10 Biofuel Use from Bioenergy Crops
Internal Combustion Engines in Transportation

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10.1 POWERTRAIN—PROPULSION SYSTEMS

Internal combustion (IC) engines are inherently linked to the specific physical, thermodynamic, and chemical properties of the fuel and the effects of these properties on fuel–air preparation and mixing, combustion initiation, combustion rates, combustion anomalies, and emissions formation. Throughout history, different engine technologies have been developed and used to operate with different fuels (Cummins 1989), including the 1908 Ford Model T, which operated on gasoline, ethanol, and their blends.

In the United States, spark-ignited engines fueled with gasoline (gasoline engines) prevail as the primary mover in light-duty vehicles (LDVs), representing 95% of the total LDVs in the United States in 2008 (EIA 2009a). Spark-ignition (SI) engines are able to meet the most stringent emissions standards, including U.S. Tier II Bin 2 and California partial zero emissions vehicle (PZEV) standards, but they have a lower thermal efficiency with a peak at approximately 35% (U.S. DOE 2010a) in comparison to their counterpart, compression-ignition (CI) engines. CI engines fueled by diesel fuel (diesel engines) are found in a high percentage of medium-duty vehicles (MDVs) and dominate heavy-duty vehicle (HDV) and heavy equipment applications. See
Table 10.1 for definitions of vehicle classifications for light-duty applications (trucks and passenger vehicles) and heavy-duty engines (U.S. DOT RITA 2010). Diesel engines are characterized as having a higher efficiency, with a peak of 45% (U.S. DOE 2010a), but are hampered by high engine-out particulate matter (PM) and oxides of nitrogen (\(\text{NO} + \text{NO}_2 = \text{NO}_x\)) emissions, which require complex exhaust aftertreatment systems to meet emissions standards. There are many places that energy is “lost” from the vehicle as an automobile travels down the road. A summary of these losses, as a percentage of the fuel’s total energy, is shown in Figure 10.1 (U.S. DOE and EPA 2008), where it is seen that the most losses originate from the engine. Current LDV hybrid electric vehicles (HEVs) (e.g., Toyota Prius, and hybrid versions of the Ford Escape and Chevy Tahoe) include on-board storage of electrical energy and electric drives, yet still derive nearly all required energy for vehicle operation from the combustion of fuel in the on-board IC engine. However, HEVs are designed to reduce the losses in several of the areas shown in Figure 10.1. HEVs achieve reductions in energy consumption by permitting the vehicle system to manage power requirements such that the IC engine is operated near its peak efficiency more frequently than a nonhybrid powertrain (targeting the engine losses), including allowing the engine to be shut off when not needed on decelerations and when the vehicle is stopped (targeting the idle losses). Additionally, hybrid electric systems are able to recapture kinetic and potential energy when a vehicle is stopping or descending a hill (targeting the braking losses). This energy, which would otherwise be lost to heat in the friction brakes,

<table>
<thead>
<tr>
<th>Table 10.1</th>
<th>Vehicle Categories Used in Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross Vehicle Weight Rating (GVWR)</td>
</tr>
<tr>
<td>Category</td>
<td>Passenger Vehicle Classifications</td>
</tr>
<tr>
<td>Light</td>
<td>&lt;8500 lb</td>
</tr>
<tr>
<td>Medium</td>
<td>8500–10,000 lbs</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt;33,000 lb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Losses</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine losses</td>
<td>62.4%</td>
</tr>
<tr>
<td>Idle</td>
<td>17.2%</td>
</tr>
<tr>
<td>Braking</td>
<td>5.8%</td>
</tr>
<tr>
<td>Drivetrain losses</td>
<td>5.6%</td>
</tr>
<tr>
<td>Aerodynamic drag</td>
<td>2.6%</td>
</tr>
<tr>
<td>Accessories</td>
<td>2.2%</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

**FIGURE 10.1** The losses in a typical LDV shown as a percentage of the fuel’s total energy, assuming an SI engine. (From U.S. DOE and EPA, Advanced technologies & energy efficiency, 2008.)
can be used to assist in propelling the vehicle at a later time. Together, these effects result in fuel consumption reductions on the order of 30% (Jones 2008).

Electrified vehicles, including “plug-in” hybrids, “extended range” hybrids (e.g., GM’s Chevrolet Volt), and full electric vehicles (e.g., Nissan’s Leaf), can use electrical energy from the municipal power grid for vehicle propulsion, directly displacing energy produced from the liquid-fueled IC engine. However, despite high mile per gallon (MPG) ratings based on fuel from the tank, the overall energy conversion process from source to wheels must still be considered. When analyzing the electrical generation processes, it is found that nearly 70% of the source energy is wasted (EIA 2006a), and furthermore, 71% of the U.S. electrical power production is from fossil fuels (EIA 2006b). Considering this, it becomes clear that even when electricity is used as the primary source for power, these vehicles are still contributing to the depletion of fossil fuels and the increase of atmospheric carbon dioxide (CO₂). However, as the penetration of renewable sources of electricity production increases, including raw biomass, biomass-based syngas, hydroelectric, solar, and wind, these vehicles will certainly show added benefit. Nevertheless, debate will likely remain as to whether electrified vehicles running on electricity generated from renewable sources or conventional vehicles running on renewable liquid fuels is the optimal long-term solution.

