The 21st Century Electric Car

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The electric car, once the "zero-emissions" darling of environmentalists, is sometimes maligned as an "emissions-elsewhere" vehicle, since the electricity to charge its batteries must be generated in electrical generation plants that produce emissions. This is a reasonable point, but we must then ask how much pollution an electric car produces per mile – accounting for all emissions, starting from the gas or oil well where the source fuel is extracted, all the way to the final consumption of electricity by the car's motor. When we work through the numbers, we find that the electric car is significantly more efficient and pollutes less than all alternatives.

In this paper, we will investigate the Tesla Roadster™, which uses commodity lithium-ion batteries instead of lead-acid batteries or nickel-metal-hydride batteries as most electric cars have used. Not only does this lithium-ion–based car have extremely high well-to-wheel energy efficiency and extremely low well-to-wheel emissions, it also has astonishing performance and superior convenience.

Energy Efficiency

To compute the well-to-wheel energy efficiency of any car, we start with the energy content of the source fuel (e.g. crude oil or natural gas) as it comes from the ground. We then track the energy content of this fuel as it is converted to its final fuel product (e.g. gasoline or electricity), subtracting the energy needed to transport the fuel to the car. Finally, we use the fuel efficiency of the car itself (e.g. its advertised mpg) to complete the equation.

All fuels can be described in terms of the energy per unit of mass. In this paper, we will express the energy content of fuels in terms of mega-joules per kilogram (MJ/kg). Well-to-wheel efficiency is then expressed in terms of kilometers driven per mega-joule (km/MJ) of source fuel consumed – a higher number is better.

Gasoline Cars

In this section, we will calculate the well-to-wheel energy efficiency of a normal gasoline-powered car. First, let's take gasoline's energy content, which is 46.7 MJ/kg,[1] or 34.3 MJ/l.[2] Second, we know that production of the gas and its transportation to the gas station is on average 81.7% efficient,[3] meaning that 18.3% of the energy content of the crude oil is lost to production and transportation. Third, 34.3 MJ/l / 81.7% = 42 MJ/l; 42 mega-joules of crude oil are needed to produce one liter of gasoline at the gas pump.

The most efficient ordinary gasoline car made was the 1993 Honda Civic VX, which was EPA-rated at 51 mpg for combined city and highway driving.[4] Converting to metric, this car was rated at 21.7 kilometers per liter of gasoline. Thus, its efficiency is 21.7 km/l / 42 MJ/l = 0.52 km/MJ. Keep in mind that the Honda Civic VX got about twice the gas mileage of typical cars – a car like a Toyota Camry is rated around 0.28 km/MJ. [5]

Hybrid Cars

All hybrid cars available today have no provision to charge their batteries except by using energy that is ultimately generated by their gasoline engines. This means that they may be considered, from a pollution and energy efficiency perspective, to be nothing more than somewhat more efficient gasoline cars. If the EPA-certified gas mileage for such a car is 51 mpg, this is exactly the same as an ordinary gasoline car that gets 51 mpg. (If a hybrid car could recharge its batteries by plugging in when at home, and if its batteries held enough charge for a meaningful drive, this would not be true.)

The most efficient hybrid car is the 2005 Honda Insight, which gets 63 mpg for combined city and highway driving.[6] Using similar math as we used for the Civic VX above, the Insight's well-to-wheel energy efficiency is 0.64 km/MJ. The famous Toyota Prius is EPA-rated to get 55 mpg in combined city-highway driving, for an energy efficiency of 0.56 km/MJ.[7]

Electric Cars

Even with tires and gearing optimized for performance (rather that absolute efficiency), the Tesla Roadster only consumes about 110 watt-hours (0.40 mega-joules) of electricity from the battery to drive a kilometer, or 2.53 km/MJ.

The energy cycle (charging and then discharging) of the lithium-ion batteries in the Tesla Roadster is about 86% efficient.[8] This means that for every 100 mega-joules of electricity used to charge such a battery, only 86 mega-joules of electricity are available from the battery to power the car's motor. Thus, the "electrical-outlet-to-wheel" energy efficiency of the Tesla Roadster is 2.53 km/MJ x 86% = 2.18 km/MJ.

The most efficient way to produce electricity is with a "combined cycle" natural gas-fired electric generator. (A combined cycle generator combusts the gas in a high-efficiency gas turbine, and uses the waste heat of this turbine to make steam, which turns a second turbine – both turbines turning electric generators.) The best of these generators today is the General Electric "H-System" generator, which is 60% efficient,[9] which means that 40% of the energy content of the natural gas is wasted in generation.

Natural gas recovery is 97.5% efficient, and processing is also 97.5% efficient.[10] Electricity is then transported over the electric grid, which has an average efficiency of 92%,[11] giving us a "well-to-electric-outlet" efficiency of 60% x 92% x 97.5% x 97.5% = 52.5%.

