Inevitable Electrics

By Eric Kriss

A hundred years from now, historians may view the early evolution of the automobile as something of a happy confluence of unlikely events that could never be sustained; the electric car was completely inevitable, notwithstanding the gas-powered blip of the 20th century.

“You may find it remarkable,” a professor in 2108 might tell her (virtual) classroom, “but in 2008 everyone drove cars powered by petroleum engines so hot they could boil water and so poisonous they could kill you within the hour if left running in your closed garage.” But let's start at the beginning: 127 years ago.

The beginning

The first automobile, introduced at an 1881 exhibition in Paris, was – surprisingly – an electric one. But the internal combustion engine quickly eclipsed the electric motor due to the unique physical qualities of gasoline, refined in Russia for the first time in the 1860s. A German mechanical genius, Karl Benz, conceptualized the gasoline engine in the late 1870s, and just four years after the first electric car's premiere in Paris, the first *gas*-powered vehicle – a Benz, naturally – was introduced to the public, and the fledgling automotive industry never looked back.

Ironically, the term *motor*, which applies to electrically-driven rotating magnet machines, stuck in the public mind instead of *engine*, a much more accurate label for the internal combustion process actually inside today's vehicles. Had a grammarian been in charge, we would today carry *engine* vehicle licenses in our wallets, drive on *engineways*, watch the Indianapolis *Engine* Speedway on TV, and buy cars from companies like Ford *Engine* Company and General *Engines*. But perhaps a hidden wisdom, forecasting eventual electric dominance, led to early (and premature) adoption of *motor* to minimize the inconvenience of a later change in terminology.

Energy density

All engines and motors need an energy source to run. For transportation, this energy obviously needs to be portable (unless you use overhead power lines, but that's a separate discussion relevant only to trains and buses). Energy density is the physical attribute that describes how much usable energy is stored in a particular amount – weight and/or volume – of material. For an engine, usable energy must be released by burning; for a motor, usable energy must be in the form of electrons. Whatever the mode of delivery, the total amount of energy, the material's energy density, can be accurately measured.

The mode of energy delivery – combustion versus electron flow – can be confusing in terms of the units of measure. Fortunately, physical laws make it possible to construct equivalents, and a widely used measure of energy density is how many *watts* a set amount of a substance generates in one hour; this is designated by the symbol *Wh*. In another ironic twist of nomenclature, the *watt*, generally used as a measure of electric power, honors James Watt who spent most of his time working on steam engines.

With the assistance of lab equipment, we can measure the energy density of gasoline at about 12700 Wh per kilogram, or using the convenient metric convention, 12.7 kWh/kg. This means that a kilogram of liquid gasoline contains the equivalent of 12700 watts of power generated for one hour. It is *only* an equivalence, since obviously a kilogram of gasoline cannot, by itself, generate a single watt; it just burns.

Not all gasoline, by the way, has exactly the same energy density; ethanol's density is 29% lower than gasoline, or about 9.0 kWh/kg, while diesel's density is higher than gasoline. The increasingly common E85 ethanol/gasoline blend has an energy density of around 12.1 kWh/kg. EPA efficiency ratings are based on pure gasoline in the tank, so published MPG test results will typically be 4-5% less in actual driving conditions as E85 use becomes pervasive. The discussion below assumes 100% pure gasoline is in the tank.

The energy density of a battery is much easier to measure in kWh units since its output can be easily converted to watts using the

```
volts x amps = watts
```

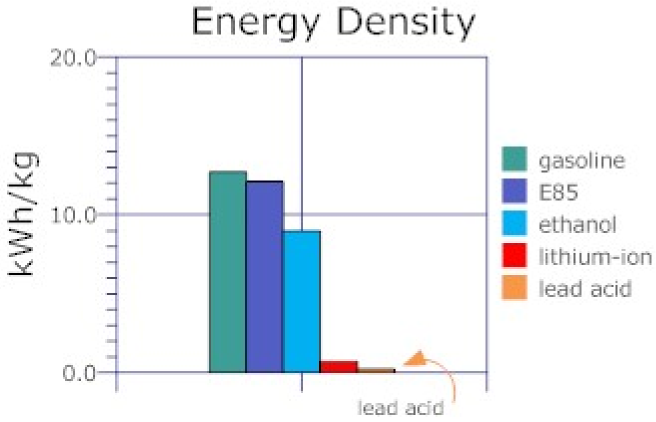
relationship. Batteries are often rated in milliampere-hours (mAh) instead of watt-hours (Wh). Conversion to Wh is easy if the average voltage discharge of the battery is known. For instance, a 1.2-volt NiMH battery rated at 4500 mAh (larger battery shown at right) will contain 5400 milliwatt-hours, or 5.4 Wh. Assuming this battery weighs 50 grams, then its energy density is 108 Wh/kg, or 0.108 kWh/kg. (The 20 gram smaller battery shown here has the same energy density: [1800 x 1.2]/20 = 0.108 kWh/kg.)

