

A Lesson in the Physics of Hybrid Electric Vehicles

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Preface

There is growing interest worldwide in the incorporation of hybrid electric vehicles in the automotive consumer market. The U.S. government and major U.S. car companies have united in the Partnership for a New Generation of Vehicles¹, which has designated that hybrid electric vehicles will be an important step on the way to its goal of tripling fuel economy. Hybrid electric vehicles are appearing as prototypes in auto shows and in some neighborhood dealerships. This paper explores, in a twofold manner, the physical principles that permit the hybrid electric vehicle to demonstrate higher fuel economy and lower emissions than the traditional car. Firstly, these principles receive a scientific treatment. In the article appended to this paper, I explain these physical principles to the non-scientific audience in a less technical way.

Abstract

A hybrid drivetrain combines two modes of propulsion to achieve results that are unproducible with a single drivetrain. This paper explores hybrid electric vehicles that employ a spark-ignition internal combustion engine and an electric motor. The engine demonstrates lowest brake specific fuel consumption at only a small region of its ranges of speed and load, and demonstrates particularly high fuel consumption and high emissions use under transient engine operation. The electric motor demonstrates high efficiency over the entire range of its operations, and demonstrates high torque at low speeds. The hybrid electric vehicle combines

these features to minimize transient engine operation, to take advantage of the electric motor's suitability to acceleration. Many different configurations of the system are possible.

Introduction to Hybrid Electric Vehicles

Hybridization of the automotive drivetrain attempts to combine the low emissions of electric automobiles with the extended range of gasoline engines. A hybrid electric vehicle (HEV) increases the fuel economy and decreases the emissions of the system when compared to a vehicle functioning only on a gasoline engine. The greatest benefit of the gasoline engine is the high energy density² of gasoline, on the order of 12,000 Wh/kg, in contrast with the much lower energy density of batteries, on the order of 500 Wh/kg. This allows the much greater range of vehicles run on gasoline engines. The benefits of electric motors include high torque at low speeds, the absence of on-board emissions, and regenerative braking. Traditionally, there are two ways to configure the system, series or parallel.

Series Configuration

In a series configuration, the gasoline engine is connected via a generator to the electric motor, and only the electric motor provides power to the wheels. Torque produced by the gasoline engine generates electric energy in the generator, which is stored in the battery for use by the motor. In this system, the gasoline engine often runs continually in its zone of highest efficiency or lowest emissions, eliminating transient operation of the engine.

Numerous types of control strategies are being employed with series configuration. The gasoline engine can be controlled to optimize either fuel consumption or emissions production.

Design of the generator-motor system takes into consideration whether or not the car will be “charge-dependent” or “self-sustaining.”² A charge-dependent car relies on external electric input whereas a self-sustaining car does not. The charge-dependent car, thus very similar to a pure electric vehicle, releases fewer emissions; but the self-sustaining car demonstrates a longer running range. Of the two, the self-sustaining car requires a generator of a larger capacity and the charge-dependent car requires a battery of a larger capacity.

There are a number of other factors to be taken into consideration in the design and control of series hybrid electric vehicles. The engine does not have to run consistently throughout a driving cycle; thus, the number of times that an engine is started over the cycle is an important variable in influencing the production of emissions.³ Another factor is the relation of the battery’s state-of-charge and the traction motor output to the input from the gasoline engine. In a “thermostat” strategy, the gasoline engine runs at a single power level; it is started when the battery’s state-of-charge reaches a designated minimum and stops when the state-of-charge has reached an upper set point.⁴ In a “power-follower” strategy, the gasoline engine follows the immediate demands of the motor output, and the battery’s state-of-charge remains constant⁵. Because this strategy matches the engine’s torque to the motor torque second-by-second, bypassing the need to store the torque in the batteries, battery losses are reduced, increasing fuel economy.⁴

Parallel Configuration

In a parallel configuration, either the gasoline engine or the electric motor, or both can supply torque directly to the wheels. As a general principle, the electric motor is used for

starting and low vehicle speeds, and the gasoline engine provides the power for steady-state operation. This configuration presents the designer with an even greater number of design options than the series configuration. Control and control strategy are thus very important.

Control systems function primarily to match the drivetrain with the driving conditions. Some principles are common to most parallel control systems. For example, the gasoline engine is never allowed to idle. When the vehicle is stopped or when it is decelerating, the engine is shut off. Only the electric motor provides torque for all slow-moving operations. A minimum vehicle speed is usually set to govern the entrance of the gasoline engine. Both the gasoline engine and the electric motor are used together for operations that demand high torque. Regenerative braking is employed.

A number of factors vary among designs. Designers must choose a minimum speed below which the gasoline engine is turned off. They also determine a minimum operating torque as a function of engine speed for the gasoline engine⁴. If the torque required to meet the trace, which is the instantaneous torque demand on the vehicle, falls beneath this mark, the excess torque is used to drive the motor as a generator, recharging the batteries. A parallel-configured hybrid can run the gasoline engine in a number of ways; the gasoline engine can be used to meet the trace, it can be used only for steady-state operation, or there can be an intermediate control strategy.

Comparison of the Two Control Systems

Control strategy in both series and parallel configuration is a significant determining factor for the operations and performance of hybrid electric vehicles. Variations in strategy can

produce large variations in emissions production and fuel economy.⁴ The parallel configuration is being most commonly chosen by automobile manufacturers. The operation of parallel hybrids more closely resembles the operation of traditional cars than does the operation of series hybrids, thus rendering them more appealing to the consumer. Also, the parallel hybrid has been shown to be 4% more fuel efficient than the series hybrid, primarily because the gasoline engine supplies power directly to the wheels, converting from mechanical power to electrical power and back again, as occurs in the series hybrid.⁴

Internal Combustion Engine: Fundamentals and Efficiencies^{6,7}

The design and success of the hybrid electric vehicle depends on certain characteristics of the internal combustion engine. The internal combustion engine demonstrates highest fuel efficiency and lowest emissions when it is run at cruising conditions in a small domain of its torque-speed curve. Also, the engine's fuel efficiency is limited to a theoretical maximum of around 60% by the 2nd law of thermodynamics.

This analysis is made for the four-stroke (Otto cycle) spark-ignition engine, the most commonly used for automobiles today. Some hybrid electric vehicles will use diesel engines, and these have not been treated extensively in this paper. Like spark-ignition engines, diesel engines also operate most efficiently in a small region of their torque and speed curves - the characteristic of engines that most justifies the hybridization of the drivetrain. Most of the analysis applies equally; however, diesel engines have a slightly different thermodynamic cycle.

Basic operating principles

The purpose of internal combustion engines is the production of mechanical power from the chemical energy contained in the fuel. Each cylinder of the engine contains a piston; it is the movement of the piston in response to the combustion of the engine that produces work.

During one cycle, the piston moves through the cylinder four times, each of which is called a stroke. In the first stroke, the intake stroke, the piston travels down the cylinder creating a vacuum, which pulls air into the cylinder, and fuel is added to the air. In the second stroke, the compression stroke, the piston travels up the cylinder to its highest point, top dead center, compressing the fuel-air mixture. Then combustion occurs; a spark ignites the gases, and changes the composition of the mixture, raising the pressure and the temperature to their highest values. In the third stroke, the expansion, or power stroke, the high pressure of the gases pushes the piston down to its lowest point in the cylinder, bottom dead center. This produces the work output of the cycle. Then, during exhaust blowdown, the exhaust valve is opened. The pressure within the cylinder is higher than atmospheric pressure, so the exhaust gases leave the cylinder. In the fourth stroke, the exhaust stroke, the cylinder starts full of exhaust gases at atmospheric pressure. The piston moves from bottom dead center to top dead center, pushing those gases out of the exhaust valve.

