APPENDIX A: Method for Evaluating Vehicle Performance

The Office of Technology Assessment's (OTA's) analysis of vehicular performance and fuel economy hinges on examining the vehicle on the Environmental Protection Agency (EPA) driving cycle, using average ("lumped parameter") estimates of key variables such as motor efficiency and battery efficiency over the urban or highway portions of the cycle. Ideally, a performance analysis of complex vehicles such as hybrids should be based on detailed engine and motor maps coupled with models that are capable of capturing the second-by-second interactions of all of the components. Such models have been developed by the auto manufacturers and others. Nevertheless, OTA believes that the approximate performance calculations described here give results that are adequate for our purposes. Also, the detailed models require a level of data on technology performance that is unavailable for all but the very near-term technologies.

ENERGY CONSUMPTION IN CONVENTIONAL AUTOMOBILES

It is relatively easy to derive a simple model of energy consumption in conventional automobiles that provides insight into the sources and nature of energy losses. In brief, the engine converts fuel energy to shaft work. This shaft work is used to overcome the tractive energy required by the vehicle to move forward, as well as to overcome driveline losses and supply accessory drive energy requirements. The tractive energy can be separated into the energy required to overcome aerodynamic drag force, rolling resistance, and inertia force. It is useful to consider energy consumption on the EPA urban and highway test cycles, which provide a reference for comparing fuel economy.

The engineering model used in this study follows the work by GM Research Laboratory scientists Sovran and Bohn.[1] Defining the average engine brake specific fuel consumption over the test cycle as bsfc, fuel consumption FC[2] is given by:

[1] G. Sovran and M. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedules," SAE paper 810184, 1981.

[2] In other words, bsfc is an expression of the average efficiency of the engine as one element of the total vehicle system; and FC expresses the fuel consumption of that complete vehicle system.

$$FC = \frac{bsfc}{\eta_d} \cdot [E_R + E_A + E_K] + bsfc\, E_{AC} + G_i\,(t_i + t_b)$$

where

η_d	is the drive train efficiency
E_R	is the energy to overcome rolling resistance
E_A	is the energy to overcome aerodynamic drag
E_K	is the energy to overcome inertia force
E_{AC}	is the accessory energy consumption
G_i	is idle fuel consumption per unit time
t_i, t_b	are the time spent at idle and braking

The first term in the above equation represents the fuel consumed to overcome tractive forces. Because the Federal Test Procedure (FTP) specifies the urban and highway test cycle, ER, EA, and Ek can be readily calculated as functions of the vehicle weight, the rolling resistance, body drag coefficient, and frontal area. Note that weight reduction reduces both inertia force and rolling resistance. It should also be noted that not all of the inertia force is lost to the brakes, as a vehicle will slow down at zero input power owing to aerodynamic drag and rolling resistance, without the use of brakes. The fuel energy is used not only to supply tractive energy requirements but also to overcome transmission losses, which accounts for the transmission efficiency that is in the first term.

The second term in the equation is for the fuel consumed to run the accessories. Accessory power is needed to run the radiator cooling fan, alternator, water pump, oil pump, and power-steering pump (but the water pump and oil pump are sometimes excluded from the accessory drive loads). The air conditioner is not included because it is not turned on during the FTP. Idle and braking fuel consumption are largely a function of engine size and idle rpm, while transmission losses are a function of transmission type (manual or automatic) and design. The engine produces no power during idle and braking but consumes fuel so that factor is accounted for by the third term.

Tables A-l(a) and (b) show the energy consumed by all of these factors in a typical midsize car with a three litre overhead valve (OHV) engine, four-speed automatic transmission with lockup, power steering, and typical alternator size. Table A-l(a) shows the distribution of the vehicle’s tractive energy and total fuel consumption for the two cycles as well as the EPA 55/45 composite cycle. Table A-l(b) indicates the absolute energy consumption and estimates the car’s engine efficiency.

The values in table A-l(a) can be easily utilized to derive sensitivity coefficients for the reduction of various loads. For example, reducing the weight by 10 percent will reduce both rolling resistance and inertia weight forces, so that tractive energy is reduced by (30.5 + 39.6) x O. I or 7.01 percent on the composite cycle. Fuel consumption will be reduced by 7.01 percent x 0.708 which is the fraction of fuel used by tractive energy, or 4.96 percent. This matches the common wisdom that reducing weight by 10 percent reduces fuel consumption by 5 percent.

However, if the engine is also downsized by 10 percent to account for the weight loss, fuel consumption will be reduced by 6.02 percent as idle and braking fuel consumption will be reduced in proportion to engine size. **Table A-1 provides a framework by which total fuel consumption for any automobile can be analyzed for the FTP cycle.**

On a total energy basis, energy can be allocated to the various losses using different conventions on the treatment of idle and accessory power loss. One example of this allocation is provided in a chart from the Partnership for a New Generation of Vehicles (PNGV)[3] shown in figure A-1. The figure implies that the engine usefully converts 20.4 percent of fuel energy into useful power in the city cycle, and 10.8 percent of this useful power (or 2.2 percent of fuel energy) is used for accessory drives. The other 18.2 percent is used by the drivetrain. The PNGV chart specifies a drivetrain efficiency of 69.2 percent in the city cycle, which appears unusually low. Most modern transmissions with lockup converters operate at efficiencies of over 85 percent in the city cycle, and 92 to 94 percent on the highway cycle. The PNGV allocations to kinetic energy, rolling resistance, and drag force are also different born the values shown in table A-1, especially in the allocation between the rolling resistance and inertia forces, but these differences may be owing to the conventions followed in allocating energy to the different loads. The source of these numbers is not documented.

A separate analysis,[4] shown in figure A-2, also differs somewhat from the tractive energy values calculated from Sovran and Bohn's formula, probably because of differences in the accounting conventions. Their estimate of overall energy efficiency appears low, as engine thermal efficiency (excluding idle loss) is shown at 20.1 percent for the composite cycle, rather than the more common 23 to 24 percent. Although these differences may seem academic, they may play a significant part in explaining the widely different results estimated in the literature for the fuel economy of hybrid vehicles. For example, if the PNGV value for transmission efficiency is connect, a 30 to 35 percent fuel economy increase (or a 23 to 26 percent fuel consumption decrease) would be possible simply by eliminating the transmission, as is likely with electric motor drives. The resolution of these figures is one key to reconciling the widely varied findings regarding hybrid vehicle efficiency.

The analysis of conventional vehicles in this report is based on the formulae and sensitivity indices computed using a methodology similar to the one described for weight. The weighting factors for E_K, E_A and E_R utilize the relationships developed by Sovran and Bohn. All of the other coefficients are computed as ratios so that the actual equation used is in the form of FC_{new}/FC_{old}. This is particularly convenient as most of the variables such as bsfc have been analyzed in terms of potential changes from current values. For example, engine average bsfc over the composite cycle was forecast to be reduced by 18 percent from current values. All of the analysis is in fuel consumption space. The same tractive energy equations also hold for electric and hybrid vehicles, although the bsfc and weight calculations for hybrid vehicles are far more complex.

