

# Future Substitutes for Diesel Fuel in U.S. Truck and Railroad Freight Transportation

by C. Phillip Baumel

*This paper explains why diesel fuel is the preferred fuel in freight transportation. It identifies possible substitute fuels for motor carriers and railroads that are currently available and under development. It identifies which of these substitutes are likely to be used in the near and medium term years and the circumstances under which they will be used. The paper discusses which fuel efficiency measures have been successfully adopted by railroads and motor carriers. Finally, it suggests opportunities for transportation researchers to evaluate investment options to improve fuel efficiencies in freight transportation.*

## INTRODUCTION

In 1878, Rudolph Diesel, a student in Munich, Germany, learned that the new internal combustion gas engine, developed by Nikolaus Otto, converted only a small percent of the fuel energy into mechanical energy (Kong 2012). He also learned that a higher compression ratio in a combustion cylinder should produce greater fuel efficiency and more power. The theory was that higher air compression would create enough heat to ignite the fuel in the cylinder. The resulting high temperature explosion would burn more of the energy in the fuel; this would create greater energy efficiency and more power than Otto's spark-ignited engine. Five years later, Rudolph Diesel developed a compressed ignition—diesel—engine that worked. In 2010, medium- and heavy-duty trucks consumed 91% (33.3 billion gallons) of all the diesel fuel consumed on U.S. highways (U.S. Department of Energy 2012). Class I railroads consumed 3.5 billion gallons (AAR 2011).

The fundamental difference between diesel- and gasoline-powered internal combustion engines is the method of igniting the fuel in the combustion chambers (Kong 2012). The mixture of air and fuel injected into the cylinders of gasoline engines is ignited by a spark from the spark plug in each cylinder. Diesel engines have no spark plugs. Rather, the fuel is ignited by the very high air temperature in the high compression ratio diesel combustion chamber. The compression ratio is the volume of the cylinder and combustion chamber at the bottom of the piston stroke divided by the volume at the peak of the piston stroke (Kong 2012). The compression ratio in gasoline engines ranges from 8 to 12. The compression ratio of diesel engines ranges from 14 to 25. The lower compression ratio of gasoline engines restricts them to converting about 35% of the energy in the fuel to move a vehicle. The higher compression ratio of diesel engines enables them to convert up to 55% of the energy in the fuel to move a vehicle or ship. However, if a mixture of fuel and air is injected into the cylinder of a diesel engine, the high compression ratio could induce an undesired pre-ignition, causing the engine to knock. Thus, in Diesel's new engine, only air is induced into the cylinder and the liquid fuel is injected into the combustion chamber near the peak of the compression stroke.

Other advantages of diesel power over gasoline include:

1. Diesel fuel contains more energy than gasoline. One gallon of diesel fuel contains about 128,700 British Thermal Unit (Btu) while one gallon of gasoline contains 115,400 Btu (Table 2). One Btu is the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit.

2. Diesel fuel emits only small amounts of carbon monoxide and hydrocarbons that are attributed to global warming. However, diesel fuel emits large amounts of nitric compounds and soot that lead to acid rain, smog and health problems.
3. Diesel fuel has better lubricating properties than gasoline, which helps make diesel engines last longer. However, reducing the sulfur content in diesel fuel decreases its lubricating property.
4. Until recently, diesel fuel prices were lower than those for gasoline. Currently, diesel fuel prices exceed gasoline prices, in part, because of increased costs of removing sulfur, soot, and other pollutants.

With all of the advantages of diesel engines and fuel, why are we searching for alternative fuels?

1. Diesel fuel is made from crude petroleum. At the end of 2010, the United States had proven technically recoverable reserves of about 25.2 billion barrels of petroleum, up from 22.2 billion barrels in 2009 (Energy Information Administration [EIA] August 2, 2012). This increase was the result of crude oil discoveries associated with the recent major increases in natural gas reserves, mainly in Texas and North Dakota. Total domestic crude petroleum extraction in 2010 was 2.0 billion barrels (EIA August 2, 2012). At this rate of extraction, the U.S. has about a 13-year supply of proven domestic crude petroleum reserves. Of course, supplies in proven reserves change with discoveries, prices, and annual production. Proven recoverable reserves do not include non-conventional supplies like shale and sand oil and some off-shore deposits. The EIA (April 15, 2013) estimated that the total U.S. proved and unproved petroleum reserves in 2011 were 219 billion barrels.
2. The U.S. imported 40% of its 2012 petroleum usage (EIA April 15, 2013). A substantial amount of those imports came from Middle East and African countries that are hostile to the U.S.
3. The huge outflow of dollars to pay for petroleum imports increases our balance of payment deficits, and the cost of all imports, including oil.
4. Combustion of diesel fuel produces large amounts of carbon dioxide.
5. In 45 years, at current rates of extraction, conventional world petroleum prices will rise to a level that will prohibit its use for many of its current purposes (Brown and Brown 2012).

## **ALTERNATIVES TO DIESEL FUEL**

### **Biodiesel**

The major commercially available biofuel substitute for diesel fuel in the United States is biodiesel. A large amount of biodiesel is made from inedible fats and oils, waste restaurant oils, and byproducts like inedible corn oil. Biodiesel is also made from virgin vegetable oils, including soybean and canola oil. However, soybean and canola oil prices are higher than those of used and inedible fats and oils. Therefore, virgin oils are typically used in biodiesel plants that are not designed to use waste and inedible fats and oils, or if there are insufficient supplies of lower cost feedstocks.

The December 2007 Energy Independence and Security Act mandated that biomass diesel be blended into diesel fuel. Beginning in 2010, the Environmental Protection Agency (EPA) mandated that 800 million gallons of biomass diesel be blended into diesel fuels. This mandate could be satisfied by biodiesel and/or biomass diesel. Thus far, biodiesel has been the dominate fuel to satisfy the EPA mandate. This mandate increased to one billion gallons in 2011 and to 1.28 billion gallons in 2013 (Renewable Energy Group, Inc. [REG] 2012). This mandate insures that there will be a market for biodiesel even if biodiesel costs more than petroleum-based diesel. Data from REG, the producer of the largest number of gallons of biodiesel in 2012, illustrate this point. In 2012, this company sold 188 million gallons of diesel fuel in the United States (Table 1). The feedstocks for 84% of that production were inedible animal fat, used cooking oil, and inedible corn oil extracted

from distillers' grains, a byproduct of ethanol production. The use of these lower-cost fats and oils helped make this company one of the low-cost biodiesel producers in the industry. Only 16% of its production came from higher-cost soybean oil.

Table 1 indicates that the average 2012 wholesale price of these 188 million gallons of biodiesel produced by this low-cost biodiesel producer was \$5.31 per gallon. The average 2012 U.S. retail price of petroleum diesel was \$3.97 per gallon (EIA February 5, 2013). This indicates that the average 2012 wholesale price of biodiesel paid to this low-cost biodiesel producer was approximately \$1.34 per gallon above the average U.S. retail price of petroleum diesel. Table 2 suggests that, with a diesel price of \$4.00 per gallon, the Btu value of 100% biodiesel is \$3.64. There are four major reasons why this low-cost producer of biodiesel, with 9% fewer Btu than diesel, was able to sell its 2012 output at a price that was, on average, \$1.34 above the average 2012 retail price of petroleum-based diesel. These reasons are:

1. The federal government mandated that one billion gallons of biodiesel be blended into diesel fuel in 2012.
2. To track the sales of renewable fuel production, the EPA created the renewable identification number (RIN) system. All EPA registered producers of renewable fuels may create an RIN for each gallon of renewable fuel produced (REG 2012). RINs have value to "obligated parties" to satisfy their renewable volume obligation under the Renewable Fuel Standard legislation. Most biodiesel is sold with its RIN attached. RINs may also be sold as a separate commodity. The 2012 values of RINs ranged from \$2.39 per gallon in January to a low of \$0.63 per gallon of the average Jacobsen B100 Upper Midwest spot price of a gallon of biodiesel (REG 2012).
3. The blender's tax credit provided a \$1.00 excise tax credit per gallon of 100% biodiesel to the first person who blended biodiesel with petroleum-based diesel fuel (REG 2012). The tax credit could then be credited against the blender's excise tax liability, or the blender could obtain cash refunds from the U.S. Treasury for the value of the credits. This tax credit expired on December 31, 2011, and was renewed on January 1, 2013.
4. Many states and cities offer various types of mandates and financial incentives to encourage the use of biodiesel over petroleum-based diesel (National Biodiesel Board 2012).