The energy density of portable batteries has, until very recently, been so low that a comparison to gasoline seems almost silly. A typical lead acid battery, like the one that starts a car, has an energy density of about 50 Wh/kg or 0.05 kWh/kg which means that gasoline can store over 250 times more energy.

With a 250-to-1 energy source disadvantage, electric motors didn't have much of a chance in mobile form unless they were connected to a continuous wire; early batteries simply weighed too much to move around. But electric motors do dominate other transportation modes, like trains, where batteries can be eliminated through the use of long-distance power lines and electrified rails.

In the past year or so, new battery technology has dramatically increased energy density (while gasoline, of course, has remained exactly the same). Lithium-ion technology, as demonstrated by A123 Systems new Series 32 automotive batteries assembled with nano-sized anode strands (still in development as of January 2008), yields dramatic improvements.

The Series 32 prototype is a small cell that weighs only 70 grams, but many cells can be connected together. If you connect one kilogram of these cells



together, the resulting “battery” has an energy density of 660 Wh/kg (0.66 kWh/kg), or about 13 times better than the familiar lead acid battery. The Series 32 density is still only 5% of the energy density of gasoline, but the improvement makes enough of a difference, as we will see, to put electric cars back in the game.

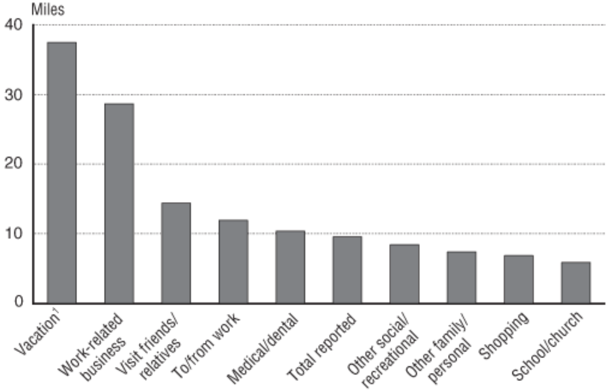
Compared to lithium-ion batteries, the energy density advantage of gasoline slips to 19-to-1 from 250-to-1. Putting this differential into a more familiar setting is helpful. A typical car gas tank holds 15 gallons. Since gasoline weighs about 6 pounds per gallon, a filled up tank holds 90 pounds of fuel. We can also translate this amount of gasoline into its kWh equivalent: 85 kWh. So how many pounds of Series 32 lithium-ion batteries would it take to generate the same 85 kWh? The answer is about 1,725 pounds of batteries, or over 19 times as much weight.

The curb weight of a typical sedan, like a 2007 Ford Taurus, is about 3,300 pounds (with a full gas tank). Obviously, an electrified Taurus wouldn't handle very well with 1,635 extra pounds (battery weight minus the gas weight above), since this would be like stuffing ten adults inside, as in one of those college stunts. Battery energy density still has a long way to go.

A practical battery weight limit for a typical sedan is around 400 pounds, or a net increase in curb weight of about 10% (for a Taurus, that would mean about 3,600 pounds in an electric version versus the factory standard 3,300 pounds). The implication is that an electric car can carry around 20-25% of the energy density of gasoline in the form of batteries, given today's technology.

A lower total energy density means a lower vehicle range, assuming that everything else, like engine efficiency, is exactly the same. As we will see in a moment, this assumption isn't justified, but – as a first approximation – an electric vehicle will have a range 4 to 5 times shorter than its gas-powered counterpart. The typical 15-gallon-tank sedan gets, say, 22 mph in a combination of city and highway driving. So a reasonable maximum range is 330 miles, but since no one drives down to the last drop, a practical range is about 300 miles. Assuming equal efficiency (which is not the case, as we will see), a comparable electric would have only a 60 to 75 mile range.