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[3] P.G. Patil, "Partnership for a New Generation of Vehicles", Automotive Technology Development Contractors Coordination Meeting, U.S. Department of Energy, October 1994.

[4] M Ross and W Wu, "Fuel Economy of a Hybrid Car Based on a Buffered Fuel-Engine Operating at It's Optimal Point," SAE paper 95000, 1995.

PERFORMANCE, EMISSIONS, AND FUEL ECONOMY

The previous section described energy use over a prescribed driving cycle, and treated the variable of average engine brake specific fuel consumption, bsfc, as constant. The value of bsfc is dependent on the size of the engine, the gear ratios and final drive ratio, as well as the engine's emission calibration. The size of the engine and the transmission/axle ratios have an impact upon vehicle performance capability and affect bsfc, although the driving cycle over which fuel economy is measured remains constant. These issues and the resultant tradeoffs with fuel economy are discussed below.

Different levels of performance can be attained most simply be varying axle ratio, which determines the engine rpm to vehicle speed ratio in any particular gear. Increased numerical values of axle ratio imply higher rpm at a given speed and increased performance. The tradeoff of fuel economy with axle ratio is nonlinear, however; fuel economy increases with decreasing axle ratio up to a point, but decreases beyond this maximum level at even lower axle ratios. The reason is that, at very low axle ratios, gear shifts must be delayed owing to insufficient torque at low speed to follow the driving cycle. Figure A-3 provides an illustration of the tradeoff between fuel economy and performance with changing axle ratio, holding all else constants As can be seem axle ratios below 3:1 (in this example) make both performance and fuel economy worse, and would make no sense for a manufacturer to employ. The tradeoff between axle ratio, performance, and fuel economy is defined to the right of the fuel economy maximum point in the figure. Statistical analysis of data from EPA tests indicates that a linear approximation of the effect of a 10 percent increase in axle ratio is a 2.0 percent decrease in fuel economy, and a 5 percent decrease in O to 60 mph time.[6]

The next option is to increase engine size, and figure A-4 shows the family of tradeoff curves of fuel economy and performance with axle ratio for different engine sizes.[7] Larger engines obtain worse fuel economy than smaller engines for two reasons:

- increased fuel consumption during braking and idling, when the fuel consumption rate is largely a fiction of engine size, and
- lower average load relative to the maximum which requires more throttling and higher pumping loss.

Of course, a larger engine could be utilized with a lower axle ratio that changes the performance and fuel economy tradeoffs. As can be seen in the figure, for some combinations of axle ratios and engine size, different engine sizes have nearly identical fuel economy and only slightly different performance. Statistical analysis has shown that increasing engine size by 10 percent, while keeping all other factors constant (including weight and axle ratio), leads to approximately a 3.6 percent increase in fuel consumption.

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[5] Ford Motor Co., presentation to the Department of Energy on five-speed automatic transmissions, September 1992.
[6] H.T. McAdams, "Statistical Projection of Fuel Economy to the Year 2000," presentation at the SAE Government Industry Meeting, 1992.
[7] Ford Motor Co., see footnote 5.

With larger engines and more performance potential, however, many other vehicle factors change. Larger engines require stronger drivetrain components and better suspension and brakes, all of which increase weight. In addition heavier "performance" tires with higher rolling resistance may be used. Increased engine displacement could also require that the number of cylinders be increased, leading to an even larger weight increase and increased internal engine fiction. Hence, the tradeoff leads to even larger differences in fuel economy for each increment of performance.

Manufacturers have a wide set of options to improve performance to a given level, and the actual fuel economy impact depends on the particular set of options chosen. A statistical analysis of data from the EPA test car list at constant engine technology showed a tradeoff of the form:

$$\text{Percent change in F/E} = -0.20 * (\text{A HP}) - 0.560 * (\Delta \text{HP})^2$$

which represents an average of all strategies represented in the data, where A HP is percent change in horsepowers

The impact of emission standards ***on*** fuel economy and performance is less clear, but this is principally because the impacts are relatively small. Most modem cars calibrated to current Tier I standards produce very little emissions once the engine is warmed up, and the cold start phase (which lasts about two minutes after cold start) is responsible for 75 percent of all emissions on the test.[9] In this context, the ability to meet future low emission vehicle/ultralow emission vehicle (LEV/ULEV) standards is based on reducing emissions in the first two minutes of operation, and the methods developed include the use of small "start" catalysts that light-off very quickly, electrically heated catalysts, intake air heaters, improved fuel atomization and heated fuel spray targets. An evaluation of different methods conducted for NESCAUM[1°] concluded that the direct effects were small but the indirect effects, such as the increased back pressure owing to start catalysts and increased weight associated with more components, would cause fuel economy penalties in the 2 percent range. Electrically heated catalysts could have larger penalties, but recent data suggests that they may not be necessary in most vehicles, even at ULEV emission levels. For example, the 1995 Toyota Camry (California version) comes very close to meeting ULEV standards with virtually no advanced aftertreatment methods, while Honda plans[11] to certify an Accord to ULEV standards for 1998, and has publicly stated that fuel economy penalties are very small.[12] The impact on performance owing to increased back pressure is also likely to be in the same range as the impact on fuel economy--that is, about 2 percent, and Honda hopes that costs will be below $300 (as an incremental retail price effect (RPE)).

"Off-cycle" emissions are also of concern as the EPA and Air Resources Board have found that emissions increase dramatically during hard accelerations and high speeds, which currently are not represented in the FTP but occur often in actual driving. These increases are associated with the engine going into enrichment mode (i.e. increased fuel-air ratio) at high loads, which increases

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8 Energy and Environmental Analysis, Inc., "The Fuel Economv Model - Documentation report to EL%" October 1993.
9 Honda R&D Co. "Honda ULEV Technology," brochure, January 1995.
1O E.H. Pechan and Energy and Environmental Analysis, Inc., "Adopting the California LEV Program in the North Eastern States," report prepared for NESCAUM, September 1991.
11 U.S. Environmental Protecti"on Agency, 'EPA Certification List," 1995.
12 The issue of fuel composition ia important but not discussed here.

hydrocarbon and carbon monoxide emissions dramatically. EPA is now planning a separate "high-speed driving cycle" (that is, unfortunately, independent of vehicle characteristics) with new emission standards for these cycles.[13] Such an approach would favor the high-performance vehicle as the engine may not reach the high load levels to require enrichment on such a vehicle during the new EPA cycle. Low performance vehicles however will be hurt more, because the enrichment levels must be cut back, which will improve fuel economy but hamper performance. In sum, the effect of this potential new regulation will not be to hurt fuel economy directly, but will indirectly affect it by making the trend toward higher performance more attractive.

