# 8

# Transportation Systems

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## 8.1 Introduction

This chapter presents trends in land use, freight, ground-transportation modes for people and freight, transportation fuel supply, and the opportunities for conservation that exist within each area. The chapter starts with a discussion of the transportation–land use relationship for a better understanding of the framework within which the transportation system functions and the design theories that aim to influence mode choice and trip generation. Next is a description of mass transit, with particular emphasis on how its energy use compares to the energy use of the automobile. The movement of freight, its modes, and energy consumption relative to the rest of the transportation system follows. Then, emerging future technologies are described; the focus of this section is on vehicle efficiencies to conserve energy resources. Finally, the well-to-wheel energy analysis combining fuel production and vehicle performance is presented, focusing on what feedstocks are available and how they can be refined efficiently into a fuel.

## 8.2 Land Use

### 8.2.1 Land Use and Its Relationship to Transportation

There is a fundamental relationship between transportation and land use, because the distance between one's origin and destination will determine the feasibility, route, mode, cost, and time necessary to travel from one place to another. Likewise, transportation influences land use as it impacts people's decisions about where to live and work, considering factors such as commute time and cost, the distance to a

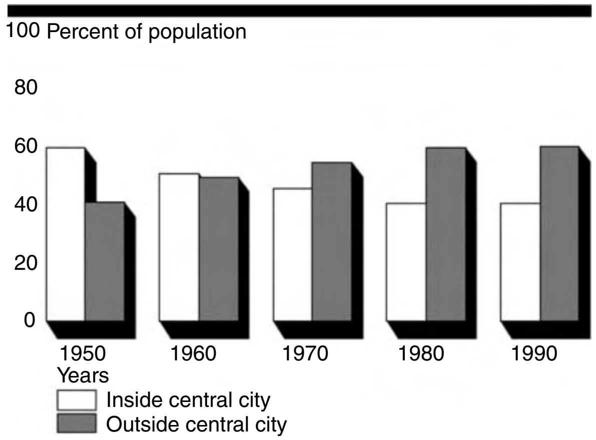

FIGURE 8.1 Location of population relative to central city. (From U.S. General Accounting Office (GAO), *Community Development: Extent of Federal Influence on "Urban Sprawl" is Unclear*, GAO-RCED-99-87, Washington, DC, 1999.)

quality school for a family's children, the safety and convenience of the routes to school, work, activities, and access to goods and services.

The best opportunity for conservation in transportation begins with the transportation–land use relationship. An energy-efficient transportation system exploits and integrates all modes rather than just the highway. However, current land use regulations, codes, and development trends are designed exclusively for the single-occupant vehicle (SOV) and do not efficiently support other travel options. A more balanced system that incorporates mass transit, walking, bicycling, and other alternatives would be more energy-efficient. These modes are less energy intensive and would reduce traffic congestion, vehicle idling, and inefficient stop-and-go traffic. However, land use must be designed for multimodal movement for such a balanced system to be realized.

Land use and the population in the U.S. have become more decentralized over time (see Figure 8.1). The distribution of land uses into residential, commercial, and business areas increases the distances between the many daily necessities of life so that walking and bicycling are either infeasible or unsafe; it also makes mass transit inefficient because stops would be required to serve each individual's needs. Therefore, personal vehicles are the most convenient and most widely chosen mode of transportation for daily travel needs given the type of development most commonly used in the U.S. A more systems-oriented approach, integrating pedestrian, bicycle, automobile, and mass-transit networks within a higher-density developmental structure would be more energy-efficient, but this situation is not the norm in the U.S. today.

### 8.2.2 Smart Growth

The terms "urban/suburban sprawl" and "smart growth" first appeared in the 1990s and often together, with the first assumed to be a problem and the latter assumed to be the solution. Without making vague generalizations, it should first be recognized that at the heart of the smart growth debate are "the rights of the individual versus the goal of the community" (Miller and Hoel 2002); but there is no reason that both individuals' rights and community goals cannot be achieved at the same time. In fact, the realization of community goals can enhance the realization of individuals' rights by increasing choices and improving livability. The point at which one or the other becomes threatened is when regulations begin to restrict individual rights or a few individuals prohibit the community from realizing its goals (Miller and Hoel 2002).

**TABLE 8.1** Fundamental Principles of Smart Growth

| Downs (2001) | Cervero (2001) |
|---|---|
| "Preserving large amounts of open spaces and protecting the quality of the environment" | Embracing "urban planning by anticipating and creating a vision of the future" |
| "Redeveloping inner-core areas and developing infill sites" | "Balanc[ing] the twin and often competing aims of urban design-form versus function" |
| "Removing barriers to urban design innovation in both cities and new suburban areas" | "Infrastructure investments are cleverly used to shape and leverage development" |
| "Creating a greater sense of community…and a greater recognition of regional interdependence and solidarity" | Regional governance to "deal with spillover and cross-boundary problems" |

*Source*: From Downs, A., *Planning*, April, 20–25, 2001; Cervero, R., *Australian Planner*, 38(1), 29–37, 2001.

The term "urban/suburban sprawl" is generally defined as the growth of "low-density, automobile-dependent development on the fringe of cities" with both positive (increased home ownership, lower prices for business real estate) and negative (high infrastructure costs due to low-density development, increased traffic congestion, and consumption of green space) results (U.S. General Accounting Office 1999; Miller and Hoel 2002). In contrast, "smart growth" is considered the antidote to urban sprawl, by planning land use and transportation simultaneously for an integrated result. Specifically, the goals and strategies listed in Table 8.1 have been offered as the fundamental principles of smart growth.

Usually, these principles translate to high-density, mixed-use growth that incorporates transportation alternatives into design, such as transit-oriented development, pedestrian pockets, and bicycle networks. Shortening distances and providing transportation alternatives can conserve energy by decreasing the use of the automobile and increasing the use of less energy-intensive modes. The key is to maintain mobility and accessibility while curtailing the need for a motor vehicle for each and every trip.

Like most aspects of transportation and land use, the strategies to implement smart growth overlap and are interrelated, as shown in Figure 8.2 (Miller and Hoel 2002). As with any project, it is important to take each situation on a case-by-case basis, remembering that there is no silver bullet to design and execute the ideal transportation–land use plan.

### 8.2.3 Designing for Smart Growth

In an effort to implement smart growth, architectural movements, such as New Urbanism, neo-traditional or traditional neighborhood development (TND), and transit-oriented development (TOD), have appeared with the intention of countering sprawl and improving livability. These design strategies stress the importance of pedestrian accessibility through high-density development to reduce distances that would otherwise require an automobile or other motorized mode to travel. Typically, the standard design distance for pedestrians is one-quarter mile. Ten factors to improve the walkability of an area are shown in Figure 8.3. It is often assumed that people can walk that distance in about 5 min and that for any distance greater than that, they will choose to drive rather than walk. The designs mix land uses and housing affordability within an area so that residents can easily access shops, services, schools, employment centers, and other facilities from their homes. An emphasis on interconnectedness encourages streets laid out in a grid pattern as opposed to winding roads that terminate in cul de sacs. The designs often incorporate traffic calming features to reduce automobile speeds for safe and enjoyable walking and bicycling, as well as strict parking management to conserve the amount of land traditionally devoted to vehicle storage. TODs offer the added benefit of focusing on transit access for greater regional accessibility. Studies suggest that these high-density, mixed-use designs reduce automobile dependence (Cervero and Gorham 1995; Ewing 1995) and, therefore, the congestion and pollution associated with it. Table 8.2 indicates the impact of the design elements on vehicle travel.

Among the obstacles to New Urbanism and other smart growth approaches is the perceived risk of investment that financiers associate with the multiuse nature of such designs: developers understandably

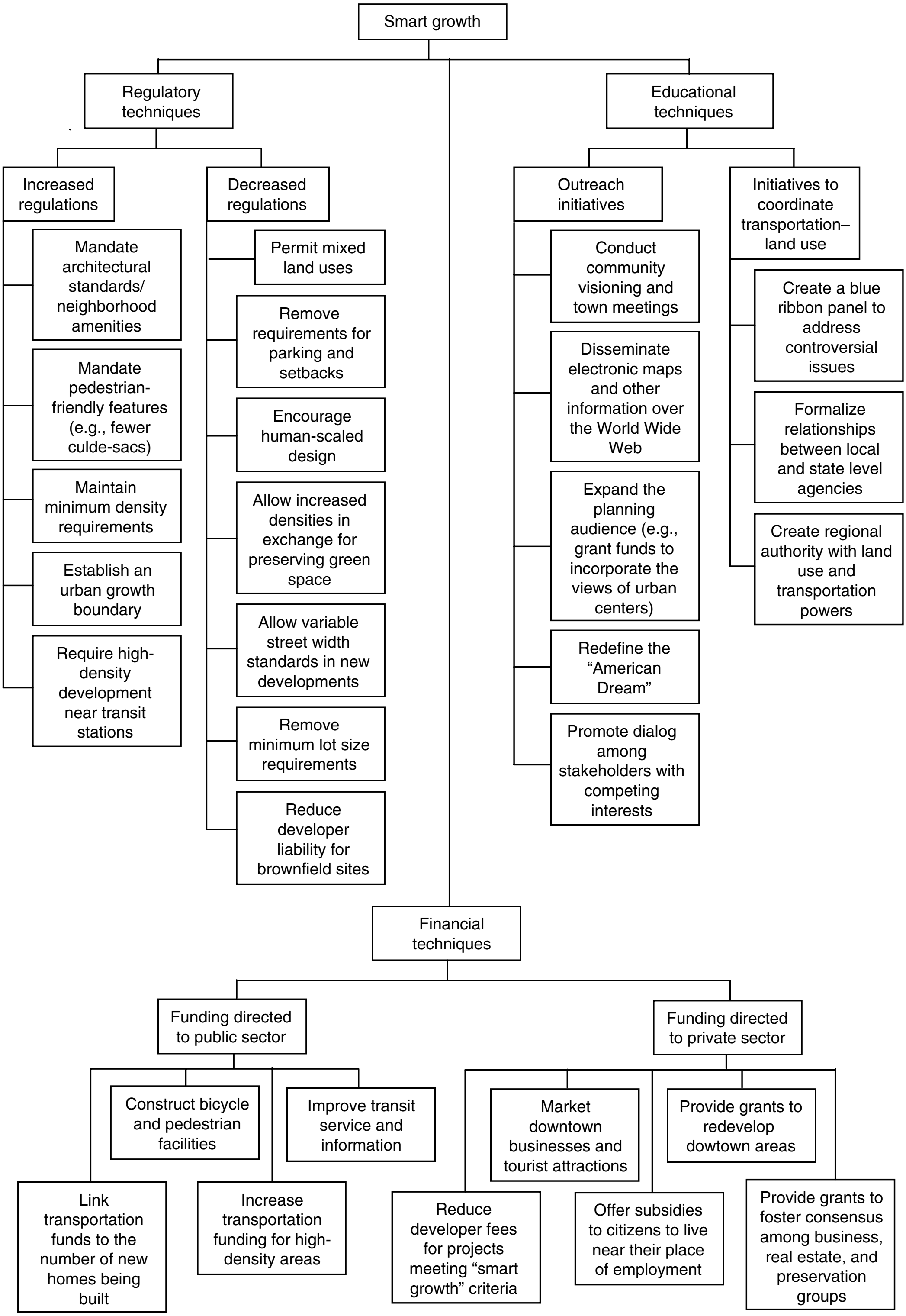

**FIGURE 8.2** Emphasis areas for smart growth techniques. (From Miller, J. S., and Hoel, L. A., The “smart growth” debate: Best practices for urban transportation planning, pp. 1–24, 2002.)

10. Narrow streets
9. Traffic volumes
8. Sidewalks
7. Street trees
6. Interconnected streets

5. On-street parking
4. Lower traffic speeds
3. Mixed land use
2. Buildings fronting the street
1. Small block size

**FIGURE 8.3** Top 10 walkability factors. (From Hall, R., Walkable thoroughfares through balanced design. Presentation at The Nuts & Bolts of Traditional Neighborhood Development Conference, Richmond, VA, 2005.)

want evidence that a new design concept will produce a high return on their investment. While a public–private partnership would help to dissipate the risk, these are frequently difficult to form and/or work within. Moreover, the cost of untouched land (greenfields) is often lower than land available for redevelopment (brownfields) that is usually located in infill areas between suburbs and central business districts. Brownfield redevelopment frequently carries with it the condition that the developer upgrade the infrastructure serving the area and/or assume responsibility for any known or unknown liabilities on the property, which can ultimately become a very expensive contingency. Finally, outdated zoning ordinances that prohibit the mixing of land uses and/or high-density development are another existing barrier to new urbanist designs (Farris 2001).