Taking into account the well-to-electric-outlet efficiency of electricity production and the electrical-outlet-to-wheel efficiency of the Tesla Roadster, the well-to-wheel energy efficiency of the Tesla Roadster is 2.18 km/MJ x 52.5% = 1.14 km/MJ, or double the efficiency of the Toyota Prius.[12]

Hydrogen Fuel-Cell Cars

Hydrogen does not exist in nature except as part of more complex compounds such as natural gas (CH_4) or water (H_2O). The most efficient way to produce large quantities of hydrogen today is by reforming natural gas. For new plants, the well-to-tank efficiency of hydrogen produced from natural gas, including generation, transportation, compression, is estimated to be between 52% and 61% efficient.[13]

The upper limit of efficiency for a PEM fuel cell is 50%[14]. The output of the fuel cell is electricity for turning a drive motor, and we can assume the same 2.78 km/MJ vehicle efficiency as with the electric car. With these numbers, we can calculate the well-to-wheel energy efficiency for our hydrogen fuel-cell car: 2.78 km/MJ x 50% x 61% = 0.85 km/MJ.

This is impressive when compared to a gasoline car, though it is 32% worse than our electric car. But real fuel-cell cars do not perform nearly this well. Several car companies have produced a small number of demonstration fuel-cell cars, and the EPA has rated the efficiency of some of these. The best fuel-cell demonstration car measured by the EPA is the Honda FCX, which gets about 49 miles per kilogram of hydrogen,[15] equal to 80.5 kilometers per kilogram.

We know that the energy content of hydrogen is 141.9 MJ/kg,[16] so we can calculate the vehicle efficiency to be 80.5 km/kg / 141.9 MJ/kg = 0.57 km/MJ. (Clearly, the Honda fuel cell is nowhere near the theoretical 50% efficiency assumed above.) When we calculate the well-to-wheel energy efficiency of this Honda experimental car, we get 0.57 km/MJ x 61% = 0.35 km/MJ, not even as good as the ordinary diesel Volkswagen Jetta, let alone the gasoline-powered Honda Civic VX or the Honda Insight hybrid car.

However, some proponents of hydrogen fuel cells argue that it would be better to produce hydrogen through electrolysis of water. The well-to-tank efficiency of hydrogen made through electrolysis is only about 22%,[17] and the well-to-wheel energy efficiency of our theoretical fuel-cell car would be 2.78 km/MJ x 50% x 22% = 0.30 km/MJ, and the well-to-wheel energy efficiency of the Honda FCX would be 0.57 km/MJ x 22% = 0.12 km/MJ, even less efficient than a Porsche Turbo.

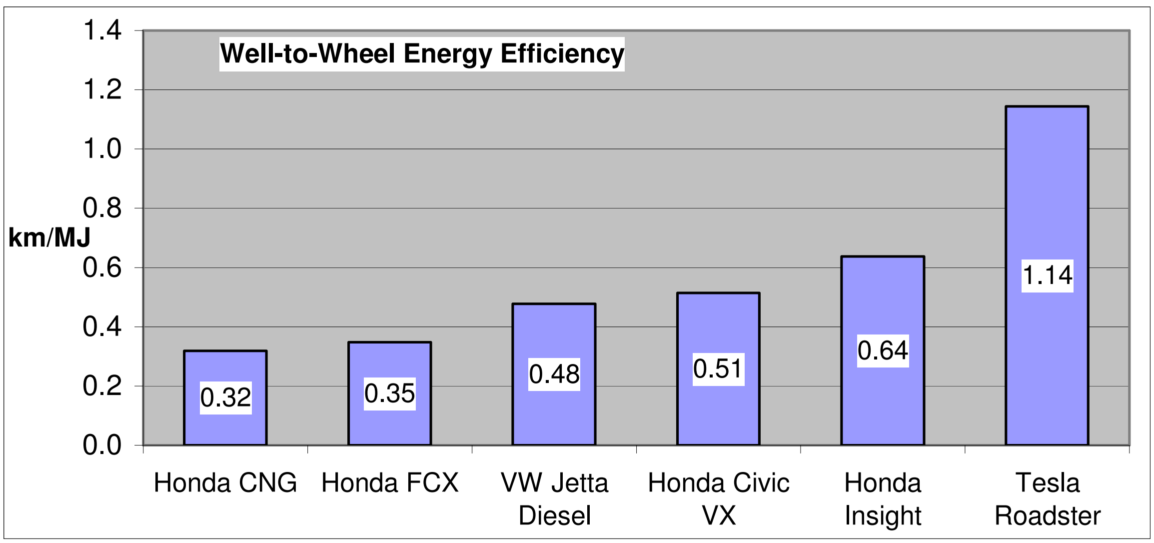
Even with the $1.2 billion U.S. government initiative to reduce U.S. dependence on foreign oil by developing hydrogen-powered fuel cells, a recent report by a panel at the National Academy of Sciences shows that Americans should not hold their breath waiting for the cars to arrive in showrooms.