10.1.1 U.S. AND WORLD TRANSPORTATION FUEL USAGE

Transportation fuel usage continues to increase worldwide. Transportation accounts for almost 30% of the total global energy delivered in 2007, making up more than 50% of global liquid fuel consumption (EIA 2010). Of the 97.9 quadrillion (10¹⁵) Btu (10³ quadrillion kilojoules) of energy consumed for transportation in the world, the United States uses nearly 30% of this (EIA 2010). To put this into perspective, if the petroleum used for transportation in the United States in 1 day was placed in 55-gallon oil drums, and these drums were placed next to each other, they would form a line from New York to Los Angeles, passing through Detroit and Houston (Figure 10.2). Petroleum makes up the largest portion of transportation energy consumption, providing nearly
94% of transportation energy in 2009, with only 3.4% of transportation energy consumption being provided by renewables (Davis et al. 2010). This current dependence on petroleum is detrimental to the U.S. economy and national security, especially as shortages and high oil prices become increasingly prevalent (EIA 2009b). In 2009, renewable energy represented only 8% of the total U.S. energy consumption, with biofuels composing 20% of this renewable energy use (EIA 2009b). Efforts are in place, including the U.S. Renewable Fuel Standard (RFS) 2, which requires 36 billion gallons of renewable fuels to be used for transportation by 2022. (U.S. EPA 2007a, 2010a) This will promote the development and incorporation of renewable fuels into the transportation sector to overcome the current low percentage of consumption, assist with greenhouse gas reduction, and decrease reliance on imported petroleum. However, biofuel and engine operational challenges must be understood and overcome to ensure the success of renewable transportation fuels.

Vehicle and engine original equipment manufacturers (OEMs) have developed engines to use ethanol–gasoline and methyl–ester biodiesel–petroleum diesel blends. These two biofuels have received significant attention and development in the United States. As of 2010, nearly 8 million E85 (85% volume ethanol, 15% volume gasoline) ethanol flex-fuel vehicles (FFVs) were estimated to be on the road in the United States (U.S. DOE 2010b), and automotive manufacturers have committed to making one half of their vehicles ethanol flex-fuel capable by 2012 (GM 2007). These vehicles are able to utilize gasoline–ethanol blends in the range of 0 to 85% ethanol by volume. Additionally, 10% ethanol is approved for blending with gasoline for use in vehicles with conventional SI gasoline engines, with higher blend ratios likely being approved soon. Similarly, the use of biodiesel is approved at levels of 5–20% concentrations by many of the diesel engine and vehicle OEMs (Cummins 2007). Standards are placed upon these fuels to ensure they do not significantly deteriorate the IC engine performance or emissions (ASTM D7467-09a and ASTM D6751-10). However, other fuels, including Fisher–Tropsch (green or synthetic) diesel (Goodger 1975), dimethyl ether (DME) (Silva-Petrobras 2006), methanol, butanol, biogas [a mixture of methane (CH₄) and CO₂ produced via anaerobic digestion of biodegradable matter (IEA 2005)], and hydrogen (Naber and Siebers 1998) are also notable alternatives for transportation fuels for use in IC engines (SAE 2007) and other power generation systems including fuel cells.

### 10.1.2 Biofuel Characteristics

Combustion fuels are primarily composed of the atomic elements hydrogen, carbon, and oxygen, although trace amounts of other elements, including sulfur and nitrogen, can also be present (Goodger 1975). These fuels are suitable for SI or CI engines, depending on the fuel characteristics, with varying requirements for modification of the fuel, engine, control, and aftertreatment systems. SI and CI fuels are subject to detailed specifications (ASTM D4814-10a–SI Fuels, ASTM D975-10a–CI fuels) to ensure they meet minimum requirements for operation of modern IC engines. Petroleum hydrocarbon fuels (gasoline and diesel) are a complex mixture of hundreds of compounds of different molecular structures and atomic weights. The composition is made up of straight-chained paraffins, cycloparaffins, alkenes, and aromatics. Ranges of atomic weights result in a nearly continuous distillation curve. Gasoline is composed of C₅–C₁₄ molecules with a 50% distillation point of 99°C (Totten et al. 2003). Diesel is composed of higher-molecular-weight compounds (C₇–C₂₄) with a 50% distillation point of 256°C (Totten et al. 2003). Ratios of the molecular components affect autoignition (Taylor et al. 2004), combustion, and emissions of soot (Svensson 2005). Limits are placed on aromatics in fuels because they decrease the hydrogen-to-carbon ratio and result in high soot emissions (ASTM D975-10a). Regulations as documented in the standards also require reduced sulfur in the fuel to enable and improve performance of advanced exhaust aftertreatment systems.

Table 10.2 lists characteristics of petroleum-based fuels and biofuels along with their applications. Included are the hydrogen- (column A) and oxygen (B)- to carbon ratios, mass density (C), and specific energy and specific CO₂ emissions. As can be seen in Table 10.2, oxygenated fuels have a lower energy density. For example, the energy density of gasoline is 44 MJ/kg, whereas that of
### TABLE 10.2
Transportation Fuel Properties Including Specific Energies and CO₂ Production

