CHAPTER 13

Transportation Energy and Efficient Vehicles

Transportation is the fastest growing use of global energy and petroleum and a major source of GHG emissions. If we hope to arrest energy demand growth, petroleum dependency, and global warming, we must deal with energy in transportation. Next time you fill up at the gas station, think about these stunning facts:

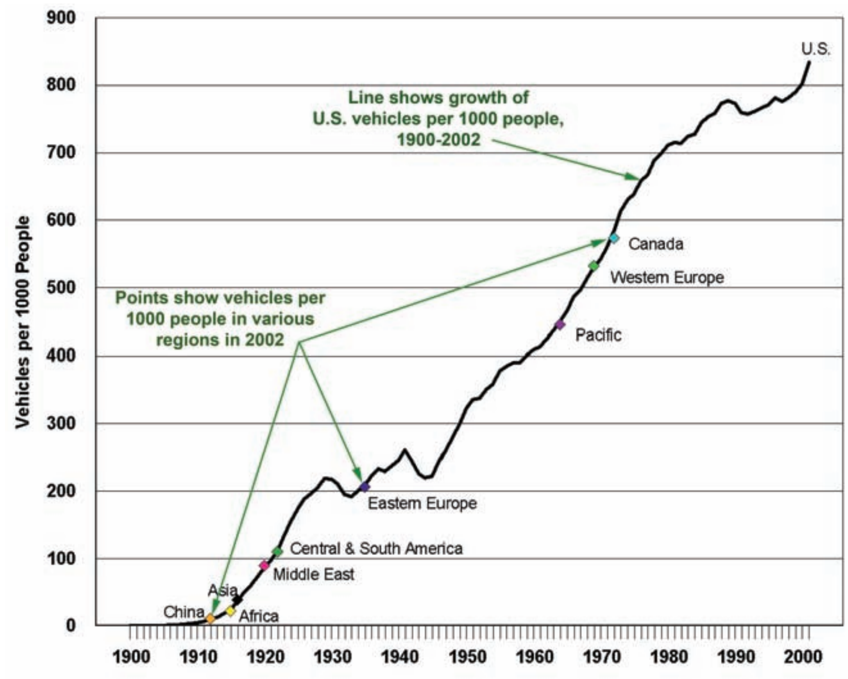
- Transportation and oil go hand in hand. Transportation relies almost exclusively (96%) on oil, and it uses more than two-thirds of the petroleum products consumed in the United States and more than half of world oil.
- Transportation produces one-third of all U.S. carbon dioxide emissions and is the primary source of urban air pollution.

If the oil-intensive U.S. patterns of transportation, dominated by personal vehicles, are adopted by developing countries, such as China, pressure will continue on oil markets, GHG emissions, and urban air pollution. The line in Figure 13.1 shows the growth in U.S. vehicles per 1000 people since 1900, and the 2002 levels for different countries and regions. For example, in 2002 Canada had the same ratio that the United States had in 1972. As of 2004, the United States, Canada, and Western Europe vehicles per 1000 people have stabilized, but this indicator is growing in all other regions of the world except Africa. There are about 800 million vehicles in the world today. If trends continue, that number could grow to 3.25 billion by 2050, led by China and India, each of which now has a middle-class population exceeding the total U.S. population. Each has a growing auto industry.

Solving energy problems posed by oil and carbon emissions requires more sustainable patterns of transportation energy use. The key factors that drive transportation energy and related air emissions are as follows:

- **Vehicle energy intensity,** measured by efficiency or economy; for example, miles per gallon (mpg)
- **Fuel type,** for example, petroleum-based gasoline or diesel; alternative fossil-fuel natural gas or coal-liquids; renewable biofuels, ethanol, or biodiesel; or electricity

figure 13.1 Growth of U.S. Vehicles per 1000 People, 1900–2002, with 2002 Values for Selected Countries and Regions



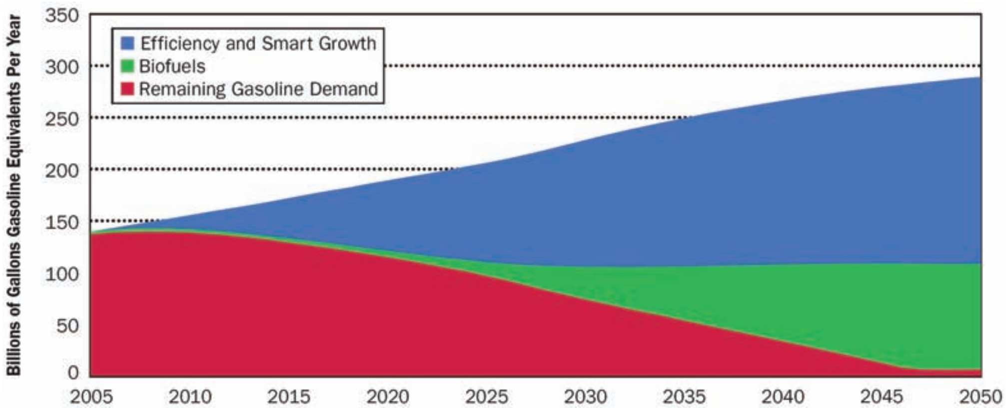
Source: U.S. DOE, 2006

- **Vehicle miles traveled** (VMT), affected by load factor (people per vehicle), distance of travel, and use of other modes (e.g., transit, walking)

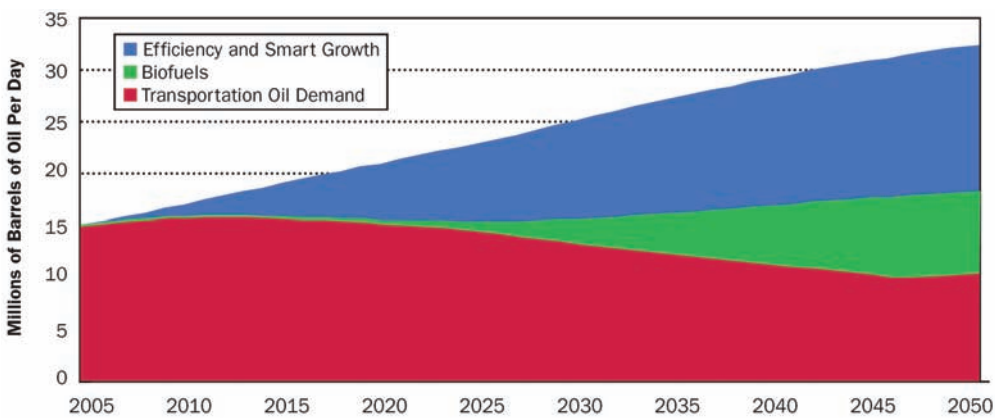
U.S. EIA 2007 Annual Energy Outlook to the year 2030 forecasts continued growth in petroleum-based fuels and VMT, small changes in vehicle efficiency, and replacement of some petroleum with alternative fuels, mostly from coal-to-liquids, oil shale, and natural gas-to-liquids (70%) and biofuels (30%). However, other studies show greater opportunities for efficiency and biofuels. For example, the Natural Resources Defense Council (NRDC) estimates that vehicle efficiency, reduction of VMT through smart growth land-use practices, and use of biofuels could eliminate the need for vehicle gasoline by 2050 (see Figure 13.2).

This section of the book describes in greater detail transportation energy use patterns and discusses the roles that vehicle efficiency, modes of transport, alternative and renewable fuels, transit, and land-use and spatial development patterns, can play in transitioning to more sustainable transportation. After reviewing data on transportation energy use, this chapter focuses on vehicle technologies. In the United States and increasingly in the rest of the world, we have a fixation on personal vehicles fueled by petroleum, and any solution must improve vehicle efficiency and replace petroleum with alternative fuels.

figure 13.2 **NRDC Estimate of Potential Savings in Gasoline and Transportation Oil Demand, 2005–2050**



(a) Gasoline savings.



(b) Oil savings.

Potential savings come from: increased use of biofuels, vehicle efficiency, and smart growth, or land-use changes that reduce vehicle miles traveled.

Source: Greene, 2004. Used with permission of NRDC.

Chapter 14 discusses the development of biofuels and other alternative fuels, including cellulosic ethanol and biodiesel from algae. Efficient and alternative fueled vehicles can help reduce per-mile energy and environmental impacts of transportation, but increasing vehicle miles traveled (VMT) can offset those improvements. VMT and land-use trends that drive them are discussed in Chapter 15. That latter chapter also applies our concept of Whole Community Energy to transportation. In the Whole Community approach, we can plan and develop building location and land use to reduce travel distances and enhance transit and pedestrian modes to reduce VMT. In addition, as introduced in Chapter 10, electrification of vehicles can make excellent use of distributed renewable electricity in communities.

13.1 Energy Use in Transportation

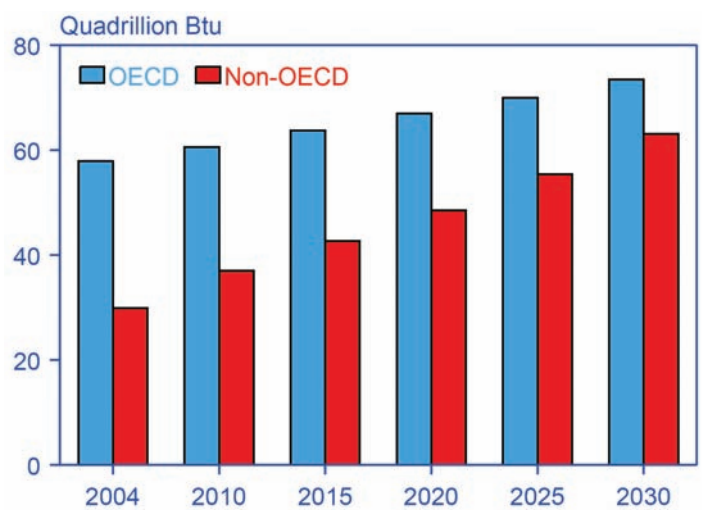
Before discussing vehicle technologies and efficiency, it is useful to review patterns of transportation energy use. This can help us to see where we should focus our efforts to reduce oil use and carbon emissions.

13.1.1 Global Transportation Energy Use

Global transportation consumes more than 20% of world energy and it comes almost entirely from oil. It is growing faster than other uses of energy, and U.S. EIA expects transportation energy to increase by 2.5% per year through 2025 when it would be *double* the levels of 2000. Developed countries, including the United States (represented by the OECD nations in Figure 13.3) consumed 56% of global transportation energy in 2002, but they are expected to grow slowly (at 1.3% per year) compared to developing countries (non-OECD) led by China and India. This is where nearly two-thirds of the growth in transportation energy is expected to occur, at an astounding rate of 4.4% per year.

Will we have enough oil and the atmospheric capacity to absorb the carbon associated with these trends? We are already feeling the economic and environmental effects of transportation dependency on oil. It is hard to imagine that we can sustain the expected growth of transportation energy if it follows current patterns of oil use. We must either slow the growth of transportation energy, change to less oil- and carbon-dependent patterns of transportation, or both.

figure 13.3 **International Transportation Energy Outlook by Region, 2004–2030**



13.1.2 Transportation Energy Use in the United States

In Chapter 1 we saw that transportation is the fastest growing and most oil-dependent energy-consuming sector in the United States (see Figures 1.5[c] and 1.13). Our goal is to arrest these trends: this section provides more detail to help identify opportunities for improved efficiency.

13.1.2.1 Transportation Modes and Energy Use

We use various modes to transport people and goods, including highway vehicles, airplanes, rail, waterways, and pipelines. Let's not forget pedestrian and bicycle transport, but these do not use fuel energy. As shown in Table 13.1, highway (81%) dominates non-highway (19%) transport, and light vehicles (including autos, pickups, and sport-utility vehicles [SUVs]) dominate highway transport with 61% of total transportation energy. Heavy trucks consume 19%, and other modes are small in comparison: air transport (8%), waterborne (5%), pipeline (4%), and rail (2.4%).

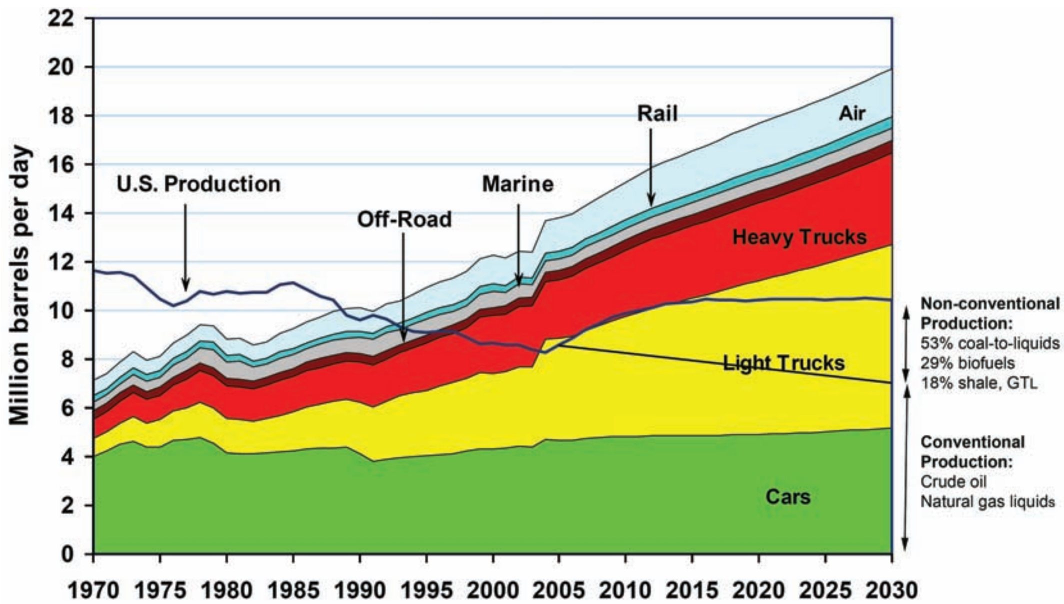
Figure 13.4 shows the growth of petroleum use by these modes of transportation to 2004 and projections to 2030. These government projections are an extension of current trends, but are we destined to continue these current patterns of petroleum use for transportation? They are probably not attainable, because they require doubling our current imports of oil, even with large-scale production of nonconventional liquid fuels from coal, biofuels,

table 13.1 U.S. Transportation Energy Use by Mode, 2004

	Trillion Btu	% of Total Transport Energy	1000 Barrels/Day Crude Oil Equivalent
HIGHWAY	**21,945**	**81.1**	**11,242**
Light vehicles	**17,217**	**63.6**	**8820**
Automobiles	9330	34.5	4780
Light trucks	7861	29.0	4027
Motorcycles	25	0.1	13
Buses	**193**	**0.7**	**99**
Medium/heavy trucks	**4535**	**16.8**	**2323**
NON-HIGHWAY	**5121**	**18.9**	**2623**
Air	**2348**	**8.7**	**1203**
Water	**1300**	**4.8**	**666**
Pipeline	**822**	**3.0**	**421**
Rail	**659**	**2.4**	**338**
TOTAL Hwy + Non-Hwy	**27,066**	**100.0**	**13,866**

Source: U.S. DOE, 2007

figure 13.4 **Growth of Transportation Petroleum Use by Mode, 1970–2004, with U.S. EIA Projections to 2030**



EIA foresees declining domestic petroleum production offset by new sources of nonconventional liquid fuels, especially coal-to-liquids (CTL). Most current and projected growth comes from light and heavy trucks.

Source: U.S. DOE, 2006

and oil shale. We currently don't produce any commercial liquid fuels from coal or oil shale, and doubling imports may have significant economic, trade balance, and geopolitical consequences. On the other hand, other scenarios for transportation energy take advantage of opportunities for efficiency, modal change, and non-fossil alternative fuels.

What do we want from transportation? Our objective is not to consume energy but to move around ourselves and the materials we want. And we want to do that with timeliness, flexibility, convenience, comfort, safety, style, and performance (vroom, vroom). Modes of transport and vehicle markets have shifted to maximize these objectives. And as travel distances have increased due to growing (and sprawling) metropolitan areas, traditional pedestrian and transit passenger travel is less practical. Passenger travel has shifted more to single-occupancy vehicles (SOV) to maximize flexibility, convenience, and style. Passenger vehicles have increased in size to maximize comfort, perceived safety, and style.

