Module 12: Design of Hybrid Electric vehicles

Lecture 40: Design of HEVs A Primer

Design of HEVs A Primer

In this lecture following topics are covered:

- Power and Mass Computations for Initial Vehicle Sizing
- Power Requirements
- Acceleration Power
- Grade-Climbing Power
- Vehicle Mass
- Component Sizing

Power and Mass Computations for Initial Vehicle Sizing

Hybrid electric vehicles (HEVs) are expected to meet two performance criteria in order to compete successfully with conventional vehicles. The first criterion is the time required to accelerate from zero to 60 mph. The vehicles must also be able to negotiate a minimum grade at a constant speed. Argonne developed a model to compute power requirements associated with these criteria. Each drivetrain component is sized to meet the power requirements and its mass is then computed. The model is described in this section.

Power Requirements

The procedure presented here estimates power requirements for accelerating on a flat road (no grade) and negotiating a grade represented by an angle θ at a constant speed. We assume that the air is still and vehicles are not required to accelerate from a stop to the maximum speed up a hill or a ramp.

Acceleration Power

A hybrid vehicle that has an inertia mass of M_v and is accelerating on a flat road (i.e., 0° grade) would require a power P_a specified by the following equation.

$$P_a = M_v v \frac{dv}{dt} + \frac{1}{2}\rho A C_d v^3 + M_v g v C_r \tag{1}$$

where

v = Vehicle speed,

ρ = Air density,

A = Vehicle frontal area,

C_d = Coefficient of aerodynamic drag,

g = Gravity, and

C_r = Coefficient of rolling resistance.

The power in equation 1 is at the wheels. After the acceleration power is determined, the drivetrain components would be sized to allow for losses at various levels. Since the vehicle is accelerating from a stop to a maximum speed v_m, the acceleration power requirements in equation 1 can be restated by integrating the first term from zero to v_m.

$$P_a = \frac{M_v}{t_m}\left\{\frac{1}{2}v_m^3 + C_r g \int_0^{t_m} v\,dt\right\} + \frac{\rho A C_d}{2t_m}\int_0^{t_m} v^3 dt \tag{2}$$

where,

t_m is the time taken to reach the maximum speed. The speed v in equation 2 is a function of time t. Under conditions involving a smooth acceleration, the speed and time relationship can be plotted as shown in Figure 1. Assuming that the vehicle speed and time relationship is approximated by a hyperbolic function, speed v in equation 2 can be expressed as: x

$$V = Vm\left(\frac{t}{t_m}\right)^x \tag{3}$$

The exponent x in the above equation has a value in the range of 0.5-0.66 for zero to 60 mph acceleration (Z60) times of 8-13 seconds.

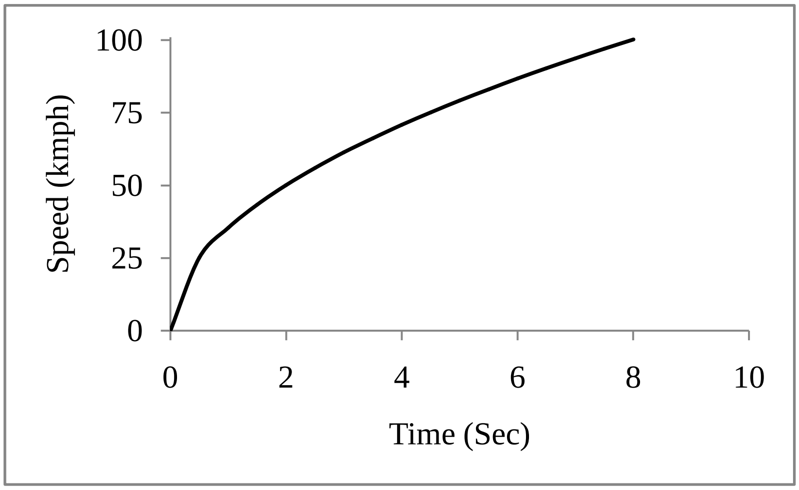


Figure 1 Vehicle Speed and Time Relationship during Acceleration [1].

Two approaches were explored for computing the acceleration power requirements: (i) by integrating equation 2, and (ii) by solving the power equation between time t_m and $t_m+0.1$. The first approach provides an average value for the acceleration power. The integrated equation 2 has two terms. The first term provides the power requirement for moving the vehicle mass and the second term provides the average power required for overcoming air resistance. The simplified equation for acceleration power P_a can be written as shown below.

$$P_a = a_1 M_v + b_1 \tag{4}$$

where

$$a_1 = \frac{V_m^2}{2t_m} + \frac{C_r g}{t_m}\int_0^{t_m} v\,dt = \frac{V_m^2}{2t_m} + \frac{1}{1+X} C_r g V_m \tag{5}$$

and

$$b_1 = \frac{\rho A C_d}{2t_m}\int_0^{t_m} V^3 dt = \frac{1}{2(1+2X)} \rho A C_d V_m^3 \tag{6}$$

Equation 4 shows that the acceleration power has two parts: one is linear to vehicle mass and the other is a constant that depends on vehicle design. The term “a_1” is a function of acceleration specifications (i.e., maximum speed and time to reach it) and rolling resistance. The term “b_1” represents power required to overcome the aerodynamic drag and is a function of drag coefficient and frontal area. The aerodynamic power requirement does not depend on vehicle mass.

The second approach provides an estimate of passing power requirement at the maximum speed v_m. Since the vehicle accelerates for only 0.1 seconds, this estimate would be very close to the maximum power required to reach the target speed. This approach would provide a power value higher than the first approach.

Equation 2 is used for this approach. The value of v is v_m, here for aerodynamic drag and rolling resistance, the time range is t_m to $t_m+0.1$, and dt has a value of 0.1. The equation can be used in the following form.

$$P_a = M_v V_m \left[V_m \left(\frac{t_m + 0.1}{t_m} \right)^x - Vm \left(\frac{t_m}{t_m} \right)^x \right] \div 0.1 + \frac{1}{2} \rho A C_d V_m^3 + M_v g V_m C_r \tag{7}$$

$$= M_v \frac{V_m^2}{0.1} \left[\left(\frac{t_m + 0.1}{t_m} \right)^x - 1 \right] + \frac{1}{2} \rho A C_d V_m^3 + M_v g V_m C_r \tag{8}$$

This equation can be simplified in a form similar to that of equation 4:

$$P_a = aM_v + b \tag{9}$$

where

$$a = \frac{V_m^2}{0.1} \left[\left(\frac{t_m + 0.1}{t_m} \right)^x - 1 \right] + C_r g V_m \tag{10}$$

$$b = \frac{1}{2} \rho A C_d V_m^3 \tag{11}$$

Grade-Climbing Power

Power (P_g) required for negotiating a grade that is represented by angle θ at a constant speed v_g could be written as follows:

$$P_g = \frac{1}{2}\rho A C_d V_g^3 + M_v g V_g \sin\theta + M_v g V_g C_r \cos\theta \tag{12}$$

This equation can be simplified as:

$$P_g = cM_v + d \tag{13}$$

where

$$c = gV_g(\sin\theta + C_r \cos\theta) \tag{14}$$

$$d = \frac{1}{2}\rho A C_d V_g^3 \tag{15}$$

The grade-climbing power requirement also has two parts, one linear to vehicle mass and the other a constant dependent on vehicle design. The term *c* represents the effects of grade specifications (i.e., speed and grade angle) and rolling resistance, while the term *d* represents the power required to overcome aerodynamic drag.

Both the acceleration and grade climbing power requirements are dependent on vehicle mass. The acceleration power requirement is usually higher than the grade-climbing power requirement because the inertial forces that must be overcome during rapid acceleration generally will outweigh the weight force of a grade climb (unless the grade is extremely steep). The Partnership for a New Generation of Vehicles (PNGV) has compiled a set of vehicle specifications. Under these specifications a high fuel economy vehicle should accelerate from zero to 60 mph in 12 seconds and should be able to sustain a constant speed of 55 mph for 20 minutes while climbing a 6.5% grade. Figure 2 shows the general relationship between the two power requirements and vehicle mass under these specifications. The gap between the two power requirements increases as vehicle mass increases.

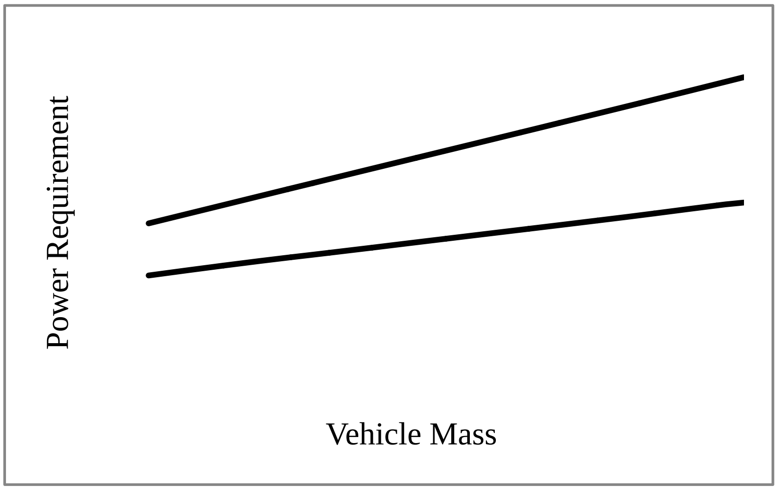


Figure 2 Power Requirements as a Function of Vehicle Mass [1].

Vehicle Mass

A vehicle has three distinct mass groups: (1) body, (2) chassis, and (3) drivetrain. The body and chassis for the hybrid and conventional vehicles would be nearly identical. The conventional vehicle mass and contributions by individual group have been analyzed earlier. Conventional steel vehicles have 73-74% of their total vehicle mass in body and chassis groups. The optimal use of ultra light steel might reduce the total vehicle mass by 10-12% while optimal use of aluminum would reduce the total mass by 31%. In the case of a hybrid vehicle, a smaller power unit (PU), a motor and an inverter, a generator, a battery pack, and a gear-drive or transmission (depending upon the hybrid design) will replace the conventional engine and transmission.

