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Inside Alternatively Powered Vehicles: The Problems and the Possibilities

Roxanne Greitz Miller
Chapman University, rgmiller@chapman.edu

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Like all things natural or human-made, all modes of transportation, from horses to spacecraft, are governed by the following scientific principles or laws:

Principle of conservation of matter

Matter can neither be created nor destroyed, only changed in form. A basic translation: What comes in must come out—nature accounts for every atom.

First law of thermodynamics

Energy—like matter—can neither be created nor destroyed, only changed in form. As C.P. Snow said, you can't win, because you can't get something for nothing.

Second law of thermodynamics

Due to increasing entropy in systems, no energy conversion can be 100% efficient. Snow's translation: You can't break even.

All of these principles are at the center of understanding the workings of the most common method of personal transportation worldwide: the automobile. In analyzing the cost-to-benefit ratio of a variety of automobile engine and fuel technologies, as we attempt to find methods that meet our transportation needs but are less expensive to operate and less damaging to our environment in the process, we must always keep these three scientific tenets in mind. In short, while some newer automobile power technologies increase fuel efficiency and/or decrease emissions related to the operation of the vehicle, there are other issues—such as the environmental impact of the processes undergone to produce the alternative technology, or the end product solid wastes that will be yielded by the alternative technology—that must also be considered when making decisions about the benefits of these new alternatives.

A brief history of the automobile

In 1885, German engineer Gottlieb Daimler and Wilhelm Maybach patented their four-stroke design for the internal combustion engine, enabling a worldwide transformation in how people and goods were transported. By 1900, there were about 8,000 registered vehicles; by 1912 nearly one million cars were registered. After World War II, increases and improvements in industrialized machinery and technology, along with an improved U.S. economy, resulted in significant increases in the number of cars on the road. Between 1949 and 1972, the number of cars in the United States increased from 45 million to 119 million; worldwide the number of cars increased from 19 million to 161 million. By 2000, there were 2.1 cars per person in the United States, and as developing countries grow and increase their demand for automobiles, the number of automobiles worldwide is expected to continue to increase in the future.

Unfortunately, there are well-known environmental consequences to the internal combustion machine. Fossil fuel combustion results in the release of carbon dioxide, nitrogen oxides, carbon monoxide, and other air pollutants that contribute to global warming and poor outside air quality. While improvements in design and emissions control technologies have reduced the amount of emissions and improved fuel efficiency considerably over the last few decades, the emissions of carbon dioxide and nitrogen oxides in particular remain a problem.

Despite improvements in internal combustion engine technology, the average overall fuel economy of vehicles in the United States has actually been declining due to the increase in use of larger and less-efficient personal vehicles such as trucks and sports utility vehicles, which get fewer miles to the gallon than other smaller passenger vehicles. In 2002, 50% of the personal vehicles sold in the United States were light-duty trucks or SUVs. The recent rise in gasoline prices has made the cost to operate these less-efficient vehicles higher than ever.

The future is today

Given the need to find more affordable personal transportation, the inevitable increase of automobiles worldwide, and the need to lessen the impact on our environment, many research and development efforts are underway to cultivate improved automotive technologies. Each of these has environmental and economic costs and benefits; it is not yet clear which technologies will be widely adopted in the cars of the future. New automobile technologies include the following:

Hybrid vehicles, in principle, combine two types of energy sources, such as gasoline-electric (found most often in hybrid cars), diesel-electric (locomotives), or nuclear-electric (submarines). In the gasoline-electric car, our current popular form

Roxanne Greitz Miller (rgmiller@chapman.edu) *is assistant professor of secondary and science education at Chapman University in Orange, California, and a former middle school and senior high school science teacher in the public schools of Florida.*

of hybrid automobile, an internal combustion engine is combined with an electric motor. Unlike pure electric vehicles, hybrid gasoline-electric vehicles do not get “plugged in” to recharge (this is a common misconception); the battery for the electric motor is recharged by the car’s generator while it is running. There have been hybrid vehicles on the market for the past few years; the first widely available gasoline-electric hybrids included the Toyota Prius and the Honda Insight. Several automotive manufacturers have either already released or have announced plans to market additional hybrid vehicles, including a hybrid truck and a hybrid SUV.