"In the best-case scenario, the transition to a hydrogen economy would take many decades, and any reductions in oil imports and carbon dioxide emissions are likely to be minor during the next 25 years," said the Academy.[18]

Comparison

The following table shows the well-to-wheel energy efficiency of several types of high-efficiency cars – including an efficiency estimate of the Tesla Roadster – based on the measured performance prototypes.

Technology	Example Car	Source Fuel	Well-to-Station Efficiency	Vehicle Mileage	Vehicle Efficiency	Well-to-Wheel Efficiency
Natural Gas Engine	Honda CNG	Natural Gas	86.0%	35 mpg	0.37 km/MJ	0.32 km/MJ
Hydrogen Fuel Cell	Honda FCX	Natural Gas	61.0%	64 m/kg	0.57 km/MJ	0.35 km/MJ
Diesel Engine	VW Jetta Diesel	Crude Oil	90.1%	50 mpg	0.53 km/MJ	0.48 km/MJ
Gasoline Engine	Honda Civic VX	Crude Oil	81.7%	51 mpg	0.63 km/MJ	0.51 km/MJ
Hybrid (Gas/Electric)	Honda Insight	Crude Oil	81.7%	63 mpg	0.78 km/MJ	0.64 km/MJ
Electric	Tesla Roadster	Natural Gas	52.5%	110 Wh/km	2.18 km/MJ	1.14 km/MJ



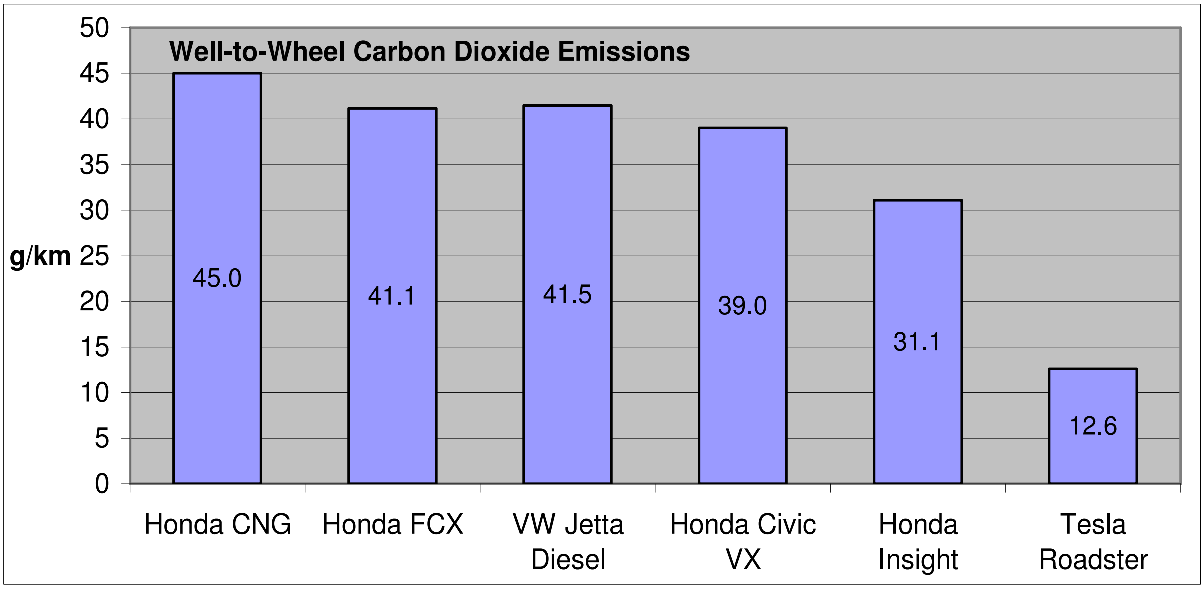
Emissions

Burning fuel produces a variety of emissions, including sulfur, lead, unburned hydrocarbons, carbon dioxide, and water. Through the years, we have improved the emissions of both cars and power plants by reformulating the fuels to eliminate sulfur and metals, and by improving combustion and post-combustion scrubbing to eliminate unburned hydrocarbons. In the end, an ideal engine or power plant will only emit carbon dioxide and water. Water is fine, but carbon dioxide is the greenhouse gas that cannot be avoided.