The total inertia mass M_v is expressed as follows:

$$M_v = M_b + M_{ch} + M_{dt} + M_l \tag{16}$$

where,

M_b = Body mass, M_{ch} = Chassis mass, M_{dt} = Drivetrain mass, and M_l = Load.

The body and chassis mass, M_b and M_{ch}, depend on vehicle design and their sum M_f can be treated as fixed.

The drivetrain has several components, each with its own efficiency and specific power. The efficiency helps determine the power rating for the component, and the specific power determines it's mass. The drivetrain mass is specified as:

$$M_{dt} = M_{pu} + M_{bat} + M_{mot} + M_{gen} + M_{tran} \tag{17}$$

where,

M_{pu} = PU mass, M_{bat} = Battery mass, M_{mot} = Motor and inverter mass, M_{gen} = Generator mass, and M_{tra} = Transmission mass.

Let S_{pu}, S_{bat}, S_{mot}, S_{gen}, and S_{tran} be the specific power for each of the five components and P_{pu}, P_{bat}, P_{mot}, P_{gen}, *and* P_{tran} is the power ratings. Then mass of each component can be computed as power divided by specific power:

$$M_{pu} = P_{pu} / S_{pu} \tag{18}$$

$$M_{bat} = P_{bat} / S_{bat} \tag{19}$$

$$M_{mot} = P_{mot} / S_{mot} \tag{20}$$

$$M_{gen} = P_{gen} / S_{gen} \tag{21}$$

$$M_{tran} = P_{tran} / S_{tran} \tag{22}$$

These mass and specific power values are for the complete component assembly including auxiliary and/or supporting units. For example, the motor assembly includes the inverter.

Component Sizing

The acceleration and grade-climbing power estimates from the above described procedure represent power delivered at the wheels. Each component has its own power conversion efficiency and some losses are involved in mechanical components such as bearings. A design factor, *k*, is used to account for other losses and contingencies.

The power rating of a drivetrain component depends upon the HEV system configuration, series or parallel. The motor delivers all the required power through the transmission in a series HEV while both the power unit and motor deliver power through the transmission in a parallel HEV. A series HEV's transmission is simple, consisting of a few reduction gears, while a parallel HEV's transmission is relatively complex, requiring linking of the two power sources. Also, the power unit's link to the drive axle requires greater control compared to the link of a motor. The component sizing procedures are different for the two configurations with some assumptions common to both. We assume that the power unit supplies the total power necessary for grade climbing in both the configurations. The battery usually supplies the difference between the power required to accelerate from zero to 60 mph and that for grade climbing. The battery power would be higher if the HEV is required to have some all-electric travel capability unless much lower acceleration capability was acceptable for the all-electric vehicle operations.

When HEV's internal combustion engine (ICE) power unit is sized to meet the minimum grade-climbing power and the battery pack is sized to meet the difference between acceleration and grade-climbing power values, the battery-supplied power is usually greater than 25% of the total HEV power. Such HEVs are termed *full* HEVs. The ICE represents a mature and affordable technology while the electric drive, consisting of motor, inverter/controller, and battery pack, represents an evolving technology. Consequently, it would be economical to reduce the size of the electric drive in some cases. By specifying a higher grade-climbing requirement and keeping the Z60 time unchanged, a user may increase the power rating of the ICE power unit. Since traction motor and battery provide the difference between acceleration and grade-climbing power requirements, their sizes are reduced with increase in the grade ability specification. Consequently, the battery power share of total power drops. Such HEVs are termed *mild* HEVs.

Reference

1. "Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results," Center for Transportation Research Argonne National Laboratory, United States Department of Energy

Lecture 41: Design of Series HEV

Design of Series HEV

In this lecture series and parallel hybrid electric vehicle are presented. The following topics are covered in this lecture:

- Series HEV
- Mass for a Series HEV with No All-Electric Acceleration Capability
- Mass for a Series HEV with All-Electric Acceleration Capability
- Parallel HEV
- Mass for a Parallel HEV with No All-Electric Acceleration Capability
- Mass for a Parallel HEV with All-Electric Acceleration Capability

Series HEV

Figure 1 shows a schematic diagram of the series HEV drivetrain. The power unit is connected to the generator. The generator supplies power to either the motor or the battery pack. The battery pack supplies power to the motor and also receives some recharge electricity fed back from the motor (acting as a generator) during regenerative braking. The motor is connected to the transmission (or reduction gears) to drive the wheels. The gears also transmit power back to the motor during regenerative braking.

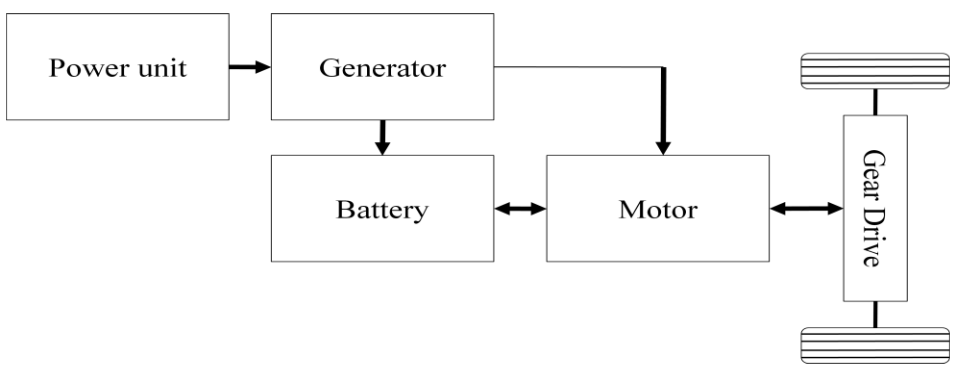


Figure 1 Series HEV Drivetrain Components and Their Connections [11]

Let η_{gen}, η_{mot}, *and* η_{tran} be the average power efficiency of the generator, motor, and transmission, respectively. These efficiencies are for the component assemblies including supporting units. The formulas for computing acceleration power requirement P_a and grade-climbing power requirement P_g are specified in equations 1 and 2, respectively.

$$P_a = aM_v + b \tag{1}$$

where,

$$a = \frac{V_m^2}{0.1}\left[\left(\frac{t_m + 0.1}{t_m}\right)^x - 1\right] + C_r g V_m \quad b = \frac{1}{2}\rho A C_d V_m^3$$

Power (P_g) required for negotiating a grade that is represented by angle θ at a constant speed v_g could be written as follows:

$$P_g = \frac{1}{2}\rho A C_d V_g^3 + M_v g V_g \sin\theta + M_v g V_g C_r \cos\theta$$

This equation can be simplified as:

$$P_g = cM_v + d \tag{2}$$

where,

$$c = gV_g(\sin\theta + C_r\cos\theta) \text{ and}$$

$$d = \frac{1}{2}\rho A C_d V_g^3$$

The component power ratings for a series HEV that is not required to have any all-electric acceleration capability can be computed as follows:

$$P_{pu} = P_g / \eta_{tran}\ \eta_{mot}\ \eta_{gen} \tag{3}$$

$$P_{gen} = P_g / \eta_{tran}\ \eta_{mot} \tag{4}$$

$$P_{mot} = P_a / \eta_{tran} \tag{5}$$

$$P_{bat} = (P_a - P_g) / \eta_{tran}\ \eta_{mot} \tag{6}$$

The acceleration power requirement is assumed to be larger than the grade-climbing power requirement in the above equations. Alternatively, the pu (per unit) power can be computed on the basis of the smaller of P_a and P_g, with motor power based on the larger of the two values, and battery power on the absolute value of the difference. The grade-climbing power requirement will exceed the acceleration power requirement when the grade to be negotiated is high and the time allowed to accelerate from zero to 60 mph is also high. In such a case, the battery would be used only at low speeds and during grade climbing. The battery would also serve its usual function of a sink to absorb excess energy during the periods of low power demand and braking. The motor power should always be based on the larger of the two power requirements to satisfy the highest power demand.

A series HEV that is required to have an all-electric acceleration capability will have a larger battery pack. This battery pack size is determined by the time required to accelerate from a stop to the maximum speed v_m on battery power alone. Let P_e be the all-electric acceleration power requirement:

$$P_e = a'M_v + b' \tag{7}$$

Where a' and b' are parameters that match the required all-electric acceleration time tm in equation 8. The battery power is computed as follows:

$$P_{bat} = P_e / \eta_{tran}\eta_{mot} \tag{8}$$

The equations 1 and 2 for power computation require that the vehicle inertia mass M_v be known. However, the vehicle inertia mass has four contributors: body, chassis, drivetrain, and load. The body and chassis mass depend on the type of vehicle (i.e., small or midsize car) and type of material (i.e., conventional steel, ultra light steel, or aluminum) while the drivetrain mass depends on the power requirements. The load is usually fixed, but may have different values for acceleration and grade climbing (the PNGV vehicle criteria measure acceleration with a load of 300 pounds (1 pound equals to 0.45359237 kg), whereas grade ability is measured with a higher load of 1100 pounds). Thus, the power and mass computation, in part, depend on the drivetrain component mass.

Mass for a Series HEV with No All-Electric Acceleration Capability

The total vehicle mass M_{veh} is defined as:

$$M_{veh} = M_f + M_{dt}$$

where

M_f = Fixed mass (i.e., sum of body and chassis mass), M_{dt} = Drivetrain mass,

Let

P_a = Power requirements for acceleration, P_g = Power requirements for grade climbing, M_c = Mass of drivetrain component “c”, P_c = Power rating of drivetrain component “c”, S_c = Specific power of drivetrain component “c”, and η_c = efficiency of drivetrain component “c.”