Hybrid vehicles vary in their design, but typically the electric motor is used to get the car moving and to assist the gasoline engine during periods of heavy load, such as in passing and climbing hills. The electric motor powers the car during idling periods, which further reduces emissions and increases fuel efficiency. When the car is braking or coasting downhill, the wheels power the generator, which stores the electricity in the battery pack to power the electric motor. A typical hybrid vehicle boasts between 15% and 50% more fuel efficiency than a typical internal combustion engine vehicle.

However, the use of a hybrid vehicle does not remove the environmental impact of petroleum use, it reduces it. Hybrids also typically have more parts, and therefore cost more to purchase; and, because not only energy but also matter can neither be created nor destroyed, the nonrecyclable parts will have greater environmental impact in terms of solid waste disposal.

While available and common in trucks and buses, but not widely popular for personal vehicles in the United States, *diesel engine vehicles* are very popular in Europe, where the cost of gasoline is generally higher. Diesel engines are more energy-efficient than other gasoline-powered designs, last longer than gasoline engines, and release less carbon dioxide to the atmosphere than petroleum engines.

However, diesel vehicles release high emissions of sulfur dioxide, nitrogen oxides, and particulate matter, all of which contribute to environmental problems such as acid rain, smog, and poor air quality. For these reasons, diesel vehicles are not available for sale in several states, such as California and New York, with strict emissions laws. New “clean diesel” technologies, including biofuels and biodiesels, are being developed to reduce emissions from these engines. However, the environmental impacts (such as the water, energy, pesticides, fertilizer, and land use that go into the creation of biofuels) need to be considered in an assessment of environmental impacts of these new, cleaner technologies.

Zero emissions vehicles is a term used to refer to vehicles that release no emissions from their use, such as fully electric vehicles. However, most electric vehicles are actually *partial* zero emission vehicles, a term that better represents the fact that while the vehicle itself releases no emissions, the environmental impacts of generating the electricity should be considered. In the vast majority of situations today, the electricity used to recharge zero emission vehicle batteries is not generated by 100% emissions-free methods (such as electricity generated from coal or natural gas powered power plants). In contrast, electricity generated from solar or wind power would be an example of 100% emissions-free technology. Depending on the method used to generate the electricity, electric vehicles are estimated to be between 35% and 97% cleaner than traditional gasoline-powered vehicles.

Until now, electric vehicles have not been widely used for highway or city transportation due to the current inability of the vehicles to travel long distances without recharging and the time required to recharge (typically eight hours of recharging time for every 100 miles driven), but most trips made by automobile—such as daily commutes—are within the 100 mile range that electric vehicles can generally travel between charges. While mostly found in use by corporate fleets (such as Southern California Edison), General Motor’s Impact EV1, Honda’s EV Plus, and Toyota’s RAV EV are examples of electric vehicles that have been successfully produced. These vehicles must be plugged in for recharging, and may be recharged at home or in a commercial or public recharging station such as those provided in many state-operated facilities or retail shopping centers in geographic areas where electric vehicle ownership is promoted. Unfortunately, few fully electric vehicles are still in production for normal road use (GM, Honda, and Toyota have ceased production of the cars mentioned above); however, neighborhood-use electric vehicles (such as Daimler-Chrysler’s GEM car) are increasing in demand.

Fuel cells as a power source for vehicles are currently under considerable research and many approaches to their application are being studied. In most fuel cells, hydrogen and oxygen are converted into water, and through the process the cell produces electric power. Hydrogen is the most plentiful element on Earth, and its attraction as a fuel source is that, once isolated, it is a clean burning fuel that produces neither carbon dioxide (a greenhouse gas) nor toxic emissions and can be used for electricity production, transportation, and other energy needs. However, before hydrogen can be used as fuel it must first be extracted from hydrogen-bearing compounds either through electrolysis or high temperature reformation (via a device called a *reformer*) of organic compounds like coal. Many of the extraction processes can create substantial pollution, and so for hydrogen to be truly pollution-free, the extraction process must be pollution-free. Unfortunately, this conversion is not perfectly efficient (remember the second law of thermodynamics)—it generates heat and other gases, and the hydrogen must then be cleaned up to increase its efficiency. In addition, hydrogen is difficult to store in cars and distribute.