ELECTRIC VEHICLES

The energy use of an electric vehicle (EV) is governed by the same equation shown on page A-2, except that there is no "idle" energy consumption so that:

$$FC = E_{TR}/(\eta_m \ \eta_d) + E_{AC}$$

where η_m is motor efficiency,

E_{TR} is the traction energy $E_R + E_A + E_K$, and
FC is fuel consumption in kWh.

The relative energy efficiency of electric vehicles can be discussed with reference to this equation. First, the electric vehicle gains back the fuel consumption associated with braking and idling--a 10.8 percent savings. Second, most of the accessories used in the internal combustion engine-powered car, such as the water pump, oil pump, cooling fan, and alternator, can be eliminated if battery heat losses are not high, as motor and electronics cooling requirements do not require much power. In addition the conventional power steering must be replaced by electric power steering, which consumes only a fraction of the power of conventional systems, and consumes no power on an EPA dynamometer test where the steering is not used. This saves as much as 9.5 percent of fuel consumption on the test cycle. The EV may need power for the brakes, however, but this requirement is probably small owing to the use of regenerative braking, as described below.

Third, some of the energy lost during braking can be recovered by electric vehicles, because the motor can act as a generator when it absorbs power from the wheels. The energy can be stored in battery and later released to drive the motor. As noted earlier, the energy lost to the brakes in a conventional car in the FTP city cycle is about 35 percent of total tractive energy. For the motor to convert this to electricity, however, transmission loss and motor loss in generator mode must be considered. Typically, transmissions for electric motors are simple drive gears, and can be 95 to 96 percent efficient. Motors operated in reverse generator mode typically have cycle average efficiency in the 80 to 84 percent range. Hence, only 78 percent of the braking energy can be

[13] Honda *R&D (h.,* see footnote 9.

converted to electricity, which is about 27.0 percent of traction energy. The storage and retrieval of electricity in a battery causes further loss, but this is very dependent on both the battery type and its efficiency in terms of absorbing power pulses. This efficiency is only 80 percent or lower for lead acid and nickel-cadmium batteries, so that regenerative braking recaptures only 0.82 x 0.95 x 0.80x 0.35, or 21.8 percent of tractive energy using such batteries. This assumes that all of the braking can be done regeneratively, but this is not true in practice, because the motor generally is connected to only two wheels, leaving the other two wheels to be braked conventionally .14 As a result, actual systems in the Toyota EV[15] and the Cocconi CRX[16] have been reported to provide range increases of about 17 to 18 percent maximum since other system losses prevent reaching the 21.8 percent figure. These figures quoted for the Toyota EV and Cocconi CRX are the <u>best</u> achieved, as regenerative braking more typically extends range by only 8 to 10 percent in many vehicles, such as the BMW El.

Fourth, the motor is quite efficient in converting electrical energy to shaft energy, with typical cycle average efficiencies in the 75 to 80 percent range in the city cycle, as opposed to gasoline engines, which have an efficiency of only 20 to 23 percent on the fuel economy test cycle. Of course, the production of electricity from fossil fuels has an efficiency of only 35 to 40 percent, and there are other transmission losses, so that direct efficiency comparisons are more complex. Nevertheless, electricity stored on a car can be converted to useful power almost 300 percent more efficiently than gasoline.

Substituting these efficiency values into the fuel consumption equation, and assuming that EV accessory power consumption is only 25 percent of the power consumed by accessories in conventional vehicles, it can easily be shown that an EV uses only 14 percent of the energy used by a similar current conventional vehicle, *if the weight of both* ***vehicles are identical and if battery losses are not considered.*** When electricity generation efficiency, transmission loss, charger efficiency, battery storage efficiency, and battery internal self discharge are considered, however, the picture is quite different, and the EV of the same weight consumes 60 percent or more of the energy consumed by a current conventional gasoline vehicle of equal weight. In order to obtain sufficient range and performance, however, EV's can be much heavier than conventional vehicles, so that the EV can be less efficient on a primary energy basis than even a conventional vehicle of equal size and acceleration performance.

The analysis of overall vehicle weight, and the range/performance tradeoffs are especially important for an electric vehicle. A simple analytical framework allows the calculation of these tradeoffs. The battery energy storage capacity and the peak-power capacity affect the range and performance capability, and the more batteries used, the greater the capacity. As battery weight increases, however, structural weights must also increase to carry the loads, and a larger motor is required to maintain performance. The weight spiral effects lead to a situation where there are rapidly declining benefits to each additional battery weight increment.

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[14] Proper handling during braking requires that all four wheels be braked for stability.

[15] K. Kanamaru, "Toyota EV-50: AnEffort to Realize Practical EVs paper presented at the 12th International Electric Vehicle Symposium, December 1994.

[16] A Burke Institute of Transportation SW&~ University of California at Davis, "Dynamometer and Road Testing of Advanced Electric Vehicle," 1995.

For a vehicle of a given size, there is a specific "zero weight engine" body weight that is essentially a theoretical body weight if engine weight were zero, assuming a flow through of secondary weight reduction. This was calculated to be 50 to 54 percent for several cars whose detailed weight breakdowns were available, assuming a secondary weight reduction of 0.5 for each unit of primary weight reduction. Denoting this "zero weight engine" body weight as M_{B_Z} we have total EV weight given by:

$$M_{EV} = M_{Bz} + 1.5\, M_{BATT} + 1.5\, M_{MOTOR}$$

where: M_{BATT} is the battery (including tray and thermal management system) weight

M_{MOTOR} is the weight of the motor and controller.

The traction energy needed to move a vehicle forward normalized by total vehicle weight is the specific traction energy, and one analysis[17] has shown that this number is relatively constant in city driving, being a weak function of rolling resistance coefficient and the ratio of drag force to mass. Denoting specific traction energy as E, we have the range, R, given by:

$$R = (M_{BATT} \cdot S_E) / (E \cdot M_{EV})$$

where S_E is the battery specific energy. This equation simply balances the energy stored in the battery to the energy demanded by the car. Of course, this range represents the maximum range, if the battery were discharged down to zero charge, which is not recommended for some battery types. This leads to a simple relationship to derive the ratio of battery to vehicle weight, as follows:

$$M_{BATT}/M_{EV} = R\, E/S_E$$

The above equation effectively links the battery weight to vehicle range and battery specific energy.

The size of the motor is simply determined by the output requirement as set by performance requirements. Setting the performance requirement in the form of horsepower to vehicle weight ratio, we have:

$$P' \frac{HP}{lM_{EV}} = K \cdot M_{MOTOR}/M_{EV}$$

where k is the power to weight ratio of the motor. As discussed in chapter 4, a typical vehicle with average performance requires 80 HP per ton (1000 kg) of weight (curb + payload), but an electrical motor of 20 percent lower output can provide equal performance at low to mid speeds.

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[17] Sovran and Bohn, see footnote 1.

Hence, an electrical motor power output of 50 kW (or 67 HP) per ton of vehicle weight provides comparable or average performance. Typically, electrical motors (and their controllers) weigh about 1.0 to 1.2 kg for each kW of output so that a M_{MOTOR}/M_{EV} ratio of 0.05 provides a reasonable approximation of motor weight to vehicle weight.

