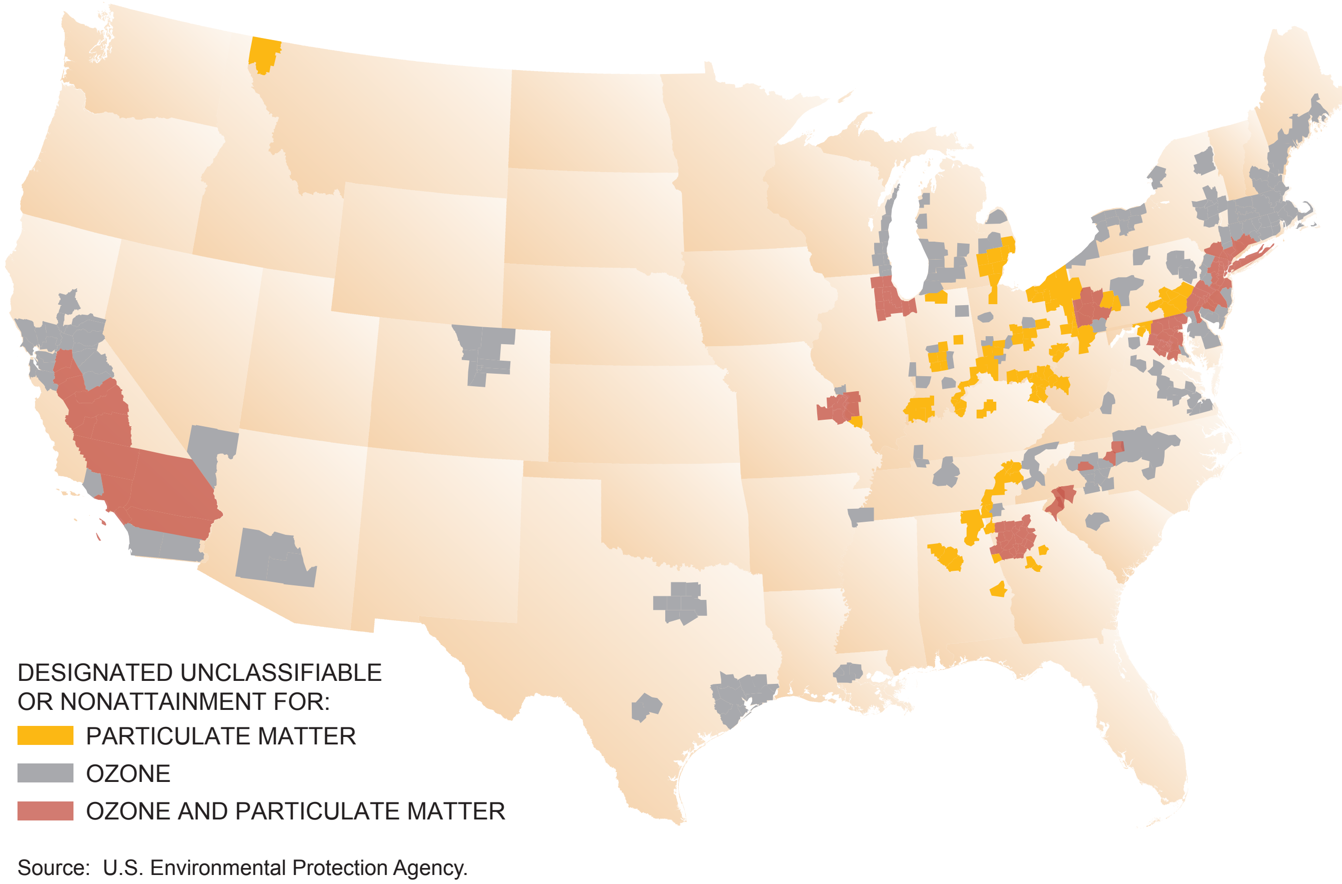


Figure 6-26. *U.S. Counties Designated as Nonattainment for Ozone and Particulate Matter Standards*

is a complex process dependent on assumptions about fuel and vehicle technologies, processes, and the selection of analysis boundaries. In addition to possible differences in methodology, each of the inputs may have uncertainty. (For example, tailpipe emissions are dependent on the performance of on-board diagnostic systems and vehicle maintenance.) GREET includes an analysis to assess the impact of uncertainty.

Comparing Criteria Air Pollutant Emissions from Alternate Fuel and Vehicle Pathways

An analysis was performed using GREET 1.8d to compare 2020 CAPs emissions of the fuel-vehicle systems in the study to a 2005 gasoline vehicle CAPs emissions on a per-mile basis. The year 2020 was used as the basis of comparison because it is the most forward-looking data available in GREET 1.8d; however, fuel economies were adjusted to the study's forecasts for 2050. While urban VOC and urban NOx contribute most to ground-level ozone in populated areas, all of the fuel-vehicle systems are comparable to or lower than the 2005 gasoline vehicle baseline emissions as shown in Figure 6-27. In addition, Topic Paper #28, "Criteria Air Pollutants Considerations," contains an analysis of each of the six criteria pollutants modeled for both urban and total emissions.