**Table 1: REG Biodiesel Sales and Cost of Goods Sold, 2012**

Biodiesel sales	\$1,006,471,000
Gallons sold	188,000,000
Sales per gallon	\$5.35
Less assumed byproduct sales per gallon	\$0.04
Net biodiesel sales per gallon	\$5.31
Cost of goods sold	\$956,448,000
Cost of goods sold per gallon	\$5.09

Source: REG 2012

**Table 2: Btu Content and Diesel Equivalent Gallons of Alternative Fuels**

Fuels	Unit of Measure	Btu Content	Diesel Gallon Equivalent
Diesel	Gallon	128,700***	1
Gasoline	Gallon	115,400***	1.12
Biodiesel	Gallon	117,093***	1.1
Compressed Natural Gas	100 Cubic feet	96,000***	1.34
Liquified Natural Gas	Gallon	75,000**	1.72
Ethanol	Gallon	75,670***	1.7
Hydrogen	100 Cubic feet	31,900**	4.03
Synthetic Diesel	Gallon	128,639*	1

Source:

\*KiOR (2013)

\*\*Wikipida (May, 2013)

\*\*\*U.S. Department of Energy (2011-2013)

The market value of the RINs, in combination with the blender's tax credit, the Federally mandated blending of biodiesel, and state and city incentives, enabled biodiesel producers to sell biodiesel to obligated parties in a market in which the competitive product, petroleum-based diesel, is sold at a substantially lower price.

Biodiesel sold for transportation purposes is blended with petroleum-based diesel. A common blend, B10, is 10% biodiesel and 90% petroleum diesel. Blends can range from B1 to B99. There are several reasons for blending these two fuels:

1. The federal government mandates blending of biodiesel with petroleum based diesel.
2. The higher cost of biodiesel is an incentive to spread its high cost over a large number of gallons of a lower cost petroleum diesel fuel.
3. The blended biodiesel helps improve the lubricity of low sulfur petroleum-based diesel. Lubricity is the capacity to reduce friction.
4. Blending reduces the "cloud point" of biodiesel. The cloud point is the temperature below which the appearance of a fuel becomes cloudy. Cloudiness indicates that the fuel is likely to gel (REG 2012). This could lead to plugged fuel filters and other handling and performance problems. Biodiesel begins to gel at 30 to 60. The cloud point for diesel fuel is below 20° F. Blending reduces the cloud point for the blended biodiesel, but increases the cloud point of the blended petroleum diesel.
5. Diesel fuel contains 128,700 Btu. Biodiesel contains 117,093 Btu. Blending results in a weighted average of the two.

There are three other issues with biodiesel. First, biodiesel contains oxygen, while diesel contains none. Oxygen makes the fuel unstable and tends to make it crystallize over time as well as in cold temperatures. The crystals tend to clog engine fuel delivery systems. Therefore, a good biodiesel management program is needed to prevent these problems (Ring 2011).

Second, there are limited supplies of low-cost feedstocks to produce biodiesel. Reidy (2012) suggests that finding feedstocks to produce the mandated blending, 1.28 billion gallons of biodiesel in 2013, will be tricky. According to Reidy (2012), the supply of inedible corn oil will top out at 300 million gallons of biodiesel production. The meat packing industry, the source of most animal fats, will supply enough animal fats to produce about 400 million gallons of biodiesel. The remaining 580 million gallons will need to come from used cooking oils and virgin soybean and/or canola oil. Reidy (2012) indicates that the EPA and USDA believe the additional soybean oil will come

from reduced U.S. soybean exports; she also indicates that world demand for virgin vegetable oil is increasing. Thus, if Reidy (2012) is right, biodiesel producers will be forced to compete with international vegetable oil buyers for virgin vegetable oils. This suggests that biodiesel producers could be forced to pay higher prices for virgin vegetable oils and for inedible feedstocks to meet the 2013 EPA mandate of 1.28 billion gallons of biodiesel. Potential shortages of biodiesel feedstocks could increase the costs and/or slow the growth of biodiesel production above its current 3% of diesel consumed on U.S. highways.

Third, a fundamental principle of economics is that a firm will not produce a product if the price it receives for that product is equal to or less than the variable cost of producing that product. The logic of this principle is that a firm will continue to produce a product only if the price it receives covers its variable costs per unit of output and, at least, some of its fixed costs. Assuming that the REG (2012) variable cost of production was the \$5.09 per gallon cost of goods sold (Table 2), it is likely that biodiesel producers would shut down some of their high-cost plants after the EPA mandated blending of 1.28 billion of gallons is reached. This is because wholesale buyers would no longer be forced to buy biodiesel when its price is substantially above the wholesale price of petroleum diesel. Unless the EPA increases the biodiesel mandate above the one billion or 1.28 billion gallons, biodiesel firms are likely to first close those plants that must use higher cost vegetable oils as their only feedstocks. Then, if biodiesel prices continue to fall to the variable cost per unit of plants that use lower-cost feedstocks, firms would then begin to close some of these plants as well.

How will trucking firms respond to biodiesel fuels in the future? As long as the EPA continues to mandate a minimal use of biodiesel fuel in transportation fuels, trucking firms have little choice but to buy biodiesel blended fuels. However, not all refueling stops sell biodiesel blended fuels. So, at least, truckers can avoid using some biodiesel blended fuels by their selection of where they refuel. Once the mandated quantities are sold, truckers can seek biodiesel that is priced below the cost of petroleum or avoid the use of biodiesel in states that do not mandate that all diesel fuel must be blended with biodiesel. Moreover, truckers will especially attempt to avoid purchasing biodiesel blended fuels in northern states during cold winter months to avoid fuel that becomes cloudy and clogs their fuel distribution systems.

How will railroad companies respond to biodiesel fuels in the future? Numerous biodiesel performance tests have been made on medium-speed diesel engines in North American railroad locomotives. These tests, including various blends of biodiesel and petroleum-based diesel, raised concerns about the following issues (Majewski et al. 2011):

1. Compatibility between biodiesel fuel and medium-speed diesel locomotive engines. These issues include material compatibility, fuel system compatibility including fuel leakage, and engine oil dilution. These issues were more serious on heavy-duty, line-haul locomotives than on lower power switch engine locomotives.
2. Higher NO<sub>x</sub> emission from biodiesel powered locomotives, particularly in heavy duty, line haul service.
3. Lower Btu content of biodiesel generally causing reduced locomotive power.
4. Handling, storage and engine performance problems associated with gel forming in low temperatures and oxidation of biodiesel.
5. Higher cost of biodiesel.
6. Potential problems with manufacturer's warranties on diesel engines and fuel injection systems, particularly with higher amounts of biodiesel blended with petroleum-based diesel fuel.