We can compute the well-to-wheel carbon dioxide emissions for a given vehicle in a way similar to how we computed energy efficiency, since we know the carbon content of the source fuel. With perfect combustion, all of the carbon in the source fuel will eventually become carbon dioxide. Assuming perfect combustion, we can calculate the "CO_2 content" of any source fuel. Crude oil has a CO_2 content of 0.07164 grams per watt-hour, and natural gas has a CO_2 content of 0.05184 grams per watt-hour.[19]

With these numbers, we can calculate the well-to-wheel emissions of the various vehicles, based on the carbon content of the source fuel and the energy efficiency of the vehicles:

Technology	Example Car	Source Fuel		Well-to-Wheel	
			CO_2 Content	Efficiency	CO_2 Emissions
Natural Gas Engine	Honda CNG	Natural Gas	14.4 g/MJ	0.32 km/MJ	45.0 g/km
Hydrogen Fuel Cell	Honda FCX	Natural Gas	14.4 g/MJ	0.35 km/MJ	41.1 g/km
Diesel Engine	VW Jetta Diesel	Crude Oil	19.9 g/MJ	0.48 km/MJ	41.5 g/km
Gasoline Engine	Honda Civic VX	Crude Oil	19.9 g/MJ	0.51 km/MJ	39.0 g/km
Hybrid (Gas/Electric)	Honda Insight	Crude Oil	19.9 g/MJ	0.64 km/MJ	31.1 g/km
Electric	Tesla Roadster	Natural Gas	14.4 g/MJ	1.14 km/MJ	12.6 g/km



Again, the electric car shines – from the perspective of CO_2 emissions, it is three times better than the hybrid car, and nearly four times better than the hydrogen fuel-cell car.

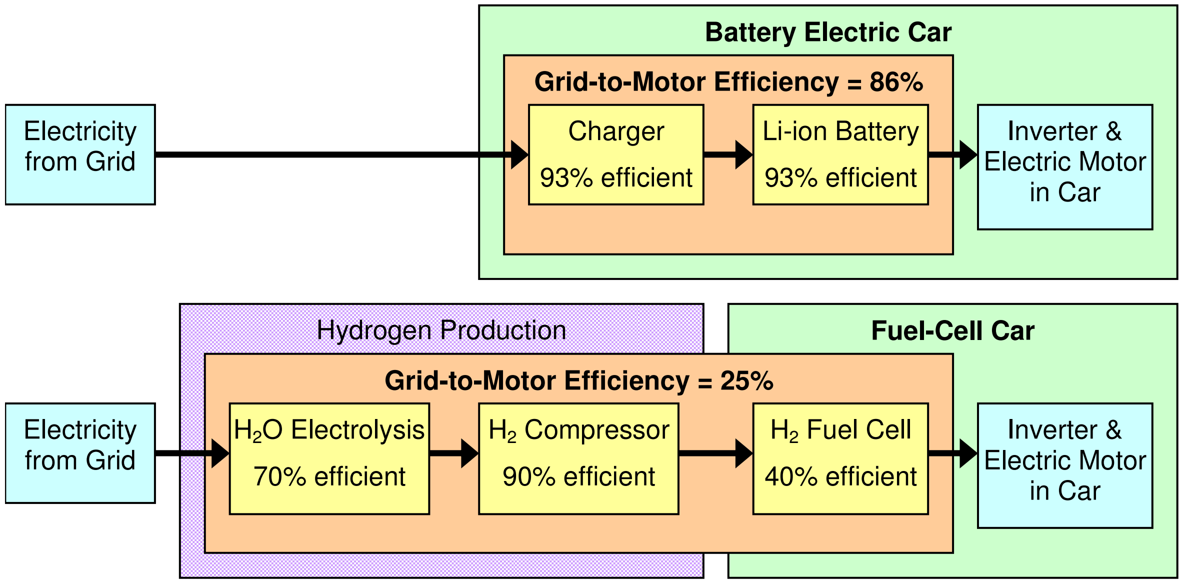
The True Multi-Fuel Car

The beauty of powering cars with electricity from the grid is that we can generate the electricity any way we want without changing the cars. As we have seen, we can generate electricity with our choice of fossil fuels. We can also use nuclear fuel, or we can generate it with any of a number of "green" sources, such as hydroelectric, geothermal, wind, solar, or biomass. Electricity is the universal currency of energy, and we already have a comprehensive distribution system for it.

Proponents of hydrogen fuel-cell cars regularly compare the forecasted best efficiency of hydrogen production and conversion – in futuristic plants and fuel cells that have never been built – to the efficiency of the average existing electric generation plant – including all those 25% to 30% efficient power plants that were built in the 1950s. This is not a fair comparison – if we are willing to build all-new hydrogen production plants to power a hydrogen car future, then we should be just as willing to build new electric generators to power an electric car future. We have assumed 60% efficient best-of-breed electric generators, but not science-fiction electric generators.