Then the drivetrain mass is estimated as shown below:

$$\begin{aligned}
M_{dt} &= M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran} \\
&= \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}} \\
&= \frac{P_a}{\eta_{tran} S_{mot}} + \frac{P_g}{\eta_{tran}\eta_{gen}\eta_{mot} S_{pu}} + \frac{P_g}{\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_a - P_g}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{P_a}{\eta_{tran} S_{tran}} \\
&= P_a\left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{1}{\eta_{tran} S_{tran}}\right) + Pa\left(\frac{1}{\eta_{tran}\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{tran}\eta_{mot} S_{gen}} - \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right)
\end{aligned}$$

$$M_{dt} = e_s P_a + f_s P_g \tag{9}$$

Here

$$e_s = \left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{1}{\eta_{tran} S_{tran}}\right) = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}} + \frac{1}{S_{tran}}\right)$$

$$f_s = \left(\frac{1}{\eta_{tran}\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{tran}\eta_{mot} S_{gen}} - \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right) = \frac{1}{\eta_{trans}}\left(\frac{1}{\eta_{mot} S_{gen} S_{pu}} + \frac{1}{\eta_{mot} S_{gen}} - \frac{1}{\eta_{mot} S_{bat}}\right)$$

Total vehicle mass $M_{veh} = M_f + M_{dt} = M_f + e_s P_a + f_s P_g$

Note that acceleration power P_a and grade-climbing power P_g are computed with inertia mass values that include some load. The design factor k is applied to account for other losses.

$$M_{veh} = M_f + e_s k\left[a\left(M_{veh} + M_{aload}\right) + b\right] + f_s k\left[c\left(M_{veh} + M_{gload}\right) + d\right]$$

where,

M_{aload} = the load during acceleration and M_{gload} = the load during grade climbing.

$$M_{veh} - e_s k a M_{veh} - f_s k c M_{veh} = M_f + e_s k\left(aM_{aload} + b\right) + f_s k\left(cM_{gload} + d\right)$$

$$M_{veh} = \frac{M_f + e_s k\left(aM_{aload} + b\right) + f_s k\left(cM_{gload} + d\right)}{1 - k\left(e_s a + f_s c\right)} \tag{10}$$

Mass for a Series HEV with All-Electric Acceleration Capability

The above procedure applies to a series HEV that is not required to accelerate on battery power. A series HEV may be required to have some all-electric acceleration capability to reduce emissions. Such an HEV would function as an electric vehicle as long as its battery maintains a state of charge above a predetermined minimum level. The power unit would turn on when the battery charge reaches this predetermined level. The State of California appears to prefer such an HEV because it would not have any tailpipe emissions while running on battery power.

The drivetrain mass of such a series HEV is determined as follows. Let P_e = Power requirements for all-electric acceleration ($P_e <= P_a$). Then,

$$M_{dt} = M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran}$$

$$M_{dt} = \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}}$$

$$M_{dt} = \frac{P_a}{\eta_{tran} S_{mot}} + \frac{P_g}{\eta_{tran}\eta_{gen}\eta_{mot} S_{pu}} + \frac{P_g}{\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_e}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{P_a}{\eta_{tran} S_{tran}}$$

$$M_{dt} = P_a\left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran} S_{tran}}\right) + P_g\left(\frac{1}{\eta_{tran}\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{tran}\eta_{mot} S_{gen}}\right) + P_e\left(\frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right)$$

$$M_{dt} = e_s P_s + f_s P_g + h_s P_e \tag{11}$$

where

$$\mathrm{e}_s = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{S_{tran}}\right)$$

$$f_s = \frac{1}{\eta_{tran}}\left(\frac{1}{\eta_{mot}\eta_{gen} S_{pu}} + \frac{1}{\eta_{mot} S_{gen}}\right)$$

$$h_s = \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}$$

Total vehicle mass, $M_{veh} = M_f + M_{dt} = M_f + e_s P_a + f_s P_g + h_s P_e$. The power requirements P_a *and* P_e are computed with a load of M_{aload} and Pg is computed with a load of M_{gload}. Also, the design factor k is applied:

$$M_{veh} = M_f + e_s k\left[a\left(M_{veh} + M_{aload}\right) + b\right] + f_s k\left[c\left(M_{veh} + M_{gload}\right) + d\right] + h_s k\left[a'\left(M_{veh} + M_{aload}\right) + b'\right]$$

where a' and b' are the parameters that match the all-electric acceleration time requirement.

$$M_{veh} - e_s' ka M_{veh} - f_s' kc M_{veh} - h_s' ka' M_{veh} = M_f + e_s' k\left(aM_{aload} + b\right) + f_s' k\left(cM_{gload} + d\right) + h_s' k\left(a' M_{aload} + b'\right)$$

$$Mweh = \frac{M_f + e_s' k\left(aM_{aload} + b\right) + f_s' k\left(cM_{gload} + d\right) + h_s' k\left(a' M_{aload} + b'\right)}{1 - k\left(e_s' a + f_s' + h_s' a'\right)} \tag{12}$$

Parallel HEV

A schematic diagram of the parallel HEV drivetrain is shown in Figure 2. In a parallel HEV, both power unit and motor supply power to the wheels. A generator is optional because the motor can be reversed during episodes of low power demand to recharge the battery. Normally, the motor is the primary source of power during low speeds and congested conditions. Since extended periods of congested driving under such a control strategy could drain the battery and the motor cannot generate any power to recharge the battery when the vehicle is stopped, parallel HEVs may be equipped with a generator. In our analysis, we assumed that all parallel HEVs would be equipped with a generator.

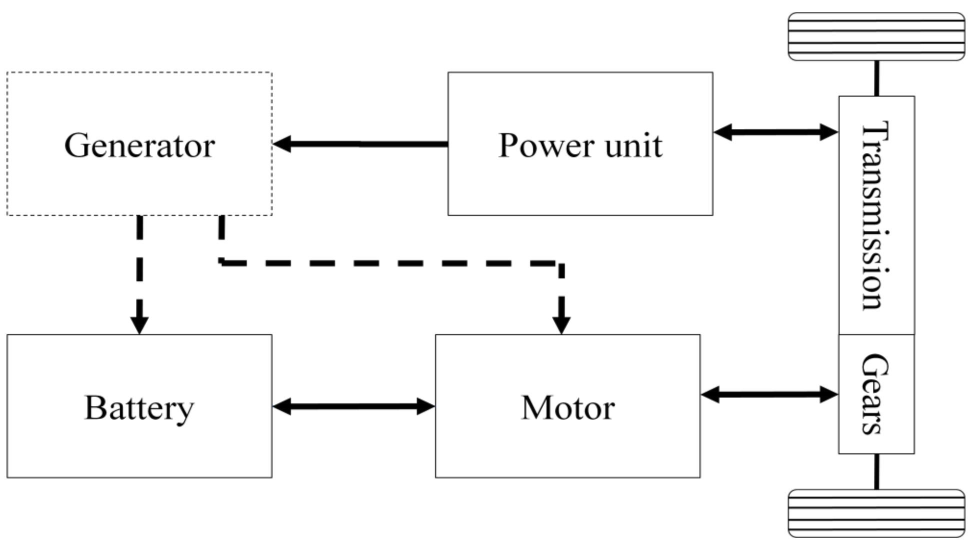


Figure 2 Parallel HEV Drivetrain Components and Their Connections [1]

The power rating of the generator would depend on the vehicle control strategy. It could supply power directly to the motor or only to the battery pack. Thus, a generator's power rating could be equal to or lower than the power rating of the motor. We assumed the generator to have one-third the power rating of the power unit in our computations. Using the earlier described convention, the power ratings of parallel HEV drivetrain components are computed as follows, assuming no all-electric acceleration capability:

$$P_{pu} = P_g / \eta_{tran} \tag{13}$$

$$P_{gen} = P_g / 3\eta_{tran}\eta_{mot} \tag{14}$$

$$P_{mot} = (P_a - P_g) / \eta_{tran} \tag{15}$$

$$P_{bat} = (P_a - P_g) / \eta_{tran}\eta_{mot} \tag{16}$$

In the above computations, acceleration power demand is assumed to be larger than the grade-climbing power demand. This assumption is true for most driving conditions in the United States. The battery supplies the difference between acceleration and grade-climbing power demands. The motor is connected to the transmission and uses power from either the battery or the generator. The motor may draw power from both the battery and the generator under some control strategies.