Much has been made of statistics that the average American drives less than 40 miles in a "typical" trip, so a 60-75 mile range could satisfy a lot of supermarket runs and school pickups. True, but a battery cannot be recharged nearly as quickly as a gas tank can be filled. Even a 30-minute recharge is technically heroic today, and not too many of us are willing to pockmark our busy schedules with 30-minute timeouts for our batteries, not to mention searching for a electric outlet in the middle of a thunderstorm.



Average car trip distances, U.S. DOT

So range remains a significant issue in terms of mass market acceptance of electric cars. For this reason, some manufacturers are planning backup generators, in a sort of strong hybrid model, where the battery powers the car unaided by the engine directly, but is replenished, from time to time, by a “trickle” of electrons from the generator. Putting a generator in the car, even a very small one, still relies on gasoline; it's a bridge technology between today's vehicles and the completely gasoline-free electrics of the future.

Efficiency

Cars with internal combustion engines clearly enjoy longer ranges given today's state of battery development. But what about other operating characteristics, like cruising speed and acceleration? While gasoline enjoys an overwhelming energy density advantage, the method of generating motion from an engine is inherently wasteful compared to an electric motor, and waste has a big impact on vehicle performance.

Efficiency is the technical measurement of wastefulness – for a given input of energy, how much useful work do you get out? A machine that is 100% efficient will exactly transform energy input to work output without any waste. Surprisingly, the least wasteful vehicle yet invented is the common bicycle with an efficiency rating close to 99% for a modern lightweight version!

To understand efficiency differences, we need to compare internal combustion engines, known by the acronym *ICE* that specifically refers to reciprocating piston engines, to electric motors in greater detail. A car *engine* (and here we refer to the typical piston engine, not to uncommon variants like the Wankel or the Stirling) mixes gasoline with air and then, using a spark, ignites it in a chamber. The resulting explosion creates a force exerted on a piston that turns a shaft, and eventually rotates the vehicle's wheels.

This process has three major points of energy waste, or inefficiency.

- First, the explosion creates excess heat that cannot be harvested to produce rotary motion and instead must be carried away, or cooled. This is what the radiator does in a car; it collects excess heat and then, using an air flow, dissipates it into the atmosphere.
- Second, the remnants of the explosion – including gas particles that were not completely burned during combustion – must be cleared out of the chamber, which is the function of the car's exhaust system and familiar tailpipe. This energy is also released into the atmosphere and, depending on the mixture of chemicals in the vented fumes, contributes to pollution and global warming.
- Third, the force from the initial explosion in the chamber must be successively translated from the downward movement of the piston to a rotating crankshaft and finally to the wheel. At each step energy is inevitably lost to friction. In fact, so much friction is generated by combustion-driven motion that car engines must be continuously lubricated for them to work at all, and that's why engines need oil – not as fuel, but to prevent the engine from melting down due to metal-on-metal frictional heat.

Engine efficiency is a function of design, but even very high efficiency internal combustion engines waste 75% of the energy they initially derive from gasoline! As a rule of thumb, a third of gasoline energy density is lost to the cooling system, a third is lost to the exhaust system, and 10% is lost as a result of friction.

The inefficiency of gasoline engines was well understood by Karl Benz back in 1878. But the amazing energy density of gasoline was so compelling that the automobile industry had no alternative but to invest billions to minimize the enormous waste inherent in internal combustion. Today, after more than 100 years of intense development, the modern internal combustion engine stands as one of the most highly evolved machines ever created, and it is unlikely to get much better (bigger, yes; more powerful, yes; but not more efficient).