The weight-compounding effect is best illustrated by the ratio of battery weight to "zero weight engine" body weight, which is a constant for a car of a given design and size. Using the above relationship, it can be shown that:

$$M_{BATT}/M_{Bz} = \frac{RE/S_E}{1 - 1.5\,RE/S_E - 1.5\,P/K}$$

$$= \frac{RE/S_E}{0.9025 - 1.5RE/S_E}$$

for an acceptable performance car. This relationship is very useful in illustrating the effects of different specific energy storage capability and the choice of vehicle range on battery weight.

Table A-2 lists the actual and specific energy consumption of several recent EV models, based on the city cycle test procedure. The energy consumption values for these EVs indicate that the specific traction energy E is similar across most cars ranging between 0.084 to 0.151 kWh/ton-km or 0.12 to 0.22 kWh/ton-mile. Vehicles at the high end of the spectrum were models with low regenerative braking efficiency or with less efficient motor/electronics, but the body characteristics or total weight did not have a significant impact on the specific energy efficiency. (For example, the GM Impact is slightly less efficient than the Cocconi CRX-4 using this measure). The Cocconi CRX stands out with an energy consumption of 0.084 kWh/mi but it has no accessories, not even power steering. These energy consumption figures are based on federal city cycle driving, and are often not the ones quoted in the press.

Many publications also provide inconsistent and in many instances, significantly lower estimates of energy used for each ton-mile, based on the same cars shown in table A-2. For example, ARB tests of the Cocconi CRX were used to derive energy from the battery used as 96.5 Wh/km, but this is based on subtracting all of the regenerative energy going into the battery from the battery output[18]; this is incorrect because not all of the regenerative power going in can be recovered owing to charge/discharge loss in the battery. The GM Impact is another car where city cycle energy consumption has been reported as low as 0.065 kWh/km.[19] However, GM claims a range of 70 miles in the city based on the discharge of a 16.3 kWh battery to 80 percent DoD.[20] If 13 kWh (0.8x 16.3) is required to travel 70 miles (112.6 km), it is easy to see that the quoted 0.065 kWh/km cannot be correct. Finally, it should be noted that E is calculated in Wh/km per kg of

[18] Air Resources Board Tests of Cocconi CRX, private communication with ARB.
[19] A. Burke, personal communication, April 19, 1995.
[20] General Motors, preview brochure on Impact specifications, 1994.

empty weight in this calculation, as opposed to Wh/km per kg of inertia weight (empty weight + 300 lbs), which yields lower results.

Using a representative value of E of 0.1 kWh/ton-km for a vehicle with power steering and developed from a glider body, figure A-5 shows the relationship between battery weight and "zero engine" body weight, and its nonlinear increase with range is obvious. At an R/SE of 6, battery weight is infinite, as the added weight of the battery does not provide enough energy to increase range while maintaining performance. When battery weight equals zero engine body weight, the value Of R/S_E is 3.6. To place this in perspective, an advanced lead acid battery, which has an S_E of 42 Wh/kg, provides a range of 150 km (42 x 3.6) or 90 miles, when battery weight equals zero engine body weight. For a current (1995) mid-size car such as the Taurus, the "zero engine" body weight is about 730 kg or 1,600 lbs. Hence, to obtain a 90-mile range even with an advanced semi-bipolar lead acid battery, 1,600 lbs of battery are required, and the total weight of the car increases from the current 3,100 lbs to 5,240 lbs. (In reality, usefud range is only about 70 miles since lead acid batteries should be discharged only to 20 percent of capacity). In contrast, a nickel-metal hydride battery, with an S_E of 72 Wh/kg, of the same weight will provide a range of more than 150 miles. The weight of nickel-metal hydride battery to provide a 100-mile range is 957 pounds, while the car weight falls to 3,305 lbs, illustrating the importance of weight compounding effects in an EV.

The second constraint on the battery size is that it must be large enough to provide the peak-power requirement of the motor, or else some peak-power device such as an ultracapacitor or flywheel may be necessary. To meet this requirement, we have the following:

$$M_{BATT} \cdot S_P > K \cdot M_{MOTOR}$$

where S_p is the specific power capability of the battery. Algebraic manipulation and substitution can be employed to show that:

$$S_P/S_E \geq P/R \cdot E$$

For a value of P of 50 kW/ton, a range of 160 km, and a value of E = 0.1 kWh/ton-km (or 0.1 Wh/kg-km), we have:

$$S_P/S_E > 3.125 \text{ hr}^{-1}$$

At a range of 100 miles or 160 km, the specific power to specific energy ratio must be at least 3.125 hr^{-1}; otherwise, the power requirement becomes the limiting factor on battery size. If the range requirement is doubled to 200 miles, then the minimum ratio declines to 1.56 hr^{-1}. For a 100-mile range, the advanced semi bipolar lead acid battery meets this requirement, with an S_p/S_E ratios of almost 5, while the Ni-MH battery has a ratio of about 3.1, close to the minimum. The existing "hot-battery" designs provide ratios of only 1.25, while more recent advanced designs provide ratios closer to 2. The important point of this discussion is that doubling the specific energy does not automatically lead to half the battery size, if the battery's power capability is inadequate to provide "average performance. " Relaxing the performance requirement reduces the required ratio, illustrating that hot batteries with good specific energy but low specific power have best application in commercial vehicles, where range is more important than performance. One alternative is to include peak-power devices such as ultracapacitors with such batteries to provide adequate peak power.

HYBRID **VEHICLES**

Series Hybrids

The equations governing hybrid fuel consumption, performance, and weight are similar to these for EV's, with the motor generator added. The total weight of the vehicle, using the notation employed for EVs is given by:

$$M_{HEV} = M_{Bz} + 1.4M_{BATT} + 1.4M_{MOTOR} + 1.4M_{EG}$$

where M_{EG} is the weight of the engine + generator. The performance, P, as defined by the peak power (kW) to vehicle weight ratio, is given by:

$P = K \cdot \text{Motor}/M_{HEV}$ (using the same notation employed for EVs

and $K \cdot M_{Motor} = S_p M_{BATT} + C \cdot M_{EG}$

where C is the specific power output of the engine and generator in kw/kg. The main defining idea of the series hybrid is that the engine can be run at nearly constant output, and the output level be matched to the engine peak efficiency point. Hence, the engine is either run at this optimal point or shut off, and the energy stored in the battery for use over any arbitrary driving cycle (in practice, running at exactly one point is quite a restrictive operating strategy, as explained below).