Water Usage Considerations

Water is used in significant quantities for producing energy. It is an essential part of the fuel life cycle. To understand the relative impacts of water use in the production of transportation fuels and energy carriers, it is important to first place this use within the context of total global and U.S. water supply and dispositions. Water use is generally described by two measures; volumes withdrawn from a water resource and volumes consumed. Consumed water, a subset of total water withdrawn, is the more relevant measure for resource utilization because this represents the volume of water that

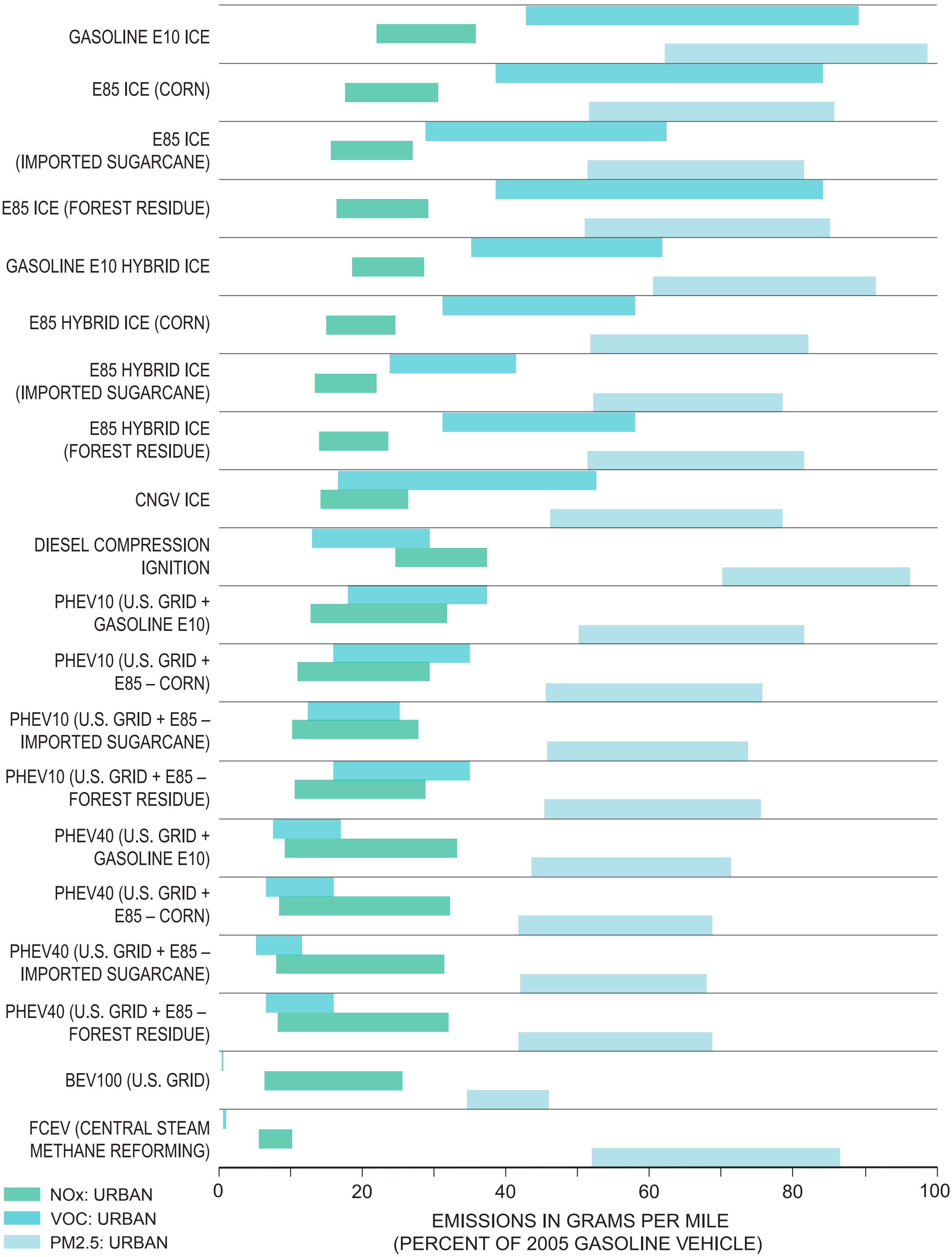


Figure 6-27. *2020 Urban NOx, VOC, and Particulate Matter Emissions Compared to a 2005 Gasoline Vehicle*

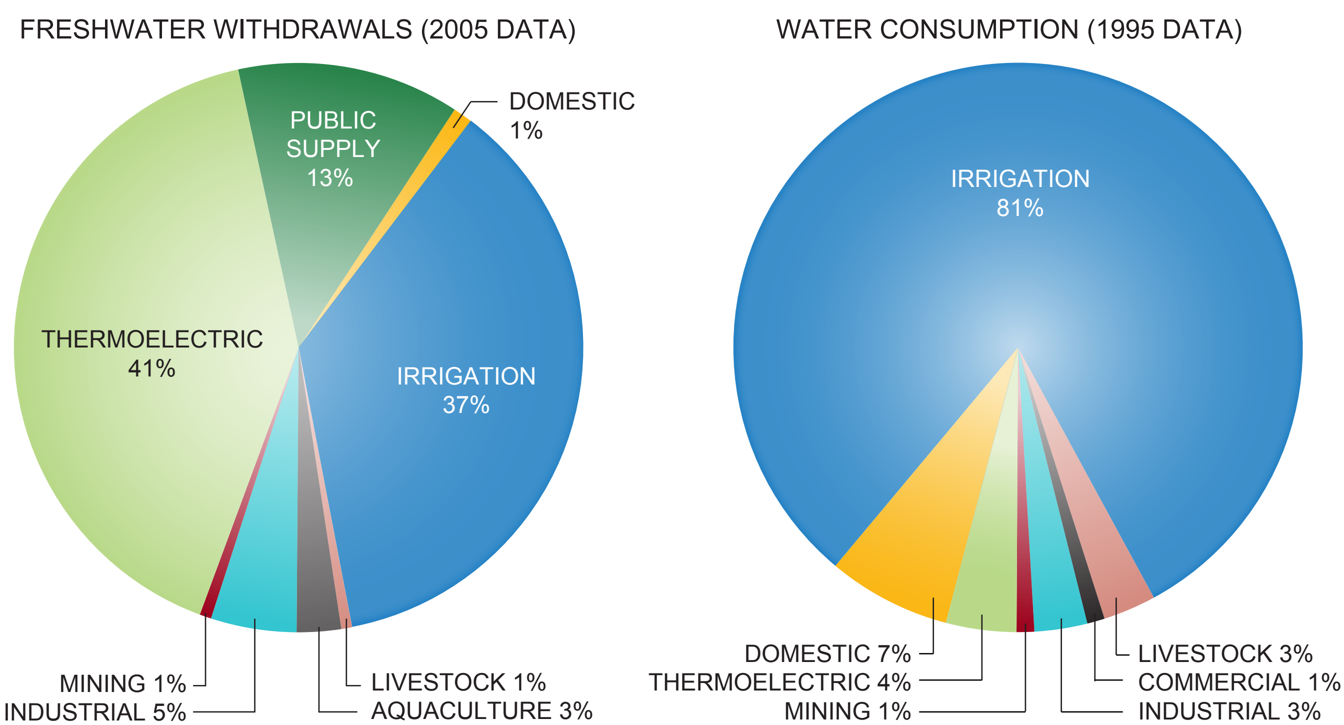
is removed from the watershed and made unavailable for future use, water lost to evaporation for example. Processes that consume freshwater are highly scrutinized and must be justified to determine if the use of water resources is prudent.