<table>
<thead>
<tr>
<th>Application</th>
<th>Fuel</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H/C (–)</td>
<td>O/C (–)</td>
<td>Density (kg/m³)</td>
<td>Energy Unit Mass (MJ/kg)</td>
<td>Energy Unit Volume (–)</td>
<td>CO₂/Fuel (g CO₂/g Fuel)</td>
<td>CO₂/Energy (g CO₂/MJ)</td>
<td>Octane Number (–)</td>
<td>Cetane Number (–)</td>
<td></td>
</tr>
<tr>
<td>Spark ignition</td>
<td>Gasolinea</td>
<td>1.87</td>
<td>0.00</td>
<td>760</td>
<td>44.0</td>
<td>1.00</td>
<td>3.17</td>
<td>72</td>
<td>87–93</td>
<td>14–20</td>
</tr>
<tr>
<td>(liquid fuels)</td>
<td>Methanol</td>
<td>4.00</td>
<td>1.00</td>
<td>792</td>
<td>20.0</td>
<td>0.47</td>
<td>1.37</td>
<td>69</td>
<td>99</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>3.00</td>
<td>0.50</td>
<td>785</td>
<td>26.9</td>
<td>0.63</td>
<td>1.91</td>
<td>71</td>
<td>98</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Butanolb</td>
<td>2.50</td>
<td>0.25</td>
<td>810</td>
<td>32.0</td>
<td>0.78</td>
<td>2.37</td>
<td>74</td>
<td>96</td>
<td>15</td>
</tr>
<tr>
<td>Compression</td>
<td>Diesel</td>
<td>1.86</td>
<td>0.00</td>
<td>827</td>
<td>43.2</td>
<td>1.07</td>
<td>3.17</td>
<td>73</td>
<td>33–54</td>
<td>40–50</td>
</tr>
<tr>
<td>ignition</td>
<td>Biodieselc</td>
<td>1.83</td>
<td>0.11</td>
<td>885</td>
<td>37.3</td>
<td>0.99</td>
<td>2.83</td>
<td>76</td>
<td>15–31</td>
<td>52–58</td>
</tr>
<tr>
<td>FT diesel</td>
<td>1.74</td>
<td>0.01</td>
<td>761</td>
<td>44.6</td>
<td>1.01</td>
<td>3.14</td>
<td>70</td>
<td>–</td>
<td>70–90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DMEd</td>
<td>3.00</td>
<td>0.50</td>
<td>668</td>
<td>28.4</td>
<td>0.57</td>
<td>1.91</td>
<td>67</td>
<td>–</td>
<td>55–60</td>
</tr>
<tr>
<td>Spark ignition</td>
<td>Methanee</td>
<td>4.00</td>
<td>0.00</td>
<td>165</td>
<td>50.0</td>
<td>0.25</td>
<td>2.74</td>
<td>55</td>
<td>120</td>
<td>–</td>
</tr>
<tr>
<td>(gaseous fuels)</td>
<td>Natural gasf</td>
<td>3.80</td>
<td>0.00</td>
<td>185</td>
<td>45.0</td>
<td>0.25</td>
<td>2.78</td>
<td>62</td>
<td>130</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Hydrogene</td>
<td>Inf</td>
<td>–</td>
<td>29</td>
<td>120.0</td>
<td>0.10</td>
<td>0.00</td>
<td>0</td>
<td>106</td>
<td>–</td>
</tr>
</tbody>
</table>

A H/C ratio is the molar ratio of hydrogen to carbon atoms.
B O/C ratio is the molar ratio of oxygen to carbon atoms.
C Density is the mass of fuel per unit volume.
D Energy content on a mass basis. Known as the heating value [e.g., lower heating value (LHV)] and is the quantity of energy contained per unit mass of fuel.

(Continued)
TABLE 10.2 (Continued)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Energy content on a volume basis. The product of the energy per unit mass times the density normalized to the value for gasoline.</td>
</tr>
<tr>
<td>F</td>
<td>CO₂ production in terms of grams of CO₂ produced from each gram of fuel.</td>
</tr>
<tr>
<td>G</td>
<td>CO₂ production in terms of grams of CO₂ produced per unit energy of the fuel.</td>
</tr>
</tbody>
</table>

a Petroleum-based gasoline has typically only trace amounts of oxygen; however, current regulations allow for blending with 10% ethanol. The table lists properties typical of petroleum-derived gasoline.

b Butanol properties are those of n-butanol (or 1-butanol). Various forms of butanol exist that have the same chemical formula (C₄H₁₀O) but different chemical structure and hence thermodynamic properties and combustion characteristics. These include sec-butanol, tert-butanol, and iso-butanol (Szwaia and Naber 2009).

c Soy-based methyl-ester biodiesel.

d DME is a gas at ambient temperature (20°C) and pressure (1 bar), but it is a liquid at relatively low pressures (5 bar) (Arcoumanis et al. 2008). Specific energies in the table are for liquid DME. DME can be mixed with diesel fuel, but it requires a specialized fuel system and vapor handling not needed for diesel or biodiesel (Chapman et al. 2003; Arcoumanis et al. 2008).

e Pressurized to 25.0 MPa.

f Pressurized to 25.0 MPa.

g Pressurized to 34.5 MPa.

h \((R + M)/2\)
methanol, an oxygenated fuel also used in SI engines, has an energy density of only 20 MJ/kg, a 55% reduction. Despite this energy density reduction, a benefit of oxygenated fuels is that they require less air (oxygen) during combustion and provide carbon monoxide (CO) and PM emission reductions. The use of oxygenated fuels in SI engines was mandated as part of the 1990 Clean Air Act (CAA) (U.S. EPA 2004) in regions of CO emission nonattainment because oxygen in the fuel assists with more complete oxidation of the carbon to CO$_2$, thereby reducing CO emissions (CFDC 2008).

Specific energy on a unit volume basis relative to gasoline is given in column E of Table 10.2. Examining the alcohol liquid fuels, it is seen that all have a lower energy density, which indicates that under the same fuel conversion efficiency, their specific fuel consumption (mass or volume of fuel per unit output) will be higher. Neat ethanol has 63% of the energy density of gasoline, and E85 has 70% of the energy density of gasoline. This is the cause of the reduced fuel economy (MPG) observed in FFVs. The alternative CI fuels have energy densities that are more similar to petroleum diesel, except for DME. The gaseous fuels have low energy densities on a volumetric basis because of their low mass densities, even when compressed. As Table 10.2 shows, hydrogen, even when compressed to 34.5 bar (5000 psi), has a lower energy density, only one tenth that of gasoline. This brings to light that we should not be paying for fuels based upon a volumetric basis (dollars per gallon), but on an energy basis (dollars per MJ), which can be computed based on the ratio in column E.

