A Study in Hybrid Vehicle Architectures: Comparing Efficiency and Performance

by

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1) Abstract

This paper presents a comparison of performance and efficiencies for four vehicle power architectures; the internal combustion engine (ICE), the parallel hybrid (i.e. Toyota Prius), the serial hybrid (i.e. Chevrolet Volt), and the electric vehicle (i.e. Chevrolet EV-1). These four power schemes represent the most prominent power architecture options available to automotive designers and engineers today. Experimentation was preformed using a one-man power scooter, a five horsepower ICE, an alternator, three 12 volt batteries, and an electric motor. Data was collected using an accelerometer and timing device. The ICE architecture transmits power to the wheels from only from the engine, the parallel hybrid from both the ICE and the electric motor, the serial hybrid from only the electric motor with the ICE and alternator acting as a generator, and the electric vehicle (EV) from only the electric motor. Performance was quantified through top speed and acceleration numbers for each respective architecture. Each power scheme was modeled analytically to determine theoretical efficiencies and performance numbers. These theoretical numbers were then compared to experimental data for validation. Results from testing, as well as the factors represent the ratio of each attribute to the lowest value within that category (given the value 1), are shown in figure 1 below.

	ICE	Series	Parallel	EV
Top Speed (mph)	25.6	14.1	25.6	14.1
Acceleration (m/s^2)	2.5	3.7	3.7	3.7
Fuel Efficiency (mpg)	32.4	62.7	54.3	74.0
Top Speed	1.8	1	1.8	1
Acceleration	1	1.5	1.5	1.5
Fuel Efficiency	1.0	1.9	1.7	2.3

Figure 1: Performance and Efficiency Values for Experimental Power Schemes

These conclusions would allow, given desired output efficiencies or performance values, an automotive designer to determine which architecture(s) would best suit their needs.

2) Introduction

The transportation industry in the United States (and globally as well) has run on oil and the internal combustion engine for the duration of the past century. The ICE provides high power to weight ratios, enabling technological advancements ranging from the automobile to aircraft and space travel. However, these accomplishments have come at a price. Global warming and other negative environmental effects have been attributed to carbon and other pollutants associated with the combustion process that drives the modern transportation industry. Environmental factors, along with rising gas prices and increasing dependency on foreign oil have led to the design and production of gas-electric and other hybrids that greatly increase vehicle efficiency and consume less gas than their standard combustion-only counterparts. The four most prominent methods of providing vehicle power, with varying levels of gas and electric contribution, are the ICE, the series and parallel hybrids, and the electric vehicle.

Internal Combustion Engine:

Most cars today still run on an internal combustion engine, as they have since the original Ford Model T of the early 1900s. These cars rely solely on the engine to provide power to the wheels.

Series Hybrid:

The series hybrid also employs an ICE, although it provides no power to the wheels themselves. Instead, the ICE functions solely as a generator, providing energy to charge the batteries on board. The wheels are powered solely by an electric motor, using the energy stored in the batteries. This power scheme is illustrated below in figure 2.

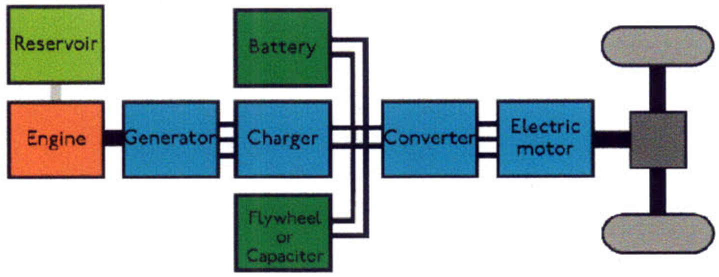

Figure 2: Series Hybrid Vehicle

In the figure above, the gray box represents the transmission (differential gear). Energy storage can be in either the battery or in a flywheel or capacitor, represented by the green boxes above. The Chevy Volt, soon to reach production, is the only mass-produced hybrid that employs this hybrid architecture. Most current hybrids to not involve a flywheel or supercapacitor due to added design complexity and cost. However, these methods of energy storage provide an advantage over batteries due to their ability to release energy at a much higher rate, as is necessary during rapid vehicle acceleration. Supercapacitors are very effective for providing this short burst of energy, but cannot provide sustained power over a long period of time. Batteries are therefore used due their ability to store considerably larger amounts of energy that can provide sustained energy source, although they are less effective at releasing it to the motor in short spurts. [1]

Parallel Hybrid

The parallel hybrid provides power to the wheels from both the ICE and an electric motor. This system requires a more complex transmission to accommodate the power from two separate power sources with very different power and RPM profiles. This power scheme is illustrated below in figure 3.

