

Physics of Electric Vehicles

Derek Walker

University Physics II Spring 2011

Dr. John Stewart

The Physics of Electric Vehicles

In March of 1897, the Electric Carriage and Wagon company was formed in New York, offering rides for up to two people at \$.50 per mile as an alternative to horse-drawn cab service (Kirsch 2000). Fast-forward more than 100 years. The vast majority of the world's passenger trains run on electricity alone. Most freight trains and large ships are powered not by fossil fuels directly but by electric motors and generators, turned by diesel engines. In recent years entirely electric vehicles and plug-in hybrids like the Tesla Roadster and the Chevrolet Volt have been making a comeback, but the question I want to investigate is this: If electric power makes for such efficient means of locomotion, why then the 100+ year hiatus of electric cars from American roadways? One answer, I believe, lies in the physics of the electric vehicle. In the first part of this project I will explore several key components of modern electric vehicles, including the battery, the generator, two types of electric motor, and the hydrogen fuel cell, relating the workings of each to concepts learned in UPII. In the second part of the project I will explore the physics of several electric vehicles of the past, the present, and the future, placing emphasis on the technological advancements made in each case to make the dream of clean, green, transportation a reality.

One of the key components to many electric vehicles is the generator. The physics behind the generator were first explored by English physicist and chemist Michael Faraday. A pioneer in the field of modern electromagnetics, Faraday is one of several scientist credited with the discovery of electromagnetic induction- the concept that makes electrical generators work. He noted if he moved a coil of conductive material, such as copper, over a permanent magnet in a certain way, he could induce a current in the wire (Magnet Lab).

His observations demonstrated that a changing magnetic field produces an electric field. They were first published in a quantitative form by Scottish physicist and mathematician James Clerk Maxwell, as Faraday's Law in his set of four equations that now form the foundations of classical electrodynamics. Faraday's Law states that the electromotive force around a closed curve C is proportional to the time rate of change of the magnetic flux through the surface S bounded by C :

$$emf = -\frac{d\Phi_m}{dt}$$

One of the earliest types of electric generators, called a dynamo, uses this concept to generate an emf. A dynamo consists of a stationary magnet called the stator, which produces a uniform magnetic field, and a set of loops of wire called the armature that rotates within the field (Figure 2). For a flat coil in a uniform magnetic field, we can use Gauss' Law for Magnetism, another of Maxwell's equations, to compute the flux through the coil as follows:

$$\Phi_m = N \int_c \vec{B} \cdot \hat{n} dA = N\vec{B} \cdot \hat{n}A = NBA \cos \theta$$

where N is the number of turns of the coil, B is the uniform magnetic field, A is the cross-sectional area of the coil, and $\cos\theta$ is the angle between the surface normal of the coil and the direction of the magnetic field. Since the coil is spinning, the flux is modeled as:

$$\Phi_m = NBA \cos \theta = NBA \cos (\omega t)$$

where ω is the angular frequency of rotation in radians/second

Applying Faraday's Law, we get:

$$emf = -\frac{d\Phi_m}{dt} = NBA \omega \sin \omega t$$

Since the ΔV varies with time in a sinusoidal fashion, in order to provide a direct current (DC) rather than AC, a device called a commutator must be employed, which reverses the current direction periodically, “picking off” power selectively from the generator.

Another key component of any electric vehicle is the electric motor. Once you have the electrons flowing, you have to find a way to convert their energy into kinetic energy- a way to use them to do work. Many attribute the first successful electric motor- a device utilizing electricity to create motion- to Michael Faraday, an English physicist and chemist, in the year 1821. Faraday’s motor consisted of a conducting rod, the top end connected to one pole of a battery and the bottom end resting in a dish of mercury, itself connected to the other pole of a battery (Magnet Lab). In the center of the dish stood a permanent magnet, aligned so that its magnetic moment pointed upward (Figure 1). The device relied on the Lorentz force applied by the magnetic field on a current-carrying wire, given by:

$$F_m = \vec{I}L \times \vec{B}$$

where I is the current flowing through the wire, L is its length, and B is the magnetic field produced by the permanent magnet. When we use the right-hand-rule to find the direction of the cross product in this situation, we see that the resultant force causes the rod to spin around the magnet in the mercury dish, thus becoming the first true electric motor (Magnet Lab). Faraday’s device, however, is not very practical for doing work: the top end of the rod must remain fixed and the bottom end is just swirling around in a dish of mercury. Within the next hundred years, though, engineers were able to come up with several much more practical electric motor designs, each with its own benefits and drawbacks. Many of these

designs are still in widespread use today; two designs I will explore in detail are the brushed DC motor and the AC asynchronous induction motor.