Intercity passenger travel in the United States has shifted from rail and car to air, again for added convenience and timeliness. Freight has shifted from rail to heavy trucks as markets have had to become more responsive to customer expectations for timeliness and convenience.

Energy use has increased not only because of modal shift and increased transportation miles but also because of lower load factors. **Load factor** is the quantity per vehicle, such as passenger per vehicle or freight tons per vehicle. Modal shift, load factors, and vehicle miles traveled, as well as market and user preferences, are issues transportation planners have to accommodate in planning and developing transportation systems. Below, we look a little more closely at highway and freight transport before discussing the largest energy user, passenger transportation.

13.1.2.2 Highway Transportation Energy

We saw in Table 13.1 that highway miles traveled are by far the biggest energy user (81%). Highway energy use doubled from 1970 to 2005 (Table 13.2). Overall, highway energy increased 1.9% per year from 1995 to 2005, with the largest growth coming from light trucks (pickups and SUVs; 3.6%/year growth). Consumer preference created a shift from autos to light trucks. Manufacturers encouraged this shift with advertising because bigger vehicles meant bigger profits. As fuel prices rose in 2005–2006, the market fell for larger SUVs, but as gas prices returned to $2 per gallon, the market rebounded. Freight transport has shifted from rail and water to heavy trucks, spurred by market preference for faster delivery. We will see how these shifts have reduced the efficiency of our transportation energy as measured by energy per passenger-mile and energy per freight-ton-mile (see Tables 13.3 and 13.6).

Clearly, highway passenger miles are the biggest energy use in U.S. transportation (> 61%) and we will spend much of this chapter discussing passenger transport and vehicles. Before doing so, the next section looks at the opportunities for increasing energy efficiency of freight transport.

13.1.2.3 Freight Transportation Energy

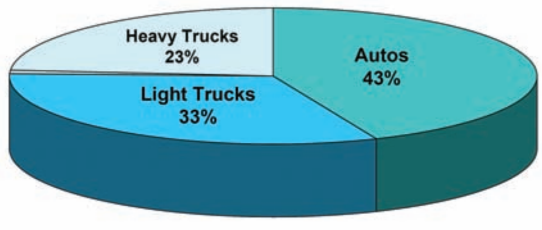
Passenger travel amounts to about 75% of transportation energy, and freight movement uses about 25%. Table 13.3 compares the three major modes of freight shipments: trucks, water-

table 13.2 Highway Transportation Energy Consumption by Mode, 1970–2005 (trillion Btu)

Year	Autos	Light Trucks	Light Vehicles Subtotal	Motor-Cycles	Buses	Heavy Trucks	Highway Subtotal	Total Transportation
1970	8479	1539	10,018	7	129	1553	11,707	15,402
1980	8800	2975	11,774	26	143	2686	14,629	18,937
1990	8688	4451	13,139	24	167	3334	16,663	21,598
2000	9100	6607	15,707	26	208	4819	20,760	26,268
2005	9140	8108	17,248	27	191	4577	22,043	27,385
Average Annual Percentage Change								
1970–2005	0.2%	4.9%	1.6%	3.9%	1.1%	3.1%	1.8%	1.7%
1995–2005	0.7%	3.6%	2.0%	0.8%	0.4%	1.5%	1.9%	1.6%

Source: U.S. DOE, 2007

figure 13.5 **Highway Transportation Energy, 2005**



Source: U.S. DOE, 2006

borne, and Class I railroads. Class I includes the seven major railroads that handle 92% of the nation's rail freight. In 2002, 44% of the Class I tonnage and 21% of revenues came from rail shipments of coal.

Whereas heavy truck vehicle miles and energy use has grown during the last three decades by 3.1% per year (doubled every 20 years), more efficient domestic waterborne ton-miles have declined in the last decade, although foreign waterborne commerce has increased steadily. Rail freight has also had little growth in tonnage over the last three decades but has increased at 2.4%/year since the mid-1990s. The trend from water and rail to trucks is disturbing for energy use, because trucks are seven times less energy efficient than rail and waterborne transport on a Btu/ton-mile basis (Figure 13.6).

13.1.2.4 Freight Transport Efficiency

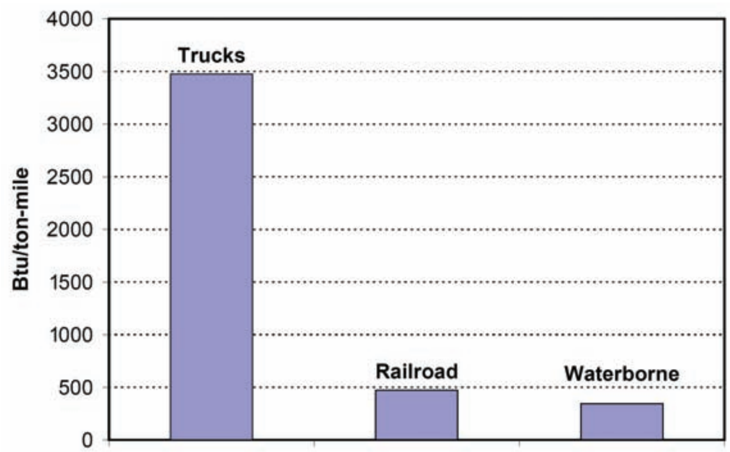
Heavy trucks consume nearly 19% of total U.S. transportation energy, and their use has grown considerably (Tables 13.1 and 13.2). Freight has moved from rail to trucks because of the flexibility and effectiveness of time-to-delivery. Increasing amounts are moved by air to improve time-to-delivery even more. Consumers have become used to overnight delivery and this has enhanced our economy, but at a cost of more energy for materials transport.

table 13.3 **Intercity Freight Movement and Energy Use in the United States, 2005**

	Trucks (2003)	Waterborne Commerce	Class I Railroads
Ton-miles (billions)	1051	591	1696
Tons shipped (millions)	4122	1029	1899
Energy intensity (Btu/ton-mi)	3476	514	337
Energy use (trillion Btu)	3653	304	571

Source: U.S. DOE, 2006, 2007

figure 13.6 Freight Energy Intensity, 2003



SOURCE: U.S. DOE, 2006

But there are opportunities for improving the energy efficiency of freight movement. Efficiency studies have demonstrated opportunities for efficiency improvements from aerodynamics and other design changes, hybrid electric drives, idle reductions and other operations improvements, modal shift to rail, and increased use of B-20 biodiesel. Dierkers' (2005) estimates of energy savings as indicated by reduction in CO_2 emissions are given in Table 13.4.

table 13.4 U.S. Freight Truck Potential Efficiency Opportunities to 2025 (Dierkers, 2005)

Option	Technical Potential Fuel and CO_2 Reduction	Additional Penetration	Total Savings	Total MMTCO$_2$ Reduction
		Technology Measures		44.4
Aerodynamics	10.9%	50%	5.4%	
Tire base/inflation	3.2	50%	1.6%	
Weight reduction	1.8	50%	0.9%	
Low-friction lubricant	1.5	50%	0.8%	
		Drive Train		
Hybrid technology	25%	25%	6.3%	33.3
		Operations		50.4
Idle reduction	8.9%	50%	4.5%	
Speed reduction	13.6%	25%	3.4%	
Driver training	3.8%	50%	1.9%	
		Modal Shift		
Shift to rail	80%	10%	8%	42.7
		Fuel Options		
Biodiesel 20% (B-20)	20%	50%	6.9%	36.8

SOURCE: Dierkers, 2005

13.1.3 Passenger Miles Traveled and Energy Intensity

13.1.3.1 International Variation in Passenger Miles, Modes, and Energy Intensity

The patterns of transportation passenger miles vary considerably throughout the world. Kenworthy (2003) conducted a study of urban passenger transport systems in eighty-four global cities. He grouped the cities into five "higher income" regions and six "lower income" regions. He argued that "automobile cities" such as those in the United States are more vulnerable during the transition to a post-petroleum world.

His results in Table 13.5 reveal that the major factors associated with high energy and CO_2 emissions from passenger transportation do *not* include the wealth of cities. One key factor underlying automobile dependency and energy use is the extent and quality of the public transportation system, especially the amount of service provided by rail. Urban density is also a key factor, as higher densities are associated with higher levels of transit use and non-motorized transport (walking and bicycling), and lower densities are associated with lower levels. Lower densities and reduced transit use are associated with more freeways and parking requirements.

The high U.S. levels of energy use per passenger mile and passenger CO_2 per capita result from travel distances, patterns of land use (urban density), automobile dependency, and low levels of rail transit use. Western Europe and high-income Asia, with comparable levels of urban wealth, have much higher densities and public rail transport use, while lower passenger energy and CO_2 emissions. Cities in lower-income regions have a much higher percentage of public transport passenger miles, but little of this is by efficient rail. The table's 1995 data for China do not reflect the recent changes going on there. Vehicle registrations grew by more than 8% per year in both China and India from 1992 to 2002, and by more than 19% in China from 2004 to 2005. Both China and India (lower income Asia) have much to do to approach the indicators of the higher income countries, but they appear well on their way.

13.1.3.2 U.S. Passenger Miles, Miles, Load Factors, and Energy Intensity

Passenger miles make up most of highway transportation but also include a significant portion of air and about 16% of rail transportation energy. Indicators of energy use for different modes of passenger travel are given in Table 13.6. Automobiles and personal pickups and SUVs dominate in number of vehicles, passenger miles, and energy use (Figure 13.7).

Energy efficiency is given by energy intensity measures of Btu per passenger mile (Btu/p-m) and Btu per vehicle mile. Vanpools and motorcycles have the best Btu/p-m (1294–2270), and autos, personal trucks, SUVs, buses, and overall rail have comparable Btu/p-m (3496–4329). Energy intensity depends not only on vehicle efficiency (Btu per vehicle mile) but also on load factor or persons per vehicle (P/v). The overall efficiency of autos and personal trucks is constrained by their low load factors (1.5–1.7 P/v). The potential efficiency of bus transit is also

table 13.5 **Urban Passenger Transport Indicators in Major Global Cities by Region, 1995**

		Higher Income				Lower Income			
Indicator	Units	USA*	ANZ	WEU	HIA	EEU	LAM	LIA	CHN
Number of cities in group sample		10	5	32	6	3	3	8	3
Average population of cities	million people	5.7	2.0	2.2	11.0	1.3	7.9	9.7	7.2
Urban density	persons/ha	15	15	55	150	53	75	204	146
Metropolitan GDP/cap†	US$/person	$31K	$20K	$32K	$32K	$6	$5	$4	$2
Length freeway per person	m/person	0.16	0.13	0.08	0.02	0.03	0.003	0.015	0.003
Parking spaces/1000 CBD jobs		555	505	261	105	75	90	127	17
Total reserved public transport routes per urban hectare	m/ha	0.8	3.4	9.5	5.9	10.7	1.2	2.5	0.3
Passenger cars/1000 persons		587	575	414	210	332	202	105	26
Passenger car passenger-km/cap	p-km/person	18,155	11,387	6,202	3.614	2,907	2,862	1,855	814
Private passenger vehicles/road km	units/km	99	73	182	144	169	144	236	117
Average road network speed	km/hr	49	44	33	29	31	32	22	19
Public transport seat-km service/cap	seat km/person	1,557	3,628	4,213	4,995	4,170	4,481	2,699	1,171
% public transport seat-km rail	%	48%	68%	62%	46%	59%	7%	15%	4%
Ratio public/private transport speed	km/hr	0.58	0.75	0.79	1.04	0.71	0.60	0.81	0.73
% non-motorized mode trips	%	8	16	31	28	26	31	32	65
% motorized public mode trips	%	3	5	19	30	47	34	32	19
% motorized private mode trips	%	89	79	50	42	27	35	36	16
% motorized pass-km on public	%	3	8	19	46	53	48	41	55
Private passenger energy/cap	1000 MJ/person	60.0	29.6	15.6	9.6	6.7	7.3	5.5	2.5
Private passenger energy/$GDP	MJ/$1000	1913	1497	489	303	1119	1477	1471	1055
Public transport energy/capita	MJ/person	809	795	1118	1423	1242	2158	1112	419
Energy per private pass-km	MJ/p-km	3.25	2.56	2.49	2.33	2.35	2.27	1.78	1.69
Energy per public pass-km	MJ/p-km	2.13	0.92	0.83	0.48	0.40	0.76	0.64	0.28
Overall energy per pass-km	MJ/p-km	3.20	2.43	2.17	1.40	1.31	1.60	1.20	0.87
Passenger CO_2 emissions/capita	kg/person	4405	2226	1269	825	694	678	509	213

* USA = United States; ANZ = Australia-New Zealand; WEU = Western Europe; HIA = High Income Asia; EEU = Eastern Europe; LAM = Latin America; LIA = Low Income Asia; CHN = China

† Abbreviations: cap = capita; CBD = central business district; GDP = gross domestic product; ha = hectare; hr = hour; kg = kilogram; km = kilometer; MJ = mega-joules, million joules; pass = passenger

Source: Kenworthy, 2003

limited by a low average load factor (8.7 P/v), but commuter rail has a better load factor (32.9) and a lower Btu/p-m (2569; Table 13.6 and Figure 13.8).

13.1.4 Overview

Transportation is a critical sector of energy use because of its dominant use of petroleum and because it is a major source of air pollution and GHG emissions. Transport may conjure

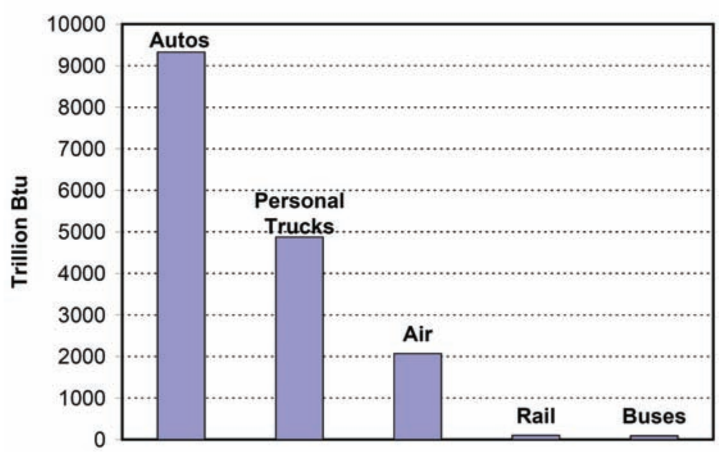
table 13.6 Passenger Travel and Energy Use, 2004

	Number of Vehicles (thousands)	Vehicle-miles (millions)	Passenger-miles (millions)	Load Factor (persons/vehicle)	Energy Intensity: Btu per vehicle-mile	Energy Intensity: Btu per passenger-mile	Energy use (trillion Btu)
Automobiles	136,431	1,699,890	2,668,827	1.57	5489	3496	9331
Personal trucks	80,818	859,902	1,479,031	1.72	7447	4329	6403
Motorcycles	5768	10,122	11,134	1.1	2500	2272	25
Demand response	37	890	930	1	14,952	14,301	13
Vanpool	6	85	541	6.4	8,226	1294	0.7
Bus—Transit	78	2435	21,262	8.7	38,275	4318	93
Air certificated	NA	6071	548,629	90.4	357,750	3959	2,172
Rail	19	1313	31,160	23.7	70,694	2978	93
Intercity	<1	308	5511	17.9	51,948	2760	15
Transit	13	710	15,930	22.4	70,170	2750	44
Commuter	6	295	9719	32.9	91,525	2569	25

Source: U.S. DOE, 2007

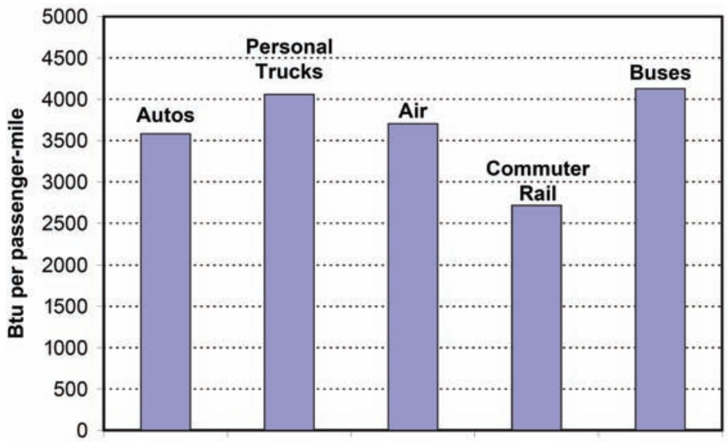
up visions of the movie *Trains, Planes, and Automobiles,* but 60% of transportation energy is used just for the latter: highway passenger miles in light vehicles. Compared to the rest of the world, passenger travel in U.S. cities is much more energy intensive because of its greater dependence on automobile use and fewer rail transit options.

figure 13.7 U.S. Passenger Travel Energy Use, 2003



Source: U.S. DOE, 2006

figure 13.8 U.S. Passenger Travel Energy Intensity, 2003



Source: U.S. DOE, 2006

Shifts from smaller to larger vehicles, from rail to truck freight, and from higher to lower load factors create additional challenges as we try to improve transportation efficiency. But the most important factor affecting energy use is light vehicles, and the next section discusses progress and opportunities for their improved efficiency and reduced emissions.