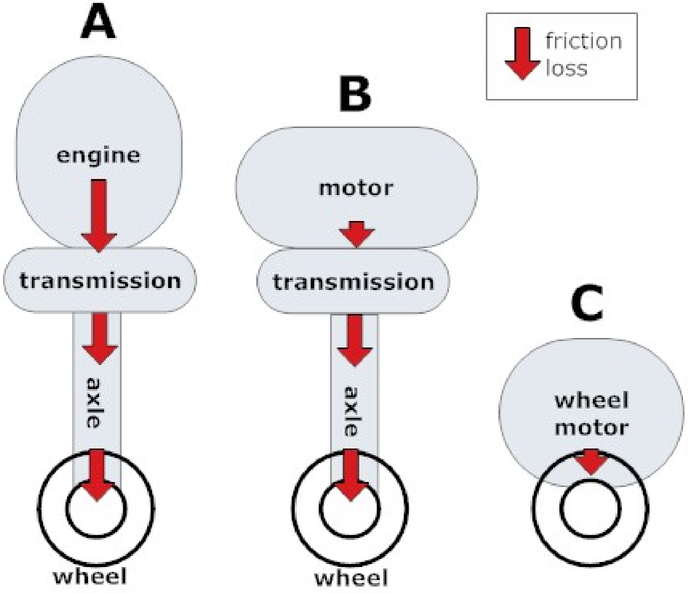
State-of-the-art Ford 302 Boss

In contrast to gas engines, electric motors are models of efficiency. There is no heat to dissipate from an explosion, and no aftermath to exhaust away. Energy loss in a motor is caused by friction (and a few other minor technicalities that we won't cover here) and by the balance between motor capacity and current load. In optimal conditions, an electric motor can achieve an efficiency close to 99%, and even in sub-optimal operation, efficiency is very high. Thus – in stark contrast to the energy density advantage of gasoline – the electric motor is roughly 16 times more efficient than the gas engine.

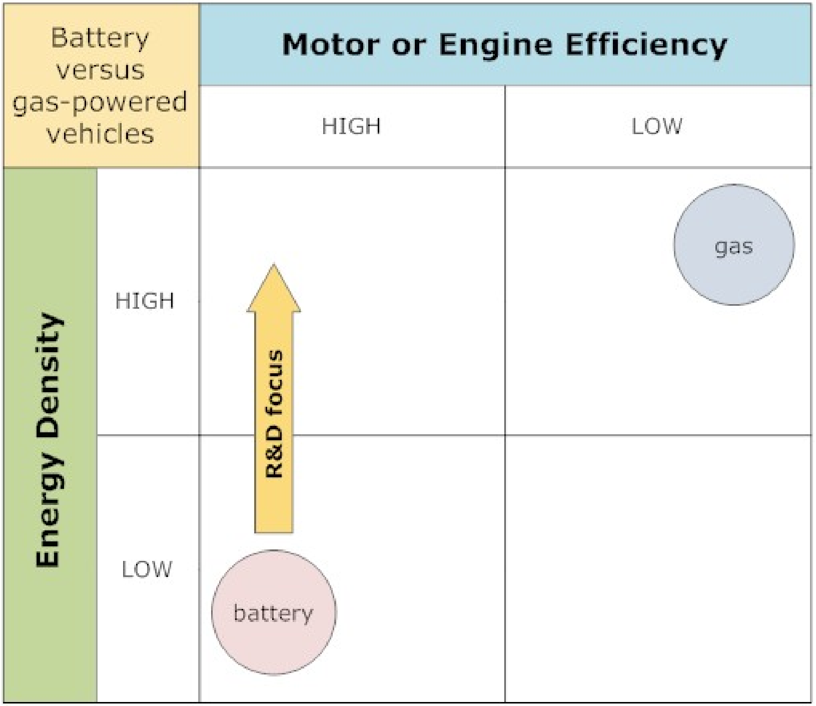
So far, we are only comparing a car's power plant efficiency – electric motor versus gasoline engine – without comparing how the car's power plant system, whether electric- or gas-powered, transfers its rotational energy to the wheels. The method of energy transferral from engine/motor to wheels is called the *drivetrain*.

The ICE car has only one drivetrain option: the crankshaft turns and, though a transmission, rotates an axle which is attached to the wheel hub (option ***A*** in illustration). If an electric car mimics this drivetrain layout, it will experience the same friction losses from transmission to wheel (option ***B***), but will retain the inherent efficiency advantages of electric motors.

Since electric motors do not emit exhaust or create excessive heat, they can be placed in areas of the car unavailable to gas engines. One novel idea is to make motors that can fit inside the wheel itself as part of the hub assembly (option ***C***). If configured in this way, the friction loss due to the traditional drivetrain – crankshaft to transmission to axle to wheel which consumes 10% of input energy – is completely eliminated. This further pushes the advantage of electric motors to around 19 times higher efficiency versus ICE cars, about the same as the energy density advantage that gasoline has over lithium-ion batteries.



What we have is akin to a technology tug-of-war, where the significant energy density advantage of gasoline faces off against the significant efficiency advantage of electric motors. For the past century, this has been a one-sided contest, since battery density has been too low to achieve electric vehicle performance on par with ICE cars.

