ECEN2060 Course Notes

Hybrid and Electric Vehicles

Fall 2010

In 2005 there were almost 240 million vehicles (cars, buses and trucks) in the US. Transportation accounts for about one third of US energy consumption and about one third of U.S. carbon emissions. Almost 90% of energy for transportation comes from petroleum (gasoline 62%, diesel 24%). Corporate Average Fuel Economy (CAFE) regulations in the United States, enacted in 1975, set minimum fleet fuel economy standards for cars and light trucks. Figure 1 compares the CAFE standards to fuel economy standards around the world as of 2004. The Energy Bill of 2007 raised the US fuel economy standards to an average of at least 35 mpg by 2020.

The objectives of this section are to introduce hybrid electric, plug-in hybrid and all-electric vehicle technologies. A hybrid electric vehicle combines an internal combustion engine with an electrical drive to improve fuel economy. A recent analysis conducted at the U. S. Department of Energy's National Renewable Energy Laboratory (NREL), shows that the average fuel economy improvement for a hybrid electric vehicle (HEV) over the replaced conventional vehicle is approximately 45 percent. Topics include opportunities for efficiency improvements, HEV architectures, operation and models of system components, and cost issues.

Hybrid electric vehicles do not change the makeup of energy supply for transportation: just as conventional motor vehicles, HEVs are powered by petroleum, only more efficiently. In contrast, in addition to potentials for further efficiency improvements, plug-in HEVs (PHEVs) and all-electric vehicles (EVs) have potentials for more substantial changes in the overall energy flow by supplying energy for transportation at least in part from the electrical power grid. Briefly addressed are technical and economic challenges in plug-in HEVs and all-electric vehicles.

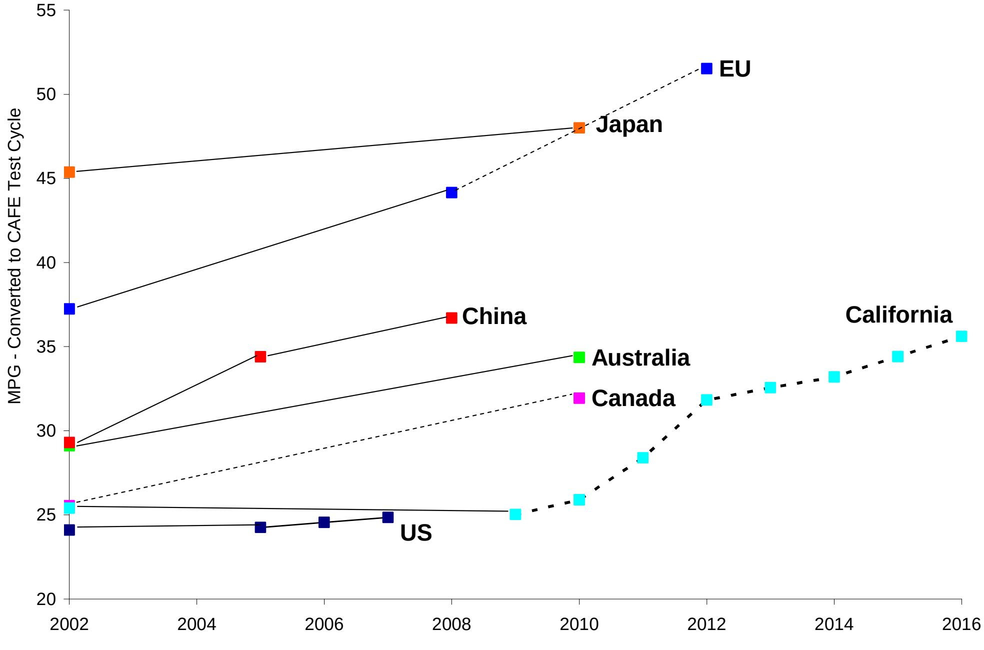

Figure 1. Comparison of fuel economy standards[1]

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[1] A. Sauer, Global Competitiveness in Fuel Economy and Greenhouse Gas Emission Standards for Vehicles, www.nrel.gov/analysis/seminar/docs/2005/ea_seminar_feb_10.ppt