13.2 Highway Passenger Vehicle Technologies, Efficiency, and Emissions

13.2.1 Commercially Available Vehicle Types and Technologies

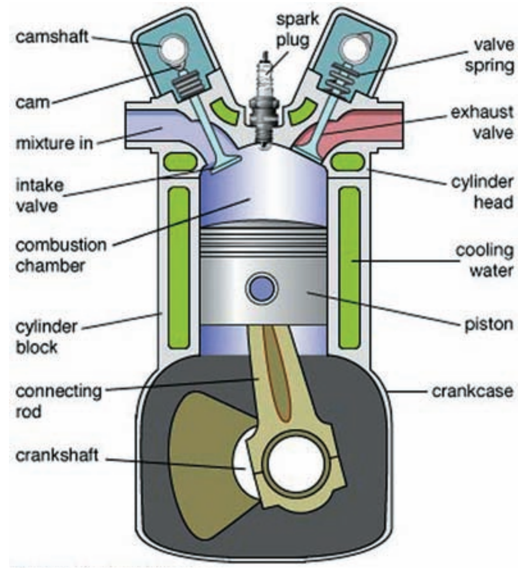
Before discussing vehicle efficiency and environmental emissions, we need to introduce vehicle types, technologies, and fuels. Nearly all vehicles currently use internal combustion engines (ICE), but new technologies are being introduced to the market. Because of constraints on oil and carbon, future vehicles may turn to electrification, through currently popular hybrid electric vehicles (HEV), all-electric vehicles (EV), and/or fuel cell technologies. We look at emerging technologies in Section 13.2.4.

13.2.1.1 Internal Combustion Engines

Because of their fascination with automobiles, most people are familiar with the workings of internal combustion engines. In these engines, fuel is burned in the engine itself as opposed to in an external combustion engine such as the steam engine. Most cars use the classic **Otto cycle gasoline engine** that takes a mixture of gas and air into a cylinder, compresses it with

figure 13.9 **Otto Cycle Gasoline Engine Cylinder, Piston, Valves, and Spark Plug**

Fuel-air mixture is injected through the intake valve into cylinder at downstroke of piston, then is ignited on upstroke by spark, driving piston down. Exhaust gases are expelled through exhaust valve on next upstroke of piston.



Source: Encyclopedia Britannica Online, 2007. Used with permission of Encyclopedia Britannica, Inc.

a piston, and ignites it with a spark. The ignition explosion drives the piston down, turning the crankshaft into mechanical rotational motion and that energy is transferred to the rotating wheels (see Figure 13.9).

The **diesel engine** also operates with cylinders, pistons, and rotating crankshaft, but differs from the Otto gasoline engine. It takes air into the cylinder, compresses it, then injects distillate or diesel fuel. The higher compression ratio (piston downstroke to upstroke volume) of the diesel engine (about 15:1 or 20:1 compared to 8:1 or 10:1 for the Otto cycle) heats the compressed air hot enough to ignite the fuel without a spark, driving the piston downward and turning the crankshaft. Diesel vehicles tend to operate more efficiently than gasoline engines and are a mainstay in heavy-duty vehicles. Despite their higher efficiency, diesel engines have been plagued by higher particulate emissions than gasoline engines and have not penetrated the light vehicle market in the United States. However, recent advances by Daimler-Chrysler, Volkswagen, and others in “clean diesel” technologies have spurred sales of diesel cars especially in Europe (see Section 13.2.3).

The efficiency of internal combustion engines varies considerably because of tradeoffs between power performance, engine longevity, compression ratio, and controls of air pollution of exhaust emissions. Engines can operate as hot as 1000 K, giving a maximum thermal efficiency of about 70% assuming ambient temperature of 300 K. Efficiency losses occur as a result of exhaust and water heat losses; friction losses in motor, drive train, and braking; and in-vehicle energy (e.g., lights, air-conditioning). Overall efficiency of fuel energy to transport energy for a typical vehicle is about 20%–25%, meaning only one-fifth to one-fourth of the fuel energy is converted to energy of motion. And we thought electric power plants were inefficient. Of course, of greater meaning to users is the fuel efficiency rating given as miles per gallon of fuel, which we discuss in the next section.

13.2.1.2 Flex-Fuel Vehicles (FFV)

Otto cycle engines run primarily on gasoline, but they can also operate on non-petroleum fuels including compressed natural gas (CNG), liquid petroleum gas (LPG or propane), hydrogen, methanol, and ethanol. Generally, methanol and ethanol are blended with gasoline at various mixtures (e.g., M10 is 10% methanol, E85 is 85% ethanol).

"Flex fuel" Otto cycle engines can run on gasoline or alcohol blends up to M- or E85. Maintaining 15% gasoline helps with cold starts and requires only simple engine modification. The only difference between an FFV and a gasoline engine is an oxygen sensor that measures the amount of ethanol in the fuel at any time, provides this information to the onboard computer, which then adjusts the fuel injector to maximize efficiency and performance. The cost is less than $100, and FFVs generally cost the same as gasoline-only versions of the same model. E85 has a higher octane rating than gasoline so it enhances engine wear and performance, but it has lower energy content so it achieves only about three-fourths of the miles per gallon compared to straight gasoline. This is usually offset by a lower cost. Where E85 is available, gasoline price averages about 15% more per gallon than that of the E85 fuel.

There are sixty-two flex-fuel vehicle models on the market for 2008 in the United States, including mostly larger vehicles and light trucks made by Ford, GM, and Daimler-Chrysler. The primary motivation for manufacturing these vehicles is a credit these companies get on meeting the CAFE efficiency standards. There are about 6 million FFVs on the road in the United States today, and about 700,000 new FFVs have been sold each year. GM announced plans to double FFVs sold, and Toyota announced its plans to market FFVs in the United States by 2008. Brazil ramped up its sales of FFVs from 4% to 70% in just three years.

Although there are many FFVs on the road and more being brought to market, as of 2007, there were only 1200 E85 filling stations out of the 170,000 gas stations in the United States. One-quarter of them were in Minnesota. As a result, most flex-fuel vehicle owners are just filling up with gasoline.

Diesel engines use diesel (distillate) fuel, but they can also run on synthetic diesel derived from vegetable or animal oils, so-called biodiesel. Like alcohol blends, biodiesel is usually mixed with petroleum diesel at a variety of mixtures, from B-2 (2% biodiesel) to B-10, B-20, and B-100. We will see in Chapter 14 that biodiesel production has grown significantly in Europe. The U.S. market, which was essentially nonexistent in 2000, grew from 25 million gallons (Mgal) in 2004 to an estimated 450 Mgal in 2007. Wow! Chapter 14 discusses the significant prospects for bringing more ethanol and other biofuels to market.

13.2.1.3 Hybrid Electric Vehicles (HEV)

One of the most significant recent advances in vehicle technology is the hybrid electric vehicle (HEV). The HEV has an Otto cycle gasoline engine like conventional vehicles but it also has an electric motor drive that works in tandem with the gasoline engine (Figure 13.10). The electric motor is run by a battery bank that is charged by the engine when excess engine power is available. There are three variations of hybrid drivetrains.

- In the **Series** drivetrain (Figure 13.10[a]), the gasoline engine simply charges the batteries and the electric motor drives the car. The Chevy Volt under development uses this technology.
- In the **Parallel** drivetrain (Figure 13.10[b]), the electric and gasoline motors work together to drive the wheels and are coordinated by computer controls and transmission. Honda uses this drivetrain in its Integrated Motor Assist technology in the Civic and Accord hybrids.
- In the **Parallel-Series** drivetrain (Figure 13.10[c]), the electric motor and the gasoline engine operate independently as a dual drivetrain, so that the gas engine can operate at near optimum efficiency and the electric motor can drive the vehicle on its own. Toyota's Synergy Drive uses this technology.

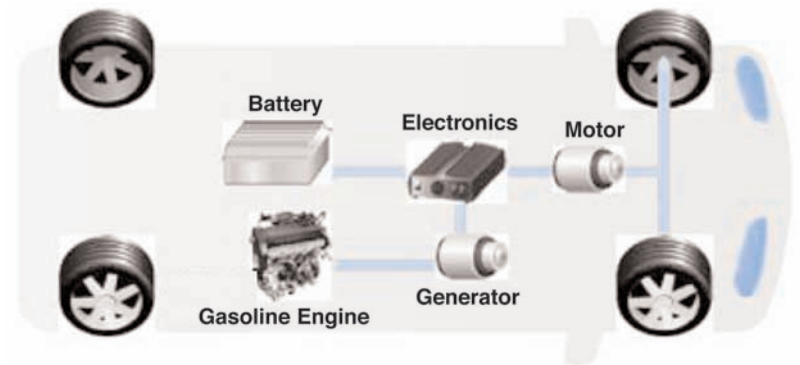
Most hybrids have **regenerative braking** that helps charge the battery. The electric motor normally helps power the car, but when the brakes are engaged, the motor acts as a generator, slowing the car by converting the vehicle's kinetic energy into electrical current that recharges the batteries. Only the Series and Parallel-Series drivetrains can be converted to plug-in hybrids (Section 13.3.1) because they have independent electric drive.

HEVs are the most efficient vehicles sold today. The 2007 Prius with EPA rating of 60 mph (city) and 51 mpg (highway) is the most efficient midsize car, the Honda Civic Hybrid (49 city, 51 hwy) is the most efficient compact car, and the Ford Escape Hybrid is the most efficient SUV (36 city, 31 hwy). EPA changed the way it measures fuel economy ratings for 2008 to reflect faster speeds and acceleration, air conditioner use, and colder outside temperatures. The 2008 Prius is still the leader at 48 mpg (city), 45 mpg (highway).

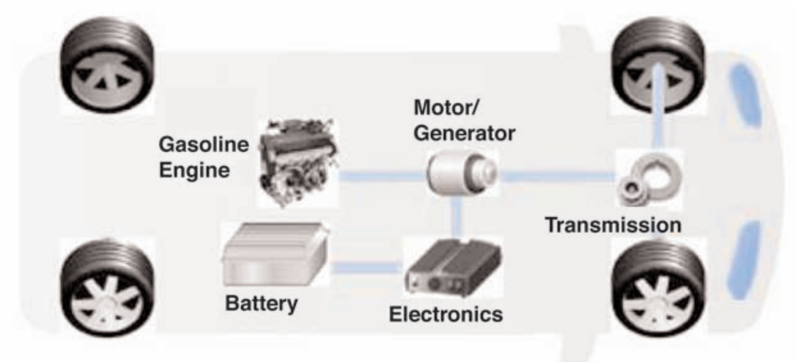
The market for hybrid vehicles has grown rapidly. For 2008 there are seventeen hybrid models on the market and more are expected. As shown in Table 13.7, U.S. HEV sales, less than 10,000 in 2000, increased to more than 300,000 in 2007, or 2% of all sales. Toyota had a 76 percent share of the hybrid market in 2006, with the Prius commanding 43 percent of all sales.

Future sales of hybrid vehicles will depend on consumer choice for low-impact vehicles, government incentives, and especially gas prices. Estimates range from 5%–6% of U.S. car sales by 2010 (Oak Ridge National Lab) to 30% of sales in 2030 (ExxonMobil). Although these forecasts vary and nobody really knows for sure, one thing is clear: HEVs have begun to capture the market and that market will grow. An important factor in the growth of the HEV market is that current technology is compatible with emerging technologies, especially

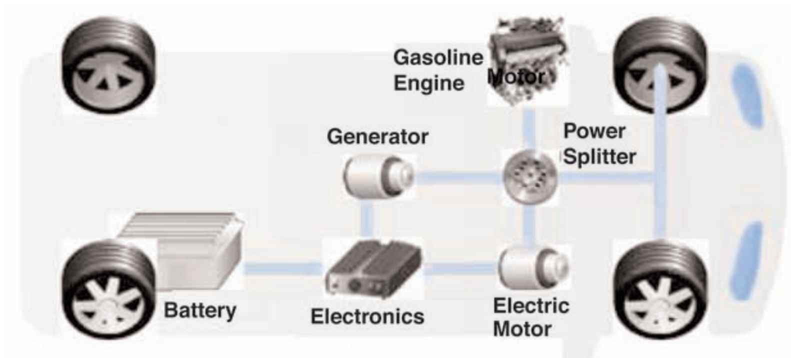
figure 13.10 **Basic Components of Series, Parallel, and Parallel-Series Hybrid Electric Vehicles**



(a) Series hybrid has only electric drive motor and gas engine simply drives generator to charge the battery (e.g., Chevy Volt under development).



(b) Parallel hybrid has electric drive motor that assists gas-engine drive (e.g., Honda).



(c) Parallel-Series hybrid has independent gasoline drive and electric drive motors (e.g., Toyota).

Source: Union of Concerned Scientists, 2007

table 13.7 U.S. Hybrid Electric Vehicle Sales, 2000–2007

Year	Number Sold
2000	9350
2001	20,287
2002	35,000
2003	47,525
2004	88,000
2005	210,000
2006	268,000
2007	330,000[p]

p = preliminary

flex-fuel options and, for series and parallel-series drivetrains, enhanced electrification through plug-in hybrids (PHEV). Before investigating emerging technologies the following sections review current vehicle efficiency and emissions.

13.2.2 Energy Efficiency of Light Duty Vehicles

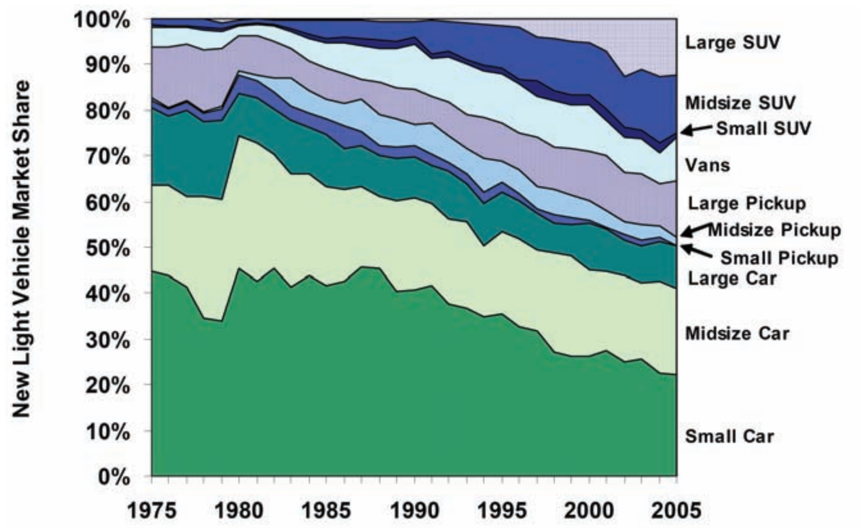
13.2.2.1 Factors Affecting Vehicle Efficiency

Technology, fuel prices, public policy, and consumer choice influence the average efficiency of light duty vehicles. Consumer choice in the United States for larger (and less efficient) passenger vehicles such as SUVs increased considerably in the last two decades. Large SUV sales began to decline in 2005, but despite higher fuel prices, other SUVs, vans, and pickups have increased, and "car" sales dropped below 50% of light vehicle sales for the first time in 2006 (Figure 13.11).

Fuel prices affect travel behavior (discretionary travel and choice of transport mode) over the short term, and consumer choice for vehicle efficiency over the long term. Prices have increased dramatically since 2004 (Table 5.4), and they vary considerably around the world. Much of the international variation is the result of differing gasoline taxes. Figure 13.12 compares mid-2007 gasoline prices and taxes for selected countries in U.S. dollars per gallon. The gasoline portion of the total price is fairly consistent, but taxes vary considerably from $0.38/gallon in the United States to $4.68/gallon in the United Kingdom, where total price exceeded $7.00/gallon.