A parallel HEV may be required to have some all-electric acceleration and travel capability. Such a parallel HEV would have a larger battery pack, a larger motor, and could benefit from a larger generator. However, the generator size is limited by the PU power rating, its prime mover. The power requirements for these three components are determined as follows:

All-electric acceleration power requirement $P_e = a' M_v + b'$.
where a' and b' satisfy the all-electric acceleration time requirement.

$$P_{bat} = P_e / \eta_{tran}\eta_{mot} \tag{17}$$

$$P_{mot} = P_e / \eta_{tran} \tag{18}$$

$$P_{gen} = P_e / 3\eta_{tran}\eta_{mot} \tag{19}$$

Mass for a Parallel HEV with No All-Electric Acceleration Capability

The total vehicle mass $M_{veh} = M_f + M_{dt}$

Where Mf is the fixed mass and M_{dt} is the drivetrain mass.

$$M_{dt} = M_{mot} + M_{pu} + M_{gen} + M_{bat} + M_{tran}$$

$$M_{dt} = \frac{P_{mot}}{S_{mot}} + \frac{P_{pu}}{S_{pu}} + \frac{P_{gen}}{S_{gen}} + \frac{P_{bat}}{S_{bat}} + \frac{P_{tran}}{S_{tran}}$$

$$M_{dt} = \frac{P_a - P_g}{\eta_{tran} S_{mot}} + \frac{P_g}{\eta_{tran} S_{pu}} + \frac{P_g}{3\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_a - P_g}{\eta_{tran}\eta_{mot} S_{bat}} + \frac{P_a}{\eta_{tran} S_{tran}}$$

$$M_{dt} = P_a\left(\frac{1}{\eta_{tran} S_{mot}} + \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right) + P_g\left(\frac{1}{\eta_{tran} S_{pu}} - \frac{1}{\eta_{tran} S_{mot}} + \frac{1}{3\eta_{tran}\eta_{mot} S_{gen}} - \frac{1}{\eta_{tran}\eta_{mot} S_{bat}}\right)$$

$$M_{dt} = e_p P_a + f_p P_g \qquad (20)$$

where

$$\mathrm{e}_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}} + \frac{1}{S_{tran}}\right)$$

$$f_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{pu}} - \frac{1}{S_{mot}} + \frac{1}{3\eta_{mot} S_{gen}} - \frac{1}{\eta_{mot} S_{bat}}\right)$$

The vehicle mass M_{veh} can be computed the same way as was done for the series HEV (**equation 20**):

$$M_{veh} = \frac{M_f + e_p k\left(aM_{aload} + b\right) + f_p k\left(cM_{gload} + d\right)}{1 - k\left(e_p a + f_p c\right)} \qquad (21)$$

Mass for a Parallel HEV with All-Electric Acceleration Capability

A parallel HEV that is required to have some all-electric acceleration capability would likely have a larger battery pack, motor, and generator. The drive train mass is computed as follows:

$$M_{dt} = \frac{P_g + P_e}{\eta_{tran} S_{tran}} + \frac{P_g}{\eta_{tran} S_{pu}} + \frac{P_e}{\eta_{tran} S_{mot}} + \frac{P_g}{3\eta_{tran}\eta_{mot} S_{gen}} + \frac{P_e}{\eta_{tran}\eta_{mot} S_{bat}}$$

$$M_{dt} = \frac{P_g}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot} S_{gen}}\right) + \frac{P_g}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}}\right)$$

$$M_{dt} = f_p^{'} P_g + h_p^{'} P_e \tag{22}$$

where,

$$f_p^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot} S_{hen}}\right)$$

$$h_p^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot} S_{bat}}\right)$$

Notice that $h_p^{'}$ is computed the same way as $e_p^{'}$ in equation 20.

The vehicle mass M_{veh} is computed as follows:

$$M_{veh} = M_f + f_p^{'} k P_g + h_p^{'} k P_e$$

$$M_{veh} = M_f + f_p^{'} k\left[c\left(M_{veh} + M_{gload}\right) + d\right] + h_p^{'} k\left[a'\left(M_{veh} + M_{aload}\right) + b'\right]$$

$$M_{veh} = \frac{M_f + f_p^{'} k\left(cM_{gload} + d\right) + h_p^{'} k\left(aM_{aload} + b'\right)}{1 - k\left(f_p^{'} c + h_p^{'} a'\right)} \tag{23}$$

Reference

2. "Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results," Center for Transportation Research Argonne National Laboratory, United States Department of Energy

Lecture 42: Examples of Design of Series HEV and Parallel HEV

Examples of Design of Series HEV and Parallel HEV

In this lecture the following topics are covered:

- Application of the Procedure
- Midsize HEV
- Battery
- Component-Specific Power and Efficiencies
- Power and Mass Computations
- Parallel HEV with No (or Minimal) All-Electric Acceleration
- Parallel HEV with All-Electric Acceleration Capability
- Series HEV with No All-Electric Acceleration Capability
- Series HEV with All-Electric Acceleration Capability

Application of the Procedure

The following example demonstrates the application of the above-described power and mass computing procedure to a midsize car. Data for the example were gathered from several sources and were complemented with technical judgment in some cases.

Midsize HEV

Two midsize cars (1998 model year Chrysler Cirrus and Chevrolet Malibu) provide a baseline conventional vehicle (CV) for this example. The cars have an average mass of 1,418 kg (3,125 lb). Assuming that the future cars will use ultralight steel, we can assign a mass of 1,322 kg (2,915 lb) in 2005, an 11% reduction. We assume that more improvements will result in a 0.5% reduction in mass every 5 years after 2005. We also assume that the body and chassis mass contribute 73.5% of the total vehicle mass. An HEV's body and chassis are assumed to have 5% higher mass than a CV's due to additional components for power electronics and stiffeners to support the battery pack. The resulting body and chassis mass values are shown in Table 1. Three body types are listed in Table 1: (1) ultralight steel body, (2) partial aluminum body, and (3) maximum aluminum body. A partial aluminum vehicle could weigh 10% less than its ultralight steel body counterpart and a maximum aluminum vehicle could weigh 22% less than its ultralight steel body counterpart.

The selected baseline vehicles are 70.5 inches wide and 55.3 inches tall. These dimensions were kept unchanged in this analysis. A factor is applied to the vehicle cross section to account for ground clearance and side curvatures. This factor was 0.83 in 2005, 0.82 in 2010, 0.81 in 2015, and 0.80 in 2020. The resulting frontal area ranged from 2.09 square meters in 2005 to 2.01 square meters in 2020. We also assume that the future cars will have much lower aerodynamic drag coefficients and their tires will have very low rolling resistance. Table 1 also lists aerodynamic and rolling resistance parameters.

Some design criteria are necessary for computing power requirements. The vehicle is required to accelerate from zero to 60 mph (26.82 m/s) in some fixed time. It should also have sufficient power to climb a predetermined grade at a constant speed. Table 2 lists maximum grade and acceleration requirements. The vehicles characterized here are capable of negotiating the maximum grade on PU power only. They do not have enough electrical power to negotiate these grades. We characterize two vehicles each for parallel and series hybrids. One of these two vehicles does not have any all-electric acceleration capability while the other has such a capability. The vehicles with all-electric acceleration capability would have larger battery packs that would be charged from the electricity grid. They are often referred to as grid-connected HEVs. The all-electric acceleration time is specified the same for both series and parallel grid connected HEVs in our example. The table also shows vehicle loading during acceleration and grade climbing. The acceleration load of 136 kg is adapted from USEPA's standard procedure. The grade-climbing load of 499 kg represents 6 passengers and 91 kg of luggage and is adapted from the vehicle specifications compiled by the Partnership for a New Generation of Vehicles (PNGV).

Table 1 Midsize Vehicle Characteristics

Characteristics	2005	2010	2015	2020
Body & Chassis Mass in kg (lb in parenthesis)				
Ultralight steel body	974 (2,147)	969 (2,136)	964 (2,125)	959 (2,114)
Partial aluminum body	876 (1,931)	872 (1,922)	868 (1,914)	863 (1,903)
Maximum aluminum body	759 (1,673)	756 (1,667)	752 (1,658)	748 (1,649)
Aerodynamic and Rolling				
Frontal area (m^2)	2.09	2.06	2.04	2.01
Coefficient of drag (C_d)	0.27	0.26	0.25	0.24
Coefficient of rolling resistance (C_r)	0.0080	0.0075	0.0070	0.0065

Table 2 Other Design Parameters

Item	2005	2010	2015	2020
Maximum grade at 55 mph (%)	6.5	6.5	6.5	6.5
Time to accelerate from zero to 60 mph (s)	12	12	12	12
Time to accelerate from zero to 60 mph all-electrically (s) (where applicable)	16	16	16	16
Loading during acceleration (kg)	136	136	136	136
Loading during grade climbing (kg)	499	499	499	499

Battery

This example uses a modified version of the ANL's Delphi Study data for the nickel metal hydride battery. Delphi respondents appear to have specified battery technologies that were prevalent in the early 1990s. These data should now reflect the availability of high specific-power batteries for HEV use (Table 3). This update was done by applying factors to the Delphi Study data. The factors for specific power and specific energy were computed by using the battery data for Toyota Prius and Toyota RAV-4.59

Table 3 Nickel Metal Hydride Battery Characteristics for CV-like, Grid-Independent HEV

Characteristic	2005	2010	2015	2020
Specific power at 20% SOC (W/kg)	500	520	546	573
Specific energy (Wh/kg)	43	46	48	50

An alternative set of battery characteristics that has lower specific power and higher specific energy was developed for the grid connected HEV. Such batteries would have characteristics that fall somewhere in the middle of the characteristics of Toyota Prius and RAV-4 batteries. Factors were developed to arrive at a set of battery characteristics that would provide a range of 20 miles in 2005. The characteristics in Table 4 incorporate these factors.

Component-Specific Power and Efficiencies

The power computation procedure requires specific power and efficiency information for each drivetrain component. Table 5 lists the values used in this analysis. We analyzed data on Unique Mobility motor SR218H and inverter CA40-300L. The motor has a peak specific power of 1,110 W/kg and the two units have a combined specific power of 875 W/kg. We assumed a 10% increase in the specific power by 2005.

Power and Mass Computations

In this analysis, we assumed that the hybrid cars would have ultra light steel bodies. Values for such fixed parameters as gravity and air density are taken from standard physical tables. The value for gravity is 9.8 m/s2 and air density is 1.23 kg/m3. Also, we apply a design factor, *k*, in computing power to account for other mechanical losses and contingencies. The value of *k* is 1.1 in these examples.