## 8.3 Alternative Transportation: Mass Transit

The efficiency of mass-transit service typically decreases with the density of land uses. However, density is not the single factor determining the success or failure of a transit system. Vuchic (1999) notes the success of the transit networks in spread-out areas of San Francisco, Washington, Montreal, Calgary, and particularly the suburbs of Philadelphia (with a lower population density than that of Los Angeles: 3500 people per square mile). Many planners and architects suggest a "hierarchy" of modes rather than the single mode system that dominates most areas: at the base is a network of bicycle- and pedestrian-friendly streets that support the local bus system, which in turn feeds a regional transit network. As each component relies on the others, their integration is essential for transit's success (Calthorpe and Fulton 2001). Furthermore, "the balance between car and transit use in central cities is strongly influenced by the character of the area (its physical design, organization of space, and types of development) and by the relative convenience and attractiveness of the two systems" (Vuchic 1999).

**TABLE 8.2** Travel Impacts of Land use Design Features

| Design Feature | Reduced Vehicle Travel (%) |
|---|---|
| Residential development around transit centers | 10 |
| Commercial development around transit centers | 15 |
| Residential development along transit corridor | 5 |
| Commercial development along transit corridor | 7 |
| Residential mixed-use development around transit centers | 15 |
| Commercial mixed-use development around transit centers | 20 |
| Residential mixed-use development along transit corridors | 7 |
| Commercial mixed-use development along transit corridors | 10 |
| Residential mixed-use development | 5 |
| Commercial mixed-use development | 7 |

*Source*: From Victoria Transport Policy Institute (VTPI), In *Transportation Demand Management Encyclopedia*, 2005. http://www.vtpi.org/tdm/tdm45.htm

Several different types of transit exist to serve the needs of the public. “Demand response” describes the paratransit mode, by which a passenger calls a dispatcher who sends the transit vehicle (a shuttle bus or taxi) to the passenger’s door and delivers her to her destination. Commuter rail denotes regional rail operating between a city and its suburban areas; light rail implies one or two cars using overhead electricity as a power source and operating within a city, often sharing the streets with automobiles; heavy rail operates at high speeds within a separate right-of-way. Bus rapid transit (BRT) is gaining popularity as a system that grants buses their own right-of-way so that they do not get caught in traffic congestion. BRT operates parallel to the street, such as in the median between travel lanes or in an exclusive bus-only lane (see Figure 8.4), and depending on the system, may also get prioritization at traffic signals so that upon approach, the light turns green and the bus will not have to wait at a red light. Table 8.3 summarizes the characteristics of each mode. Table 8.4 illustrates what percentages of the transit fleets use alternative fuels (i.e., fuels other than the conventionally used gasoline).

The factors that determine what mode and what technology are best for a given transit system include:

- The availability of a separate right-of-way
- The distance between/frequency of stops (i.e., will it be regional, express or local service?)
- The density of the surrounding area (to determine at what speeds the vehicle can safely travel)
- Expected passenger volumes
- Size of the city being served

A separate right-of-way is not dependent on the existing conditions of the street network and provides great reliability (since there are no traffice congestion delays), high speed, short trip times, and overall convenience for passengers.

The potential of mass transit to conserve energy is a large, untapped resource. Table 8.5 illustrates how much fuel could be saved by one person switching to mass transit for their daily commute to work. The reason for mass transit’s high efficiency is its energy intensity, which is a result of the load factor of each vehicle. Table 8.6 provides passenger travel and energy use data for 2002, while Figure 8.5 provides the transit mode split on a passenger-mile basis (i.e., the distribution of travel on each mode per passenger per mile). Mass transit’s efficiency could certainly be much higher compared to automobiles if more passengers used it and increased its load factor (Greene and Schafer 2003).

**FIGURE 8.4** BRT photo. (From U.S. General Accounting Office (GAO), *Mass Transit: Bus Rapid Transit Shows Promise*, GAO-01-984, Washington, DC, 2001.)

**TABLE 8.3** Summary of Transit Mode Characteristics

| Mode | Vehicle | Fuel Options | Right-of-way | Notes |
|---|---|---|---|---|
| *Technologies currently in use* | | | | |
| Bus | 30- to 70-passenger bus | Gasoline, diesel, hybrid, battery, alternative fuel (e.g., natural gas, ethanol, etc.) | Existing street network | Can be caught in traffic congestion, potentially making service slow and unreliable<br>Flexible routes can be adjusted as needed because travel medium is the existing street network |
| Bus rapid transit (BRT) | Conventional or guided buses | Gasoline, diesel, hybrid, battery, alternative fuel (e.g., natural gas, ethanol, etc.) | Separate from street, guideway, or exclusive “bus only”/high occupancy vehicle (HOV) lane | Generally has lower capital costs per mile than LRT (U.S. General Accounting Office 2001)<br>Often combined with intelligent transportation systems for fast fare collection and traffic prioritization |
| Light rail (LRT) | One to two rail cars | Overhead electricity | Existing street network, elevated railway, subway, or at-grade track system (separate from street) | Also known as trolleys or streetcars<br>Lower construction costs than conventional rail systems<br>High-design flexibility because of many travel medium options<br>Maximum speed: 65 mph |
| Metro/rapid transit system/heavy rail | Train | Electricity | Subway, elevated railway, or at-grade track system | Has very high passenger-carrying capacities and can operate at high speeds |
| Commuter/regional rail | Train | Electricity or diesel locomotive | Track system | Has very high passenger-carrying capacities and can operate at high speeds |
| *Advanced technologies* | | | | |
| Monorail | Train | Electricity | Single rail, beam, or tube | Example: Seattle Center Monorail |
| Magnetic Levitation (MagLev) | Train | Electricity | Magnetic guideway | Uses magnetism to lift and propel train over tracks<br>No wheels or moving parts; therefore, no friction<br>Can operate at 300+ mph<br>Still in research stage in most areas |

**TABLE 8.4** Alternative Power Vehicles by Mode, 2005

| Mode | Percent Using Alternative Power |
|---|---|
| Bus | 16.0 |
| Commuter rail | 47.8 |
| Commuter rail locomotive | 31.2 |
| Demand response | 4.9 |
| Ferryboat | 41.5 |
| Heavy rail | 100.0 |
| Jitney | 0.0 |
| Light rail | 100.0 |
| Other rail | 74.9 |
| Trolleybus | 100.0 |
| Vanpool | 0.8 |

*Source*: From Danchenko, D., *Public Transportation Fact Book*, American Public Transportation Association, Washington, DC, 2005.

## 8.4 Freight

The movement of goods in the U.S. is increasing. On an average day in 1993, 37 million tons of goods valued at $20 billion traveled 10 billion ton-miles; in 2002, those numbers rose to 43 million tons of goods valued at $29 billion moving almost 12 billion ton-miles (U.S. Department of Transportation/ Bureau of Transportation Statistics 2005a, 2005b). Freight is typically transported by air, truck, rail, pipeline, water, or any multimodal combination of these; the energy use and intensities of the modes are shown in Table 8.7 and Table 8.8. In 2002, the average value per ton shipped by air was $75,000, followed by truck at $725 and rail at $205. The U.S. DOT notes that, as value per ton rises, shipment sizes are likely to shrink to save costs: "shipments weighing less than 50,000 pounds (average payload of a typical truck) grew twice as fast (28%), measured by weight, than those weighing more than 50,000 pounds (13%) between 1993 and 2002, reflecting growth in smaller sized just-in-time deliveries" (U.S. Department of Transportation/Bureau of Transportation Statistics 2005a). Air is increasingly chosen for its timely deliveries, and air-freight shipments nearly doubled between 1993 and 2002 to $770 billion. As air shipments increase, so do truck shipments in order to fill the intermodal gap and deliver goods from their origin to the airport and from the airport to their destination. Trucking is by far the most widely used freight mode (Figure 8.6), increasing its ton-miles 44.4% between 1993 and 2002. For other shipments such as perishables and time-sensitive goods that need to travel very long distances (Figure 8.7), rail is used to ship low value-per-ton goods like coal, ores, and grains. It therefore has a relatively low share by value compared to its ton-miles,

**TABLE 8.5** Examples of Fuel Savings to a Person Commuting to Work on Public Transportation

| Length of Trip (miles) | Miles Traveled per Year (Based on 472 Trips per Year) | Annual Fuel Savings (gallons) Based on the Following Personal Vehicle Fuel Efficiencies | | | | | |
|---|---|---|---|---|---|---|---|
| | | 15 mpg | 20 mpg | 25 mpg | 30 mpg | 35 mpg | 40 mpg |
| 2 | 944 | 62.9 | 47.2 | 37.8 | 31.5 | 27.0 | 23.6 |
| 5 | 2,360 | 157.3 | 118.0 | 94.4 | 78.7 | 67.4 | 59.0 |
| 10 | 4,720 | 314.7 | 236.0 | 188.8 | 157.3 | 134.9 | 118.0 |
| 20 | 9,440 | 629.3 | 472.0 | 377.6 | 314.7 | 269.7 | 236.0 |
| 30 | 14,160 | 944.0 | 708.0 | 566.4 | 472.0 | 404.6 | 354.0 |
| 40 | 18,880 | 1,258.7 | 944.0 | 755.2 | 629.3 | 539.4 | 472.0 |
| 50 | 23,600 | 1,573.3 | 1,180.0 | 944.0 | 786.7 | 674.3 | 590.0 |
| 60 | 28,320 | 1,888.0 | 1,416.0 | 1,132.8 | 944.0 | 809.1 | 708.0 |

*Source*: From Danchenko, D., *Public Transportation Fact Book*, American Public Transportation Association, Washington, DC, 2005.

**TABLE 8.6** Passenger Travel and Energy Use, 2002

| | Number of Vehicles (Thousands) | Vehicle-miles (Millions) | Passenger-miles (Millions) | Load Factor (Persons/Vehicle) | Energy Intensities (Btu per Vehicle-mile) | Energy Intensities (Btu per Passenger-mile) | Energy Use (Trillion Btu) |
|---|---|---|---|---|---|---|---|
| Automobiles | 135,920.7 | 1,658,640 | 2,604,065 | 1.57 | 5,623 | 3,581 | 9,325.9 |
| Personal trucks | 65,268.2 | 698,324 | 1,201,117 | 1.72 | 6,978 | 4,057 | 4,872.7 |
| Motorcycles | 5,004.2 | 9,553 | 10,508 | 1.22 | 2,502 | 2,274 | 23.9 |
| Demand Response | 34.7 | 803 | 853 | 1.1 | 14,449 | 13,642 | 11.6 |
| Vanpool | 6.0 | 77 | 483 | 6.3 | 8,568 | 1,362 | 0.7 |
| Buses | [a] | [a] | [a] | [a] | [a] | [a] | 191.6 |
| Transit | 76.8 | 2,425 | 22,029 | 9.1 | 37,492 | 4,127 | 90.0 |
| Intercity[b] | [a] | [a] | [a] | [a] | [a] | [a] | 29.2 |
| School[b] | 617.1 | [a] | [a] | [a] | [a] | [a] | 71.5 |
| Air | [a] | [a] | [a] | [a] | [a] | [a] | 2,212.9 |
| Certified route[c] | [a] | 5,841 | 559,374 | 95.8 | 354,631 | 3,703 | 2,071.4 |
| General aviation | 211.2 | [a] | [a] | [a] | [a] | [a] | 141.5 |
| Recreational boats | 12,409.7 | [a] | [a] | [a] | [a] | [a] | 187.2 |
| Rail | 18.2 | 1,345 | 29,913 | 22.2 | 74,944 | 3,370 | 100.8 |
| Intercity[d] | 0.4 | 379 | 5,314 | 14.0 | 67,810 | 4,830 | 25.7 |
| Transit[e] | 12.5 | 682 | 15,095 | 22.1 | 72,287 | 3,268 | 49.3 |
| Commuter | 5.3 | 284 | 9,504 | 33.5 | 90,845 | 2,714 | 25.8 |

[a] Data are not available.

[b] Energy use is estimated.