The work output of the cycle is created by the movement of the piston at high pressure over the displacement volume.

$$W = \int P \, dv$$

As the volume under the integral is always the displacement volume and the pressure

continuously changes during the cycle, another parameter is defined: mean effective pressure, the work per unit displaced volume.

$$mep = \frac{W}{V_d}$$

where W is the work of one cycle and V_d is the displacement volume. The torque of the engine, the force acting at a moment distance, is defined as

$$\tau = \frac{bmep * V_d}{4\pi} \text{ N-m}$$

where $bmep$ is the brake mean effective pressure, the work applied to the crankshaft per unit displaced volume. The 4π appears in the denominator because, for the four-stroke cycle, there are two revolutions per cycle. The power of the engine is the rate of work of the engine, and is defined as follows:

$$P = 2\pi N\tau = \frac{WN}{n}$$

where N is the engine speed in revolutions per minute, rpm, and n is the number of revolutions per cycle.

Thermal Efficiency

The thermal efficiency of the internal combustion engine, determined by the second law of thermodynamics, is defined as follows:

$$\eta_t = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

where Q_1 is the heat of the reaction, and Q_2 is the heat released to the environment. Taking into account some characteristics of combustion, the mass of the fuel, m_f , the heating value of the fuel, Q_{HV} , and the combustion efficiency, the percentage of fuel that combusts, η_c , the

equation becomes the following:

$$\eta_t = \frac{W}{Q_1} = \frac{W}{m_f Q_{HV} \eta_e}$$

The equation that follows is an equivalent way of writing the thermal efficiency equation for the Otto cycle engine:

$$\eta_t = 1 - \left(\frac{1}{r_c}\right)^{\gamma-1}$$

where r_c is the compression ratio and γ is the adiabatic compressibility of air. With typical values of 10 for the compression ratio, and 1.4 for adiabatic compressibility, the theoretical thermal efficiency is .60. Actual performance of the internal combustion engine is even lower than this theoretical efficiency because of heat losses, friction, air flow, and air-fuel equivalence ratio.

An important quantity is the brake specific fuel consumption, defined as follows:

$$bsfc = \frac{\dot{m}_f}{W_b}$$

where \dot{m}_f is the rate of fuel flow into the engine and W_b is the brake power, the power applied to the crankshaft.

Island of Minimum Brake Specific Fuel Consumption

The performance map of a typical internal combustion engine, a graph which plots the brake specific fuel consumption over the load and speed ranges of the engine, shows distinctly a region of minimum brake specific fuel consumption, as seen in Fig. 1. This region typically lands at a point at mid-load and mid-speed, in the middle of the engine's speed range and towards the top of its load range.

These map characteristics can be understood in terms of variations in volumetric efficiency, fuel conversion efficiency, and mechanical efficiency as the equivalence ratio and the importance of heat losses and friction change. Starting at the minimum bsfc point, increasing speed at constant load increases bsfc due primarily to the increasing friction mep at higher speeds, which decreases mechanical efficiency. While gross indicated fuel conversion efficiency increases as speed increases, friction increases dominate. Decreasing speed at constant load increases bsfc due primarily to the increasing importance of heat transfer per cycle (which decreases gross indicated fuel conversion efficiency). Friction decreases, increasing mechanical efficiency, but this is secondary. Any mixture enrichment required to maintain a sufficiently repeatable combustion process at low engine speeds contributes too. Increasing load at constant speed from the minimum bsfc island increases bsfc due to the mixture enrichment required to increase torque as the engine becomes increasingly air-flow limited. Decreasing load at constant speed increases bsfc due to the increased magnitude of friction (due to increased pumping work), the increased relative importance of friction, and increasing importance of heat transfer.⁵

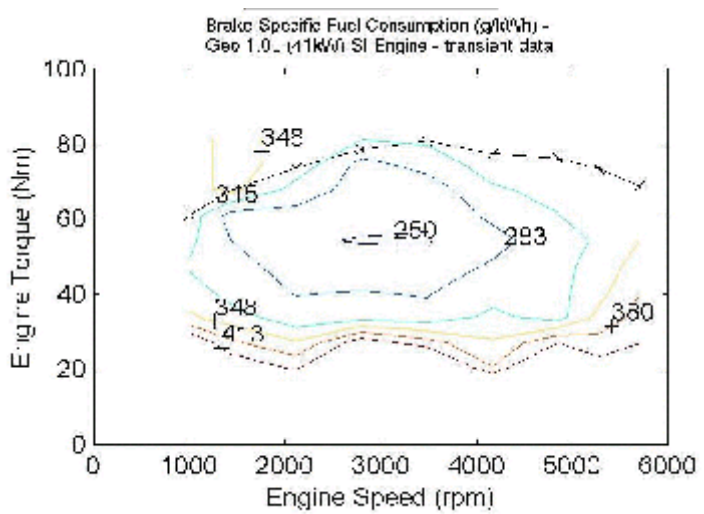


Figure 1 Graph of brake specific fuel consumption showing the “island” of minimum consumption¹³

Mechanical Efficiency/Friction Work

As engine speeds increase, the mechanical efficiency of the engine decreases, causing the increase of brake specific fuel consumption. Mechanical efficiency is defined as the ratio of work delivered to the crankshaft to work created in the compression and expansion strokes, or the ratio of brake work to indicated work.

$$\eta_m = \frac{W_b}{W_i} = 1 - \frac{W_f}{W_i}$$

Friction work has three major components: 1) the friction work of the mechanical bearings, 2) the pumping work to exhaust gases and induct fresh charge, and 3) the work needed to drive the engine accessories. For all three of these components, friction work increases with increasing engine speed.

Friction of the mechanical bearings can be approximated with the following quadratic equation as a function of the speed of the engine, N :

$$W_f = C_1 + C_2 * N + C_3 * N^2$$

C_1 is the constant for the frictional force components that are independent of speed, like boundary friction. C_2 is the constant for the components that are proportional to speed, like hydrodynamic friction, and C_3 is the constant for the components that are proportional to speed squared, particularly turbulent dissipation. Hydrodynamic friction, the work needed to overcome the viscous shear of the lubricated components, dominates. All of the following individual mechanical bearings add to the friction work: water pump and alternator at no charge; oil pump; valve train; pistons, rings, pins, and rods (without valves); and crankshaft and seals.

Power requirements of the accessories similarly increase with increasing engine speed.

The engine fan, the engine generator, and the power-steering pump are major components.

The fan requirements are the largest and with a direct drive increase with the cube of the speed.

Mechanical efficiency, by definition, is also significantly affected by the load requirements, independent of speed. At idling, zero load, mechanical efficiency is zero, and increases with increasing load, from 0 to about 90%. Friction work also includes pumping friction, the negative work of the intake and exhaust strokes. Pumping friction comprises throttling friction and valve pumping friction, both of which increase with increasing speed at constant load.

Combustion Efficiency

The combustion efficiency η_c is the fraction of the energy of the fuel supplied which is released in the combustion process.

$$\eta_c = \frac{H_R(T_2) - H_P(T_2)}{m_f Q_{HV}}$$

where $H_R(T_2) - H_P(T_2)$ is the net chemical energy release. Combustion efficiency depends primarily on the air-fuel equivalence ratio, ϕ , which is the stoichiometric air-fuel ratio divided by the actual air-fuel ratio. For lean mixtures, when ϕ is less than unity, η_c is approximately 98%. For rich mixtures, η_c decreases approximately as $\frac{1}{\phi}$. As the equivalence ratio is decreased below unity, i.e. the fuel-air mixture is made progressively leaner than stoichiometric, the efficiency increases slightly. As the equivalence ratio increases above unity, i.e. the mixture is made progressively richer than stoichiometric, the efficiency decreases because of lack of sufficient air for complete oxidation of the fuel.

