Relative Efficiency of Various Electric and Hybrid Drivetrains

The graph and table below attempt to quantify the subtle differences in operating efficiencies offered by different types of electric, or electrically enhanced vehicles (i.e. Hybrids). This comparison assumes that all drivetrains are powering the same vehicle, a standard compact sedan, and that in that configuration they provide equal acceleration when all available power sources are engaged. We assumed the Plug-in Hybrid Electric Vehicles (PHEVs) have an "electric range" of 60 miles and the "All-Electric vehicles" have a range of 200 miles.

I suggest finding some interesting feature in the graph in Figure 1, then using Table 1 to compare two configurations at a time along with the drivetrain descriptions below to understand the source of the differences observed.

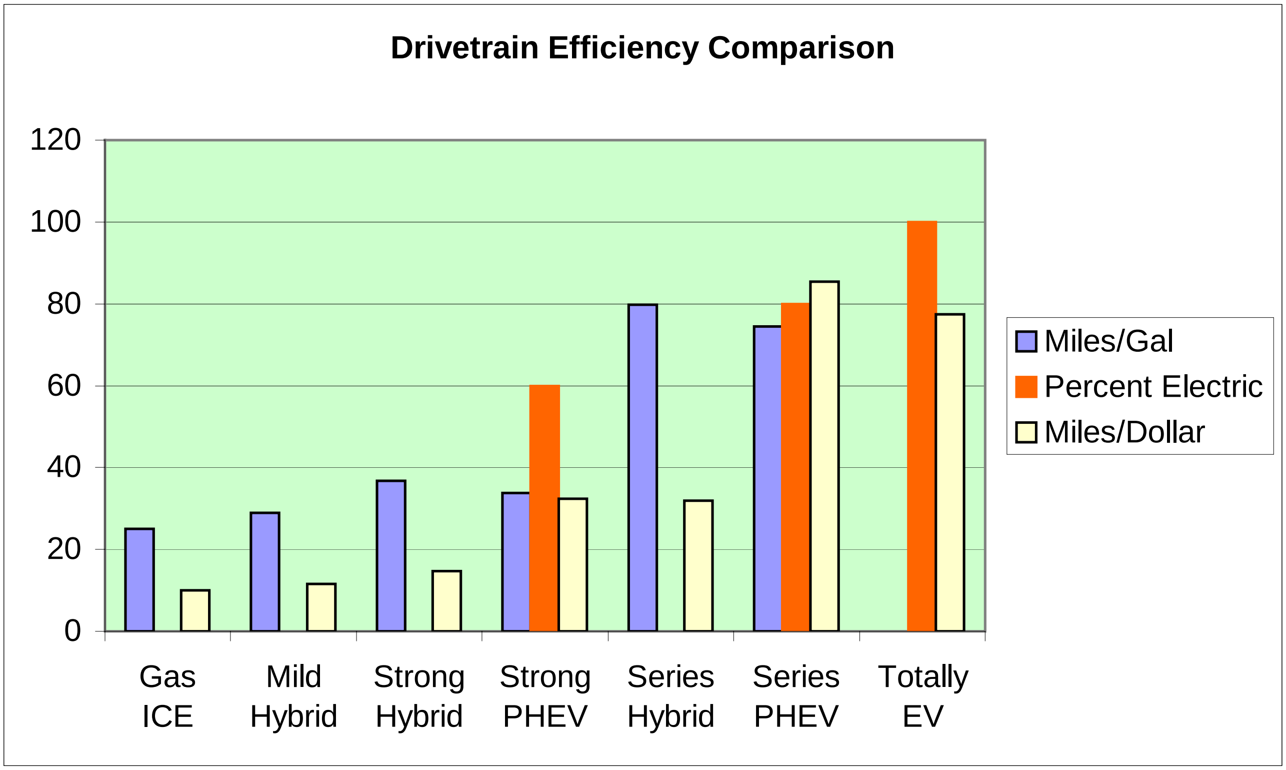

Figure 1 - Drivetrain efficiencies in terms of miles per gallon and miles per dollar.

Definition of drivetrains and terms compared in Figure 1:

1. *Any Gas-Electric Hybrid* - Compared to a conventional Internal Combustion Engine (ICE) drivetrain, any type of hybrid adds the weight and complexity of the electric motor and battery pack. However, this is offset to varying degrees by being able to use a smaller, lighter gasoline engine. To date (thru model year 2007) the hybrids sold in America have all been non-PHEV parallel hybrids.
2. *Parallel Hybrid* - A standard parallel hybrid uses it's ICE to power the drive wheels directly as well as using the excess ICE power to store energy via an electric generator

and a battery pack to be used later by the electric drive motor. When maximum power is required a parallel hybrid uses the electric motors to boost the power of the ICE. So the parallel hybrid is basically a conventional gasoline powered car with “Boost Power” supplied by an auxiliary electric drive system, which allows the use of a smaller ICE than would be needed in a conventional car. However, this advantage of lower engine weight is more than offset by the added weight of the electric drive components and the parallel transaxle used to combine power from the gasoline ICE and the electric motor.