The lower cost of fuel in the United States has contributed to the patterns of transportation energy, vehicle efficiency, and modal choice relative to other developed countries as demonstrated by the data in Table 13.5. Fuel taxes are an example of public policy that indirectly affects vehicle efficiency and behavior through market forces.

figure 13.11 Changing Market Share for Light Vehicles in the United States, 1976–2005



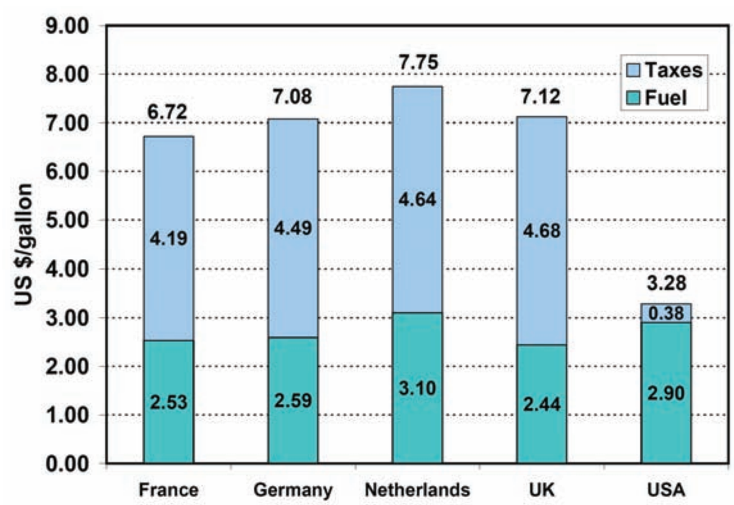
Market for large SUVs began to slow in 2005–2006, but other SUVs vans and large pickups increased their share despite higher gas prices.

Source: U.S. DOE, 2007

13.2.2.2 U.S. CAFE Standards and Efficiency Trends

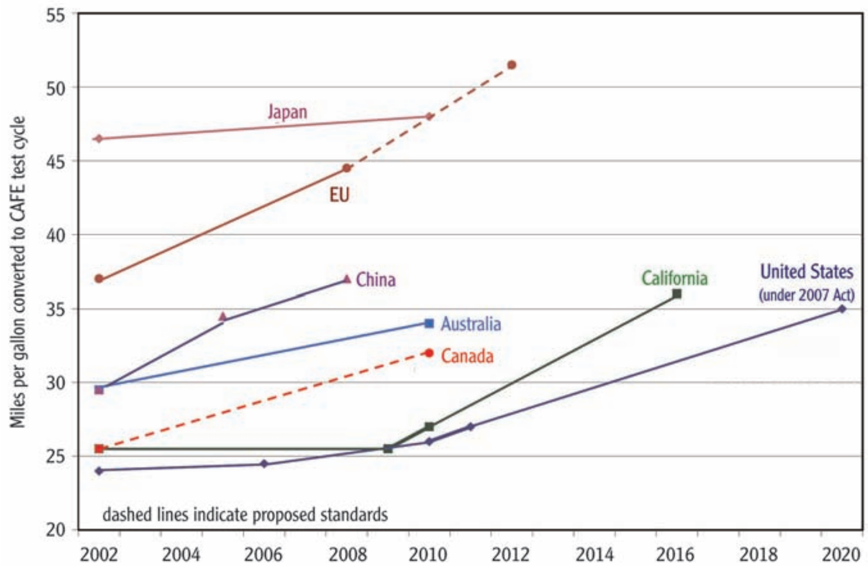
Regulatory standards are a more direct policy tool that affects vehicle efficiency. The United States first adopted federal auto efficiency standards in the 1975 Energy Conservation Policy Act, which mandated doubling average 1974 new auto fuel efficiency to 27.5 mpg by 1985. The average efficiency of all cars sold by each manufacturer must meet the Corporate

figure 13.12 Gasoline Price and Taxes, Selected Countries, 2007



Source: U.S. EIA, 2007

figure 13.13 **Auto Efficiency Standards in Various Countries**



Includes proposed standards, all converted to U.S. CAFE test cycle.

SOURCE: CEC, 2007; data from Pew Center on Global Climate Change, Comparison of Passenger Vehicle Fuel Economy and Greenhouse Gas Emission Standards Around the World, December 2004

Average Fuel Economy (CAFE) standard. The program is administered by the National Highway Transportation Safety Administration (NHTSA), which has authority to raise or lower the standard. It did lower the standard to 26 mpg in 1986–1989 but raised it back to 27.5 mpg in 1990. Figure 13.13 shows that the U.S. vehicle efficiency standards lag behind the standards of many other countries, including China and especially Japan and the EU. California vehicle efficiency implied by its proposed GHG emission standards is also shown, as is the 35 mpg U.S. standard for all light vehicles by 2020 adopted in the 2007 Energy Act.

Congress did not set a target for light trucks but gave NHTSA authority to set a standard at the "maximum feasible" level. Light trucks and SUVs now make up more than half of the passenger vehicle market. In 2006, NHTSA announced higher standards for 2008–2011 rising to 24 mpg in 2011, including the largest SUVs (8500–10,000 lb gross vehicle weight rating [GVWR]) that had not been regulated before. The agency estimates the new standard will save 10.7 billion gallons of fuel. However, in November 2007, the federal 9th Circuit Court of Appeals in San Francisco ruled in a suit brought by eleven states that NHTSA's new light truck/SUV standard was inadequate considering the criteria on which they were to be based and ordered NHTSA to conduct a full environmental impact statement of the standard.

If manufacturers' annual sales do not comply with the standards, they pay a penalty. The penalty is $55 per mpg under the target value per vehicle sold. To determine the penalty the company calculates the average mpg of its sales weighted by volume, subtracts this average from the standard, and multiplies this difference by $55 and the total sales volume. Through 2004, manufacturers paid more than $590 million in CAFE civil penalties. Most European manufacturers regularly pay CAFE civil penalties ranging from less than $1 million to more than $20 million annually. Asian manufacturers have never paid a civil penalty. Automakers get a credit of 0.9 mpg for flex-fueled vehicles, and U.S. makers have taken advantage of this provision.

Have total sales matched the standards? They have but not by much. Table 13.8 gives the automobile standards and average new fleet estimates for autos and autos/light trucks combined for various years. Figure 13.14 plots those values for passenger cars, light trucks, and overall average. New car fleet average and the standards themselves stagnated after 1985. In fact, the overall combined *new* car and light truck average efficiency was lower in 2004 than it was in the mid-1980s. By the way, the new EPA fuel economy testing procedures for 2008 vehicles (that reduced the fuel economy displayed on windshield stickers compared to prior years) does not affect compliance with the CAFE standards because the two tests are different.

These data are for new vehicles, but what about vehicles on the road? On-the-road efficiency for all vehicles increased in 1980 to 1990 from 13 to 17 mpg as new vehicles meeting the standards replaced older, less efficient ones. But on-the-road average stagnated after 1990 because less efficient light trucks and SUVs have a bigger market share. In 2004, on-the-road efficiency for all vehicles was 17.1 mpg (only up from 16.9 in 1991); for autos, it was 22.4 (up from 21.1); for light trucks, 16.2 (down from 17.3); and for heavy trucks, 6.7 (up from 6.0). No wonder people are upset over higher gas prices.

How would improvement in vehicle fuel economy affect our concerns about oil and carbon? We'll see in the next section that improvement in fuel economy directly reduces CO_2 emissions. What about oil imports? Solution Box 13.1 calculates the effect of average light vehicle efficiency on oil consumption and imports. Increasing average efficiency from 22 to 32 mpg would reduce vehicle oil use by 31% and imports by 20%. Increasing to an HEV-equivalent 42 mpg would cut vehicle oil use by half and imports by 30%. If average

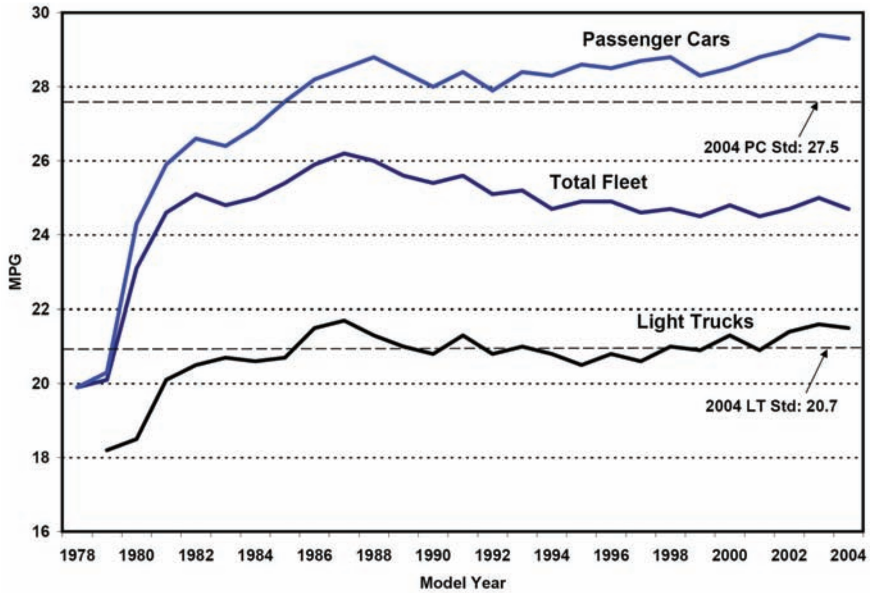
table 13.8 **Automobile Corporate Average Fuel Economy Standards* versus Sales-Weighted Fuel Economy Estimates, 1978–2004**

Model Year	CAFE Standards	Passenger Cars: CAFE Estimates: Domestic	Import	Combined	CAFE Estimates: Autos and Light Trucks Combined
1978	18.0	18.7	27.3	19.9	19.9
1985	27.5	26.3	31.5	27.6	25.4
1995	27.5	27.7	30.3	28.6	24.9
2004	27.5	29.3	29.3	29.3	24.7

* Standards are in miles per gallon.

Source: U.S. Department of Transportation, NHTSA, "Summary of Fuel Economy Performance," Washington, DC, March 2004.

figure 13.14 **Actual Fleet Corporate Average Fuel Economy, Model Years 1978–2004**



Average light vehicle sold in the United States in 2004 had less than 25 mpg.

Source: NHTSA, 2004

efficiency were as high as emerging technologies plug-in HEV (100 mpg) and flex-fuel PHEV (500 mpg gasoline; see Section 13.2.4), oil imports would drop by 50% and 62% respectively. See also Figure 10.6.

13.2.3 Vehicle Air Emissions: Criteria Air Pollutants and GHG Emissions of Current Vehicles

A great peripheral benefit of higher vehicle efficiency is that it reduces GHG emissions and urban air pollution. Transportation vehicles contribute about half of the nation's NO_x and volatile organic compounds (VOC). These two pollutants combine to form photochemical smog, which is measured by atmospheric ozone (O_3), our most serious urban air pollution problem (see Figure 2.17). The 1970 Clean Air Act (CAA) mandated significant reductions in regulated, "criteria" air pollutants. Congress boldly called for a 90% reduction in vehicle emissions by 1975. Vehicle manufacturers said it couldn't be done, but with a two-year extension, and the development of the catalytic converter, they did it. The CAA also let California, given its severe smog problem and its large auto market, develop its own stricter emissions standards, and gave other states the option to adopt California's regulations. For such standards, California must file a petition to EPA for a waiver from federal preemption under the

SOLUTION

SOLUTION BOX 13.1

Passenger Vehicle Efficiency and Oil Imports

If current on-the-road efficiency of light passenger vehicles of 22 mpg were improved to 32 mpg (assuming the same vehicle miles traveled), what quantity and percent of current oil imports could we avoid? What if efficiency were improved to 42 mpg, to 100 mpg (PHEV), to 500 mpg (FF-PHEV) of gasoline?

Current data show that the United States is importing 13.5 million barrels of oil per day (MMbbl/d) and 8.7 MMbbl/d of oil products are used to fuel light passenger vehicles. Let's calculate the fuel it would take for 22 miles under our different mpg scenarios.

Gallons used for 22 miles @ 22 mpg = 22 mi/22 mpg = 1 gal
Gallons used for 22 miles @ 32 mpg = 22 mi/32 mpg = 0.688 gal or (1 – 0.688)100 or 31% less than 22 mpg
Gallons used for 22 miles @ 42 mpg = 22 mi/42 mpg = 0.524 gal or 48% less than 22 mpg
Gallons used for 22 miles @ 100 mpg = 22 mi/100 mpg = 0.22 gal or 78% less than 22 mpg
Gallons used for 22 miles @ 500 mpg = 22 mi/500 mpg = 0.044 gal or 96% less than 22 mpg
Reduction of oil imports @ 32 mpg = (8.7 MMbbl/d)(0.312) = 2.71 MMbbl/d or 2.71/13.5 = 20% less imports
Reduction of oil imports @ 42 mpg = (8.7 MMbbl/d)(0.476) = 4.14 MMbbl/d or 4.14/13.5 = 31% less imports
Reduction of oil imports @ 100 mpg = (8.7 MMbbl/d)(0.78) = 6.79 MMbbl/d or 6.79/13.5 = 50% less imports
Reduction of oil imports @ 500 mpg = (8.7 MMbbl/d)(0.956) = 8.32 MMbbl/d or 8.32/13.5 = 62% less imports

CAA. EPA always granted such petitions (until 2007 as discussed below), and California has established stricter emission standards. Several other states have adopted them.

The situation with GHG and CO_2 emissions is not as positive. Transportation vehicles contribute about one-third of the CO_2 emissions in the United States, but EPA has chosen not to include CO_2 among regulated pollutants. Two prominent court cases could affect how vehicle CO_2 emissions are addressed. In the first, *Massachusetts v. EPA*, twelve states and other parties claim that EPA must regulate CO_2 emissions from vehicles. Lower courts gave mixed opinions but generally sided with EPA. In April 2007, the U.S. Supreme Court ruled in a 5 to 4 decision that GHG are air pollutants and remanded the case to the Circuit Court to determine how EPA should regulate them.

The second case relates to California's 2002 Pavley statute (AB 1493) to reduce vehicle CO_2 emissions beginning in 2009 and achieving 30% reduction by 2016. Reducing vehicle CO_2 emissions can be done by higher efficiency, use of lower or non-carbon fuels or biofuels, or new technology. California petitioned EPA for waiver from federal preemption under the CAA, and EPA denied the petition in late 2007 after passage of new federal vehicle efficiency standards for 2020, prompting California to file suit. The *Massachusetts v. EPA* ruling will likely affect California's suit. So will a September 2007 Vermont Federal District Court decision. In *Green Mountain Chysler Plymouth Dodge Jeep v. Crombie*, the judge rejected all of the industry's claims challenging the validity of the California standards which Vermont is poised to adopt. Two other cases are pending in Rhode island and California.

13.2.3.1 Vehicle Emission Rates and Standards

Let's look at current emission rates for different vehicles. Table 13.9 gives emission rates in grams per vehicle mile traveled (g/vmt) for vehicles on the road (2nd through 4th columns), federal and state emissions standards for new vehicles (5th through 7th columns), and the Toyota Prius, the lowest emission vehicle on the market (8th column) that far exceeds existing standards.

The last two rows give EPA's Air Pollution (AP) score and GHG emission score that it uses to rate "green vehicles." A maximum AP score of 10 is a zero-emission vehicle (ZEV). To qualify for EPA's **SmartWay** class of green vehicles, a car or light truck must have a minimum AP score of 6, a minimum GHG score of 6, and a combined score of 13.

Vehicle emission standards are a bit complicated because of the number of regulated pollutants, the variety of vehicle types, and the categories of emission reduction (e.g., from low-emission vehicle [LEV] to partial zero-emission vehicle [PZEV]). We should know the basic framework of the standards given in Table 13.10 that shows various Bin number categories of emission reduction, comparable California standards, and applicable AP scores.

We should also know that the maximum U.S. emission rates for 2004–2008 passenger vehicles are given as EPA Tier 2, Bin 10 (in Tables 13.9 and 13.10), and that California's LEV II emissions standards, adopted by several other states, are the most stringent in the country, comparable to Bin 5.

