
Alternative Fuels for Vehicles

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Alternative Fuels for Vehicles

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All documents are taken from the website of the Alternative Fuels and Advanced Vehicles Data Center of the Office of Energy Efficiency & Renewable Energy, U. S. Department of Energy:

<http://www.afdc.energy.gov/afdc/fuels/index.html>

Biodiesel Basics

Biodiesel is a domestically produced, renewable fuel that can be manufactured from new and used vegetable oils, animal fats, and recycled restaurant grease. Biodiesel's physical properties are similar to those of petroleum diesel, but it is a cleaner-burning alternative. Using biodiesel in place of petroleum diesel significantly reduces emissions of toxic air pollutants.

What is a biodiesel blend?

Biodiesel can be blended and used in many different concentrations, including B100 (pure biodiesel), B20 (20% biodiesel, 80% petroleum diesel), B5 (5% biodiesel, 95% petroleum diesel), and B2 (2% biodiesel, 98% petroleum diesel). B20 is a common biodiesel blend in the United States.

Can I use B20 in my vehicle's diesel engine?

For vehicles manufactured after 1993, biodiesel can be used in diesel engines and fuel injection equipment with little impact on operating performance. But if your vehicle is older than that, the engine could be assembled with incompatible elastomers, which can break down with repetitive high-blend biodiesel use.

Most original equipment manufacturers (OEMs) approve blends up to B5 in their vehicles. Some approve blends up to B20, and one manufacturer even approves B100 for use in certain types of its farm equipment. However, some OEMs don't recommend using



Biodiesel works well in many applications, such as this B20 transit bus at the University of Colorado at Boulder. Photo by Pat Corkery, NREL/PIX 18103

biodiesel blends above B5 in on-highway vehicles manufactured in model year 2007 and later. In these vehicles, high levels of fuel may accumulate in the engine lubricant under certain conditions. It's not known whether those high levels of biodiesel might affect lubricant performance.

Check your OEM's website or speak with a dealer to determine which biodiesel blend is right for your vehicle. You can also find general and manufacturer-specific information on the National Biodiesel Board website (www.biodiesel.org).

How can I find biodiesel?

Biodiesel is available in all 50 states. According to the U.S. Energy Information Administration, annual consumption of biodiesel in the United States totaled 316 million gallons in 2009.¹ As of June 2009, the country had an annual production capacity of more than 2.69 billion gallons.² According to the Alternative Fuels and Advanced Vehicles Data Center (AFDC) website, there are more than 600 B20 fueling sites across the country. To look up biodiesel stations in your area, use the Alternative Fueling Station Locator at www.afdc.energy.gov/stations.

Will biodiesel perform as well as diesel?

Engines operating on B20 exhibit similar fuel consumption, horsepower, and torque to engines running on conventional diesel. And biodiesel has a higher cetane number (a measure of the ignition value of diesel fuel) and higher lubricity (the ability to lubricate fuel pumps and fuel injectors) than U.S. diesel fuel. B20's energy content is between those of No. 1 and No. 2 diesel.

Will biodiesel perform well in cold weather?

The cold-flow properties of biodiesel blends vary depending on the amount of biodiesel in the blend. The smaller the percentage of biodiesel in the blend, the better it performs in cold temperatures. Regular No. 2 diesel and B5 perform about the same in cold weather. Both biodiesel and No. 2 diesel have some compounds that crystallize in very cold temperatures. In winter weather, manufacturers combat crystallization in No. 2 diesel by adding flow improvers. For best cold weather performance, drivers should use B20 made with No. 2 diesel manufactured for cold weather.



U.S. Department of Energy

1. U.S. Energy Information Administration Monthly Energy Review, Table 10.4 (www.eia.doe.gov/emeu/mer/renew.html)
2. National Biodiesel Board (www.biodiesel.org/pdf_files/fuelsheets/Production_Capacity.pdf)

For more information about cold-flow properties and biodiesel handling, download the Biodiesel Handling and Use Guide from www.nrel.gov/vehiclesandfuels/nrbf/pdfs/43672.pdf.

Will biodiesel plug my vehicle filters?

Biodiesel has a solvent effect. It cleans your vehicle's fuel system and could release deposits accumulated from previous diesel fuel use. The release of deposits may initially clog filters, so you should be proactive in checking for and replacing clogged fuel filters. Once the build-up is eliminated, return to your regular replacement schedule. This issue is less common with B20 and lower-level blends.

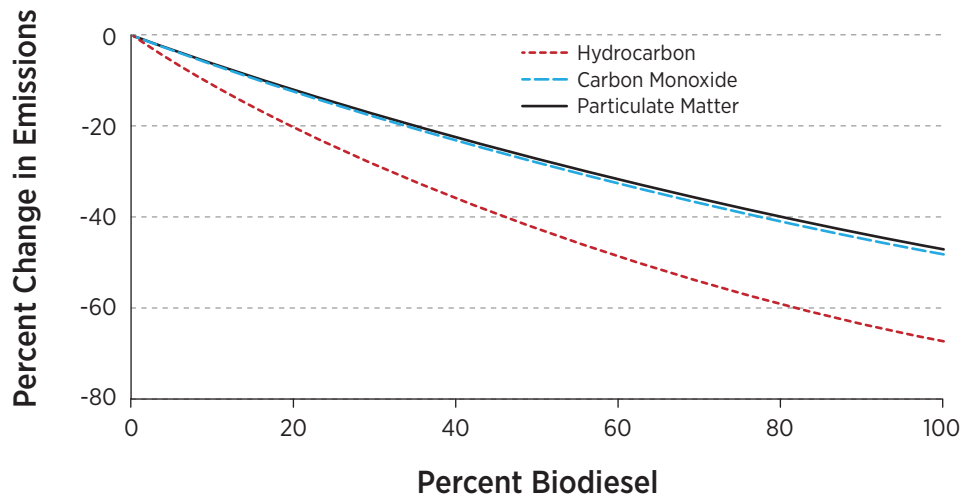
Will long-term biodiesel use affect my engine?

Studies of B20 and lower-level blends in approved engines have not demonstrated negative long-term effects. Higher-level blends (above B20) can impact fuel system components (primarily fuel hoses and fuel pump seals) that contain elastomer compounds incompatible with biodiesel. The effects are lessened as the biodiesel blend level decreases. For more information, visit www.biodiesel.org.

Does biodiesel need to meet any standards?

Biodiesel used in blends should meet specification D6751, a quality standard set by ASTM International. Biodiesel that meets this standard is legally registered as a fuel blendstock or additive with the U.S. Environmental Protection Agency. Biodiesel blends containing 5% or less biodiesel are required to meet the same fuel-quality specifications as conventional diesel fuel, according to ASTM D975. Biodiesel

Figure 1. Average Emission Impacts of Biodiesel for Heavy-Duty Highway Engines



Environmental Protection Agency. Draft Technical Report, *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, EPA420-P-02-001, 2002.

blends containing 6% to 20% biodiesel must meet the requirements of ASTM D7467.

Is biodiesel cleaner-burning than diesel?

The use of biodiesel in conventional diesel engines substantially reduces emissions of pollutants that impact air quality, including unburned hydrocarbons (HCs), carbon monoxide (CO), sulfates, polycyclic aromatic HCs, nitrated polycyclic aromatic HCs, and particulate matter (PM). B100 provides the greatest emissions reductions, but lower-level blends also provide benefits. B20 has been shown to reduce PM emissions by 10%, CO by 11%, and unburned HCs by 21% (see Figure 1). Studies of oxides of nitrogen emissions have provided contradictory results, and additional testing and analysis is ongoing.

Biodiesel use also reduces greenhouse gas emissions. The carbon dioxide released in biodiesel combustion is

offset by the carbon dioxide sequestered while growing the feedstock from which biodiesel is produced. B100 use reduces carbon dioxide emissions by more than 75% compared to petroleum diesel. Using B20 reduces carbon dioxide emissions by 15%.

Can I use vegetable oil in my diesel engine?

Straight vegetable oil is not a legal motor fuel and doesn't meet biodiesel fuel specifications or quality standards. For more information, download the fact sheet, "Straight Vegetable Oil as a Diesel Fuel," from the AFDC website at www.afdc.energy.gov/afdc/pdfs/47414.pdf.

Where can I read more?

For more information on biodiesel, including production, distribution, and fueling station locations, visit the biodiesel section of the AFDC at www.afdc.energy.gov/afdc/fuels/biodiesel.html.

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Hybrid and Plug-In Electric Vehicles

Hybrid and plug-in electric vehicles use electricity either as their primary fuel or to improve the efficiency of conventional vehicle designs. This new generation of vehicles, often called electric drive vehicles, can be divided into three categories: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs). Together, they have great potential to reduce U.S. petroleum use.

Hybrid Electric Vehicles

HEVs are powered by an internal combustion engine that can run on conventional or alternative fuel and an electric motor that uses energy stored in a battery. The extra power provided by the electric motor allows for a smaller engine, resulting in better fuel economy without sacrificing performance. HEVs combine the benefits of high fuel economy and low emissions with the power of conventional vehicles.

HEVs do not require a plug to charge the battery; instead, they charge using regenerative braking and the internal combustion engine. They capture energy normally lost during braking by using the electric motor as a generator and storing the captured energy in the battery.



All-electric and plug-in hybrid electric vehicles are charged by plugging the vehicle into an electric power source. *Photo by Andrew Hudgins, NREL/PIX 17634*

The energy from the battery provides extra power during acceleration and auxiliary power when idling.

Plug-In Hybrid Electric Vehicles

PHEVs are powered by conventional fuels and by electrical energy stored in a battery. Using electricity from the grid to charge the battery some of the time costs less and reduces petroleum consumption compared with conventional vehicles. PHEVs can also reduce emissions, depending on the electricity source.