The equivalence ratio is varied to adjust to the operating conditions of the vehicle.

Maximum power and load demands an increase in ϕ above stoichiometric conditions.

Maximum mean effective pressure occurs when ϕ is between 1 and 1.1, slightly rich of stoichiometric. At wide-open throttle, maximum power occurs when ϕ is near 1.1. Mixture requirements are different for full-load (wide-open throttle) and for part-load operation. For full-load operation, complete utilization of the inducted air to obtain maximum power for a given displaced volume is the critical issue. The engine runs on a rich mixture. When less than the maximum power at a given speed is required, efficient utilization of the fuel is the critical issue, and the engine runs lean.

Mixture requirements are usually discussed in relation to steady and transient engine operation. Steady operation includes operation at a given speed and load over several engine cycles with a warmed-up engine. Transient operation includes engine starting, engine warm-up to steady state temperatures, and changing rapidly from one engine load and speed to another. Whenever the engine operates at transient conditions, valves are adjusted to provide a rich equivalence ratio. Therefore, operating the engine under any transient conditions necessarily reduces its fuel economy by lowering its combustion efficiency.

Volumetric Efficiency

Volumetric efficiency is an overall measure of the effectiveness of a four-stroke cycle engine and its intake and exhaust systems as an air-pumping device. It is defined as follows

$$\eta_v = \frac{m_a}{P_0 V_d}$$

where m_a is the mass of the air inducted into the cylinder, P_0 is atmospheric pressure, and V_d

is the displacement volume. It measures the ratio of the air mass inducted into the cylinder to the maximum air mass possible, determined by air density and the displacement volume in the cylinder.

Volumetric efficiency strongly depends on the speed of the engine, peaking at an intermediate speed and falling off at the extremes, based on a number of factors which affect the air flow rate. Independent of speed, and setting an overall maximum volumetric efficiency, are quasi-static effects, such as fuel vapor pressure. The presence of gaseous fuel (and water vapor) reduces the air partial pressure below the mixture pressure. At low engine speeds, charge heating and backflow decrease volumetric efficiency. Heating of the charge in the manifold and cylinder has a greater effect at lower engine speeds due to longer gas residence times. Backflow becomes a problem when the inlet valve is closed late, a technique used to boost charging at high speeds; at low speeds, backflow decreases volumetric efficiency.

At higher engine speeds, friction flow and choking decrease the volumetric efficiency. Frictional flow losses increase as the square of engine speed (here \bar{S} is the mean piston speed):

$$P_{int} - P_e = \rho \bar{S}^2 \sum \eta \left(\frac{A_p}{A_j} \right)^2$$

At higher engine speeds, the flow into the engine during at least part of the intake process becomes choked. Once this occurs, further increases in speed do not decrease the flow rate significantly so volumetric efficiency decreases sharply. The induction ram effect raises the curve at higher speeds. Intake or exhaust tuning can increase the volumetric efficiency over part of the engine speed range.

Heat Transfer

The internal combustion engine operates at extremely high temperatures in the cylinder. High engine temperatures are necessary to produce high work output. Heat transfer occurs between the working fluid, the walls of the intake system, combustion chamber, and exhaust system, and to the coolant. Three modes of heat transfer play a role in the engine: conduction, convection, and radiation, although radiation is negligible. The magnitude of heat transfer affects the engine's specific power and efficiency. As you increase heat transfer per a unit of fuel, the gas temperatures and pressure in the cylinder decrease, decreasing the work output, and the fuel efficiency decreases. At lower engine speeds, a longer amount of time elapses per cycle, allowing greater heat transfer. The relative importance of heat transfer is greatest at low speeds and loads. If the engine remains at a certain speed, as you lower the load, you decrease the maximum temperatures in the cylinder, decreasing the work load. The rate of heat transfer also decreases, but, the relative importance of the heat transfer to the work load increases.

Heat transfer depends on a number of variables, including engine size, equivalence ratio, speed, load, brake mean effective pressure, spark timing, compression ratio, and materials. Of these, speed and load have the greatest effect. The peak heat flux in an SI engine occurs at the mixture equivalence ratio for maximum power $\phi=1.1$, and decreases as ϕ is leaned out or enriched from this value. However, as a fraction of the fuel's chemical energy, the heat transfer per cycle is a maximum at $\phi=1.0$ and decreases for richer and leaner mixtures.

Emissions

The combustion of fuel in the engine necessarily produces emissions. The most harmful by-products of the combustion process are hydrocarbons, carbon monoxide, oxides of nitrogen, sulfur, and solid carbon particulates. The major causes of emissions are non-stoichiometric combustion, dissociation of nitrogen, and impurities in the fuel and air.⁶ Hybrid electric vehicles reduce emissions by reducing both the amount of fuel used and by reducing the amount of time that the engine burns fuel via non-stoichiometric combustion. The production of emissions is also a strong function of the operating conditions of the engine; and hybrid electric vehicles permit less variation in the operating conditions of the engine while often optimizing those conditions for the minimization of the release of emissions.

The production of both hydrocarbon emissions and carbon monoxide emissions depends greatly on the equivalence ratio, ϕ , as shown in Figure 2. Fuel-rich air-fuel ratio does not have enough oxygen to react with all the carbon and hydrogen, and emissions increase above stoichiometric values. The engine runs on a rich air-fuel ratio during engine startup, to ensure that the engine starts, and during rapid acceleration under load, to demand the highest power out of the engine. The production of nitrogen oxides is a function of temperature in the cylinder, and peaks when the equivalence ratio is slightly lean of stoichiometric.

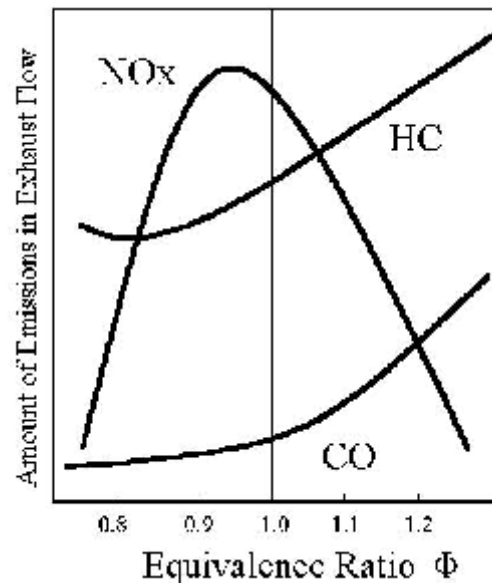


Figure 2 Emissions in the engine as a function of equivalence ratio⁶

Variation of the equivalence ratio facilitates the engine's successful performance under numerous operating conditions. For power operation at wide-open-throttle, increasing the equivalence ratio gives maximum power. For idling and low engine speeds, when the throttle is mostly closed, a large exhaust residual is created, which leads to poor combustion. Making the fuel-air ratio richer helps to compensate. Start-up of a cold engine demands a very high air-fuel ratio to ensure that there will be enough fuel vapor for combustion. This is a large source of emissions.

Electric Motors ^{8,9}

Electric motors demonstrate a number of features that are desirable for application to personal transportation. Electric motors have a very high drivetrain efficiency, at least 90%. They also produce high torque at low speeds, a feature which has many applications in the varied driving conditions and need for quick acceleration of personal transportation.

Early electric vehicles and hybrid electric vehicles employed dc motors, but these are rarely used anymore. Now, hybrid electric vehicles most frequently employ polyphase ac motors, because of the several advantages they offer over dc motors, such as 1) they operate without a commutator, and so require virtually no maintenance, 2) they are relatively small and light in weight, for a given voltage, power and speed rating. 3) they are less expensive.⁷ Of these, the permanent magnet synchronous motor and the ac induction motor are most frequently used. As batteries provide only dc current, the use of ac motors requires a system to convert dc current to ac current, a system of controls.