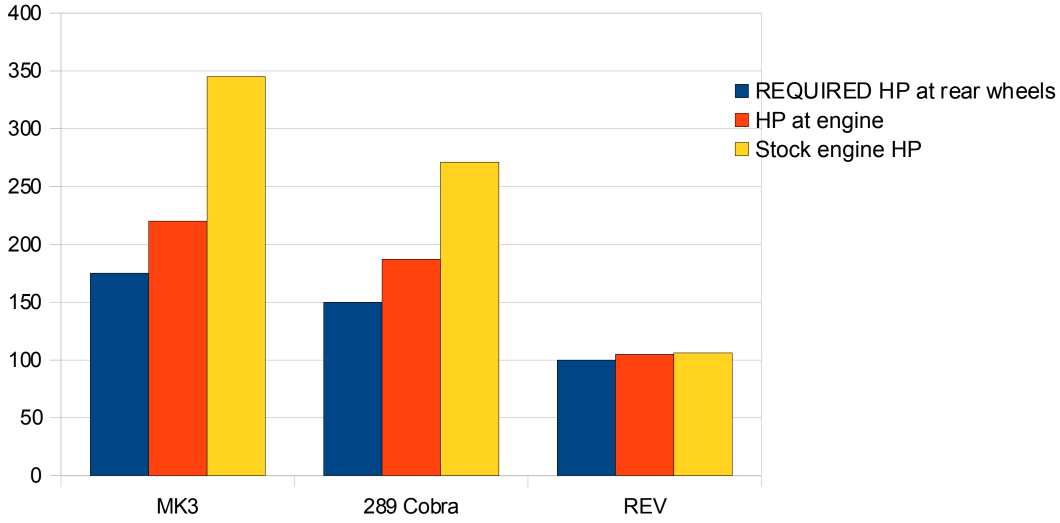


However, the advent of lithium ion batteries makes the contest more interesting. This chart shows the relative competitive position of battery and gas-powered cars. In a steady-state world, we might expect a standoff in gasoline's favor.

But the R&D focus on batteries is tilting the advantage strongly towards batteries which implies a major discontinuity in the way we think about personal vehicles, a discontinuity that will become evident soon.

Assuming that the gap in energy density will be bridged over time, the electric motor advantage in efficiency has major implications for vehicle performance. Energy *output* (as opposed to density) refers to the flow of power, ultimately to the wheels.   A more efficient system means that less energy output is required for a specific level of wheel torque (torque is a measure of the rotational power available for the car's tires). Calculation of available wheel torque involves a complex set of variables.

Horsepower requirements for ¼ mile in 13.9 seconds for electric (REV) & ICE Cobra



Stock Engines: MK3 is Ford Racing 302 modified block popular for many kit ICE Cobras; 289 Cobra is 289 block without high performance modification; REV electric Cobra is PML model HPD 30 wheel motor

Kriss Motors has developed a simulation model based on the 1964 Cobra, the classic race car, using detailed available specifications to calculate the energy output drag racing requirements.

The electric Cobra (referred to as the *REV* Cobra due to the hub wheel motor drivetrain concept, or **R**adial **E**lectric **V**ehicle) requires about 100 HP to achieve drag race performance in the ¼ mile of 13.9 seconds (a benchmark time used in the Kriss Motors simulation). The original 289 Cobra required 50% *more* horsepower at the wheels (due to drivetrain inefficiency) and over 2.5 times *more* engine horsepower. The MK3 Cobra, a popular kit model that uses modern engine technology, requires slightly higher horsepower than the 289 Cobra due to its higher curb weight (refer to chart on prior page).

A hub wheel motor

Lower energy output requirements to achieve the same vehicle acceleration means electric vehicles enjoy superior performance characteristics. In fact, the fastest race track cars will soon be electric (providing that the racing industry allows them to compete).