The general conclusion from the biodiesel tests on railroad locomotives is that railroads are unlikely to use biodiesel beyond the federal, state, and city usage mandates. After the mandated quantities are sold, railroads, like truckers, will likely try to purchase lower-cost petroleum in states that do not mandate that all diesel fuel must be blended with biodiesel or seek biodiesel that is priced below the cost of petroleum diesel.

## Renewable Diesel

Renewable diesel usually refers to hydro-treated vegetable oils or animal fats (Majewski et al. 2011). The feedstocks for biodiesel are treated with hydrogen to remove their oxygen. This process produces a diesel fuel with no stability or low temperature operability problems that have been associated with biodiesel. The properties of renewable diesel are similar to gas-to-liquid (GTL) synthetic diesel fuels. The cetane number for renewable diesel, a measure of the fuel's ability to self ignite, is very high; the higher the better for diesel fuel. Renewable diesel has no sulfur, oxygen, or nitrogen. Its clouding point is well below freezing and its heating value is similar to diesel. Also, its storage stability is good (Majewski et al. 2011).

There are no published cost analyses of renewable diesel production costs, but they are believed to be higher than the cost of producing biodiesel, which is currently higher than the wholesale price of petroleum-based diesel. There are no commercial renewable diesel production plants in the United States. There are, however, two production plants in Finland (Majewski et al. 2011).

## Algae Biofuel

Algae biofuel is a popular potential alternative to diesel fuel. President Obama suggested “a plant-like substance, algae” as a way of cutting dependence on oil by 17% (Gehrke 2012). Several companies, and some research institutions, predict that they will be capable of producing algae fuel on a commercial scale at the same price as petroleum in the near future (Brown and Brown 2012).

The algae that are proposed as a partial solution to our energy problem are not the algae plants commonly found in ponds of water across the country. Rather, it is a group of single-cell microorganisms that produce large amounts of lipids. Lipids can be transformed into hydrocarbons that are essentially indistinguishable from gasoline or diesel fuels (Brown and Brown 2012). There are about 50,000 species of microalgae (Wen 2012). One of the major problems facing researchers in the development of algae fuels is finding those species of microalgae that produce the most lipids. At the present time, the average lipid content of algae is 5%–10% of their liquid content (Wen 2012). In theory, it is possible to genetically modify microalgae to contain in excess of 50% of lipids (Wen 2012). Other major problems include designing the most productive methods of growing the algae. Two methods of production currently getting the most research attention are open ponds and enclosed plastic “photobioreactors” (Brown and Brown 2012). Open ponds cost \$100,000 per acre and the photobioreactors cost \$1 million per acre. Another major problem is the harvesting and extraction of the lipids on a daily basis. A Department of Energy study suggests that it costs over \$10 to produce a gallon of algae diesel from open ponds and about \$20 per gallon from photobioreactors (Davis et al. 2011). The study suggests that the cost of algae diesel could fall to about \$4 per gallon with major improvements in algae lipid content and production, greatly reduced harvesting and extraction costs, and the sale of the spent biomass at \$500 per ton (Davis et al. 2011). Some researchers suggest that they are three to five years from large-scale production (Herman 2010). Others indicate that there have been no major breakthroughs and that commercialization of algae diesel is decades away (Wen 2012).

Algae fuels are sometimes referred to as third generation biofuels. Other potential sources of lipids for diesel fuel are palm oil, jatropha, a hardy group of wild tropical plants, and salicornia, a salt-tolerant plant that grows in marshes and beaches. Both jatropha and salicornia face several decades of development if they prove to be good sources of lipids (Brown and Brown 2012). There is substantial environmental resistance to the use of palm oil for fuels because of the destruction of rainforests to produce palm oil (Brown and Brown 2012). Trucking and railroad firms will not need to decide if they should purchase algae fuels until it becomes available commercially, likely some decades away.



## Natural Gas

Natural gas (NG) consists of about 90% methane. It originated from the remains of historical plants and animals and was formed by the great pressure exerted over centuries by the thousands of feet of rocks, sand, and debris covering the plant and animal remains. Small droplets of the odorless gas accumulated into NG deposits and petroleum and coal deposits. Recently, large quantities of NG have been found in shale formations.

In 2010, the United States had proven NG reserves of 317 trillion cubic feet (tcf). The 2012 production of NG was 23.2 tcf (EIA May 2013). At that level of production, the 317 tcf would only last 13 years. The good news is that the U.S. has huge quantities of unproven NG reserves locked deep in shale formations. The EIA (June 2012) estimated that the total technically recoverable NG reserves in the United States were 2,214 tcf. At the 2012 level of production, 2,214 tcf would be more than a 95-year supply. Other observers suggest that the EIA estimate of total technically recoverable reserves is too low (National Geographic News 2012).

A large portion of the huge unproven reserves of NG has been made available to U.S. markets by hydraulic fracturing, commonly called fracking. Fracking pumps more than one million gallons of water, chemicals, and sand under high pressure into each well. These wells vary in depth, but can be as deep as 10,000 feet. After reaching the desired depth, the drilling extends horizontally across the shale formation (EIA September 19, 2011). The high pressure of injected water, chemicals, and sand fractures the shale formations and allows the NG and other hydrocarbons that exist there to escape the shale and flow up the well. The sand keeps the fractures open, allowing the gases to flow into the well over time.

NG has been used extensively to heat homes and buildings, in industrial production and for generating electricity. Because of its gaseous nature, only about 3% of NG has been used in transportation, much of it to propel NG through pipelines. The huge quantity of NG now being produced from shale formations has resulted in sharp declines in NG prices. In March 2008, the NG futures price was above \$13 per million Btu (MMBtu). By late November 2011, the price had declined to just over \$2 MMBtu, a decline of 85% (Irwin 2012). During the same period, the NYMEX crude oil futures price declined from \$140 per barrel to \$98 per barrel, a decline of 30% (Irwin 2012). These sharply declining NG prices have made it a potential fuel for freight transportation.

Table 3 shows the average national retail prices of diesel, CNG, and biodiesel prices on a diesel equivalent basis for seven time periods from October 2011 to April 2013. These were retail pump prices and included state and federal taxes. CNG prices averaged \$1.61 per diesel gallon equivalent below diesel prices. B100 biodiesel prices averaged 77 cents per gallon higher than diesel prices. Table 2 suggests that the BTU value of a gallon of B100 biodiesel is about 9% below the Btu value of a gallon of petroleum-based diesel.

**Table 3: Natural Gas, Diesel, and Gasoline Prices in Diesel Gallon Equivalent, Selected Months, 2011-2013**

Month	Year	CNG	Biodiesel*	Diesel
April	2013	\$2.34	\$4.72	\$3.99
January	2013	2.34	4.88	3.96
October	2012	2.36	4.82	4.13
July	2012	2.28	4.64	3.75
April	2012	2.32	4.78	4.12
January	2012	2.38	4.61	3.86
October	2011	2.33	4.59	3.81

\*B100

Source: U.S. Department of Energy, (various issues, 2011-2013)

NG has several major advantages as an alternative to diesel fuel. These include:

1. As shown in Table 3, its low price is its major advantage.
2. A large domestic supply is made available mostly by fracking
3. Its use as an alternative to diesel fuel would help reduce U.S. petroleum imports. This would help reduce the deficit in the U.S. balance of payments, and increase the value of the U.S. dollar. It would also help decrease the cost of imports and domestic and imported petroleum.
4. NG is safer to use than petroleum diesel. It is inflammable in liquid form. In gaseous form, NG is flammable only in the range of a 5%–15% mixture of NG with air. It is lighter than air and, if spilled, quickly rises and dissipates into the air. NG fuel tanks are sturdier than diesel fuel tanks. In an emergency, release valves in NG tanks open above ambient temperatures and below ignition temperatures to allow the gas to harmlessly rise into the atmosphere (about.com 2013).