Columns F and G characterize the specific emission of CO$_2$ of these fuels. Column F is the mass-specific CO$_2$ produced per unit mass of fuel consumed, and column G is the energy-specific CO$_2$ in grams of CO$_2$ per MJ of fuel energy. This energy-specific CO$_2$ provides a useful metric for comparing the energy/CO$_2$ tradeoff of the fuels. Examining the values for the liquid fuels, their energy-specific CO$_2$ values cover a relatively small range and are within 7% of gasoline. On first approximation, engine efficiency will not change significantly for these different fuels when used in the same IC engine technology. Thus, a good estimate of the relative CO$_2$ impact for alternative fuels on a tank-to-wheels analysis would be the ratio of the biofuel to the reference fuel (JRC/IES 2007). For example, comparing ethanol to gasoline would be $\frac{71}{72} = 0.99$, or a 1% estimated reduction in tank-to-wheels CO$_2$. Therefore, to produce less CO$_2$ at this stage of the life-cycle, aside from the solution of decreasing the miles driven, the efficiency at which the IC engine converts the chemical energy in the fuel to useful mechanical work at the wheels needs to be improved and/or the amount of mechanical work required to propel the vehicle must be reduced. One may note that although some gaseous fuels, and in particular hydrogen, have a high energy content per unit mass (120 MJ/kg for H$_2$ compared with just 44 MJ/kg for gasoline), they still cannot deliver the same vehicle range as liquid fuels such as gasoline or diesel because of the low energy per unit volume in the gas state. Technologies do exist to store hydrogen at low temperatures (−253°C or −423°F) in a liquid state (BNL 2008) and at high pressures. However, in addition to adding considerable cost, these solutions require a significant amount of additional energy to compress and cool the hydrogen, and this extra energy must be taken into account when evaluating the overall energy requirements throughout the life-cycle of hydrogen (see Figure 10.3 for comparisons of vehicle driving ranges for several types of fuel). From Figure 10.3, it is apparent that the typical CI liquid fuels of diesel, FT diesel, and biodiesel yield the largest distance range, followed by liquid SI fuels of gasoline, butanol, and ethanol. The gaseous SI fuels (CH$_4$, hydrogen, and biogas) yield the lowest driving range. These trends all relate back to the energy content of the fuel on a volume basis, determined by the energy contained in the fuel on a mass basis and the fuel density. The gaseous fuels, although having a reasonably high energy content, have low densities that yield reductions in driving ranges. CI and SI fuels have comparable energy contents and densities that provide similarities in driving ranges, with exceptions to this including methanol, ethanol, and DME, each of which has a lower energy content relative to the other fuels considered. It should also be noted that electrical energy storage can be used, but considering that gasoline has a volumetric energy density that is over 60 times greater than that of a nickel metal hydride battery (Komatsu et al. 2008), the issue becomes the ability to physically store enough energy onboard the vehicle. Furthermore, electric vehicles currently need batteries that are 12 times the size of conventional plug-in hybrid batteries to provide
the same vehicle range (Komatsu et al. 2008). It is factors such as these that led to 93.6% of LDVs sold in the United States in 2005 being designed to run on only gasoline or diesel. When adding to this number hybrids and FFVs that use gasoline or diesel as one of the on-board energy sources, the percentage increases to 99.96 (EIA 2007). However, with current increases in alternative energy mandates, this percentage is likely to decrease in coming years.

10.1.3 Fuel Economy and \( CO_2 \) Regulations

It is through the reaction of fuel with air to produce \( CO_2 \) and water that chemical energy is converted to sensible (thermal) energy that elevates the product gas temperature and enables a heat engine such as the IC engine to extract energy from the working fluid. Therefore, \( CO_2 \) is an unavoidable byproduct of combustion when fuel contains carbon, and for a given fuel, \( CO_2 \) production is directly proportional to fuel consumption (every carbon atom in the fuel produces one \( CO_2 \) molecule). On a mass basis, every kilogram of carbon (molecular weight of 12.01) in the fuel produces 3.67 kg of

FIGURE 10.3 A hypothetical comparison of maximum driving range between fueling stops for different types of fuels, assuming no changes to the vehicle, including constant fuel tank volume and constant overall fuel conversion efficiency.
CO$_2$ (molecular weight of 44.01). For modern IC engines that are regulated by toxic emission standards and operate under normal conditions, the conversion of the chemical energy to sensible energy is typically greater than 97% (Heywood 1988). For on-road vehicles, over 99.9% of the carbon in the fuel is converted to CO$_2$ through combustion and aftertreatment devices such as catalytic converters (Heck and Farrauto 2002). However, because of several losses and limitations, not all of that released chemical energy results in usable work transmitted to the output shaft of the engine. Therefore fuel consumption and CO$_2$ emissions are directly coupled and need to be considered jointly.

There are two common measures of fuel usage in vehicles. The United States uses a rating of MPG whereas Europe and many other countries use a rating of liters per 100 kilometers (L/100 km). Per above, CO$_2$ specific emissions in grams of CO$_2$ per kilometer (g(CO$_2$)/km) is proportional to L/100 km for a given fuel. The relationships between these metrics are shown in Figure 10.4 for gasoline on the basis of the properties in Table 10.2. MPG is a measure of efficiency in that it is the useful output in miles divided by the input in gallons of fuel, whereas L/100 km is a specific consumption metric (input over output). It is then clear that they are inversely proportional (L/100 km = 234.2/MPG). Following through, the g(CO$_2$)/km-specific emissions metric is proportional to L/100 km and is dependent on the fuel properties [density (column C) and CO$_2$/fuel (column F) in Table 10.2]. Here we note that because of the inverse relationship between MPG and L/100 km or g(CO$_2$)/km, when changes are discussed, a specific percentage change in one does not correspond to the same percentage change in the other. For example a 42% increase in MPG from 35 to 50 corresponds only to a 30% decrease in L/100 km or g(CO$_2$)/km of CO$_2$ emissions.