The brushed DC motor works a lot like the dynamo described earlier, only in reverse. Indeed, if run in reverse, some function as generators (known as “regenerative braking” in the automobile world). The first one was constructed by accident in 1873 when Belgian electrical engineer Zenobe Gramme hooked up one of his Gramme machines, an early DC dynamo, to a DC power supply (Ehsani 2005, 182). The design soon became the first industrially successful electric motor. The basic anatomy of Gramme’s machine and similar motors is shown in figure 2. The design consists of a pair of permanent magnets called the *stator*, a current-carrying loop called the *rotor*, a ring called a *commutator*, and several brushes made from a conductive material like copper or carbon. We can draw the wire as a coil of current coming out of the page at one end and going into the page at the other, as seen in the diagrams. If we do so and use the right-hand rule to find the forces on each end of the coil (and thus the net torque), at each point during its rotation, we come up with one small problem. For half of each cycle the net torque on the rotor is clockwise, and for the other half of the time, it’s counterclockwise. To solve this problem, we employ a commutator (the “brushed” part of a brushed DC motor,) a device to “shut” off current to the rotor for a portion of each rotation, making sure that the current always flows in such a direction as to impart a torque in only one direction to the rotor (much as the sanded portion did for our lab motors). With such a design, though there is always a “zero-torque” point- a point where the current is not providing a torque to the rotor, and thus the motor would be impossible to self-start. To compensate for this fact, most armatures are constructed with multiple coils wound in different directions, allowing the current to produce torque and the

motor to start from any position. Many of this motor's disadvantages stem from this use of brushes to interrupt the current periodically: brushes can cause miniscule sparking, leading to a loss of efficiency, and they wear down with time, meaning eventual replacement is necessary.

A type of motor commonly used to drive electric vehicles is the 3-phase asynchronous AC induction motor, first developed by Nikola Tesla in the 1880s (figure 3). An induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side (Unneweher 1982, 117). As a transformer it uses mutual induction, defined as the ratio of flux through one coil to the current induced in the other coil:

$$M_{BA} = \frac{\Phi_b}{I_a}$$

to induce a current in the rotor.

The key component of an induction motor is the three stators, which when fed by a polyphase power supply, create a rotating magnetic field inside the motor. The stators can be thought of as three electromagnets, their "poles" reversing in such a way the direction of the magnetic field they create is constantly changing (see diagram 3) By Faraday's law, this rotating magnetic field induces a current through the bars of the "squirrel cage". This current then interacts with the magnetic field to produce a Lorentz force on the rotor, causing it to rotate in the direction of the rotating field at a speed of:

$$n_s = \frac{120f}{p}$$

where f : supply freq., p : # of poles on the stator. To produce torque, the speed of the motor must be $< n_s$. When the two are in sync, no torque is being produced. When motor speed exceeds the synchronous speed, it operates as an inductive generator (Unnewehr 1982, 116). The speed of the motor is controlled by electronics which vary the frequency (f) of the stator current, and thus its torque characteristics (Ehsani 2005, 161).

One key component of most electric vehicles is the battery. The specs of the battery- things like its volumetric and gravimetric energy density, voltage, and amp-hour rating determine many of the characteristics of the vehicle it's installed in. A battery is a device that converts the chemical energy contained in its materials directly into electrical energy by means of an oxidation-reduction (redox) reaction (Linden 1984, 1-3). The basic unit of any battery is the *cell*, a typical diagram of which is shown in (Figure 4). During discharge, electrons originate in the anode, which is undergoing oxidation- loss of electrons. After travelling through a load where they do work, they arrive at the cathode, which is undergoing reduction- gain of electrons. A conductor or electrolyte connects the anode and the cathode, completing the circuit. When all the material from the anode has been oxidized and all the material from the cathode has been reduced, the battery must be connected to a power supply for a charge cycle, in which the process is run in reverse. Every battery is rated with a voltage- the electromotive force it can provide, and an amp-hour rating- the theoretical amount of current the battery delivers when discharged 100% in one hour.

$$\text{theoretical time to 100\% discharge (h)} = \frac{\text{current drawn (A)}}{\text{amp - hour rating}}$$

There are many materials one can use to make a battery, and the properties of some of the major commercially available types are shown in (table 1). As you can see, each

variety has its benefits and its disadvantages. The theoretical capacity of each is calculated from the Ah/g weights of the reactants involved- an intrinsic property of each- and the properties of the electrolyte linking the two (Linden 1984, 1-8).