PHEVs have an internal combustion engine and an electric motor, which uses

energy stored in a battery. PHEVs have larger battery packs than HEVs, making it possible to drive using only electric power (about 10 to 40 miles in current models). This is commonly referred to as the all-electric range of the vehicle.

PHEV batteries can be charged several ways: by an outside electric power source, by the internal combustion engine, or through regenerative braking. If a PHEV is never plugged in to charge, its fuel economy will be about the same as that of a similarly sized HEV. If the vehicle is fully charged and then driven a shorter distance than its all-electric range, it is possible to use electric power only.

All-Electric Vehicles

EVs use a battery to store the electrical energy that powers the motor. EV batteries are charged by plugging the vehicle into an electric power source. Although electricity production may contribute to air pollution, the U.S. Environmental Protection Agency (EPA) considers EVs

Electric Drive Vehicles at a Glance

HEVs: HEVs are powered by conventional or alternative fuels as well as electrical energy stored in a battery. The battery is charged through regenerative braking and the internal combustion engine and is not plugged in to charge.



PHEVs: PHEVs are powered by conventional fuels and electrical energy stored in a battery. The vehicle can be plugged into an electric power source to charge the battery in addition to using regenerative braking and the internal combustion engine.



EVs: A battery stores the electrical energy that powers the motor. EV batteries are charged by plugging the vehicle into an electric power source.



to be zero-emission vehicles because their motors produce no exhaust or emissions. Since EVs use no other fuel, they help reduce petroleum consumption.





Currently available EVs have a shorter range per charge than most conventional vehicles have per tank of gas. EV manufacturers typically target a minimum range of 100 miles. According to the U.S. Department of Transportation's Federal Highway Administration, 100 miles is sufficient for more than 90% of all household vehicle trips in the United States.

Light-duty HEV, PHEV, and EV models are currently available from a number of auto manufacturers, with additional models expected to be released in coming years. There are also a variety of



HEVs work well for both light-duty and heavy-duty applications. This hybrid electric transit bus carries passengers along the 16th Street Mall in Denver, Colorado.

Photo by Pat Corkery, NREL, PIX 17975

What are the Benefits of Electric Drive Vehicles?			
Benefits	Hybrid Electric Vehicles	Plug-In Hybrid Electric Vehicles	All-Electric Vehicles
Fuel Economy 	Better than similar conventional vehicles The fuel savings of driving a Honda Civic Hybrid versus a conventional Civic is about 38% in the city and 20% on the highway.	Better than similar HEVs and conventional vehicles PHEVs use 40% to 60% less petroleum than conventional vehicles and permit driving at slow and high speeds using only electricity.	No liquid fuels Fuel economy of EVs is usually expressed as cost per mile, which is discussed below.
Emissions Reductions 	Lower emissions than similar conventional vehicles HEV emissions vary by vehicle and type of hybrid power system. HEVs are often used to offset fleet emissions to meet local air-quality improvement strategies and federal requirements.	Lower emissions than HEVs and similar conventional vehicles PHEV emissions are projected to be lower than HEV emissions, because PHEVs are driven on electricity some of the time. Most categories of emissions are lower for electricity generated from power plants than from vehicles running on gasoline or diesel.	Zero emissions EV emissions do not come from the tailpipe, so EVs are considered zero-emission vehicles. However, emissions are produced from the electric power plant. Most categories of emissions are lower for electricity generated from power plants than from vehicles running on gasoline or diesel.
Fuel Cost Savings 	Less expensive to operate than a conventional vehicle Because of their improved fuel economy, HEVs usually cost \$0.05 to \$0.07 per mile to operate, compared to conventional vehicles, which cost \$0.10 to \$0.15 per mile to operate.	Less expensive to operate than an HEV or conventional vehicle When operating on electricity, a PHEV can cost \$0.02 to \$0.04 per mile (based on average U.S. electricity price). When operating on gasoline, the same vehicle can cost \$0.05 to \$0.07 per mile, compared to conventional vehicles, which cost \$0.10 to \$0.15 per mile to operate.	Less expensive to operate than conventional vehicles EVs operate using only electricity. A typical electric vehicle costs \$0.02 to \$0.04 per mile for fuel (based on average U.S. electricity price).
Fueling Flexibility 	Same as conventional vehicles	Can get fuel at gas stations or charge at home or public charging stations	Can charge at home or public charging stations

Source: Alternative Fuels and Advanced Vehicles Data Center; www.afdc.energy.gov/afdc/vehicles/electric_benefits.html

EVSE Options						
	Current Type	Amperage (amps)	Voltage (V)	Kilowatts (kW)	Charging Time (for fully depleted battery)	Primary Use
Level 1	Alternating current (AC)	Up to 15 amps	120V	Up to 1.8 kW	6 to 20 hours	Residential charging
Level 2	AC	Up to 80 amps	240V	Up to 19.2 kW	3 to 8 hours	Residential and public charging
Level 3 (in development)	AC	To be determined	To be determined	To be determined	Under 30 minutes	Public charging
DC Fast Charging	Direct current (DC)	Up to 200 amps	480V	50 to 150 kW	Under 30 minutes	Public charging

medium- and heavy-duty options available. For up-to-date information on available vehicle models, refer to the Alternative Fuels and Advanced Vehicles Data Center's (AFDC) Electric Vehicle Availability page (www.afdc.energy.gov/afdc/vehicles/electric_availability.html) and FuelEconomy.gov.

How are EV and PHEV batteries charged?

Charging EVs and PHEVs requires plugging the vehicle into charging equipment, also called electric vehicle supply equipment (EVSE). Charging times vary based on how depleted the battery is, how much energy it holds, and the type of battery and EVSE. The charging time for a fully depleted battery can range from 30 minutes to more than 20 hours, depending on the vehicle and the type of charging equipment used. Because charging an EV or PHEV takes significantly longer than fueling a conventional vehicle at a gas station, most EVSE will be available in locations where vehicles park for extended periods, including residences, workplaces, and parking garages. The table above presents several EVSE options.

Modern charging equipment and vehicles are designed with standard connectors and plug receptacles, so drivers do not need to worry about whether their vehicles are compatible with charging equipment. Utilities are also working to upgrade local distribution infrastructure in neighborhoods with higher EV and PHEV concentrations to handle increased



Drivers of EVs and PHEVs will soon have access to thousands of charging stations across the country. Photo by Andrew Hudgins, NREL, PIX 17834

electricity demand and ensure uninterrupted service.

To locate EVSE in your area, see the Alternative Fueling Station Locator (www.afdc.energy.gov/afdc/locator/stations).

Are electric drive vehicles safe?

HEVs, PHEVs, and EVs undergo the same rigorous safety testing as conventional vehicles sold in the United States and must meet the Federal Motor Vehicle Safety Standards. In addition, their battery packs are encased in sealed shells and meet testing standards that subject batteries to conditions such as overcharge, vibration, extreme temperatures, short

circuit, humidity, fire, collision, and water immersion. Manufacturers also design vehicles with insulated high-voltage lines and safety features that deactivate electric systems when they detect a collision or short circuit. For additional electric-drive vehicle safety information, refer to the AFDC's Maintenance and Safety of Hybrid, Plug-In Hybrid, and All-Electric Vehicles page (www.afdc.energy.gov/afdc/vehicles/electric_maintenance.html).

How do maintenance requirements compare to those of conventional vehicles?

Because HEVs and PHEVs have internal combustion engines, their maintenance requirements are comparable to conventional vehicles. The electrical system (battery, motor, and associated electronics) doesn't require scheduled maintenance. Due to the effects of regenerative braking, brake systems on these vehicles typically last longer than those on conventional vehicles.

EVs typically require less maintenance than conventional vehicles because:

- They have fewer moving parts
- Their brake fluid is the only fluid to change
- Regenerative braking reduces brake wear
- Their electrical systems don't require regular maintenance.



Well-to-wheels emissions of PHEVs and EVs depend on the source of electrical power used for charging. If electricity is generated from nonpolluting, renewable sources, these vehicles have the potential to produce zero emissions. *Left photo from iStock/6381513; right photo by Mike Linenberger, NREL/PIX 15152*

How do fuel costs compare to those of conventional vehicles?

When discussing electric drive vehicles, “fuel” includes the gasoline, diesel, or alternative fuel used in the internal combustion engine, as well as the electricity used to charge the EV or PHEV battery. Taking both fuel types into account, fuel costs for electric drive vehicles are generally less than conventional vehicles due to higher vehicle fuel economy and low costs for electricity. Electricity prices also tend to be more stable than conventional fuel prices, allowing greater certainty when budgeting for fuel costs.

Where can I learn more about electric drive vehicles?

For additional information, refer to the AFDC’s Hybrid, Plug-in Hybrid, and All-Electric Vehicles website, created by the National Renewable Energy Laboratory (www.afdc.energy.gov/afdc/vehicles/electric.html).

For EPA fuel economy ratings and fuel cost comparisons between different vehicle models currently available in the United States, refer to the FuelEconomy.gov website.

What are the emissions benefits of electric drive vehicles?

In general, HEVs, PHEVs, and EVs produce lower emissions than conventional vehicles. Vehicle emissions can be considered in terms of tailpipe emissions or well-to-wheel emissions. Tailpipe emissions refer to emissions produced through fuel combustion during a vehicle’s operation. Well-to-wheel emissions take into consideration the production and distribution of the fuel as well as the actual operation of the vehicle.

HEV tailpipe emissions are generated from the vehicle’s internal combustion engine and vary by vehicle and type of hybrid power system. Because HEVs generally achieve better fuel economy than comparable conventional vehicles, they produce lower emissions.