As with all alternatives to petroleum diesel, NG has some obstacles. These include:

1. NG is a gas, not a liquid. It requires major costly changes in engine and fuel distribution systems.
2. Its low energy density and gaseous form requires that it be converted into alternative forms to be used as a fuel for freight transportation. Two common conversions are “compressed NG” (CNG) and “liquefied NG” (LNG). CNG is NG under pressure of 3,000- to 3,600-pounds per square inch. LNG is NG that has been cooled to -260°F. At that temperature, it changes from a gas to a liquid that is 1/600<sup>th</sup> of its original volume. CNG is less expensive to produce and store than LNG, because it does not require expensive cooling and cryogenic tanks.
3. There are only a limited number of public NG fueling stations. Moreover, most of these early NG fueling stations have low capacity — one-to-two gallons per minute — refueling pumps, requiring long wait times to fill the NG tanks of trucks.
4. There is substantial environmental resistance to fracking. The argument is that the waters and chemicals used in fracking contaminate local water supplies.
5. NG is less energy dense than diesel. The reduced energy density means that a vehicle powered with CNG must either be used for short distances before being refueled, or carry large amounts of CNG. LNG-powered vehicles can travel longer distances before refueling, but still shorter distances than with diesel-powered vehicles.
6. Special refueling infrastructure must be provided to refuel vehicles that travel beyond the vehicle CNG or LNG carrying capacity. CNG powered trucks are typically limited to 200 one-way mile trips.



7. It is not clear that natural gas emissions, particularly nitric oxide emissions, are always less than those of diesel fuel (Majewski et al. 2011).

The recent availability of large supplies of NG, combined with its dramatic decline in price, make NG a potential substitute for diesel fuel.

EIA (June 2012) estimates that only 1,000 (0.3%) of the 360,000 heavy-duty vehicles sold in the U.S. in 2010 were NG fueled. In 2012, approximately 1% of the heavy-duty trucks sold in the U.S. were NG fueled (Carrick 2012). What is preventing NG from becoming a dominate fuel for the heavy duty, long-distance trucking industry? The major reasons are:

1. Higher NG vehicle costs
2. Reduced NG vehicle operating range
3. Insufficient number of refueling stations
4. Inadequate fuel pumping capacities at some existing NG refueling stations
5. Inadequate size NG engines to pull full loads over hills and mountains at acceptable speeds

The major additional costs of heavy-duty NG-fueled trucks over diesel-fueled trucks are fuel-storage and non-fuel-storage costs. The non-fuel-storage costs are the basically the costs of modifying the diesel engine to burn CNG or LNG. To make the engine operate entirely on NG, the piston is replaced to reduce the compression ratio and a spark plug is installed to ignite the fuel (Kong 2012). This modification makes the NG engine perform like a gasoline engine (Kong 2012). For new engines designed to operate on both NG and diesel, NG can be introduced into the intake port or directly into the cylinder. Another option is to use a new fuel injector designed to inject both NG and diesel into the cylinder (Kong 2012). EIA (June 2012) reports the cost of modifying the diesel engine of a semi-tractor-trailer truck to use NG is \$30,000. One firm, operating several NG-fueled semi-tractor-trailer trucks, reported non-fuel storage costs of less than \$20,000 per truck.

The fuel-storage cost is to replace the diesel tanks with tanks to hold either CNG or LNG. CNG storage tanks are designed to withstand internal pressure of up to 3,600 pounds per square inch. The tanks can be mounted on the sides of the frame and/or on the back of the cab. EIA (June 2012) estimates the cost of CNG storage tanks at \$350 per gallon of storage.

The amount of storage needed depends on the miles per gallon, the length of the haul, and the distance between NG refueling stations. The firm that operates several CNG semi-tractor trucks reported that its trucks each have four high pressure tanks, one on each side of the frame and two on the back of the cab. Each tank costs \$10,000 plus installation. Thus, the cost of the four CNG tanks was over \$40,000. The total additional cost of converting these tractors to CNG was \$60,000 each. EIA (June 2012) reports the incremental cost of NG class 8 (semi) trucks at \$80,000.

The trucking firm reported the CNG tractors achieved 5.53 mpde (miles per diesel equivalent). A diesel equivalent gallon is the amount of alternative fuel required to equal the energy content of one gallon of diesel fuel. Table 1 illustrates the diesel gallons equivalent of several alternatives to diesel fuel. The round-trip distance for its NG trucks was a maximum of 400 miles. Therefore, these trucks need enough fuel storage for the 400-mile round trip.

LNG is NG cooled to -260°F (Center for Liquefied Natural Gas 2012). At that temperature, the gas turns to a liquid that is 1/600<sup>th</sup> of its original volume. It is stored at this very cold temperature but not under high pressure. LNG must be stored in cryogenic tanks to maintain the very low temperature. Therefore, LNG tanks are more expensive than CNG tanks. LNG tanks cost about \$475 per gallon of capacity (EIA June 2012). The advantage of LNG over CNG as a transportation fuel is that it is more energy dense. It requires fewer gallons of tank storage for a given distance, or it can power a truck for longer distances on the same tank storage. Some companies are developing new materials that will likely allow more CNG or LNG to be stored in smaller containers (Carrick 2012). These developments offer the promise of longer lengths of haul per tank of NG and possibly lower cost per gallon of NG storage.

A third problem hindering increased usage of NG by trucking firms is the lack of NG fueling stations. In May 2012, there were only 1,047 CNG fueling stations and 53 LNG fueling stations in

the United States (EIA June 2012). Only 47% of the CNG stations and 43% of the LNG stations were accessible for public purchase of NG fuels. This means that many CNG trucks are limited to 400 round-trip miles.

The fourth problem is that the NG refill pumps at many of the existing fueling stations have very low pumping capacities (one-to-two gallons per minute) (Carrick 2012). These low pumping capacities require long refueling stops, adding to the cost of NG as a fuel. The longest refueling times are for trucks waiting in line to be refueled. These refueling problems are in the process of being solved. First, new fueling stations are coming on stream each month, most with refueling capacities of up to 10 gallons per minute. Some observers are predicting that within three years, there will be an additional 500 fueling stations, each with pumping capacities of 10 gallons per minute (Carrick 2012). Moreover, existing fueling stations are upgrading their refueling capacity.

The fifth obstacle to increased purchases of NG-powered trucks is that, until recently, the maximum size NG engine available for heavy-duty trucks was nine liters with 320-hp and 1,000 foot-pounds of torque. Liter refers to the volume of the cylinder from the top of the piston stroke to the bottom. Thus, a nine-liter NG engine has six cylinders. Therefore, each cylinder has a volume of 1.5 liters. One liter equals 1.0567 U.S. quarts. The relatively low Btu content of NG enables the nine-liter engine to generate adequate power for only local and regional service pulling 80,000 pound loads over level terrain (Carrick 2012).