If the problems of extracting hydrogen can be solved in a pollution-free, cost-effective manner, and if technologies such as fuel cells can be made cost-effective, then hydrogen has the potential to provide clean, alternative energy for not only transportation, but also for lighting, heating, cooling, and other applications.

Natural gas can be used in vehicles in two forms: compressed natural gas (CNG) or liquefied natural gas (LNG). The gas used is a mixture of hydrocarbons, but consists mostly of methane, is abundantly available from domestic sources, is clean burning, and can be used in existing gasoline-powered engines with modifications. In 2004, it was estimated that 130,000 CNG or LNG vehicles were operating in the United States, with two million operating worldwide.

Natural gas is one of the cleanest burning alternative fuels available and offers a number of advantages over gasoline. Air exhaust emissions from natural gas vehicles are much lower than those from gasoline-powered vehicles. In addition, smog-producing gases, such as carbon monoxide and nitrogen oxides, are reduced by more than 90% and 60%, respectively, and carbon dioxide, a greenhouse gas, is reduced by 30% to 40%.

Modifications to convert traditional gasoline-powered vehicles to natural gas are available for between $2,000 and $3,000. CNG is gaining popularity with automobile manufacturers for personal use; more vehicles designed by the factory to use CNG were available in 2005 than in any previous year, and included models from Honda, Chevrolet, and General Motors. Factory-produced CNG vehicle models typically cost somewhere between $1,500 and $6,000 more than their gasoline-powered counterparts. Recent developments toward the creation of an at-home filling system for CNG vehicles promises to allow CNG vehicle owners the ability to fill their own tanks from their home's natural gas line in the near future.

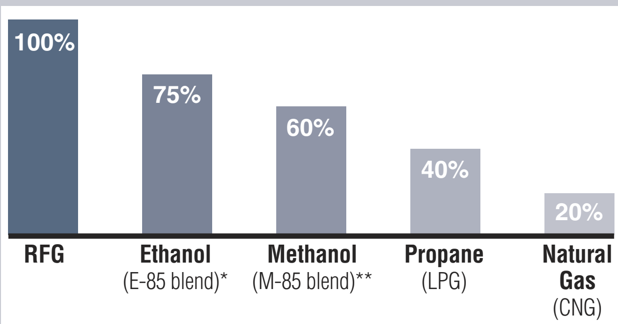
Liquefied petroleum gas (LPG) generally refers to propane-powered vehicles. While not widely recognized, propane has been used to power vehicles since the 1920s. Propane is produced as a byproduct of natural gas processing and petroleum refining; approximately 85% of propane used in the United States is produced domestically. Cleaner than many other types of fuels, LPG vehicles emit 60% less ozone-forming emissions than gasoline-powered vehicles. More than 200,000 vehicles are already operating on LPG in the United States and more than 4,000 refueling stations are now available, making the distribution infrastructure for LPG currently more developed than for other alternative fuels. Converting traditional gasoline-powered engines to operate on clean-burning LPG is relatively inexpensive; estimates on factory-installed and nonfactory-installed conversions run around $2,500. Considering the greatly reduced cost of LPG compared to gasoline, the end price for such a conversion is regarded as very low.

However, LPG vehicles are currently primarily medium- to heavy-duty vehicles such as school buses, trolleys, garbage trucks, shuttle buses, and passenger buses. As such, it is difficult to find ready-to-purchase LPG vehicles from an auto dealer, and vehicles that do undergo conversion and are owned by private individuals sometimes encounter difficulties refueling since many of the refueling stations are geared toward fleets of commercial vehicles rather than single private individuals.