In addition to the specific emission scale in Figure 10.4, also shown are the related standards and targets for CO$_2$ and CO$_2$-equivalent greenhouse gases (GHGs). With this figure, comparisons can be made between U.S. Corporate Average Fuel Economy (CAFE) standards, including the newly adopted U.S. CAFE standard (Sissine 2007), European CO$_2$-specific emissions targets (Brink et al. 2005), and California CO$_2$ equivalent GHG specific emissions standards (California Legislation 2002; ARB 2005). From this figure we can see that these standards, including the CAFE fuel economy standard, are in application all regulating CO$_2$-specific emissions. Additionally, although the measured emissions are determined on different vehicle test cycles, it can be seen that the U.S. 2016 MPG CAFE regulation is set at a higher CO$_2$-specific emission level than the European targets and California limits.

From the previous discussion, it can be seen that regulating fuel economy not only provides benefits regarding reduction in oil consumption, but also directly reduces CO$_2$ emissions. With the implementation of the latest LDV CAFE standards, U.S. GHG emissions could decrease by 960 million metric tones, saving 1.8 billion barrels of oil over the lifetime of the vehicles sold between 2012 and 2016 (U.S. EPA 2010c). This is a measureable savings for the economy and the environment, as well as providing increased energy surety by reducing reliance on imported oil. However these estimates do not account for increases in miles driven that have been observed with increased vehicle fuel economy. Although the original CAFE standards in 1975 increased vehicle fuel economy by 37.5% from 1980 to 2007 (U.S. DOT 2004), over this time the total driven miles in the United States increased by 199% (U.S. DOT RITA 2010), resulting in an overall increase in fuel consumption. Hence, fuel consumption is not decreasing as rapidly as desired from these CAFE standards. One method proposed to compensate for this trend is to increase fuel costs via gasoline taxes as an example, to motivate the demand for fuel-efficient vehicles meeting stringent CAFE standards while also reducing miles driven on the basis of the increased cost of fuel (NRC 2002, 2010a).

Various methods have been proposed to improve fuel economy for SI and CI engines, as will be discussed further for both engine technologies in subsequent sections. Options to reduce fuel consumption applying to SI and CI engines include vehicle improvements such as mass reduction, decreased rolling resistance and friction, improved aerodynamics, advanced materials and body designs, transmission modifications (Jones 2008; NRC 2010b), and hybridization. In the case of MDVs and HDVs, proposed methods are similar to those mentioned, but other options include automated manual transmissions, wide-base low-rolling resistance tires, and intelligent transportation systems that include appropriately training drivers, modifying truck size and weight restrictions,
and idle reduction (NRC 2010a). In addition, manufacturers have other options to assist in meeting fuel economy standards. This includes credits that can be received and transferred between car and truck MPG ratings or applied to prior or future standards. Credits can be earned for improvements in air conditioning systems by reducing hydrofluorocarbon refrigerant losses. Credits can also be earned for reducing indirect CO₂ emissions and for advanced technology and alternative fuel vehicles. Credits have also been proposed for overcompliance to standards (U.S. EPA 2010c).

Current CAFE standards apply to LDVs, including passenger cars and light trucks because they are responsible for almost 60% of GHG emissions from transportation (U.S. EPA 2010d). However,
heavy-duty engines in commercial trucks do not currently have regulations on fuel economy or GHG emissions, despite being the second-largest transportation sector oil consumer and GHG emission producer, accounting for approximately 20% of transportation GHG emissions (U.S. EPA 2010e). This is changing; the EPA and U.S. Department of Transportation (DOT) recently proposed fuel efficiency and GHG standards to be phased in beginning with model year 2014 for heavy-duty engines (U.S. EPA 2010f). In addition to CO2 GHG regulation, two other GHGs, nitrous oxide (N2O) and CH4, will also be regulated under this proposed program (U.S. EPA 2010e). Similar to CO2, N2O and CH4 are suspected of contributing to global warming, but they have a higher impact than CO2 for the same level of emissions concentration (U.S. EPA 2006). It is estimated that these proposed new standards for heavy-duty engines could reduce GHG emissions by 250 million metric tones, saving approximately 500 million barrels of oil over the vehicle life, for those sold in 2014–2018 (U.S. EPA 2010e).

10.1.4 EMISSIONS REGULATIONS

The combustion process inside of an IC engine leads to the production of harmful compounds, including CO, NOx, unburned hydrocarbons (UBHCs or HCs), and PM. These chemicals, commonly referred to simply as “emissions”, are harmful to humans and the environment, and as a result are regulated in the United States by the EPA. The development of advanced engines and aftertreatment systems has reduced emissions to comparatively extremely low levels. For automotive LDVs, the trends in emissions reduction are shown in Figure 10.5 for U.S. and European standards for NOx and HC (CO has been similarly reduced, but not shown). As can be seen, the emissions have decreased by more than a factor of 100 over this period. For heavy-duty diesel engine applications, similar reductions have been mandated. The latest regulations in 2007 and 2010 require a reduction

by a factor of 10 in PM (from 0.1 to 0.01 g/bhp-h) and NO\textsubscript{x} (from 2 to 0.2 g/bhp-h), respectively (U.S. EPA 2010g). In the case of diesel CI engine combustion, there is an inherent NO\textsubscript{x}-soot tradeoff that is based on the temperature-equivalence ratio path that combustion follows, making emission control difficult. To meet the 2007–2010 standards, diesel engines now incorporate complex after-treatment systems that typically include an oxidation catalyst, a continuously regenerating PM trap, and a lean NO\textsubscript{x} reduction system such as a selective-catalyst-reduction/urea system.