[c] Includes domestic scheduled services and ½ of international scheduled services. These energy intensities may be inflated because all energy use is attributed to passengers; cargo energy use is not taken into account.

[d] Amtrak only.

[e] Light and heavy rail.

*Source*: From Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.

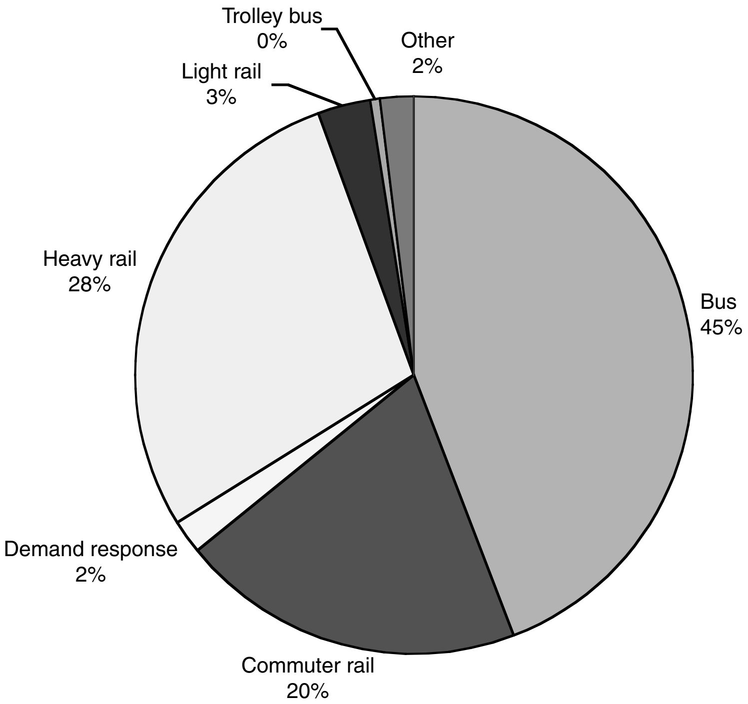

**FIGURE 8.5** Transit mode split for 2003. (From Danchenko, D., *Public Transportation Fact Book*, American Public Transportation Association, Washington, DC, 2005. http://www.apta.com/research/stats/factbook/index.cfm)

which increased 33.8% between 1993 and 2002. U.S. pipelines transport crude oil and petroleum products around the nation, thereby playing a role not only in the movement of transportation fuel as freight, but also in supplying fuel for other transportation modes. In 2002, pipelines moved 750 billion ton-miles of crude oil and petroleum products. Water transportation modes are classified by shallow-draft and

**TABLE 8.7** 2002 Transportation Energy Use by Mode

| | | Trillion Btu | Thousand Barrels per Day Crude Oil Equivalent |
|---|---|---|---|
| Medium/heavy trucks | | 5,026.8 | 2,397.7 |
| Air | | 2,212.9 | 1,071.1 |
| | General aviation | 141.5 | 70.2 |
| | Domestic air carriers | 1,734.5 | 838.1 |
| | International air | 336.9 | 162.8 |
| Water | | 1,184.8 | 541.1 |
| | Freight | 997.6 | 444.6 |
| | Recreational | 187.2 | 96.5 |
| Pipeline | | 935.4 | 12.8 |
| Rail | | 621.0 | 259.9 |
| | Freight (class I) | 520.3 | 244.7 |
| | Passenger | 100.7 | 15.2 |
| | Transit | 49.3 | 1.9 |
| | Commuter | 25.8 | 5.4 |
| | Intercity | 25.6 | 7.9 |

*Source*: From Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.

**TABLE 8.8** 2002 Energy Intensities of Freight Modes

| | |
|---|---|
| Heavy single unit and combination trucks | 23,432 Btu per vehicle-mile |
| Class I freight railroad | 15,003 Btu per freight car-mile |
| | 345 Btu per ton-mile |
| Domestic waterborne commerce | 471 Btu per ton-mile |

*Source*: From Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.

deep-draft vessels: shallow-draft vessels operate on rivers, canals, harbors, the Great Lakes, the Saint Lawrence Seaway, the Intracoastal Waterway, the Inside Passage to Alaska, major bays and inlets, and in the ocean along the shoreline; deep-draft vessels operate in the open ocean. Water's domestic share of freight has declined since 1982, but its international share has increased to almost 80% of all U.S. international freight. The shares of multimodal freight include parcel, postal, and courier services that since 1993 have grown heavily to 11.8% of all U.S. freight shipments and average $39,000 per ton (the overall multimodal

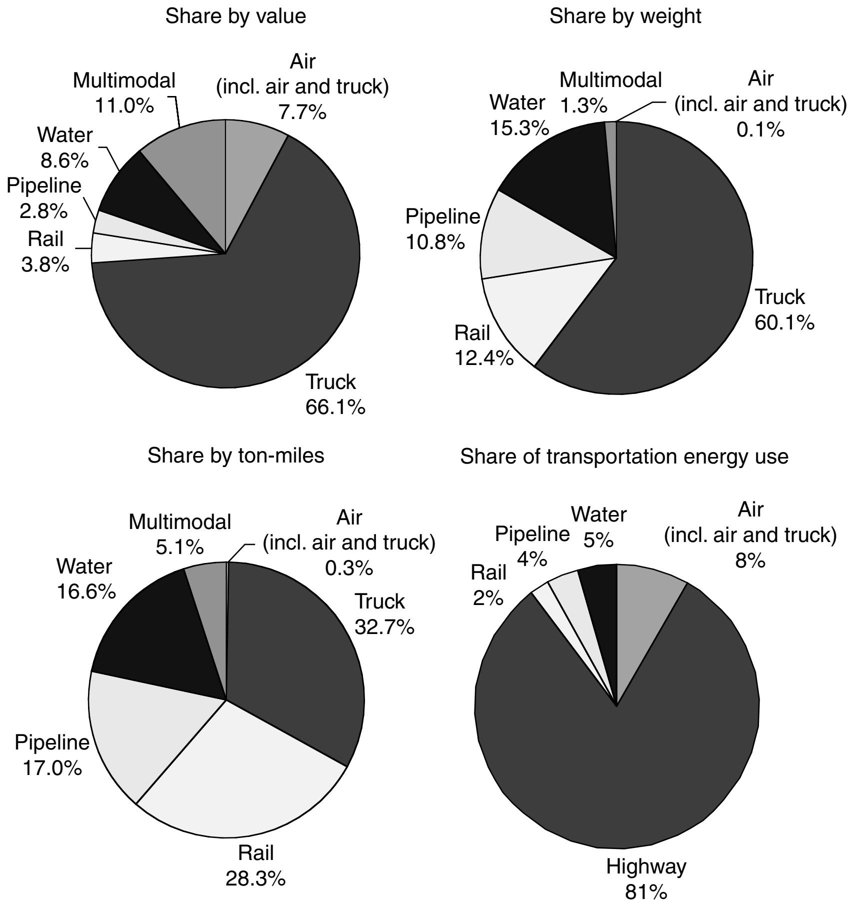

**FIGURE 8.6** Shares of commercial U.S. freight activity in 2002. Transportation energy share data reflects all transportation modes, not just freight. (From U.S. Department of Transportation/Bureau of Transportation Statistics, Freight, 2005, http://www.bts.gov/programs/freight_transportation/html/more_freight.html; Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.)

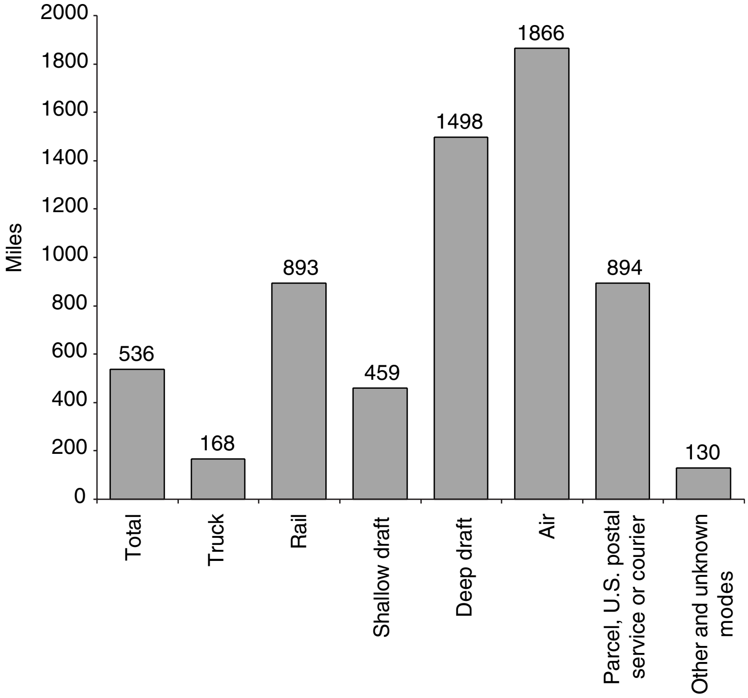

**FIGURE 8.7** Average miles per shipment by mode in 2002. (From U.S. Department of Transportation/Bureau of Transportation Statistics, *2002 Commodity Flow Survey, United States*, 2004. http://www.bts.gov/publications/commodity_flow_survey/2002/united_states_final/)

average is $5000 per ton). The truck–rail combination is the most widely used multimodal combination (U.S. Department of Transportation/Bureau of Transportation Statistics 2004, 2005a).

Table 8.9 illustrates the top commodities shipped in 2002. The U.S. Commodity Flow Survey notes that pharmaceutical shipments are among the fastest growing commodities and hold the highest value per ton at almost $19,000, whereas gravel and crushed stone are the lowest at $7 (U.S. Department of Transportation/Bureau of Transportation Statistics 2004).

**TABLE 8.9** Top Three Commodities Shipped in 2002 by Value, Weight, and Ton-Mile

| Top Three Commodities | Total | Percent of Total |
|---|---|---|
| *Shipped by value* | | |
| Electronic, electrical, and office equipment | $948 billion | 11.2 |
| Mixed freight (includes supplies and food for restaurants, grocery and convenience stores; hardware and plumbing supplies, office supplies, and miscellaneous) | $858 billion | 10.1 |
| Motorized and other vehicles (including parts) | $736 billion | 8.7 |
| *Shipped by weight* | | |
| Gravel and crushed stone | 1775 million tons | 15.3 |
| Coal | 1255 million tons | 10.8 |
| Nonmetallic mineral products | 910 million tons | 7.9 |
| *Shipped by ton-mile* | | |
| Coal | 562 billion ton-miles | 17.6 |
| Cereal grains | 264 billion ton-miles | 8.2 |
| Basic chemicals | 174 billion ton-miles | 5.4 |

*Source*: From U.S. Department of Transportation/Bureau of Transportation Statistics, 2002 Commodity Flow Survey, United States, 2004. http://www.bts.gov/publications/commodity_flow_survey/2002/united_states_final/

Within freight, long-haul trucks have a vast potential for energy conservation. Trucks used 3653 trillion Btu in 2002 and have an energy intensity of 3476 Btu/ton-mile (Davis and Diegel 2004). Although heavy-duty trucks are equipped with turbo-charged, direct-injection diesel engines that are the most efficient internal-combustion engine (ICE) available with approximately 46% peak thermal efficiency (Greene and Schafer 2003), long-haul trucks consume more than 800 million gallons of fuel per year just idling. It is estimated that, on average, a tractor-trailer spends 6 h per day idling to heat and cool the sleeper cabs, keep the fuel warm, and eliminate the need for cold starts of the engine. While cab heaters, auxiliary power units, and truck-stop electrification could meet these needs with much greater efficiency, economics, regulatory legislation, and driver behavior are barriers. For example, there is concern that a truck's engine will be difficult to start after being shutdown all night, as well as the fact that the hum of the engine masks exterior noises that would otherwise disrupt the driver's sleep (Stodolsky, Gaines, and Vyas 2000; Sharke 2005).

Increases in the efficiency of air travel are expected to come through technological improvements in engine efficiency and aerodynamics (Greene and Schafer 2003). The efficiency of rail and water transport can be improved by advances in diesel engine technology, which powers nearly all locomotives and some ships, barges, and ferries. All modes (with the exception of the pipeline) can reduce consumption through improved aerodynamic designs (e.g., ship hulls), reduced friction (e.g., between moving parts), and weight reductions.