Electric motors operate on three fundamental laws of electromagnetism: Ampere's circuit law, Ampere's force law, and Faraday's law. Ampere's circuit law relates a current to the magnetic field it creates,

$$\oint \vec{H} \cdot d\vec{l}$$

where \vec{H} is the magnetic field, $d\vec{l}$ is an element of length, and I is the current passing through the bounded area. It is integrated over the path. The magnetic field circles around the current.

Ampere's force law states,

$$\vec{f} = \vec{i} \times \vec{B}$$

where \vec{f} is the vector force per unit length on the wire, I is the current in the wire, and \vec{B} is the vector flux density due to I . Faraday's law describes the emf produced by changing flux. It is as follows:

$$\mathcal{V} = n \frac{d\phi}{dt}$$

where \mathcal{V} is the total induced voltage in the coil, n is the number of turns in the coil, ϕ is the time-varying magnetic flux.

All electric motors are made of a stator, which does not rotate, and a rotor, which can rotate, and an air gap between them to permit motion. They are composed of two circuits, the field circuit, whose current produces the magnetic flux in the motor, and the armature circuit, that carries the current from the battery. Depending on the type of motor, the field circuit can be on either the rotor or the stator, and the armature is always on the opposite. Power is created in the motor by the interaction of the magnetic flux and the current; the basic equation

for power in all motors is as follows:

$$P = \tau \times \omega$$

where τ is the torque, and ω is the rotational speed in radians/second. Steady energy transformation, both from electrical energy to mechanical energy and from mechanical energy to electrical energy, requires both torque and rotation.

Synchronous Motors

In three-phase synchronous motors, the dc field current is placed on the rotor, which is a dc electromagnet, and the armature circuit is placed on the stator and carries three-phase currents. The flux on the rotor is controlled by the dc field current. The stator is composed of distributed coils placed in slots on its inner surface. Torque is generated through a displacement in the rotor and stator poles. The stator flux rotates due to the three-phase currents and torque is developed when the electromagnet on the rotor is rotating at the same speed.⁸ That speed, called the synchronous speed, depends on the number of stator poles, P , and the electrical frequency, ω , as is determined from the following relationship:

$$\omega_r = \frac{\omega}{P/2} \text{ spatial radians/second}$$

The rotor and stator fluxes always rotate in synchronism. The two fluxes are separated by a physical angle, the rotor-stator power angle, δ_{RE} . Developed torque depends on the flux magnitudes, the angle between the

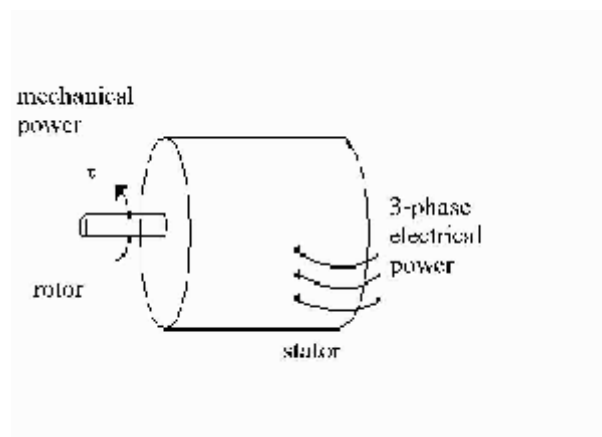


Figure 3 Schematic diagram of a basic synchronous motor⁹

fluxes, and the geometry of the machine:

$$T_{dev}(\delta_{RF}) = -\frac{\pi R l g}{\mu_0} B_R B_S \sin \delta_{RF}$$

where R , l , and g are the air-gap radius, length, and width respectively. The general equation for a rotating flux wave is

$$B(t, \theta_m) = B_r \cos[\omega t \mp \frac{P}{2}(\theta_m - \theta_{m0})]$$

where B_r is the magnetic flux on the rotor, P is the number of poles, θ_m is the angle of maximum total flux density, and θ_{m0} is the position of the flux maximum at $t=0$.

The synchronous motor has no starting torque, as it requires that the rotor and stator both be rotating at synchronous speed in order to produce torque. Although this seems like a major limitation of synchronous motors, this problem can be eliminated by adding circuitry to cause the excitation of the windings to advance in step with the rotor. Use of this technique with a synchronous motor creates the electronically commutated motor.

The synchronous machine also functions as a generator. An external mechanical drive provides torque to the rotor, and a dc field current must be kept on the rotor. The electrical frequency is determined by the speed of the mechanical drive:

$$\omega = \left(\frac{P}{2}\right)\omega_m$$

and the voltage of the generated power is controlled in part by the field current.

A synchronous motor runs at very high efficiencies, and has only one major source of losses. The power supplied to the dc field circuit supplies relatively small resistive losses in the field winding. When running as a motor, all of the input electrical power, minus the ohmic losses in the field winding, is transformed into mechanical power. Similarly, when running as a

generator, all of the mechanical power is transformed into electrical power except the power to resistive losses in the field winding. This results in a very high efficiency:

$$\eta = \frac{P_{out}}{P_{\epsilon}} = \frac{P_{\epsilon} - P_{losses}}{P_{\epsilon}}$$

The losses are very small compared to the input power, so η usually has a value in the 90th percentile.

AC Induction Motors

In induction motors, the field circuit is on the stator, the armature circuit is on the rotor, and the rotor poles are induced by transformer action. Both the stator poles and the rotor poles rotate at synchronous speed, but the rotor rotates physically at a speed slightly less than synchronous speed and slows down as the load torque and power requirements increase.

The stator is identical to a stator of a synchronous machine: three phases, P poles, sinusoidal mmf and flux distribution, and synchronous speed. In induction motors, the stator carries the field. The rotor is much different; in induction motors, the rotor is an iron cylinder with large embedded conductors, which are shorted to allow the free flow of current. The stator flux induces an ac current in the each of the rotor conductors, and an ac voltage is induced in the rotor to drive the currents. The currents in the conductor produce a magnetic flux, \vec{B}_R , and combined with the stator flux, \vec{B}_S , they produce a third flux, \vec{B}_{RS} , a rotor-stator flux, which produces the developed torque, which opposes the torque used to cause rotation. The developed torque, T_{dev} , is proportional to the induced currents and the sine of the power angle, and hence varies with slip speed, ω_{Δ} , the angular velocity in the negative direction of the rotor conductors relative to the stator flux.

$$T_{dev} = -i_R(\omega_{\Delta}) \sin(\theta_R)$$

Many of the features of the induction motor depend on the slip speed or the slip, which is the normalized slip speed:

$$s = \frac{\omega_{\Delta}}{\omega_s} = \frac{\omega_s - \omega_m}{\omega_s}$$

Mechanical speeds below synchronous

speed produce motor action, because torque

is developed in the same direction as

rotation. Mechanical speeds above

synchronous speeds produce generator

action because the developed torque is

opposite the rotation. In order to drive the

rotor, external mechanical torque is required. Regenerative braking is achieved by lowering the

frequency of the stator current so that it is lower than the rotor frequency, creating positive slip,

and generator action.⁴ Regenerative braking is one of the features of the electric motor that

makes the hybrid electric vehicle exploits to become more fuel-efficient.