Table 4 Nickel Metal Hydride Battery Characteristics for EV-like, Grid-Connected HEV

Characteristic	2005	2010	2015	2020
Specific power at 20% SOC (W/kg)	335	350	370	385
Specific energy (Wh/kg)	49	52	54	56

Table 5 Specific Power and Efficiency Values for Drive train Components

Component	Type	2005	2010	2015	2020
Specific Power (W/kg)					
Motor & generator	Permanent magnet	1225	1300	1350	1400
Power unit	Gasoline	325	330	335	340
Motor with inverter		360	985	1010	1035
Transmission	For parallel HEV	1300	1320	1340	1360
	For series HEV	1625	1650	1675	1700
Efficiency (%)					
Motor & inverter	Permanent magnet	90	92	92	93
Generator	Permanent magnet	95	95	95	93
Transmission-during acceleration		90	92	92	92

Parallel HEV with No (or Minimal) All-Electric Acceleration

First we apply the procedure to the year 2005 parallel HEV that is not required to have any all-electric acceleration capability. The HEV will have the high specific-power battery with the characteristics shown in Table 3. The vehicle will accelerate from zero to 60 mph in 12 seconds. The value of exponent *x* was set at 0.56.

The power requirement *Pa* for acceleration from zero to 60 mph (26.82 m/s) $=k(aM_v+b)$

$$a=\frac{V_m^2}{0.1}\left[\left(\frac{t_m+0.1}{t_m}\right)^x-1\right]+C_r g V_m=\frac{26.82^2}{0.1}\left[\left(\frac{12+0.1}{12}\right)^{0.56}-1\right]+0.008\times 9.8\times 26.82$$
$$=33.5+2.1=35.6W/kg$$

$$b=\frac{1}{2}\rho A C_d V_m^3=\frac{1}{2}1.23\times 2.09\times 0.27\times 26.82^2 W$$

The power requirement P_g for grade climbing at a constant speed of 55 mph (24.59 m/s) $= k(cM_v + d)$.

$$a = gV_g(\sin\theta + C_r\cos\theta) = 9.8\times 24.59\left(\frac{0.065}{\sqrt{1+0.065^2}} + 0.008\times\frac{1}{\sqrt{1+0.065^2}}\right) = 17.6\ W/kg$$

$$d = \frac{1}{2}\rho A C_d V_g^3 = 0.5\times 1.23\times 2.09\times 0.27\times 24.59^2 = 5160.1\ W$$

$$M_{veh} = \frac{M_f + e_p k\left(aM_{aload} + b\right) + f_p k\left(cM_{gload} + d\right)}{1 - k\left(e_p a + f_p c\right)}$$

$$\mathrm{e}_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{\eta_{mot}S_{bat}} + \frac{1}{S_{tran}}\right) = \frac{1}{0.9}\left(\frac{1}{960} + \frac{1}{0.9\times 500} + \frac{1}{1300}\right) = 4.481\times 10^{-3}$$

$$f_p = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{pu}} - \frac{1}{S_{mot}} + \frac{1}{3\eta_{mot}S_{gen}} - \frac{1}{\eta_{mot}S_{bat}}\right) = \frac{1}{0.9}\left(\frac{1}{325} - \frac{1}{960} + \frac{1}{3\times 0.9\times 1225} - \frac{1}{0.9\times 500}\right) = 0.128\times 10^{-3}$$

$$M_{veh} = \frac{974 + 4.481\times 10^{-3}\times 1.1\times\left(35.6\times 136\times 6695.2\right) + 0.128\times 10^{-3}\times 1.1\times\left(17.6\times 499 + 5160.1\right)}{1 - 1.1\times\left(4.481\times 10^{-3}\times 35.6 + 0.128\times 10^{-3}\times 17.6\right)} = 1{,}257kg$$

$$P_a = k\left(aM_v + b\right) = 1.1\times[35.6\times(1257 + 136) + 6695.2] = 61{,}909W = 61.9\ kW$$

$$P_g = k\left(cM_v + d\right) = 1.1\times[17.6\times(1257 + 499) + 5160.1] = 39{,}575W = 39.6\ kW$$

$$P_{pu} = P_g/\eta_{tran} = 39.6/0.9 = 44\ kW$$

$$P_{gen} = P_g/3\eta_{tran}\eta_{mot} = 39.6/(3\times 0.9\times 0.9) = 16.3\ kW$$

$$P_{mot} = (P_a - P_g)/\eta_{tran} = (61.9 - 39.6)/0.9 = 24.8\ kW$$

$$P_{bat} = (P_a - P_g)/\eta_{tran}\eta_{mot} = (61.9 - 39.6)/(0.9\times 0.9) = 27.6\ kW$$

$$M_{pu} = P_{pu}/S_{pu} = 44000/325 = 135.3\ kg$$

$$M_{mot} = P_{mot}/S_{mot} = 24800/960 = 25.8\ kg$$

$$M_{gen} = P_{gen}/S_{gen} = 16300/1225 = 13.3\ kg$$

$$M_{bat} = P_{bat}/S_{bat} = 27900/500 = 55.2\ kg$$

$$M_{tran} = P_{tran}/\eta_{tran}S_{tran} = 61900/(0.9\times 1300) = 52.9\ kg$$

Parallel HEV with All-Electric Acceleration Capability

In this example, the parallel HEV is expected to accelerate, all-electrically, from zero to 60 mph in 16 seconds. The battery power is assumed to be available immediately and no gearshifts are necessary. The power unit is sized to provide the grade climbing power. The value of exponent *x* in equation 3 is 0.49 for all-electric acceleration. The combined power unit and battery power would be much higher than what is needed for accelerating the vehicle from zero to 60 mph in 12 seconds. The vehicle is assumed to be equipped with a battery pack that has the characteristics listed in Table 4. The battery pack has lower specific power and higher specific energy compared to the battery pack used for the parallel HEV that has no all-electric acceleration capability.

Power for accelerating the vehicle, all-electrically, from zero to 60 mph (26.82 m/s) is

$$P_e = k(a'M_v + b')$$

$$a' = \frac{V_m^2}{0.1}\left[\left(\frac{16+0.1}{16}\right)^x - 1\right] + C_r g V_m = \frac{26.82^2}{0.1}\left[\left(\frac{16+0.1}{16}\right)^{0.49} - 1\right] + 0.008\times 9.8\times 26.82 = 22 + 2.1 = 24.1W/kg$$

$$b' = b = 6695.2W$$

The values of *c* and *d* remain unchanged.

$$M_{veh} = \frac{M_f + f_p' k\left(aM_{gload} + d\right) + h_p' k\left(a'M_{aload} + b'\right)}{1 - k\left(f_p' c + h_p' a'\right)}$$

$$\mathrm{f}_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{pu}} + \frac{1}{3\eta_{mot}S_{gen}}\right) = \frac{1}{0.9}\left(\frac{1}{1300} + \frac{1}{325} + \frac{1}{3\times 0.9\times 1225}\right) = 4.609\times 10^{-3}$$

$$h_p' = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{tran}} + \frac{1}{S_{mot}} + \frac{1}{\eta_{mot}S_{bat}}\right) = \frac{1}{0.9}\left(\frac{1}{1300} + \frac{1}{960} + \frac{1}{0.9\times 335}\right) = 5.697\times 10^{-3}$$

$$M_{veh} = \frac{974 + 4.609\times 10^{-3}\times 1.1\times\left(17.6\times 499\times 5160.1\right) + 5.697\times 10^{-3}\times 1.1\times\left(24.1\times 136 + 6695.2\right)}{1 - 1.1\times\left(4.609\times 10^{-3}\times 17.6 + 5.697\times 10^{-3}\times 24.1\right)} = 1,457kg$$

$$P_e = k\left[\left(a'M_{veh} + M_{aload}\right) + b'\right] = 1.1\times\left[54.1\left(1457 + 136\right) + 6695.2\right] = 49,582W = 49.6\ kW$$

$$P_g = k\left[c\left(M_{veh} + M_{gload}\right) + d\right] = 1.1\left[17.6\left(1457 + 499\right) + 5160.1\right] = 43,441W = 43.4\ kW$$

$$P_{pu} = P_g/\eta_{tran} = 43.4/0.9 = 48.3\ kW$$

$$P_{mot} = P_e/\eta_{tran} = 49.6/0.9 = 55.1\ kW$$

$$P_{gen} = P_g / 3\eta_{tran}\eta_{mot} = 43.4/(3\times 0.9\times 0.9) = \ 17.9\ kW$$
$$P_{bat} = P_e / \eta_{tran}\eta_{mot} = 49.6/(0.9\times 0.9) = \ 61.2\ kW$$
$$M_{pu} = P_{pu} / S_{pu} = 48300/325 = \ 148.5\ kg$$
$$M_{mot} = P_{mot} / S_{mot} = 55100/960 = \ 57.4\ kg$$
$$M_{gen} = P_{gen} / S_{gen} = 17900/1225 = \ 14.6\ kg$$
$$M_{bat} = P_{bat} / S_{bat} = 61200/335 = \ 182.7\ kg$$
$$M_{tran} = \frac{P_{pu} + P_{mot}}{S_{tran}} = 103400/1300 = \ 79.5\ kg$$

Because this HEV has a large battery pack and a power unit that is capable of negotiating a 6.5% grade at a constant speed of 55 mph, its performance on combined PU and battery power would be very good. The acceleration time can be computed by solving the equation for time (t_m). The power Pa is replaced by the sum of grade climbing power Pg and all-electric acceleration power P_e.

$$P_e + P_g = k\left(\frac{V_m^2 M_v}{0.1}\left[\left(\frac{t_{m+0.1}}{t_m}\right)^x - 1\right] + C_r g V_m M_v + \frac{1}{2}\rho A C_d V_m^3\right)$$

$$t_m = 0.1 \div \left(\left(\left[\frac{\left(P_g + P_e\right)/k - 0.5\rho A C_d V_m^3 - C_r g V_m M_v}{V_m^2 M_v}\right]0.1 + 1\right)^{1/x} - 1\right)$$

Because the Z60 time on combined PU and battery power is expected to be close to 8 seconds, we assign a value of 0.6 to the exponent *x*.