## 8.5 Motor Vehicles: Tank-to-Wheel Technologies

### 8.5.1 The Well-to-Wheel Efficiency Analysis

It is essential that any discussion of vehicle efficiency include the well-to-wheel analysis, shown in Figure 8.8. This section focuses on vehicle engines and their operational—or "tank-to-wheel"—efficiency (i.e., how efficiently the vehicle converts the fuel in its tank to energy to rotate its wheels and move the vehicle). Section 8.5 on transportation fuels will consider the other half of the well-to-wheel cycle, specifically, the well-to-tank portion of the cycle that examines the efficiency of obtaining a feedstock, refining it to a fuel fit for engine use, and distributing that fuel to the vehicles.

### 8.5.2 Background: Conventional Vehicles

In 2003, 228 million light vehicles and trucks were registered in the U.S.; since 1998, there has been an average increase in these registrations of 2% per year. If this trend continues, there will be 353 million light vehicles registered by 2025 (U.S. Department of Transportation/Bureau of Transportation Statistics 2005b). These vehicles accounted for 5,203,140 U.S. passenger-miles traveled, with 90% by highway.

Given these figures, the nation's dependence on oil is not surprising. The 1970s gasoline crisis created by OPEC's restriction of oil production prompted the federal government to regulate fuel consumption

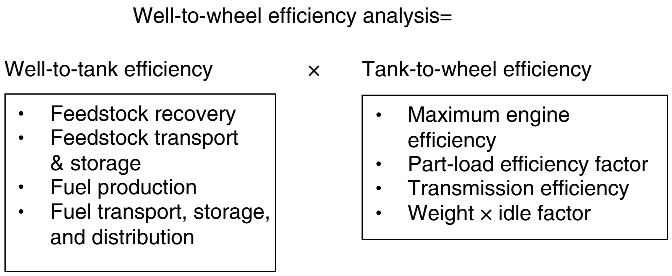

**FIGURE 8.8** Well-to-wheel efficiency analysis. (From Kreith, F., West, R. E., and Isler, B., *Transportation Quarterly*, 56(1), 51–73, 2002a.)

**TABLE 8.10** Automobile CAFE Standards Versus Sales-Weighted Fuel Economy Estimates, 1978–2004[a] (mpg)

| Model Year[b] | CAFE Standards | CAFE Estimates[c]: Autos and Light Trucks Combined |
|---|---|---|
| 1978 | 18.0 | 19.9 |
| 1979 | 19.0 | 20.1 |
| 1980 | 20.0 | 23.1 |
| 1981 | 22.0 | 24.6 |
| 1982 | 24.0 | 25.1 |
| 1983 | 26.0 | 24.8 |
| 1984 | 27.0 | 25.0 |
| 1985 | 27.5 | 25.4 |
| 1986 | 26.0 | 25.9 |
| 1987 | 26.0 | 26.2 |
| 1988 | 26.0 | 26.0 |
| 1989 | 26.5 | 25.6 |
| 1990 | 27.5 | 25.4 |
| 1991 | 27.5 | 25.6 |
| 1992 | 27.5 | 25.1 |
| 1993 | 27.5 | 25.2 |
| 1994 | 27.5 | 24.7 |
| 1995 | 27.5 | 24.9 |
| 1996 | 27.5 | 24.9 |
| 1997 | 27.5 | 24.6 |
| 1998 | 27.5 | 24.7 |
| 1999 | 27.5 | 24.5 |
| 2000 | 27.5 | 24.8 |
| 2001 | 27.5 | 24.5 |
| 2002 | 27.5 | 24.7 |
| 2003 | 27.5 | 25.0 |
| 2004 | 27.5 | 24.7 |

[a] Only vehicles with at least 75% domestic content can be counted in the average domestic fuel economy for a manufacturer.

[b] Model year as determined by the manufacturer on a vehicle by vehicle basis.

[c] All CAFE calculations are sales weighted.

*Source*: From Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.

by lowering the national speed limit to 55 mph and by legislating via the U.S. Energy Policy and Conservation Act of 1975 that automakers increase vehicle mileage by creating corporate average fuel economy (CAFE) standards. It has been suggested that it takes 15 years or more for an increase in fuel economy to be reflected in the global fleet due to market penetration, so any immediate advances take a while to make an impact (Greene and Schafer 2003). Table 8.10 provides the average estimated fuel economy of vehicles between 1978 and 2004. The data show that the CAFE standards have not changed since 1990, reflecting the supply-side approach to transportation management taken by the federal government. CAFE estimates are weighted by sales and therefore illustrate the increase in sales of light trucks (i.e., sport utility vehicles (SUVs), minivans, and pickup trucks) shown in Table 8.11, the share of which has increased from 20% in 1976 to over half of total light vehicle sales today. Reducing vehicle weight, aerodynamic drag, and rolling resistance are basic areas (other than the engine) to target when attempting to improve fuel economy[1]: large SUVs and minivans are designed from the opposite end of the spectrum with their heavy weight, high and wide frontal cross-sections, and large tires. Fuel economy projections to 2025 from the Energy Information Administration predict that:

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[1] It is suggested that a 10% reduction in weight on an average production vehicle can result in a 6% increase in fuel economy; a 10% reduction in aerodynamic drag can improve fuel economy by 3%; and a 10% reduction in rolling resistance can result in an increase in fuel economy of 2% (Office of Technology Assessment 1995; Bosch 1996).

**TABLE 8.11** Light Vehicle Market Shares by Size Class, Sales Periods[a] 1976–2003

| Sales Period[a] | 1976 | 1980 | 1985 | 1990 | 1995 | 2000 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|
| Mini-compact | 0.0% | 3.8% | 0.3% | 0.6% | 0.3% | 0.1% | 0.3% | 0.5% |
| Sub-compact | 21.7% | 30.4% | 15.7% | 14.8% | 10.4% | 10.4% | 3.7% | 2.8% |
| Compact | 23.5% | 5.3% | 23.2% | 23.0% | 22.4% | 13.9% | 18.8% | 18.5% |
| Midsize | 15.0% | 27.2% | 20.5% | 18.3% | 17.0% | 19.4% | 17.2% | 16.1% |
| Large | 18.2% | 11.8% | 10.0% | 9.3% | 9.0% | 7.5% | 8.1% | 8.3% |
| Two-seater | 1.7% | 1.9% | 2.5% | 1.2% | 0.4% | 0.7% | 0.8% | 1.0% |
| Small pickup | 1.4% | 4.6% | 5.7% | 8.3% | 7.3% | 6.2% | 4.5% | 4.6% |
| Large pickup | 13.1% | 9.9% | 11.1% | 8.1% | 10.0% | 11.4% | 13.0% | 12.7% |
| Small van | 0.2% | 0.1% | 2.9% | 7.4% | 8.6% | 7.4% | 6.9% | 6.5% |
| Large van | 4.8% | 2.9% | 3.5% | 2.3% | 9.1% | 2.1% | 2.1% | 2.0% |
| Small utility | 0.0% | 0.5% | 2.9% | 2.9% | 3.5% | 4.4% | 5.2% | 5.2% |
| Medium utility | 0.4% | 1.3% | 1.2% | 3.2% | 7.3% | 12.5% | 14.3% | 16.5% |
| Large utility | 0.1% | 0.3% | 0.5% | 0.7% | 1.0% | 4.1% | 5.1% | 5.3% |
| Total light vehicles sold | 12,096,613 | 11,311,043 | 15,203,880 | 13,739,090 | 14,658,736 | 17,285,055 | 17,009,538 | 16,315,470 |
| Cars | 80.1% | 80.4% | 72.1% | 67.1% | 59.5% | 51.9% | 49.0% | 47.2% |
| Light trucks | 19.9% | 19.6% | 27.9% | 32.9% | 40.5% | 48.1% | 51.0% | 52.8% |

[a] Sales period is October 1 of the current year through September 30 of the next year.

*Source*: From Davis, S., and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.

"…in addition to increases in market penetration of advanced technologies, sales of hybrid and diesel vehicles will continue to increase. As a result, new car fuel economy in 2025 is projected to average 31.0 mpg, and new light truck fuel economy is projected to average 24.6 mpg—increases of 5.4% for cars and 14.1% for light trucks over the respective model year 2003 CAFE levels. Similar to historic trends, average engine power output is projected to increase to 215 horsepower for new cars sold in 2025 (26.3% higher than model year 2003) and 243 horsepower for new light trucks sold in 2025 (18.0% higher than model year 2003). Light truck sales are projected to account for 58.6% of new light-duty vehicle sales in 2025, and as a result the average fuel economy for all new light-duty vehicles sold is projected to increase by 7.2%, to 26.9 mpg in 2025." (U.S. Department of Energy/Energy Information Administration 2005)

The Energy Efficiency and Renewable Energy sector of the U.S. Department of Energy (DOE) offers suggestions for reducing gasoline consumption to improve vehicle mileage and efficiency. Table 8.12

**TABLE 8.12** U.S. Department of Energy Recommended Gasoline Saving Methods

| | Method | Estimated Fuel Economy Benefit |
|---|---|---|
| 1. | Avoid driving aggressively | 5%–33% |
| 2. | Observe speed limit | 7%–23% |
| 3. | Avoid keeping unnecessary items in vehicle/ remove excess weight | 1%–2% per 100 lbs. |
| 4. | Avoid excessive idling | NA |
| 5. | Use cruise control | NA |
| 6. | Use overdrive gears | NA |
| 7. | Keep engine properly tuned | 4%–40% |
| 8. | Check and replace air filters regularly | Up to 10% |
| 9. | Keep tires properly inflated | Up to 3% |
| 10. | Use vehicle's recommended grade of motor oil | 1%–2% |

*Source*: From U.S. Department of Energy/Energy Efficiency and Renewable Energy, Gas Mileage Tips, 2005e. http://www.fueleconomy.gov/feg/drive.shtml

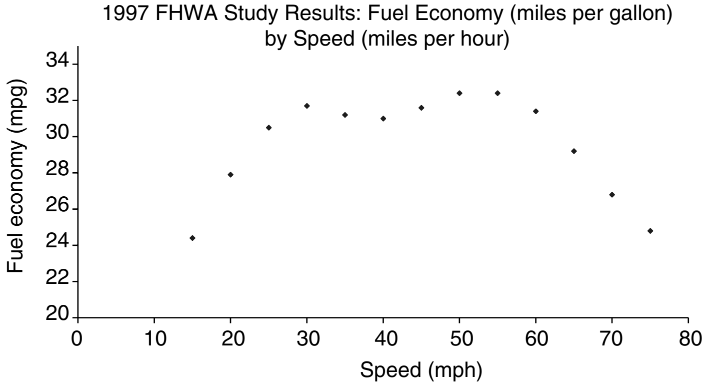

**FIGURE 8.9** Relationship of engine speed to fuel economy. (From Davis, S. and Diegel, S., *Transportation Energy Data Book*, Oak Ridge National Laboratory/U.S. Department of Energy, Oak Ridge, TN, 2004.)

summarizes these methods and the estimated fuel savings of each. Method 2 is illustrated by a 1997 FHWA study examining fuel economy by speed in which nine conventional vehicles were tested. The result (Figure 8.9) shows that mileage suffers at speeds over 55 mph, mainly due to pumping and mechanical friction losses, wind resistance, and the fact that complete gas exchange is difficult to achieve at high engine speeds.

### 8.5.3 Internal Combustion: Spark Ignition and Compression Ignition

The ICEs that power motor vehicles function on a four-stroke cycle as shown in Figure 8.10, consisting of the compression, power/expansion, exhaust, and intake strokes.

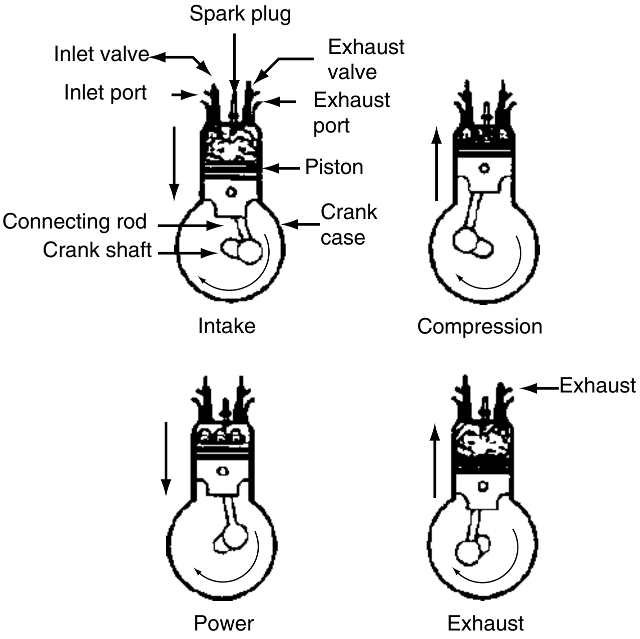

**FIGURE 8.10** The four-stroke cycle of an IC engine. (From Klett, D. E. and Afify, E. M., In *The CRC Handbook of Mechanical Engineering*, ed. F. Kreith and D. Y. Goswami, Taylor & Francis, Boca Raton, FL, 2005.)