Because PHEVs can operate either in all-electric mode or with the help of the internal combustion engine, emissions vary based on the vehicle’s operating mode. When the vehicle is charged by an electrical power source, emissions calculations must take electricity production into account. On average, most categories of emissions are lower for electricity generated from power plants than from engines running on gasoline or diesel. However, emissions from electricity production depend on the efficiency of the power plant and the mix of fuel sources used. To determine your region’s specific fuel mix, as well as the emissions rates of electricity in your zip code, see EPA’s Power Profiler (www.epa.gov/cleanenergy/energy-and-you/how-clean.html).

All-electric vehicles do not produce tailpipe emissions, so EVs are considered zero-emission vehicles by EPA. However, as with PHEVs, there are emissions associated with most U.S. electricity production. If electricity is generated from nonpolluting, renewable sources, EVs have the potential to produce zero well-to-wheel emissions.

Flexible Fuel Vehicles: Providing a Renewable Fuel Choice

Today, almost 8 million vehicles on U.S. highways are flexible fuel vehicles (FFVs). These vehicles can operate on gasoline or blends of gasoline and ethanol up to E85 (85% ethanol, 15% gasoline). As a renewable fuel, ethanol offers significant advantages. It is manufactured predominantly in the United States, made from homegrown feedstocks, and is cleaner burning than gasoline.

What is an FFV?

An FFV, as its name implies, has the flexibility of running on more than one type of fuel. FFVs can be fueled with unleaded gasoline, E85, or any combination of the two. Like conventional gasoline vehicles, FFVs have a single fuel tank, fuel system, and engine. And they are available in a wide range of models such as sedans, pickups, and minivans. Light-duty FFVs are designed to operate with at least 15% gasoline in the fuel, mainly to ensure they start in cold weather.

FFVs are equipped with modified components designed specifically to be compatible with ethanol's chemical properties. In the illustration on the back, the main modifications for FFVs are described. These modifications ensure seamless operation and a long useful life across a wide range of ethanol blends.

Clean Cities posts a list of alternative fuel vehicles, including FFVs, on its Alternative Fuels and Advanced Vehicles Data Center (AFDC) Web site at www.afdc.energy.gov. To find out about available models, go to the Vehicles section of the AFDC and use the Light-Duty Vehicle Search.

Can existing vehicles be converted to FFVs?

Converting a conventional gasoline vehicle to one that runs on E85 is technically possible. FFV conversions need to be done by authorized companies and require certification by the U.S. Environmental Protection Agency (EPA) or the

California Air Resources Board. Using noncertified conversions is illegal and may affect warranties.

For more information on the vehicle conversion process, refer to the EPA's Updated Certification Guidance for Alternative Fuel Converters on its Web site at www.epa.gov/otaq/cert/dearmfr/cisd0602.pdf.

Does E85 affect vehicle performance?

FFVs operating on E85 generally handle and perform just as well as when fueled with gasoline. Sensors in the FFV system automatically prompt adjustments for fuel composition, so emissions and standard performance areas such as power and acceleration are not significantly affected by E85. One difference between E85 and gasoline, however, is fuel economy. Ethanol contains less energy per gallon, which translates into a reduction in fuel economy compared to gasoline. No matter what type of fuel is used, however, fuel mileage is affected by driving habits, weather, and other factors.

Standard test results for fuel economy of FFVs and their gasoline counterparts are posted on the combined EPA and U.S. Department of Energy Web site at www.fueleconomy.gov.



Flexible fuel vehicles can be fueled with unleaded gasoline, E85, or any combination of the two.

What are the costs and benefits of using E85?

Special features enabling vehicles to run on E85 can add a minimal cost to their purchase price. Because they have a solid performance history, manufacturers provide standard warranties for FFVs equal to those for gasoline vehicles at no additional charge.

Fuel, however, may be a cost factor. E85's reduced energy content compared to gasoline, as explained in the previous section, can increase fuel costs. This cost differential is highly variable because it is based on ethanol and gasoline price differences. Like gasoline, ethanol prices fluctuate and are set based on market supply and demand. This variability means that a driver may or may not experience a difference in overall fuel costs, depending on local pump prices. To compare the price of fueling with E85 versus gasoline, use the AFDC's Flexible Fuel Vehicle Cost Calculator at www.afdc.energy.gov/afdc/progs/cost_anal.php?0/E85.

Although your FFV's fuel economy on E85 is somewhat less than when operating on gasoline, a bonus for its use is lower greenhouse gas emissions. Using the GREET model, Argonne National Laboratory indicates in "Ethanol, The Complete Energy Lifecycle Picture" that greenhouse gas emissions are reduced approximately 15% when ethanol produced from corn is used.¹ Using E85 also reduces CO₂ emissions and provides significant reductions in emissions of many harmful toxics, including benzene, a known human carcinogen. However, E85 also increases emissions of acetaldehyde—a toxic pollutant.² Additional testing is being completed to expand the understanding of the emissions impacts of E85.

How are FFVs identified?

Since September 2006, the Energy Policy Act of 2005 requires auto manufacturers to place a label inside the FFV fuel compartment that states the vehicle can run on either E85 or gasoline. Flexible-fuel capability also is outlined in the owner's manual and encoded in the vehicle identification number, or VIN.

Where are E85 stations located?

Stations offering E85 continue to increase across the nation. As of January 2010, more than 1,900 stations in 44 states sold E85. To find E85 stations throughout the country, check out the Alternative Fuel Station Locator at www.afdc.energy.gov/stations, a database maintained by the AFDC. This easy-to-use database allows users to plot routes either across town or across the nation, showing E85 stations along the way.

¹ Wang, Michael. *Ethanol: The Complete Energy Lifecycle Picture*, Argonne National Laboratory, March 2007.

² Whitney, Kevin (Southwest Research Institute); Fernandez, Tony (U. S. Environmental Protection Agency). "Characterization of Cold Temperature VOC and PM Emissions from Flex Fuel Vehicles Operating on Ethanol Blends." Presented at the 17th CRC On-Road Vehicle Emissions Workshop, March 26-28, 2007.

Resources

Alternative Fuels and Advanced Vehicles Data Center:
www.afdc.energy.gov

American Coalition for Ethanol:
www.ethanol.org

Clean Cities:
www.cleancities.energy.gov

Fuel Economy: www.fueleconomy.gov

Growth Energy: www.e85fuel.com

Handbook for Handling, Storing, and Dispensing E85:
www.afdc.energy.gov/afdc/ethanol/publications.html

Renewable Fuels Association:
www.ethanolrfa.org

U.S. Environmental Protection Agency:
www.epa.gov/otaq/consumer/fuels/altfuels/altfuels.htm

Flexible Fuel Vehicle Features

Engine calibration updates:

Fueling and spark advance calibrations are directed by vehicle computer to control combustion, enable cold start, and meet emissions requirements.

Internal engine parts: Piston rings, valve seats, valves, and other components must be made of ethanol-compatible materials that are designed to minimize the cleansing effects of alcohol fuels, which can wash lubrication from parts.

Fuel identifier system:

System automatically senses the composition of the fuel and adjusts engine for varying ethanol-gasoline blends.

Fuel system electrical connections and wiring:

System must be electrically isolated and made of materials designed to handle ethanol's increased conductivity and corrosiveness (if exposed to fuel).

Fuel injection system: Must be made of ethanol-compatible materials and designed for higher flow to compensate for ethanol's lower energy density.

Fuel pump assembly: In-tank components must be made from ethanol-compatible materials and sized to handle the increased fuel flow needed to compensate for ethanol's lower energy density.

Fuel filler assembly: Anti-siphon and spark arrestor features are included to handle ethanol's increased conductivity.

Fuel tank: Must be made of ethanol-compatible materials and designed to minimize evaporative emissions from ethanol.

Fuel rail and fuel lines: Must be made of ethanol-compatible materials with seals, gaskets, and rubber fuel hoses rated for ethanol use.



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Quick Facts

- Hydrogen fuel cell vehicles (FCVs) have a significant potential to reduce emissions from the transportation sector, because they do not emit any greenhouse gases (GHGs) during vehicle operation. Their lifecycle GHG emissions depend on how the hydrogen fuel is made.
- A future mid-size car in the 2035-2045 time frame, powered by fuel cells and using hydrogen generated from natural gas, is projected to have lifecycle GHG emissions slightly lower than that for a hybrid electric vehicle (HEV), powered by gasoline. A fuel cell vehicle would produce 200 grams of carbon dioxide-equivalent per mi (CO₂e/mi), compared to 235g CO₂e/mi for a HEV. An FCV would have near-zero lifecycle GHG emissions if the hydrogen were made, for example, from electrolysis powered by renewable electricity.
- Several major hurdles to commercial deployment must be overcome before any environmental benefits from FCVs are realized. These challenges include the production, distribution, and storage of hydrogen; fuel cell technology; and overall vehicle cost.

Background

Hydrogen FCVs are a potential option for reducing emissions from the transportation sector. Combusting fossil fuels to power conventional vehicles releases GHG emissions and other pollutants from the vehicle exhaust system (i.e., “tailpipe” emissions). In addition, there are also emissions associated with producing petroleum-based fuels (i.e., “upstream” emissions), notably emissions from oil refineries. FCVs emit no tailpipe GHGs or other pollutants during vehicle operation, and depending on how hydrogen is produced, there can be substantially lower upstream GHG emissions associated with producing hydrogen fuel.