Figure 6-28 provides the breakdown between freshwater withdrawn and consumed in the United States, along with primary end users of that water. In total, approximately 100 billion gallons per day of freshwater is consumed in the United States. Irrigation for agriculture is the dominant consumer of freshwater in the United States. Thermoelectric power generation withdraws about a third but consumes less than a twentieth of water resource. Industrial and mining activities, which include extraction and processing of fossil hydrocarbon fuels, use a small fraction of freshwater resources.

Water consumed in the full fuel life cycle of relevant fuels are compared to one another, to show the difference in water withdrawals for the fuels under review. Figure 6-29 illustrates inputs, outputs, and losses for water balance calculations. Water consumption is considered on a well-to-tank life-cycle analysis basis—from the well (or mine, farm, etc.) to the vehicle tank (or battery).

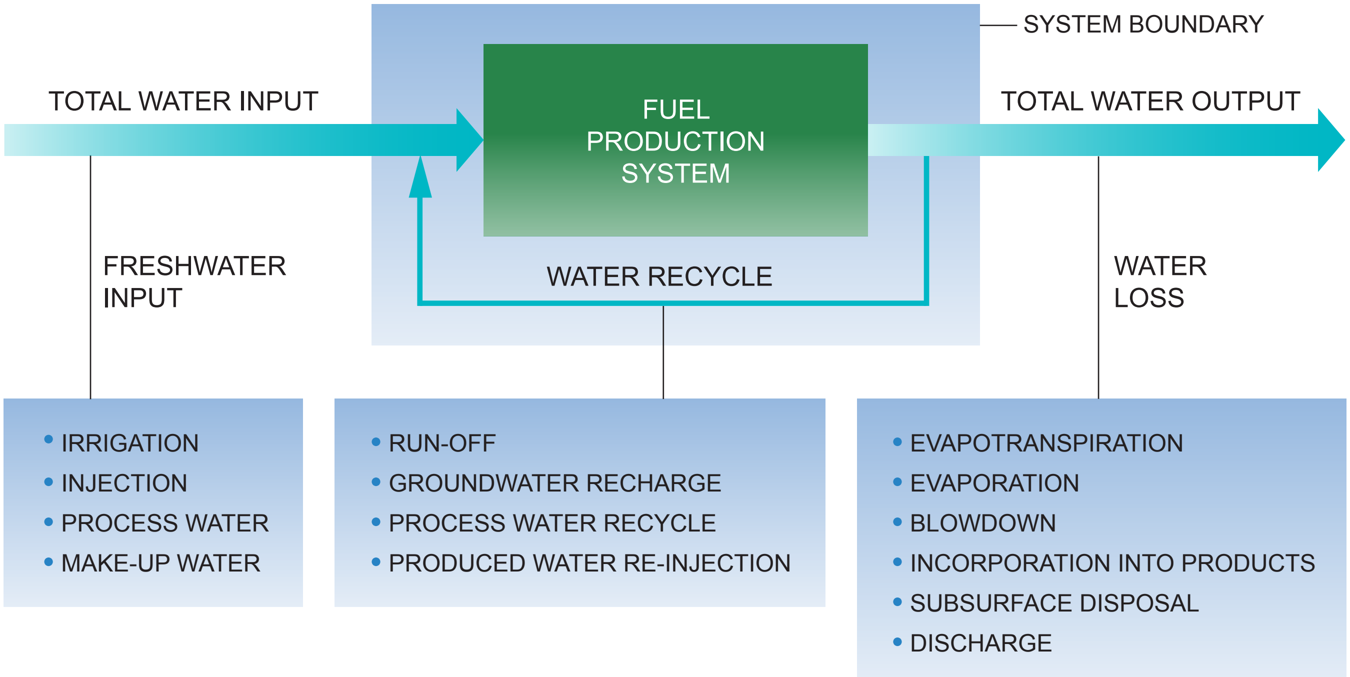
Water consumption for a given energy feedstock can vary significantly depending on feedstock production technology (e.g., electricity from various sources, biofuels from agriculture, oil production by primary recovery vs. water flood, or gas production by primary recovery vs. hydraulic fracturing). Similarly, the process configuration of a fuel manufacturing facility or power plant has a material impact on net water consumption. This includes the choice of cooling technology, plant operating conditions (e.g., power plant operating temperature), and extent of internal recycling of water. This report utilizes publicly available literature to show ranges for freshwater consumption for fuel and energy pathways.