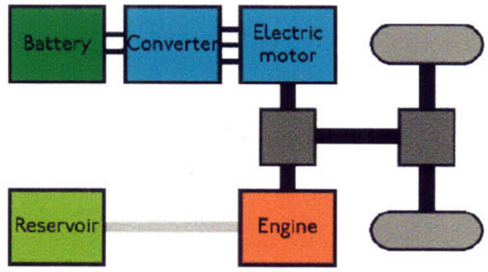

Figure 3: Parallel Hybrid Power Scheme

In a another common parallel architecture, the ICE still functions to transmit power to the wheels through a differential but also acts as a generator providing energy to maintain the batteries, known as the power-split or series-parallel hybrid. This power scheme is illustrated below in figure 4.

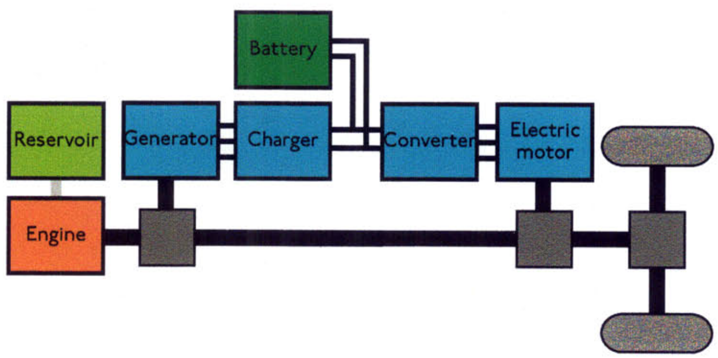

Figure 4: Power-Split or Series-Parallel Hybrid

The Toyota Prius and many other full hybrid models employ this system. This system needs less power from the electric motor due to additional contributions from the ICE, allowing designers to scale down from the series hybrid motors. At the same time the ICE needs to be scaled up from the series architecture in order to both generate electricity and provide power to the wheels. This architecture also requires a complicated electronics package to determine which power source is providing power to the wheels and in what quantity at different times during vehicle operation. [1]

3) Theoretical Model

Acceleration

In order to obtain a model for vehicle acceleration, Newton's second law was used as follows [4]:

$$F = m \times a \qquad (1)$$

With a known vehicle mass, it is necessary only to find a value for the force *F* applied at the wheels. This force can be determined from the torque applied by the powerplant as follows [4]:

$$T = F \times d \times \frac{d_1}{d_2} \qquad (2)$$

Combining these equations, the acceleration of the vehicle can be expressed as follows:

$$a = \frac{T}{m \times d \times \frac{d_1}{d_2}} \qquad (3)$$

Peak Velocity

The peak velocity of the vehicle can be predicted in various ways. If the acceleration profile of the vehicle is known, the velocity can be predicted simply by integrating acceleration values as follows [4]:

$$v = \int a \, dt \qquad (4)$$

If the peak RPM of the powerplant is known, the velocity can be predicted as follows:

$$v = RPM \times \pi D \times \frac{d_1}{d_2} \qquad (5)$$

Where *RPM* represents the peak RPM of the powerplant, *D* represents the tire diameter, and d_1 and d_2 represent the sprocket diameters. For models used in this experiment, peak RPM values from the manufacturer were used with equation 5 to predict maximum vehicle velocity.

Efficiency

The most comprehensive measure of efficiency for a gas powered vehicle is the miles traveled per gallon of gas consumed, or MPG, value. All hybrid vehicles currently on the market have no "plug in" charging system. This means that MPG is the only necessary measure of general vehicle efficiency. For this experiment, batteries were charged separately "from the grid", meaning that not all power was produced through combustion in the engine.