These numbers may look pretty impressive, but not so much when compared to conventional gasoline, which has a rating of around 44.4MJ/kg, some 100X as greater than even the best lithium ion batteries. They simply cannot compete on the basis of energy density alone. Although cheaper to operate on a cost-per-joule basis (roughly equivalent to \$.30 per gallon gasoline at current electrical rates), modern battery packs can't offer the kind of range, convenience, or flexibility that gasoline provides. Currently, many more advanced battery types are being developed that could someday dethrone the king that is gasoline, but until that day, it will likely be the most economical way to get around.

There are several equations, such as this one, out there for calculating the necessary battery capacity based on things like desired range, topography, voltage of the system, etc.

$$E_{tot} = (d * E_c * C_t * C_{tf})$$

$$C = (E_{tot} / V_{pack}) * .50$$

where d: desired range, E_c : vehicle efficiency in Wh/mile, C_t and C_{tf} represent terrain and traffic type, respectively, and C: needed battery capacity in amp-hrs. (Ehsani 2005, 115).

This is one area where modern electronics have really come in handy. As vehicle computers have advanced, they've become better and better at measuring and anticipating changes in any of these variables and adjusting the system accordingly to maximize efficiency and range.

The operation of a fuel cell is very similar. The main difference is that one or both of the components are not permanently contained in the cell, but are fed in whenever power

is desired. A fuel cell has characteristics of both a battery and a more conventional internal combustion engine. Like a battery, it relies on the flow of electrons and their ability to do work. Like a gas engine, it needs a fuel tank, and produces an exhaust. The most promising fuel cell over the past several years has been the hydrogen fuel cell, shown in (diagram). Hydrogen atoms at the anode lose their electrons, the electrons do work, and the electrons combine with two of the original H atoms and one oxygen atom at the electrode to form a water molecule. The electrolyte in this case is a PEM (proton exchange membrane), made from a specially formulated catalytic polymer. Its advantages over traditional chemical batteries and gasoline engines are many: as the fuel is used there is less weight to move, they can be refueled quickly and easily, and unlike internal combustion engines, the exhaust is good ole' H₂O- pure water. Its current disadvantages, however: cost due to the Pt catalyst, storage of H₂, and lack of fuelling infrastructure, currently outweigh its benefits.

Electric Vehicles Throughout History

1897: First commercial application, Electric Carriage and Wagon Company of New York

- cars had a top speed of <20 mph
- heavy, exchangeable lead-acid batteries
- range of 50 mi

1981: TGV, world's fastest wheeled train (357.2 mph in April 2007)

- operate on 25,000V 50Hz overhead power, stepped down to 1500V inside the train
- inverters feed 3-phase AC synchronous motors, each drawing 1100kW

1997: Toyota Prius- first mass-produced gasoline-electric hybrid

- 70hp gasoline engine, 44hp electric motor, overall fuel economy around 50 mpg
- permanent magnet synchronous AC motor
- regenerative braking uses motor as an inductive generator

2001: NASA Helios Prototype- world's largest solar-powered aircraft

- wingspan of 247 feet, covered with almost 2,000 ft² of solar panels
- powered by 14 2-hp DC motors, >31 kW solar power output
- world record altitude of 96,863 feet for sustained flight by a fixed-wing aircraft

2011: Chevrolet Volt

- 149hp 3-phase synchronous AC motor linked to 74hp gasoline generator
- driven exclusively by electric motor, gas generator helps out
- multiple driving modes, electric-only 40-mile range using Li-Ion batteries

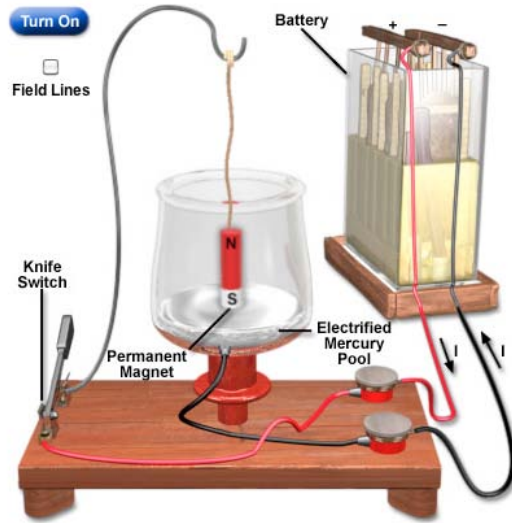


Figure 1: Faraday's Motor
<http://www.magnet.fsu.edu/education/tutorials/java/faradaymotor/index.html>