The impact of water on the economics of power and fuels production is related to: (1) the cost, availability, and quality of the source water; (2) treatment required for use in the process; and (3) the treatment and regulatory compliance necessary for disposal of wastewater. These factors influence



Sources: U.S. Department of Energy, *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water,* December 2006; and U.S. Department of the Interior, U.S. Geological Survey, *Estimated Use of Water in the United States in 2005,* Circular 1344, 2009, http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf.

Figure 6-28. *U.S. Freshwater Withdrawals and Consumption*



Source: Argonne National Laboratory, Energy Systems Division, *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline*, ANL/ESD/09-1, January 2009.

Figure 6-29. *Water Balance for Energy Production Facility*

the choice of process technology and the extent of water reuse and recycling within the facility.

Water Consumption per Vehicle Mile Traveled

A useful metric for comparing water consumption is gallons used per mile for selected fuel-vehicle systems. The use of biofuels may have a relatively high water requirement if irrigated feedstocks are used. Fuels with relatively low water consumption include diesel, gasoline, natural gas, hydrogen, and certain non-irrigated biofuels. The use of electricity as a transportation fuel may also offer a relatively low water consumption option if electricity is sourced by non-hydroelectric technologies or if the water consumption by hydroelectric installations is allocated across multiple reservoir uses.

Figure 6-30 shows the WTW water consumption ranges in gallons per mile traveled. (Note: this is a semi logarithmic scale, which amplifies the lower range and shrinks the upper range of the chart.) Water consumption data are used in combination with 2050 fuel economy data from the NPC analysis (see Chapter Two, "Light-Duty Vehicles") to estimate ranges for water consumption per vehicle mile traveled. Water requirement data for each fuel option are from publicly available data presented in Topic Paper #31, "Water Usage Considerations." The U.S. grid water consumption factor was derived from a combination of the reported thermoelectric power water consumption and range of water consumption for non-thermoelectric technologies. In 2005, the National Energy Technology Laboratory reported that 3.7 billion gallons per day in 2005 were consumed[68] for producing 3.732 million gigawatt hours of electricity.[69] This gives a thermoelectric consumption factor of 362 gallons per megawatt hour, to which the water consumption for the renewables mix is added, based on the analysis in this report. The mix of renewables by technology is assumed to be the same in 2050 as it was 2010. In cases where projections out to 2050 were not

68 National Energy Technology Laboratory, *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements: 2008 Update,* DOE/NETL-400/2008/1339, September 2008.

69 EIA energy statistics for 2005.

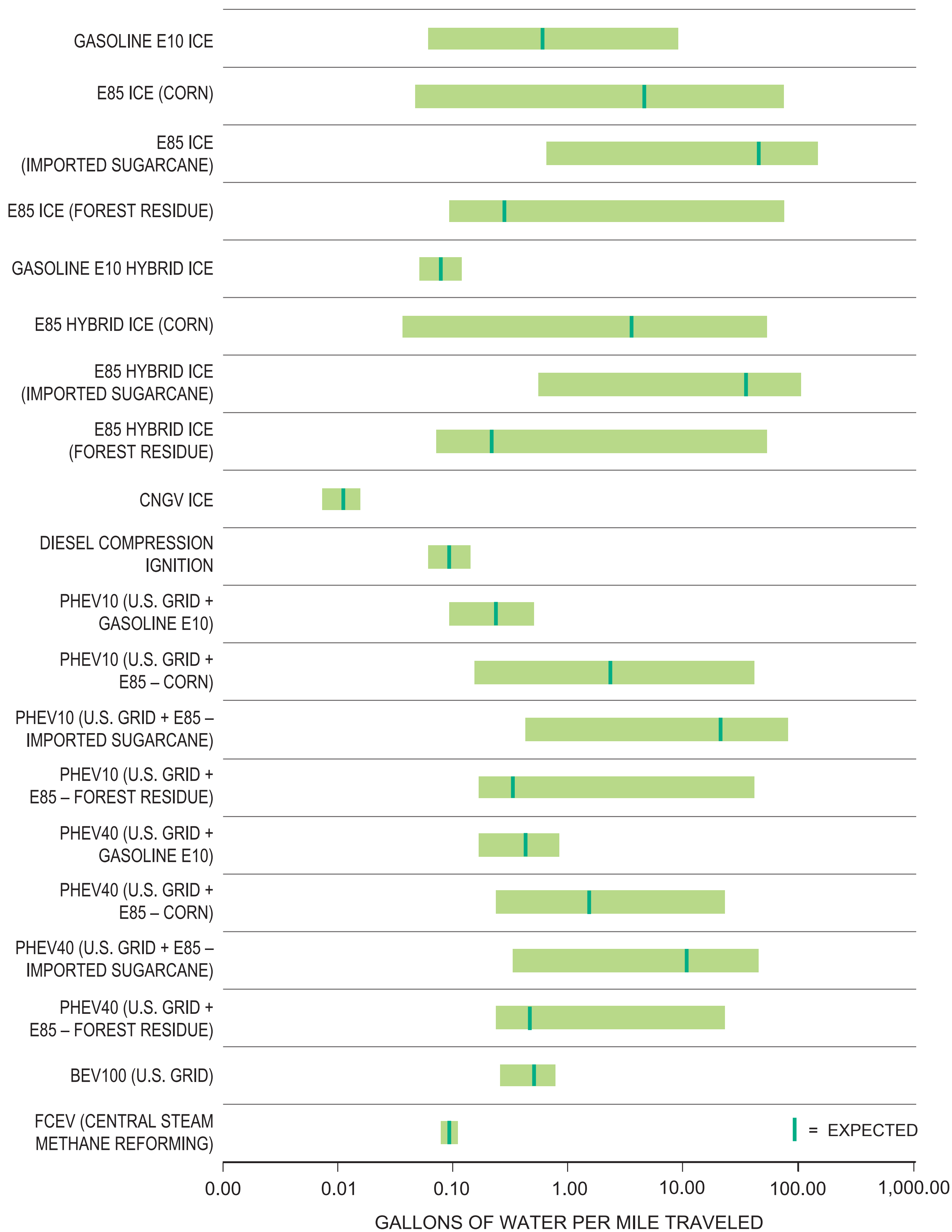


Figure 6-30. *Well-to-Wheels Water Consumption Ranges for Fuel and Vehicle Pathways*