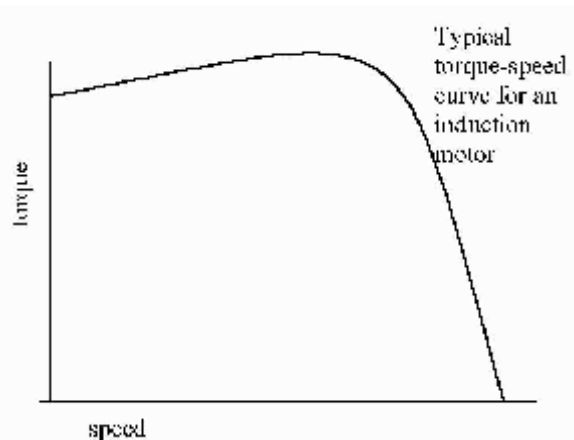


Figure 4⁴

The characteristic torque-speed curve for the induction motor indicates two of the most

important features of the motor for application to vehicle use. Even at no speed, there is a

starting torque, so the motor can start and accelerate itself. Near synchronous speed, the

torque is linear function of slip, and this region, called the small-slip region, is the normal

operating region of the motor.

Developed power, the power converted from electrical to mechanical form, depends

on the developed torque and the mechanical speed:

$$P_{dev} = \omega_m \times T_{dev} = (1-s)\omega_s T_{dev}$$

The mechanical input power needed to turn the rotor against the developed torque is

$$P_c = P_R = \omega_s T_{dev} = s\omega_s T_{dev}$$

where P_R is the rotor copper loss, the power converted into losses because the resistive loss is the only energy-conversion mechanism at work. The air-gap power, the power crossing the air gap from the stator to the rotor is the sum of the developed power and the rotor-copper losses:

$$P_{ag} = P_{dev} + P_R = \omega_s T_{dev}$$

Power flow in the induction motor includes three sources of losses. From the input power to the stator, there are losses from the heating of the copper and iron in the stator, P_{st} . Power between the stator and the rotor is the air-gap power. In the rotor, power is converted to losses P_R , that depends on the slip speed as $P_R = sP_{ag}$. Developed power is then

$P_{dev} = (1-s)P_{ag}$. There are also

mechanical losses, P_m , which are

subtracted from developed power to

yield the output power, P_{out} .

Induction motors have more

instances of losses than synchronous

motors, because of the copper losses

in the rotor, which do not appear in

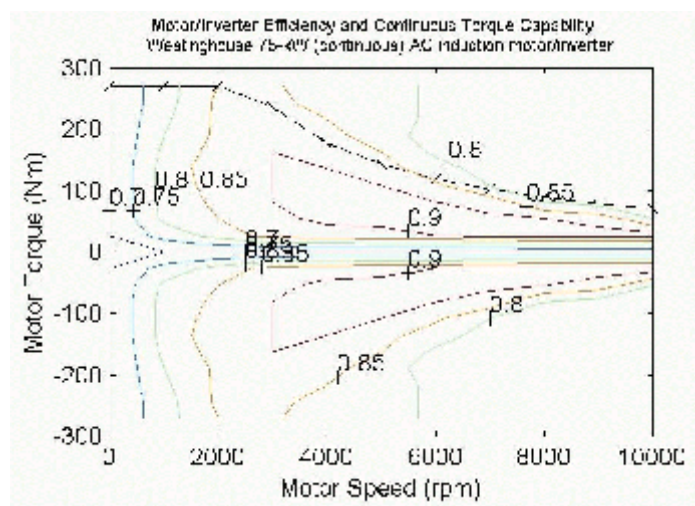


Figure 5¹³

synchronous motors. The efficiency of induction motors is as follows:

$$\eta = \frac{P_{out}}{P_{\epsilon}} = \frac{P_{\epsilon} - (P_{\delta} + P_{R} + P_{m})}{P_{\epsilon}}$$

Even though the induction motor has more sources of losses than the synchronous motor, the efficiency is still quite high.

Motor Control

Electronic control of motors is essential for their application to vehicle use for primary reasons: 1) the motor must be matched to the varying load demands of vehicular operation, and 2) most motors employed in the vehicles will run off ac current, but battery current is dc, requiring a device to transform alternating current to dc current. The advent of solid-state devices, specifically the transistor, the silicon-controlled rectifier (SCR), and gate-turnoff thyristors led to the re-emergence of electric vehicles in the 1970's⁵. They provided the rugged and reliable power control needed for vehicles.

Synchronous machines always run at synchronous speed, which is determined by the electrical frequency and the number of poles. Both the rotor and the stator fluxes rotate at this same speed. The only way to vary the synchronous speed is to vary the frequency of the excitation of the stator windings.

The induction motor is not a constant-speed machine as the synchronous motor is. The speed of the rotor must be less than the speed of the stator, synchronous speed, in order to develop a torque. The speed varies with the load on the rotor; speed decreases as the load increases. Speed can also be varied by varying the frequency of the stator excitation. In both,

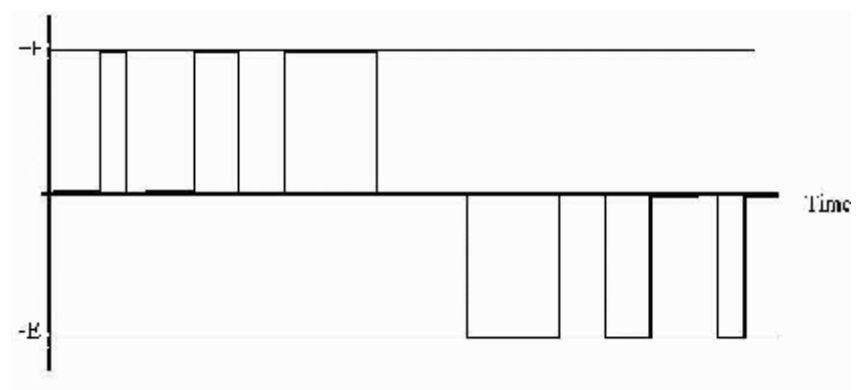
torque can be increased by increasing the amplitude of the current.

Batteries provide a single constant voltage between two terminals; inverters are necessary to mimic the balanced three-phase sinusoidal voltages, with controllable amplitude and frequency, that run ac motors. Most inverters obtain a set of three voltages using a system of switching elements; the switches make the three voltage waveforms 120 degrees “out of phase” with each other in the sense that each of the three leads one of the other two a one third of a cycle and lags the other by one third of a cycle⁶. The switching of the elements is designed so that the fundamental components of the three output voltages produce the desired motor response. A problem is caused by the higher harmonics, which cause undesired heating and torque variation. Filtering the input harmonics degrades the efficiency and the power factor; and higher harmonics in the output waveforms increase losses in the motor and produce no torque.

For these reasons, pulse-width modulation is employed in the inverter; it shifts the harmonics to high

frequencies that are easily filtered by the inductance of the motor.

The idea of pulse-width modulation is to chop



pieces out of the wave to **Figure 6** Pulse-width modulation in an inverter¹²

control the fundamental in the output. The width of each conduction interval is equal to a large fraction of the repetition period.⁷

It is also important to regulate the current. As voltage slips below the rated voltage, current can increase significantly, causing magnetic saturation. Motor controllers thus vary applied voltage in proportion to frequency to keep the current roughly constant; this is called constant volts/hertz drive.

A Generic Control Strategy

Hybrid electric vehicles attempt to capitalize on the complementary characteristics of the internal combustion engine and the electric motor in order to minimize fuel consumption and the production of emissions. There are numerous ways to configure the system and strategize the control system. The following is a generic control strategy. It is chosen both for its characteristics of minimal fuel

consumption and emissions production, and because this system can make the HEV perform in a very similar manner to the traditional car, an important reason for widespread acceptability in the consumer market.