How do U.S. standards compare with those of other countries? The United States has been a world leader in pollution control, but some countries now exceed U.S. standards. For example, Table 13.11 gives European Union emission standards for passenger vehicles. They have specific standards for diesel and gasoline fueled vehicles because diesel is a popular and growing fuel for cars there. Standards are given in both g/km and g/mi, the latter so that they can be compared to U.S. standards. The Euro 5 standards proposed for mid-2008 gasoline cars are much more stringent than the U.S. Tier 2 Bin 10 standards.

What about GHG emissions? As discussed above, the United States does not yet regulate CO_2 emissions as an air pollutant, but EPA must address this issue under

table 13.9 **Emission Rates for Light Vehicles, Per Vehicle Mile Traveled**

	Emission Factors (gs/vmt)						
	Vehicles on the Road			New Vehicles			
	Average	Passenger Car	Light Truck	EPA Tier 1 2003 std	EPA Tier 2 Bin 10 2004+ std	CA/NE States LEV II std	2005 Prius
NO_x	1.54	1.39	1.81	0.60	0.60	0.07	0.009
PM-10	0.07			0.10	0.08	0.01	0.01
PM-2.5	0.05						
SO_2	0.09						
CO	23.4	20.9	27.7	4.2	4.2	4.2	1.0
VOC/NMOG	3.06	2.8	3.5	0.31	0.156	0.09	0.004
NH_3	0.09						
CO_2 (lb/mi)	1.0	0.92	1.15	0.9*	0.9*	**	< 0.45
CH_4	0.08						
N_2O	0.03						
Gasoline (gal/mi)		0.047	0.058		0.036		0.018
EPA AP Score	0	0	0	0	1	5	9.5
EPA GHG Score	4	5	2	5	5	**	10

* There is no federal standard for CO_2 emissions, but 0.9 is based on CAFE fuel economy standards.

** California has promulgated a CO_2 emissions standard, and, if approved, 16 other states will also adopt it.

CA/NE states LEV II is California low-emission vehicle standards also adopted by northeastern states.

Pollutants: NO_x = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide; CO = carbon monoxide; VOC/NMOG = non-methane organic gases; NH_3 = ammonia; CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide

Source: U.S. DOE, Transportation Energy Data Book; EPA Green Vehicle; fueleconomy.gov; EPA, 2005

direction from the *Massachusetts v. EPA* Supreme Court decision and other pending suits over its denial of California's vehicle GHG emission standard. EPA does recognize that vehicles cause one-third of our GHG emissions and the agency created a scale for the vehicle GHG score based on fuel economy and fuel type to inform consumers of the impact of their vehicle purchases. Shown in Table 13.12, the scale penalizes diesel fuel vehicles with higher minimum fuel economy relative to gasoline vehicles, whereas alternative fuel (E85, compressed natural gas, and liquid petroleum gas) vehicles are credited with lower minimum miles per gallon. EPA provides an online interactive **Green Vehicle Guide** that allows users to find AP and GHG scores for any vehicle on the market. See http://www.epa.gov/green-vehicles/.

Solution Box 13.2 gives an example that shows how we can use these emission rates to assess air pollution and GHG emission impacts of vehicles and driving patterns.

table 13.10 **U.S. EPA Federal Light Duty Vehicle Emissions Standards for Air Pollutants, Tier 2**

Standard	Model Year	Vehicle Types	Emission Limits at Full Useful Life (100,000–120,000 miles) — Maximum Allowed Grams per Mile					Air Pollution Score and California Standard Category	
			NO_x	NMOG	CO	PM	HCHO	CA Std Cat	AP Score
Bin 1	2004+	LDV, LLDT, HLDT, MDPV	0.00	0.000	0.0	0.0	0.0	ZEV	10
–	2004+	LDV, LLDT	0.009	0.004	1.0	0.01	0.004	PZEV	9.5
Bin 2	2004+	LDV, LLDT, HLDT, MDPV	0.02	0.010	2.1	0.01	0.004	SULEV II	9
Bin 3	2004+	LDV, LLDT, HLDT, MDPV	0.03	0.055	2.1	0.01	0.011	—	8
Bin 4	2004+	LDV, LLDT, HLDT, MDPV	0.04	0.070	2.1	0.01	0.011	ULEV II	7
Bin 5	2004+	LDV, LLDT, HLDT, MDPV	0.07	0.090	4.2	0.01	0.018	LEV II	6
Bin 6	2004+	LDV, LLDT, HLDT, MDPV	0.10	0.090	4.2	0.01	0.018	LEV II option 1	5
Bin 7	2004+	LDV, LLDT, HLDT, MDPV	0.15	0.090	4.2	0.02	0.018	–	4
Bin 8a	2004+	LDV, LLDT, HLDT, MDPV	0.20	0.125	4.2	0.02	0.018	–	3
Bin 8b	2004–2008	HLDT, MDPV	0.20	0.156	4.2	0.02	0.018	SULEV LT	3
Bin 9a	2004–2006	LDV, LLDT	0.30	0.090	4.2	0.06	0.018	–	2
Bin 9b	2004–2006	LDT2	0.30	0.130	4.2	0.06	0.018	–	2
Bin 9c	2004–2008	HLDT, MDPV	0.30	0.180	4.2	0.06	0.018	ULEVII HT	2
Bin 10a	2004–2006	LDV, LLDT	0.60	0.156	4.2	0.08	0.018	–	1
Bin 10b	2004–2008	HLDT, MDPV	0.60	0.230	6.4	0.08	0.027	LEV II HT	1
Bin 10c	2004–2008	LDT4, MDPV	0.60	0.280	6.4	0.08	0.027	–	1
Bin 11	2004–2008	MDPV	0.90	0.280	7.3	0.12	0.032	–	0

Vehicle type: L = light; D = duty; V = vehicle; T = truck; M = medium; H = heavy; P = passenger

CA Cat: E = emission; V = vehicle; Z = zero, P = partial; S = super; U = ultra; L = low; LT = light truck; HT = heavy truck

Pollutants: NMOG = non-methane organic gases; HCHO = formaldehyde; NO_x = nitrogen oxides; CO = carbon monoxide; PM = particulate matter

Source: EPA, 2005

table 13.11 European Emission Standards and Clean Diesel, g/km (g/mi)

Tier	Date	CO	HC	HC + NO_x	NO_x	PM
Diesel						
Euro 4	2005.01	0.50 (0.80)	-	0.30 (0.48)	0.25 (0.40)	0.025 (0.40)
Euro 5	mid-2008	0.50 (0.80)	-	0.25 (0.40)	0.20 (0.32)	0.005 (0.008)
Gasoline						
Euro 4	2005.01	1.0 (1.6)	0.10 (0.16)	-	0.08 (0.13)	-
Euro 5	mid-2008	1.0 (1.6)	0.075 (0.12)	-	0.06 (0.10)	0.005 (0.008)

13.2.3.2 Vehicle Emission Control Technologies

We have made impressive progress in reducing vehicle emissions as a result of innovative technology. Emissions come from two primary sources: exhaust emissions from fuel combustion and evaporative emissions fuel vapors from refueling, the tank, and the engine. Exhaust emissions include the full range of pollutants given in Table 13.9, whereas evaporative emissions are primarily the volatile organic compounds (VOC).

In gasoline engines, the evaporative emissions are easier to control with a canister system shown in Figure 13.15(b). Vapors from the tank and the engine flow to a holding

table 13.12 U.S. EPA Vehicle Information Program: Greenhouse Gas Score

		Minimum Fuel Economy: Combined mpg				
Greenhouse Gas Score	Max. lbs CO_2/mile	Gasoline	Diesel	E85	LPG	CNG
10	0.45	44	50	31	28	33
9	0.54	36	41	26	23	27
8	0.64	30	35	22	20	23
7	0.74	26	30	19	17	20
6	0.84	23	27	17	15	18
5	0.94	21	24	15	14	16
4	1.04	19	22	14	13	14
3	1.14	17	20	13	12	13
2	1.24	16	18	12	11	12
1	1.34	15	17	11	10	11
0	> 1.34	< 15	< 17	< 11	< 10	< 11

E85 = 85% ethanol fuel; LPG = liquid petroleum gas; CNG = compressed natural gas
Source: EPA, 2005

SOLUTION

SOLUTION BOX 13.2

Calculating Vehicle Emissions

When I bought my 2005 Prius, my neighbor bought a 2005 4WD Ford Explorer. We both drive our vehicles about 1000 miles per month. How do the vehicles compare in fuel use, fuel cost (at \$3/gal), air pollution emissions, and CO_2 emissions?

Solution:

On the EPA Green Vehicles Web site, I look up Air Pollution and GHG scores for the two vehicles. The Prius has values of 9.5 and 10, and the Explorer has values of 2 and 2, respectively. Tables 13.11 and 13.12 give emission rates for these scores. The rates in grams or pounds per mile can be multiplied by 12,000 miles per year to give annual emissions.

For example, the Explorer NO_x emission rate is taken from Bin 9a in Table 13.12 as 0.30 g/mi, and the CO_2 emissions rate is taken from Table 13.13 as 1.24 lb/mi.

Explorer annual NO_x emissions = 0.30 g/mi × 12,000 mi/yr = 3600 g/y = 3.6 kg/yr

Explorer annual CO_2 emissions = 1.24 lb/mi × 12,000 mi/yr
= 14,880 lb/yr × 1/2.2 kg/lb = 6763 kg/yr

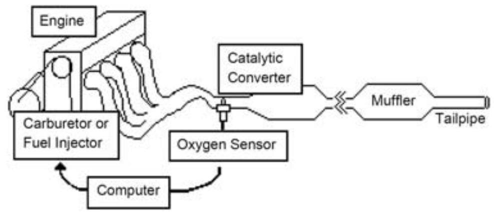
The full results are given in the table below.

	AP Score	GHG Score	Mpg	CO_2 (kg/yr)	NO_x (kg/yr)	NMOG (kg/yr)	CO (kg/yr)	Gas (gal/yr)	Gas Cost (\$/yr)
Explorer	2	2	16	6763	3.6	1.10	50.4	750	2250
Prius	9.5	10	55	2182	0.1	0.05	12.0	218	654

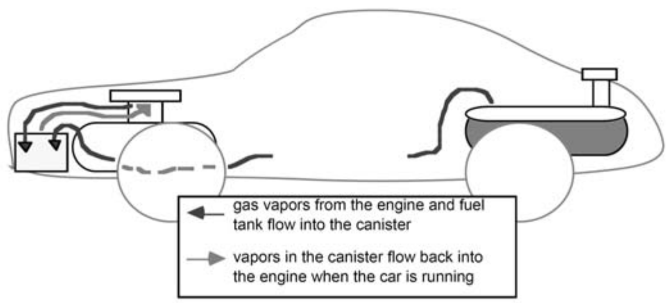
Not only do I enjoy economic benefits from a gas bill 70% less than my neighbor's, but I take pleasure in living more lightly on the planet: my Prius emits 68% less CO_2 and 95% less urban air pollutants than his Explorer.

canister and then are burned in the engine. Exhaust emissions are more complicated. In gasoline engines, it is difficult to control both NO_x and volatile hydrocarbons and CO. NO_x is basically burnt air (air is 78 percent nitrogen) and results from lean fuel mixtures with more air. A richer mixture produces less NO_x but more volatile hydrocarbons and CO from incomplete combustion. The invention of the catalytic converter (CC) helped solve this conundrum. As shown in Figure 13.15(a), the engine can be run rich to control NO_x and then remaining unburned volatile hydrocarbons and CO are combusted in the CC. An oxygen sensor in the exhaust stream can provide data to fine-tune the fuel mixture to optimize the operation.

figure 13.15 Basic Controls for Exhaust and Evaporative Emissions



(a) Typical catalyst system for exhaust emissions.



(b) Typical canister system for evaporative emissions.

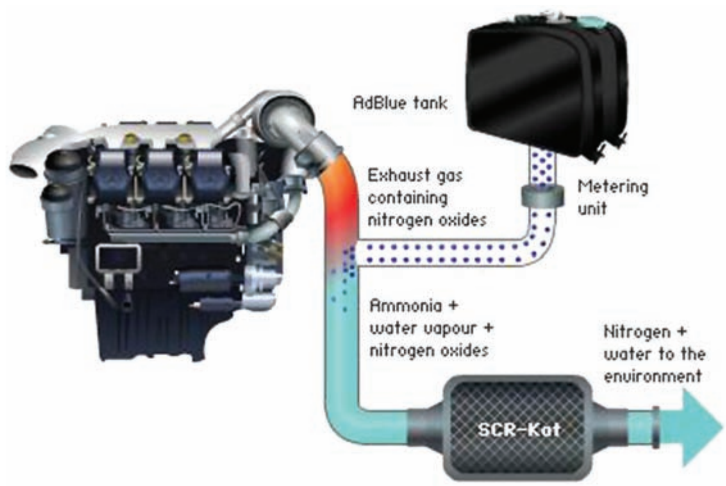
Source: U.S. EPA, 1994

Diesel engines offer additional challenges because of particulate and sulfur emissions. Emissions from heavy diesel trucks have been blamed for public health effects. EPA has initiated a National Clean Diesel Campaign to reduce diesel emissions. For light vehicles, diesel engines are more energy efficient, and if emissions could be controlled, diesel could be a more effective alternative to our energy and emissions challenge. As mentioned earlier, the Europeans seem to be banking on "clean diesel." Volkswagen and Daimler-Chrysler use "BlueTec" technology combined with low-sulfur diesel fuel to meet clean-diesel Euro 5 standards. Figure 13.16 shows that after the diesel exhaust passes through a particle filter, the BlueTec system adds urea to the exhaust from a separate "AdBlue" tank. The urea releases ammonia that converts NO_x in harmless N_2. The system also uses a conventional catalytic converter (SCR-Kat in the figure). These companies hope that clean diesel can find a strong U.S. market.

13.3 Emerging Vehicle Technologies

13.3.1 Plug-In Hybrid Electric Vehicles (PHEV)

Hybrid electric vehicles can improve efficiency considerably, but they are still dependent on gasoline for energy. Flex-fuel hybrids are under development, and should be on the market soon. Another option is to enhance the battery capacity of a series or parallel-series hybrid figure 13.16 **BlueTec System for Clean Diesel**



Source: Daimler-Chrysler

(Figure 13.10), use grid power to assist in charging the battery, and make greater use of the electric motor drive. These so-called plug-in hybrids (PHEV) offer certain advantages:

1. With greater use of the electric drive, the vehicle uses less gasoline per mile than conventional HEVs. Plug-in Prius retrofits can easily achieve 100 mpg.
2. With a battery capacity of 5 kWh and all-electric travel at 200 Wh/mile, a fully charged PHEV has a range of 25 miles at a cost of 50¢, about one-fourth the cost of an efficient gasoline car and about one-third the cost of a hybrid car (see Solution Box 13.3). Half the cars on the road today drive 25 miles/day or less.
3. With use of the electric drive in city driving, the PHEV is a zero-emission vehicle (ZEV) that can reduce emissions and improve urban air quality.
4. PHEV can be easily adapted to flex-fuel option with the added advantage of further offsetting petroleum use with E85.

Of course, PHEV batteries must be charged with grid power, and we know that electricity is high-value energy that is usually inefficient to produce and has its own environmental impacts. Are we just trading in one energy problem for another? Isn't electricity the most expensive form of energy we have? Well, PHEVs have significant benefits for the power grid:

1. PHEVs can be charged by grid power at night during off-peak hours when grid capacity is idle and base-load power is available. At off-peak rates, this power can be very inexpensive. As we saw in Figure 10.5, 40% of California's auto VMT could be met by night-charged electricity without needing additional power plant capacity.
2. PHEVs can be charged by excess power from rooftop photovoltaics (your garage roof is your filling station [Solution Box 13.4]), wind power, or other renewable

electricity. They may offer a significant opportunity for our growing wind electric capacity. As discussed in Chapter 12, one disadvantage of wind power is that it is intermittent and cannot be programmed to meet the peak demands when the grid needs the power the most. A fleet of PHEV (and/or all-electric or battery electric vehicles [BEV]) could provide a ready market for grid wind power whenever it is produced.