The efficiency at peak RPM of both the gas engine and electric motor are given by their manufacturers. The overall efficiency of the vehicle can then be determined from these numbers, with some losses due to frictional and aerodynamic factors. To simplify both modeling and experimentation, efficiency was only calculated at peak RPM (full throttle), where engine efficiency was known from manufacturer's specifications and kinetic energy calculations would involve the previously modeled top speed values. The ICE and EV architecture efficiency can be calculated simply from the efficiency of the ICE or electric motor, respectively. ICE and EV architecture efficiency are modeled in equations 6 and 7 below:

$$\eta = \frac{E_{gas}\eta_{ICE}}{\frac{1}{2}mv^2} \qquad (6)$$

$$\eta = \frac{E_{batt}\eta_{motor}}{\frac{1}{2}mv^2} \qquad (7)$$

However, the alternator output, as well as its effect on ICE power delivery, must also be considered for both the series and parallel hybrid architectures. Given the output of the alternator in relation to engine RPM, electrical energy generated can be determined. This linear relationship is shown in equation 8 below:

$$A = RPM \times .00042 \qquad (8)$$

Where *A* is the alternator output in amps, and *RPM* is the revolutions per minute of the gas engine.

In a series hybrid architecture, the gas engine is free to run at peak RPM solely to power the alternator. Therefore, power produced by the gas engine is used entirely by the alternator, and can be represented as shown in equation 9 below.

$$P_{engine} = A \times V \qquad (9)$$

Where *P* is the power consumed, *A* is the alternator output in amps, and *V* is the alternator voltage, all calculated at peak engine RPM. This gives the following equation for series hybrid efficiency:

$$\eta = \frac{(E_{gas}\eta_{ICE}\eta_{alt} + E_{batt})\eta_{motor}}{\frac{1}{2}mv^2} \qquad (10)$$

In parallel hybrid architecture however, the engine must also provide power to the wheels. This results in a split of power between the alternator and wheels that can be expressed as:

$$P_{engine} = P_{alt} + P_{wheels} \qquad (11)$$

In this case, the full 5 hP of the ICE is employed for use to both the wheels and alternator, also at peak RPM. This power split indicates the quantity of energy consumed by each, as power and energy are related by the following equation [4]:

$$E = P \times t \qquad (12)$$

Knowing the efficiencies of the alternator, ICE, and electric motor, the overall efficiency of the parallel hybrid can be expressed as:

$$\eta = \frac{(E_{gas}\eta_{ICE})\frac{P_{wheels}}{P_{engine}} + \left((E_{gas}\eta_{ICE})\frac{P_{alt}}{P_{engine}}\eta_{alt} + E_{batt}\right)\eta_{motor}}{\frac{1}{2}mv^2} \quad (13)$$

4) Experimentation

Experimentation was performed using a one man power scooter, powered by both an electric motor and a gas engine. The kart is shown below in figure 5.