available, the most forward looking projection is used and assumed to remain unchanged to 2050. The assumed 2050 electricity generation mix is from the AEO2010 Reference Case.

Fuel-vehicle systems that rely solely on fossil fuels (diesel, gasoline, and natural gas) have the smallest estimated water consumption ranges. Diesel and natural gas fuels have the lowest WTW water use profiles in this analysis. Diesel has lower water use than the E10 gasoline because it has no biofuel component. The biofuel contribution to gasoline was assumed to be corn ethanol. Electricity (BEV) has relatively low water use per mile traveled compared to biofuels.

Though nearly all of the fuel and technology configurations present low water consumption per mile traveled under specific production scenarios, the maximum potential water use for some configurations is significantly higher than others. In general, the use of biofuels will increase water consumption per mile traveled in comparison to fossil fuels and electric vehicles. Water consumption is the highest when irrigation is required to produce biofuel feedstocks. Avoiding irrigated feedstocks puts consumptive water use for all fuel-vehicle systems on a similar order of magnitude; however, most biomass feedstock conversion is expected to consume more freshwater than fossil feedstock conversion.

The availability of water varies greatly from region to region, and water resources are typically managed at a local and state level. Fuel production options can be constrained by regional water resource availability.

FINDINGS

1. **Economically competitive low-carbon fuels and efficient vehicles can make significant progress towards significant GHG emissions reduction.**

Comparing the calculated GHG emissions from the 2050 LD fuel-vehicle systems considered in this study to the average 2005 LD vehicle (~550 gCO_2e/mile) reveals that all the 2050 LD fuel-vehicle systems under consideration can have significant efficiency improvements that result in greater than 40% GHG reduction on a per-mile-traveled basis.

Comparing the GHG emissions ranges for 2050 LD fuel-vehicle systems to each other suggests ICEs, hybrids, and PHEV10/40 running on advanced biofuels have the lowest GHG emissions on a per-mile-traveled basis if uncertainties such as ILUC are not considered. However, a U.S. LD vehicle fleet that is fueled exclusively with advanced biofuels is not feasible. The expected supply of advanced biofuels is insufficient to meet the entire expected LD demand due to limited biomass availability. FCEVs fueled by hydrogen produced from natural gas have the next lowest GHG emission on a per-mile-traveled basis after vehicles fuel by advanced biofuels. Hybrid gasoline vehicles, CNGVs, PHEVs, and BEVs have comparable GHG emissions to each other and lower emissions than ICE gasoline and compression-ignition diesel vehicles.

Reducing GHG emissions in the LD fleet to 50% of 2005 LD vehicle segment levels requires limiting LD vehicle GHG emissions to ≤750 MMT CO_2e. If technology and transition hurdles are overcome and advanced fuel-vehicle systems are commercialized, a very limited number (<3%) of study analysis fleet portfolios achieved <750 MMT CO_2e and required the following conditions: high fuel economy, low VMT, and significant economic volumes of cellulosic biofuels (not considering the impact of indirect land use changes). In the study modeling, this was achieved under Reference Case and High Oil Price Case conditions (2050 oil prices of ~$155–215/barrel in 2008 dollars) with the availability of up to ~70 billion gallons of cellulosic ethanol equivalent plus >20 billion gallons of corn-based ethanol per year. Vehicles in these low emission cases are designed considering fuel expenditures over the long term (up to 17 years—the life of the vehicle). Additionally, these low GHG emissions vehicle portfolios were typically characterized by significant shares of FCEVs and limited availability of CNGVs.

Improvements in MD/HD vehicle fuel economy and the adoption of lower emissions alternative fuel-vehicle systems may be sufficient to offset emissions increases from the projected growth in VMT demand from 2005 to 2050. This would result in total 2050 MD/HD fleet emissions comparable to 2005 levels. MD/HD sector is not expected to achieve a 50% GHG emissions reduction relative to 2005 MD/HD segment levels. Further GHG emissions reductions beyond those calculated in this analysis are feasible through additional efforts such as the use of bio-based diesel, advanced biofuels, renewable natural gas, and/or improved freight efficiency on a ton-mile basis.

The following conditions are necessary to achieve the lower end of the range of MD/HD fleet GHG emissions presented in this analysis: nearly twofold fuel economy improvement for Class 7&8, significant penetration of natural gas into Class 7&8 vehicles, availability of advanced biofuels for Class 3-6 (not considering the impact of ILUC), and VMT projections lower than those in AEO2010 (e.g., AEO2012 Early Release).

2. The benefit of advanced biofuels are constrained by biomass availability and are subject to GHG emissions uncertainty.

Advanced biofuels offer a significant potential for reducing GHG emissions on a per-mile basis and can be used in all transportation modes: on-road, air, marine, and rail. The availability of biofuels for the transportation sector is constrained by biomass availability, infrastructure (feedstock collection and fuel production), and the relative cost of fuel. Additional considerations that can materially impact the emissions benefits of biofuels include GHG measurement uncertainty (e.g., ILUC) and sustainability elements such as water and land use.