Outline

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1. Vehicle Dynamics and Traction Power Requirements

Consider a vehicle accelerating up a road sloped at an angle α as shown in Fig. 1. The vehicle propulsion must generate a total force (i.e. "traction effort") F_v to overcome aerodynamic drag (F_d), rolling resistance (F_r) and gravity (F_g), and F_a to accelerate,

$$F_v = F_d + F_r + F_a + F_g = \frac{1}{2}\rho C_d A_v v^2 + f_{rr} M_v g \cos\alpha + M_v \frac{dv}{dt} + M_v g \sin\alpha \,, \qquad (1.1)$$

where:

ρ	air density = 1.204 kg/m^3 at 20^{o}C, 1 atm
C_d	aerodynamic drag coefficient
A_v	vehicle frontal surface area (in m^2)
v	vehicle speed (in m/s)
M_v	vehicle mass, i.e. weight (in kg)
g	gravity = 9.81 m/s^2
f_{rr}	rolling resistance coefficient, or coefficient of rolling friction, typically 0.01 for car tires on concrete or asphalt

$\sin\alpha \approx \tan\alpha = H/L$ = road grade Z (for small α)

$\cos\alpha \approx 1$ (for small α)

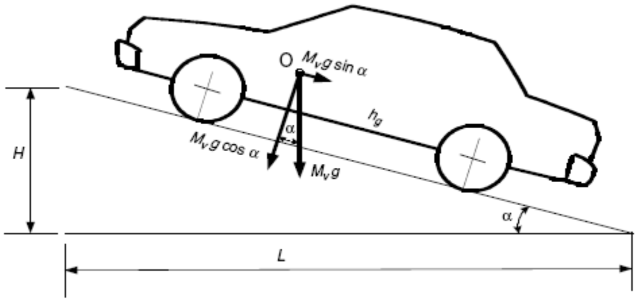

Figure 1: Vehicle ascending a road with grade $Z = H/L$.

The required traction power is

$$P_v = F_v v \approx \frac{1}{2}\rho C_d A_v v^3 + f_{rr} M_v g v + M_v v \frac{dv}{dt} + M_v g Z v \,. \qquad (1.2)$$

1.1 Traction drive characteristics

The required vehicle traction power can be generated by an internal combustion engine (ICE), an electric motor, or a combination of the two. Ideally, the maximum available traction power would be independent of vehicle speed. Examples of real ICE and electric motor capabilities are compared in Fig. 2.

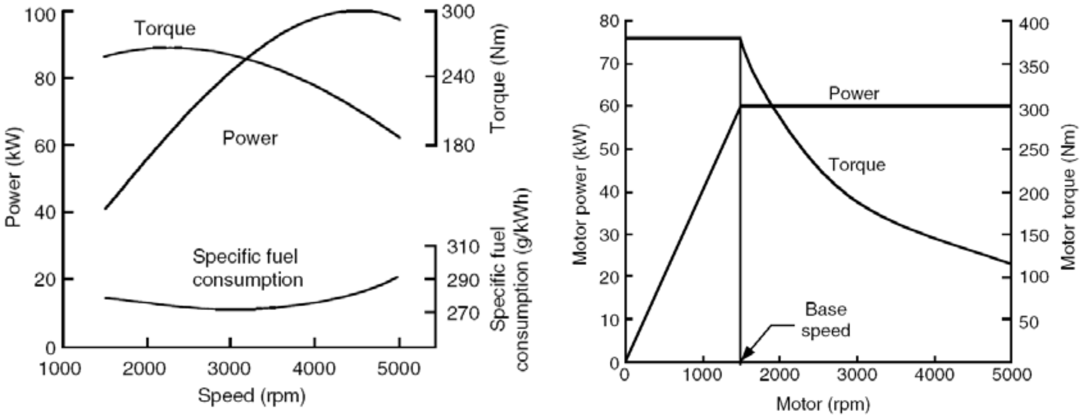

Figure 2: Examples of ICE (left) and electric (right) motor characteristics (Figs. 2.11 and 2.12 from [1])

The ICE power and torque as functions of speed are far from the ideal constant power characteristic. The engine cannot operate at speeds below a minimum (idle) speed. The available output power reaches a maximum at relatively high speed. In contrast, an electric motor can produce maximum torque starting from zero speed, and has the desirable constant power characteristic starting from a base speed v_b up to a maximum speed limit. To match the engine capabilities with the traction power requirements over a wide range of vehicle speeds, a conventional ICE driven vehicle must include a multi-gear transmission. In contrast, an electric vehicle can operate with a simpler, more efficient single-gear transmission.