However, natural gas accounts for only 14.9%[20] of U.S. electricity generation; the rest is a mix of coal, nuclear, and others. The average well-to-outlet efficiency of U.S. electric generation, including all the old, inefficient power plants, is about 41%.[21] With this efficiency, our electric car has a well-to-wheel energy efficiency of 0.83 km/MJ, still the most efficient car on the road.

Of course, fuel-cell cars are also multi-fuel cars, since hydrogen can be produced from water using electricity from any source. But this is a very inefficient way to use electricity. Consider the following chart:



It is obvious that when we start with electricity (however it is produced), it is hard to beat the 86% efficiency of the currently available lithium-ion batteries and chargers. Even when we assume extremely high efficiencies for electrolysis, compression, and the fuel cell, the fuel-cell car requires more than three times as much electricity from the grid to drive the same distance.

Performance

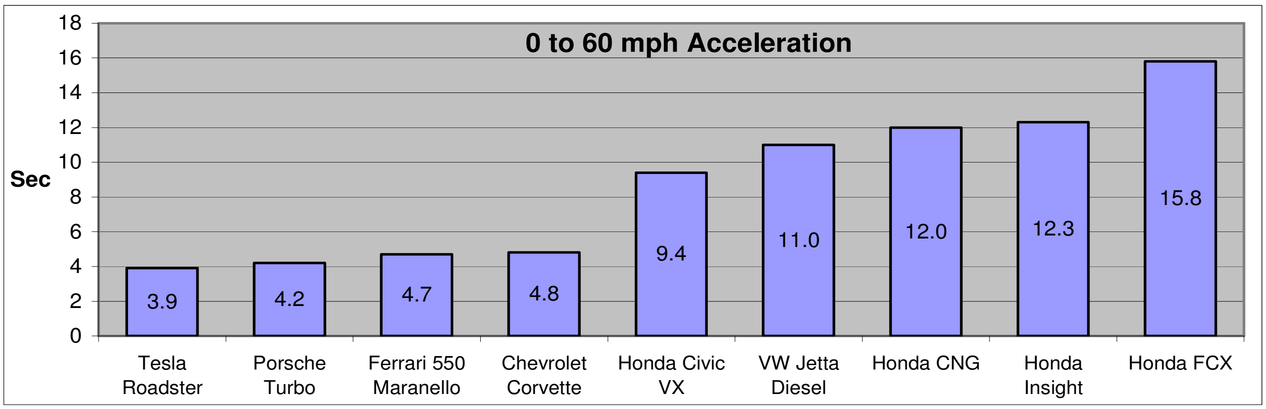
The vision of replacing many of the cars on the road with clean commuter vehicles has caused most producers of electric cars to build low-end cars with as low a price as possible. But even if a solid argument could be made that electric cars will ultimately be cheaper than equivalent gasoline cars, they will certainly not be cheaper until their sales volume approaches that of a typical gasoline car – many thousands per year at least.

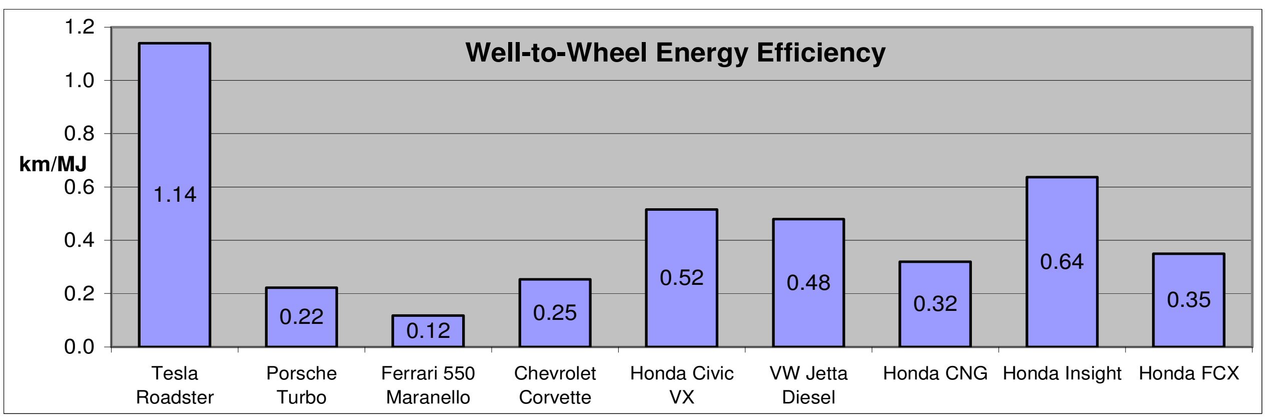
Until an electric car manufacturer achieves high enough sales to approach a gasoline car manufacturer's volume efficiencies, electric cars will need to compete on other grounds besides price. Aside from the obvious emissions advantage, there is another way that an electric car can vastly outperform a gasoline car – in a word, torque. A gasoline engine has very little torque at low rpm's and only delivers reasonable horsepower in a narrow rpm range. On the other hand, an electric motor has high torque at zero rpm, and delivers almost constant torque up to about 6,000 rpm, and continues to deliver high power beyond 13,500 rpm. This means that an electric car can be very quick without any transmission or clutch, and the performance of the car is available to a driver without special driving skills.