3. As we discussed in Chapter 10 (section 10.3.2), a large fleet of PHEV and BEV enables a vehicle-to-grid (V2G) power system, where batteries in electric vehicles (charged primarily at night) can provide a bank of electricity storage for the grid when they are parked and plugged in at parking ramps and lots during the day when peak power is needed.

Although PHEVs are not yet available in new vehicles, they are likely to be on the market soon. Daimler-Chrysler, Ford, Toyota, and others are actively developing plug-in hybrids. GM's Chevy Volt is a concept plug-in series hybrid with a small gasoline motor that simply keeps the batteries charged for long trips. There is already a fledgling market for retrofitting HEV to PHEV, which indicates that converting or adapting existing parallel-series hybrids would be straightforward, if not inexpensive at the moment. *EDrive Systems* and *Hymotion* are two firms that are offering plug-in retrofit packages for Prius and Ford Escape hybrids (Figure 13.17).

Both use lithium ion (Li-ion) batteries either as replacement or in addition to the standard nickel metal hydride (NiMH) batteries. The keys to effective batteries for both PHEV and BEV

figure 13.17 **Hymotion L5 Lithium Power Specifications**

(a) Plug-in Hybrid Priuses being tested at Argonne National Lab.

(b) *Hymotion*™ retrofit lithium-ion battery package for HEV to convert them to PHEV.

Battery Type:	Lithium Polymer
Energy:	5kWh
Charge temperature range:	-10 deg C to 35 deg C
Operation temperature range:	-20 deg C to 45 deg C
Charge Voltage:	120V/240V (15A circuit)
Charge Time:	5.5hrs/4.0hrs
Weight:	72.5 Kg

Source: Argonne National Lab, 2007; Hymotion, Inc., 2007

SOLUTION

SOLUTION BOX 13.3

Electric-Drive Vehicles: Gas-Equivalent "Price per Gallon" and CO_2 Emissions

What are the cost and CO_2 per 25 miles of a grid supplied plug-in vehicle vs. a gasoline supplied 37.5 mpg vehicle?

Solution:

Assumptions:

- Electric drive: 200 Wh/mi = 5 mi/kWh = 37.5 mi/7.5 kWh
- Gasoline drive: 37.5 mi/gal
- CO_2 emissions
  - Electricity: 1.4 lb/kWh (U.S. average, see Table 5.7)
  - Gasoline, auto: 37.5 mpg = 0.54 lb/mi (Table 13.13)

Gasoline cost per 37.5 mi = 299¢/gal = 299¢/37.5 mi
Electricity cost = 10¢/ kWh × 7.5 kWh/37.5 mi = 75¢/37.5 mi

CO_2 emissions gasoline = 37.5 mi × 0.54 lb-CO_2/mi = 20 lb CO_2
CO_2 emissions electric = 37.5 mi = 7.5 kWh × 1.4 lb/kWh = 10 lb CO_2

are low cost and low weight. The laptop computer industry has helped advance lithium ion battery technology to reduce both weight per Wh and cost. It is expected that increased production will lead to further technical improvements and cost and weight reductions (see Figure 10.4).

Solution Box 13.3 demonstrates the potential economic and environmental benefits of plug-in electric drive vehicles. The figure from *EPRI Journal* (Sanna, 2005) gives a gas-equivalent price of 75¢ per "gallon" for plug-in electric vehicles. The box gives assumptions and calculations for this price to hold up. Assuming gas at $2.99/gal and electricity at 10¢/kWh, an electric-drive vehicle would operate at only **one-fourth the cost** of an efficient 37.5 mpg gasoline car. Because there would be no CO_2 emissions from the vehicle tailpipe, it would have **half the CO_2** emissions as gasoline vehicles, even when assuming the plug-in electricity comes from average U.S. power plants (i.e., 52% coal).

Plug-in electric drive vehicles can take advantage of renewable solar and wind power. These intermittent sources crave a storage system, and a fleet of vehicle batteries could provide it. One vision of the future would have our garage rooftops turned into solar recharging stations. Solution Box 13.4 shows that a south-facing garage roof size photovoltaic array (150–225 ft^2 depending on location) is sufficient to charge a PHEV (or all-electric vehicle)

SOLUTION BOX 13.4

Sizing a Rooftop PV Array to Charge a Plug-In Hybrid

How much roof area dedicated to a PV system does it take to produce equivalent electricity for a PHEV or BEV?

Solution:

It depends where you live, how much sun you get, and how much you drive. For example, Table 11.1 tells us that Atlanta has an annual average of five hours of full sun per day (or average insolation of 5.0 kWh/m^2/day) on a stationary south-facing collector at Lat –15° tilt. To produce 45 miles of driving per day at 200 Wh/mi requires 45 mi/day × 200 Wh/mi = 9000 Wh = 9 kWh/day.

Using the method in Solution Box 11.2, assuming a 0.75 de–rating factor,

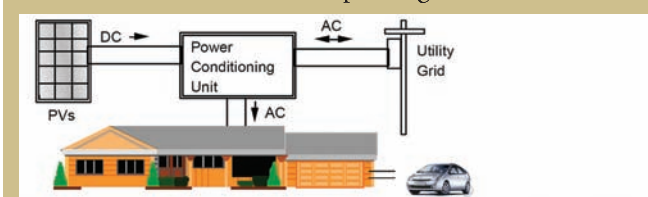
$$\text{PV } P_{DC,STC} = \frac{9 \text{ kWh/day}}{0.75 \times 5.0 \text{ hr/day}} = 2.4 \text{ kW}$$

Assuming 14% efficiency and a cost of \$4/W $P_{DC,STC}$ (current California price with rebates),

$$\text{Area (ft}^2) = \frac{P_{DC,STC} \times 10.75 \text{ ft}^2}{1 \text{ kW/m}^2 \times \text{m}^2} = \frac{2.4 \times 10.75}{0.14} = 184 \text{ ft}^2$$

$$\text{Cost} = \$4/\text{W} \times 2400 \text{ W} = \$9600$$

The table shows the rooftop area and cost needed for such a photovoltaic array in different cities with the assumptions given.



CITY	Hr/day 1-sun	kW STC	AREA (ft^2)	PV (\$)
Atlanta	5.0	2.40	184	\$ 9,600
Boston	4.5	2.67	205	\$ 10,667
Boulder	5.4	2.22	171	\$ 8,889
Los Angeles	5.5	2.18	168	\$ 8,727
Madison	4.1	2.93	225	\$ 11,707
Phoenix	6.4	1.88	144	\$ 7,500

Small 1-car garage 14'x22' = 310 ft^2

ASSUMPTIONS:
- 9 kWh/day from grid
- PV kW STC-to-Grid AC efficiency 75%
- PV Solar-to-kW efficiency 14%
- PV south-facing, Lat-15° tilt
- PV @ \$4/W dc STC

Area and Cost of Photovoltaic Array for a Plug-In Hybrid for travel of about 45 miles per day. Of course, such a system would be grid-connected so that the PV system would mostly feed the grid during day and the grid would charge the vehicle at night. A utility might pay more for on-peak power than it would sell off-peak power, so the PV garage with a time-of-day meter would allow users to "buy low, sell high."

13.3.2 Flex-Fuel Plug-In Hybrid Electric Vehicle (FF-PHEV)

As we noted earlier, both flex-fuel vehicles and PHEVs offer significant advantages by themselves. When combined, they offer dramatic possibilities. PHEVs can use a flex-fuel engine that can run on gasoline or E85 ethanol blend. This would further reduce CO_2 emissions and reduce oil use and imports to the equivalent of 500–700 mpg of gasoline. Now we're talking! Solution Box 13.1 showed that such a FF-PHEV would use 95% less gasoline per mile than an average car on the road today.

The technology for the FF-PHEV is readily available today, and a flex-fuel option should be available on PHEVs when they hit the market in a year or two. When they do, the benefits of FF-PHEV will be constrained by ethanol production and the limited number of E85 filling stations, except in Minnesota, Iowa, and Illinois. However, as discussed in Chapter 14, these limitations may change.

13.3.3 Battery Electric Vehicles (BEV)

If plug-in systems and electric drive motors are so good for PHEV, why not just skip the hybrid part and go all electric? The battery all-electric vehicle (BEV) is not new; in fact, BEVs outnumbered gasoline cars 10 to 1 in the 1890s. But it has had fits and starts ever since and has never really captured a market. Some of the big automakers have developed concept cars and some sales, especially after 1990 when California mandated that 10% of cars sold there be ZEV by 2003. GM began producing its EV-1 in 1996 and Toyota sold the RAV4-EV in 2002–2003. However, California weakened its ZEV mandate in 2003, allowing credits for non-ZEV vehicles, and the ready market for BEVs dried up; GM and Toyota stopped production of their EVs that year.

The biggest constraints to BEVs have been cost and weight of batteries and slow recharge times that work against the U.S. driving culture to "fill 'er up" and go. But recall from Chapter 10 (Section 10.3.2), advances in Li-ion batteries have achieved an energy density of 180 Wh/kg, double that of NiMH batteries, with prospects for even higher densities and lower weight (Figure 10.4).

There has been renewed interest in BEVs in recent years as a result of surging gasoline prices and growing concern about carbon emissions. In 2007, GM announced it will get back into the BEV market by 2010: its plug-in Volt is actually a series HEV because it will have a small gasoline engine to charge batteries on long trips. But by then it may lag behind a number of entrepreneurial start-up companies which are developing high-performance BEVs using advanced motors, batteries, and controls. Although these vehicles are now at the (very) high end of the market, the experience gained is likely to spread to more affordable production models.

Leading these companies is Tesla Motors, which unveiled its Tesla Roadster EV in 2006 to high acclaim (Figure 13.18). The stylish, high-performance two-seater boasts 0 to 60 mph in 4 seconds, 250 miles per charge at about 1¢ per mile, the equivalent of 135 mpg, and one-third the carbon emissions of a Prius. The fuel economy and emissions are based on well-to-wheel studies assuming natural gas combined-cycle electricity generation (see Section 13.4). The two-gear transmission, watermelon-sized 70-pound motor, power electronics module that can control over 200 kW during peak acceleration, and the modular battery energy storage system (ESS), make this one of the simplest vehicle technologies.

The heart of the vehicle is the ESS. It consists of 6800 lithium-ion (Li-ion) cells, each just a bit larger than a AA battery, making a 1000 lb (450 kg) battery bank. The ESS can be fully charged in 3.5 hours, usually overnight. It has a 250-mile range, and is designed for 500 full charge-discharge cycles. Thus the ESS is estimated to last 125,000 miles before replacement. The 250-mile range, easy recharging, and high performance output of the ESS helps the Tesla Roadster stand apart from other BEVs. So does its price—at $92,000 it is targeted at the high-end sports car market. But the lessons Tesla Motors is likely to learn in coming years may have lasting effects on the broader vehicle market.

figure 13.18 **Tesla Roadster Electric Vehicle**

High performance (0 to 60 mph in 4 seconds); 250-mile battery range from $3\frac{1}{2}$ hour charge; 1¢ per mile; 135 mpg energy equivalent.

Source: Tesla Motors www.tesla.com

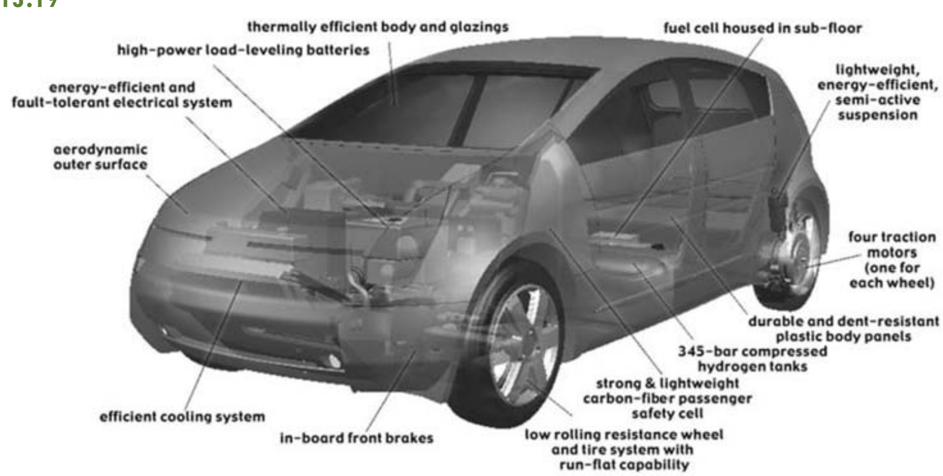
13.3.4 The Hypercar™: Ultralight Composite Materials and Vehicle Efficiency

Independent of propulsion system, all vehicles can be made more efficient if they were lighter. Conventional vehicles consume 7–8 units of fuel energy to deliver 1 unit of power to the wheels; the ratio for hybrid vehicles is 3–5 to 1. Thus, reducing the power needed at the wheels can result in 7–8 times the fuel savings. Power at the wheels is needed to overcome drag, rolling resistance, and weight, with weight requiring two-thirds to three-fourths of the fuel consumption of a typical midsize sedan. Amory Lovins maintains that "contrary to folklore, it's more important to make a car light and low-drag than to make its engine more efficient or change its fuel" (RMI, 2004). And of course, these measures of lightness, low-drag, engine efficiency, and renewable fuel are not mutually exclusive.

In 1999, Lovins founded *Hypercar, Inc.* to support the transition of the auto industry to higher efficiency vehicles. The key element of its design concept, incorporated in its 2000 concept car *Revolution*, was the use of ultralight carbon composite materials (Figure 13.19). These materials have been used in some auto body parts and other lightweight applications such as airplanes and high-performance vehicles, but they have long been considered too expensive to replace steel in typical cars. Although they are ultralight, carbon composites can also be ultrastrong, so there is no sacrifice in safety.

Lovins suggests that the concept car would triple the efficiency of a comparable steel car. Because of its reduced weight, the concept car could use a smaller, lighter engine, and use efficient engine systems such as hybrids or fuel cells much more effectively. Lovins argues that the lessons of ultralight materials can be easily transferred to other non-automotive markets once prices drop.

figure 13.19 **Hypercar *Revolution***



Ultralight composite materials, aerodynamic design, and fuel cell electric drive create an efficient, oil-free car.

Source: Lovins, 2004. Used with permission.

figure 13.20

Fiberforge carbon-fiber panels reduce vehicle weight and improve efficiency.

Source: Fiberforge, Inc. Used with permission.

The key to this revolution in the vehicle industry is the improvement in cost of manufacturing the composite materials. As a result, since 2002, Lovins has focused not on vehicle design, but on composite materials manufacturing processes to reduce costs. He co-founded Fiberforge, Inc., in Glenwood Springs, Colorado, to perfect high-volume thermoforming of advanced composites (Figure 13.20). In 2007, Fiberforge was named a Technology Pioneer by the World Economic Forum.

13.3.5 Fuel Cell Electric Vehicles (FCEV)

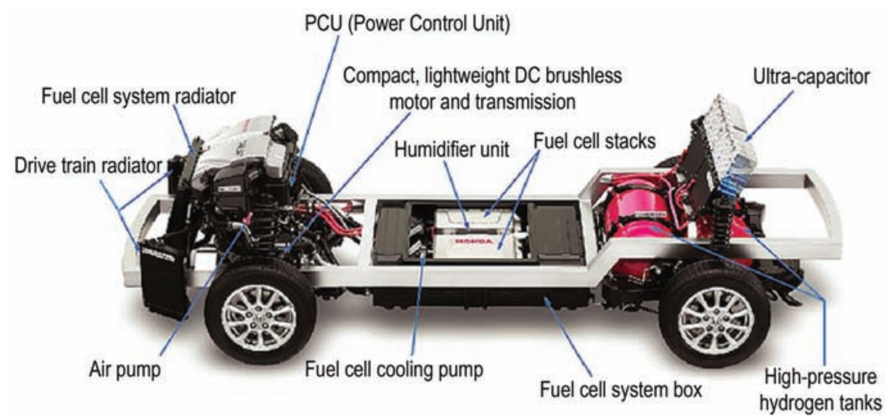
We introduced fuel cell technology in Chapter 10. Considerable attention has been given to fuel cells because of their efficient means of converting hydrogen fuel to electricity and doing so without pollution. In transportation they can offset use of petroleum and of all fossil fuels if the hydrogen can be produced from renewables. Most hydrogen is now produced from natural gas. Lovins' vision for the Hypercar assumes it to ultimately run on hydrogen fuel cells.