Figure 3 shows how the required vehicle traction effort (i.e. force F_v) as a function vehicle speed v can be accomplished by the ICE having a 4-gear transmission and by an electric motor using a single-gear transmission.

1.2 Vehicle Performance Requirements

Vehicle performance requirements typically include:

- Acceleration, typically defined as the time t_a it takes to accelerate the vehicle from 0 to $v_f = 100$ km/h (0-60 mph) on a flat road ($Z = 0$)
- Top cruising speed v_{max}
- Gradeability, i.e., the road grade Z_{max} (in %) the vehicle is capable of ascending at a particular speed v_z

For a given set of performance requirements, Equation (1.2) and the vehicle characteristic of Fig. 3 can be used to estimate the required power rating P_{drive} of the vehicle traction drive (ICE or electric).

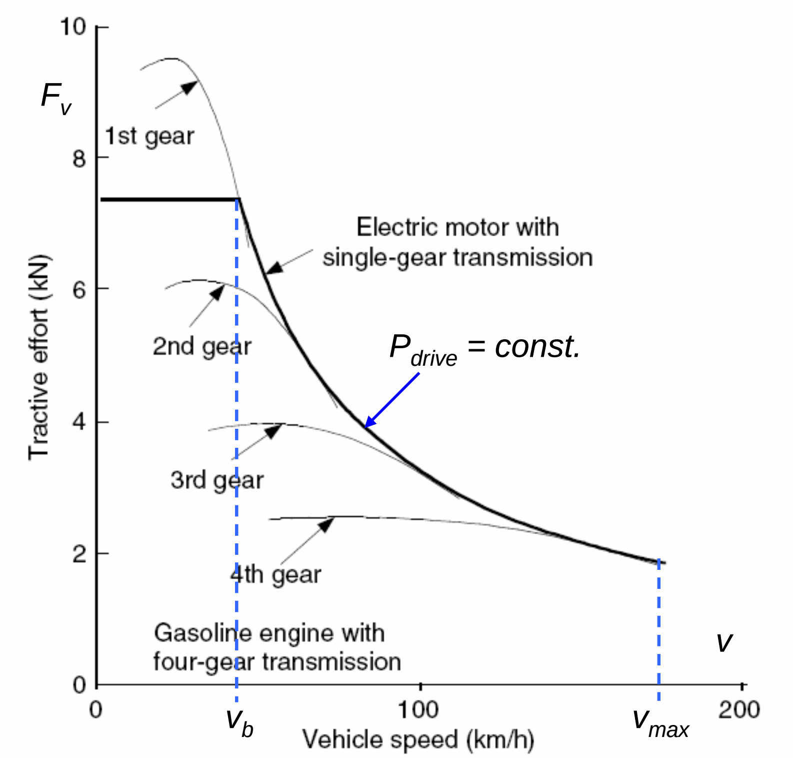

Figure 3 Vehicle traction characteristic using an ICE with 4-gear transmission or an electric motor with single-gear transmission (Fig.2.17 from [1]).

In most cases, acceleration is the most demanding requirement. The goal is to find P_{drive} so that the vehicle can accelerate from $v = 0$ to $v = v_f$ (100 km/h) in t_a seconds on a flat road, $Z = 0$. From (1.2), it follows that

$$M_v v \frac{dv}{dt} = P_v - \frac{1}{2}\rho C_d A_v v^3 - f_{rr} M_v g v \tag{1.3}$$

$$dt = \frac{M_v v}{P_v - \frac{1}{2}\rho C_d A_v v^3 - f_{rr} M_v g v} dv \tag{1.4}$$

where, according to the characteristic in Fig. 3,

$$P_v = \begin{cases} P_{drive}\dfrac{v}{v_b}, & \text{for } 0 \le v \le v_b \\ P_{drive}, & \text{for } v_b < v \le v_f \end{cases} \tag{1.5}$$