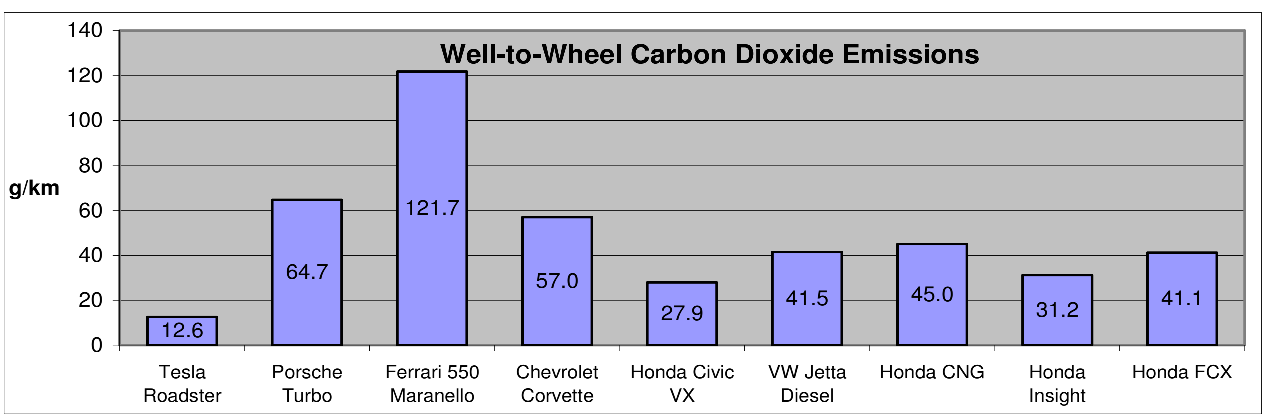
With a gasoline engine, performance comes with a big penalty – if you want a car that has the ability to accelerate quickly, you need a high-horsepower engine, and you will get poor gas mileage even when you are not driving it hard. On the other hand, doubling the horsepower of an electric motor from 100 hp to 200 hp only adds about 25 pounds, and the efficiency is, if anything, improved. It is therefore quite easy to build an electric car that is both highly efficient and also very quick.

At one end of the spectrum, the electric car has higher efficiency and lower total emissions than the most efficient cars. At the other end of the spectrum, the electric car accelerates at least as well as the best sports cars, but is six times as efficient and produces one-tenth the pollution. The chart on the following page compares the Tesla Roadster with several high-performance cars and with several high-efficiency cars.

Technology	Example Car	Gas mileage	Well-to-Wheel Efficiency	Well-to-Wheel CO_2 Emissions	0 to 60 mph Acceleration
Electric	Tesla Roadster	110 Wh/km	1.14 km/MJ	12.6 g/km	3.9 sec
Gasoline Engine (Turbo 6-cyl)	Porsche Turbo	22.0 mpg	0.22 km/MJ	64.7 g/km	4.2 sec
Gasoline Engine (V12)	Ferrari 550 Maranello	11.7 mpg	0.12 km/MJ	121.7 g/km	4.7 sec
Gasoline Engine (V8)	Chevrolet Corvette	25.0 mpg	0.25 km/MJ	57.0 g/km	4.8 sec
Gasoline Engine (VTEC 4-cyl)	Honda Civic VX	51.0 mpg	0.52 km/MJ	27.9 g/km	9.4 sec
Diesel Engine (4-cyl)	VW Jetta Diesel	50.0 mpg	0.48 km/MJ	41.5 g/km	11.0 sec
Natural Gas Engine (4-cyl)	Honda CNG	35.0 mpg	0.32 km/MJ	45.0 g/km	12.0 sec
Hybrid (3-cyl Gas/Electric)	Honda Insight	63.0 mpg	0.64 km/MJ	31.2 g/km	12.3 sec
Hydrogen Fuel Cell	Honda FCX	64 mi/kg	0.35 km/MJ	41.1 g/km	15.8 sec