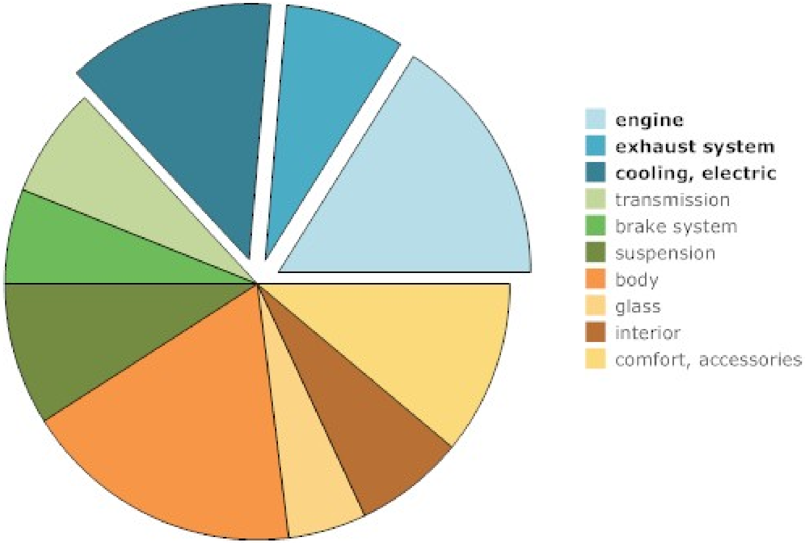
The competitive landscape is therefore complicated: ICE vehicles have longer range, while electrics enjoy superior acceleration performance. Aside from range, however, the major barrier to electric vehicles in 2008 is cost, specifically the cost of batteries, which we turn to next.

Economics

The physical characteristics of electric versus ICE cars must be put into the context of their respective economic positions, both in terms of initial manufacturing cost and on-going operating cost. Vehicles are extremely complicated, probably the most complex of any consumer product. Of the manufacturer's retail price (MSRP), about half the value is in direct materials and labor (shown in the pie chart below), and the other half pays for the amortized costs of design, plant fabrication, engineering, testing, marketing, and sales, with the balance, if any, contributing to corporate gross profit.

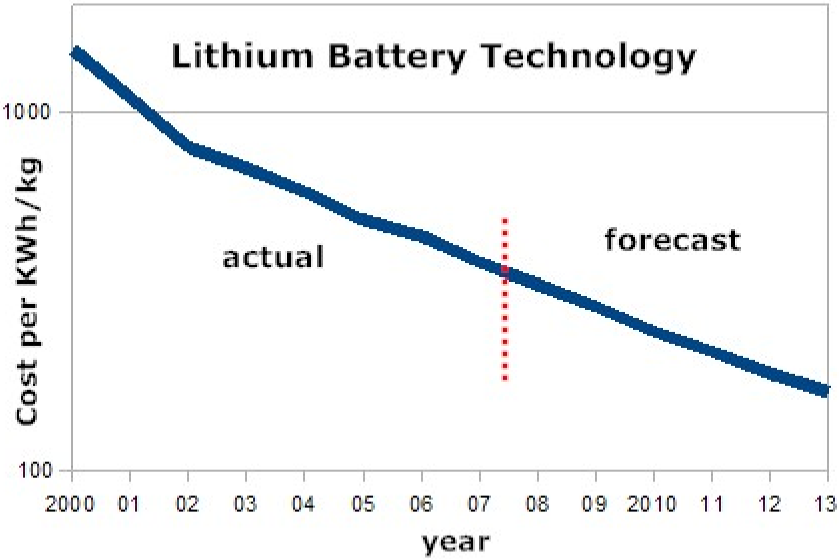
Components specifically needed for ICE vehicles cost about one-third of total direct materials and labor (the blue pie slices).

Let us assume – again, an oversimplification that is a first approximation only – that these gasoline-related components offset the cost,



Vehicle cost components, typical sedan for similar performance specifications, of electric motors and their subsystem control components.

For this base comparison (again, a first approximation only), all other vehicle systems are shared (green and orange pie slices). In this simplified cost comparison, the only differential cost factor are the batteries in the electric car; gas-powered vehicles come from the manufacturer with an empty tank, so the energy source is supplied later as an operating cost.



Derived from U.S. DOE METI data

In terms of capital expense, batteries are very expensive compared to an empty gas tank that typically costs about $100. The chart at right shows the dollar cost experience of lithium battery technology since 2000, with costs plotted in log format. This means that a constant percentage cost change is displayed as a straight line. In this case, lithium cost has historically declined at least 2.5% per year, and our 2008-2013 forecast assumes a continuation of the 2.5% average annual cost decline trend.

Translated into a 20 kWh battery pack weighing 400 pounds (the target size modeled previously as the maximum weight acceptable for a standard sedan, and assuming no improvement in energy density), today's capital cost would be about $60,000! This clearly exceeds the U.S. retail price of all but very high end luxury cars, and makes a 400 pound battery impractical except for special vehicles today. But technological improvements will almost certainly reduce costs; within 5 years, the cost will be cut in half for the same battery.