Note that (1.5) is based on the electric drive capability, while it approximates the ICE capability with multi-gear transmission. Using (1.5), integration of (1.4) from $t = 0$ to $t = t_a$ yields the acceleration time as a function of P_{drive}:

$$t_a = \int_0^{v_b} \frac{M_v v_b}{P_{drive} - \frac{1}{2}\rho C_d A_v v_b v^2 - f_{rr} M_v g v_b} dv + \int_{v_b}^{v_f} \frac{M_v v}{P_{drive} - \frac{1}{2}\rho C_d A_v v^3 - f_{rr} M_v g v} dv \qquad (1.6)$$

Form (1.6), assuming that in the range of speeds from 0 to v_f the power required to overcome rolling resistance and drag is relatively small, an approximate result for the required traction power rating P_{drive} as a function of acceleration time has been found in [1]:

$$P_{drive} \approx \frac{M_v v_f^2}{2t_a}\left(1 + \frac{1}{x_f^2}\right) + \frac{1}{5}\rho C_d A_v v_f^3 + \frac{2}{3} f_{rr} M_v g v_f \qquad (1.7)$$

where $x_f = v_f/v_b$.

To find the required power rating $P_{t\max}$ of a car engine or of an electric motor providing the traction power, the transmission efficiency η_t should also be taken into account,

$$P_{t\max} = \frac{P_{drive}}{\eta_{tran}} \qquad (1.8)$$

***Example* 1.1**: find the required drive train power

Consider a vehicle having approximately the size of Toyota Prius: total weight $M_v = 1500$ kg, front area $A_v = 2.16\ \mathrm{m}^2$, aerodynamic drag coefficient $C_d = 0.26$, and tire rolling resistance $f_{rr} = 0.01$. Find the required drive train power rating P_{tmax} using a motor with $x_f = 3$, and a single-gear transmission with $\eta_t = 0.9$. The acceleration performance objective is to reach $v_f = 100$ km/h in $t_a = 11$ s.

From (1.7) and (1.8),

$$P_{t\max} = \frac{1}{0.9}\left(58.4 + 2.9 + 2.7\right) = 71.2\ \mathrm{kW} \text{ or 95 hp} \qquad (1.9)$$

2. Opportunities for improvements in efficiency and fuel economy

Before discussing hybrid electric vehicles, it is instructive to examine fuel economy limitations of conventional vehicles powered by petroleum fuels using conventional internal combustion engines.

2.1. Ideal Gasoline Powered Vehicle

Based on the basic vehicle dynamics and power requirements found in Section 1, it is of interest to find limits of fuel economy for an ideal vehicle capable of converting energy stored in gasoline into traction power with 100% efficiency.

Energy density of regular gasoline is about 45.7 MJ/kg, which equals 12.7 kWh/kg. The volumetric energy density of regular gasoline is about 34.6 MJ/l, which equals 131 MJ/gallon, or 36.4 kWh/gallon. Both mass and volumetric densities of gasoline are relatively high. One may note, for example, that the energy density of lead acid batteries is less than 0.1 kWh/kg, or more than 100 times lower than the gasoline energy density.

Consider the case when a vehicle runs at constant cruising speed v on a flat surface, $dv/dt = 0$, $Z = 0$. Over a period of time t_{trip}, the trip distance is $l_{trip} = v\, t_{trip}$, and the total energy required is $E_{trip} = P_v\, t_{trip}$, where the required traction power P_v is given by (1.2) Therefore, the trip distance per unit energy is

$$\frac{l_{trip}}{E_{trip}} = \frac{v}{P_v} = \frac{1}{\frac{1}{2}\rho C_d A_v v^2 + f_{rr} M_v g} \quad \text{[m/J]}, \tag{2.1}$$

Result (2.1) can be used to compute the ideal vehicle fuel economy in miles per gallon (mpg) assuming 100% energy conversion efficiency.

***Example* 2.1**: ideal fuel economy at constant cruising speed

Consider the vehicle of Example 1.1 and assume that it is cruising at constant speed, $v = 60$ mph.