Typically, a modem internal combustion engine (ICE) produces its peak output at 5,000 to 6,000 rpm and the weight of an engine (dressed) is about 2 kg/kW of peak output. Other items such as the radiator, exhaust system, and catalyst, however, which are required to operate the engine, make the total weight closer to 2.2 to 2.6 kg/kW as shown in table A-3. The peak efficiency point usually occurs at 40 to 45 percent of peak rpm and 70 percent to 80 percent of maximum torque. Hence, a typical engine operating at its best efficiency point produces about 40 percent of its peak output, and such an engine and generator would weigh 7.5 to 8.5 kg/kW, and its specific power is about 117 to 130 W/kg. (i.e., the value of C in the equation is 117 to 130). Advanced lead acid batteries of the semi-bipolar or bipolar type provide specific power of over 300 W/kg for a 30-second rating, while ultracapacitors and flywheels can provide 2 kW/kg or more. These specific power values make it clear that the engine should provide energy while the battery, ultracapacitor, or flywheel can provide peak power. Hence, the engine should be small and provide the total energy for driving, while the battery or other storage device should be sized to provide the peak power output, so that the total weight is kept low. This also implies that batteries with high specific peak power are better suited for use in Hybrid Electric Vehicles (HEVs).

Because the battery is capable of providing peak power in short bursts only, the critical engine size is limited by the maximum continuous demand under the most severe design condition. Consistent with the analysis for EVs we impose the requirement that an HEV must have a continuous power capability of 30 kW/ton of vehicle and payload weight. This sets a lower limit on engine size. Peak-power requirement is 50 kW/ton of vehicle and payload, which permits a zero to 60 mph time of about 12 seconds, so that the batteries must supply the (50-30) kW/ton for peak accelerations. Calculations are performed to show that operating the engine at its single "best efficiency" point at all times is not an optimal solution.

Given these specifications, it is easy to solve for the weight of the vehicle given M_{Bz}, the zero engine body weight. Using the mid-size vehicle as the example, with an M_{Bz} of 750kg and a payload weight of 200 kg, we have the following HEV characteristics, derived from the equations shown in table A-4:

Vehicle curb weight	1843 kg
Engine output (nominal)	61.3 kW
Battery peak output	40.9 kW
Battery weight	136.2 kg
Battery type	Semi-bipolar lead acid, 300 w/kg

The engine must be a 3.3L four-valve valve engine that can be rated 155 kw at its normal peak. The amazing result is that the engine must actually be more powerful than that of the current Taurus. The reason of course, is that the engine of the current Taurus already operates near the maximum efficiency point at an output of 30 kW/ton. Hence, if the engine of the HEV is sized in the same proportion it must be larger to provide the increased power to overcome the weight associated with the motor, battery, electrical system, and generator, which adds 360 kg to the weight.

This is only one of the unattractive aspects of limiting engine operation to only one output level. Another factor is that on the FTP city cycle, the engine operates for a very brief duration. The 23-minute cycle requires about 2.3 kwh of energy at the motor to cover the cycle, which means that the engine needs to run 2.3/(61.3 x 0.8) percent of the cycle time (where 61.3 x 0.8 is the electrical output of the engine ***in*** kW stored and retrieved from the battery), or about 1.1 minutes, and be shut off the rest of the time. Hence, cold-start fuel consumption will add a significant penalty to total fuel consumption. The battery is capable of storing 5.7 kWh, and the vehicle can be run as a reduced performance EV over the entire FTP cycle, if it starts with the battery fully charged.

A less restrictive scenario could allow the engine to operate at much higher peak ratings, if the control logic determines that the load is not a transient one. For example, if high peak-loads persist for more than 20 or 30 seconds, the control logic can allow the ICE to provide more power rapidly (albeit with much lower efficiency), so that the batteries are not taxed too heavily. In addition the engine can provide a range of horsepower, if efficiency is allowed to decline to within 10 percent of the maximum. Such an operating strategy does not require as much power to be available from the battery with attendant charge/discharge losses, so that the 10 percent efficiency loss in the ICE is compensated by a 20 percent gain (for example) in avoiding the charge/discharge loss.

These requirements could be achieved by a smaller engine that is capable of providing the peak-power requirement at its normal maximum RPM. Such an engine would weigh 2.3 kg/kW, and assuming the generator weighs 1.0 kg/kW, we find the value of C_2 increases to 285 W/kg (i.e. 1/(2.3+1)). However, the batteries must now be able to provide more power for short duration accelerations when the engine is still providing only 140 W/kg. Again, solving for vehicle weight for the same Taurus example, we have the following HEV specification:

Vehicle curb weight		1385 kg
Engine peak output		44.7 kW
	Continuous output	19.0 kW
Engine + generator weight		167 kg
Battery:	Peak output	59.1 kW
	Energy stored	8.3 kWh
	Weight	197 kg
	Type	Semi-bipolar lead acid
Motor:	output	79.3 kW
	Weight	80 kg

Here, the solution is far more reasonable, as an engine of 44.7 kW peak rating, with a displacement of 1.0 litre would be all that is required. The total weight of this type of system is very similar to the current intermediate size car. On the urban cycle, the engine would be on 28 percent of the time, and shut off for the rest of the cycle. On the highway cycle, the engine is on for 62 percent of the time, and the engine would be operating continuously at speeds above 70 mph cruise on level ground. This is favorable for fuel efficiency as the engine would be operating at or near its optimal bsfc point, and energy can flow directly from generator to motor without going through the battery.

Efficiency calculations shown are not as detailed as those that would be obtained from a simulation model, but a reasonably accurate picture can be established using the equations presented earlier in this section. The major assumption here is that the engine can be operated at close to optimal bsfc (but run occasionally at higher output when it is needed for high accelerations or prolonged periods of hill climbing or other high vehicle loads), or else be turned off. Using the details provided in table A-1, one can compute the following fuel consumption reduction. First, as there is no idling, the 16 percent of fuel consumed on the city cycle and 2.0 percent on the highway cycle is saved. Second, accessory power demand is not likely to be reduced in a hybrid, because an engine running at or near its optimal bsfc point rejects much more heat to the coolant, and, hence, cooling fan and water-pump requirements will increase, but the engine itself is much smaller. Accessory fuel consumption will be reduced by the improvement in bsfc or efficiency. Third, the use of regenerative braking will reduce tractive energy requirements by an amount similar to that for an EV, but the smaller battery (relative to an EV) may not be able to absorb the power spikes as efficiently. Fourth the use of an electric motor drive eliminates the transmission and improves drivetrain efficiency. Finally, by operating at or near its optimal efficiency point, the engine bsfc is greatly reduced.

On the negative side, a small engine (with smaller cylinders) is inherently less efficient owing to the higher surface/volume ratios of its combustion chamber. In the Taurus example, the engine would be a 1.0 litre four-valve four-cylinder engine, rather than the 3. O-litre two-valve V-6 currently used. Although some have discussed using one-or two cylinder engines, the noise and vibration characteristics of such engines are so poor that only a four-cylinder engine is thought to be acceptable in a midsize car (Even the three-cylinder Geo Metro engine is considered quite rough in automotive circles). Hence, peak efficiency is sacrificed by 2 percent to 3 percent relative to a 2.0 litre four-cylinder or 3.0 litre six-cylinder engine. The generator also must be sized for peak continuous output of 45 kW, while operating at a nominal output of 19 kW, which makes it heavier and less efficient under the standard operating mode.