Alcohol fuels have been used since Henry Ford invented his first automobile, which ran on ethanol in the late 1800s. Ethanol (ethyl alcohol) is usually produced from corn, but other grains such as wheat or barley can be used. Ethanol is widely available domestically since it is made from domestically grown crops it does not pollute the air as much as other liquid fuels, and gasoline-powered engines are easily converted to run on

FIGURE 1 **Cleaner alternatives**

According to the U.S. Department of Energy, alternative fuels reduce ozone-causing emissions. The following chart shows the percentage of combined carbon monoxide and nitrogen oxide for each alternative fuel compared to 100% of emissions from reformulated gasoline (RFG):



*E-85 is a blend of 85% ethanol and 15% gasoline.
**M-85 is a blend of 85% methanol and 15% gasoline.
Source: U.S. Department of Energy

ethanol. Ethanol should not be confused with gasohol, which is a mixture of 90% gasoline and 10% ethanol. Ethanol produces fewer emissions during combustion, but the agricultural production is energy, water, and land intensive.

Methanol (methyl alcohol) is produced from natural gas, but can also be produced from less efficient and less affordable nonpetroleum products such as coal or biomass. M-85, which is a blend of 85% methanol and 15% gasoline, is currently used in limited applications and 100% methanol (M-100) is expected to be pursued as a fuel source in the future.

The down side

There are three primary reasons for pursuing alternatives to gasoline fuel for transportation: (1) pollution reduction; (2) increased fuel efficiency; and (3) decreased cost to the operator. However, trade-offs occur between these three rationales; to reduce pollution, efficiency is sometimes sacrificed; to decrease cost, pollution reduction is sometimes sacrificed, and so on. No matter how you look at it, the three scientific principles always govern what is taking place, and the second law of thermodynamics reigns supreme. The HowStuffWorks website (see Resources) does a great job of discussing efficiency for a variety of alternatives to gasoline-powered vehicles; much of the following and additional information on fuel efficiency of various vehicles can be found on their website.

Pollution reduction is one of the primary goals of the fuel cell. By comparing a fuel cell–powered car to a gasoline-powered car and an electric battery–powered car, you can see how fuel cells might improve the efficiency of cars today. If the fuel cell is powered with pure hydrogen, it has the potential to be up to 80% efficient, meaning 80% of the energy content of the hydrogen is converted into electrical energy. But pure hydrogen is difficult to store in a car, and therefore fuel cells often rely on converting a hydrocarbon, such as methanol, into hydrogen. When a reformer is added to the system to achieve this, the overall efficiency of the fuel cell drops to about 30% to 40%.

Then, the electrical energy must still be converted into mechanical work, which is accomplished by the electric motor and inverter. A reasonable number for the efficiency of the motor/inverter is about 80%. So we have 30% to 40% efficiency at converting methanol to electricity, and 80% efficiency converting electricity to mechanical power. That gives an overall efficiency of about 24% to 32% for a vehicle powered by a fuel cell.

The efficiency of a *gasoline-powered car* is surprisingly low. All of the heat that comes out as exhaust or goes into the radiator is wasted energy. The engine also uses a lot of energy turning the various pumps, fans, and generators that keep it going. So the overall efficiency of an automotive gasoline-powered engine is about 20%, meaning that only about 20% of the thermal energy content of the gasoline is converted into mechanical work.

A *zero emission, battery-powered electric vehicle* has a fairly high efficiency. The battery is about 90% efficient (most batteries generate some heat, or require heating), and the electric motor/inverter is about 80% efficient. This gives an overall efficiency of about 72%.

However, as was discussed previously, the electricity used to power the car had to be generated somewhere. If it was generated at a power plant that used a combustion process, then only about 40% of the fuel required by the power plant was converted into electricity. The process of charging the car requires the conversion of alternating current (AC) power to direct current (DC) power. This process has an efficiency of about 90%.

So, if we look at the whole cycle, the efficiency of an electric car is 72% for the car, 40% for the power plant, and 90% for charging the car. That gives an overall efficiency of 26%. The overall efficiency varies considerably depending on what sort of power plant is used. If the electricity for the car is generated by a hydroelectric power plant, for example, then it is basically free (we didn't burn any fuel to generate it), and the efficiency of the electric car is about 65% overall.

The pollution issues for each alternative technology have been highlighted throughout this article. The main governing principle here is that matter and energy can neither be created nor destroyed; therefore, to create these fuels some process that has converted matter into energy has taken place, and with it, a range of environmental issues must be considered and explored.