Fuel cells are already used to generate electricity for other applications, including in spacecraft and in stationary uses, such as emergency power generators. Although the concept of a fuel cell was developed in England in the 1800s, the first workable fuel cells were not produced until much later, in the 1950s. During this time, interest in fuel cells increased, as NASA began searching for ways to generate power for space flights.¹

Hydrogen FCVs are considered one of several possible long-term pathways for low-carbon passenger transportation (other options include vehicles powered by electricity and/or biofuels). The benefits of hydrogen-powered vehicles include the following:

- High energy efficiency of fuel cell drivetrains, which use 40 to 60 percent of the energy available from hydrogen, compared to internal combustion engines, which currently use only about 20 percent of the energy from gasoline;²
- Diverse methods by which hydrogen can be produced (see Box 1 below);
- Unlike all-electric vehicles (EVs), comparable vehicle range and refueling time to gasoline vehicles;
- Similar to EVs, quick starts due to high torque from the electric motor and low operating noise; and

- Lack of any GHG emissions and few other air pollutants during vehicle operation³ and the potential for very low or no upstream GHG emissions associated with hydrogen fuel production.

Yet several key hurdles must be overcome before the introduction of FCVs on a large scale can become possible. These challenges include the production, distribution, and storage of hydrogen; fuel cell technology; and overall vehicle cost.

Description

FCVs resemble normal gasoline or diesel-powered vehicles from the outside. Similar to EVs, they use electricity to power a motor that propels the vehicle. Yet unlike EVs, which are powered by a battery, FCVs use electricity produced from on-board fuel cells to power the vehicle.

An FCV includes four major components:⁴

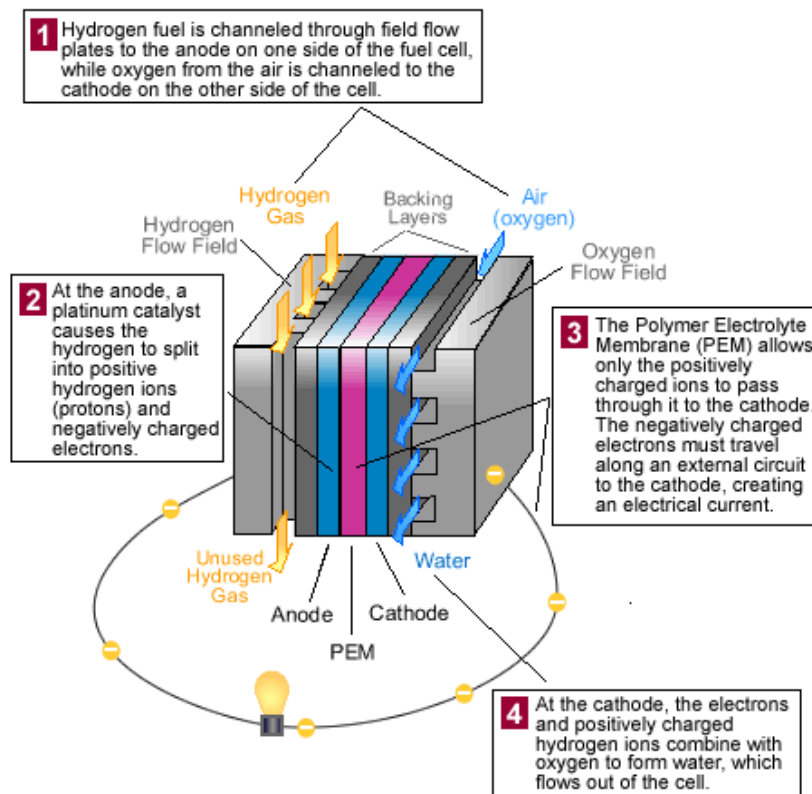
1. **Fuel cell stack:** The fuel cell is an electrochemical device that produces electricity using hydrogen and oxygen. In very simple terms, a fuel cell uses a catalyst to split hydrogen into protons and electrons, the electrons then travel through an external circuit (thus creating an electric current), and the hydrogen ions and electrons react with oxygen to create water.

To obtain enough electricity to power a vehicle, individual fuel cells, like the one described below, are combined in series to make a fuel cell stack. There are several different types of fuel cells, each of which is suited for a different application. Fuel cells are typically grouped according to their operating temperature and the type of electrolyte used.⁵ The amount of power generated by a fuel cell is determined by several factors including fuel cell type, size, operating temperature, and pressure at which the gases are supplied to the cell.⁶ The most common type of fuel cell used in FCVs is polymer electrolyte membrane (PEM).⁷

A fuel cell is composed of an electrolyte,⁸ placed between an anode (a negative electrode) and a cathode (a positive electrode), with bipolar plates on either side. A fuel cell works as follows:⁹

- First, the hydrogen gas flows to the anode. Here, a platinum catalyst is used to separate the hydrogen molecule into positive hydrogen ions (protons) and negatively charged electrons.¹⁰
- The PEM allows only the protons to pass through to the cathode, while the electrons travel through an external circuit to the cathode. The flow of electrons through this circuit creates the electric current (or electricity) used to power the vehicle motor.
- On the other side of the cell, oxygen gas, usually drawn from the outside air, flows to the cathode.
- When the electrons return from the external circuit, the positively charged hydrogen ions and electrons react with oxygen in the cathode to form water, which then flows out of the cell. The cathode also uses a platinum catalyst to enable this reaction.

Figure 1: Diagram of a fuel cell.



Source: http://www.fueleconomy.gov/feg/fcv_PEM.shtml

- Hydrogen storage tank:** Instead of a gasoline or diesel tank, an FCV has a hydrogen storage tank. The hydrogen gas must be compressed at extremely high pressure at 5,000 to 10,000 pounds per square inch (psi) to store enough fuel to obtain adequate driving range. In comparison, compressed natural gas (CNG) vehicles use high-pressure tanks at only 3,000 to 3,600 psi.¹¹

FCVs can also be powered by a secondary fuel – e.g., methanol, ethanol, or natural gas – which is converted into hydrogen onboard the vehicle. Vehicles powered through a secondary fuel emit some air pollutants during operation due to the conversion process.¹²

- Electric motor and power control unit:** The power control unit governs flow of electricity in the vehicle. By drawing power from either the battery or the fuel cell stack, it delivers electric power to the motor, which then uses the electricity to propel the vehicle.
- Battery:** Like HEVs, FCVs also have a battery that stores electricity generated from regenerative braking,¹³ increasing the overall efficiency of the vehicle.¹⁴ The size and type of these batteries, similar to those in HEVs, will depend on the “degree of hybridization” of the vehicle, i.e., how much of the power to propel the vehicle comes from the battery and how much comes from the fuel cell stack.¹⁵

Environmental Benefit/Emission Reduction Potential

Because FCVs are more energy efficient than vehicles powered by gasoline and because hydrogen as a transportation fuel can have much lower lifecycle GHG emissions than fossil fuels, FCVs have the potential to dramatically reduce GHG emissions and other air pollutants from the transportation sector.

FCVs are more energy efficient than gasoline-powered vehicles. A fuel cell uses about 40 to 60 percent of the available energy in hydrogen. Internal combustion engines use only about 20 percent of the energy available in gasoline, although this is expected to improve over the long term.¹⁶ EVs are more efficient than FCVs, using about 75 percent of available energy from the batteries.¹⁷

There are two models of FCVs available currently but with limited distribution, and these models' fuel economy ratings illustrate the higher efficiency of FCVs. The Honda FCX Clarity for model year 2011 has a fuel economy equivalent to 60 miles per gallon of gasoline (mpg), while the 2011 Mercedes-Benz F-Cell has a fuel economy of 53 mpg.¹⁸ In comparison, the average fuel economy for passenger cars from model year 2010 is 33.8 mpg for a gasoline vehicle,¹⁹ and the most efficient HEV from the same model year has a fuel economy rating of 50 mpg.²⁰

In addition to being more energy efficient than gasoline-powered vehicles, FCVs can also have much lower lifecycle GHG emissions compared to vehicles fueled by petroleum-based fuels. FCVs emit only heat and water during operation (i.e., no tailpipe GHGs). Lifecycle GHG emissions from FCVs thus depend, mainly, on the process used to produce hydrogen. Hydrogen can be produced from fossil fuels (coal and natural gas), nuclear, renewable energy technologies (wind, solar, geothermal, biomass), and hydroelectric power (see Box 1 for more information).

Lifecycle GHG emissions for an FCV are the sum of emissions from the production and distribution of hydrogen, the production of the vehicle, and vehicle operation. Estimates made for the U.S. Department of Energy (DOE) project that a future mid-size FCV (in the years 2035 to 2045), powered by hydrogen from natural gas, will have lifecycle GHG emissions slightly lower than that for an HEV, powered by gasoline (200g CO₂e/mi compared to 235g CO₂e/mi).²¹ Another study, from the Massachusetts Institute of Technology (MIT), found similar results: lifecycle emission from an FCV, using hydrogen produced from natural gas, would be comparable to those from a hybrid vehicle.²²

With hydrogen produced using less carbon-intensive methods – coal gasification with CCS, biomass gasification, or electrolysis powered by nuclear power or renewable – lifecycle GHG emissions would drop significantly. With biomass gasification or electrolysis, lifecycle emissions for an FCV are lower than all other vehicle types, with the exception of EVs recharged using electricity from renewable sources.

Over the long term, the reduction of overall transportation sector emissions attributable to FCVs will depend on the total number of vehicles in use. A 2008 study by the National Academy of Sciences (NAS) provides one measure of the potential for GHG emission reductions from FCVs. The NAS study estimated the maximum practicable penetration rate for FCVs in the United States in the 2008 to 2050 time frame. The study projected that FCVs could account for approximately 2 million vehicles, out of a total of 280 million light duty vehicles, in 2020, and grow rapidly from then on, increasing to 25 million vehicles in 2030.

Box 1: Hydrogen Production Pathways

Natural gas: Nearly all of the hydrogen used in the United States (95 percent) is produced through a process called steam methane reforming. This process breaks down methane (CH₄), a hydrocarbon, into hydrogen and carbon dioxide (CO₂). The methane in natural gas is reacted with water (in the form of high-temperature steam) to produce carbon monoxide and hydrogen. These gases are reacted with water again, in a process called a water shift reaction, to produce more hydrogen and CO₂.