Detailed analysis of the efficiency without a comprehensive simulation model requires some assumptions regarding average generator and motor efficiency. For a “2005 best” calculation, the assumptions are as follows:

• Generator efficiency:	at 19.0 kw	91 percent
	at 45 kw	94 percent
. Motor Efficiency:	Urban cycle	82 percent
	Highway cycle	90 percent
. Drivetrain gear efficiency:	Urban	94 percent
	Highway	96 percent

The motor and generator efficiency values are 3 to 4 percent higher than those of the “best” current motor/generators.

Engine efficiency was assumed at a slightly off-peak value of 33 percent (in reality, this is higher than the peak efficiency of small engines today). A cold-start related fuel economy loss of 5 percent was also used on the urban cycle. A sample calculation is shown in table A-5; the calculations assumes the 1995 mid-size car body and a 1995 “prototype” battery and motor/generator with the 2005 production component efficiencies detailed above. Urban fuel economy for the HEV “Taurus” is computed to be 32.74 mpg, and highway fuel economy is 41.2 mpg, yielding a composite fuel economy of 36.07 mpg, about 30 percent better than the current Taurus. Most of the improvement is in the urban cycle, with only a small (8.4 percent) improvement on the highway cycle.

The 30 percent value is an optimistic number for current technology, since every ***one*** of the components have been selected to be at the 2005 expected values, which are higher than the actual observed range. It also assumes the availability of a semi-bipolar battery that can produce high peak power for acceleration. It is easy to see that in the absence of such high peak-power capability, fuel economy drops precipitously. If a normal lead acid battery with a peak-power capability of 125 W/kg is used, composite fuel economy is only 24.5 mpg, which is almost 12 percent lower than the conventional Taurus! These findings are in good agreement with the observed fuel efficiency of some HEVS with conventional lead acid batteries. As noted, both Nissan and BMW reported lower fuel economy for their series hybrid vehicles, even though they used nickel cadmium batteries with specific peak power of 125 to 150 W/kg.

TABLE A-1 (a): Energy Consumption as a Percent of Total Energy Requirements for a Mid-size Car

	Percentage of total tractive energy		
	City	**Highway**	**Composite**[a]
Rolling resistance	**27.7**	**35.2**	30.5
Aerodynamic drag	18.0	50.4	29.9
Inertia (weight) force	54.3	14.4	39.6
Total	100	100	100
	Percentage of total fuel consumed		
Tractive energy	**58.5**	**81.5**	**66.6**
Accessory energy	11.0	7.0	9.6
Idle + braking consumption	16.0	2.0	10.7
Transmission + driveline loss	14.5	9.5	12.9

[a]Assumes that highway fuel economy = 1.5 X city fuel economy.

NOTE: Mid-size car of inertia weight= 1588 kg, CD= 0.33, A = 2.1 m^2,CR=0.011, 3L OHV V-6, power steering, four-speed automatic transmission with lockup, air conditioning.

SOURCE: Derived from G. Sovran and M. Bohn, “Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedules,” SAE paper 810184, 1981.

TABLE A-1 (b): Energy Consumption for a Mid-size Car
Consumption in kWh/mile

	City	Highway	Composite
Tractive energy requirement	0.2064	0.1974	0.2024
Transmission loss	0.0336	0.0160	0.0257
Accessory energy	0.0314	0.0164	0.0247
Total energy required	0.2714	0.2298	0.2528
Total fuel energy used	1.2146	0.8469	1.0490
Idle and braking loss	0.2314	0.0173	0.1348
Total fuel used	1.4460 (22.7 mpg*)	0.8642 (38.0 mpg*)	1.1838 (27.72mpg*)
Engine efficiency (w/idle)	22.34% 18.77%	27.13% 26.59%	24.10% 21.35%

*Fuel lower heating value of 32.8 kWh/gallon.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 10-6.

TABLE A-2: Specifications of Some Advanced Electric Vehicles

Vehicle type	Total weight (kg)	Motor output peak (hp)	Fuel consumption (kWh/km)	P (hplkg)	E (Wh/kg-km)
GM Impact	1,348	137	0.115	0.091	0.086
Cocconi Honda CRX	1,225	120	0,103	0.087	0.084
BMW E-1	880	45	0.133	0.044	0.151
Chrysler Van	2,340	70	0.300	0.028	0.128
Ford Ecostar	1,405	75	0.188	0.040	0.134
Honda CUV4	1,680	66	0.155	0.036	0.093

KEY: P = performance rating of vehicle + payload; E = specific efficiency of vehicle.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economyto 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-39. Compiled from manufacturer brochures; Cocconi data from California Air Resource Board tests.

TABLE A-3: Engine and Accessory Weights (lbs)

	Ford Taurus 3.OL	Toyota Corolla 1.5L
Base engine	444	264
Accessories[a]	*34*	*26*
Electrical system[b]	*38*	*27*
Emission controls	30	incl.
Exhaust system	*33*	*33*
Catalyst	30	**24**
Total	609 lbs (276 kg)	374 lbs (170 kg)
output	105 kW	78 kW
Specific output	0.3 kWlkg	0.460 kW/kg
Specific weight	2.63 kg/kW	2.17 kg/kW

[a]Includes radiator, water pump, hoses, coolant.
[b]Includes starter, alternator and ignition system

SOURCE: American Automobile Manufacturers Association, 1994.

TABLE A-4: Equations for Deriving HEV Weight

1) Engine operates at optimal bsfc only.

$$M_{HEV} + \text{Payload} = M_{Bz} + \text{Payload} + 1.4\ M_{BATT} + 1.4 M_{MOTOR} + 1.4 M_{EG}$$

$$\text{Peak Performance} = (S_P \cdot M_{BATT} + C \cdot M_{EG})/(M_{HEV} + \text{Payload})$$

$$\text{Maximum Continuous Performance} = C \cdot M_{EG}/(M_{HEV} + \text{Payload})$$

If peak-power requirements are *50* kW/ton and the continuous requirement is 30 kW/ton, we have:

$$\frac{M_{Bz} + \text{Payload}}{M_{HEV} + \text{Payload}} = 1 - \frac{1.4 * 30}{C_1} - \frac{1.4 * (50-30)}{S_P} - \frac{1.4 * 50}{K}$$

2) If the engine normally operates at or near optimal bsfc but can produce higher power output for a continuous requirement, such as hill climb, we have:

$$\text{Maximum Continuous Performance} = C_2\ M_{EG}/(M_{HEV} + \text{Payload})$$

$$\frac{M_{Bz} + \text{Payload}}{M_{HEV} + \text{Payload}} = 1 - \frac{1.4 * 30}{C_2} - \frac{1.4 * (50 - 30 * C_1/C_2)}{S_P} - \frac{1.4 * 50}{K}$$

where M_{HEV}	=	weight of hybrid electric vehicle
M_{Bz}	=	"zero engine" body weight
M_{BATT}	=	weight of battery
M_{MOTOR}	=	weight of motor
M_{EG}	=	weight of ICE + generator
C or C_1	=	continuous specific output of engine + generator, kW/ton
K	=	specific output of motor, low/ton
C_2	=	peak specific output engine + generator, kW/ton
S_P	=	peak specific power of battery, kW/ton

Note: Typical values used are S_P = 300 kW/ton,
K = 1000 kW/ton, C_1 = 125 kW/ton, C2 = 285 kW/ton

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 10-60.