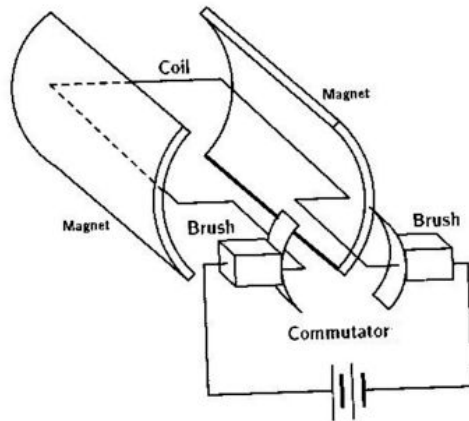


Figure 2: Brushed DC Motor/Dynamo
<http://www.electricdcmotordetails.info/link/dc-motor-magnet.html>

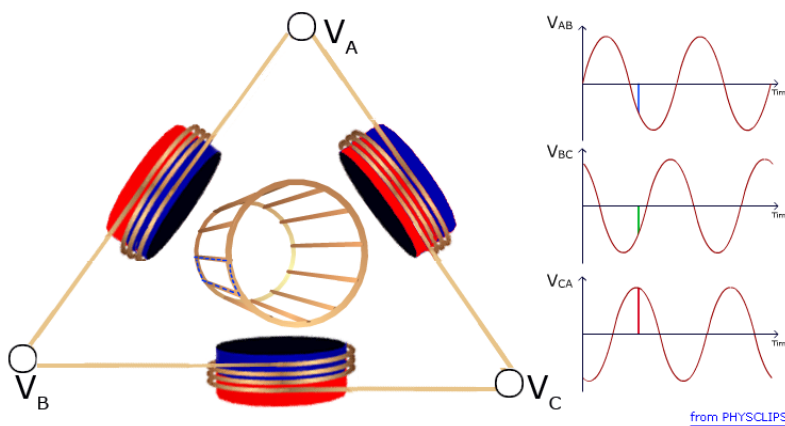


Figure 3: squirrel-cage type 3-phase AC induction motor
<http://www.animations.physics.unsw.edu.au/jw/electricmotors.html#DCmotors>

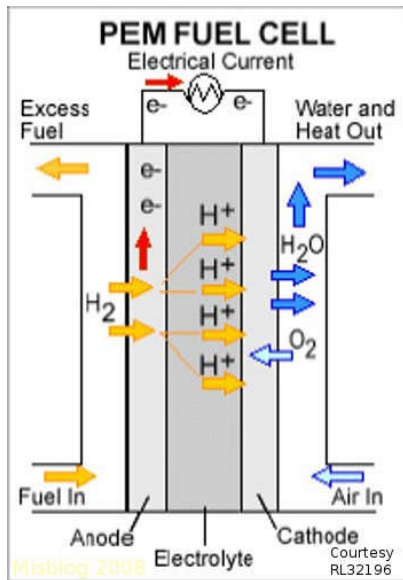


Figure 4: PEM Hydrogen Fuel Cell
 <<http://www.lbl.gov/Science-Articles/archive/MSD-H-fuel-cells.html>>

Table 1: Major modern battery types: costs and statistics <<http://www.allaboutbatteries.com/Battery-Energy.html>>

Battery Type	Cost \$ per Wh	Wh/kg	Joules/kg	Wh/liter
Lead-acid	\$0.17	41	146,000	100
Alkaline long-life	\$0.19	110	400000	320
Carbon-zinc	\$0.31	36	130000	92
NiMH	\$0.99	95	340000	300
NiCad	\$1.50	39	140000	140
Lithium-ion	\$0.47	128	460000	2302

Works Cited

- Ehsani, Mehrdad. 2005. *Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design*. Boca Raton: CRC Press.
- Kirsch, David A. 2000. *The electric vehicle and the burden of history*. New Brunswick, N.J.: Rutgers University Press.
- Linden, David. 1984. *Handbook of batteries and fuel cells*. New York: McGraw-Hill.
- Magnet Lab: National High Magnetic Field Laboratory. n.d. *Faraday Motor*.
<http://www.magnet.fsu.edu/education/tutorials/java/faradaymotor/index.html>
(accessed April 22 2011).
- Unnewehr, L. E., and S. A. Nasar. 1982. *Electric vehicle technology*. New York: Wiley.