> *a*. *Mild Hybrids* are a type of parallel hybrid that uses electric motors only to provide “boost power” to the gasoline ICE. The electric motors don’t have sufficient power to provide “electric-only” operation in any of the vehicle’s normal operating regimes. The main purpose of the mild hybrid is to reap some benefit from regenerative braking, and since the recovered electric power has to be put to some use the auxiliary electric motor is used to provide “boost power” which in turn allows the use of a smaller ICE.
>
> *b*. *Strong hybrids* are also a parallel hybrid, which has sufficient power in the electric motor to run the vehicle in "All-Electric" mode, over some limited range of speeds and distances. However, when maximum power is required both the gas and electric drives are combined to improve performance. When the ICE is operating at low or medium power levels (like cruising) the excess power available from the ICE is used to recharge batteries and to extend the operating range beyond the “all-electric” range.

3. *Series Hybrid* - In contrast to the parallel hybrid ALL drive power in a Series Hybrid is delivered to the wheels by the electric motor(s). The ICE is only used to drive a generator to produce electricity. The Series Hybrid is “stronger” than a Strong Hybrid since the electric motor has to be powerful enough to provide the desired performance with no assistance from an ICE powerplant. This mode of operation drastically reduces the size of the ICE since it only provides the ***average power*** required by the car not the ***peak power***. The power required from the ICE is only 25 to 50 horsepower and the need for a transmission can be eliminated with good electric motor design. When the ICE runs it does so at its most efficient operating point (for instance at 6000 RPM while creating 40 HP) since any excess power above what is immediately needed by the drive motor, is collected in the batteries. Because our means of controlling engine speed in gasoline engines is to choke off the air supply and increase resistance to airflow they are terribly inefficient when operated at low speed and low power, and the larger the engine, the more inefficient it is. Typical efficiencies for city driving are as low as 15%, while at highway speeds it could be as high as 25%. But an electric motor runs with nearly the same efficiency (usually over 90%) at all operating speeds, and a 250 HP electric motor is just as efficient as a 60 HP electric motor.

   The benefits of the Series Hybrid configuration are:

   a. Efficiency improvements of up to 300%, resulting in 75 mpg instead of 25 mpg (yes that’s what 300% means) for the same size automobile!!

   b. A “non-pluggable” Series Hybrid is the lightest configuration discussed here, and should be the cheapest to build. Dropping the large ICE and transmission/transaxle reduces vehicle weight by about 750 lbs, while the replacement items total about 400 lbs (small ICE/generator = 100lbs, electric motor = 220 lbs, and a battery pack similar to current strong hybrids = 90 lbs).

    c. Maintenance benefits due to only one moving part.

    d. Easy upgrade to an all-electric EV or a PHEV; just add batteries. The Series Hybrid is just an Electric Vehicle with an on-board generator, which reduces the need for massive amounts of battery storage. At today’s prices the tradeoff is $600 worth of Ni-metal hydride batteries vs over $5000 worth of Li-ion batteries for a PHEV, and $20,000 for an EV. If there is a well-defined upgrade path, consumers could reap the benefits of improved efficiency now, and still have a totally emission-free and petroleum free vehicle when battery technology matures in the future. Another alternative, which has been shunned by most developers, is that it takes less than $1000 worth of lead-acid batteries to make a PHEV-60. Maybe when gas is $4.00 / gallon the market will be less particular.

NOTE: Regardless whether the power comes via the batteries or directly from the ICE, ALL ENERGY USED by a hybrid originates from the gas tank, unless the hybrid is a PHEV (see below). The electrical “Boost power” supplied by the batteries was either originally generated by the ICE, or was put there by re-generative braking using energy originally expended by the ICE. No power comes from the electric power utility grid unless the batteries can be recharged from a wall outlet. So, the benefit of a non-pluggable hybrid is only in the subtle differences in operating efficiencies, which Figure 1 and Table 1 attempt to quantify.