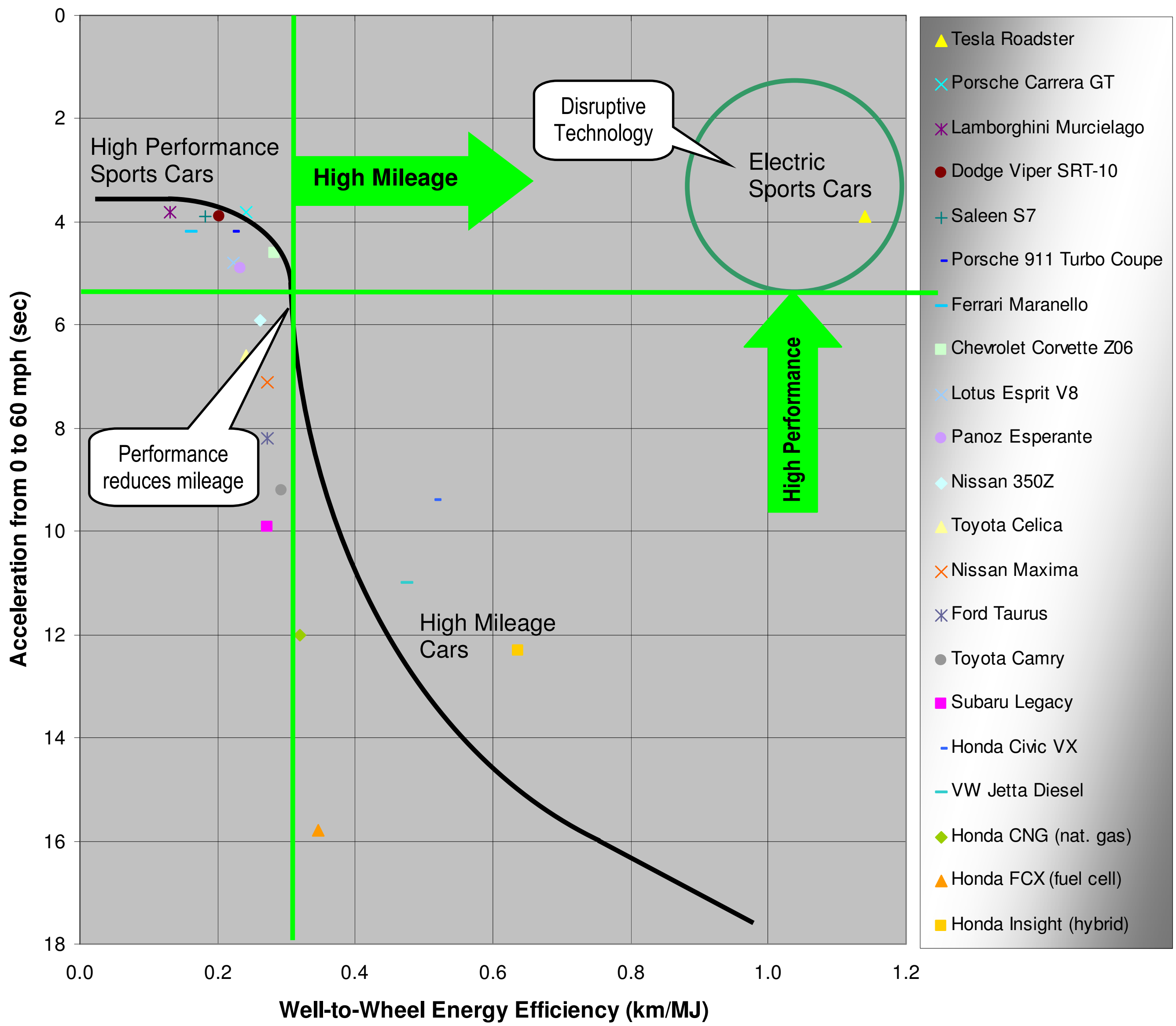






When we plot well-to-wheel energy efficiency against acceleration, almost all cars fall along a curve that shows exactly what we expect: the better the performance, the worse the mileage.

But there is one car that is way off the curve: the Tesla Roadster. This car is clearly based on a disruptive technology – it simultaneously offers great acceleration and high energy efficiency.



Convenience

The fundamental trade-off in convenience with electric cars is the advantage of starting every day with a "full tank" (and never visiting a gas station) versus inconvenient refueling on the road. While it is wonderful never to visit a gas station, this would be a bad trade-off if the driving range was too short.

Electric cars like the EV1 gained notoriety for their short, 60-mile driving ranges.[22] In contrast, a typical gasoline car can go more than 250 miles on a tank of gas. The main reason that we want to have 250-mile range on our gasoline cars is not primarily because we want to drive 250 miles in a day, but rather because we don't want to go to the gas station every day – a tank of gas should go about a week. From this perspective, the 60-mile range of the electric car might be enough for a commuter car.