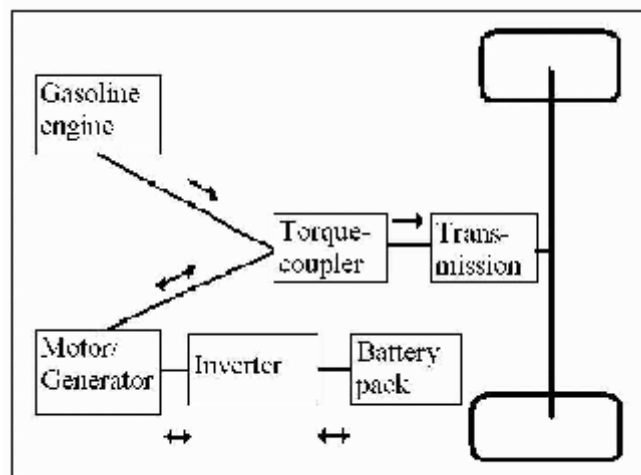


Figure 7 Schematic diagram of a generic parallel control system⁴

Figure 7 shows the

schematic diagram for this control strategy. In this parallel-configured system, both the engine and the motor provide torque to the wheels. For the most part, the internal combustion engine is used for the high-energy demands on the car, because of the relatively high specific energy level of gasoline. The engine is set to operate as much as possible in the region of lowest brake specific fuel consumption, and to minimize transient engine operation. The electric motor is used mostly for the high power demands on the car, because it produces high torque at low speeds, and because it demonstrates a high drivetrain efficiency over its range of torques and speeds. When the motor is not in use providing motive power, it can be run as a generator for two purposes. In regenerative braking, the generator converts torque from the wheels in order to decelerate the vehicle and store this energy in the battery. The vehicles are also equipped with friction brakes for safety purposes. Also, the generator can convert torque from the gasoline engine to electrical current; this is done to maintain the state of charge of the battery to a desirable level, and also, to demand higher torque from the engine to keep it in its zone of highest efficiency.

A system of electronic controls (equipped with computer technology) and mechanical controls matches the driving conditions for the vehicle to the appropriate drivetrain or combination of drivetrains. The following represents a typical system: 1) starting the vehicle, (speeds from 0 to approximately 10 mph): electric motor only (in this way, the engine is restricted from idling and low speeds, part-load conditions where combustion efficiency is very low); 2) braking: engine is shut off and motor runs as a generator (engine is again restricted

from idling, and energy is recaptured and stored that would be wasted in a vehicle without regenerative braking capacity); 3) cruising conditions: engine only; 4) rapid acceleration and climbing hills: engine and motor together to account for elevated power demands. In this fashion, hybrid electric vehicles have been shown to double fuel economy over a comparable traditional automobile and halve the production of emissions.

No universal control strategy is in use. The design of HEVs permits great flexibility, allowing the designers to optimize for a number of different benefits, such as fuel economy, emissions, cost of the vehicle, and safety. Comparison of the three HEV concept cars produced by the automobile manufacturers and displayed at the January, 2000 Detroit Auto Show reveals this large variability in design. In the GM Precept, the electric motor powers the front wheels and the gasoline engine powers the rear wheels. Toyota employs the “Prius Hybrid System” using a continuously variable transmission, and both an electric motor and a separate generator. Hybrids could be programmed to learn the driving patterns of its owner and adjust to them for maximum improvements in emissions and fuel economy¹¹. A number of other systems are possible.

Conclusion

HEVs capitalize on the complementary characteristics of the gasoline engine and the electric motor. Hybridization of the drivetrain combines the high efficiency of the electric motor with the high energy density of gasoline. The HEV eliminates the idling of the engine and aims to run the engine only in the island of minimum brake specific fuel consumption. The HEV also

prevents the engine from operating at transient conditions. The electric motor demonstrates high torque at low speeds, a characteristic that makes it suitable to the variable conditions of driving, and allows it to provide power efficiently. In a parallel-configured hybrid, the most common configuration of the system, either the gasoline engine, the electric motor, or both can provide torque directly to the wheels. A system of mechanical and electrical controls matches the drivetrain to the driving conditions. This method has been shown to halve the consumption of fuel and the production of emissions.

Although HEVs are not zero-emission vehicles, but still produce emissions and consume gasoline, the remarkable improvements in emissions and fuel consumption that they demonstrate will secure them a solid position on the road to more environmentally friendly vehicles. HEV technology is the most advanced and developed out of the group of personal transportation technology that is in the works. Many people expect that hydrogen fuel cell technology will eventually become the best choice for environmentally friendly personal transportation, but much research lies ahead before that can happen. HEVs are the most likely technology to appear and make a large impact on the consumer market.

Appendix: The Article

Preface

This article translates the scientific treatment of the principles explained above into the language of the non-scientific and less technical. The article is nonetheless scientifically accurate. It's audience is the non-scientific adult community. A generic HEV is described, with parallel configuration, and with the performance modeled on the conventional car; this is the type of HEV I consider the most likely to mass-produced.

A Lesson in the Physics of Hybrid Electric Vehicles

Half gas, half electric, half fuel use, half the emissions: the remarkable characteristics of the brand-new hybrid-electric car.

But is it really brand-new? The car as we know it was not necessarily a shoo-in to be our car. At the turn of the last century, engineers were racing to develop a personal transportation vehicle to replace the horse-and-buggy, and a number of ideas were in the air. Three major types of these horseless vehicles were in the race: the gasoline-engine vehicle, the electric vehicle, and the steam-powered vehicle. For a number of years they were neck-to-neck, each with its own particular advantages and disadvantages. Even then, the electric vehicle suffered from the familiar problem of a much shorter range than the other two cars. And even then, a number of engineers built hybrid-electric cars to combine the high efficiency of the electric motor with the large energy-storage capacity of gasoline, extending the

range of the electric and making the entire vehicle more energy-efficient. The first one appeared in Philadelphia as early as 1897. These hybrids offered their own particular advantage - one that we've since outgrown. In the days of the cranky and difficult internal combustion engines, and reliable electric motors, hybrids boasted a security measure - if you were out on a trip, and the engine stalled or refused to start, you could rely on the trusty electric motor to get you home!

The idea to incorporate both gasoline and electric under one hood is no 20th century innovation - rather, it is a rediscovery of a century-old concept. What urged us to this rediscovery? Design strategies during the last few decades have increasingly been influenced by environmental considerations, specifically, the need to reduce the engine's contribution to air pollution, and the need to reduce automotive fuel consumption⁷. An electric car - which neither releases emissions nor consumes gasoline - is often touted as the answer; but its perennial weakness obstructs the path to wide acceptance: limited range. It renders the car too inconvenient for most people - we need a car that can make long trips. This recalls the line of thinking that led to the first hybrid electric, and so it leads today's car manufacturers to the same conclusion.

Everyone knows that the gasoline engine won that early race, and people began to forget that there had ever been any competition. Why did it win? It was not that it was any faster than the others. Gasoline is a very potent fuel, storing large amounts of energy in a relatively lightweight package. However, the engine was only about 20% efficient in converting

this energy to the energy of motion. An electric motor is about 90% efficient in converting the energy in batteries to mechanical energy. Choosing the gasoline engine was a choice of high energy over high efficiency. Gasoline had become widely available and relatively cheap - it was common enough and cheap enough to justify the engine's inefficient conversion¹⁰. With the enormous number of cars the earth now supports (around 600 million) the validity of this reason has expired - since gasoline is a non-renewable energy source, the low efficiency of the engine is no longer dismissible. So if one of the major reasons why we originally chose the gasoline-powered vehicle no longer applies, perhaps we should be urged towards a new choice.

The first HEV derived from a perceptive observation about the choice between the gasoline vehicle and the electric vehicle: the two complement each other. The benefits of the electric motor include zero emissions and high efficiency of converting energy into motion. However, present battery technology limits the range of pure electric vehicles - even massive batteries store relatively little energy. The strengths of the gasoline engine include the high energy density of gasoline (300 to 400 times that of batteries), the resulting longer range, the extensive infrastructure supporting it, and the whole century of development that has rendered it refined and reliable. But fossil fuels are both a blessing and a curse; although they were the preferred energy source for the 20th century, they cannot continue to predominate. There are two environmental limiting factors: the production of greenhouse gases and the recognition that fossil fuels are a non-renewable resource.