There are key areas of scientific uncertainty in quantifying the GHG emissions of biofuels (ILUC, GHG emissions accounting from land use change, etc.). For robust biofuel policy frameworks, decision makers should acknowledge and consider this uncertainty and balance GHG reduction and sustainability goals of different regulations.

3. Additional GHG reduction strategies may be needed to achieve 50% transportation sector GHG emissions reduction.

The quantitative analysis performed in this study suggests that it will be challenging to achieve a 50% transportation sector GHG emissions reduction. As a result, additional GHG reduction strategies, such as carbon intensity reduction of electricity and other fuels, improved travel efficiency and reduced travel demand enabled by technology, consumer behaviors, and policy may be needed to supplement the GHG emissions reductions beyond those achieved through advance fuel-vehicle technologies. These GHG reduction strategies, a limited subset of which have been highlighted and discussed in this document, do not replace, but are complimentary to, the fuel-vehicle systems discussed.

Additionally, given the broad range of GHG reduction costs within and across each U.S. economic sector, it will be important to consider full life-cycle environmental impacts and cost effectiveness across all sectors when evaluating GHG emission reduction options in the transportation sector.

4. Criteria air pollutants and water usage are important considerations.

When compared to incumbent gasoline and diesel vehicles, all alternative fuel and vehicle options analyzed provide comparable or improved urban criteria air pollutant emissions on a vehicle-mile-traveled basis. For water consumption, all alternative fuel and vehicle options analyzed, except for irrigated biomass used for biofuels, generally have similar or improved water consumption performance on a VMT basis.

APPENDIX 6A:
CALCULATION OF 2005 GHG EMISSIONS AND 50% REDUCTION

SUMMARY

Secretary Chu requested the Future Transportation Fuels (FTF) study to consider:

> What actions could industry and government take to stimulate the technological advances and market conditions needed to reduce life-cycle greenhouse gas emissions in the U.S. transportation sector by 50 percent by 2050, relative to 2005 levels, while enhancing the nation's energy security and economic prosperity?

The methodology and data described below suggest that 2050 U.S. transportation sector life-cycle GHG emissions would be ~1,250 million metric tons of CO_2 equivalent (MMT CO_2e) if transportation sector GHG emissions were 50% of 2005 levels. This is comprised of 1,000 MMT CO_2e for the on-road light- and heavy-duty vehicle segments, which makes up about 80% of the transportation fuel sector on an energy basis. The remaining 250 MMT CO_2e is for non-road transportation comprised of rail, marine, and air. It is important to note that these on-road and non-road 50% GHG reduction levels should be treated as reference points only. This study does not address 50% GHG reduction levels for additional end-use categories beyond the broad on-road and non-road segments due to differences in future demand growth rates for each end-use category as well as differences in GHG reduction options available for each end-use category.

SCOPE

The FTF study scope includes auto, truck, air, rail, and waterborne transport end-use categories. The FTF GHG reduction analysis is more quantitative for light- and heavy-duty vehicles while a qualitative approach is applied to air, rail, and marine transport. This analysis primarily used AEO data to establish the 2005 U.S. transportation sector GHG baseline.[70]

70 The only transportation end-use category that was excluded from study scope was AEO's "other" category, which includes recreational boats, military, lubricants, and pipeline fuel. The "other" end-use category represents about 6% of the total U.S. transportation fuel sector on an energy basis.

METHODOLOGY

While tailpipe emissions are important, several fuel and vehicle technologies such as battery electric and hydrogen fuel cell electric vehicles considered in the NPC study have little or no tailpipe GHG emissions. Therefore, this analysis considers a full fuel cycle GHG analysis of the transportation sector to achieve 50% emission reduction. Since the National Energy Modeling System (NEMS) and AEO generally report transportation sector GHG emissions on a tank-to-wheel or fuel-combustion basis, not on a full fuel well-to-wheels basis, an alternate methodology was required to define a 2005 well-to-wheels (WTW) GHG emissions baseline for calculating 2050 GHG emission levels.[71]

Argonne National Laboratory's VISION model was used to establish a 2005 life-cycle GHG emissions baseline for light- and heavy-duty vehicles while an alternate approach described below was developed for non-road transport. The VISION tool models all types of highway transportation but excludes non-highway transportation as well as passenger buses.[72] The VISION model was used to extract light- and heavy-duty vehicle WTW GHG emissions for 2005 and then calibrate to the Reference Case, using GHG carbon intensity coefficients from Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[73]

The 2005 WTW GHG emissions for bus, marine, rail, and air transportation was estimated by taking 2005 AEO energy usage for these end-use categories and multiplying by GREET GHG carbon coefficients[74] associated with the petroleum

71 While it can be argued that well-to-wheels terminology does not accurately portray the full life-cycle GHG emissions of certain pathways such as grid-charged battery electric vehicles, this analysis uses life-cycle GHG and WTW GHG emissions terminology interchangeably.

72 Additional details about the VISION model, NEMS, and AEO can be found in Chapter One, "Demand," and Chapter Eight, "Transportation Fuels Reference Case."

73 Additional information on GREET can be found in Topic Paper #29, "Green House Gas Life Cycle Assessment/Analysis," on the NPC website.