Capital cost – where electric cars have a significant disadvantage due to batteries – is only half the economic equation; operating costs must be considered as well. Accountants have devised a way to compare capital with operating costs by amortizing the capital expense over the assumed useful life of the asset. While simple in theory, this often is difficult to do in practice, since it raises complex real world questions; a common convention is to compare costs over the standard accounting period of a year where a year of operating costs is added to a fraction of capital costs – the total capital cost divided by the useful life in years – to get total annual cost.

For example, if an electric car driven 12,500 miles in 2007 with a useful life of 10 years carried $60,000 worth of batteries and cost $175 to recharge, then its operating cost would be $6,175 ($60,000 divided by a 10 year useful life, plus $175 in annual electric cost), or about 49¢ per mile.

To forecast the economics of electric car ownership over time, we need to estimate both the capital cost of batteries (as discussed above) and the generation cost of electricity each year. To then compare gas-powered cars, we need to estimate gasoline prices over the same time period.

For simplicity, we will assume that the basic vehicle itself (before adding in batteries) has exactly the same capital cost for both electric and gas-powered versions, and that the car is driven 12,500 miles per year, a reasonable U.S. commuter average. The U.S. Department of Energy, a clearinghouse of energy data, reports that the average residential price of electricity is about 11¢ per kWh, with seasonable variation of about 10%. The DOE's short-term electricity price forecast is for 2.4% annual increases in 2008-09; for the purpose of this comparison, we will use 2.5% for the 2008-2013 period. Gasoline prices are more volatile, now averaging about $3 per gallon. An optimistic forecast is that gasoline will follow the electricity generation inflation pattern of 2.5% per year; a pessimistic view is that gasoline will mirror the price history of crude oil since 2004, and this implies annual cost increases of 20% or more. No forecast of gasoline prices is possible with any confidence, but for this analysis we assume a 10% annual rate of gasoline inflation.

To accurately compare operating costs, we turn again to the Kriss Motors simulation model based on the 1964 Cobra that we used earlier to compare horsepower requirements.   The original Cobra carried a 15-gallon tank and averaged 15 mpg (its high performance engine is balanced by low weight and wind resistance, leading to gas mileage not much different from a family sedan). Translated into watts, the Cobra burns the equivalent of 2.21 kW per mile. An electric Cobra with the exact same body but modified with electric wheel motors, would use 0.12 kW per mile. This 19 times differential – 2.21 versus 0.12 kW – between

between electric and ICE Cobras is due to the efficiency differences between engines and motors, as well as drivetrain configurations.

At today's energy cost, the gas-powered Cobra burns 20¢ of gasoline per mile, while the electric Cobra needs 1.25¢ per mile to recharge its batteries with household current. This is a 16 times price differential; it varies from the 19-to-1 *vehicle* efficiency differential because of the current relative pricing of gasoline versus electricity (gasoline prices are more competitive than household electricity – when was the last time you shopped around for a better deal on residential power?).

On an annual basis, the ICE Cobra would consume $2,500 worth of gasoline, while the electric Cobra would cost only $156 to recharge the 1,625 kW used. However, amortizing the capital cost puts the electric Cobra at a disadvantage: $6,156 versus $2,500. But what happens over time as the cost of batteries drop and the differential changes between gasoline and electricity prices?

Year	Amortized Battery	Electricity Recharging	Total Electric	Total Gasoline	Advantage	Cost Ratio (elect/gas)
2008	$6,000	$156	$6,156	$2,500	gasoline	2.5x
2009	$5,240	$160	$5,400	$2,750	gasoline	2.0x
2010	$4,460	$164	$4,624	$3,025	gasoline	1.5x
2011	$3,890	$168	$4,058	$3,330	gasoline	1.2x
2012	$3,380	$172	$3,552	$3,660	tie	1.0x
2013	$3,020	$176	$3,196	$4,025	electric	0.8x

The strong cost advantage of ICE cars versus electrics in 2008 (2.5 times l*ess expensive* as shown in the table above) declines to parity by 2012. That means within 5 years, the gas-powered car – long dominant over the past 125 years of automotive history – will finally lose its low cost position to the electric car. Of course, this is just a simplified economic model and a change in various assumptions could shorten or lengthen this time frame. Nevertheless, the direction of technology implies a significant realignment within the automotive industry, one that will have lasting and important implications for all of us. The critical transition period will be 2011 to 2013 when the 20% cost position *advantage* of ICE vehicles swings to a 20% *disadvantage*.