Evaporative emissions are those that can come from fuel in storage tanks during various drive and park cycles and as a result of refueling the vehicle. These, in addition to the tailpipe emissions outlined above, have been regulated for gasoline-fueled vehicles because of the fuel’s high volatility. Evaporative emissions are composed of light volatile organic compounds (VOCs) in the fuel and cause ground-level ozone problems and human health issues (U.S. EPA 2007b; de Nevers 2000). Tier 2 evaporative emission standards for LDVs include a three-diurnal test combined with a hot soak (after engine operates above ambient temperatures and is shut down) along with running losses, being 0.50 g/test and 0.05 g/mi for LDVs in model year 2009 (U.S. EPA 2009).

To maintain these standards, vehicles must include on-board-diagnostic (OBD) systems to continuously monitor all components that would result in the failure of the vehicle to meet these standards. If a failure occurs, a diagnostic check engine light informs the driver of a problem and diagnostic codes on the faulty component(s) are stored and used for servicing purposes.

\section*{10.2 IC ENGINES}

\subsection*{10.2.1 BASIC ENGINE OPERATION}

The IC engine has existed since the 19th century, when pioneers including Jean Lenoir, Nicholas Otto, and Rudolf Diesel proved that the concept of a heat engine relying upon IC was a viable mechanism (Cummins 1989). An IC engine is a mechanical device that converts energy contained within chemical bonds in the fuel into kinetic energy in the form of a rotating shaft that can be used to do useful work. The four-stroke cycle engine, which is used in nearly all transportation vehicles, consists of a piston moving up and down within a cylinder inside of the engine. The piston is connected to a crankshaft; thus, the reciprocating motion of the piston is translated via the connecting rod and crankshaft into rotational kinetic energy at the shaft. The engine operates on a cycle, wherein the piston makes four distinct strokes of the cylinder over two revolutions of the crankshaft as shown in Figure 10.6. These four strokes are described as follows:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{four_stroke_cycle.png}
\caption{Four-stroke engine operating cycle. SI engine shown with spark-plug for ignition.}
\end{figure}
• **Intake stroke**: Fuel and air are brought into the cylinder through intake valve(s) as the piston moves down the cylinder [from top dead center (TDC) to bottom dead center (BDC)].

• **Compression stroke**: As the piston moves up the cylinder (from BDC to TDC), the intake valves are closed and gases are compressed, thus increasing the temperature and pressure.

• **Expansion stroke**: The combustion of fuel and air creates CO₂, H₂O, and other products at high temperature and pressure. The high pressure pushes the piston down the cylinder (TDC to BDC). This is the only stroke in which work is extracted from the engine.

• **Exhaust stroke**: The exhaust valves open and the piston moves up the cylinder (from BDC to TDC), pushing the combustion products to the exhaust system. After the exhaust stroke is complete, the intake stroke begins again, signifying the start of another cycle.

Although all four-stroke engines operate on this same basic cycle, there are two distinctly different variations. These two variations, the SI and CI engine, differ in how the fuel is introduced and how the fuel and air mixture is ignited and burned. These are shown visually in Figure 10.7. This includes SI engines that use a premixed fuel–air mixture and exhibit a homogeneous propagating flame. CI combustion is based on a diffusion flame with nonpremixed combustion. The SI and CI engine are discussed in the following two sections, along with effects of fuels on their performance and emissions.

### 10.2.2 SI Engines

Inside of the combustion chamber of the engine, the correct fuel–air mixture must be present to initiate and sustain combustion in a controlled manner over a portion of the cycle. In SI engines, as
the name indicates, combustion is initiated by a high-energy electrical discharge, a spark, which causes the fuel–air mixture locally to ignite. Once the fuel–air mixture starts to burn, the flame propagates through the combustion chamber, consuming the premixed fuel and air in a controlled manner. To avoid uncontrolled combustion, the autoignition of the fuel–air mixture at any stage of this must be prevented. Gasoline and other SI fuels must have a high resistance to autoignition, which is measured by the octane rating of the fuel. The higher the octane, the more resistant the fuel is to autoignition (see values in Table 10.2, column H). If the octane rating is not high enough, combustion knock (unwanted autoignition) will occur, reducing efficiency and potentially damaging the engine. The SI biofuels in Table 10.2 all exhibit octane numbers higher than gasoline, indicating that they are better than the standard petroleum gasoline regarding resisting autoignition. However, additional fuel properties need to be considered as they influence performance, startability, and emissions.

### 10.2.2.1 Influence of Fuel on Operating Characteristics of SI Engines

Two very important pathways for improving the efficiency of an engine are (1) to increase the compression ratio (CR), which is a measure of how much the fuel and air mixture is compressed before ignition, and (2) to reduce the amount of work that is wasted pumping air and fuel into the cylinder and out the exhaust port.

In SI engines, the maximum compression ratio is limited by the fuels octane number. A higher compression ratio leads to higher temperatures during the combustion process, and this can cause a portion of the fuel to autoignite and burn rapidly at the wrong time in the engine cycle, leading to combustion knock. Fuels with a higher octane rating, such as alcohol-based fuels like ethanol, methanol, or some isomers of butanol, will resist autoignition, which allows engine developers to increase an engine’s compression ratio and thus improve efficiency. However, because these alternative fuels, even ethanol, remain a low portion of the overall fuel supply, vehicle OEMs must produce engines that are capable of running on gasoline in addition to alternative fuels. Unfortunately, the requirement that these vehicles, called FFVs, operate on gasoline limits the engines compression ratio, and thus limits the full benefit of the higher octane of the alternative fuel. Engines with variable compression ratio (VCR) systems are a developing technology that shows promise in alleviating this limitation because these systems would allow the compression ratio to be automatically optimized as the fuel in the tank changes (Drangle 2002; Moteki 2003; Rosso 2006).