In an HEV, either the gasoline engine or the electric motor can be used to provide power to the wheels directly, allowing the car to match the driving conditions to the most suitable source of energy, either the gasoline engine, or the electric motor, or both. So, the HEV uses the gasoline engine for the high-energy demands of cruising and long trips. It uses the electric motor for high-power conditions of starting, accelerating, and climbing hills. And, in the meantime, the HEV halves the consumption of fuel and the production of emissions.

Half Gasoline

In order to understand how the HEV works, it is necessary to examine each of the components in a little more detail. An engine converts chemical energy stored in the fuel to the mechanical energy of driving. Gasoline is combustible: in the presence of oxygen, it reacts with it, breaking down into a number of different, smaller compounds, and releasing the energy of the bonds. This energy takes the form of pressure and heat. The smaller compounds are the exhaust gases; and the energy is transferred by the engine into mechanical work.

The engine capitalizes on a fundamental physical principle: the equivalence of heat and work. Both are different forms of energy. The engine takes a large amount of heat, produced by the combustion of gasoline, and produces useful work - mechanical movement. An automobile engine creates this work through the movement of a piston within a cylinder. For the spark-ignition engine, the piston sweeps down the cylinder, and air and fuel follow the piston into the cylinder. Next, the piston moves up the cylinder, compressing the fuel-air mixture, raising its pressure and temperature. This makes the mixture easier to combust. Next,

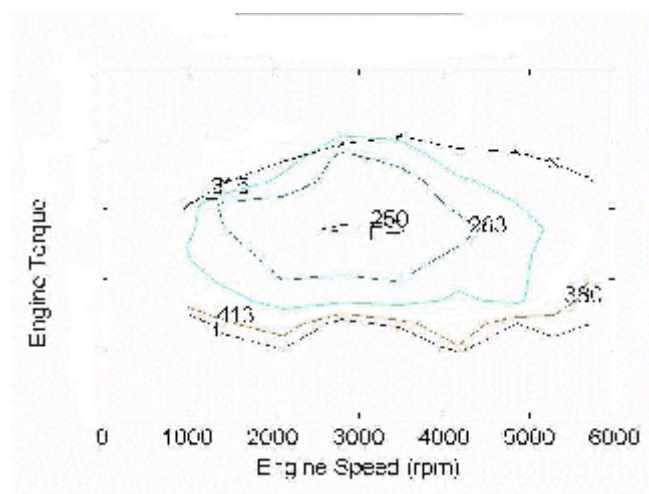
combustion: the spark-plugs send a spark through the mixture, igniting it. This explosion pushes the piston down the cylinder. This movement creates the work of the engine: the piston is attached to the crankshaft, which transfers this movement to the wheels. Lastly, the piston moves back up the cylinder, pushing the exhaust gases out of the cylinder. That completes the cycle. Since the piston has moved through the cylinder four times during the cycle, it is often called a four-stroke cycle. In a diesel engine, the cycle is a little different, but the principles of combustion are the same.

Any use of the engine brings along inefficiencies much greater than those in the electric motor. The laws of physics place a strict upper limit on the efficiency of the engine - there will never be an engine as efficient as the electric motor, for nature denies it. This is not a problem to be fixed by clever engineering. An engine converts heat that came from the combustion of gasoline to work to move the car forward, relying on the equivalence of heat and work. But the 2nd law of thermodynamics limits the quantity of heat that can be converted to work, and this maximum hovers at around only 50%. Even an ideal engine can only produce half the amount of work from a larger amount of heat. Any time you fill up the tank, about half the energy stored in that gasoline can never be used to drive the car - half of the energy is inaccessible because of the 2nd law! There is no way around it. Electric energy does not have such restraints - a major reason to move away from heat engines.

A consumer, looking for a new car, notices one thing about fuel economy immediately: every car on the market advertises two numbers for fuel economy, not one. Urban driving gets

the lower of the two numbers, and highway driving gets a higher number. It is a universal: every single car on the market has two different figures for these driving conditions, and urban driving is always lower. Traffic jams, lights, pedestrians, and road-work characterize the choppy motion of urban driving. This “stop and go” driving has lower fuel economy partially because of the large amount of time that the engine idles. Whenever the engine is not producing power, such as when the car is stopped or during braking, it is still running and using fuel, essentially wasting it. In fact, braking acts as a double culprit. If the purpose of the engine is to convert fuel energy (stored in the gasoline) to mechanical energy (the energy of movement), then braking, by its very purpose of slowing the car, subverts that purpose. In braking the energy of forward motion of the car is dissipated as heat in the brake pads. All this time, too, fuel is added to the engine to keep it running.

Idling and braking contribute to the greater fuel consumption of urban driving, but that is not the only reason why the engine uses less gas during highway driving. Let us first remark that highway driving is characterized by cruising: driving at a relatively constant speed and under relatively constant conditions. For the most part, one doesn't accelerate, brake, or idle. And this type of driving



Fuel consumption graph for an engine. Note the island of minimum fuel consumption.

maximizes the engine's fuel efficiency - the engine is designed to be most efficient on the highway. The graph depicts the fuel consumption contours over the ranges of the engine's speed and load - notice that the region of lowest fuel consumption is a very distinct and small region, "an island," within the entire range of the engine's operation. Furthermore, straying from this region causes dramatic increases in fuel consumption. Thus the engine performs its job most efficiently only under specific conditions of speed and load, which correspond to cruising on the highway.

A peek under the hood reveals that the actual engine is a maze of pipes, wires, and steel: all these mysterious pieces don't relate well to the relative simplicity of the basic principles of the engine. But the engine must also facilitate its own operation: it must have valves and manifold for the air to enter the cylinder and for the exhaust to exit; it must have a similar system for gasoline to enter, it must have a cooling system to keep the engine at functional temperatures, and it must have a system for lubricating all of the moving parts. Although the basic principle of the engine is relatively simple, the actual design of the engine is tortuously complicated. And all of these systems bring along their own inefficiencies - a fact that limits the engine to a small region of speed and load where it can be the most efficient. For example, the intake manifold, the engine system that provides the air into the cylinder, tries to fill each cylinder completely with air for each cycle of the engine. If it provides less air than the maximum, less fuel can combust. But when a lot of power is demanded from the engine, not enough air can move quickly enough through all the pipes, and the engine gasps for more air

than it can get. In this case, not all of the fuel burns, and the engine's efficiency is lower. Friction of all of the moving parts in the engine, and transfer of heat to the cooling systems, like the fan and the radiator, also decrease greatly the efficiency of the car.

Even some of the engineers building the earliest gasoline-powered cars, (those with sensitive noses) recognized a major drawback of their engines. In Detroit, in 1897, an engineer named Barton Peck commented about his car, "There is one great obstacle that must be overcome and this is the offensive odor from gasoline that has been burned and is discharged into the air. It is a sickening odor and I can readily see that should there be any number of them running on the street, there would be an ordinance passed forbidding them¹⁰." Mr. Peck's prediction of a law banning cars fell through - now the world has 600 million of them - but his observation on exhaust was full of foresight. Emissions from the world's swelling fleet of cars causes environmental problems such as urban air pollution and global warming - and this is the major force in favor of electric cars. A pure electric has no tailpipe, visual evidence that it releases no emissions. (Electric cars are not completely innocent - if the initial source of their electricity is a fossil fuel burning electric plant, then some emissions are released into the atmosphere. These are usually of less concern, though, because of the higher pollution controls at power plants.)