Gasification: Gasification processes include a series of chemical reactions in which coal or biomass is “gasified” (i.e., converted into gaseous components) using heat and steam. A series of chemical reactions is then used to produce a synthesis gas (a gas mixture that contains varying amounts of carbon monoxide and hydrogen), which is reacted with steam to produce more hydrogen. Producing hydrogen via coal gasification is significantly more efficient than burning coal to produce electricity that is then used in electrolysis.

Although gasification technology is commercially available, the challenge is lowering the amount of CO₂ emitted from the process to decrease upstream emissions from the use of FCVs. Coal gasification with carbon capture and sequestration (CCS) or biomass gasification can produce hydrogen with very low or no net GHG emissions, although both these technologies are only in the early stages of commercial-scale deployment. (See Climate Techbook: Carbon Capture and Storage <http://www.pewclimate.org/technology/factsheet/ccs>.)

Electrolysis: In electrolysis, an electric current is used to split water into hydrogen and oxygen. Electrolysis is in advanced stages of technological development and could play an important role in the near to mid term. Net GHG emissions from electrolysis for hydrogen production depend on the source of the electricity used. If powered by electricity from low-carbon sources (i.e., renewable technologies, nuclear, power, or fossil fuels coupled with CCS), the process generates little to no GHG emissions.

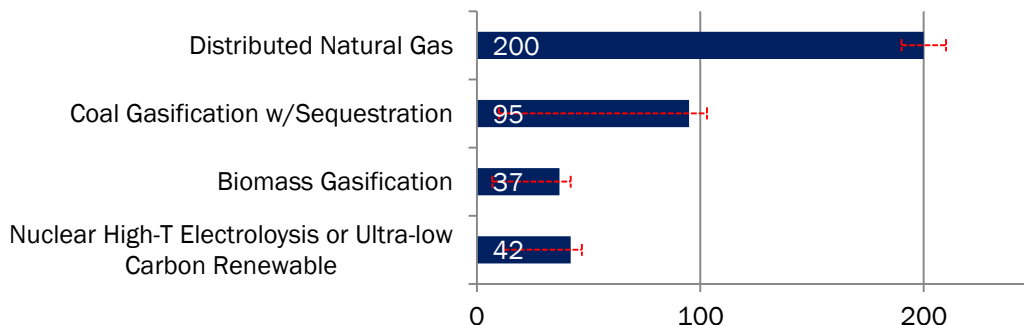
With nuclear high-temperature electrolysis, the efficiency of the process increases. In this type of electrolysis, the heat from the nuclear reactor is used to increase the water temperature and thereby reduce the amount of electricity needed for electrolysis.

High-Temperature Thermochemical Water-Splitting: This is another water-splitting method that uses high temperatures from nuclear reactors or from solar concentrators (lenses that focus and intensity sunlight) to generate a series of chemical reactions that split water, producing hydrogen. The process is in the early stages of development but considered a potential long-term technology, since it is powered by non-GHG emitting technologies and yields a very low-carbon hydrogen fuel.

Photobiological and Photoelectrochemical Processes: These processes use energy from sunlight to produce hydrogen, although both are currently in early stages of research. Photobiological processes use microbes, such as green algae and cyanobacteria. When these microbes consume water in the presence of sunlight, hydrogen is produced as a byproduct of their metabolic processes. Using special semiconductors and sunlight, photoelectrochemical systems produce hydrogen from water as well.

*From U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Production.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_production.pdf, November 2008; and Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen*. Washington, DC: National Academies Press, 2008.*

Figure 2: Well-to-Wheels GHG Emissions for Future FCV based on different hydrogen production processes in gCO₂e/mi.



Source: http://www.hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

With these levels of market penetration, the study estimated that gasoline use would decrease by 24 percent in 2035 and by nearly 70 percent in 2050, compared to business-as-usual (BAU) levels. GHG emissions for light-duty vehicles would decline by 20 percent in 2035 and by more than 60 percent in 2050, as compared to BAU levels.²³ In this scenario, hydrogen is initially produced from natural gas, then from a mixture of sources – natural gas, biomass gasification, and coal gasification with CCS. These estimates assumed that all technical goals were met, consumers accepted FCV technology, and the appropriate policies were implemented for the market transition period.

There are multiple options for reducing GHG emissions from transportation over the long-term. The actual role that FCVs will play will depend on the relative costs of FCV and other low-carbon transportation options and measures adopted by policymakers to reduce GHG emissions.

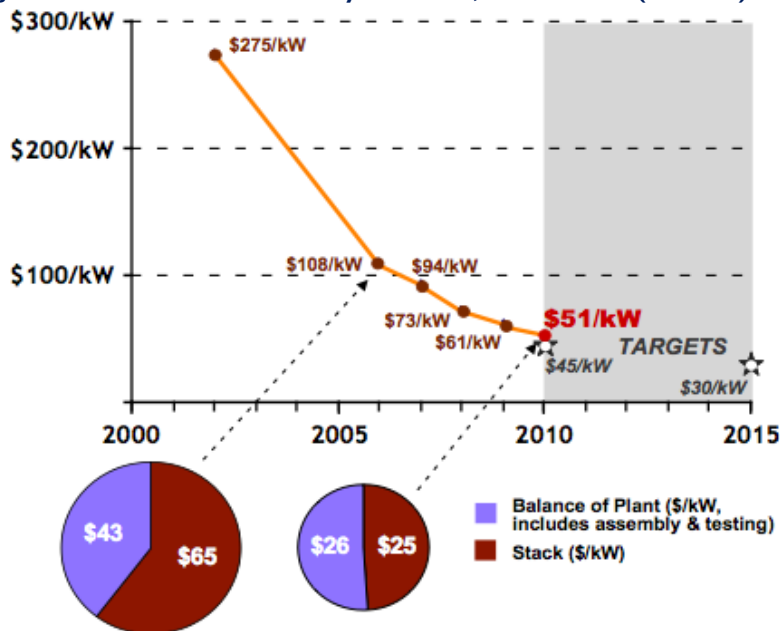
Cost

Although the cost of fuel cells have decreased significantly, the cost for a fuel cell system is almost double that of an internal combustion engine.²⁴

A study by Directed Technologies, Inc. for the DOE estimated the lowest production costs for an FCV with an 80 kilowatt (kW) system with production levels of 500,000 systems a year. The study found that current costs for a fuel cell system (in 2010) are approximately \$51/kW, close to the DOE target of \$45/kW. For 2015, the study projected that costs would decrease to \$39/kW by 2015. The DOE goal for that year is \$30/kW.²⁵

In addition to system costs, the costs of hydrogen storage are still much higher than the target set for commercialization, which is \$2 per kilowatt-hour (kWh). Currently, onboard storage costs are \$15-18/kWh, depending on the level of storage pressure.²⁶

Figure 3: Reduction in Fuel Cell System Cost, 2002 to 2010 (in 2002\$).



Source: http://www.hydrogen.energy.gov/pdfs/10004_fuel_cell_cost.pdf

Overall vehicle costs are also substantially higher than that for conventional vehicles. Toyota has announced plans to sell an FCV in 2015 for \$50,000, approximately two times that for a comparable conventional vehicle.²⁷ In a 2008 study, the NAS estimated the average cost of an FCV from 2008 to 2023 at \$39,000 per vehicle, including research, development, and deployment (RD&D) costs.²⁸ A study by MIT that examined energy and environmental impacts of fuel and vehicle technologies for light-duty vehicles indicated the costs would decrease over the long-term. The study estimates that a fuel cell car in 2035 will cost \$5,300 more than its gasoline counterpart, which would have a retail price of \$21,600 (in 2007\$).²⁹

Current Status

Some believe that FCVs are the most promising long-term solution to the challenge of low carbon transportation. Until recently, FCVs were one of the DOE's main areas of focus for long-term research. In 2010, DOE's proposed budget reduced funds for RD&D significantly to focus on nearer-term options for GHG reductions, such as plug-in electric vehicles (PEVs).³⁰

FCVs are not yet commercially available, but manufacturers are producing small fleets of demonstration vehicles. Both Honda and Mercedes have FCVs available for lease currently but with limited distribution only in Southern California.³¹ Significant penetration of FCVs will require a substantial development of hydrogen refueling infrastructure, as well as improvements in performance and reductions in costs.³² Studies by the NAS and MIT project that FCVs will be available commercially by 2020, but only if technological and cost issues are resolved.³³

The development of any new technology often exhibits a “chicken-and-egg” problem – vehicle manufacturers are unwilling to produce vehicles unless there is a guaranteed supply of hydrogen, while hydrogen producers will not supply fuel unless there is a demand for it. Currently, there is no nationwide hydrogen distribution infrastructure, which limits the use of FCVs to areas where filling stations do exist.

Box 2: Hydrogen Distribution

Currently, there is no infrastructure for distributing hydrogen, like that for fossil fuels. Because hydrogen has less energy per unit volume, distribution costs are higher than those for gasoline or diesel. Most hydrogen is produced either on-site or near where it is used, usually at large industrial sites. It is then distributed by pipeline, high-pressure tube trailers, or liquefied hydrogen tankers. Pipeline is the least expensive way to distribute hydrogen; the last two, while more expensive, can be transported using different modes of transportation – truck, railcar, ship, or barge.

Building network of pipelines and filling stations for FCVs would require high initial capital costs. One potential solution is to produce hydrogen regionally or locally to limit issues with distribution. A second is to use a phased approach. At first, hydrogen distribution (and sales of FCVs) could be concentrated in a few key areas. The next phase would expand the distribution sales network by targeting geographic corridors (e.g., New York-Boston-Washington, D.C.) and then gradually expand to other regions. This phased approach would remove the need for stations all across the United States at the outset, and allow for a slower and affordable build-up in the number of stations and areas served over time.