The difference between spark ignition (typically gasoline) and compression ignition (typically diesel fuel) is that spark ignition (SI) engines operate on the Otto cycle and use an air–fuel mixture in the cylinder at the beginning of the cycle and ignite this mixture via a spark plug. A compression ignition (CI, or diesel) engine operates on the diesel cycle, which begins with air in the cylinder that is compressed to a temperature above that of the autoignition temperature of the fuel; the fuel is then injected into the chamber and ignites on contact with the high-temperature air (Lichty and MacCoull 1967).

The thermal efficiency of diesel engines is higher than that of spark ignition engines: 29.5% tank-to-wheel efficiency for diesel engines compared to 22.0% for SI engines[2] (Kreith, West, and Isler 2001). One estimate suggests that "replacing a gasoline engine with a diesel in a 3000 pound car could result in a 30- to 40-percent improvement in fuel efficiency and such an exchange in a sport utility vehicle could provide a similar improvement in the range of 40- to 50-percent" (DeGaspari 2005). The primary reason for the difference in efficiency is that the diesel engines have higher compression ratios (the ratio of the cylinder's volume when the piston is at bottom dead center to the volume at top dead center) than spark ignition engines. SI engines have compression ratios between 8:1 and 12:1, while CI engines operate with compression ratios between 20:1 and 24:1. However, these higher combustion temperatures cause greater $NO_x$ emissions from diesel engines (Bosch 1996).

Further reasons for the higher efficiency of diesel engines are that the engines are not throttled; they run lean and at lower revolutions per minute, and they burn the fuel more completely than SI engines. Although diesel engines usually have a higher initial cost than gasoline engines, diesel fuel tends to be less expensive than gasoline and it contains approximately 10% more energy per gallon than gasoline. These facts make diesels the choice for large engines such as those used in heavy equipment, large trucks, ships, train locomotives, and emergency power generators. In the past, poor emissions control and noise offset the efficiency of light-vehicle diesels, handicapping their popularity. But improvements in direct-injection, turbo-charging, and electronic controls are causing many consumers to reconsider diesels and to take advantage of their efficiency and torque.

These improvements have been so significant that in the spring of 2005, the Bush administration endorsed clean-diesel vehicles as part of its energy policy. Previously, diesels had only been popular in areas where gasoline is more heavily taxed than diesel fuel. A 2003 JD Power LMC forecast expects the global sales of light-diesel vehicles to increase from 12.5 million in 2003 to 27 million by 2015. The report notes a significant portion of this increase will be in North America, predicting that light diesels will secure 16% of new light-vehicle sales in 2015, compared to 4.5% in 2002 (JD Power LMC 2003). Provided that diesels can reduce their emissions to meet future standards, there is no reason why they should not become more popular in the market given their performance and efficiency.

A simpler version of the four-stroke cycle is the two-stroke that, unlike the four-stroke, does not require separate compression and expansion strokes to exhaust and intake gases; rather, the fresh air–fuel mixture enters the chamber at the end of the expansion stroke, while exhaust gases are forced out at the beginning of the compression stroke. This lighter and simpler SI engine is often used for motorcycles and mopeds; however, its less efficient gas exchange results in higher fuel consumption and greater hydrocarbon emissions. Two-stroke engines are frequently found in developing countries where motorized bicycles and rickshaws are popular modes of transportation.

Four sources of inefficiency in ICEs are: (1) the fact that combustion is not instantaneous, so the ideal cycle cannot be replicated; (2) mechanical friction losses (from the piston, crankshaft, and valves), particularly at high engine speeds; (3) aerodynamic frictional and pressure losses from air flow through the muffler and catalytic converter; (4) pumping losses due to throttling (in SI engines) (Office of Technology Assessment 1995). Therefore, opportunities for improved efficiency start in the actual combustion of the fuel in the chamber. Partial combustion occurs due to poor circulation of the air–fuel mixture in the chamber that is determined by the kinetic energy of the fuel spray, the thermal energy of the space, the combustion chamber shape, air flow, and utilization of partial combustion in a swirl chamber

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[2] Tank-to-wheel efficiency used by Kreith, West, and Isler (2001) is the peak brake engine efficiency × part-load efficiency factor × transmission efficiency × weight × idle factor.

(Bosch 1996). Direct injection uses combinations of these attributes to influence the turbulence within the combustion chamber to improve air and fuel mixing and thereby induce more complete combustion.

Further opportunities exist in gas exchange to ensure that the available chamber volume is filled with a fresh air–fuel mixture instead of old exhaust gases from the previous stroke cycle. Gas exchange in four-stroke engines is entirely dependent on valve timing to open and close the valves at the right instant for exhaust release and fresh air intake, and for combustion. Variable valve timing, made possible by the introduction of electronics into IC engines, has helped to drastically improve the efficiency of conventional SI and CI engines with its ability to precisely control the valves.

Bosch (1996) further suggests that efficiency may be improved through "selective interruption of the fuel supply to individual cylinders to allow the remaining cylinders to operate at higher efficiency levels with improved combustion and gas exchange. Valve deactivation provides further reductions in power loss by allowing the intake and exhaust valves for the deactivated cylinders to remain closed. Cylinder deactivation entails immobilizing the mechanical power transfer components in these resting cylinders for further increases in mechanical efficiency." However, these measures "are not yet ready for general series production."

One version of the SI engine that may become competitive with diesel engines' efficiency is the direct injection stratified charge (DISC) engine. Rather than premixing the air and fuel, the fuel is injected into the chamber and aimed at the spark plug. The DISC engine is almost completely unthrottled (thereby reducing pumping losses), uses variable valve timing, and has a higher compression ratio than conventional engines (estimated at 13) (Office of Technology Assessment 1995). It is estimated that the DISC engine may offer 15%–20% higher fuel economy than conventional gasoline engines (U.S. Department of Energy/Energy Efficiency and Renewable Energy 2005b). However, because the DISC engine has not been able to meet emissions standards, it is not yet available in the U.S.

## 8.5.4 Electric Vehicles

Electric vehicles (EVs) have three main components: the battery pack, the controller, and the electric motor. The controller links the battery pack and the motor, regulating the amount of energy provided to the motor depending on the demands communicated by the accelerator. A significant feature of EVs is regenerative braking, which recovers the energy from the momentum that would otherwise be wasted when slowing down. EVs have a tank-to-wheel efficiency of 82% (Electric Power Research Institute 2004).

An EV battery must have/be:

- Quick discharge and recharge capability
- A long life cycle
- Low cost
- Recyclable
- Safe
- High specific energy (i.e., energy per unit mass, watt-hours per pound or Wh/kg), so that the battery pack's weight will not restrict vehicle performance
- High energy density (energy per unit volume), so that the battery pack will not take up too much room in the vehicle
- High specific power, so that the EV's performance will be comparable to that of a conventional IC vehicle
- Ability to function in a range of extreme operating temperatures

A summary of viable EV battery types and their attributes is shown in Table 8.13. Zinc and aluminum air batteries, ultracapacitors, and flywheels are also under research as energy storage devices for EVs, although whether they can deliver on their promises of long life cycles and high specific energy ($>200$ Wh/kg) is not fully known (U.S. Department of Energy/Energy Efficiency and Renewable Energy 2005c).

**TABLE 8.13** Summary of Viable EV Batteries

| Battery Type | Life Cycle (80% DOD) | Cost ($/kWh) | Recyclable | Specific Energy (Wh/kg) | Energy Density (Wh/l) | Operating Temperature |
|---|---|---|---|---|---|---|
| Lead acid | 600–900 cycles[a] (85,000 miles[b]) | 150–200[3] | Yes[b] | 45–50[b] | 100–130[a] | Ambient[b] |
| Nickel cadmium (NiCad) | 700–1200 cycles[a] (100,000 miles[b]) | 300–500[3] | Yes[b] | 55[b] | 100–150[a] | NA |
| Nickel metal hydride (NiMH) | > 1200 cycles[c] (130,000–150,000 miles[c]) | 300–700[3] | Yes[b] | 63[c] | 150–200[a] | NA |
| Lithium ion (Li ion) | 400–1200 cycles[a] | 150–220[3] | NA | 100[c] | 100–200[a] | NA |
| USABC[d] | 1000 cycles | 100 | NA | 200 | 300 | −40 to +85°C |

[a] Data from Kreith, Potestio, and Kimbell (1999).

[b] Data from U.S. Department of Energy/Energy Efficiency and Renewable Energy (2005c).

[c] Data from Electric Power Research Institute (2004).

[d] U.S. Advanced Battery Consortium long-term goal for advanced batteries for EVs (U.S. Advanced Battery Consortium 1999).

Lawrence Berkeley National Laboratory notes that cost is the biggest barrier to battery technology: 1 kWh costs between $150 and $300 to store in an advanced battery, and an electric vehicle requires at least 30 kWh (Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division 2004). However, the popularity of cell phones, laptop computers, and other portable electronic devices has led to significant advances in battery technology. A recent report by the Electric Power Research Institute (EPRI) found that although past estimates of electric vehicle battery lifetimes were only about 6 years or 75,000 miles, 5-year-old test vehicles had already traveled over 100,000 miles "with no appreciable degradation in battery performance or vehicle range" (Electric Power Research Institute 2004). This finding is extremely significant as it means that the high cost of replacing the battery pack of an electric vehicle is no longer a market barrier if the battery pack lasts the lifetime of the vehicle. Original projections estimated that battery packs would have to be replaced at least once during an EV's lifetime, but the EPRI report says that "it is highly probable that (nickel metal hydride) batteries can meet 130,000–150,000 lifetime mileage," thereby making hybrid and electric vehicles cost-competitive with conventional gasoline vehicles over the vehicle's lifetime (see Table 8.14). The results of the EPRI study show that the long-term life cycle goal (1000 cycles at 80% depth of discharge (DOD)) of the United States Advanced Battery Consortium for advanced batteries for EVs—and perhaps the largest barrier to consumer acceptance—have been surpassed.

## 8.5.5 Hybrid Technologies

The introduction of the Toyota Prius and Honda Insight into the vehicle market in 2000 brought hybrid technology to the general public. The combination of a smaller ICE with an electric motor and battery

**TABLE 8.14** Battery Cost to Break-Even Net Present Value

| | Battery Price, $/kWh (at Which Net Present Values Are Equal After 10 Years, 117,000 miles) | |
|---|---|---|
| | Gasoline @ $1.75 per Gallon, EPRI | Gasoline @ $2.50 per Gallon, Our Recalculation of EPRI Values |
| Conventional vehicle | — | — |
| HEV 0 | $385 | $1135 |
| PHEV 20 | $316 | $1648 |

*Source*: From Kreith, F. and West, R. E., Personal communication, 2005.