In looking at cost, gasoline remains one of the cheaper forms of fuel for transportation, despite its recent high price in the United States. When comparing the cost of varied alternative fuel technologies, a gallon of gasoline is compared to a gallon equivalent of the alternative fuel (abbreviated as *gge*). Figure 2 shows that when gasoline is compared to the other fuels for which a gallon equivalent is available (note: electric vehicles do not have an easily computed gge), only compressed natural gas (CNG) was lower in cost than gasoline as of March 2005, when the last comparison figures were made public. It would be expected that electric vehicles would also rank below gasoline from basic calculations of equivalency.

Student activities

How can we approach this topic with middle grade students? A good place to start would be to have students

FIGURE 2 **Fuel comparison chart**

	Gasoline	No. 2 Diesel	Biodiesel (B20)	Compressed Natural Gas (CNG)	Electricity	Ethanol (E-85)	Hydrogen	Liquefied Natural Gas (LNG)	Liquefied Petroleum Gas (LPG)	Methanol (M-85)
Main fuel source	Crude oil	Crude oil	Soy bean oil, waste cooking oil, animal fats, and grapeseed oil	Underground reserves	Coal; however, nuclear, natural gas, hydroelectric, and renewable resources can also be used.	Corn, grains, or agricultural waste	Natural gas, methanol, and other energy sources	Underground reserves	A by-product of petroleum refining or natural gas processing	Natural gas, coal, or woody biomass
Energy content per gallon	109,000–125,000 Btu	128,000–130,000 Btu	117,000–120,000 Btu (compared to diesel #2)	33,000–38,000 Btu @ 3,000 psi; 38,000 –44,000 Btu@ 3,600 psi	N/A	~ 80,000 Btu	Gas: ~6,500 Btu@3,000 psi; ~16,000 Btu@10,000 psi Liquid: ~30,500 Btu	~73,500 Btu	~84,000 Btu	56,000–66,000 Btu
Energy ratio compared to gasoline			1.1 to 1 or 90% (relative to diesel)	3.94 to 1 or 25% at 3000 psi; 3 to 1@ 3,600 psi		1.42 to 1 or 70%		1.55 to 1 or 66%	1.36 to 1 or 74%	1.75 to 1 or 57%
Physical state	Liquid	Liquid	Liquid	Compressed gas	Electricity	Liquid	Compressed gas or liquid	Liquid	Liquid	Liquid
Environ-mental impacts of burning fuel	Produces harmful emissions; however, gasoline and gasoline vehicles are rapidly improving and emissions are being reduced.	Produces harmful emissions; however, diesel and diesel vehicles are rapidly improving and emissions are being reduced, especially with after-treatment devices.	Reduces particulate matter and global warming gas emissions compared to conventional diesel; however, NOx emissions may be increased.	CNG vehicles can demonstrate a reduction in ozone-forming emissions compared to some conventional fuels; however, HC emissions may be increased.	EVs have zero tailpipe emissions; however, some amount of emissions can be contributed to power generation.	E-85 vehicles can demonstrate a 25% reduction in ozone-forming emissions compared to reformulated gasoline.	Zero regulated emissions for fuel cell-powered vehicles, and only NOx emissions possible for internal combustion engines operating on hydrogen.	LNG vehicles can demonstrate a reduction in ozone-forming emissions compared to some conventional fuels; however, HC emissions may be increased.	LPG vehicles can demonstrate a 60% reduction in ozone-forming emissions compared to reformulated gasoline.	M-85 vehicles can demonstrate a 40% reduction in ozone-forming emissions compared to reformulated gasoline.
Fuel availability	Available at all fueling stations.	Available at select fueling stations.	Available in bulk from an increasing number of suppliers. There are 22 states that have some biodiesel stations available to the public.	More than 1,100 CNG stations can be found across the country. California has the highest concentration of CNG stations. Home fueling was made available in 2003.	Most homes, government facilities, fleet garages, and businesses have adequate electrical capacity for charging, but special hookup or upgrades may be required.	Most of the E-85 fueling stations are located in the Midwest, but in all, approximately 150 stations are available in 23 states.	There are only a small number of hydrogen stations across the country. Most are available for private use only.	Public LNG stations are limited (only 35 nationally), LNG is available through several suppliers of cryogenic liquids.	Propane is the most accessible alternative fuel in the United States. There are more than 3,300 stations nationwide.	Methanol remains a qualified alternative fuel as defined by the EPA, but it is not commonly used.
Average Cost/gge (March 21, 2005)	$2.11	$2.24	$2.30	$1.56	N/A	$2.29	N/A	N/A	$2.65	N/A