Twelve-liter, six-cylinder engines (each cylinder having two liters of volume) with 400-hp and 1,450-foot pounds of torque are required for local and regional trucking service at acceptable speeds (Carrick 2012). The first 12-liter NG engine (Cummins Westpoint ISX12G) with an automatic transmission became available in early 2013 (Carrick 2013). This engine, with sufficient power to pull a full 80,000-pound load, enables NG-fueled trucks to become more prevalent in local and regional truck movements. Moreover, a 15-liter NG engine with 450-hp and 1,650-foot pounds of torque is under development for highway use. This engine will pull an 80,000-pound load at acceptable speeds over all types of U.S. terrain. With the introduction of the 15-liter engine in four to five years, and continued improvements in NG refueling infrastructure, trucking firms will likely be using NG as a fuel in coast-to-coast truck freight movements (Carrick 2012).

The question facing trucking companies is “What is the return on investment from NG fueled trucks?” One study reports that when diesel fuel is \$1.50 per gallon higher than CNG, and the trucks are driven at least 70,000 miles per year with a spark-ignited CNG engine, the return on investment from CNG will be about 20% per year. Romba (2012) suggests that NG can be a viable alternative to diesel for relatively short line haul distances.

Carrick (2012) suggests that a good rule of thumb to evaluate the economic feasibility of investing in NG trucks is that, with 80,000 miles per year, and the CNG price at 50% of the diesel fuel price, the initial investment in an NG truck will be recovered in 18 months. The data in Table 3 indicate that CNG prices were 40% below diesel prices. However, these were retail pump prices. A trucking firm, with its own NG facilities and/or contracts with refueling companies, is likely to face CNG prices near a 50% discount to diesel prices. After the recovery of the initial investment, NG-fueled trucks will save \$25,000 in fuel cost per truck per year. Carrick (2012) also suggests that by 2020, 5% to 10% of all heavy duty trucks sold in the U.S. will be NG trucks.

Under the assumption of no change in government programs and business as usual, EIA (June 2012) projects that NG heavy-duty truck sales will be about 26,000 per year by 2035 and the total number of heavy-duty NG trucks in the fleet would be 275,000 units.

Under more optimistic assumptions, including:

1. The availability of NG fueling stations
2. NG priced on a cost basis rather than on competing fuel prices
3. Differential NG prices for fleet and non-fleet operators
4. Taxes remain at current levels

EIA (June 2012) projects that heavy duty NG truck sales will increase dramatically to 275,000 per year by 2035. Under the more optimistic assumptions, EIA (June 2012) projects that the number of heavy duty NG trucks in the U.S. fleet would total 2,750,000 units or 21.8% of the fleet.

Railroads have been experimenting with NG products as a fuel for locomotives for over 75 years (AAR 2007). The first experiment took place in Missouri in 1936. The Joplin-Pittsburg Railroad placed a propane-fueled, 450-hp spark-ignited locomotive in service. This locomotive was later put in local service by the Kansas City Public Service Company. Several experiments were conducted from 1959-1980. One experiment, with a gas turbine locomotive, was abandoned because of low fuel efficiency; other experiments were conducted with locomotives using propane and CNG.

In 1992, the Burlington Northern Railway converted two diesel-electric SD-40 locomotives to run on a dual LNG-diesel mode. A 25,000-gallon fuel tender (LNG tank car) placed between the two locomotives, contained fuel for both locomotives. The two locomotives were then placed in unit train coal service. They were converted back to diesel fuel and general service in 1995.

In 1993, MK Rail Corporation introduced an LNG-fueled switch engine. Burlington Northern and Union Pacific each purchased two of these new switch engines. All four switch engines are still in service in California. The LPG is hauled into California by truck from Arizona. The conversion from diesel to dual diesel-LNG fuels reduced the horsepower of the switch engines from 2,000 to 1,250. The fuel consumption of the converted diesel-LNG engines to do the same work increased by 33%.

The railroad industry reached the following conclusions from these early experiments:

1. NG is not likely to provide the needed power for heavy duty, long-distance unit train service with the locomotive technology available at that time.
2. NG would require major investments in refueling facilities across the entire railroad system. NG prices at that time would not generate the savings needed to finance these refueling investments.
3. There were no NO<sub>x</sub> benefits and all other pollutant emissions were much higher than from the clean-burning diesel electric locomotives.
4. There may be a niche market for NG in switch locomotives. Switch locomotives usually remain in one location, thereby eliminating the refueling problem that NG would impose on line-haul locomotives traveling throughout the entire United States.

These early experiments were conducted when diesel and NG prices were close to being equal. Since then, NG prices have fallen dramatically relative to diesel fuel. These much lower NG prices have motivated all Class I railroads to begin reevaluating the possibility of using NG to power both long-haul, heavy-duty locomotives and switch locomotives (Fronczak 2013). Several railroads are currently working with locomotive manufacturers to develop efficient, clean-burning, and powerful NG locomotives (Bloomberg 2013). NG engines will need to be at least as clean burning as today's diesel engines to meet EPA emission standards. These reevaluations and actual experiments will attempt to determine if NG technologies can provide the power and clean burning performance of diesel-electric technologies at a lower cost. If the NG technologies can meet or exceed the diesel-performance at lower costs, the railroad industry will likely invest in NG locomotives and fuel tenders, and refueling, maintenance, and repair facilities. Other than biodiesel, NG is the only near-term alternative to diesel fuel for trucks. Thus, it is the most likely candidate to be a major substitute for diesel fuel for some decades until other alternatives are developed in laboratories and then take the long journey to commercialization.

### **Synthetic Diesel Fuel**

Diesel fuel can be produced synthetically from NG, coal, and biomass. Biomass includes crop residues, grasses, and wood products. The United States has huge quantities of biomass and coal. The U.S. has the largest reserves of coal (27%) in the world (Brown and Brown 2012). The coal

industry points out that the U.S. has a 250-year supply of coal at current rates of consumption (Brown and Brown 2012).

The best known synthetic fuel technology is the Fisher Tropsch (FT) process (Brown and Brown 2012). The FT process was developed in Germany during World War II when Germany was denied access to world petroleum supplies. South Africa also employed FT technology to produce fuel during its apartheid period. FT fuels are synthetic hydrocarbons produced by the action of metal catalysts at elevated pressures.

Another technology being developed to produce diesel fuel from biomass is fast pyrolysis. Fast pyrolysis deconstructs the biomass at very high temperatures to produce a mixture of organic compounds called bio-oil (Brown and Brown 2012). Hydro processing is then used to convert the bio-oil into renewable diesel.

There are several advantages of synthetic diesel fuels:

1. Synthetic diesel fuels require no modifications to existing engines.
2. These fuels can be mixed with and actually improve the quality of petroleum diesel.
3. They are liquids and can be distributed within the existing diesel distribution system.
4. Their sulfur content is near zero.
5. The supply of feedstocks (NG, biomass, coal) for synthetic fuel production is large.
6. Synthetic fuels have very high cetane levels.

Their disadvantages include (Majewski et al. 2011):

1. Except for synthetic diesel made from biomass, they have little or no greenhouse benefit relative to petroleum.
2. They have poor lubricity and cold flow properties.
3. Synthetic diesel made from coal has high carbon content, unless capture and sequestration technologies are incorporated in the production process.
4. They are likely to cost more than petroleum.

Chevron is using NG as a feedstock to produce a “gas-to-liquid” (GTL) synthetic diesel fuel in a new plant being built in Escravos, Nigeria. When completed in 2013, the new plant will convert 325 million cubic feet of natural gas into 33,000 barrels (1,386,000 gallons) of low-sulfur, synthetic diesel fuel each day (Chevron 2012).