The motor drive of a fuel cell vehicle is an electric motor like that in a BEV, PHEV, or HEV. The difference is that the battery bank that drives the motor is charged by the fuel cell, not by a gasoline engine-driven generator or the grid, although a plug-in FCEV is an option. As discussed in Section 10.9.1, a single fuel cell has a small voltage, so multiple cells are stacked as shown in Figure 10.18 and in Figure 13.21(b). Honda has taken the lead in FCEV development by announcing in 2006 its intent to produce its next-generation

figure 13.21 **Honda Fuel Cell FCX**

(a) Honda FCX concept car

(b) Honda FC stack



(c) Honda FCX components and configuration

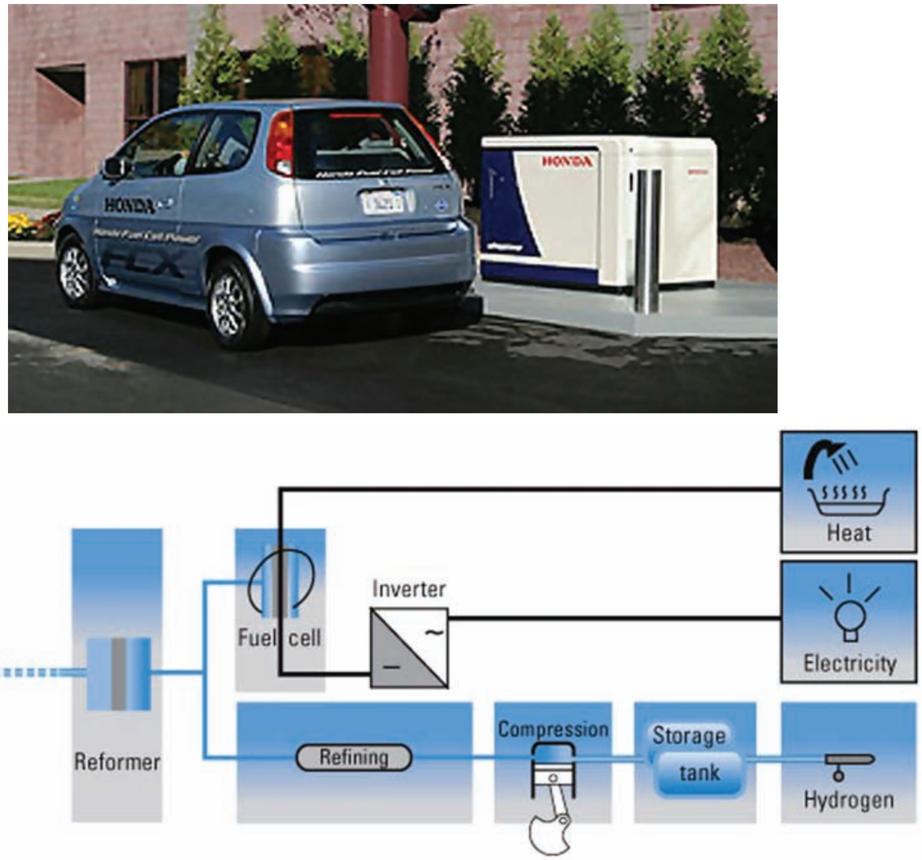
Fuel cell stacks on low-floor platform, power control unit, motor/transmission up front, ultra-capacitor electric storage, high-pressure hydrogen tanks

Source: courtesy Honda Motors, Inc., 2007

FCX for the commercial market in three to four years. Figure 13.21(a) shows Honda's FCX concept vehicle, and Figure 13.21(c) shows the configuration of system components, including the fuel cell stack on a low-floor platform, power control unit and motor/ transmission up front, and high-pressure hydrogen tanks and ultra-capacitor (battery) storage in the back.

There are complications in bringing FCEVs to market. They include developing an inexpensive, small, and lightweight fuel cell; the energy source and production of hydrogen fuel; improved hydrogen storage methods; and especially the infrastructure to deliver that fuel. All of these will take many years, and in the end hydrogen fuel cell vehicles will likely be expensive to buy and operate (see Section 3.3.4).

figure 13.22 **Honda Home Energy Station**



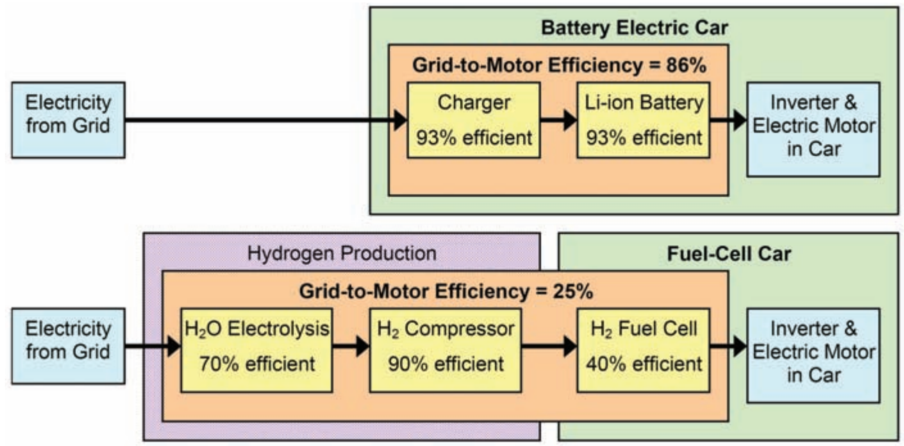
Reforms natural gas to hydrogen for use in residential fuel cell for home heat and electricity and for use in FCEV.

SOURCE: courtesy Honda motors, Inc., 2007

Understanding that marketing its FCX vehicle requires fuel options, in 2001 Honda developed an on-site solar PV electrolysis hydrogen producer at its Torrance, California, North American headquarters. In 2005, it developed a Home Energy Station that reforms natural gas to hydrogen and produces heat and electricity for home use and hydrogen for a FCEV (see Figure 13.22).

Although hydrogen fuel cell vehicles have been touted as the vehicles of the future and the center of a future hydrogen economy, EV, PHEV, and FF-PHEV have greater immediate promise. Consider the efficiency comparison of an FCEV and an EV if fuel cells rely only on hydrogen electrolysis from grid power and the EV relies on the same power to charge its batteries. Figure 13.23 shows that it would be more efficient to forget the fuel cell and use the power to charge the EV. The EV is $3\frac{1}{2}$ times as efficient, assuming 40% fuel cell efficiency (the EPA rating of the Honda FCX is 49 mi/kg H_2 or 37% efficient). We compare more vehicle technologies in the next section.

figure 13.23 **Grid-to-Motor Efficiency for BEV versus FCEV with Electrolysis**



Overall efficiency = $\eta = \eta_1 \times \eta_2 \times \eta_3 \times .....$
BEV: η = 93% × 93% = 86%
FCEV: η = 70% × 90% × 40% = 25%

SOURCE: Eberhard and Tarpenning, 2006. Used with permission of Tesla Motors, Inc.

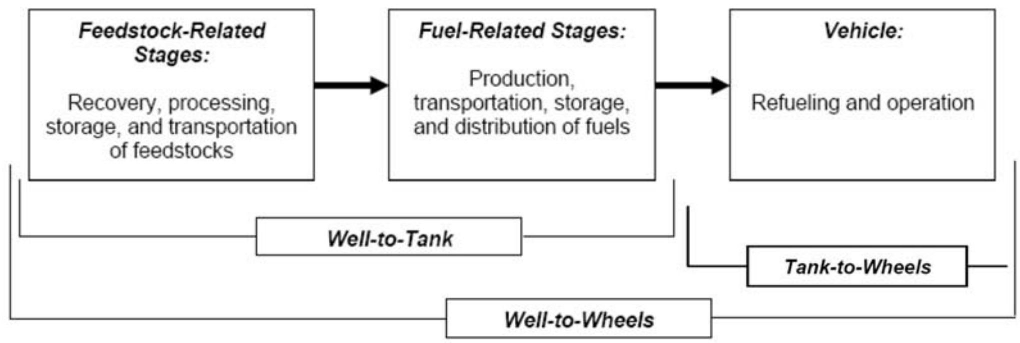
13.4 Well-to-Wheel Studies of Vehicle Technologies

13.4.1 Well-to-Wheel Studies Using the GREET Model

As we begin to choose what technologies and fuels to develop for transportation in our increasingly carbon-rich and oil-poor world, the choice is complicated by many options, impacts, and life-cycle considerations. To assist with the comparative analysis to inform decisions, in 1995 Argonne National Lab began developing a life-cycle model called GREET—the **G**reenhouse gas, **R**egulated **E**missions, **E**nergy use in **T**ransportation. The model has been used for Well-to-Tank assessments of different fuel options and Tank-to-Wheels assessments of drive train and technology options (Figure 13.24). Combining the assessments gives a Well-to-Wheel (WTW) analysis, for which GREET is now the tool of choice. The "cradle-to-grave" concept of life-cycle assessment, introduced in Chapter 5 and applied to buildings in Chapter 8, is the basis for WTW analysis. As with cradle-to-grave studies, we can focus on one part of or the entire process. GREET now deals with the fuel energy process, but, as discussed under limitations of WTW studies, its developers are currently adding assessment of the vehicle production cycle to assess embodied energy and related impacts.

Most of the studies have included a variety of vehicle technologies, including gasoline and diesel ICE, gas and diesel hybrid, and fuel cell and fuel cell hybrid. Few have included the full range of technologies discussed in this chapter. Figures 13.25 and 13.26 show results of some of the studies. Figure 13.25 from the California Energy Commission's Full Fuel Cycle Assessment

figure 13.24

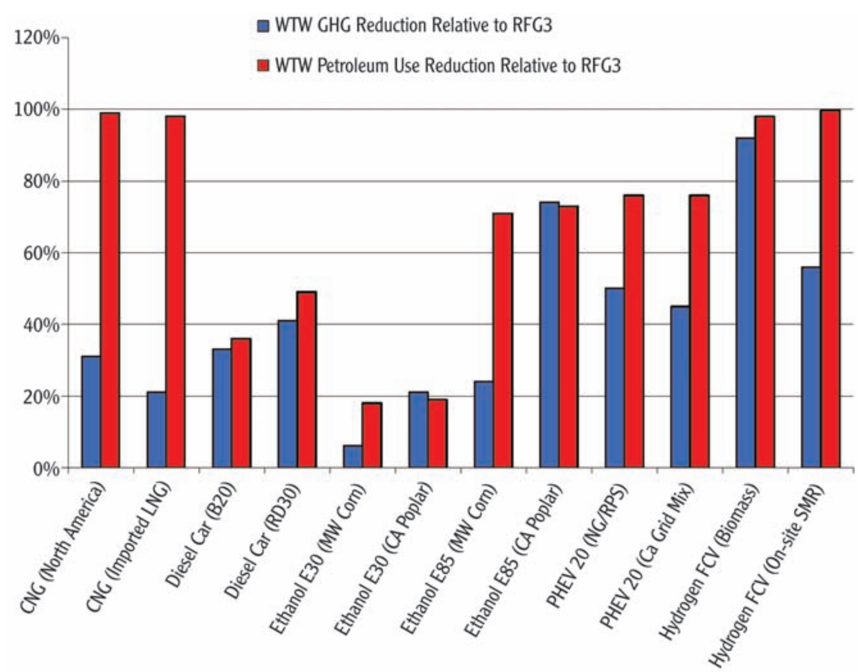


GREET model combines well-to-tank assessment of the fuel cycle and tank-to-wheels assessment of drive train technologies. The model will be adding cradle-to-grave assessment of the vehicle manufacturing cycle.

Source: adapted from Weiss et al., 2000

(2007) compares alternative fuels (CNG, biofuel blends, plug-in hybrids, and hydrogen fuel cells) to reformulated gasoline (RFG3) for petroleum and GHG emission savings. The cellulosic E85, plug-in hybrid, and fuel cell hydrogen from biomass and on-site steam methane reforming (SMR) options have the greatest savings. Figure 13.26 from Wang (2005) shows the typical results of many of these studies: that there is likely to be a path from conventional technologies to hybrids to hydrogen fuel cell vehicles (see also Demirdoven et al., 2004).

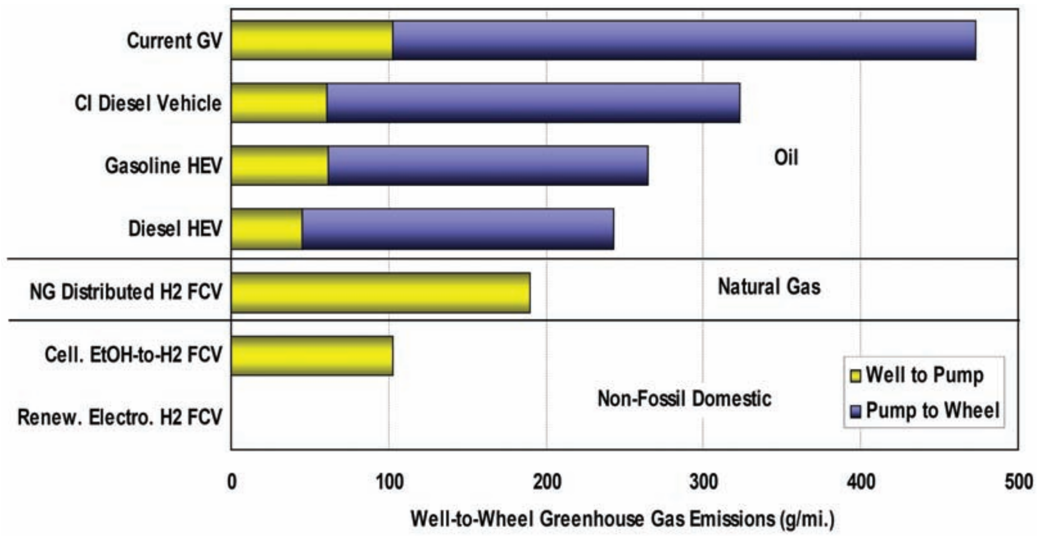
figure 13.25 **California Energy Commission Well-to-Wheels Assessment of Vehicle-Fuel Options**



CEC compared compressed natural gas (CNG), biofuel blends, lug-in hybrids, and hydrogen fuel cell vehicles for savings of petroleum and GHG emissions compared to a standard reformulated gasoline (RFG3) vehicle.

Source: CEC, 2007

figure 13.26



GREET analysis implies a path from conventional technologies to hybrids then to fuel cells to achieve zero GHG emissions if H_2 is generated from renewable energy.

Source: Wang, 2005

We are not so sure of this path. When the GREET model is applied to some different combinations of technologies and fuels, including plug-in hybrids, flex-fuel plug-in hybrids, and all-electric vehicles charged by renewable electricity, the assumption of a fuel cell vehicle future may change. Let's try our own back-of-the-envelope WTW comparison of these technologies.

13.4.2 A Simple WTW Assessment of Current and Emerging Vehicles

Given the previous discussion on vehicle technology, efficiency, and emissions, we conducted a comparison of conventional, HEV, PHEV, EV, and FCEV cars for urban uses. The six vehicles are as follows:

- Gasoline vehicle (GV) based on Ford Focus
- Hybrid electric vehicle (HEV) based on Toyota Prius
- Plug-in hybrid electric vehicle (PHEV) based on plug-in "Prius Plus"
- Flex-fuel plug-in hybrid electric vehicle (FF-PHEV) based on flex-fuel plug-in "Prius Plus"
- Battery electric vehicle (BEV) based on Tesla Roadster
- Prototype fuel cell electric vehicle (FCEV) based on Honda FCX

The assessment considers WTW energy, gasoline, cost, and carbon emissions for each vehicle. It is broken into two parts: the tank-to-wheel (TTW) efficiency for each vehicle type, and the well-to-tank (WTT) efficiency for each fuel type. The calculations are not too hard, but the most important part is setting and stating assumptions. That way everyone knows

table 13.13 **Fuel Assumptions: WTT Energy, Efficiency, and Cost**

Well-to-Tank	WTT Energy				WTT Efficiency	Cost per		CO_2	
Gasoline	150	1000 Btu/gal	42	MJ/l	80.0%	\$2.50	gal	11.2	kg/gal
E85	74	1000 Btu/gal	21	MJ/l	80%-g 125%-e	\$2.20	gal	7.85	kg/gal
Electric-grid	11.4	1000 Btu/kWh	8.3	MJ/kWh	30.6%	\$0.10	kWh	0.70	kg/kWh
Electric-ngcc	7.8	1000 Btu/kWh	12	MJ/kWh	43.7%	\$0.10	kWh	0.43	kg/kWh
H_2-reform	224	1000 Btu/kg	237	MJ/kg	60.0%	\$3.00	kg H_2	13	kg/kgH
H_2-el-grid	629	1000 Btu/kg	663	MJ/kg	21.4%	\$3.00	kg H_2	38	kg/kgH
H_2-el-ngcc	440	1000 Btu/kg	464	MJ/kg	30.6%	\$3.00	kg H_2	23	kg/kgH

what the results are based on, and if you want to change the assumptions, it is easy to do, especially if you build a spreadsheet for the analysis.