Table obtained using U.S. Dept. of Energy report function (see Resources).

track their own household's gasoline efficiency by recording the number of gallons of gasoline purchased over a fixed period of time (size of gasoline tank would need to be accounted for), price per gallon purchased, the number of miles traveled, and a general estimate of the number of miles driven under highway and city conditions. A classwide comparison chart could then be created showing the vehicles' makes and model years, overall fuel efficiency, and fuel economy. This activity can serve to raise students' consciousness about the cost of gasoline and what they are getting for their dollar at the pump, while incorporating math standards and communication standards into a worthwhile activity. It will also make students aware of what vehicles are being driven in their community, and what the trends are for car choice (such as compacts, trucks, SUVs) and the impact of those choices on fuel economy and efficiency.

Students can also research what types of fuels and fueling stations are available in their immediate area, and even visit or interview people who use alternative fuels in their region. Further extensions on this activity would be to lobby with local lawmakers to add public alternative-fuel filling and recharging stations in your area, either through a letter-writing campaign or a presentation to a public board, such as a city council or board of supervisors; or to create a map of alternative-fueling stations that could be presented to the city managers for distribution or posting on their city's website.

For those with a dramatic flair, student groups could be charged with thoroughly researching a particular type of alternative car design, and then stage a mock sales presentation for the class, a group of students from another class, or a group of adults. To simulate the competition and decision making that goes on when a potential buyer shops for a vehicle, two different types of alternative vehicles' salespersons could be staged against each other, each group trying to convince the buyer of the advantages of their group's vehicle type. This competitive edge would provide incentive to students to not only learn the advantages of their car type, but also the disadvantages of the car type they are competing against.

Lastly, the article "Fuel-Cell Drivers Wanted," by Todd Clark and Rick Jones (see References), presents a great way for students to explore the issues related to fuel-cell technology, and includes a detailed description of what they used to enable their students to create their own fuel-cell cars as a hands-on activity. Solar car activities have been around for many years, and can also be used to apply the concept of alternative power in a fun and engaging way.

Final points

Exploring the varied methods for powering our transportation needs provides students with valuable knowledge and practical experience in applying the scientific laws and principles that govern matter and energy in useful ways, and connects to multiple subjects' curriculum standards. By engaging students in a variety of activities designed to demonstrate the delicate balance between the use of technology and our environment, and the associated financial and environmental costs of basic but important decisions such as what type of vehicle we choose to drive, we will be preparing thoughtful and deliberate citizens who may actually *think* before they act when faced with these situations in the future.

Reference

Clark, T., and R. Jones. 2004. Fuel-cell drivers wanted. *Science Scope* 27 (9): 22–24.

Resources

A student's guide to alternative fuel vehicles—*www.energyquest.ca.gov/transportation/index.html*

Alternative fuels data center—*www.eere.energy.gov/afdc*

California alternative fuels and high-efficiency vehicles—*www.energy.ca.gov/afvs/index.html*

Environmental Literacy Council transportation section—*www.enviroliteracy.org/subcategory.php/106.html*

Environmental Protection Agency—*www.epa.gov*

HowStuffWorks website—*www.howstuffworks.com*

National Energy Foundation fueling the future project—*www.nef1.org/ftf/index.html*

National Renewable Energy Laboratory—*www.nrel.gov/education/resource.html*

Natural Resources Defense Council transportation page— *www.nrdc.org/air/transportation/default.asp*

The truth about gasoline—*www.cars.com/carsapp/national/?srv=parser&act=display&tf=/features/truthabout/gas/alternative1.tmpl*

Union of Concerned Scientists—*www.ucsusa.org*

U.S. Department of Energy report function—*www.eere.energy.gov/afdc/altfuel/fuel_comp.html*

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