From U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Distribution and Delivery Infrastructure.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_delivery.pdf November 2008; and Green, D., et al. “Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements.”

Obstacles to Further Development/Deployment

Fuel cell technology: Significant improvements in fuel cell durability and costs are needed for FCVs to achieve commercial success. These are limited by the properties of catalysts and available membrane materials. Targets set by industry aim for an operating life of 5,000-5,500 hours and 17,000 start/stop cycles for a fuel cell system. Achieving this target would allow FCVs to be competitive with conventional vehicles in terms of durability. To date, automotive fuel cells have not demonstrated this level of reliability.³⁴

On-board hydrogen storage: Although hydrogen contains three times more energy per weight than gasoline, it contains one-third of the energy per volume. Storing enough hydrogen to obtain a vehicle range of 300 miles would require a very large tank, too large for a typical car.³⁵ Currently the most cost-effective option is using high-pressure tanks, yet these systems are large, heavy, and too costly to make FCVs cost-competitive.³⁶ Other options include storing hydrogen in metal- or chemical-hydrides³⁷ or producing hydrogen onboard.

Hydrogen production: Hydrogen can be produced using a variety of methods, with substantially different GHG

footprints (see Box 1 above). For FCVs to be competitive as a GHG-reduction strategy, more development of low-cost and low-GHG hydrogen production methods will be needed.

Distribution infrastructure: There is currently no national system to deliver hydrogen from production facilities to filling stations, similar to that for diesel or gasoline. A completely new distribution infrastructure will be required to allow mass market penetration of FCVs (see Box 2 above).

Vehicle cost: For FCVs to become cost-competitive, high production volumes are needed to make vehicle plus fuel costs less than those for a gasoline vehicle.

Competition with other technologies: There is a range of potential alternative technologies available for use in the transportation sector, including higher efficiency gasoline- and diesel-powered vehicles, biofuels, HEVs, and PEVs. To be competitive with these technologies, FCVs will have to improve in terms of performance, durability, and cost.³⁸

Safety and public acceptance: Safety concerns include the pressurized storage of hydrogen on-board vehicles. Hydrogen gas is odorless, colorless, and tasteless, and thus unable to be detected by human senses. Unlike natural gas, hydrogen cannot be odorized to aid human detection; furthermore, current odorants contaminate fuel cells and impair cell functioning. It is also more combustible than gasoline, although flames produce lower radiant heat which limits the chance of secondary fires.³⁹ Improved on-board storage will reduce safety concerns.

Consumers will have to become familiar with and embrace fuel cell technology before FCVs can become widespread.⁴⁰ In addition, the durability and reliability of fuel cells will need to be comparable to the lifetime of a conventional passenger vehicle, approximately 14 years.

Policy Options to Help Promote FCVs

Substantial policy support and investment is required for FCVs to achieve market readiness. Policies should initially focus on RD&D and then transition to policies to aid market penetration once key challenges are overcome.

- Government support through research, development, and deployment initiatives and grants: Government support will need to deal with the “chicken-and-egg” problem by supporting both the development of FCV technology to bring it to market readiness, e.g., by helping manufacturers produce demonstration vehicles, and also build out of the infrastructure for hydrogen distribution. To achieve substantial market penetration of FCVs, the NAS estimates that the government support required will be approximately \$55 billion from 2008 to 2023, with an investment from private industry of \$145 billion over the same period.⁴¹
- Tax and/or subsidy policies to reduce the high initial cost of FCVs compared to conventional vehicles: Government tax and/or subsidy policies are needed to reduce the high initial cost of FCVs, in order to make them more cost-competitive with gasoline vehicles. These policies can be directed at either producers – manufacturers of FCVs and suppliers of hydrogen – to reduce

production and distribution costs, or consumers who purchase FCVs. There is currently a tax credit of \$0.50/gallon for hydrogen sold for use in a motor vehicle, which expires in September 2014.⁴²

- GHG reduction policies: These policies can focus on reducing sectoral and/or economy-wide GHG emissions. For example, a sectoral performance standard (e.g., a low-carbon fuel standard, or LCFS) would set targets for reductions in GHG intensity for the entire transportation fuel supply and provide a level playing field for all transportation energy sources that may be used in the future, including biofuels, electricity, or hydrogen. Economy-wide policies that reduce oil use and GHGs can include GHG cap-and-trade systems and other policies that put a price on GHG emissions. These policies can encourage a broad array of cost-effective options for reducing GHG emissions across economic sectors. A reduction in economy-wide GHG emissions would ensure that hydrogen production generates less CO₂ emissions (see Box 1 for hydrogen production pathways), reducing upstream emissions from the use of FCVs.

Related Business Environmental Leadership Council (BELC) Company Activities

[Air Products](#)

[Daimler](#)

[GE](#)

[IBM](#)

[Johnson Controls](#)

[Toyota](#)

[United Technologies](#)

Related Pew Center Resources

Greene, D. L., & Plotkin, S. (2011). [Reducing Greenhouse Gas Emissions From U.S. Transportation](#). Arlington: Pew Center on Global Climate Change.

Further Reading / Additional Resources

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. Fuel Cell Technologies Program: Informational Resources

(http://www1.eere.energy.gov/hydrogenandfuelcells/pubs_educational.html)

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. Alternative and Advanced Fuels: Hydrogen. <http://www.afdc.energy.gov/afdc/fuels/hydrogen.html>

Bandivadekar, Anup, et al. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and

GHG Emissions.” <http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/> Massachusetts Institute of Technology, July 2008.

Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008. http://www.nap.edu/catalog.php?record_id=12222

¹ US DOD, Fuel Cell Test and Evaluation Center. “History.” http://www.fctec.com/fctec_history.asp. Accessed 31 December 2010.

² U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Fuel Cells.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_fuelcell_factsheet.pdf, November 2008.

³ As with conventional vehicles, FCVs may emit GHGs directly from air conditioning systems (a “direct” source of emissions). The refrigerant used in air conditioning systems is a pressurized gas (HFC-134a, a greenhouse gas), which can leak from small openings or cracks in the system.

⁴ U.S. DOE, Office of EERE, fueleconomy.gov. “Fuel Cell Vehicles.” <http://www.fueleconomy.gov/feg/fuelcell.shtml>, 20 December 2010. Accessed 1 January 2011.

⁵ The electrolyte is an ion conducting material that allows only the appropriate ions to pass between the anode and cathode. The type of electrolyte plays an important role in regulating the chemical reaction. If other substances or free electrons travel through the electrolyte, this could disrupt the chemical reaction.

⁶ U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Fuel Cells.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_fuelcell_factsheet.pdf, November 2008.

⁷ U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Fuel Cells.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_fuelcell_factsheet.pdf, November 2008.

⁸ In a fuel cell, the electrolyte is a non-metallic conductor of electrical ions in a solid membrane. NREL. “Fuel Cells.” http://www.nrel.gov/learning/eds_hydro_fuel_cells.html, 2 December 2009. Accessed 1 January 2011.

⁹ For an animation of the process, visit <http://www.fueleconomy.gov/feg/animation/swfs/fuelcellframe.html>.

¹⁰ U.S. DOE, Office of EERE, fueleconomy.gov. “How Fuel Cells Work.” http://www.fueleconomy.gov/feg/fcv_PEM.shtml, 20 December 2010. Accessed 1 January 2011.

¹¹ Natural Gas Vehicles for America. “Technology.” http://www.ngvc.org/tech_data/index.html. Accessed 1 January 2011.

¹² U.S. DOE, Office of EERE, Alternative & Advanced Vehicles. “What is a fuel cell vehicle.” http://www.afdc.energy.gov/afdc/vehicles/fuel_cell_what_is.html, 31 August 2010. Accessed 17 December 2008.

¹³ Regenerative braking slows a vehicle by converting its kinetic energy into stored energy in a battery, which can later be used to power the electric motor.

¹⁴ U.S. DOE, Office of EERE, Alternative & Advanced Vehicles. “What is a fuel cell vehicle.” http://www.afdc.energy.gov/afdc/vehicles/fuel_cell_what_is.html, 31 August 2010. Accessed 17 December 2008.

¹⁵ See the following for more on hybridization of FCVs: Pesaran, Ahmad. “Fuel Cell/Battery Hybrids: An Overview of Energy Storage Hybridization in Fuel Cell Vehicles.” Presented at 9th Ulm Electrochemical Talks, Ulm, Germany, May 17-18, 2004.

¹⁶ U.S. DOE, Office of EERE, Fuel Cell Technologies Program. “Hydrogen Fuel Cells.” http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_fuelcell_factsheet.pdf, November 2008.

¹⁷ U.S. DOE, Office of EERE, fueleconomy.gov. “Electric Vehicles.” <http://www.fueleconomy.gov/feg/evtech.shtml>, 20 December 2010. Accessed 1 January 2011.

¹⁸ U.S. DOE, Office of EERE, fueleconomy.gov. “Fuel Cell Vehicles: Fuel Economy” http://www.fueleconomy.gov/feg/fcv_sbs.shtml 16 December 2010. Accessed 17 December 2010.