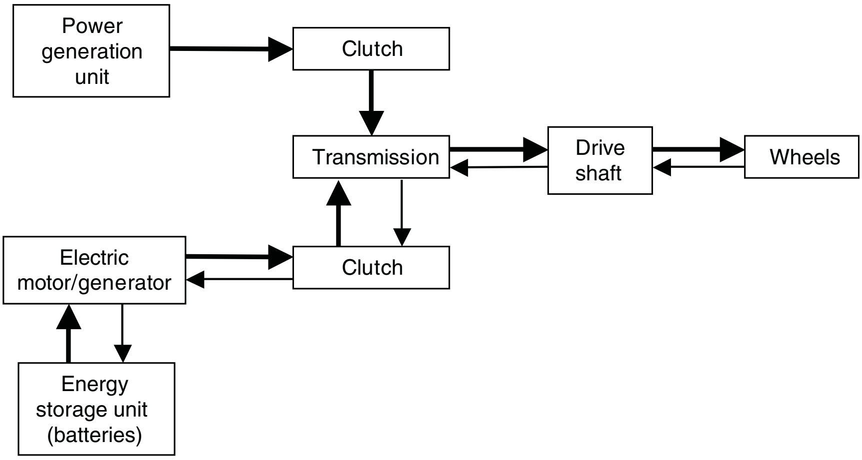


**FIGURE 8.11** Parallel hybrid–electric vehicle (HEV) schematic. (From Kreith, F., Potestio, D. S., and Kimbell, C., *Ground Transportation for the 21st Century*, National Conference of State Legislatures, Denver, CO, 1999.)

pack (typically nickel metal hydride) has proven very popular; potential buyers are placed on wait lists because demand exceeds supply for hybrid vehicles. Hybrid vehicles can be configured in series, with the ICE generating power for the electric motor that then powers the wheels, or in parallel, where both the ICE and the electric motor are directly connected to the transmission. Commercially available hybrid vehicles (HEVs) use the parallel configuration (Figure 8.11) because it does not require energy to be converted as many times as in the series configuration. Using a "power split device," a hybrid such as the Toyota Prius optimizes the "blend" of energy provided by the gasoline engine and the electric motor for maximum efficiency, even shutting off the gasoline engine and operating exclusively on the electric motor in situations that do not demand powerful acceleration, such as during idling or low-speed, stop-and-go driving (see Table 8.15). Table 8.16 compares four hybrids with two of the most popular conventional vehicles on the market: the Honda Accord (a sedan) and the Ford Explorer (a sport utility vehicle).

The fundamental reason that hybrid configurations are so efficient is that ICEs are most efficient near full loads, at which most vehicles rarely operate. The part-load efficiency factor is defined as the vehicle's average efficiency (averaged over a specified driving cycle) over its efficiency at full load. Because of the driving schedule on which most vehicles operate, the part-load efficiency factor of conventional vehicles and hybrids is less than 1, as schematically shown in Figure 8.12. Supplementing an ICE with an electric motor provides optimum efficiency by providing additional energy when needed, and gives the hybrid a higher part-load efficiency factor than conventional vehicles because at partial loads such as low speeds and stop-and-go driving, the electric motor can tap the battery for energy to power the vehicle. At high speeds, such as highway driving, the ICE is mainly used. Regenerative braking also helps hybrid efficiency,

**TABLE 8.15** Energy Optimization Schedule for Operation of a Toyota Prius

| Operation | Power Is Supplied by… | |
|---|---|---|
| | Gasoline Engine | Electric Motor |
| Low speeds | | ☼ |
| Heavy acceleration | ☼ | ☼ |
| Highway cruising | ☼ | ☼ |
| Deceleration/braking (i.e., regenerative braking) | | ☼ |

*Source*: From Toyota Motor Corporation, Hybrid Synergy Drive: Prius Demo, 2005b. http://www.toyota.com

**TABLE 8.16** Comparison of Hybrids and Conventional Gasoline Vehicles

| 2005 Model | Toyota Prius | Honda Insight | Honda Civic Hybrid | Honda Accord Hybrid | Honda Accord EX (Conventional) | Ford Explorer 4WD (Conventional) |
|---|---|---|---|---|---|---|
| Engine | 1.5-L, 4-cyl, CVT[a] | 1.0-L, 3-cyl, CVT | 1.3-L, 4-cyl, CVT | 3.0-L, 6-cyl, 5-speed automatic | 3.0-L, 6-cyl, 5-speed automatic | 4.0-L, 6-cyl, 5-speed automatic |
| Valves | 16 | 12 | 8 | 24 | 24 | 12 |
| Body/max. cargo capacity | 4-dr hatchback/16 $\text{ft.}^3$ | 2-dr hatchback/16 $\text{ft.}^3$ | 4-dr sedan/10 $\text{ft.}^3$ | 4-dr sedan/11 $\text{ft.}^3$ | 4-dr sedan/14 $\text{ft.}^3$ | 4-dr SUV/86 $\text{ft.}^3$ |
| EPA estimated mileage (mpg) | 60 city/51 hwy | 57 city/56 hwy | 48 city/47 hwy | 29 city/37 hwy | 21 city/30 hwy | 14 city/20 hwy |
| Gas tank capacity (gallons) | 11.9 | 10.6 | 13.2 | 17.1 | 17.1 | 22.5 |
| Range (miles per tank) | 714 city/607 hwy | 604 city/594 hwy | 634 city/620 hwy | 496 city/633 hwy | 359 city/513 hwy | 315 city/450 hwy |

[a] CVT, continuously variable transmission.

*Source*: From Toyota Motor Corporation, Vehicle Comparison, 2005a. http://www.toyota.com/toyotacomparator/displayComparator.do?toyotaModelCode=prius

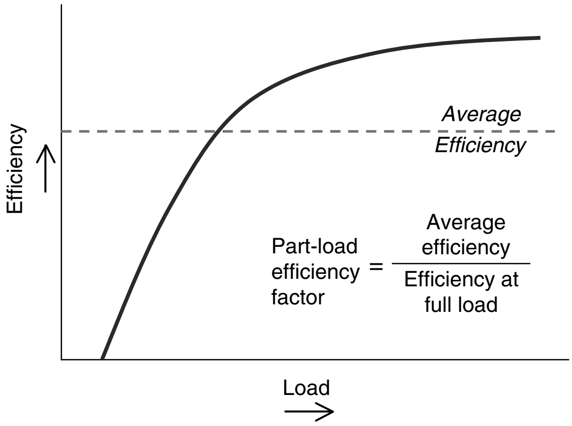


**FIGURE 8.12** Schematic of ICE efficiency curve.

as the forward momentum of the vehicle—which is normally wasted when braking in a conventional vehicle—is recovered and the energy is used to recharge the batteries. Different driving situations require different power sources as shown in Table 8.15, so hybrids can utilize a computer to manage energy sources in any given situation to optimize efficiency.

Aside from the hybrid technology currently on the market, there are more varieties of hybrids on the horizon. One such option is plug-in hybrids (PHEVs) that can reportedly achieve 100–180 mpg (based on a converted Toyota Prius model). The only difference in the configuration of a PHEV and an HEV is more batteries and the ability to be plugged into a standard household outlet to recharge the batteries. The excess battery power enables the PHEV to travel 20–60 miles on electricity alone, depending on the size of the battery pack (Carey 2005). A close examination of the well-to-tank portion of the efficiency analysis is necessary to evaluate the PHEV's efficiency because a large portion of the fuel consumed by the vehicle will be from electricity that typically has a low production efficiency (but which will be partially offset by load-leveling of the grid) (Kreith, West, and Isler 2001).

Hybrids were first introduced to the U.S. in 1999 with the Honda Insight, and the 2004 Toyota Prius received over 12,000 purchase requests before it was even available. In 2004, approximately 88,000 hybrids were sold, constituting 0.5% of total vehicle sales. Studies suggest that hybrid sales will plateau at about 3% around 2011 due to the higher price of hybrids and the increasing availability of high-efficiency gasoline and diesel engines (Greene, Duleep, and McManus 2004; Porretto 2005). Hybrid tank-to-wheel efficiency (using natural gas as the fuel for the ICE) is estimated to be 35.7% when the ICE is a spark-ignition engine and between 37.6% and 44.7% using various diesel configurations for the ICE (Kreith, West, and Isler 2001). It has been suggested that the long-term impact of current hybrid technology could raise the fleet fuel economy by about 10%, although this estimate clearly depends on the market penetration of hybrids into the global fleet (Greene, Duleep, and McManus 2004). More optimistic estimates project an increase in fuel economy up to 40% after 30 years (National Research Council 2004).

## 8.5.6 Fuel Cells

The simplest description of a fuel cell that it is an electrochemical device similar to a battery, except that a battery is recharged with electricity, whereas a fuel cell is refueled with hydrogen. There are several varieties of fuel cells, but the most promising option for transportation applications is the proton exchange membrane (PEM) fuel cell, mainly due to the fact that its operating temperature is lower than that of most other types of fuel cells and it has a high power density. The fuel cell is made up of an anode, a cathode, and an electrolyte that, in the case of the PEM fuel cell, is the proton exchange membrane.

When provided with pure hydrogen and oxygen from the air, the following chemical reactions take place:

$$\text{Anode}: \quad 2H_2 \rightarrow 4e^- + 4H^+$$

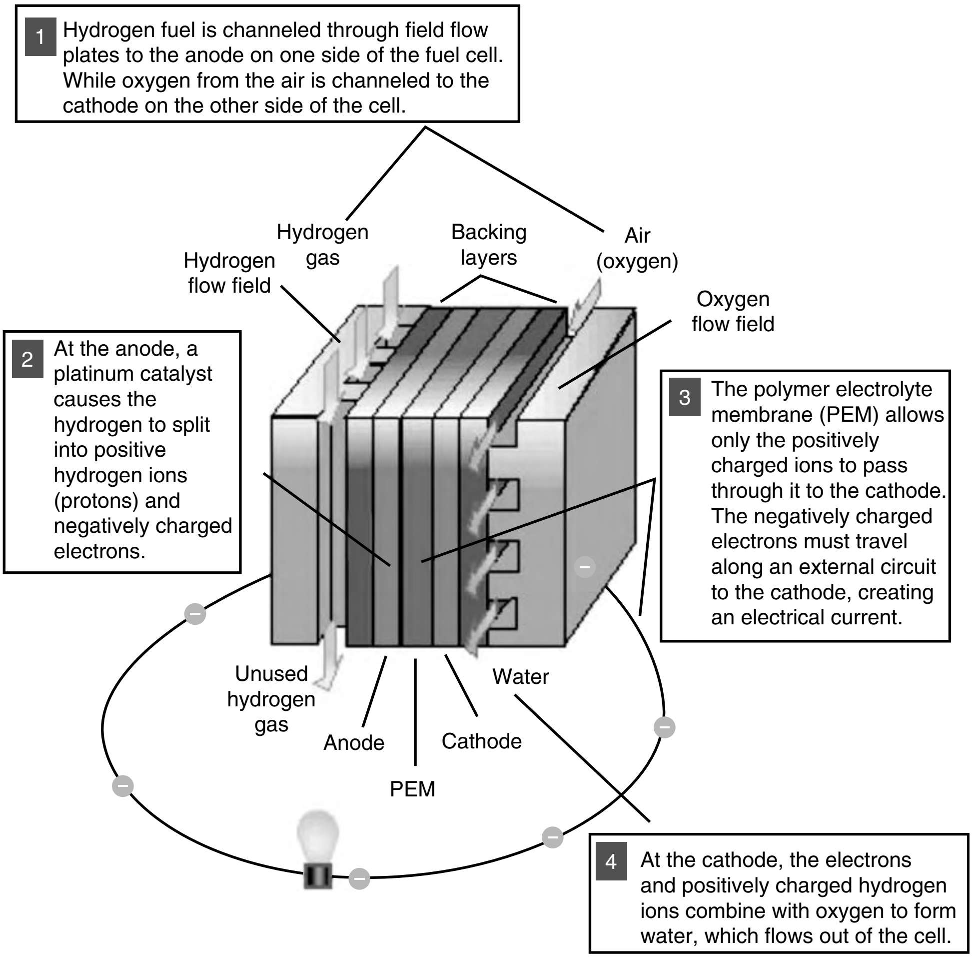
$$\text{Cathode}: \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$\text{Net reaction}: \quad 2H_2 + O_2 \rightarrow 2H_2O$$

The fuel cell provides energy by sending the electrons released from the hydrogen through an external circuit. The only by-product of hydrogen fuel cell operation is water (see Figure 8.13).

A fuel cell stack is several fuel cells bundled together, much like a battery pack in an EV. The part-load efficiency factor plays a very large part in the inherently high efficiency of a fuel cell stack. Whereas conventional and hybrid vehicles are more efficient near full loads, fuel cells are most efficient at part loads, giving them a part-load efficiency factor greater than 1 (see Figure 8.14).

For use in a vehicle, several additional components are necessary, such as an air compressor, cooling system, water management system, and hydrogen fuel supply system. Although onboard reformers were once considered a possible tool for converting a fuel such as methanol or gasoline to hydrogen, their cost,



1 Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell. While oxygen from the air is channeled to the cathode on the other side of the cell.