4. *PHEV* - Any hybrid capable of storing electric grid power and using it for motive power is called a PHEV (plug-in hybrid electric vehicle). They can be either Series Hybrids or Strong Parallel Hybrids. The key specification for a PHEV is the amount of battery storage that is provided, and they are often rated as a PHEV-20, PHEV-50 etc to show the number of miles of “all-electric” operation possible on a “full-charge”. The plug-in hybrid must add enough batteries for a day's driving, or about 200lbs more than the minimal battery pack in the non-pluggable version, therefore the parallel PHEV is the heaviest drivetrain configuration discussed in this analysis.
5. *All-Electric Vehicle or EV* - An all-electric car completely eliminates about 600lbs of engine and transmission, but adds about 200 lbs of electric motors and 700 lbs of batteries. It has no alternative power source when the batteries are depleted, so the main drawback of this configuration is that recharging a dead vehicle on the side of the road can be extremely inconvenient or dangerous.

Description of values in Table 1 below. The process efficiency figures the various columns are estimates of the efficiency of converting the energy put into the process to that delivered by the process. The processes are divided into :

1. Fuel burned in an ICE which then directly drives the vehicles wheels.

2. Fuel burned in an ICE which is stored in batteries onboard the vehicle, then used (either immediately, or at a later time) to drive the vehicles wheels via electric motor(s).
3. Energy stored in batteries onboard the vehicle which was extracted from the electric utility grid via a plug-in power cord.

The cumulative efficiency for each source is then computed by multiplying all the conversion losses (for instance: 90% times 90% = 81%). The combined efficiency for each vehicle then depends on an estimate of how much each power source is involved in the overall average operation of the vehicle. For instance, source 2 & 3 are not included in computing the combined efficiency for a conventional gasoline powered car, and source 1 & 2 are not included in the computed efficiency for an all electric vehicle. The hybrids are more complicated, since some include two sources, and one involves all three sources of power in one vehicle.

*** See Table 1 on the Next Page ***

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Table 1 - Detailed Efficiency Comparison Specifications:

Process Fractional Efficiency for:	**Intrnl Combust. Gas-engine**	**Mild Hybrid**	**Strong Hybrid**	**Strong Hybrid PHEV**	**Series Hybrid**	**Series Hybrid PHEV**	**All Electric Car**
ICE Drive Power (direct to wheels)							
-Highway	0.25	0.27	0.27	0.27	- - -	- - -	- - -
-City	0.15	0.2	0.33	0.33	- - -	- - -	- - -
Total for Gas (avg)	0.2	0.235	0.3	0.3	- - -	- - -	- - -
On-Board Generated Electric Drive Power (ICE generated, wheels driven via electric motors)							
-Generator engine (ICE)*	- - -	0.3	0.32	0.32	0.45	0.45	
-Generator Loss	- - -	0.93	0.93	0.93	0.93	0.93	
-Battery Storage Loss	- - -	0.98	0.98	0.98	0.98	0.98	- - -
-Electric Motor Loss	- - -	0.92	0.92	0.92	0.92	0.92	- - -
-Regenerative braking	- - -	1.25	1.4	1.4	1.5	1.5	- - -
Total for Electric (collective)	- - -	0.31	0.38	0.38	0.57	0.57	
Assumed percent direct gas drive	100	75	50	50	0	0	0
Total for on-board generated	0.2	0.25	0.34	0.34	0.57	0.57	- - -
Grid Electric Drive Power							
-Battery Storage Loss		0.98	0.98	0.98	0.98	0.98	0.98
-Electric Motor Loss		0.92	0.92	0.92	0.92	0.92	0.92
-Regenerative braking		1.25	1.4	1.4	1.5	1.5	1.5
Total for Grid Electric	- - -	1.13	1.26	1.26	1.35	1.35	1.35

	Gas ICE	**Mild Hybrid**	**Strong Hybrid**	**Strong PHEV**	**Series Hybrid**	**Series PHEV**	**Totally EV**
Assume percentage grid power use	0	0	0	60	0	80	100
Miles / gallon	25	31.86	42.23	42.23	70.75	70.75	- - -
Miles / dollar**	10.00	12.74	16.89	40.54	28.30	81.12	89.00
Relative Weight	2000	2200	2300	2500	1775	1900	2300

Now adjust for weight to get final mileage figures

	Gas ICE	**Mild Hybrid**	**Strong Hybrid**	**Strong PHEV**	**Series Hybrid**	**Series PHEV**	**Totally EV**
Miles / gallon	**25.00**	**28.96**	**36.72**	**33.78**	**79.72**	**74.47**	- - -
Miles / dollar**	**10.00**	**11.58**	**14.69**	**32.43**	**31.89**	**85.39**	**77.39**

** Assumes $2.50/gallon and $0.75 electrical cost for 1 gallon equivalent (i.e. 10kW-hrs)