- 19 U.S. DOE. Office of EERE. "Transportation Data Book: Table 4.21 Car Corporate Average Fuel Economy (CAFE) Standards versus Sales-Weighted Fuel Economy Estimates, 1978–2010." <http://cta.ornl.gov/data/chapter4.shtml>, 30 June 2010. Accessed 1 January 2011.
- 20 Toyota Prius. U.S. DOE, Office of EERE, fueleconomy.gov. "2010 Fuel Economy Guide." <http://www.fueleconomy.gov/feg/FEG2010.pdf>. Accessed 7 February 2011.
- 21 Nguyen, T. and J. Ward. "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles." Program Record #10001. Offices of Vehicle Technologies & Fuel Cell Technologies, U.S. DOE. 25 October 2010.
- 22 Bandivadekar, A, et al. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions." Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Report No. LFEE 2008-05 RP, July 2008.
- 23 The study used the 2008 EIA high-oil-price scenario, which was extended to 2050 by the committee, as the reference/BAU case for the analyses. Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.
- 24 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges." http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.
- 25 James, B., J. Kalinoski, and K. Baum. "Mass-Production Cost Estimation for Automotive Fuel Cell System: DOE H2 Program Review." Presentation. 9 June 2010.
- 26 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges." http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.
- 27 Ohnsman, A. "Toyota Plans \$50,000 Hydrogen Fuel-Cell Sedan by 2015." 6 May 2010, <http://www.bloomberg.com/news/2010-05-06/toyota-targets-50-000-range-for-hydrogen-powered-sedan-planned-by-2015.html>. Accessed 16 December 2009.
- 28 Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.
- 29 Bandivadekar, A, et al. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions." Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Report No. LFEE 2008-05 RP, July 2008.
- 30 LaMonica, M. "DOE to slash fuel cell vehicle research." 8 May 2009, http://news.cnet.com/8301-11128_3-10236740-54.html#ixzz1Cq42ltga. Accessed on 2 February 2011.
- 31 In addition, General Motors, Hyundai, Kia, Nissan, Toyota, and Volkswagen are also in the process of testing FCV prototypes. For more information, visit <http://www.fuelcellpartnership.org/progress/vehicles>.
- 32 Greene, D. and S. Plotkin. Reducing Greenhouse Gas Emissions from U.S. Transportation. Prepared for the Pew Center on Global Climate Change, 2011.
- 33 Bandivadekar, A, et al. "On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions." Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Report No. LFEE 2008-05 RP, July 2008; and Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.
- 34 Kromer, M, and J. Heywood. "Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet" Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Publication No. LFEE 2007-03 RP, May 2007.
- 35 U.S. DOE, Office of EERE, Alternative Fuels and Advanced Vehicles Data Center. "Hydrogen as an Alternative Fuel" http://www.afdc.energy.gov/afdc/fuels/hydrogen_alternative.html 19 February 2010. Accessed 17 December 2010.
- 36 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges." http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.
- 37 A binary compound of hydrogen with a metal.
- 38 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges."

http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.

39 U.S. DOE, Office of EERE, Fuel Cell Technologies Program. "Hydrogen Safety."
http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_safety.pdf, November 2008.

40 U.S. DOE, Office of EERE, fueleconomy.gov. "Fuel Cell Vehicles: Challenges."
http://www.fueleconomy.gov/feg/fcv_challenges.shtml 16 December 2010. Accessed 17 December 2010.

41 Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2008.

42 U.S. DOE, Office of EERE, Alternative Fuels and Advanced Vehicles Data Center. "Federal and State Incentives and Laws."
<http://www.afdc.energy.gov/afdc/laws/law/US/8320>. 25 October 2010. Accessed 17 December 2010.

Natural Gas Basics

Natural gas powers more than 100,000 vehicles in the United States and roughly 11.2 million vehicles worldwide.¹ Natural gas vehicles (NGVs) are a good choice for high-mileage fleets—such as buses and taxis—that are centrally fueled or operate within a limited area. The advantages of natural gas as an alternative fuel include its domestic availability, widespread distribution infrastructure, low cost compared with gasoline and diesel, and clean-burning qualities.

What is natural gas?

Natural gas is an odorless, nontoxic, gaseous mixture of hydrocarbons—predominantly methane (CH₄). Because it is a gas, it must be stored onboard a vehicle in either a compressed gaseous or liquefied state. Compressed natural gas (CNG) is typically stored in a tank at a pressure of 3,000 to 3,600 pounds per square inch. Liquefied natural gas (LNG) is super-cooled and stored in its liquid phase at -260°F in special insulated tanks. Natural gas is sold in units of gasoline or diesel gallon equivalents based on the energy content of a gallon of gasoline or diesel fuel.

How and where is natural gas produced and distributed?

Natural gas is drawn from wells or extracted in conjunction with crude oil production. Biomethane, a renewable form of natural gas, is produced from decaying organic materials, such as waste from landfills, wastewater, and livestock. In recent years, 80% to 90% of the natural gas used in the United States was produced domestically. The United States has a vast natural gas distribution system, which can quickly and economically distribute natural gas to and from almost any location in the lower 48 states.

How is natural gas used?

Natural gas accounts for about a quarter of the energy used in the United States. About one-third goes to residential and commercial uses, such as heating and

cooking; one-third to industrial uses; and one-third to electric power production. Only about one-tenth of 1% is used for transportation fuel.

Is natural gas safe for use in vehicles?

Yes. NGVs meet the same safety standards as gasoline and diesel vehicles and also meet the National Fire Protection Association's (NFPA) NFPA 52 Vehicular Fuel System Code. Natural gas has a narrow flammability range and, because it is lighter than air, dissipates quickly if released. NGV fuel tanks are strong and extremely puncture resistant.

What NGVs are available?

A wide variety of new, heavy-duty NGVs are available. The Honda Civic GX is the only light-duty NGV available from a U.S. original equipment manufacturer (OEM). Consumers and fleets also have the option of economically and reliably converting existing light- or heavy-duty gasoline or diesel vehicles for natural gas operation using certified installers. See the Conversions page in the Vehicles section of the Alternative Fuels and Advanced Vehicles Data Center (AFDC) Web site at www.afdc.energy.gov. For



Compressed natural gas is stored onboard a vehicle in safe, puncture-resistant tanks.

the latest new vehicle offerings, also see the AFDC's light-duty and heavy-duty vehicle searches.

How do NGVs work?

NGVs operate in one of three modes: dedicated, bifuel, or dual-fuel. Dedicated NGVs run on only natural gas. Bifuel NGVs can run on either natural gas or gasoline. Dual-fuel vehicles run on natural gas and use diesel for ignition assist. Light-duty vehicles typically operate in dedicated or bifuel modes, and heavy-duty vehicles operate in dedicated or dual-fuel modes.

A CNG fuel system transfers high-pressure natural gas from the storage tank to the engine while reducing the pressure of the gas to the operating pressure of the engine's fuel-management system. The natural gas is injected into the engine intake air the same way gasoline is injected into a gasoline-fueled engine. The engine functions the same way as a gasoline engine: The fuel-air mixture is compressed and ignited by a spark plug and the expanding gases produce rotational forces that propel the vehicle.

On the vehicle, natural gas is stored in tanks as CNG, or in some heavy-duty

¹ NGV Communications Group (www.ngvgroup.com)

vehicles, as LNG, a more expensive option. The form chosen is often dependent on the range a driver needs. More natural gas can be stored in the tanks as LNG than as CNG.

How do NGVs perform?

Natural gas vehicles are similar to gasoline or diesel vehicles with regard to power, acceleration, and cruising speed. The driving range of NGVs is generally less than that of comparable gasoline and diesel vehicles because, with natural gas, less overall energy content can be stored in the same size tank as the more energy-dense gasoline or diesel fuels. Extra natural gas storage tanks or the use of LNG can help increase range for larger vehicles.

In heavy-duty vehicles, dual-fuel, compression-ignited engines are slightly more fuel-efficient than spark-ignited dedicated natural gas engines. However, a dual-fuel engine increases the complexity of the fuel-storage system by requiring storage of both types of fuel.

How much do NGVs cost?

Light-duty NGVs cost \$5,000 to \$7,000 more than comparable gasoline vehicles, and heavy-duty NGVs cost more than their counterparts by \$30,000 or more. The price depends on the fuel-tank capacity and whether the vehicle is produced by an OEM or converted to run on natural gas. However, government incentives are available to offset NGV costs. For more information, visit the AFDC's Incentives and Laws section at www.afdc.energy.gov. Due in part to the high octane rating and clean-burning properties of natural gas, some fleets have reduced maintenance and operating costs for NGVs compared with conventional vehicles.

How much does natural gas cost?

Historically, the average retail price of natural gas has been lower—and more

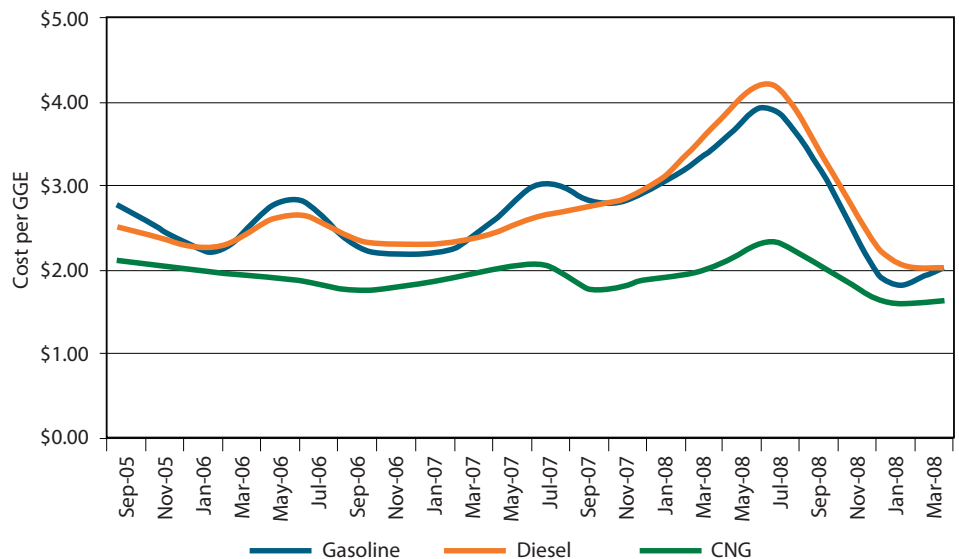


Figure 1. Nationwide Average Retail Gasoline, Diesel, and Natural Gas Prices

stable—than the price of gasoline and diesel (see Figure 1), which makes natural gas a good option for fleets that use a lot of fuel. Incentives are also available to reduce the cost of operating NGVs.