In April 2013, KiOR, a Texas company, completed construction of a synthetic fuel plant in Columbus, Mississippi, that uses fast pyrolysis to produce cellulosic gasoline and diesel fuels from biomass (KiOR 2013). This plant has an annual production capacity of 13 million gallons per year. Its preferred feedstock is southern yellow pine wood chips. KiOR indicates that it will begin construction of a second plant in Natchez, Mississippi, in late 2013 (KiOR 2013). This second plant, also using yellow pine wood chips, will have an annual production capacity of 40 million gallons per year.

KiOR’s revenues will come from the sale of gasoline and diesel fuels and from the sale of RINs to customers who are not obligated parties under the Renewable Fuel Standards. The diesel production from this plant will count toward the EPA-mandated 1.28 billion gallons of biofuels.

KiOR estimates that its cost of production of cellulosic gasoline and diesel will be about \$1.80 per gallon plus financing and facility depreciation costs (KiOR 2013). This estimate is based on assumed input quantities and prices and excludes financing and depreciation costs. KiOR’s actual cost of production awaits production cost data from the operations of its two plants.

The demand for KiOR’s products, beyond the EPA, state, and city mandates, will depend on their selling prices. If its diesel price exceeds the price of petroleum diesel, truckers and railroads are unlikely to purchase quantities above the mandated amounts. The price of its non-mandated synthetic diesel will need to be about the same as or less than the price of petroleum diesel, because KiOR states that its fuels will be 1.7 GEE (gallons ethanol equivalent) (KiOR 2013). Assuming 75,670 Btu per gallon of ethanol, 1.7 GEE converts to 128,639 Btu per gallon for the KiOR diesel.

Petroleum-based diesel contains about 128,700 Btu per gallon, approximately the same as the 128,639 Btu in the KiOR synthetic diesel (Table 2).

When synthetic diesel becomes available commercially, it will likely become part of the EPA-mandated biomass fuels that truckers and railroads will be required to purchase up to the mandated quantities. Once the mandated quantities are sold, truckers and railroads will unlikely be willing to pay more for KiOR and other synthetic diesel than for petroleum diesel. On the other hand, even if the price of KiOR diesel is less than the price of petroleum diesel, KiOR will continue producing synthetic diesel as long as the price they receive exceeds their actual variable cost of production.

Given the huge supplies of NG, coal, and biomass in the United States, it appears that substantial research funds should be allocated to the Fisher Tropsch, fast pyrolysis, and other synthetic fuel production processes; this research should focus on reducing production costs and making synthetic diesel fuels more environmentally friendly.

## Hydrogen

Fuel cells are self-contained devices that convert hydrogen directly into electricity. The electricity then powers an electric motor to move the vehicle. Some experimental fuel cells have been installed in small autos, trucks, and one railroad locomotive. Thus far, fuel cells have been unable to produce adequate power for these vehicles and costs have been high. The conclusion from these tests is that commercial use of fuel cells for freight transportation is decades away (Chevron 2012). Some observers believe that fuel cells will one day replace diesel engines (Majewski et al. 2011)

A second hydrogen option is the hydrogen internal combustion engine. The hydrogen combustion engine is closer to commercial deployment than the fuel cell and it can be manufactured at prices costing 15% more than petroleum engines (Majewski et al. 2011). It can run on pure hydrogen or on a combination of hydrogen and CNG.

Hydrogen, a tasteless, odorless, and colorless gas, is not found freely in nature. It must first be extracted from other substances such as coal and biomass. Fundamental problems with fuel cells and hydrogen internal combustion engines include (Brown and Brown 2012):

1. The extreme difficulty and cost of extracting and storing gaseous and liquid hydrogen
2. The low energy density of hydrogen
3. High levels of emissions from extracting hydrogen from fossil fuels

It is likely that fuel cells and hydrogen internal combustion engines are decades away from commercialization.

## ELECTRICITY

Almost all U.S. railroad freight locomotives use a diesel-electric drive system. The output from the diesel combustion engine is used to generate electricity. This electricity drives the electric motor on each of the six drive axles on most heavy-duty, long-distance locomotives, to provide the high torque required to move the train (AAR 2007). This idea has been in existence for over a century. In the early 1900s, General Electric Company sold a gas-electric version of this idea to railroad companies (General Electric Company 1911).

The major benefit of the diesel-electric system is that it eliminates the need for mechanical transmissions. The issue being discussed in this section is not about the use of electricity to power trains. Railroads already do that. The issue is whether the electricity should be generated on-board the locomotive by a diesel engine, or generated elsewhere and transmitted to locomotives in movement from one location to another.

In this paper, railroad electrification refers to generating the electric elsewhere and transmitting it to locomotives. There are numerous electrified transportation systems around the world. One



example is the Trans-Siberian railway that extends 9,880 km from Moscow to Nakhodka, Russia. Many U.S. railroad passenger systems are electrified.

Electricity is supplied to railroad locomotives by an overhead wire (catenary) system. The technology for this system is well established and mature. Therefore, major innovations are unlikely. The advantages of electrified rail systems include (Majewski et al. 2011):

1. Zero emissions from the locomotives
2. Reduced noise
3. High power-to-weight ratios in passenger trains allowing rapid acceleration and high speeds
4. Alternative fuels (fossil, nuclear, renewable) can be used to generate the electricity
5. The use of regenerative brakes, which put the electric motors in reverse to convert the kinetic energy of a vehicle already in motion, into electricity. Reversing the electric motors acts as a brake on the vehicle and, at the same time, the kinetic energy of the moving vehicle powers the reversed electric motors to generate electricity that is fed into batteries to be used as power at a later time (howstuffworks 2013 and Kinetic Energy 2013).

The disadvantages include:

1. There is an exceedingly high cost of infrastructure and locomotives.
2. The high infrastructure cost would be prohibitive on low-traffic main and branch rail lines. Therefore, an electrified rail system would require capital investments in the entire electrical transmission infrastructure, new electric locomotives and a completely new electrical maintenance and support system. In addition, a complete duplicate diesel-electric infrastructure system, including diesel-electric locomotives and a maintenance and support system would be required to service the traffic to and from the lower traffic main and branch rail lines.
3. There are potentially high emissions from electrical generation.
4. Some tunnels may not be large enough to accommodate the catenary system.
5. A single infrastructure failure on the electrified system would close down the entire electrified system served by that infrastructure.
6. The maturity of the technology means that major innovations are unlikely.

Given the huge cost of electric infrastructure, the need for dual electric and diesel systems and the lack of new technology, an electrified rail freight system is not likely to be economic under most short- and medium-term fuel price scenarios.

In the 1920s, the railroad system in the Northeast United States, called the Northeast Corridor, was converted from coal-fired steam engines to an electrified system. This electrified system was an improvement for both passenger and freight traffic over the steam engine system. During the 1950s and 60s, the remaining U.S. rail freight system was converted from the steam engine system to the diesel-electric system. By the 1970s, it became abundantly clear that the diesel-electric system was superior to the electrified system for freight traffic. In the 1980s, the Northeast Corridor rail freight system was converted from electricity to diesel-electric. The Northeast Corridor passenger rail system remains electrified and 80% of that system is owned and operated by the government-owned Amtrak passenger service. In fact, the fast starts and high speeds of light weight passenger trains are well served by electrified rail systems. Today's highly efficient, powerful, clean burning diesel-electric system, however, is operationally and profitably preferred for heavy-duty freight traffic over an electrified system. Nevertheless, the question continues to be asked "Should the entire current rail system be electrified to reduce petroleum consumption and imports in the United States?"