From (1.2), $P_v = 10.5$ kW. Note that the cruising traction power is much lower than the required power rating found in Example 1.1 based on the acceleration performance. From (2.1), it follows that the vehicle runs at 9.2 km/kWh. It requires about 0.1 kWh of energy per kilometer. Given the volumetric energy density of gasoline, 36.4 kWh/gallon, and assuming ideal 100% energy conversion, this corresponds to a fuel economy of (9.2 km/kWh * 36.4 kWh/gallon * 0.62 miles/km) = 208 mpg.

Example 2.1 is based on completely unrealistic assumptions of 100% efficiency and constant cruising speed. A slightly more realistic scenario is to redo Example 2.1 considering one of the standard driving cycles used to evaluate vehicle fuel economy. A driving cycle prescribes vehicle speed v as a function of time over a certain period. For example, Fig. 2.1 shows the vehicle speed v in the EPA US06 driving cycle. Notice that the vehicle accelerates to various relatively high speeds and comes back to standstill several times. The average speed for US06 is $v_{avg} = 77$ km/h or 48 mph. The total length of the trip is $t_{trip} = 10$ minutes, and distance is $l_{trip} = 8$ miles.

For the vehicle in Examples 1.1 and 2.1, Fig. 2.1 shows the vehicle speed v, and the traction power P_v as functions of time. Notice that the traction power is negative in portions of the cycle when the vehicle is decelerating. In a conventional vehicle, the excess kinetic energy must be dissipated by brakes. An ideal vehicle would be able to absorb and reuse with 100% efficiency the energy during deceleration, which is called *regenerative braking*.

Suppose first that the ideal vehicle is capable of ideal regenerative braking. The average traction power in the US06 cycle for the vehicle of Example 1.1. is then only $(P_v)_{avg}$ = 7 kW, and the ideal vehicle would have a fuel economy of 250 mpg. The ideal vehicle would require 146 Wh/mile, or 90 Wh/km. It is also worth noting that the average traction power $(P_v)_{avg}$ is much less than the maximum required traction power $(P_v)_{max}$ = 71.5 kW for the considered test vehicle in the US06 cycle.

To illustrate the potential of regenerative braking, suppose that the vehicle is ideally efficient in converting fuel to traction power for $P_v > 0$, but is not capable of regenerative braking and must dissipate $P_v < 0$ conventionally (by brakes). In this case, the average traction power for the considered ideal test vehicle in US06 is 11.3 kW, and the fuel economy drops to 158 mpg.