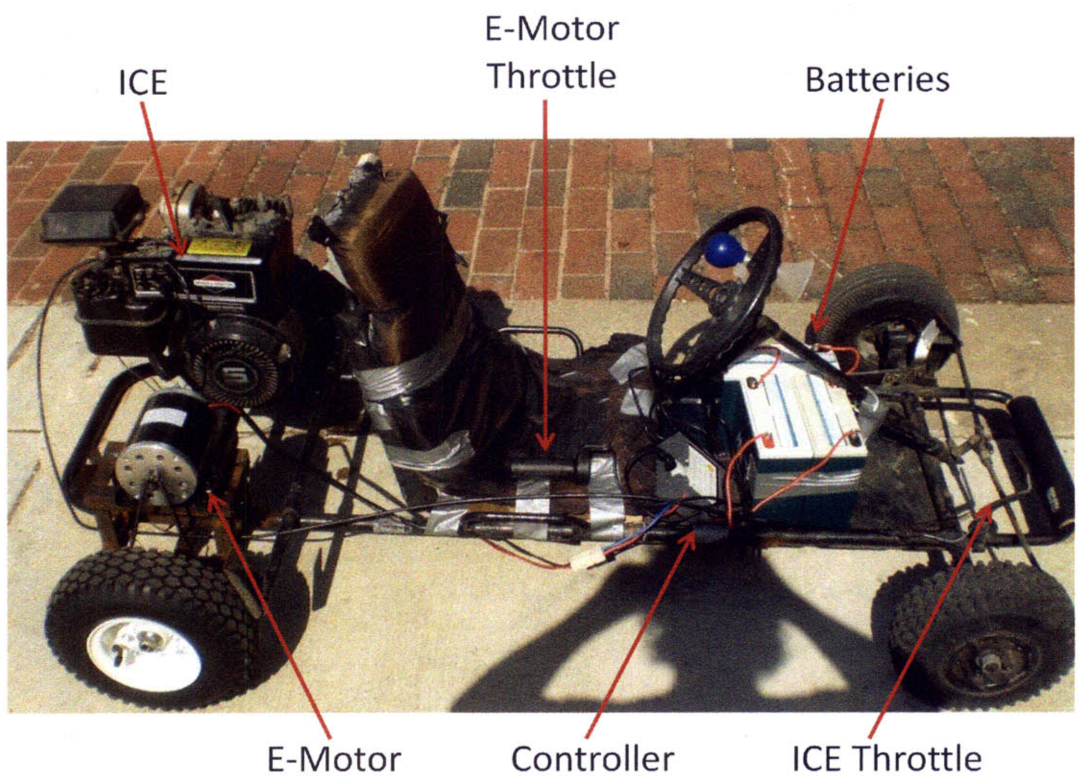

Figure 5: Kart Used in Testing and Experimentation

The gas engine is controlled by the throttle pedal on the lower right. The electric motor is controlled by the hand throttle seen on the seat in the figure above. Both the electric motor (lower left) and gas engine (upper right) drive a rear wheel, but these wheels are not connected through a rear axle. All testing was performed as pictured above to maintain constant vehicle weight, although the chain was removed from the ICE in the series hybrid and EV architectures or from the electric motor in the ICE architecture to prevent interference from an unwanted power source. A schematic of the ICE, electric motor, and electricity flow is shown in figure 6 below.

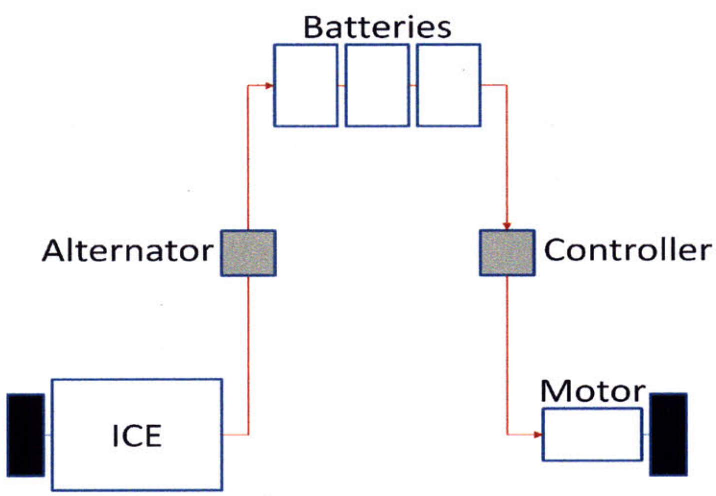

Figure 6: Electricity Flow in Parallel Hybrid, Series Hybrid, and EV Power Schemes

The alternator sits under the flywheel of the gas engine, and for this reason cannot be seen in figure 5 above. The coils of the alternator stator are shown in figure 7 below.

Figure 7: Alternator stator of the 5 hP gas engine (Removed)

This alternator is capable of producing 1.5 amps at 3600 RPM. In testing, this proved to be far too little to make any considerable contribution to the batteries. While the series hybrid did show a slight increase in range over the EV due to electricity generation from the alternator, a much larger alternator would be necessary to produce a more noticeable increase in vehicle range.

Acceleration

Vehicle acceleration was recorded using a unidirectional Low-g accelerometer. Acceleration runs were performed on a straight track. Data was recorded during accelerations from a standstill to peak velocity.

Peak Velocity

Vehicle peak velocity was recorded using a timing device and a set track distance of 50 feet. The kart was run at full speed through this entire 50 foot stretch, and times were recorded to calculate vehicle velocity.

Efficiency

Vehicle efficiency was measured by using small amounts of fuel (1 liter) and fully charged batteries with known energy content to travel as far as possible on a ½ mile track. The kart was run until fuel expired and the overall distance travelled recorded. In the case of the parallel and series hybrid power schemes, where both the ICE and electric motor were run at the same time, the kart was run until the battery power expired. At this point, the remaining quantity of gasoline was measured to determine the amount consumed. Runs were made at full throttle to simplify testing and assure accurate comparison.

5) Results & Discussion

Power Delivery

Gas engines and electric motors deliver power in very different manners. Knowing how and when torque and power are provided to the wheels is critical to developing an efficient hybrid power scheme.