But 60 miles is not enough for anything but the most basic commute. It is not uncommon to drive significantly more than 60 miles in a day – often leaving directly from work and without any planning ahead. (For example, a drive from Silicon Valley to the Pebble Beach golf course is about 90 miles each direction.) Making matters worse, the more fun a car is to drive, the more it will be driven. A sports car enthusiast may likely find a 60-mile range to be extremely restrictive.

Lithium-ion batteries (such as those in most laptop computers) have three times the amount of charge capacity as that of lead-acid batteries of the same physical size, and, at the same time, weigh substantially less. Additionally, lithium-ion batteries will last well over 100,000 miles, while lead acid batteries need to be replaced about every 25,000 miles. The original AC Propulsion tzero (a prototype electric car) had lead-acid batteries, and (like the EV1) had a range of about 60 miles.[23] However, the range of the same prototype car, when converted to lithium-ion batteries had a range of more than 250 miles and weighed 500 pounds less. Because of the additional weight of safety systems such as airbags, and because of the additional rolling drag of performance tires, the Tesla Roadster will have a range closer to 200 miles.

A 200-mile range is much more acceptable even for a sports car enthusiast. The only shortfall of such an electric sports car is the inability to take long trips, since there aren't any recharging stations along the highways, and since it takes time to charge batteries.

Until we develop a charging infrastructure (even one that only consists of simple 240-volt electrical outlets in convenient places), electric cars are best suited for local driving – around 200 miles from home.[24] This is pretty much how sports cars are driven anyway: when it's time to take a long trip, take your other car.

Electric cars are mechanically much simpler than both gasoline cars and fuel-cell cars. There is no motor oil, no filters, no spark plugs, no oxygen sensors. The motor has one moving part, there is no clutch, and the transmission is much simpler. Due to regenerative braking, even the friction brakes will encounter little wear. The only service that a well-designed electric car will need for the first 100,000 miles is tire service and inspection.

Breaking the Compromise

It is now possible build an exceedingly quick lithium-ion powered electric sports car that looks good, handles well, and is a joy to drive, at a lower price than most high-performance sports cars. And yet, this car will be the most fuel-efficient and least polluting car on the road. You can have it all.

Notes

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[1] *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle*, 29 October 2003, Ulf Bossel

[2] Density of Gasoline from *Pocket Ref*, 3rd Edition, 2002, Thomas Glover, Page 660

[3] *Exhaust Emissions From Natural Gas Vehicles* by NyLund & Lawson, page 27, and also *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, June 2001, by General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell. Vol. 3, Page 59

[4]EPA mileage numbers from www.fuelefficiency.gov

[5] EPA mileage numbers from www.fuelefficiency.gov

[6] EPA mileage numbers from www.fuelefficiency.gov

[7] EPA mileage numbers from www.fuelefficiency.gov

[8] The AC Propulsion lithium-ion tzero charging system (the basis for the design of the Tesla Roadster charging system) efficiency was confirmed by the judges at the 2003 Challenge Bibendum.

[9] General Electric "H System" Combined cycle generator, model MS7001H/9001H, as installed in Cardiff, Wales, in Tokyo, Japan, and in Scriba, New York.

[10] *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, June 2001, by General Motors Corp., Argonne National Laboratory, BP, ExxonMobil, and Shell. Vol. 3, Page 42

[11] ibid, Page 33

[12] The Department of Energy has defined “Equivalent Petroleum Mileage” as 82,049 Watt-hours per gallon, while driving the electric vehicle over the same urban and highway driving schedules as are used to compute the EPA mileage for other cars, and taking into account charging efficiency. (See Code of Federal Regulations, Title 10, Section 474.3.) This calculation would lead to the dubious conclusion that our electric vehicle gets:

82049 Wh/gal / ((110 Wh/km x 1.8 mi/km) / 86%) = **356 miles per gallon!**

[13] *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, June 2001, by General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell. Vol. 3, Page 59

[14] *Efficiency of Hydrogen Fuel Cell, Diesel-SOFC-Hybrid and Battery Electric Vehicles*, 20 October 2003, Ulf Bossel

[15] EPA mileage numbers from www.fuelefficiency.gov

[16] *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle*, 29 October 2003, Ulf Bossel

[17] *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, June 2001, by General Motors Corp., Argonne National Laboratory, BP, ExxonMobil, and Shell. Vol. 3, Page 59

[18] Reuters, February 4, 2004, 5:50 PM

[19] http://bioenergy.ornl.gov/papers/misc/energy_conv.html

[20] *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis*, June 2001, by General Motors Corp., Argonne National Laboratory, BP, ExxonMobil, and Shell. Vol. 3, Page 44

[21] ibid, Page 59

[22] General Motors EV1 specifications from www.gmev.com/specs/specs.htm

[23] www.acpropulsion.com

[24] Most RV campsites have suitable 240-volt outlets, and can be used for charging on the road today. See, for example, www.koa.com.