$$t_m = 0.1 \div \left(\left(\left[\frac{93000/1.1 - 0.5\times 1.23\times 2.09\times 0.27\times 26.82^2 - 0.008\times 9.8\times 26.83\times\left(1457+136\right)}{26.82^2\times\left(1457+136\right)}\right]0.1 + 1\right)^{1/0.6} - 1\right)$$
$$t_m = 0.92\ Seconds$$

Series HEV with No All-Electric Acceleration Capability

The year 2005 series HEV would be equipped with the high specific power battery listed in Table 3. The acceleration power requirement $P_a = k(aM_v + b)$:

$$a = \frac{V_m^2}{0.1}\left[\left(\frac{12.1}{12}\right)^{0.56} - 1\right] + C_r g V_m = \frac{26.82^2}{0.1}\left(0.004658\right) + 0.008\times 9.8\times 26.82 = 33.5 + 2.1 = 35.6\ W/kg$$

The value of *b, c, and d* remain unchanged at 6695.2, 17.6, and 5160.1, respectively.

$$M_{veh}=\frac{M_f+e_s k\left(aM_{aload}+b\right)+f_s k\left(cM_{gload}+d\right)}{1-k\left(e_s a+f_s c\right)}$$

$$\mathrm{e}_s=\frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}}+\frac{1}{\eta_{mot}S_{bat}}+\frac{1}{S_{tran}}\right)=\frac{1}{0.94}\left(\frac{1}{960}+\frac{1}{0.9\times500}+\frac{1}{1625}\right)=4.13\times10^{-3}$$

$$f_s=\frac{1}{\eta_{tran}}\left(\frac{1}{\eta_{mot}\eta_{gen}S_{pu}}+\frac{1}{\eta_{mot}S_{gen}}-\frac{1}{\eta_{mot}S_{bat}}\right)=\frac{1}{0.94}\left(\frac{1}{0.9\times0.95\times325}+\frac{1}{0.9\times1225}-\frac{1}{0.9\times500}\right)=2.43\times10^{-3}$$

$$M_{veh}=\frac{974+4.13\times10^{-3}\times1.1\times\left(35.6\times136\times6695.2\right)+2.43\times10^{-3}\times1.1\times\left(17.6\times499+5160.1\right)}{1-1.1\times\left(4.13\times10^{-3}\times35.6+2.43\times10^{-3}\times17.6\right)}=1,344kg$$

$$P_a=1.1[35.6(1344+136)+6695.2]=65,331W=65.3\,kW$$

$$P_g=1.1\times[17.6\times(1344+499)+5160.1]=41,262W=41.3\,kW$$

$$P_{pu}=41.3/0.94\times0.9\times0.95=51.3\,kW$$

$$P_{gen}=41.3/0.94\times0.9=48.8\,kW$$

$$P_{mot}=Max\left(65.3/0.94,41.3/\left(0.94\times0.675\right)\right)=69.5kW$$

The above motor power shows its peak power rating based on the higher of the two power needs: (1) for acceleration and (2) for grade climbing. We used the motor's peak power rating for the acceleration power requirement, which is to be met for 12 seconds. Because the motor is required to provide constant grade climbing power for 20 minutes or more, we used the motor's constant power rating for grade climbing. A ratio of 0.675 between constant and peak specific power, derived from the runs of Advanced Vehicle Simulator (ADVISOR) for the Unique Mobility motor SR218H, is used here:

$$P_{bat}=\left(65.3-41.3\right)/0.94\times0.9=28.5\,kW$$

$$M_{pu}=51300/325=158kg$$

$$M_{mot}=69500/360=72.4kg$$

$$M_{gen}=48800/1225=39.8kg$$

$$M_{bat}=28500/500=57kg$$

$$M_{tran}=P65300/\left(1625\times0.94\right)=42.8\,kg$$

Series HEV with All-Electric Acceleration Capability

This series HEV will accelerate, all-electrically, from zero to 60 mph in 16 seconds. The battery, which has the characteristics in Table 4, is sized to provide the power for this acceleration. The motor is sized to provide constant power for grade climbing because its constant power rating is assumed to be only 67.5 of the peak power rating.

$$a' = \frac{V_m^2}{0.1}\left[\left(\frac{t_m+0.1}{t_m}\right)^x - 1\right] + C_r g V_m = \frac{26.82^2}{0.1}\left[\left(\frac{16+0.1}{16}\right)^{0.49}\right] + 0.008\times 9.8\times 26.82 = 24.1W/kg$$

$$b' = b = 6695.2W$$

The values of *a, b, c, and d* remain unchanged at 35.6, 6695.2, 17.6, and 5158.4, respectively..

$$M_{veh} = \frac{M_f + e_s^{'}k\left(aM_{aload}+b\right) + f_{s\,p}^{'}k\left(cM_{gload}+d\right) + h_s^{'}k(a^{'}M_{aload}+b^{'})}{1-k\left(e_s^{'}a + f_s^{'}c + h_s'a'\right)}$$

$$e_s^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{S_{mot}} + \frac{1}{S_{tran}}\right) = \frac{1}{0.94}\left(\frac{1}{960}+\frac{1}{1625}\right) = 1.76\times 10^{-3}$$

$$f_s^{'} = \frac{1}{\eta_{tran}}\left(\frac{1}{\eta_{mot}\eta_{gen}S_{pu}} + \frac{1}{\eta_{mot}S_{gen}}\right) = \frac{1}{0.94}\left(\frac{1}{0.9\times 0.95\times 325}+\frac{1}{0.9\times 1225}\right) = 4.79\times 10^{-3}$$

$$h_s^{'} = \left(\frac{1}{\eta_{tran}\eta_{mot}S_{bat}}\right) = \left(\frac{1}{0.94\times 0.9\times 325}\right) = 3.53\times 10^{-3}$$

$$M_{veh} = \frac{974 + 1.76\times10^{-3}\times1.1\times\left(35.6\times136\times6695.2\right) + 4.79\times10^{-3}\times1.1\times\left(17.6\times499+5158.4\right) + 3.53\times10^{-3}\times1.1\left(24.1\times136+6695.2\right)}{1-1.1\times\left(1.76\times10^{-3}\times35.6 + 4.79\times10^{-3}\times17.6\times3.53\times10^{-3}\times24.1\right)} = 1,488kg$$

$$P_a = 1.1\left[35.6\left(1488+136\right)+6695.2\right] = 70982\text{W} = 71\ kW$$

$$P_g = 1.1\left[17.6\left(1488+499\right)+5158.4\right] = 44041\text{W} = 44\ kW$$

$$P_e = 1.1\left[24.1\left(1488+136\right)+6695.2\right] = 50414W = 50.4kW$$

$$P_{pu} = 44/\left(0.94\times0.95\times0.9\right) = 54.8kW$$

$$P_{mot} = 71/0.94 = 50414W = 75.5kW$$

$$P_{gen} = P_g/\eta_{tran}\eta_{mot} = 44/(0.94\times0.9) = 52.1\ kW$$

$$P_{bat} = P_e/\eta_{tran}\eta_{mot} = 50.4/(0.94\times0.9) = 59.6\ kW$$

$$M_{pu} = P_{pu}/S_{pu} = 54800/325 = 168.6\ kg$$

$$M_{mot} = P_{mot}/S_{mot} = 75500/960 = 78.7\ kg$$

$$M_{gen} = P_{gen}/S_{gen} = 52100/1225 = 42.5\ kg$$

$$M_{bat} = P_{bat}/S_{bat} = 59600/335 = 177.9\ kg$$

$M_{tran} = 71000/(0.94 \times 1625) = 46.5\ kg$

This grid-connected HEV has a combined power of 111 kW from its generator and battery that can be delivered to its wheels. However, its motor has a peak power of only 75.5 kW. Its Z60 time on combined power unit and battery power is limited by the size of its motor. Because the motor is sized to meet a 12-second Z60 time, the HEV cannot accelerate any faster.

Lecture 43: Design of Series-Parallel HEV Drivetrain

Design of Series-Parallel HEV Drivetrain

Introduction

The topics covered in this chapter are as follows:

- Drive Train Configuration
- Drivetrain Control Technique
- Traction Torque Control Approach

Drivetrain Configuration

A typical series-parallel HEV drivetrain configuration is shown in shown in **Figure 1**. The various connections in this drivetrain are as follows:

- The ICE and the EM are connected to the yoke and sun gear respectively.
- The ring gear of the planetary gear is connected to the drive wheels through gears g_1, g_2, g_3, g_4, g_5 and a differential gear.
- The traction motor is connected to the driven wheels through gears g_1, g_2, g_3, g_4 and the differential gear, which couples the output torques of the ring gear and the traction motor together.
- One clutch and two brakes are used. The clutch connects or disconnects the engine to or from the yoke of the planetary gear.
- Lock 1 is used to lock or release the sun gear and the shaft of the IM to or from the stationary frame of the vehicle.
- Lock 2 is used to lock or release the yoke to or from the stationary frame of the vehicle.