The ICE provides very little torque at low RPM. As the RPM of the engine increase, torque increases as well. Once a peak is reached, the torque decreases rapidly at higher RPM, usually between 6000 and 8000 for the typical automobile. For this reason, multiple gear ratios are necessary to deliver torque evenly. These gearings make up the modern transmission.

In contrast, the electric motor provides "instantaneous" peak torque. At very low RPM, peak torque is applied continuously until the RPM threshold is reached. This threshold can be seen at roughly 6000 RPM for Tesla Motors electric motor in figure 8 below.

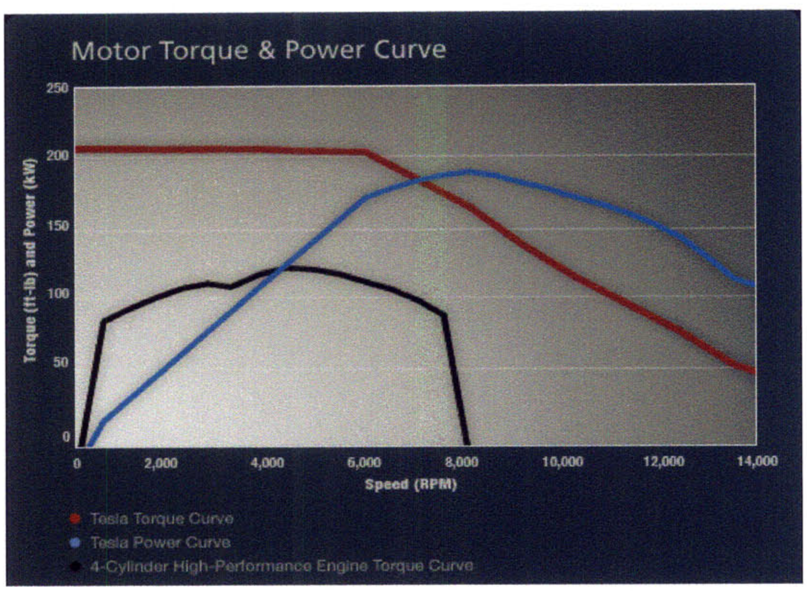

Figure 8: Torque and Power vs. RPM Curves for Tesla Electric Motors and 4 Cylinder ICE [5]

The go-kart used in testing had specific gear ratios (0.11 gas and 0.13 electric) for both the 5 horsepower ICE and the 800 watt electric motor. However, a centrifugal clutch was necessary for the ICE in order to prevent stalling at low RPM due to its low torque output.

In order to obtain the best efficiency from the vehicle, the electric motor should be responsible for providing power to the wheels at lower RPM. This corresponds to both situations where the driver is accelerating from a standstill and those when only low speeds are necessary for travel, keeping the powerplant RPM at relatively low levels. At higher speeds, the ICE becomes much more efficient, while electric motor efficiency drops off. At this point, it is more beneficial to run on gas power and conserve battery power for lower speed situations.

Power-to-Weight Ratio

The power to weight ratio is very important to the vehicle design process; the higher the ratio, the less weight necessary to reach design goals for power. This leads to increases in overall vehicle efficiency. The power-to-weight ratios for the ICE and electric motor used in testing are shown in figure 9 below.

	ICE	E-Motor	E-motor w/ Batt.
Power (hP)	5	1.1	1.1
Weight (lbs)	42	11	53
Power to Weight (hP/lb)	0.1190	0.1000	0.0208

Figure 9: Power-to-Weight Ratios for Powerplants used in Experimentation

The ICE and the electric motor have very similar power-to-weight ratios. However, once the weight of the batteries required to power the electric motor are factored in, the electric power-to-weight ratio drops drastically to roughly 1/6 of that of the ICE. In order to produce comparable amounts of electric power with a motor and sustain it with batteries, much more weight is required than that of an ICE.

Power-to-Displacement Ratio

Another important factor in vehicle design is the displacement of parts necessary for different power schemes. In today's cars, space is at a premium, and any room lost to batteries behind the seat makes vehicles less desirable to the consumer. Power-to-displacement ratios for the gas engine and electric motor used in testing are shown in figure 10 below.