For our assessment, the assumed drive cycle is 15,600 mi/year, with 6500 highway (42%) and 9100 city (58%). Assumptions on vehicle TTW and fuel WTT efficiencies, fuel price, and CO_2 emission rates are in Tables 13.13 and 13.14. For the electric drives and H_2 electrolysis, two electricity sources are included: average U.S. grid (35% efficient generation) and natural gas combined-cycle (50% efficient generation). Electricity also incurs fuel extraction and processing and transmission efficiencies.

In Solution Box 13.5, we step through a sample of the calculations for the GV, FF-HEV, and BEV to show the process. You might try some of the other fuel-vehicle scenarios on your own.

The overall WTW results are given in Table 13.15 and Figures 13.27–13.30. The FF-HEV and the BEV are the winners with the lowest WTW energy per mile, and lowest CO_2 emissions. Like the BEV, the fuel cell vehicle has zero gasoline use (good for petroleum reduction) but has high WTW energy and carbon emissions especially for the electrolysis options.

table 13.14 **Vehicle Assumptions: TTW Efficiency**

	Vehicle	Basis		TTW Efficiency
Gas	Ford Focus	24	mpg	
HEV	Prius	49	mpg	
PHEV	Prius Plus	48	mpg (highway)	5 mi/kWh (city)
FFPEV	FF Prius Plus	40	mpg (highway)	5 mi/kWh (city)
BEV	Tesla Roadster	5.6	mi/kWh	
FCEV	Honda FCX	57	mi/kg H_2	(49–66 mi/kg H_2)

SOLUTION

SOLUTION BOX 13.5

WTW Calculations for Gasoline, FF-HEV, and BEV

Given the assumptions in Tables 13.13 and 13.14, what are the WTW energy per mile and annual CO_2 emissions for the gasoline vehicle, the FF-HEV and the BEV both with NGCC electricity?

1. **Gasoline Vehicle (GV):**
   Fuel WTT: The energy value of gasoline is 120,000 Btu/gal. WTT efficiency for gasoline is estimated at 80%, that is about 20% of crude oil energy is consumed in production of crude, processing to gasoline, and transport to filling station. The WTT energy is 120,000/0.8 or 150,000 Btu/gal. CO_2 of production and combustion is given as 11.2 kg CO_2/gal.

$$\frac{\text{WTW energy}}{\text{mi}} = \text{WTT} \times \text{TTW} = \frac{150 \times 10^3 \text{ Btu} \times \text{gal}}{\text{gal } 24 \text{ mi}} = \frac{6.3 \times 10^3 \text{ Btu}}{\text{mi}} = \frac{4.1 \text{ MJ}}{\text{km}}$$

$$CO_2 \text{ emissions} = \frac{15{,}600 \text{ mi}}{\text{yr}} \times \frac{11.2 \text{ kg } CO_2}{\text{gal}} \times \frac{\text{gal}}{24 \text{ mi}} = \frac{7.3 \times 10^3 \text{ kg } CO_2}{\text{yr}}$$

2. **Flex-Fuel Plug-In Hybrid Electric Vehicle (FF-PHEV) with natural gas combined-cycle electricity:**
   Fuel WTT: This is a little more complicated because we have two fuels to deal with: E85 (85% ethanol, 15% gasoline) and electricity. So we figure out the WTT energy for each and weight them by their use in the driving cycle (42% highway E85, 58% city electric). Ethanol WTT accounts for the fossil fuel energy needed to grow and process corn into ethanol (not the solar energy that grows the corn). Wang, 2005, estimates this at 56%–79% of the energy value of the ethanol (Figure 5.4), we will conservatively use 80%. For NGCC electricity, we assume 95% well-to-power plant, 50% generation, and 92% transmission efficiency for a total of 43.7%.

$$\frac{\text{WTW energy}}{\text{mi}} = \text{WTT} + \text{TTW} = 0.42 \times \frac{74 \times 10^3 \text{ Btu}}{\text{gal}} \times \frac{\text{gal}}{40 \text{ mi}} +$$

$$0.58 \times \frac{7.8 \times 10^3 \text{ Btu}}{\text{kWh}} \times \frac{\text{kWh}}{5 \text{ mi}} = (777 + 905)\frac{\text{Btu}}{\text{mi}} = 1.7 \times 10^3 \frac{\text{Btu}}{\text{mi}} = 1.1 \frac{\text{MJ}}{\text{mi}}$$

$$CO_2 \text{ emissions} = \frac{16{,}500 \text{ mi}}{\text{yr}} \times \frac{\text{gal}}{40 \text{ mi}} \times \frac{7.85 \text{ kg } CO_2}{\text{gal}} +$$

$$\frac{9100 \text{ mi}}{\text{yr}} \times \frac{\text{kWh}}{5 \text{ mi}} \times \frac{0.43 \text{ kg } CO_2}{\text{kWh}} = 2.0 \times 10^3 \frac{\text{kg } CO_2}{\text{yr}}$$

3. **Battery Electric Vehicle (BEV) with average grid electricity:**
Fuel WTT: We don't have the complications of multiple fuels here but we assume average grid electricity, so the WTT efficiency and CO_2 emission rates are different from the case above. For grid electricity, we assume 95% well/mine-to-power plant, 35% generation, and 92% transmission efficiency for a total of 30.6% (Table 13.13).

$$\frac{\text{WTW energy}}{\text{mi}} = \text{WTT} + \text{TTW} = \frac{11.4 \times 10^3 \text{ Btu}}{\text{kWh}} \times \frac{\text{kWh}}{5.6 \text{ mi}} = 2.0 \times 10^3 \frac{\text{Btu}}{\text{mi}} = 1.3 \frac{\text{MJ}}{\text{km}}$$

$$CO_2 \text{ emissions} = \frac{15{,}600 \text{ mi}}{\text{yr}} \times \frac{0.7 \text{ kg } CO_2}{\text{kWh}} \times \frac{\text{kWh}}{5.6 \text{ mi}} = 2.0 \times 10^3 \frac{\text{kg } CO_2}{\text{yr}}$$

table 13.15 WTW Results: Gasoline, Cost, Energy, and CO_2 Emissions

WTW Results	Gasoline gal/yr	Cost $/yr	Energy 1000 Btu/mi*	Energy MJ/km*	CO_2 1000 kg/yr*
GV	650	1625	**6.3**	**4.1**	**7.3**
HEV	318	796	3.1	2.0	3.6
PHEV-grid	135	521	2.6	1.7	2.8
PHEV-ngcc	135	521	2.2	1.4	2.3
FFPEV-grid	24	540	2.1	1.4	2.5
FFPEV-ngcc	24	540	**1.7**	**1.1**	**2.0**
BEV-grid	0	279	**2.0**	**1.3**	**2.0**
BEV-ngcc	0	279	1.4	0.9	1.2
FCEV-reform	0	821	3.9	2.6	3.6
FCEV-el-grid	0	821	11.0	7.2	10.4
FCEV-el-ngcc	0	821	7.7	5.1	6.3

* Bold values are results from Solution Box 13.5.

figure 13.27 WTW Energy Consumed per Mile

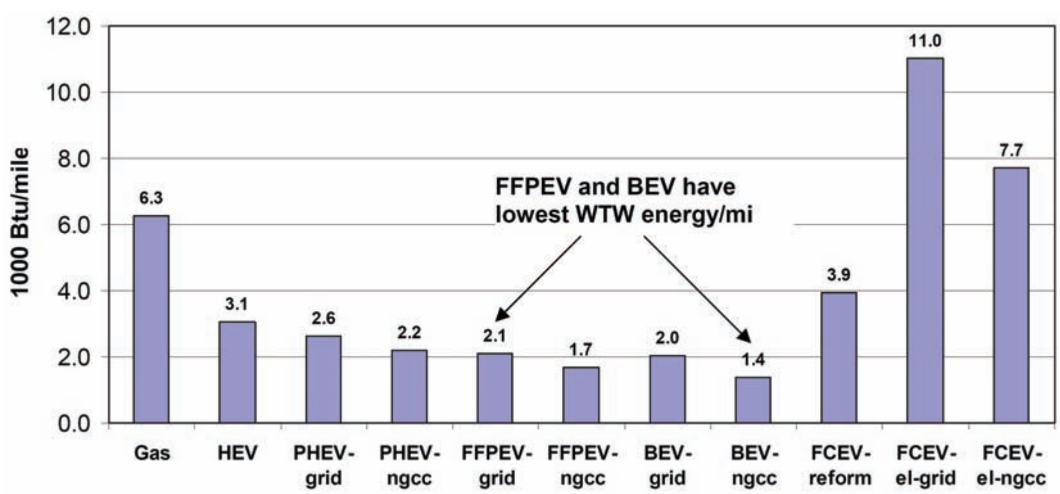
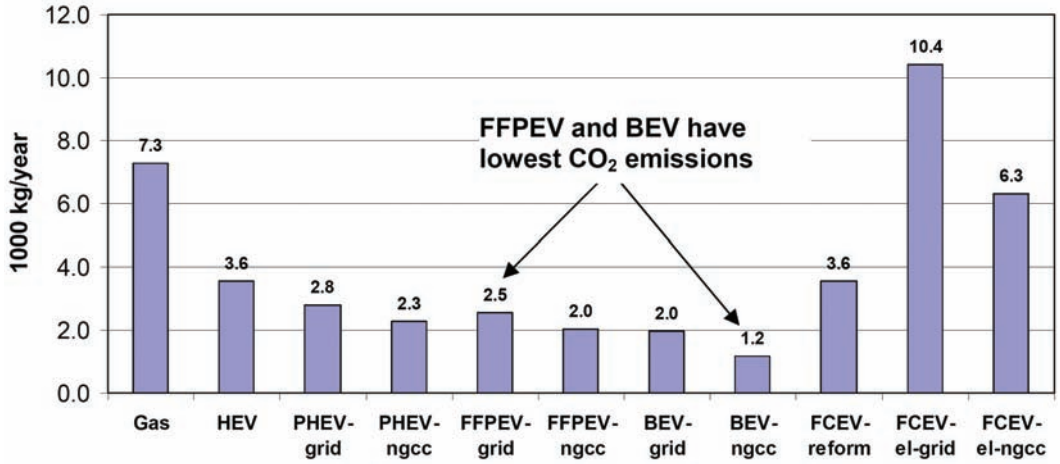


figure 13.28 WTW Annual CO_2 Emissions



13.4.3 Limitations of Well-to-Wheel Analysis

Well-to-wheel analysis aims to compare a diverse mix of vehicles and fuels in a common framework. This is a great step forward in energy analysis, but the state of the art is not complete. For example, our analysis did not consider vehicle cost and life-cycle energy and emissions for vehicle manufacturing. We were comparing a $15,000 Ford Focus to a $92,000 Tesla Roadster and assessed fuel cost only. Perhaps more importantly, we did not consider the embodied energy in the vehicles. If they were similar technologies, we could assume

figure 13.29 WTW Annual Gasoline Consumption

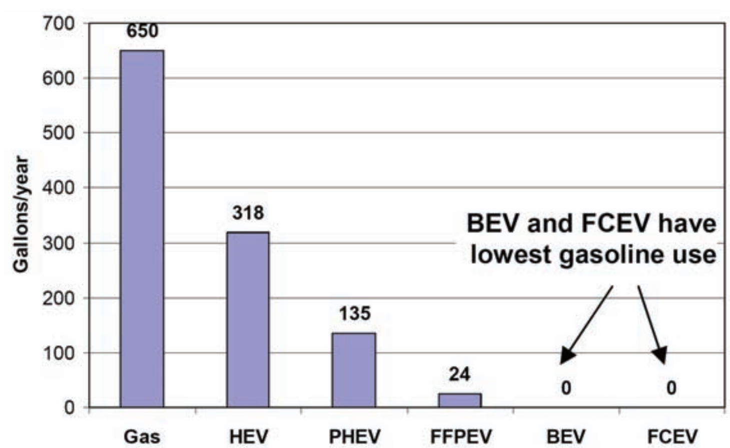
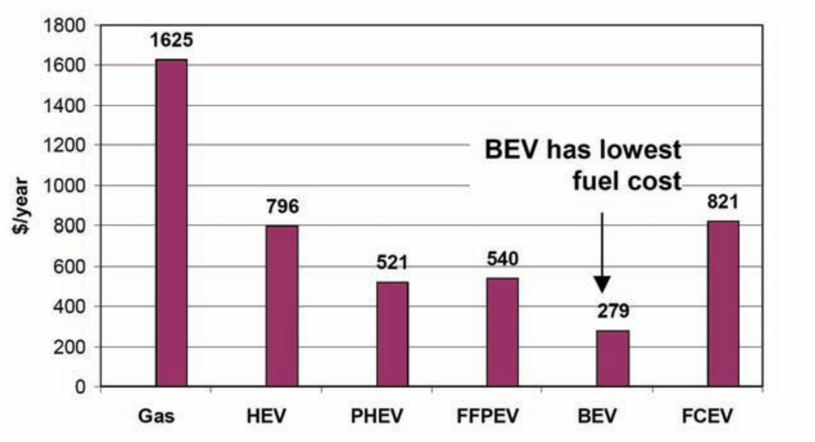


figure 13.30 WTW Annual Fuel Cost



comparable embodied energy, but they are not. For example, what is the embodied energy (and related emissions) of manufacturing a steel-intensive Ford Focus to a Li-ion battery-intensive PHEV or BEV? The answer to this question certainly would affect the results on life-cycle energy and emissions.

Even the "gold standard" WTW GREET model has dealt only with the fuel energy process. However, the model's creators recognize this limitation and are expanding the model (GREET 2 Series, GREET 2.7) to include the vehicle production cycle to assess embodied energy, GHG emissions, air emissions, and other impacts of the materials and production cycle of vehicle manufacture, decommissioning, recycling, and disposal.

13.5 Summary

Transportation is a critical energy sector because of its growing demand, its dependency on oil, and its contribution to urban air pollution and GHG emissions. If we are to adequately address our oil and carbon problems, transportation is the first place to start. We need a three-prong solution:

- Improve vehicle efficiency.
- Increase use of alternative fuels to replace petroleum fuels.
- Reduce vehicle miles traveled.

This chapter has addressed the first of these responses. The next chapter focuses on alternative fuels, and Chapter 15 discusses means of mitigating VMT.

Technology is the key to improving vehicle efficiency (i.e., mpg). It also is important for reducing energy intensity (e.g., energy per passenger mile, energy per freight ton-mile), but energy intensity is also affected by modal shifts and load factors of both passengers and freight. The world's and especially the nation's fascination with the automobile makes vehicle technology and efficiency the subject of broad consumer and public interest. Improvements in the traditional internal combustion engine and ancillary emission control equipment have succeeded in reducing emissions per vehicle mile and increasing efficiency. But these improvements have been offset by increased vehicle miles traveled and vehicle size and weight. Further, the efficiency of average new light vehicles in the U.S. market has not improved much in twenty years because the federal government has chosen not to increase fuel efficiency standards, the consumer market has turned to less efficient larger light trucks and SUVs, and fuel prices have remained relatively low compared to other countries.

Higher fuel prices and new federal efficiency standards adopted in 2007 for 2020 will help push technology development to create more efficient vehicle options for consumers. The most promising commercial development is the growing market for efficient hybrid electric vehicles. Simple enhancements of this technology, adding extra batteries and a plug-in option, as well as using a flex-fuel engine that can operate on gasoline or E85 blend, provide the best mid-term and perhaps long-term option to improve vehicle efficiency, reduce carbon emissions, and reduce oil use. This technology currently looks more promising than other options including hydrogen fuel cells.