TABLE A-5: Energy Use for a Current (1995) Mid-size Car Converted to an HEV (kWh)

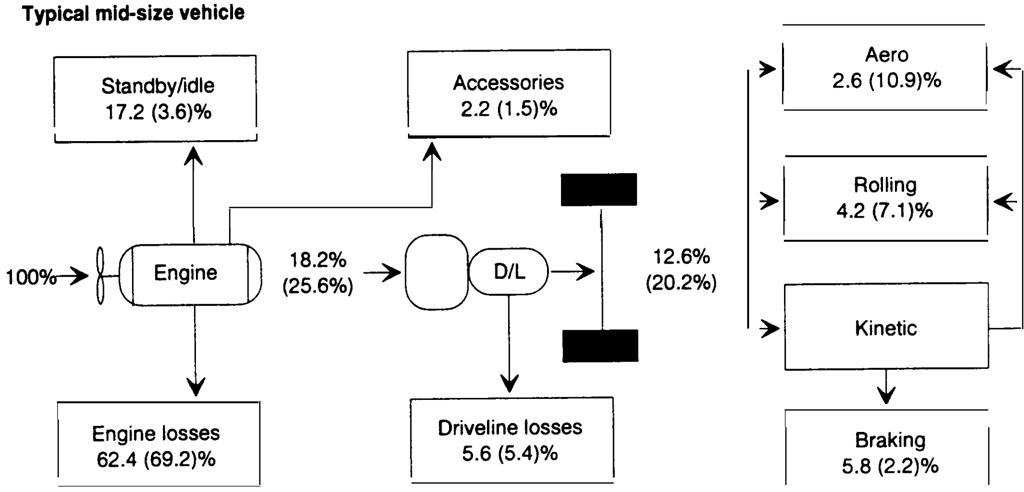
	Urban	Highway
Tractive energy	0.201	**0.184**
Motor output	0.214	**0.192**
Regenerative braking recovery	0.045	**0.008**
Tractive energy input	0.216	**0.205**
Engine output[a]	0.315	**0.263**
Fuel economy, mpg	32.7	**41.2**
Percent improvement over 1995 base	44.1	**8.4**

[a]Assumes batteries recharged to initial state at end Of Cycle. Analysis assumes highly optimized electrical drivetrain components.

SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies To Improve Fuel Economy to 2015," report prepared for the Office of Technology Assessment, June 1995, p. 1O-64.