	ICE	E-Motor	E-motor w/ Batt.
Power (hP)	5	1.1	1.1
Displacement (in.^{3})	1728	74	491
Power to Disp. (hP/in^3)	0.0029	0.0148	0.0022

Figure 10: Power-to-Displacement Ratios for Powerplants used in Experimentation

As with the power-to-weight ratio mentioned above, the power-to-displacement ratio of the e-motor is far superior to that of the ICE. However, with the addition of batteries, the ratio of the electric system becomes slightly less than that of the ICE. In most modern hybrids these extra batteries necessary for both series and parallel systems are typically stored behind the rear seat, resulting in a loss of trunk space.

In testing, both powerplants had similar range, indicating that the number of batteries (and their energy storage) in the system and the size of the gas tank included in the ICE weight and displacement measurements are accurate representations of their larger scale counterparts used in automobile design and manufacture. This also validates comparisons between the ratios.

Velocity, Acceleration, and Efficiency

` Experimental and theoretical results from performance and efficiency are shown in figure 11 below. The number on the left indicates the experimental value, while the value on the right indicates the predicted value from the model.

	ICE	Series	Parallel	EV
Top Speed (mph)	25.6/30.2	14.1/15.3	25.6/30.2	14.1/15.3
Acceleration (m/s^2)	2.5/3.0	3.7/3.8	3.7/3.8	3.7/3.8
Fuel Efficiency (mpg)	32.4/45	62.7/83	54.3/76	74.0/94

Figure 11: Experimental and Theoretical Results from Performance and Efficiency Testing

Experimental top speed, acceleration, and efficiency values were all lower than those predicted in the model for the gas engine and architectures where it was employed. This is likely due to the fact that the aging engine no longer runs at peak efficiency and power, resulting in lower peak RPM, torque, and efficiency than those given in original specifications. Additional losses due to friction and aerodynamics were also not considered in the model.

Theoretical values for the electric motor performance and efficiency were much closer to experimental values, although were still lower than those predicted. Again, this is likely due to frictional and aerodynamic losses that were not considered in the model.

6) Conclusion

	ICE	Series	Parallel	EV
Top Speed (mph)	25.6	14.1	25.6	14.1
Acceleration (m/s^2)	2.5	3.7	3.7	3.7
Fuel Efficiency (mpg)	32.4	62.7	54.3	74.0
Top Speed	1.8	1	1.8	1
Acceleration	1	1.5	1.5	1.5
Fuel Efficiency	1.0	1.9	1.7	2.3

Figure 1: Performance and Efficiency Values for Experimental Power Schemes

The most efficient hybrid architectures are those that rely most heavily on electric power. The electric vehicle is the most efficient, but requires a large amount of weight and displacement in batteries in order to produce its power for extended periods of time. The series hybrid is slightly less efficient due to the introduction of an ICE and an alternator into the architecture, but also has more range with less weight than a pure EV. A parallel hybrid is more efficient than the ICE architecture, but less than both a series hybrid and EV. This architecture also requires the added complexity of a power-split transmission and electronics to control and optimize power contributions from the gas engine and electric motor.

The best acceleration, especially at lower speeds, comes from the electric motor. With peak torque coming at low RPM, the electric motor provides its top acceleration from a standstill. Electric acceleration is roughly 50% greater than gas engine acceleration for systems with similar weights (53 and 42 lbs. respectively). At higher speeds, the gas engine provides better acceleration, but this is still less than that of the electric motor.

Top speed is best obtained from the gas engine. With higher horsepower and less weight, the ICE is much faster than the electric motor (with batteries). For this reason, both the ICE and parallel hybrid architectures reached peak velocity that was nearly twice that of the series hybrid and EV architectures.

7) Future Study

Future experimentation would involve more hybrid energy storage options. Fuel cells, hydraulic or pneumatic accumulator energy storage, and diesel ICE architectures could all be explored to provide a more complete picture of hybrid options and their predicted efficiencies and performance outputs.

8) Acknowledgements

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9) References

[1] "Electric and Hybrid Cars: A History". Curtis D. Anderson and Judy Anderson. Copyright McFarland and Company, November 2004.

[2] "How to Repair Briggs and Stratton Engines". Patrick Dempsey. Google Books 2009.

[3] "Internal Combustion Engines, Theory and Design". Robert Leroy Streeter. Google Books 2009.

[4] "University Physics". 11th Edition. Hugh D. Young and Roger A. Freedman. Copyright Pearson Education, 2007.

[5] "Tesla Roadster Power and Performance". Copyright 2009. <www.teslamotors.com>