Any combustion of fossil fuels leads to the production of emissions. But, not all types of combustion are created equal. Different levels of emissions are created depending on the ratio of gasoline to air that is used for combustion. Most of the time, the engine runs lean, with a

little more air than is necessary, because this is more fuel-efficient and creates a smaller amount of emissions. But lean-running engines do not get the most power out of the engine. Pressing down hard on the gas pedal to accelerate forces extra gasoline into the cylinder, speeds up the engine, and gets more work out of it. It also bumps it out of the island of minimum fuel consumption. Accelerating adds more gasoline to the engine than there is air, using a fuel-rich mixture in which there is not enough air to react with all of the gasoline, and not all of the gasoline combusts. For acceleration, this tactic increases the power output of the engine. Fuel-rich mixtures also coax the engine into turning over when it might want to stall, for example, when it is first starting up or when it must suddenly do much more work. Any sort of transient engine condition (when the demands on the engine are changing) or high-power demand on the engine requires a fuel-rich mixture. And fuel-rich mixtures simultaneously waste fuel and increase emissions! Any fuel that does not burn is vaporized and released in the exhaust. This is one of the greatest sources of emissions in the car.

Half Electric

The other major component of an HEV is an electric motor. The idea to use electric power for personal transportation dates back 120 years - and an electric vehicle (a man-sized tricycle powered by a motor)¹⁰ predated the first gasoline vehicles. Today, this idea seems new, but it is altogether logical. Electricity and electric motors take part inextricably in daily life - an attempt to imagine life without electricity conjures images of barbarians, wood stoves, and candlelight. With the advent of electric power came innumerable and clever ways to use it.

Electric motors, which convert electrical energy to mechanical energy, the energy of movement, supply much of our need for mechanical energy. Electric fans, stereos, hair dryers, vacuum cleaners (and endless others) all rely on electric motors. They have a relatively simple design, are enormously common, and well-understood. Since the dawn of the electric age, engineers have been striving to apply the success of the electric motor to personal transportation.

A formidable obstacle has thus far succeeded in thwarting their hopes. Electric vehicles have a limited range - a problem of batteries, not of motors. Detached, thankfully, from the mains, electric cars must store the electric energy they require onboard, in their batteries. But the batteries we know and use cannot store enough energy for most people's transportation needs. That is a separate issue. The viability of the electric motor for personal transportation becomes clear when the problem of batteries can be bypassed, as in the HEV, which does not rely solely on batteries for energy storage.

The function of the gasoline engine is to convert chemical energy to mechanical energy. Similarly, an electric motor converts electrical energy (from an electric current) to mechanical energy. Although these are similar functions, the actual process is very different. An electric motor is more simple, fundamental, and elegant than an engine. The electric motor runs at about 90% efficiency, wasting very little energy. Furthermore, this high efficiency is characteristic of the motor over the entire range of vehicle operations - a large contrast to the gasoline engine.

The concept for the motor developed from an observation by an English scientist,

Michael Faraday. He discovered the fundamental connection between electricity, magnetism, and force through an experiment involving a current-carrying wire, magnets, and a beaker full of mercury. With the wire running down the middle of the beaker, and the magnet placed alongside the wire in the beaker, the magnet revolved continuously around the wire, sweeping a circular path through the mercury. Why? This mysterious movement stems from a physical principle that links these three seemingly distinct physical processes: electricity, magnetism, and movement. The presence of electrical current moving in one direction, plus a magnetic field perpendicular to the current, causes a force that acts perpendicular to both of them, the force which caused the magnet to revolve around the wire. The electric motor capitalizes on this principle. For a car, this is the mechanical energy which can then be used to drive the wheels and propel the car.

Electric motors have a remarkable characteristic - they are able to produce high torque even at low speeds. That means that electric motors can turn the car's axle quite powerfully even when they are just starting. They do not have to be turning over very quickly in order to produce torque - in fact, they do not have to be turning over at all. Simply sending current through a still motor starts it, almost immediately, to produce high torque. Even our present cars take advantage of this trait - in the electric starter. The electric starter employs a motor to drive the engine through the first low-speed revolutions, because the engine can't start itself. Thus, in a manner of speaking, the electric starter turns every conventional car into an HEV! The electric motor not only starts itself, it can also produce high torque soon thereafter, making it

well suited to the demands of vehicle acceleration.

No engine can start with exhaust gases and convert them back to gasoline and oxygen. If that were true, the world's problems with both energy supply and air pollution would be solved immediately! No engine works backwards - but an electric motor can. It works backwards, as a generator, taking the energy of movement and returning it to electrical energy in a current. Faraday's experiment could have easily worked in reverse. If he had turned off the current in the wire, making the magnet stop revolving around it, grabbed hold of the magnet and stirred it around in the opposite direction, this would have caused a current to flow down the wire, towards the battery, charging it! Here, mechanical energy generates electrical energy. The presence of an electric motor in the car transforms the nature of braking from the dissipation of energy to regenerative braking - braking that regenerates current to be stored in the batteries. The same energy can later be used to accelerate the car. This feature greatly enhances the efficiency of the car during urban driving with its many stops and starts. It is a feature of electric motors, and therefore applicable to all electric cars, including HEVs.

The Hybrid Electric Vehicle

A hybrid electric vehicle (HEV) is intelligent. Not only does it balance an electric motor and a gasoline engine, but it manages to use a minimum amount of fuel and release a minimum amount of emissions. (And it does all of this without any effort on the part of the driver). The HEV can turn the engine and the motor on and off, as long as one of them is powering the car. When the engine is on, it runs, as much as possible, in its island of minimum

fuel consumption, getting as much energy as possible out of the gasoline. If not all of the energy is needed to drive the car, some of it can be stored in the battery, and saved for later. The HEV never lets the engine idle - at a stop light for instance - it just turns it off. The car runs electric for starting, for slow-speeds, and for high-power needs, like rapid accelerating or climbing steep hills. The electric motor is well suited to these applications, whereas the engine would use up the most fuel and release the most emissions during high-power operations. Smart! This is the key to the success of the HEV in reducing fuel consumption and emissions over a traditional car. Having identified that these high-power operations cause the majority of emissions and wasted fuel, the HEV prevents the engine from operating in these situations, turns on the motor, and consequently eliminates the greatest chunk of emissions - wasted fuel!

An HEV intelligently gets around the individual problems associated with the gasoline engine and the electric vehicle. It diminishes the production of emissions and the use of fuel. The problem of batteries for the electric vehicle is conquered. An HEV charges itself - it never has to be plugged in. When not in use providing power, the motor can run as a generator to transfer energy from regenerative braking and from the gasoline engine to the batteries. The only recharging necessary is refueling by going to the gas station. Also, there is not the same demand on the batteries as there would be in an electric vehicle, where the batteries must store *all* the energy the car needs. These batteries are smaller, and only have to be able to provide for the high-power uses. Similarly, the engine for a HEV is smaller than it would be in a traditional car, as it doesn't have to provide as much horsepower. (Again, this makes it more

fuel-efficient - most engines are too big for most of their uses.)

So, in the year 2000, we are waiting for the introduction of hybrids into the mainstream automobile market. It's now more than a century after the first HEV was built in Philadelphia. That car had an unfortunate fate. On its first trip, its designer got out of the car, and caught his foot on one of the wires. This sent an arc of electric current through the gas tank, igniting all the gas, and the first HEV was engulfed in flames! Do not take this as a sign! That disappointed engineer lacked technology that has since been developed to carefully control electric currents and voltages. Modern HEVs rely on this technology and the computer technology that intelligently controls all of the different elements of the HEV to produce its remarkable results. The HEV is the environmentally friendly car of the near future.

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