2 At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

3 The polymer electrolyte membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.

4 At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

**FIGURE 8.13** Proton exchange membrane fuel cell. (From U.S. Department of Energy/Energy Efficiency and Renewable Energy, Fuel Cell Vehicles, 2005d. http://www.fueleconomy.gov/feg/fuelcell.shtml)

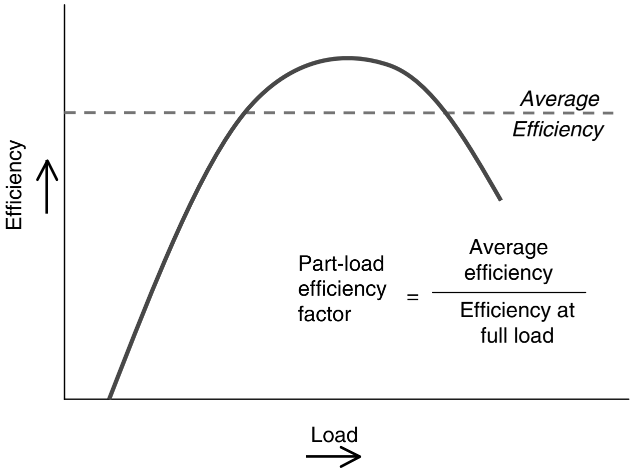


**FIGURE 8.14** Schematic of fuel cell efficiency curve.

complexity, increases in emissions, decreases in system efficiency, and safety concerns led all major automobile manufacturers to abandon this initiative by 2003 (National Research Council 2004). It has been estimated that the hydrogen fuel cell stack efficiency is between 40% and 50%, but that with the auxiliary systems needed to support the stack in a transportation application (directly supplied with hydrogen), the result is an overall system efficiency (tank-to-wheel) of between 35% and 40% (Kolke 1999; Kreith, West, and Isler 2001). Fuel cells can also be arranged in a hybrid configuration like conventional hybrids to optimize energy use by storing excess energy in a battery pack.

Several other obstacles lie in the path of mass-produced fuel cell vehicles, such as cost, fuel supply, storage, and safety. Much more research is required before fuel cells can be considered a candidate for a vehicle propulsion system: for transportation purposes, a fuel cell stack will need to be able to last 5000 h (translating to 150,000–200,000 miles) as well as be affordable. Current fuel cell stacks are very fragile, lasting only thousands of hours in the laboratory because they decay under operational pressures (Baard 2003). Moreover, the fuel cell is not the "green" technology that the tank-to-wheel operation makes it appear to be because of the energy required for and the pollution potentially created during hydrogen production (depending on production method). Until the obstacles with hydrogen production (see Section 8.6) are solved to make hydrogen safe and efficient as a fuel, it is not a feasible option as a transportation energy source for any type of propulsion system. Even if these obstacles are overcome, there is still the colossal feat of building a fueling infrastructure to distribute hydrogen to vehicles.

## 8.6 Transportation Fuels

Generating energy sources for the technologies discussed in Section 8.5 makes up most of the phases of the well-to-wheel efficiency analysis shown in Figure 8.8. Vehicle operations would not be possible without feedstock recovery, feedstock transport and storage, fuel production, and fuel transport, storage, and distribution. It is therefore imperative to consider what options are available for fuel sources before determining what technology is to be used for a mass-produced automobile propulsion system.

### 8.6.1 Feedstocks

Estimating when world oil supplies will peak is a difficult task that leads to a wide range of timeframes. Due to the many variables involved, such as market forces and technology, it is believed that world production of conventional oil will peak between year 2015 and 2030. Both "conventional" and "unconventional" feedstocks are available to supplement conventional oil production. According to Greene, Hopson, and Li (2004), "conventional oil includes liquid hydrocarbons of light and medium gravity and viscosity, occurring in porous and permeable reservoirs…unconventional oil comprises deposits of greater density than water (e.g., heavy oil), viscosities in excess of 10,000 cP (e.g., oil sands), or occurrences in tight formations (e.g., shale oil)." Although unconventional feedstocks for oil can be expensive and environmentally damaging to recover and refine, it is expected that they will be used as conventional supplies dwindle because the gasoline distribution infrastructure is already in place (Greene and Schafer 2003).

Coal, of which the U.S. has the world's largest reserves (26%) (U.S. Department of Energy/Energy Information Administration 2004), can be used as a feedstock for diesel fuel via the Fischer–Tropsch process. Coal can also be used to create a synthetic diesel fuel called dimethyl ether (DME), as well as methanol. Under ambient conditions, DME is a gas, but only mild pressure is required to liquefy it. Being a domestic fuel keeps coal relatively inexpensive and does not involve the national security concerns or energy dependence associated with foreign oil.

Natural gas (NG) is also abundant and relatively inexpensive, which, along with its versatility, make it an attractive feedstock for many fuels. It can be directly used in vehicles in its liquid form (LNG) or its compressed gaseous form (CNG). Like coal, it can be a feedstock to produce diesel fuel via the Fischer–Tropsch process. Currently, the most widely used feedstock for hydrogen is natural gas because of its low cost and abundance. Table 8.17 provides the well-to-tank efficiencies of several fuels using natural gas as the feedstock. Combining these results with the tank-to-wheel efficiencies described in Section 8.5 provides the total cycle efficiency (Table 8.18). The results indicate that of the fuels considered, CNG and diesel (created using NG via the Fischer–Tropsch process) are the most efficient to produce. The well-to-wheel results indicate that SI and CI hybrid configurations are more efficient than a fuel cell powered by hydrogen produced using NG as the feedstock. Similarly, a well-to-wheel energy and greenhouse gas emissions analysis at MIT found "no current basis for preferring either fuel cell or ICE hybrid power plants for midsize automobiles over the next 20 years or so. That conclusion applied even with optimistic assumptions about the pace of fuel cell development" (Weiss et al. 2003). Hydrogen as a fuel will only fulfill its implied environmental promises if it is produced via electrolysis of water using renewable or nuclear energy. If an efficient hydrogen production method is developed, there is still the difficulty of replacing the existing gasoline distribution infrastructure with a hydrogen one.

**TABLE 8.17** Fuel Production Efficiencies Using Natural Gas (NG) as Feedstock

| Fuel | NG Feedstock Production[a] | Conversion NG to Fuel | Fuel Storage, Transmission, and Distribution | Additional Compression[b] | Overall Efficiency of Fuel Production |
|---|---|---|---|---|---|
| CNG | 0.95 | | 0.97 | 0.89[c] | 87.5 |
| Hydrogen (gaseous) | 0.95 | 0.785[c] | 0.97[d] | 0.86[c] | 59 |
| Fischer–Tropsch (F–T) diesel | 0.95 | 0.72 | 0.97 | | 67 |
| Electricity | | | | | 48 |
| Methanol | 0.95 | 0.624[e] | 0.97 | | 57.5 |

[a] 95% = 97.0% (recovery) × 97.5% (processing).

[b] Assuming 90% compressor efficiency, 55% conversion efficiency (NG to electricity), and 93% electricity transmission and distribution.

[c] Efficiency of hydrogen from natural gas by steam reforming (see Kreith, West, and Isler (2001) for additional information).

[d] Assuming gaseous hydrogen from centralized plants.

[e] Via conventional steam reforming.

*Source*: From Kreith, F., West, R. E., and Isler, B., *Journal of Energy Resources Technology*, 124(September), 173–179, 2002b; Kreith, F. and West, R. E., *Journal of Energy Resources Technology*, 126(12), 249–256, 2004.

**TABLE 8.18** Comparison of Natural Gas Well-to-Wheel Efficiencies of Technologies Using Natural Gas as Feedstock

| Vehicle Drive Technology | Fuel | Well-to-Wheel Efficiency[a] (%) |
|---|---|---|
| Battery + electric motor | Electricity from NG combined cycle | 39[b] |
| Hybrid SI | NG | 32 |
| Hybrid diesel | NG + F–T diesel[c] | 32 |
| Hybrid diesel | F–T diesel[c] | 30 |
| Fuel cell + electric motor | Hydrogen[d] | 27 |
| Hybrid SI | Hydrogen[d] | 22 |
| Conventional diesel | NG + F–T diesel[c] | 22 |
| Conventional SI | NG | 19 |
| Conventional diesel | F–T diesel[c] | 19 |
| Fuel cell + electric motor | Methanol[e] | 16 |
| Conventional SI | Hydrogen[d] | 14 |
| Fuel cell + electric | Hydrogen[f] | 13 |

[a] Well-to-wheel efficiency is the efficiency of use of the natural gas, starting with gas in well.

[b] Given the advances in battery technology noted in Electric Power Research Institute (2004), the well-to-wheel efficiency for an EV has been reevaluated: "The tank-to-wheel efficiency for a battery all-electric vehicle according to Electric Power Research Institute (2004) is 0.82…Combining this with a well-to-grid efficiency of 48% (for an NG combined cycle plant) and a distribution efficiency of 93%, gives $(0.93 \times 0.48 \times 0.82) = 0.36$" (Kreith and West 2005).

[c] Diesel fuel made by Fischer–Tropsch synthesis from natural gas.

[d] Hydrogen made by steam reforming of natural gas.

[e] Methanol made from natural gas and converted to hydrogen by onboard reactor.

[f] Hydrogen made by electrolysis with electricity from natural gas combined cycle.

*Source*: From Kreith, F. and West, R. E., *Journal of Energy Resources Technology*, 126(12), 249–256, 2004.

## 8.6.2 Fuels

One of the often overlooked aspects of transportation fuel is storage onboard the vehicle. In addition to the phases of fuel production and distribution, critical aspects of the fuel include whether it is liquid or gas, its energy density, and the size, type, and weight of the tank needed to store it on the vehicle. Table 8.19 compares the storage needs of various fuels to gasoline. High-pressure or high-volume tanks can be quite large and/or heavy, thereby affecting the vehicle's carrying capacity and potentially degrading fuel economy. Fuels with high energy densities will have fewer requirements for onboard fuel storage systems.

Biodiesel is a combination of oils or fats (usually agricultural residue such as soybeans or animal fats) with an alcohol such as ethanol or methanol. In a vehicle, it can be used alone (neat) or blended with

**TABLE 8.19** Onboard Storage Requirements for Various Fuels

| Fuel | Tank System Containing 15 GGE of Fuel | |
|---|---|---|
| | Fuel Volume (gallons) | Total Mass (lbs) |
| Diesel | 13.6 | 115 |
| Gasoline | 15.0 | 115 |
| Liquefied petroleum gas | 20.7 | 115 |
| Ethanol | 22.7 | 179 |
| Methanol | 31.0 | 240 |
| Compressed natural gas (3600 psi) | 46.3 | 268 |
| Compressed hydrogen (5000 psi) | 175.1 | 408 |
| Liquid hydrogen | 56.9 | 298 |

GGE, gallons of gasoline equivalent.

*Source*: From Greene, D., and Schafer, A., *Reducing Greenhouse Gas Emissions From U.S. Transportation*, Pew Center on Global Climate Change, Arlington, VA, 2003.

petroleum diesel (also known as *number 2 diesel*) using 20% biodiesel and 80% petroleum diesel, which helps to alleviate the fact that it freezes at a higher temperature than conventional diesel. With the exception of $NO_x$, biodiesel has lower tailpipe emissions than conventional diesel. The energy content is comparable to conventional diesel and it can be used in existing diesel engines without modifications.

Compressed NG is used in light-duty vehicles at 3000–4000 psi, whereas liquefied NG is used in heavy-duty vehicles and stored at about −260°F. Unlike LNG, CNG requires heavy pressurized tanks for onboard storage and has a lower energy content. Both burn more cleanly than gasoline or diesel, but have expensive infrastructure requirements because one is a compressed gas and the other is a cryogenic liquid. As noted, natural gas can be—and currently is—used directly in commercially available vehicles: it is estimated that there are up to 120,000 NG vehicles now on the road. Honda recently announced that it will offer a lease on an at-home refueling device with the purchase of a NG-powered Civic. The device fills the vehicle's tank overnight using the household's NG connection, thereby freeing the vehicle's owner from finding and using a NG filling station (of which there are 1100 in the U.S.) (Woodyard 2005). This obstacle has prevented many private parties from buying an NG vehicle, and most sales have been to government or corporate fleets that have private filling stations.

Electricity has a very low energy density that requires many heavy batteries for onboard energy storage. Most electricity is generated using coal as the feedstock, which benefits the U.S. because it has large reserves of coal, but this process can increase sulfur emissions. However, some of the advantages of electricity are that it can be produced using renewable sources and it creates no tailpipe emissions.