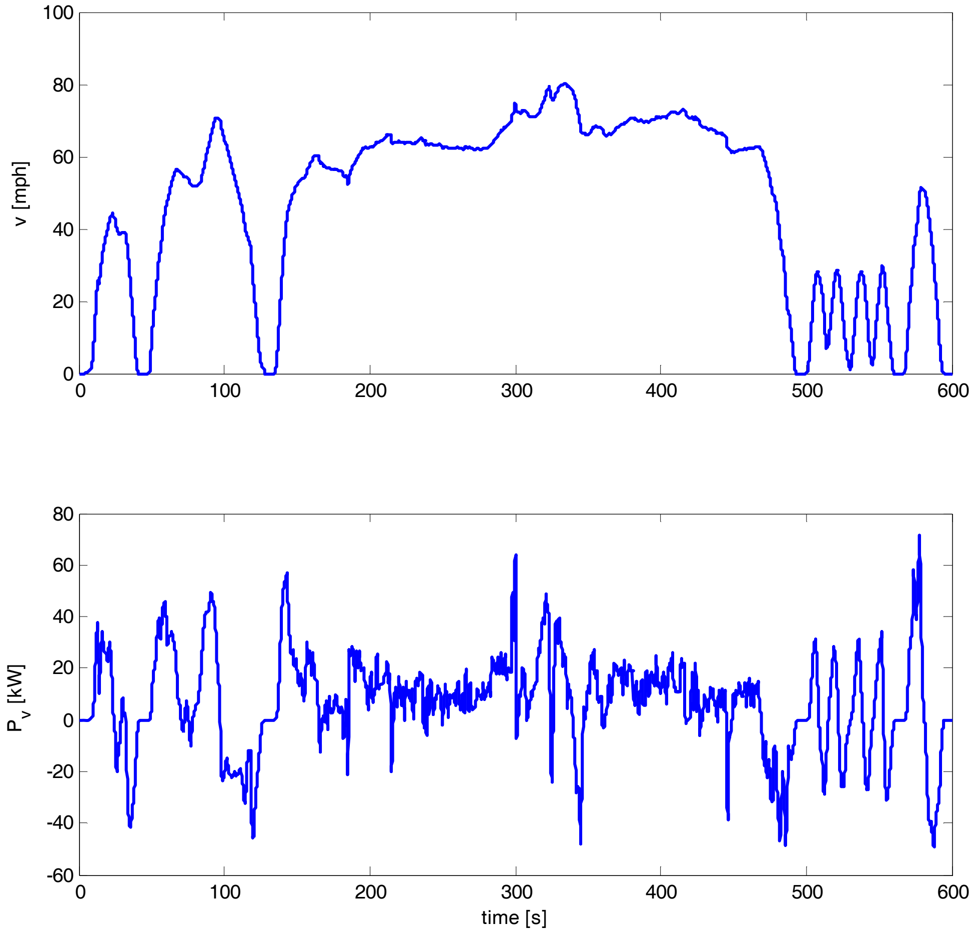

Figure 2.1 Vehicle speed v and traction power P_v for the test vehicle of Example 2.1 in the US06 drive cycle.

2.2. Efficiency of Internal Combustion Engines

The main limitation to the fuel economy of conventional petroleum powered vehicles is the relatively low efficiency of the internal combustion engine ICE. ICE is a heat engine, converting chemical energy into heat and then into mechanical energy, which means that its best possible efficiency is fundamentally limited by the Carnot efficiency. Figure 2.2 shows typical ICE efficiency maps, i.e. contour plots of the engine efficiency in the torque versus speed or power versus speed plots. One can observe that the best possible efficiency of about 34% is obtained for an intermediate speed and for an output torque close to the maximum.