74 Utilized GREET version 1.8d year 2005 GHG coefficients using a high heating value basis.

U.S. Transportation Sector By End-Use Categories	2005 Energy Use (Quadrillion BTU)	Energy Contribution From Each End-Use Category	2005 AEO Tank-to-Wheels Emissions (MMT CO_2e)	2005 Well-to-Wheels Emissions (MMT CO_2e)	2050 50% GHG Reduction Level (MMT CO_2e)
	AEO 2008 Table A7	2005 AEO Energy Basis	AEO 2011 Table A22	VISION Values in Red	VISION Values in Red
Total – Light-Duty Vehicles (LDV)	**16.23**	**59.5%**	**1,155**	**1,496**	**748**
Commercial Light Trucks	0.61	2.2%	47	Incl. in LDV	Incl. in LDV
Bus Transportation	0.26	1.0%	17	**23**	**12**
Freight Trucks	4.74	17.4%	339	Incl. in HDV	Incl. in HDV
Total – Heavy-Duty Vehicles (HDV)	**5**	**18.3%**	**357**	**451**	**226**
*50% Reduction Level, On-Road**					*1,000*
Rail, Passenger	0.04	0.1%	6		
Rail, Freight	0.55	2.0%	42		
Total – Rail	**0.59**	**2.2%**	**48**	**52**	**26**
Marine Shipping, Domestic	0.31	1.1%	23		
Marine Shipping, International	0.77	2.8%	61		
Total – Marine Shipping	**1.08**	**4.0%**	**84**	**98**	**49**
Total – Air	**2.72**	**10.0%**	**196**	**258**	**129**
*50% Reduction Level, Non-Road**					*250*
Recreational Boats	0.24	0.9%			Excluded from 50% GHG Reduction Calculation
Military Use	0.68	2.5%			
Lubricants	0.15	0.5%			
Pipeline Fuel	0.6	2.2%			
Total – Other	**1.67**	**6.1%**	**104**		
Total Transportation	**27.29**	**100%**	**1,990**		
Total Transportation (excluding "Other")	**25.62**		**1,840**	**2,378**	**1,250**

* On-road and non-road 50% GHG reduction levels rounded up to one and one-half level precision.

Table 6A-1. *2050 50% GHG Reduction Reference Level* feedstocks most predominately used for these end-use categories. This approach was deemed to be sufficiently accurate since these sectors contribute less than 20% to the entire transportation sector on an energy basis.

Table 6A-1 summarizes the transportation sector 2005 WTW GHG emissions baseline and 2050 50% GHG reduction reference levels. The VISION-derived 50% GHG reduction reference point for light- and heavy-duty vehicles is 1,000 MMT CO_2e. For non-road end-use categories including rail, marine shipping, and air, but excluding the "other" category, the 50% GHG reference point was 250 MMT CO_2e.[75]

OTHER CONSIDERATIONS

2005 biofuel GHG emissions derived from VISION modeling and GREET GHG coefficients do not include GHG emissions associated with indirect land use change (ILUC). ILUC refers to market-driven land use conversion, beyond that associated with feedstock destined for a specific production facility, which is often referred to as direct land use change.[76] This impact can be material and requires further consideration and analysis.

A second consideration involves energy use and GHG emissions from the vehicle production process, as well as from future battery manufacturing. Generally, GHG emissions associated with conventional vehicle manufacturing processes are relatively small when compared to overall life-cycle fuel GHG emissions over a vehicle's life.[77] As a result, establishing the 2005 WTW GHG baseline and the resulting 50% reduction did not include GHG emissions from vehicle manufacturing. Going forward, however, manufacturing process emissions may become more material. Manufacturing processes for some new technologies that are explored in this study, such as batteries or vehicle lightweighting, may lead to vehicle manufacturing emissions materially greater than the historical traditional vehicle manufacturing emissions values considered in this study.

75 Calculated 50% GHG reduction levels for on-road and non-road categories are rounded up and kept at one and a half digit precision, which is consistent with the quantitative analysis and approach of the FTF study.

76 FTF vehicle technology and fuel pathway evaluations that achieve 50% GHG reduction will be quantitatively analyzed without taking biofuel ILUC affects into consideration in order to be consistent with VISION modeling. However, biofuel ILUC impacts will be qualitatively addressed in the overall FTF study. Refer to Topic Paper #29, "Green House Gas Life Cycle Assessment/Analysis," on the NPC website for additional information on GHG emissions associated with ILUC from biofuels.

77 Carnegie-Mellon study on plug-in hybrids, which looked at battery production and found GHGs associated with lithium-ion battery materials and production account for 2–5% of life-cycle emissions from PHEVs. See: C. Samaras and K. Meisterling, "Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy," *Environmental Science and Technology* 42, no. 9 (2008): 3170-3176.

APPENDIX 6B: THIRD-PARTY DATA RESOURCES FOR FUEL CARBON INTENSITY VALUES

FOSSIL FUELS

Gasoline – RFG

Crude Oil

1. CARB 2/27/2009 Documentation. "Detailed CA-GREET Pathway for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) from Average Crude Refined in California": http://www.arb.ca.gov/fuels/lcfs/022709lcfs_carbob.pdf.
2. GHGenius 2009: GHGenius3.19 - Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by High Heating Value (HHV)(MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.
3. Jacobs 2009: Jacobs/Life Cycle Associates report for AERI, "Life Cycle Assessment Comparison of North American and Imported Crudes," July 2009.
4. CARB 2009: Appendix C12 of CARB's Initial Statement of Reasons for the Low Carbon Fuel Standard. Only GHGs provided; could scale energy in average mix by GHG differences to get a rough estimate: http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol2.pdf.

Diesel – ULSD

Crude Oil

1. CARB 2/28/2009. Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_ulsd.pdf.
2. Jacobs 2009: Jacobs/Life Cycle Associates report for AERI, "Life Cycle Assessment Comparison of North American and Imported Crudes," July 2009.

Electricity

U.S. Mix

1. GREET 2010: GREET1.8d. 2010 simulation. Run 9/20/2010.
2. GREET 2011: GREET1_2011 Argonne National Laboratories (ANL).