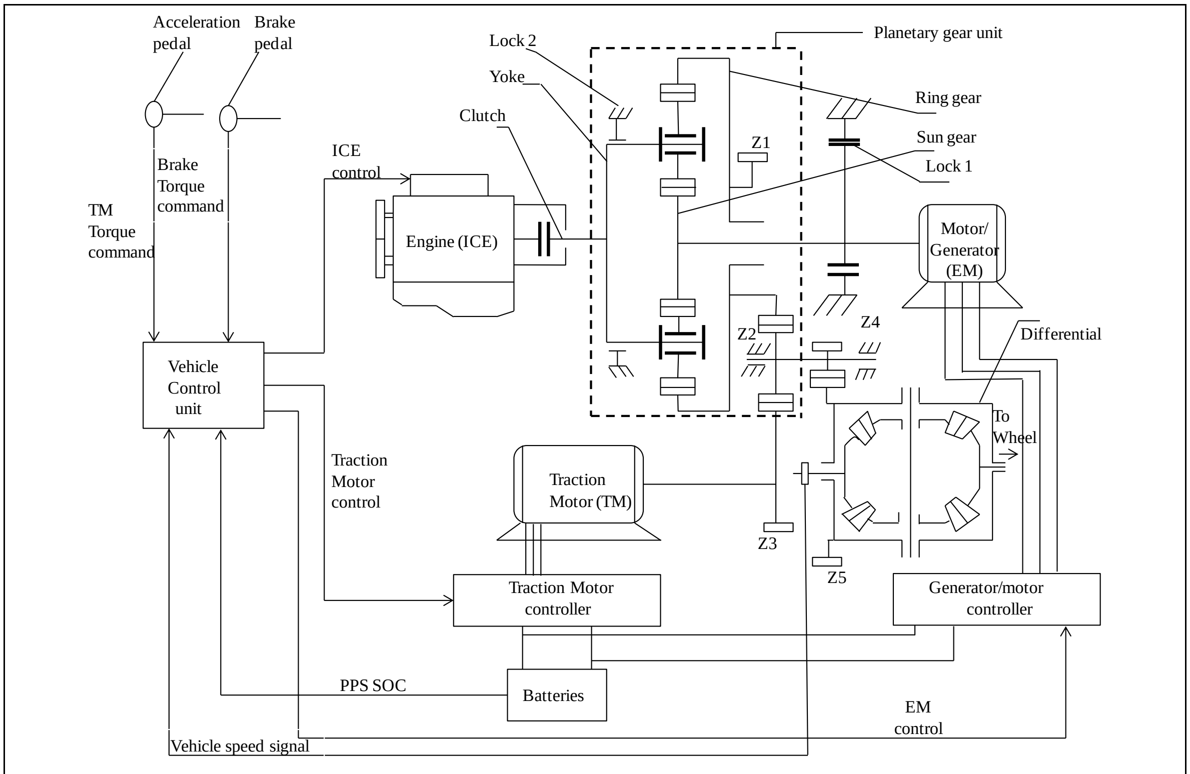


Figure 1: Configuration of a series parallel drive train [1]

By controlling the clutch, locks, engine, IM and the traction motor, the following modes of operation are available:

Speed-Coupling Mode: In this mode the traction motor is does not provide any power to the drivetrain. The speed-coupling mode has three sub-modes:

a. Engine only traction: The clutch is engaged to connect the engine to the yoke, lock 1 locks the sun gear to the vehicle stationary frame and the EM is de-energised. The energy flow path is shown in **Figure 2**. In this case the entire traction power is delivered by the engine and the relation between the engine and the driven wheels is

$$n_{wheel} = \left(\frac{n_b - 1}{n_b}\right)\frac{n_{ice}}{i_{rw}} \tag{1}$$

where

n_{wheel} is the speed of the wheel

n_{ice} is the speed of rotation the ICE

n_b gear ratio of the planetary gear (refer Lecture 8)

$i_{rw} = \frac{Z_5 Z_2}{Z_1 Z_4}$ is the gear ratio from the ring gear to the drive train wheel

The torque relation between the drive wheels and the ICE is

$$T_{wheel} = \frac{i_{rw}\eta_{yr}\eta_{rw}}{(n_b - 1)} n_b T_{ice} \tag{2}$$

where

T_{wheel} torque at the wheel

T_{ice} torque produced by the ICE

η_{yr} efiiciency from the yoke to the ring

η_{rw} efficiency from the ring to the driven wheels

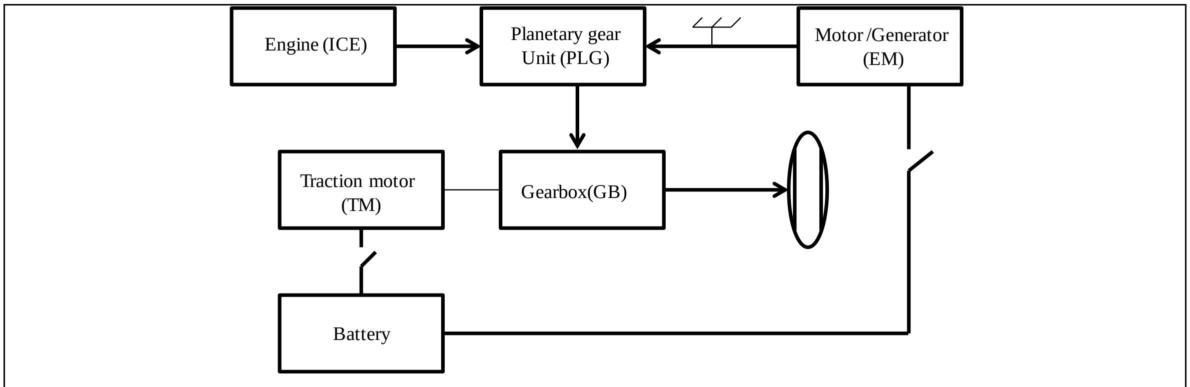


Figure 2: Traction energy flow in ICE alone mode of operation [1]

b. ***EM alone traction:*** In this mode, the ICE is shut down, the clutch is engaged and lock1 releases the sun gear and the shaft of the EM from the stationary frame. The lock 2 locks the yoke to the stationary frame. In this mode the vehicle is propelled by the EM alone. The energy path is shown in **Figure 3**. The speed and torque relation between the EM and the driven wheel is (***refer Table 1 Lecture 8***)

$$n_{wheel} = \frac{1}{n_b} \frac{n_{em}}{i_{rw}}$$

where

n_{em} is the speed of rotation the ICE

and the torque is given by

$$T_{wheel} = i_{rw}\eta_{sr}\eta_{rw} n_b T_{em} \tag{3}$$

where

T_{em} torque produced by the EM

η_{sr} efficiency from the sun to the ring

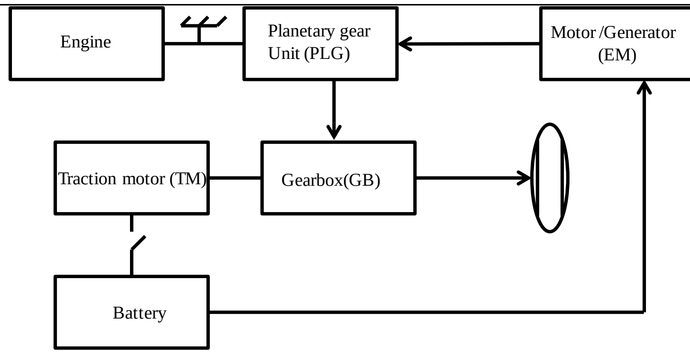


Figure 3: Traction energy flow in EM alone mode of operation [1]

c. ***ICE and EM operation with speed coupling:*** In this mode of operation the clutch is engaged and the locks 1 and 2 are released. The energy flow path is shown in **Figure 4**. The power from the ICE and the EM is transferred to the driven wheels via the planetary gear. Hence, the speed of the driven wheel is (refer ***equation 7 Lecture 8***):

$$n_{wheel} = \left(\frac{n_{ice}}{n_b} - \frac{1-n_b}{n_b} n_{em} \right) \frac{1}{i_{rw}} \tag{4}$$

The torque delivered to the driven wheels is given by

$$T_{wheel} = -i_{rw}\eta_{yr}\eta_{rw} \frac{n_b}{(1-n_b)} T_{ice} = -i_{rw}\eta_{yr}\eta_{rw} n_b T_{em} \tag{5}$$

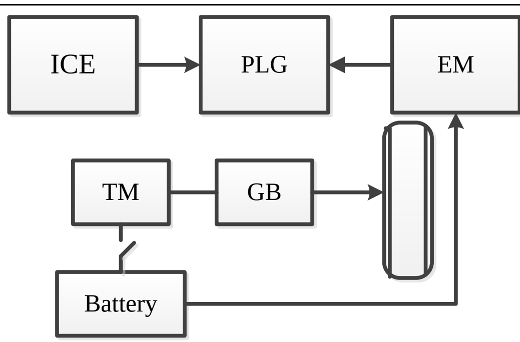


Figure 4a: Traction energy flow in EM in motoring mode [1]

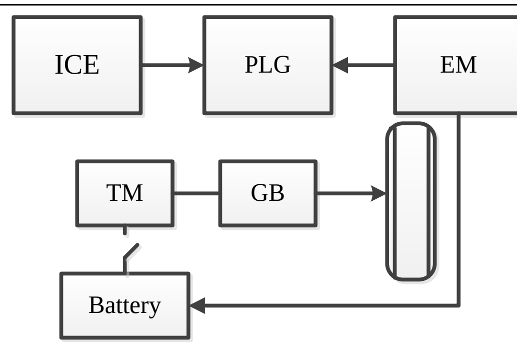


Figure 4b: Traction energy flow in EM in generating mode [1]

Torque Coupling Mode: When the traction motor is energized, its torque can be added to the torque output of the ring gear to form the torque coupling mode. There are six possible sub-modes of operation and they are shown in **Figures 5a** to **g.**

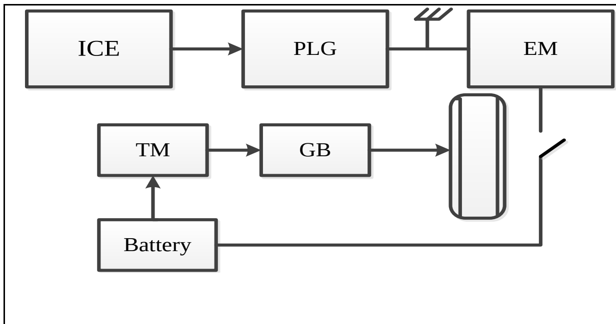


Figure 5a: Energy flow in parallel traction mode [1]