The load in SI engines is controlled by throttling the incoming air and controlling the prior cycle residuals in the cylinder by continuously adjusting the phase of the intake and exhaust valves. By restricting the air, less air enters the cylinder during the intake stroke. To maintain the proper air-to-fuel ratio, less fuel is injected, resulting in less heat being released during combustion and resultant power being reduced. Similarly, by increasing the amount of prior cycle residuals, which displace air, less fuel is injected. The disadvantage of the throttling process is that although the engine ingests less air, the added restriction in the intake air path causes the engine to do negative work during the intake stroke to bring the air into the cylinder, thus reducing the efficiency. The alternative method to control residuals via valve phasing reduces this pumping work within engines. The burned exhaust gases (primarily CO₂, H₂O, and N₂) do not participate in the combustion reaction, but instead fill space in the cylinder that would have otherwise been occupied by the air and fuel mixture. To compensate and maintain engine load, the throttling effect is reduced, which in turn reduces the pumping work. A limiting factor in this is the stability of the combustion process. As more residuals are added to the cylinder, the combustion process becomes prolonged and less stable, eventually leading to misfire. The type of fuel and its properties affect this in that some fuels can tolerate greater amounts of dilution than others, and some fuels such as gaseous fuels require less throttling because of the low density of the fuel.

Another approach to decreasing pumping losses is to reduce the size (displacement) of the engine. A smaller engine requires less throttling to achieve the same load as a large engine and thus runs more efficiently. However, to get the same maximum power out of the engine, intake air
boosting with a turbocharger or supercharger is required. Boosting under high loads leads to high temperatures in the cylinder and thus fuels with high octane ratings are more desirable for boosted applications. A related technique is to operate a larger engine with variable displacement.

SI engines are able to meet the lowest levels of regulated pollutant emissions standards (U.S. Tier II, bin 2 and CA PZEV) with relatively inexpensive three-way catalysts coupled with advanced sensing and fully electronic control. However, there is a tradeoff in efficiency to meet these stringent emissions standards: three-way catalysts require stoichiometric operation of the fuel and air to simultaneously reduce HC, CO, and NOₓ emissions. A limited number of SI gasoline-fueled engines have been produced, primarily in Europe. They have lean combustion systems in which the NOₓ emissions are not as stringent and fuel sulfur levels are lower, enabling lean NOₓ aftertreatment devices to be more effective.

SI engines are continuing to evolve, improving engine efficiency, performance, and power density. New technologies including direct injection, turbocharging with downsized engines, optimized valve timing, lift, and duration, homogeneous-charge CI technology, variable displacement, and VCRs (Jones 2008) will continue to enable significant improvements over the next decade.

10.2.3 CI Engines (Diesel Engines)

To initiate combustion in CI engines, the compression process heats the gases (including air, prior cycle residuals, and exhaust gas), and when the fuel, which is injected near the end of compression, mixes with the hot gases, it undergoes rapid exothermic reactions (autoignition and combustion). Conventional CI engines (often called diesel engines in recognition of their inventor, Rudolf Diesel) operate using diesel fuel, which has a high cetane number (see Table 10.2, column 1). The cetane number is a measure of the fuel’s ignition delay. The cetane number can be thought of as the opposite of an octane number, and fuels with a high cetane number have a low octane rating. The higher the cetane number, the easier (lower temperature) and faster autoignition will occur. In Table 10.2 it is seen that diesel has the lowest cetane rating, indicating that at least from an autoignition standpoint, the alternative diesel fuels are better fuels than the base petroleum diesel fuels.

Several factors typically give CI engines a higher efficiency than SI engines. CI engine compression ratios are higher than SI engines because the compression ratio in a SI engine is limited by combustion knock due to limited octane ratings. Compression ratios for CI engines range from 16 to 24, as opposed to 9 to 13 for a typical SI engine, as shown in Figure 10.8. Higher compression ratios lead to higher efficiency on the basis of the thermodynamics of the cycle. The two lines shown in Figure 10.8 correspond to heat addition at constant volume (CV) and constant pressure (CP) for the

**FIGURE 10.8** Compression ratio effect on ideal efficiency and ranges of current gasoline and diesel engine operation.
respective ideal thermodynamic cycles. In practice, engines use a limited pressure cycle in which combustion occurs at a rate somewhere between these, yielding ideal efficiencies that fall between these lines. Increasing the compression ratio (from SI to CI levels) yields improvements in efficiency, with actual engine efficiencies falling below these lines because of the nonideal cycles with various losses including heat transfer, rate-limited induction and exhaust of the working gases, and friction. Another unique aspect of CI engines is the load control mechanism. Unlike an SI engine, in which engine load is controlled by restricting the flow of air into the engine, a CI engine controls load by injecting more or less fuel into the cylinder. By controlling load in this manner, the engine does not waste energy across a restriction as it does in the SI engine during throttling. Furthermore, at light and even moderate loads, when a relatively small amount of fuel is being injected, the overall air-to-fuel mixture is lean of stoichiometric (excess air), which also leads to the higher efficiency of CI engines relative to SI engines. Further options to improve CI engine efficiency and fuel economy include advanced technologies such as turbocharging and injection pressure increases (Jones 2008). It should be noted that the addition of exhaust gas recirculation (EGR) typical in 2004 and newer engine systems may require the addition of an intake air restriction to draw relatively low pressure exhaust gas into the intake manifold. This restriction acts like a throttle on an SI engine and reduces the pumping efficiency. New technology using high-pressure EGR loops and variable geometry turbochargers alleviate the addition of an intake throttle for EGR implementation.