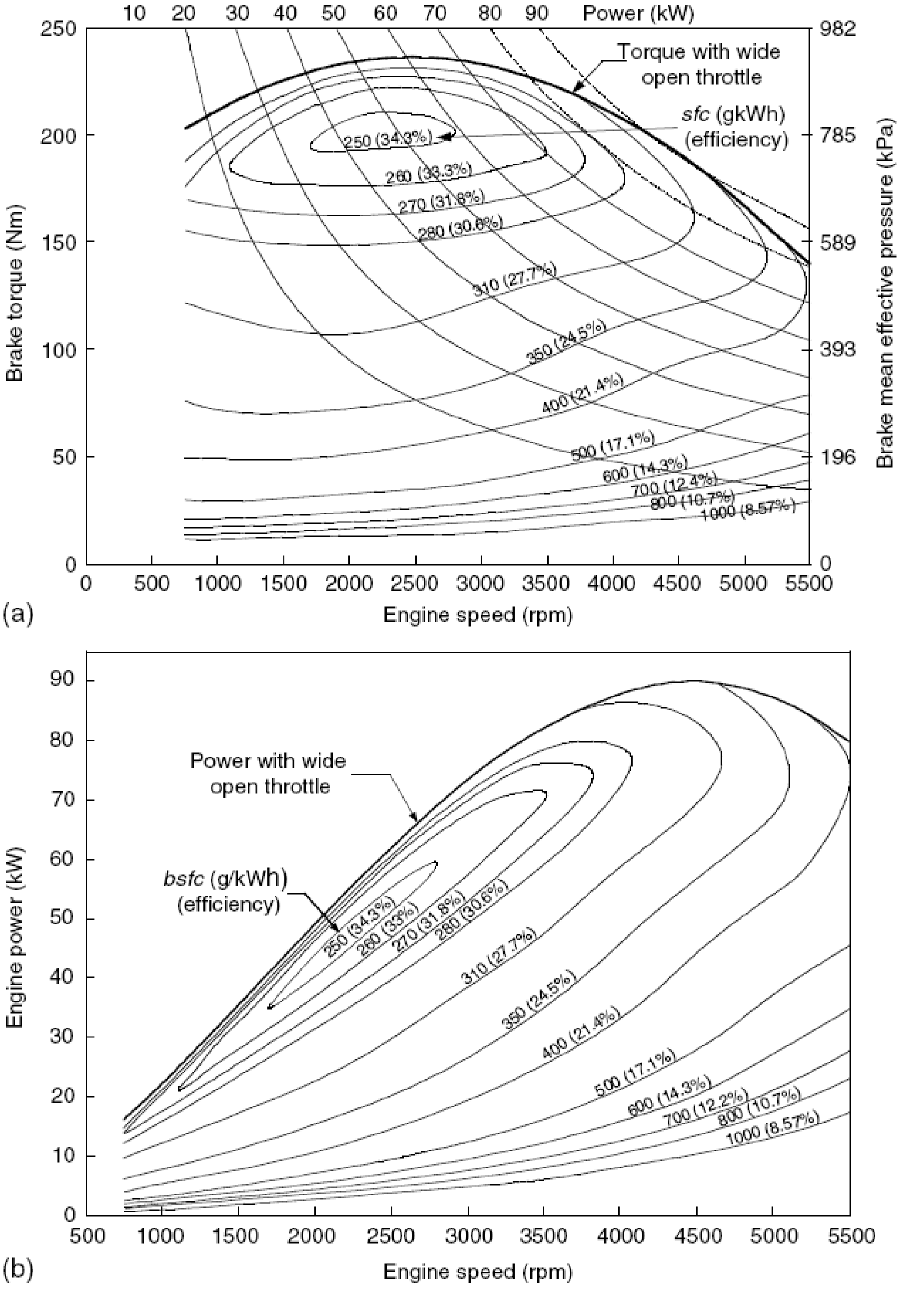

Figure 2.2 Efficiency maps for a typical ICE (Figure 3.6 from [1]).

When the engine operates under varying speed, torque and power conditions, as is always the case, the engine spends most of the time at speed/torque operating points where the efficiency is much lower than the maximum. In the examples of Section 2.1, it was found that the average traction power under realistic conditions is much lower than the maximum required power (e.g. in the US06 drive cycle), or the required power rating based on the acceleration performance. Furthermore, the vehicle efficiency is degraded by the transmission efficiency and other losses.

In a relatively modestly sized conventional car (such as the test case in Examples 1.1 and 2.1), the average ICE efficiency would typically be between 10% and 20% depending on the driving cycle (urban or highway). Assuming 15% efficiency for the US06 cycle, and no regenerative braking capabilities, a realistic value of 0.15*158 mpg = 24 mpg is obtained.

2.3 Opportunities for efficiency improvements in hybrid electric vehicles

Based on the discussion in Sections 2.1 and 2.2, drive trains in hybrid electric vehicles have been developed to take advantage of the following opportunities for efficiency improvements:

- Maximum required traction power is significantly higher than the average required traction power under realistic driving conditions. In a hybrid electric vehicle the power rating of the internal combustion engine can be reduced to a value closer to the average traction power, without compromising the vehicle performance. A reduced size ICE results in reduced fuel consumption and improved fuel economy.
- In a hybrid electric vehicle, it is possible to operate ICE closer to its maximum efficiency most of the time. This results in improved average ICE efficiency and improved fuel economy.
- Hybrid electric vehicles include rechargeable batteries, which enables regenerative braking and leads to further efficiency and fuel economy improvements.
- In a hybrid electric vehicle, ICE can be turned on and off under system control at (almost) any time, thus eliminating losses due to idling, which reduces fuel consumption further, especially under urban driving conditions.

The objectives are to explain how these efficiency improvement opportunities can be accomplished by addressing the following topics: (1) architectures of hybrid electric vehicles, (2) realization of electrical drive components including electrical motor/generators and power electronics, (3) energy storage and battery technologies, and (4) system controls.

Operation, components, and control aspects will first be introduced on a relatively simple example of the series hybrid electric drive train.

Reference

[1] M. Ehsani, Y. Gao, S. E. Gay, A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design, CRC Press, 2004. The book is available electronically (from University of Colorado network) at:
http://www.engnetbase.com/books/4675/3154fm.pdf