The answer to the above question is that electrification of the U.S. rail freight system will not occur unless and until diesel and diesel substitute prices rise to a level that will economically justify the huge expenditures needed to build and operate a new electrified system. Today, no one knows what those prices will need to be to economically justify the conversion of railroads to electrification. Another alternative is that the government, in an effort to reduce petroleum imports,



politically mandates the electrification of the railroad system. If that happens, the government will need to determine where it will obtain the huge amounts of capital to finance the electrification and operation of the rail system.

## FUEL EFFICIENCY

Freight transportation fuel efficiency is often defined as the number of miles one ton of product is moved per gallon of fuel. It is expressed as revenue ton-miles per gallon. Therefore, higher ton-miles of revenue freight per gallon indicate higher fuel efficiency. There has been more discussion of finding substitute fuels for petroleum-based fuels than in identifying the role of fuel efficiency as a substitute for petroleum. This section will discuss the role of fuel efficiency as a partial substitute for diesel fuel in the railroad and trucking industries.

In 1975, Class 1 railroads used 3.7 billion gallons of diesel fuel to produce 754 billion revenue ton-miles of freight. In other words, in 1975, Class 1 railroads achieved 206 revenue ton-miles of freight per gallon of diesel fuel (AAR 2011). In 2011, the Class 1 railroads again used 3.7 billion gallons of diesel fuel to produce 1,729 billion revenue ton-miles of freight. This represents 469 revenue ton-miles per gallon of fuel, an increase of 128% over 1975. Thus, in 2010, the Class 1 railroads moved 128% more ton-miles of freight with the same amount of fuel that they used in 1975. This is a major improvement in fuel efficiency. In effect, the gains in railroad fuel efficiency saved 4.7 billion gallons of diesel fuel in 2011 compared with the 1975 revenue ton miles per gallon. These gains in fuel efficiency were achieved in several ways, including the following (National Petroleum Council 2012):

1. The tons of revenue freight per car were increased by reducing the tare weight of the empty cars. In addition, improved wheel and truck design reduced rail car resistance.
2. Improved engine technology and shifting from direct current to alternating electric current technology reduced the amount of power needed to move a given amount of freight.
3. Positioning locomotives throughout the train reduced the power requirements to start moving the train, as well as to change speeds.
4. Infrastructure improvements reduced the number of slow speed operations, idle time, and the number of speed changes. An illustration of this infrastructure improvement was the rebuilding of the Kate Shelley Bridge, located on the heavily traveled Union Pacific Railroad mainline from Omaha to Chicago. This bridge is located three miles west of Boone, Iowa. This double track bridge, built in 1901, was designed for the small trains in use at that time. By the year 2000, typical unit coal trains on this mainline consisted of 115 cars, each with gross loaded weights of 143 tons and pulled by three highly efficient, fast locomotives. The condition of the bridge had deteriorated to the extent that train speeds were limited to a maximum of 25 mph and only one train could cross the bridge at a time. Trains would often be backed up for miles waiting for their turn to snake across the bridge. With their diesel engines idling as they waited for their turn, trains would cross the bridge at slow speeds and then use more fuel to resume their assigned travel speeds. The Union Pacific Railroad spent more than \$50 million to build a new double track bridge that was opened in 2009. Now, two trains travel across this bridge simultaneously at speeds up to 70 mph with no slowdowns or waiting stops, thus saving substantial amounts of fuel compared with the old bridge.
5. Track technology, maintenance and control systems have been improved.
6. New GenSet switch locomotives have two or three 627 or 700 hp diesel engines rather than one 2,000+ hp diesel engine (AAR 2007). The purpose of GenSet locomotives is to match the engine power with the needed power to perform an assigned function. One engine is used for light functions and the other(s) remain off. Two or three engines are used to move

heavier loads. So far, GenSet locomotives have been used mostly in switching duties and have saved up to 37% of the fuel used by single engine switch engines.

7. Lubrication of railheads and wheel flanges reduces train friction, and automatic sanding reduces locomotive wheel slippage when starting train movement.
8. Electronic controls operate trains more efficiently, and engine shutdown policies and start-stop systems have been implemented.
9. Empty backhauls have been reduced and more efficient routing has been achieved.
10. Aerodynamics have been improved.
11. Crew training, including reward programs for top fuel efficiency, have been implemented.

Each of these developments contributed to the railroad's 128% increase in revenue ton-miles per gallon of fuel since 1975. Railroad fuel efficiency is expected to continue to increase as older rail cars and locomotives are replaced by new ones that have all of the current fuel efficient features in place. In addition, railroads will implement new efficiency developments as they become available.

Trucks have also achieved substantial gains in fuel efficiency. Many of these gains were obtained from the following developments:

1. Hybrid electric vehicles have generated a 14% improvement in fuel efficiency. Most of the gains in fuel efficiency from hybrid electric trucks occur in high density stop and start service (Walkowicz et al. 2012).
2. Diesel engine technology has been significantly improved to increase the fuel efficiency and to meet exhaust emissions mandates. The advancements in the combustion technology include high fuel injection pressure to create better fuel-air mixture, multiple fuel injection pulses in one engine cycle to facilitate combustion control, variable geometry turbo for better air control, and exhaust gas recirculation to help control combustion phasing (Kong 2012).
3. Vehicle aerodynamics (including cab mounted deflector shields, trailer skirts, and wheel covers) have been improved.
4. Electronic control features, including road speed governors have been added.
5. Tire rolling resistance has been reduced.
6. Longer, wider, and higher trailers are being used.
7. Operational improvements, including reducing the number of empty and partially loaded miles, and driver training, have been implemented.

Each gallon of fuel saved through fuel efficiencies eliminates a gallon of petroleum imports. Moreover, a gallon of unused fuel emits zero pollutants. On a gallon-to-gallon basis, fuel efficiencies contribute more to clean air than replacing petroleum with lower pollutant emitting fuels.

## CONCLUSIONS

1. The U.S. does not have a shortage of freight transportation fuels. It is developing a shortage of low cost, liquid fuels for trucks and railroads that meet environmental standards.
2. The U.S. has an abundance of NG that can be used as CNG or LNG fuels. Currently, LNG and CNG prices are substantially below those of petroleum based diesel. In addition, CNG, LNG, and natural gas can be converted into liquid synthetic diesel fuels. These fuels could power some freight transportation until fuel cells and environmentally friendly synthetic biomass and coal-to-liquid diesel fuels are developed and commercialized at prices that are competitive with petroleum based diesel.
3. In the short- or medium-term years ahead, the most likely commercially available substitutes for petroleum-based diesel fuel for freight transportation will be biodiesel, NG, electricity for railroads, and fuel efficiencies.