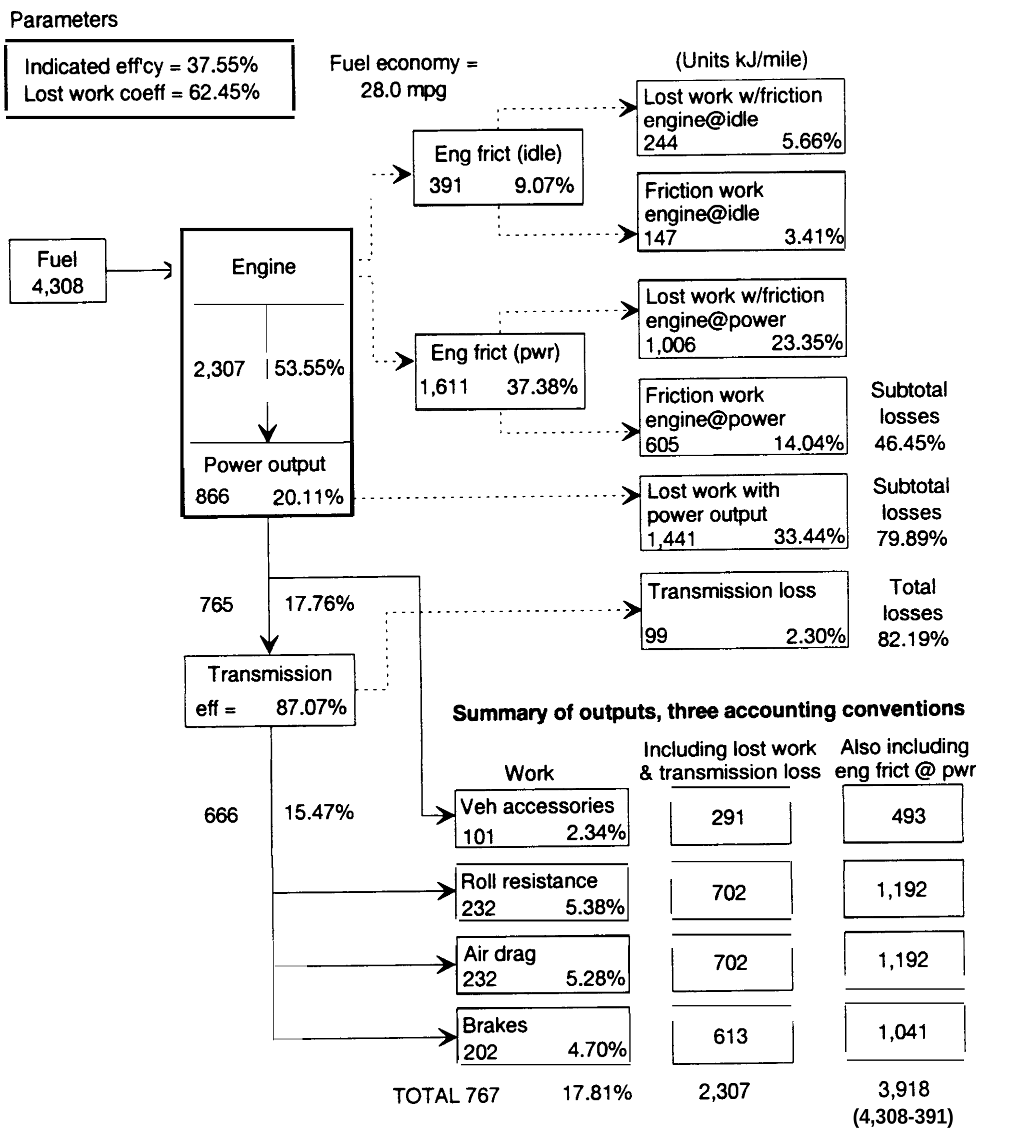
Figure A-1: Energy Distribution

Typical mid-size vehicle



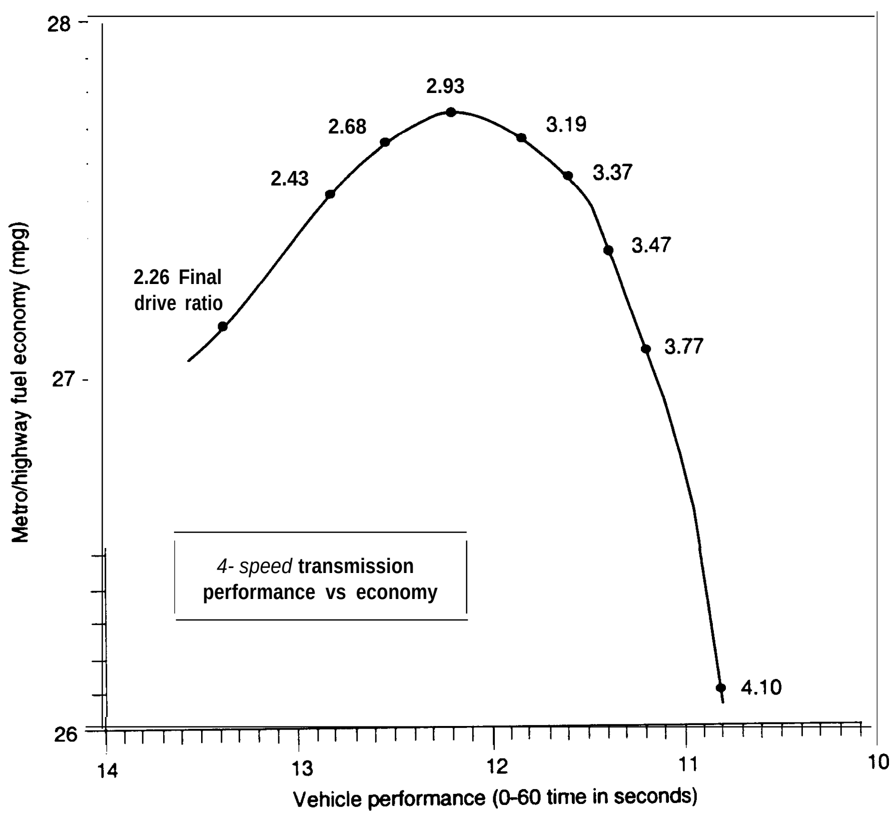
NOTE: Numbers indicate urban energy distribution. Numbers in parentheses indicate highway energy distribution.
SOURCE: Partnership for a New Generation of Vehicles.

Figure A-2: Energy Flows, AVCAR '93, EPA Composite Cycle



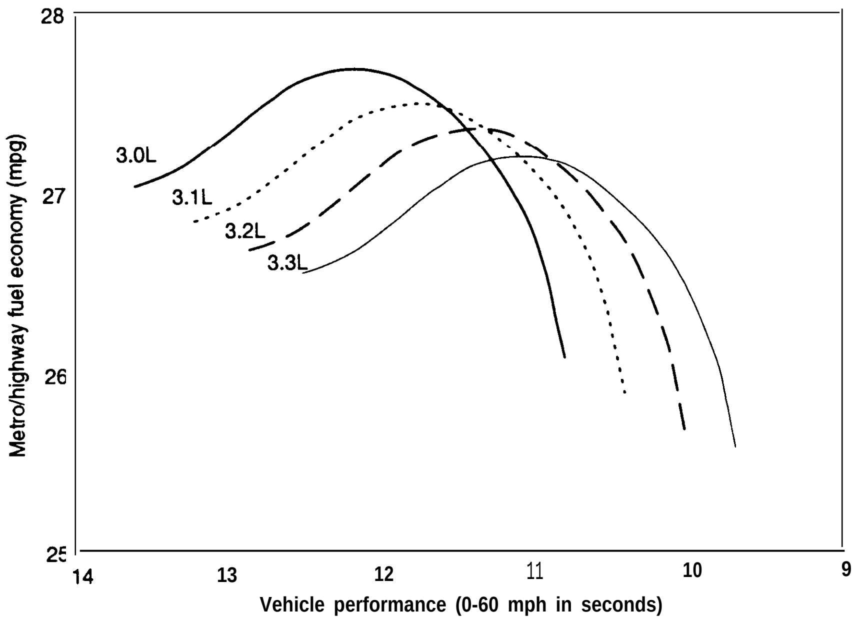
SOURCE: M. Ross and W. Wu, "Fuel Economy of a Hybrid Car Based on a Buffered Fuel-Engine Operating at its Optimal Point," SAE paper 95000,1995.

Figure A-3: Vehicle Performance vs. Fuel Economy



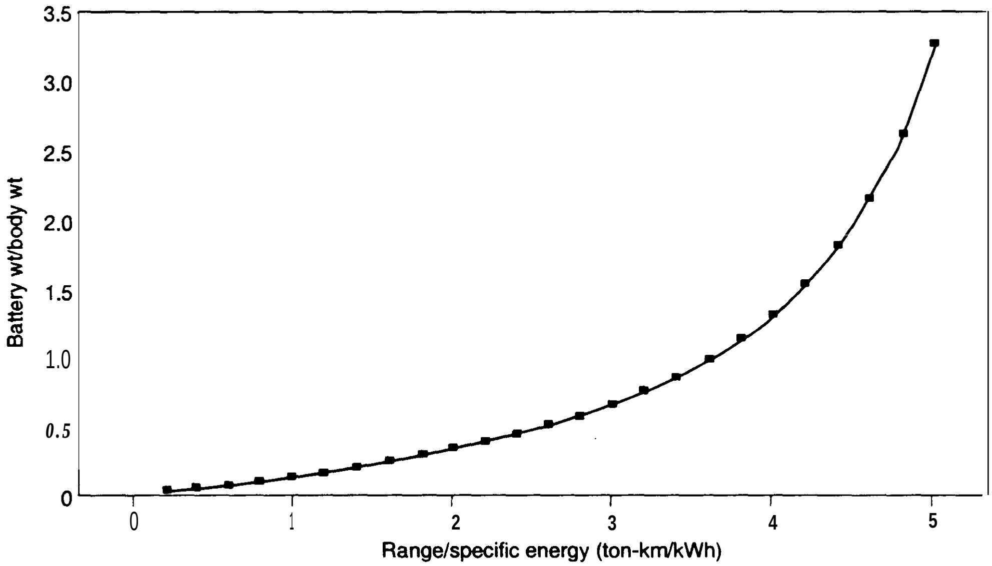
SOURCE: Ford Motor Co.

Figure A-4: Fuel Economy vs Performance (effect of displacement on best fuel economy)



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 201 5," prepared for the Office of Technology Assessment, June 1995, pp 10-13.

Figure A-5: Battery Weight vs EV Range



SOURCE: Energy and Environmental Analysis, Inc., "Automotive Technologies to Improve Fuel Economy to 2015," prepared for the Office of Technology Assessment, June 1995, p. 10-41.