Where is natural gas available?

According to the AFDC, there were 827 CNG and 38 LNG stations in the United States as of February 2010. To find natural gas station locations, visit the Alternative Fueling Station Locator at www.afdc.energy.gov/stations.

Is it easy to fuel an NGV?

Yes. CNG vehicles are fueled with easy-to-use, pressure-sealed dispensers. CNG fueling stations can be configured to fuel vehicles at various rates. Time-fill stations fuel parked vehicles overnight, taking advantage of off-peak electricity rates and smaller compression equipment. Fast-fill stations fill vehicles rapidly using larger compression equipment and high-pressure gas-storage systems. Fueling LNG vehicles requires special procedures and training, but the process is not difficult. As with all vehicles,

proper safety precautions must be taken when refueling NGVs.

How do NGV emissions compare with gasoline and diesel vehicle emissions?

Compared with gasoline and diesel vehicles, NGVs can produce significantly lower carbon monoxide, nitrogen oxide, nonmethane hydrocarbon, particulate matter, and other toxic emissions, as well as greenhouse gas emissions. In addition, because CNG fuel systems are completely sealed, CNG vehicles produce no evaporative emissions. For details, see the Natural Gas Vehicle Emissions page in the Vehicles section of the AFDC at www.afdc.energy.gov.

Where can I learn more about natural gas?

To learn more about natural gas as a transportation fuel, visit the AFDC's natural gas pages at www.afdc.energy.gov. The NGV America Web site at www.ngvc.org also features a wealth of information about natural gas and NGVs.

Propane Basics

Propane powers about 190,000 vehicles in the United States and more than 14 million worldwide.¹ Propane vehicles are a good choice for many fleet applications, including school buses, shuttle buses, taxis and light-duty trucks. The advantages of propane as an alternative fuel include its domestic availability, performance, safety, and clean-burning qualities.

What is propane?

Also known as liquefied petroleum gas (LPG), propane is an odorless, non-toxic hydrocarbon (C₃H₈) gas at normal pressures and temperatures. When pressurized, it is a liquid with an energy density 270 times greater than its gaseous form.² A gallon of liquid propane has about 25% less energy than a gallon of gasoline.

How is propane produced and distributed?

Propane is a byproduct of natural gas processing and crude oil refining with almost equal amounts of production derived from these sources. About 97% of the propane consumed in the United States is produced in North America.³ Propane is shipped from its point of production to bulk distribution terminals via pipeline, railroad, barge, truck, or tanker. Propane marketers fill trucks at the terminals and distribute the fuel to end users, such as retail fueling stations.

Is propane safe for vehicle use?

Yes. Propane vehicles must meet the same safety standards as gasoline vehicles and have passed rigorous crash testing. In addition, propane has a narrow flammability range, and its tanks are 20 times more puncture-resistant than gasoline tanks.

Are propane vehicles available?

Yes, two types of propane vehicles are available: dedicated vehicles that run

solely on propane and bifuel vehicles that have two separate fueling systems, which enable them to run on propane or gasoline. Vehicles can either be converted to use propane or delivered as dedicated propane vehicles directly through select original equipment manufacturers' (OEM) dealerships. Certified technicians can install U.S. Environmental Protection Agency (EPA) and/or California Air Resources Board certified propane conversion systems on a variety of vehicles. A list of certified systems can be found on the EPA Web site at <http://iaspub.epa.gov/otaqpub/publist1.jsp>. Medium-duty propane vehicles and heavy-duty propane engines are also available. To find them, use the Heavy-Duty Vehicle and Engine Search on the Alternative Fuels and Advanced Vehicles Data Center (AFDC) Web site at www.afdc.energy.gov/afdc/vehicles/heavy.

How do propane vehicles work?

Propane vehicles operate much like gasoline vehicles with spark-ignited engines. There are two types of fuel-injection systems available: vapor and liquid injection. In both types, propane is stored as a liquid in a relatively low-pressure tank (about 300 psi). In a vapor-injected system, liquid propane is controlled by a regulator or vaporizer, which converts the liquid to a vapor. The vapor is fed to



Lower maintenance costs are a prime reason behind propane's popularity for high-use vehicles, such as school buses.

a mixer located near the intake manifold where it is metered and combined with filtered air before being drawn into the combustion chamber and burned to produce power, just like a gasoline engine. In a liquid-injected system, fuel is delivered into the combustion chamber, or intake port, in a liquid form (instead of a vapor). This way, the fuel combusts more fully and provides optimal power and throttle response.

How do propane vehicles perform?

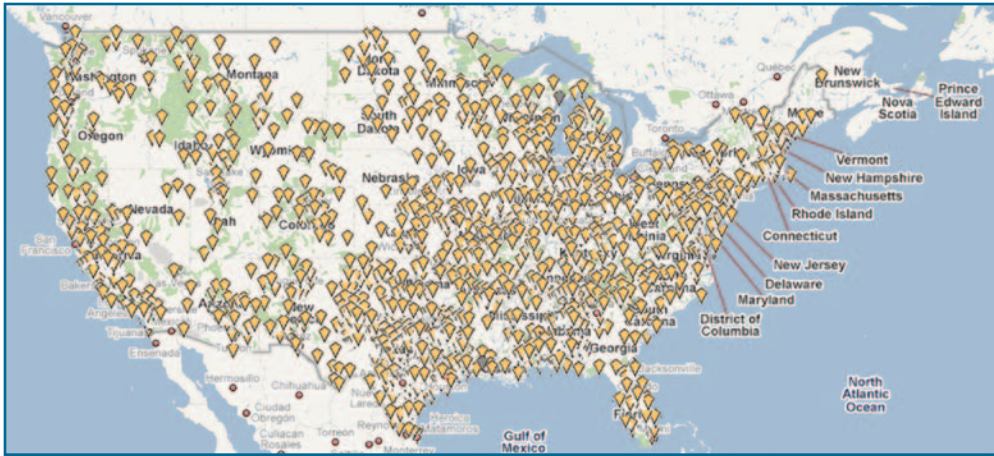
Propane vehicles are similar to their gasoline counterparts with regard to power, acceleration, and cruising speed. The driving range of bifuel vehicles is comparable to that of gasoline vehicles, and the fuel economy of dedicated propane vehicles is slightly lower due to propane's lower energy content. Larger storage tanks can increase range, but the additional weight displaces payload capacity.

¹ World LP Gas Association 2009 (<http://worldlp-gas.com/gain/key-autogas-data>)

² Energy Information Administration Web site (www.eia.doe.gov)

³ Propane Education & Research Council Web site (www.usepropane.com/climate)





According to the AFDC Stations Count, there are more than 2,400 LPG stations available to fuel the country's more than 270,000 propane vehicles.

How much do propane vehicles cost?

OEM delivered light-duty propane vehicles can cost several thousand dollars more than comparable gasoline vehicles. However, federal tax credits may offset the increased vehicle cost and many states have additional incentives that further incentivize the purchase of a propane vehicle. Vehicle conversions may also qualify for tax credits and other incentives. For the latest information on incentives for both OEM and converted vehicles, visit the Federal and State Incentives and Laws section of the AFDC at www.afdc.energy.gov.

Lower maintenance costs are a prime reason behind propane's popularity for high-mileage vehicles. Propane's high octane rating (104 to 112 compared with 87 to 92 for gasoline) and low-carbon and oil-contamination characteristics have resulted in documented engine life of up to two times that of gasoline engines.⁴

How much does propane cost?

The price of propane is typically based on the volume of fuel used. For the best

⁴ AFDC (www.afdc.energy.gov/afdc/vehicles/propane_what_is.html)

success, fleets should develop relationships with their local propane marketers and station operators who can provide them with the fair pricing and help them establish onsite infrastructure at little or no cost if a fuel contract is executed. When fleets fuel their vehicles at locations where there is no relationship with the fuel marketer or station operator, the fuel price may be equal to or higher than gasoline. Local propane marketers are present in most every community across the United States and can provide expertise and technical assistance in establishing infrastructure.

Tax credits and incentives may also be available that can help reduce the cost of propane. For more information, see the AFDC's Federal and State Incentives and Laws section at www.afdc.energy.gov.

Where is propane available?

Propane is widely available. According to the AFDC, there were more than 2,400 propane stations in the United States as of February 2010. To find propane station locations in your area, visit the Alternative Fueling Station Locator on the AFDC Web site at www.afdc.energy.gov/stations. As previously mentioned, fleets can work with their

local propane marketer to establish new fueling infrastructure at little to no cost depending on the fuel contract and the complexity of the equipment being installed.

Is it easy to fuel a propane vehicle?

Filling a propane vehicle is similar to fueling a conventional vehicle and takes about the same amount of time. In addition, spillage and ground contamination are not concerns with propane because any fuel that might escape dissipates into the air quickly and harmlessly. As with all vehicles, however, proper safety precautions—such as no smoking or cell phone use—must be recognized when refueling a propane vehicle.

How do propane vehicle emissions compare with gasoline vehicle emissions?

Compared with gasoline vehicles, propane vehicles produce significantly lower carbon monoxide, nitrogen oxide, hydrocarbon, particulate matter, and greenhouse gas emissions. In addition, propane is not a greenhouse gas when released directly into the atmosphere.

Where can I learn more about propane?

To learn more about propane as a transportation fuel, visit the AFDC's Propane Fuels and Vehicles sections (www.afdc.energy.gov), contact your local Clean Cities coordinator (www.cleancities.energy.gov), or visit the Propane Education & Research Council (www.propanecouncil.org), and the National Propane Gas Association (www.npga.org) Web sites.

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