Natural Gas

Natural Gas

1. GREET (Burnham et al, ES&T 2011): Burnham, Andrew, J. Han, C. E. Clark, M. Wang, J. B. Dunn, and I. P. Rivera. 2011. Life-cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum. Environmental Science and Technology. November 22, 2011. Downloaded from http://pubs.acs.org on November 22, 2011.
2. CARB 2/28/ 2009. Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from North American Natural Gas: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_cng.pdf.
3. GHGenius 2009: GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (MJ/l, etc) to obtain gCO2e/MJ value for various pathways.
4. GREET 2010: GREET1.8d. 2010 simulation. Run 9/20/2010.
5. GREET 2011: GREET1_2011. Argonne National Laboratories (ANL).
6. GREET 2010: Results created by ANL on 11/11/2010 using GREET1.8d.1 version, August 2010 release.

Hydrogen

Natural Gas – Steam Methane Reforming (SMR)

1. GREET 2010: Results created by ANL on 11/11/2010 using GREET1.8d.1 version, August 2010 release.
2. NREL 2009: Ruth (2009) NREL Report "Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions": http://www.nrel.gov/docs/fy10osti/46612.pdf.

BIOFUELS

Ethanol – E100

Corn

1. CARB 2/27/2009. Detailed California-Modified GREET Pathway for Corn Ethanol: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_cornetoh.pdf.

2. EPA 2010: EPA's Renewable Fuel Standard (RFS2) (2010) Regulatory Impact Analysis (RIA) Accessed 2/23/2010 at www.epa.gov/otaq/renewablefuels/420r10006.pdf.

3. GHGenius 2009: GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.

4. GREET 2010: GREET1.8d. 2010 simulation. Run 9/20/2010.

5. GREET 2011: GREET1_2011. Argonne National Laboratories (ANL). Results created by ANL on 11/11/2010 using GREET1.8d.1 version, August 2010 release.

6. GREET 2010: Produced by ANL using GREET1.8d.1 version, August 2010 release.

Biodiesel – FAME

Soybean

1. CARB 2/27/2009. Detailed California-Modified GREET Pathway for Biodiesel (Esterified Soyoil) from Midwest Soybeans: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_biodiesel.pdf.

2. EPA February 2010: EPA-420-R-10-006. EPA's Renewable Fuel Standard (RFS2) (2010) Regulatory Impact Analysis (RIA). Chapter 2.6. Accessed 2/23/2010 at www.epa.gov/otaq/renewablefuels/420r10006.pdf. Downloaded from their site 9/14/2010 (www.afdc.energy.cov/afdc/data).

3. GHGenius 2009: GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.

4. GREET 2010: GREET1.8d. 2010 simulation. Run 9/20/2010.

5. GREET 2010: Produced by ANL using GREET1.8d.1 version, August 2010 release.

ADVANCED BIOFUELS

Renewable Diesel – HRD

Soybean

1. CARB 2/27/2009: Detailed California-GREET Pathway for Renewable Diesel from Midwest Soybeans: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_rd.pdf.

2. GHGenius 2009: GHGenius model. Described in: The addition of algae and jatropha biodiesel to GHGenius. Prepared by (S&T)^2 Consultants, Inc. September 30, 2009.

3. GREET 2010: Produced by ANL using GREET1.8d.1 version, August 2010 release.

Fisher-Tropsch Diesel – FTD

Forest Residue (Wood)

1. GHGenius 2009: GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by High Heating Value (HHV) (MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.

Biogasoline

Forest Residue

1. GREET 2011: GREET1_2011. Argonne National Laboratories.

2. GHGenius 2009: GHGenius3.19 – Using Canada Default Values.

Wood

1. GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.

Ethanol – E100

Corn Stover

1. EPA February 2010. EPA-420-R-10-006. RFS2 Regulatory Impact Analysis.

http://www.epa.gov/otaq/renewablefuels/420r10006.pdf.

2. GHGenius3.19 2009 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (MJ/l, etc) to obtain gCO_2e/MJ value for various pathways.

3. GREET 2010: Results created by ANL on 11/11/2010 using GREET1.8d.1 version, August 2010 release.

Sugarcane

1. CARB 9/23/2009: Detailed California-Modified GREET Pathways for Brazilian Sugarcane Ethanol: Average Brazilian Ethanol, With Mechanized Harvesting and Electricity Co-product Credit, With Electricity Co-product Credit: http://www.arb.ca.gov/fuels/lcfs/092309lcfs_cane_etoh.pdf. Downloaded from their site 9/14/2010 (www.afdc.energy.cov/afdc/data).

2. EPA 2010: EPA-420-R-10-006. EPA's Renewable Fuel Standard (RFS2) (2010) Regulatory Impact Analysis(RIA). Chapter 2.6. Accessed 2/23/2010 at www.epa.gov/otaq/renewablefuels/420r10006.pdf.

3. GHGenius 2009: GHGenius3.19 – Using Canada Default Values. Took full life-cycle results (per unit fuel) and divided by HHV value (mj/l, etc) to obtain gCO_2e/MJ value for various pathways.

4. GREET 2010: GREET1.8d. 2010 simulation. Run 9/20/2010.

5. GREET 2010: Results created by ANL on 11/11/2010 using GREET1.8d.1 version, August 2010 release.

Switchgrass

1. EPA 2010: EPA's Renewable Fuel Standard (RFS2)(2010)RegulatoryImpactAnalysis(RIA). EPA-420-R-10-006. Accessed 2/23/2010. Downloaded from their site 9/14/2010 (www.afdc.energy.cov/afdc/data): www.epa.gov/otaq/renewablefuels/420r10006.pdf.

2. GREET 2010: Results created by ANL 11/11/2010 using GREET1.8d.1 version, August 2010 release.