Ethanol is primarily made from corn; therefore, it can be produced domestically with a renewable feedstock. It may, however, have to compete with food uses in the corn market, but research is underway to extract the sugars in cellulose (e.g., plant material such as corn stalks and wheat straw, municipal solid waste) and convert it to ethanol. As an agricultural residue, cellulose would be much more abundant (300 million tons produced in the U.S. each year) than corn kernels (Morris 2003). It is estimated that while corn-derived ethanol generates about 1.4 times the energy required to produce it, cellulosic materials can produce ethanol with a 10–1 return on energy input (Gartner 2005a).

As a fuel, ethanol can be used neat (ethanol/gasoline mixture of 85% or more ethanol, known as E85) or as a blend (ethanol/gasoline mixture of 10% or less ethanol). The blend scenario helps ethanol to penetrate the market because any conventional gasoline vehicle can use it and it can be distributed with the current infrastructure. Neat ethanol requires a unique refueling infrastructure (there are currently 200 E85 stations in the U.S.) as well as small modifications (costing about $160 per vehicle; Morris 2003) to the vehicle so that it can run on ethanol, gasoline, or any combination of the two. There are currently 2.3 million of these "flexible-fuel" vehicles on the road. Ethanol is also being tested in fuel cell vehicles that use reformers to extract the hydrogen from the ethanol; for this purpose, the ethanol can be of a lower grade than that used in conventional ICEs, which translates to more efficient ethanol production. Ethanol is a liquid at ambient temperatures, so onboard storage requirements are not difficult to meet, although if used neat, a larger tank is required to maintain the same range as a conventional gasoline vehicle.

In the U.S., 95% of the hydrogen is made from NG through steam–methane reforming, compared to 50% for global production. Electrolysis of water can be used to produce hydrogen, but this method consumes large quantities of energy. The nuclear industry expects to be a major player in hydrogen production through electrolysis because it does not contribute to greenhouse gas emissions. Coal gasification produces 20% of the world's hydrogen, but creates significant emissions during hydrogen extraction. Solar power could be used to power electrolysis, but so far this method has not been cost-competitive with other alternatives (Morris 2003). Interest in using ethanol as a feedstock for hydrogen is growing, as ethanol uses a renewable feedstock and the process of reforming it into hydrogen is similar to that of reforming NG into hydrogen. The idea that a feedstock could be reformed into hydrogen onboard the vehicle does not yet show any promise, as no onboard reformer technology has been developed that is efficient enough to make this process feasible.

Gaseous hydrogen has a very low density and must be stored under extremely high pressure (5000–10,000 psi), creating another safety hazard in addition to its explosiveness. Liquid hydrogen has a higher energy density but must be stored at −253°C. In terms of energy density, it is

**TABLE 8.20** Fuel Comparison Chart

| | Gasoline | No. 2 Diesel | Biodiesel | CNG | Electricity | Ethanol (E85) | Hydrogen | LNG | Liquefied Petroleum Gas (LPG) | Methanol (M85) |
|---|---|---|---|---|---|---|---|---|---|---|
| Main fuel source | Crude oil | Crude oil | Soybean oil, waste cooking oil, animal fats, grapeseed oil | Underground reserves | Coal, natural gas, hydroelectric, renewables | Corn, grains, agricultural waste | Natural gas, methanol, other sources | Underground reserves | A by-product of petroleum refining or natural gas processing | Natural gas, coal, woody biomass |
| Energy content per gallon | 109,000–125,00 Btu | 128,000–130,000 Btu | 117,000–120,000 Btu | 33,000–38,000 Btu @ 3000 psi; 38,000–44,000 Btu @ 3600 psi | N/A | ~88,000 Btu | N/A | ~73,500 Btu | ~84,000 Btu | 56,000–66,000 Btu |
| Energy ratio gasoline to fuel | 1.0 | 1.04–1.17 | 1.1–1 or 90% (relative to diesel) | 3.94–1 or 25% at 3000 psi; 3.0–1 @ 3600 psi | N/A | 1.42–1 or 70% | N/A | 1.55–1 or 66% | 1.36–1 or 74% | 1.75–1 or 57% |
| Physical state | Liquid | Liquid | Liquid | Compressed gas | N/A | Liquid | Compressed gas or liquid | Liquid | Liquid | Liquid |
| Types of vehicles currently available | All types of vehicle classes | Many types of vehicle classes | Any vehicle that runs on diesel—no modifications are needed for up to 5% blends. Many engines also compatible with up to 20% blends | Many types of vehicle classes | Neighborhood electric vehicles, bicycles, light-duty vehicles, medium- and heavy-duty trucks and buses | Light-duty vehicles, medium- and heavy-duty trucks and buses—these vehicles are flexible-fueled vehicles that can be fueled with ethanol, gasoline, or any combination of the two fuels | No vehicles are available for commercial sale yet, but some vehicles are being leased for demonstration purposes | Medium- and heavy-duty trucks and buses | Light-duty vehicles that can be fueled with propane or gasoline, medium- and heavy-duty trucks and buses that run on propane | Mostly heavy-duty buses |
| Environmental impacts of burning the fuel | Produces harmful emissions; but gasoline and gasoline vehicles are rapidly improving and emissions are being reduced | Produces harmful emissions; but diesel and diesel vehicles are rapidly improving and emissions are being reduced especially with after-treatment devices | Reduces particulate matter and global warming gas emissions compared to conventional diesel; but $NO_x$ emissions may be increased | CNG vehicles can demonstrate a reduction in ozone-forming emissions compared to some conventional fuels; but hydrocarbon (HC) emissions may be increased | EVs have zero emissions; but some amount of emissions can be contributed to power generation | E85 vehicles can demonstrate a 25% reduction in ozone-forming emissions compared to reformulated gasoline | Zero regulated emissions for fuel cell-powered vehicles; $NO_x$ emissions possible for ICEs operating on hydrogen | LNG vehicles can demonstrate a reduction in ozone-forming emissions compared to some conventional fuels; but HC emissions may be increased | LPG vehicles can demonstrate a 60% reduction in ozone-forming emissions compared to reformulated gasoline | M85 vehicles can demonstrate a 40% reduction in ozone-forming emissions compared to reformulated gasoline |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy security impacts | Manufactured using mostly imported oil, which is not an energy secure option | Manufactured using mostly imported oil, which is not an energy secure option | Biodiesel is domestically produced and has a fossil energy ratio of 3.3–1, which means that its fossil energy inputs are similar to those of petroleum | CNG is domestically produced. The U.S. has vast natural gas reserves | Electricity is generated mainly through coal-fired power plants. Coal is the U.S.'s most plentiful fossil energy resource and coal is its most economical and price stable fossil fuel | Ethanol is produced domestically and it is renewable | If produced from renewable resources, hydrogen can reduce dependence on foreign oil | LNG is domestically produced and typically costs less than gasoline and diesel fuels | LPG is the most widely available alternative fuel with 3400 refueling sites nationwide. The disadvantage of LPG is that 45% of the fuel in the U.S. is derived from foreign oil | Methanol can be domestically produced from renewable resources |
| Fuel availability | Available at all fueling stations | Available at select fueling stations | Available in bulk from an increasing number of suppliers. There are 22 states that have some biodiesel stations available to the public | More than 1100 CNG stations can be found across the U.S., with the highest concentration of stations in California. Home fueling is now available | Most homes, government facilities, fleet garages, and businesses have adequate electrical capacity for charging, but special hookups or upgrades may be required. More than 600 electric charging stations are available in California and Arizona | Most of the E85 fueling stations are located in the Midwest, but in all, approximately 150 stations are available in 23 states | There are only a small number of hydrogen stations across the county. Most are available for private use only | Public LNG stations are limited (only 35 nationally). LNG is available through several suppliers of cryogenic liquids | LPG is the most accessible alternative fuel in the U.S. There are more than 3300 stations nationwide | Methanol remains a qualified alternative fuel as defined by EPA, but it is not commonly used |
| Maintenance issues | | | Hoses and seals may be affected with higher-percent blends; lubricity is improved over that of conventional diesel fuel | | Service requirements are expected to be reduced, since tune-ups, oil changes, timing belts, water pumps, radiators, and fuel injectors are not required | Special lubricants may be required. Practices are very similar, if not identical to those for conventionally fueled operations | N/A | High-pressure tanks required periodic inspection and certification | Some fleets report services lives that are 2–3 years longer, as well as extended intervals between required maintenance | Special lubricants must be used as directed by the supplier and M85-compatible replacement of parts must be used |

*(continued)*

**TABLE 8.20** (*Continued*)

| | Gasoline | No. 2 Diesel | Biodiesel | CNG | Electricity | Ethanol (E85) | Hydrogen | LNG | Liquefied Petroleum Gas (LPG) | Methanol (M85) |
|---|---|---|---|---|---|---|---|---|---|---|
| Safety | Gasoline is a relatively safe fuel since people have learned to use it safely. Gasoline is not biodegradable, however, so a spill could pollute soil and water | Diesel is a relatively safe fuel since people have learned to use it safely. Diesel is not biodegradable though, so a spill could pollute soil and water | Less toxic and more biodegradable than conventional fuel; can be transported, delivered, and stored using the same equipment as for diesel fuel | Pressurized tanks have been designed to withstand a severe impact, high external temperatures, and automotive and environmental exposure | Meet all the same vehicle safety standards as conventional vehicles | Ethanol can form an explosive vapor in fuel tanks. In accidents, however, ethanol is less dangerous than gasoline because its low evaporation speed keeps alcohol concentration in the air low and nonexplosive | Hydrogen is extremely explosive and acceptable systems for widespread distribution and storage for mass-produced vehicles are yet to be developed | Cryogenic fuels require special handling procedures and equipment to properly store and dispense | Adequate ventilation is important for fueling LPG vehicles due to increased flammability of LPG. LPG tanks are 20 times more puncture resistant than gasoline tanks and can withstand high impact | Methanol can form an explosive vapor in fuel tanks. In accidents, however, methanol is less dangerous than gasoline because its low evaporation speed keeps alcohol concentration in the air low and nonexplosive |

*Source*: Adapted from U.S. Department of Energy/Energy Efficiency and Renewable Energy, Alternative Fuels Comparison Chart, 2005a. http://www.eere.energy.gov/afdc/pdfs/afv_info.pdf suggested that a hydrogen tank storing gaseous hydrogen at 5000 psi would need to be 175 gallons in volume to contain as much energy as a 15-gallon gasoline tank, as shown in Table 8.19 (Greene 2004). Hydrogen embrittles steel and requires special alloys for the storage system; it also leaks very easily, causing yet another obstacle for researchers studying storage systems.

These characteristics influence the required hydrogen distribution infrastructure that currently consists of 15 fueling stations in the U.S. There is also the question of whether to produce hydrogen at a central location and then distribute it, or to produce it at decentralized distribution areas. The cost of a decentralized hydrogen refueling station is $600,000; the cost of an ethanol refueling station that serves several times that number of vehicles is $50,000 (Morris 2003). Moreover, it is estimated that for hydrogen fuel cell cars to gain 10% market penetration, 80% of the existing conventional refueling stations would need to be retrofitted for hydrogen distribution; providing a 90/10 gasoline/ethanol blend (that would not require any station modifications) would achieve almost the same amount of petroleum displacement. It has therefore been suggested that "if hydrogen and fuel cells do prove to be a cost-effective alternative, expanding the use of alcohols (i.e., ethanol) in our engines could become a stepping-stone to using hydrogen derived from those alcohols" (Miller 2003; Morris 2003).

Liquified petroleum gas (LPG) is a by-product of petroleum refining and NG processing and is the most widely used alternative fuel in the U.S. with about 3400 refueling stations. It has lower carbon monoxide and hydrocarbon tailpipe emissions than gasoline while maintaining about 70% of the energy content. However, almost half of LPG comes from oil; consequently, in terms of feedstocks, it does not offer much of an advantage over conventional gasoline.

Methanol (M85) is not a widely used transportation fuel, but like ethanol it can be blended with gasoline (85% methanol/15% gasoline) for use in heavy-duty buses. Feedstocks for methanol include coal, wood, methane, and NG. It is a liquid at ambient temperatures but has a low energy content compared to gasoline. Its corrosiveness and toxicity require special materials for the onboard storage system and the distribution infrastructure. Although it reduces particulate, hydrocarbon, and benzene tailpipe emissions, it increases formaldehyde emissions (Table 8.20).

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