10.2.3.1 Diesel Engine Emissions: NOx and PM
Despite higher efficiencies, CI engines fueled with diesel exhibit a disadvantage in terms of regulated toxic emissions and their reduction in aftertreatment systems. Of particular concern are NOx and PM composed of dry soot and soluble organic compounds (SOCs). There is an inherent tradeoff in these two emissions in a diesel-fueled CI engine: when one is reduced the other will increase. NOx is formed in the higher-temperature, near-stoichiometric combustion regions with soot forming in the lower temperature, fuel-rich regions of the combustion zone. These emissions can be reduced using various means internal and external to the engine. Internal reduction methods include changes in fuel injection pressure and timing as well as fuel–air mixture dilution. External reduction methods include aftertreatment systems consisting of an oxidation catalyst for HC and CO reduction, a particulate filter to reduce PM emissions, and a selective catalytic reduction (SCR) catalyst to reduce NOx emissions.

The use of oxygenated fuels, such as biodiesel, in a CI engine reduces PM emissions with resultant smaller increases in NOx. As a means for decreasing NOx emissions with biodiesel, EGR can be added or combustion phasing can be delayed, resulting in similar NOx emissions but still lower PM emissions relative to diesel fuel, as seen in Figure 10.9 (Polonowski et al. 2010). In addition to biodiesel, DME is a promising fuel for CI engines, with low exhaust emissions including very low PM. However, because of its high volatility (gas at ambient temperature–pressure) and low lubricity, the fuel and injection system must be modified from a conventional design. DME can be blended with conventional diesel, but this still results in a high-volatility fuel requiring specialty systems.

10.2.4 Impact of Biofuels on Current Engine/Vehicle Operation
It should be apparent that biofuels affect engines and transportation vehicles in many ways. Biofuels affect emissions (as previously discussed) and can have a significant impact on full load power. The impact areas that vehicle owners and operators tend to be most sensitive to are fuel economy, maximum driving range between fueling, and initial purchase cost. Additionally, vehicle owners are affected by the significant variation in implementation costs for alternative fuels. From the manufacturers’ point of view, enabling a vehicle originally designed to run on petroleum-based fuel to operate on biofuel can be a significant challenge. For example, the fuel system materials may
need to be changed to be compatible with the alternative fuel as is the case in enabling a gasoline vehicle to run on ethanol or methanol blends or a diesel engine to run on biodiesel. Piston rings and valve seats are often upgraded to be compliant with the alternative fuel, which can also add cost. Electronic determination of the type of fuel currently in use can be required. In some cases this can be done with relatively low cost through the use of “virtual sensors,” which are software algorithms operating within the vehicles controller that utilize inputs from existing sensors to determine fuel type. There is an additional cost for increased engineering effort because of the additional calibration and federal certification required. However, if production volumes are sufficiently high, this increased cost is low on a per vehicle basis.

One issue with some fuels is their poor cold-start characteristics, on the basis of their fuel properties. In the case of diesel engines, DME has a higher cetane number than petroleum diesel (Table 10.2), which promotes ignition by reducing the required compression energy for autoignition. In conjunction with its low boiling point, this helps reduce ignition delay, improve fuel–air mixing, and therefore minimize cold-start issues. On the other hand, biodiesel exhibits fuel gelling in colder environments, a characteristic common in petroleum ultralow sulfur diesel (ULSD). In the case of SI engines, ethanol fuel results in different cold-starting issues. Ethanol does not vaporize significantly in low-temperature conditions because of lower vapor pressure and higher heat of vaporization (17 kPa vapor pressure vs. 62 kPa at 100°F for gasoline, and 900 kJ/kg heat of vaporization vs. 400 kJ/kg for gasoline) and hence the fuel–air mixture is not rich enough (attributed to limited vaporization) to combust (Davis et al. 2000). Hence, cold-start issues are common to alcohol fuels. Adding gasoline to the mixture (e.g., yielding E85) helps to reduce, but not overcome, this issue because the vaporized gasoline can assist with initial combustion; however, cold-start emissions can be higher (Davis et al. 2000).

10.3 SUMMARY

In this chapter, we discussed the effect and interdependencies of fuels, engine type, aftertreatment, and vehicle technologies with a focus on biofuels and where they fit into current and future technologies. The energy densities on a volumetric basis for the oxygenated biofuels are lower than their comparable petroleum fuels. Furthermore, combustion of a carbon-based fuel, be it gasoline, ethanol, diesel, or biodiesel, in the presence of oxygen, produces CO₂. When normalized, the CO₂ produced from combustion on an energy basis for the petroleum and bio-based liquid fuels are within ±7% of gasoline.
Biodiesel has the closest energy density to petroleum fuels, with butanol the next closest. For the gaseous fuels (hydrogen and CH₄), although high in energy on a gravimetric basis, the volumetric energy density is low even at high pressures. Significant advancements in storage will be required to match the energy density of the liquid fuels. Furthermore, fuels such as biodiesel and DME are better suited to CI engines, whereas other fuels such as ethanol and gaseous fuels are better suited to SI engines. Even so, it is difficult to take full advantage of biofuels such as ethanol with a high octane rating when designing a FFV because many design parameters have to be specified for the “worse-case” fuel mixture in the vehicle tank.

REFERENCES


Biofuel Use from Bioenergy Crops