The volatility of gasoline prices can impact this scenario: lower gas price inflation will stretch out the time frame, while another oil "crisis" will accelerate it. The aggressive introduction of ethanol may also impact timing, but since the lower energy density of ethanol partly offsets any price discount versus gasoline, the difference will be relatively minor. The current modest size of ethanol capacity in the U.S. also suggests a minor role for the E85 blend in the 2011-2013 transition period.

The Electric Era

Displacement of new technologies for old ones tends to follow a course not unlike diffusion models for chemicals and other physical phenomena. First, there is a period of innovative experimentation – in the form of demonstrations and prototypes that can extend over many decades – that "proves" a particular approach or technique. This is followed by an early adopter phase where initial commercial products are acquired by those whose motivations go beyond the average economic considerations; they typically place a high economic value on key attributes – speed, convenience, entertainment, and so on – that is not generally shared by most buyers. At a critical inflection point, penetration proceeds rapidly as adoption spreads to the mass market. The process ends with a long tail of late adopters, often appearing as a characteristic “S curve” when sale volumes are plotted against time. Here are some examples:

Technology	**Experimentation**	**Early Adoption**	**Mass Market**	**Late Adoption**
Black & White TV	1915-1940 (25 years)	1941-1948 (7)	1949-1964 (15)	1965-1988 (23)
Color TV	1930-1954 (24)	1955-1968 (13)	1969-1988 (19)	1989-2007 (18)
HDTV	1960-1984 (24)	1985-1998 (13)	1999-	
Personal computer	1947-1975 (28)	1976-1986 (10)	1987-2002 (15)	2003-
Cell phones	1947-1982 (35)	1983-1993 (10)	1994-2006 (12)	2007-
ICE vehicles	1885-1902 (17)	1903-1914 (11)	1915-1960 (45)	1961-
Electric vehicles	*1980-2009 (29)*	*2010-2021 (11)*	*2022-2067 (45)*	*2068-*

The last row in the table above is a projection for electric vehicles based on penetration histories of other technologies, including ICE vehicles. The early adoption step requires the release of an initial commercial product, and it appears that several electric cars, including the widely anticipated Chevy Volt, will be in showrooms by 2010.   A few years into the early adoption phase, economic analysis suggests that the cost advantage of ICE vehicles will disappear, propelling a rapid expansion into the mass market by 2022. By the 2030s, the cost *advantage* of electric vehicles will be obvious, which may prompt the *end* of ICE manufacturing during this time frame. The “natural” evolution from one technology to another can be readily seen in the TV histories – from black & white to color to HDTV. The late adoption stage of an older technology overlaps with the mass market phase of a newer one in broad time layers, as the improved technology out competes its less evolved predecessors. Note that the duration of the mass market stage appears correlated to product replacement cycles, with cars having the longest one and cell phones the shortest.

Conclusion

Electrics are inevitable. The automotive industry will begin a transformation over the next five years that – like a pendulum swing – will return to the earliest electric roots of the car.

- The penetration of electric for ICE cars will be disruptive: to car manufacturers, suppliers, and repair shops; to the oil industry; to consumers; and to our power and transportation infrastructure – creating both economic dislocation and growth opportunities.

- ICE manufacturing jobs will disappear, replaced by electrical, chemical and nano-technology manufacturing skill sets.

- The pervasive gas station distribution system, now about 100 years old, will be replaced with some kind of electric recharging network probably located where cars *park* (see below), altering once again America's roadside landscape.

- With the typical electric recharge costing $1, automatic electronic micro-payments will become the norm, which, in turn, will place increasing emphasis on vehicle information systems.

- The “analog” rent-a-space storage concept of the parking meter and parking garage will evolve into “digital” recharge stations; in addition, areas that now just warehouse cars for convenience, like shopping mall parking lots, will generate important recharge revenue streams, thus changing the relative economic value of retail parking.

- The silent and pollution-free operation of electrics will enhance the perceived value of congested city spaces (in a manner similar to the elimination of street sewage and animal waste a century ago) accelerating the trend towards population density.

- The diminished importance of oil and its lobbyists will ripple through many facets of American life (six of the ten largest corporations in the world are oil companies today).

- Freed from its long-standing environmental conflicts, the car will return as an important cultural expression of form and function, as it was in the golden 1954-69 era before the Clean Air Act.