4. Motor carriers and railroads are unlikely to use more biodiesel and other mandated fuels than government blending mandates require, unless their prices decline below those of petroleum-based diesel,
5. Motor carriers will most likely increase their consumption of NG. Larger and more powerful NG engines, improved and lower cost per gallon NG storage tanks, and a substantial increase in the number of NG fueling stations and refueling capacity will be the major forces motivating trucking firms to purchase increasing numbers of NG-fueled trucks. Within the next five years, the major focus will be in using the new 12-liter NG engine in local and regional freight movements. The introduction of the 15-liter NG engine in the next four to five years, will expand the use of NG into national coast-to-coast truck movements.
6. The dramatic decreases in NG prices has motivated all Class I railroads to reevaluate their strategy of maintaining a completely diesel-electric system. Three railroads are now testing LNG locomotives. These reevaluations and actual experiments will determine if NG technologies can provide the power and clean burning performance of diesel-electric technologies at lower costs. If the NG technologies can meet or exceed the diesel-electric power and clean burning performance at lower costs, the railroad industry will likely invest in NG locomotives and fuel tenders, along with refueling and maintenance and repair facilities.
7. Railroads will not convert their freight operations to an electrified rail system unless diesel and diesel substitute fuel prices rise to a level that justify the huge capital investments needed for electrification. At the present time, no one knows how high diesel and diesel substitute fuel prices would need to rise to make the conversion to electricity economically feasible.
8. Fuel efficiency technologies have resulted in major improvements in fuel efficiencies of railroad and truck freight operations. New and existing technologies have a high probability of continuing to make large improvements in freight fuel efficiencies. In addition to developing alternative fuels, emphasis should continue to be placed on improving fuel efficiency in freight transportation. Each gallon of fuel saved through increased fuel efficiency emits zero pollutants and helps make the U. S. economy more competitive in domestic and world trade.
9. If and as they are developed and commercialized, renewable biofuels, hydrogen-based fuel cells and internal combustion engines, and environmentally friendly synthetic biomass and coal-to-liquid diesel fuels will substitute for some petroleum diesel if mandated by the EPA or if competitively priced with diesel.

There are numerous opportunities for research on alternative fuels for freight transportation. Some that are suggested by this analysis include:

1. Investment and operating costs of alternative NG truck engine sizes and fuel storage tanks and diesel powered trucks now and in the future. This is particularly needed for the new 12- and 15-liter NG engines.
2. Costs of producing alternative types of synthetic fuels now and in the future,
3. Diesel and diesel substitute fuel prices levels that will make an electrified railroad system economically feasible,
4. Return on investments in developing and commercializing alternative synthetic fuels,
5. Return on investments in developing alternative fuel efficiency options,
6. Return on investment to shift alternative parts of the U.S. railroad system to NG and/or other alternative fuels,
7. The impact of potential U.S. energy independence on the prices and quantities of diesel fuel and alternative diesel substitute fuels for use in freight transportation,

8. The potential demand (prices and quantities) for synthetic diesel fuels and hydrogen to be used in U.S. freight transportation, and
9. Available data on comparable retail prices of alternative fuels at refueling stations are extremely limited. There is a need to generate retail price data on diesel, NG, and other substitute fuels for freight transportation.

## References

About.com. Hybrid Cars and Alternative Fuels. May 2013.

Association of American Railroads. *Railroad Facts*. Washington, D.C., 2011.

Association of American Railroads. "An Evaluation of Natural Gas-fueled Locomotives." Prepared by BNSF Railway Company; Union Pacific Railroad Company; The Association of American Railroads and California Environmental Associates. November, 2007.

Bloomberg. "GE Races Caterpillar on LNG Trains." April 29, 2013

Brown, Robert C. and Tristan R. Brown. "Why Are We Producing Biofuels? Shifting to the Ultimate Source of Energy." Brownia LLC, Ames, Iowa, 2012.

Carrick, Robert. Personal communications. Sales Manager, Natural Gas for Freightliner Trucks, Daimler Trucks North America LLC, Portland, Oregon, December 21, 2012 and May 5, 2013.

Center for Liquefied Natural Gas. *Liquefied Natural Gas Facts*. 2012.

Chevron. *Delivering Energy*. April and May 2012.

Davis, R. et al. "Techno-Economic Analysis of Autotrophic Microalgae for Fuel Production." *Applied Energy* 88, (2011): 3524-31.

Energy Information Administration. *International Energy Outlook*. September 19, 2011.

Energy Information Administration. *Annual Energy Outlook 2012*. June 2012

Energy Information Administration. *U.S. Proved Reserves Increased Sharply in 2010*. August 2, 2012.

Energy Information Administration. *Diesel Fuel Explained Prices and Outlook*. February 5, 2013

Energy Information Administration. *Annual Energy Outlook 2013*. April 15, 2013.

Energy Information Administration. *U.S. Crude, Natural Gas and NG Liquids Proved Reserves*. May, 2013.

Fronczak, Robert E. P.E. Personal communication. Assistant Vice President Environment and Haz Mat, Association of American Railroads, Washington D.C. January 2013.

General Electric Company. "Gas-Electric Motor Car." Bulletin No. 4855, Schenectady, N.Y., 1911.

Geherke, Joel. "Obama: Use 'Algae' as a Substitute for Oil." *The Washington Examiner*, February 2, 2012.

Herman, William. "Clean, Green Energy Source Could Replace Fossil Fuels." *The Arizona Republic*, August 27, 2010.

Howstuffworks. "How Regenerative Braking Works." 2013.

Irwin, Scott. "The Amazing Continuing Story of Natural Gas Prices." University News Release, University of Illinois, Champaign, Illinois. February 16, 2012.

Kinetic Energy. <http://hyperphysics.phy-astr.gsu.edu/ke.html>. May 2013.

KiOR, Inc. "Form 10-K," May 10, 2013. KiOR.com.

Kong, Song-Chang. Personal communication. Department of Mechanical Engineering, Iowa State University, Ames, Iowa. August 28, 2012.

Majewski, Addy, Hannu Jääskeläinen, Echopoint Inc., Steve G. Fritz, Southwest Research Institute and Brian Smith, TTCL. "Alternative Fuels Availability Make-up, and Potential Impact on Locomotive Engines." Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads, Pueblo, Colorado, 2011.

National Biodiesel Board (NBD) "History of Biodiesel and NBB." Jefferson City, Missouri, 2012.

National Geographic Daily News. "*Estimates Clash for How Much Natural Gas in the United States.*" February 29, 2012.

National Petroleum Council (NPC). "Advancing Technology for America's Transportation Future, Topic #2, Rail Transportation Demand, Working Paper of the NPC Transportation Fuels Study." An Oil and Gas Advisory Committee to the Secretary of Energy, August 1, 2012.

Reidy, Susan. "Biodiesel Breaking Point." *World Grain's Biofuels Business Quarterly*, August 2012, [www.World-Grain.com](http://www.World-Grain.com).

Renewable Energy Group, Inc. "Form 10-K." United States Securities and Exchange Commission. Washington, DC, December 31, 2012.

Ring, Beth. Personal communication. Missouri Department of Transportation, Jefferson City, Missouri, June, 2011.

Romba, Phil. "Studying ROI for Natural Gas." *Transport Topics*, The Weekly Newspaper of Trucking and Freight Transportation, July 9, 2012.

U.S. Department of Energy. *Transportation Energy Book Chapter 2, Energy*, July 31, 2012.

U.S. Department of Energy. Clean Energy Alternative Fuel Price Report, various issues, 2011-2013.

Walkowicz, K., M. Lammert, and P. Curren. "Coca Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluations." Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory, August 12, 2012.

Wen, Zhiyou. Personal communication. Department of Food Science, Iowa State University, Ames, Iowa, 2012.

Wikipedia. "GGE-Gasoline Equivalent (US Gallons) Tables." May 2013.

*C. Phillip Baumel is a distinguished professor emeritus at Iowa State University. He received the Transportation Research Forum's Distinguished Transportation Researcher Award in 1993, the Transportation Research Forum's Outstanding Research Paper Awards in 1982, 1989, and 1999, and the Transportation Research Forum's Agricultural and Rural Transportation Awards in 1989, 1991, and 1995. He is a fellow in the American Agricultural Economics Association. Baumel pioneered the use of network models for analyzing issues in agricultural product transportation by rail, truck, and barge. He retired in 2003 and currently lives in Iowa (summer) and Arizona (winter).*