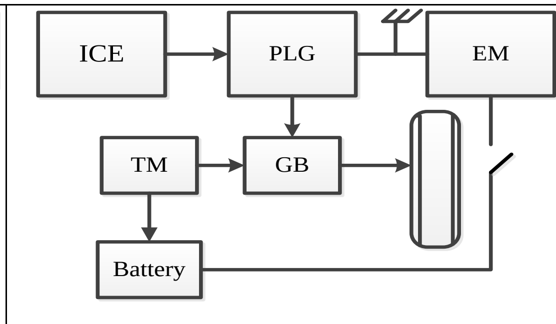


Figure 5b: Energy flow in battery charging mode [1]

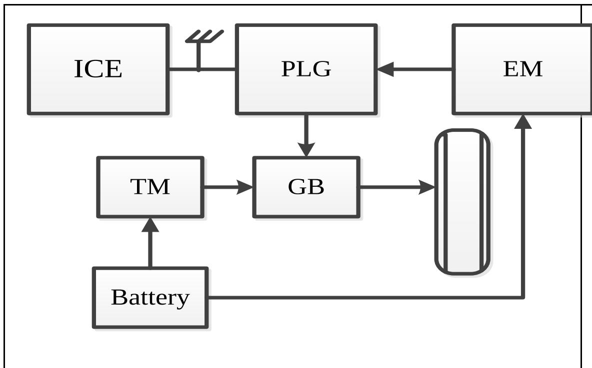


Figure 5c: Energy flow in TM and EM in parallel mode [1]

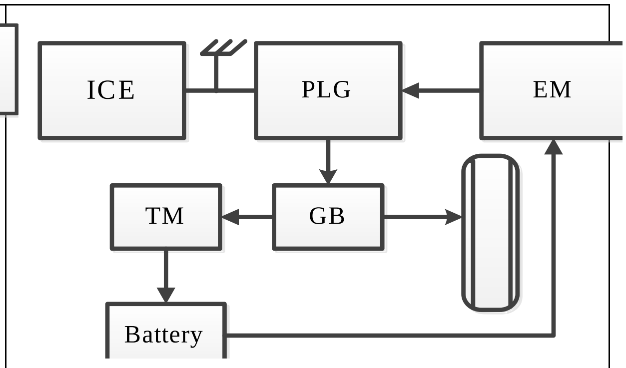


Figure 5d: Energy flow in EM motoring and battery charging mode [1]

Regenerative Braking: When the vehicle experiences braking, the traction motor, EM or both can produce braking torque and recapture part of the braking energy to charge the electrical energy storage device (also known as peaking power source). In this mode of operation the engine is switched off and the energy flow path is shown in **Figure 6**.

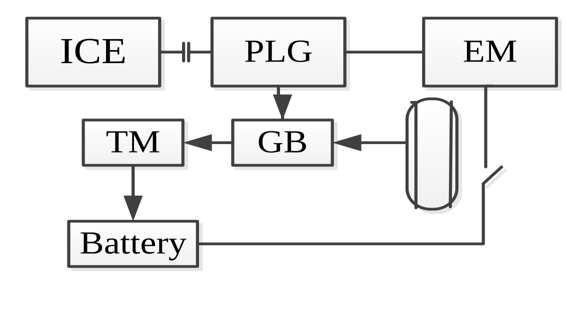


Figure 6a: Regenerative braking with TM alone [1]

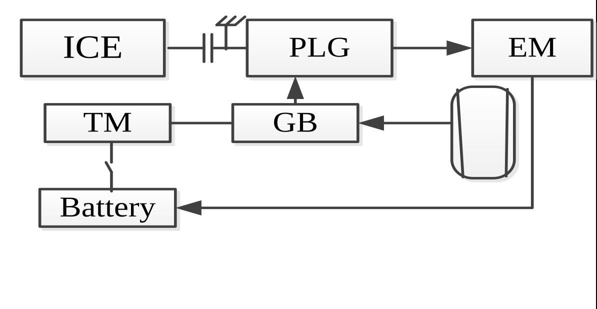


Figure 6b: Regenerative braking with EM alone [1]

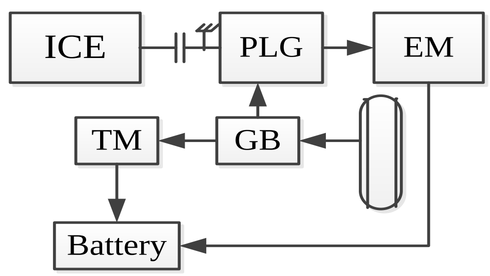


Figure 6c: Regenerative braking with both EM and TM [1]

Drivetrain Control Techniques

The control system of the drivetrain is shown in **Figure 1**. The vehicle controller unit (VCU) receives the traction or braking torque commands from the driver through the accelerator or brake pedals and other necessary operating information such as state of charge (SOC) of the PPS and the vehicle speed. Based on the real time information received and the control logic present in the VCU, the VCU generates control signals to control the ICE, EM, traction motor and the clutches and the locks. The control signals from the VCU are divided into following subsystems:

- ICE Speed Control
- Traction control
- Drive train control

ICE Speed Control:

The **equation 4** shows that the ICE speed can be (n_{ice}) can be adjusted by controlling the EM speed (n_{em}) at a given wheel speed (n_{wheel}). The control procedure is as follows:

i. Suppose the ICE is operating at point ***a*** with a speed if $n_{ice,a}$ producing a torque of $T_{ice,1}$ and the engine throttle angle (θ) is at 60^o (**Figure 7**).

ii. In order to balance the torque produced by the ICE, the EM has to produce torque $T_{em,1} = T_{ice} / (1 - n_b)$.

iii. As an example if the throttle opening angle is increased to $\theta = 70^o$ and the torque produce by ICE and EM are kept fixed at $T_{ice,1}$ and $T_{em,1}$ respectively, then the engine speed will increase and will settle at point ***b*** as shown in **Figure 7**.

iv. If the ICE and EM torques are maintained at $T_{ice,1}$ and $T_{em,1}$ respectively, reducing the throttle opening angle to 50^o will cause the engine speed to decrease to point ***c*** (**Figure 7**).

v. If the throttle opening angle θ is kept constant, then from **equation 5** it can be seen that the ICE speed can be controlled by changing the torque of EM

vi. For example if the throttle angle is kept fixed at 70^o, then reducing the EM torque will result in increase of engine speed from point ***b*** to ***b'***.

From the above discussion it can be seen that the ICE speed can be controlled within its optimal speed range by instantaneously controlling the engine throttle angle and/or the EM torque.

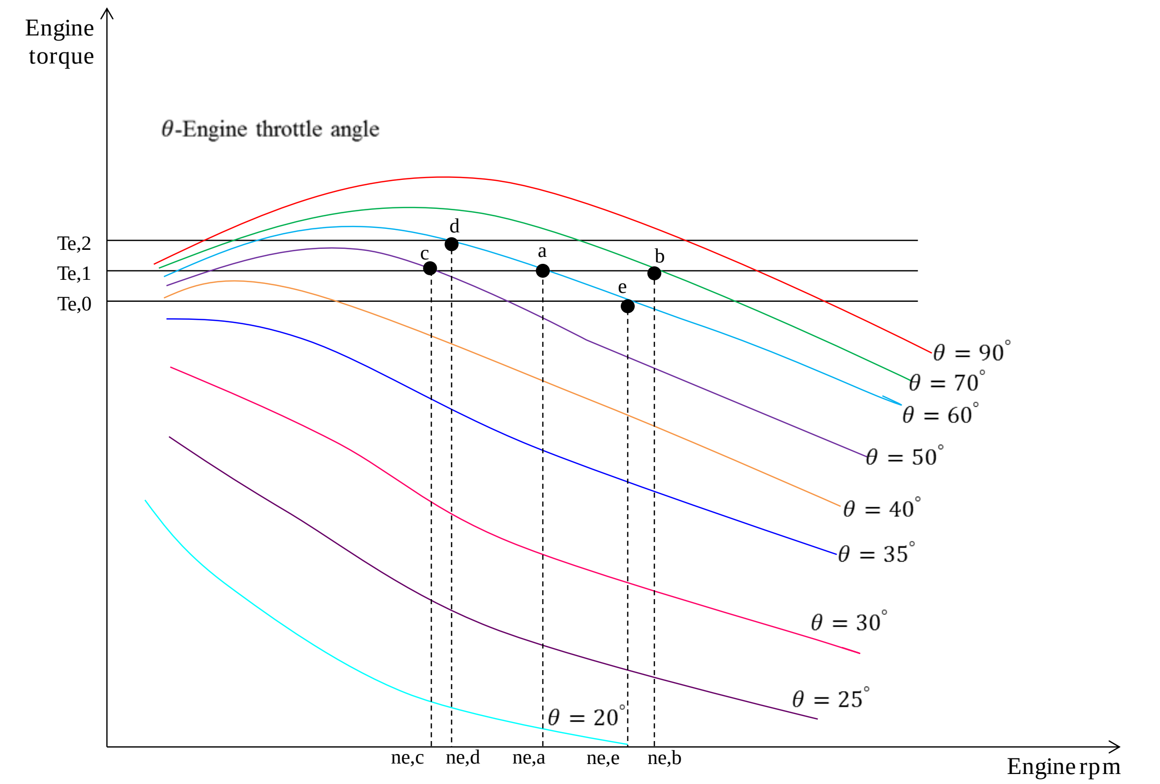


Figure 7: ICE speed controlled by ICE throttle and EM torque [1]

Traction Torque Control Approach

The traction torque on the driven wheels is the sum of the torques transmitted from the ring gear of the planetary gear units and the traction motor. The traction torque on the driven wheels can be expressed as

$$T_{wheel} = i_{rw}\eta_{rw}T_{ring} + i_{mw}\eta_{mw}T_{tm} \tag{6}$$

In **equation 6**

T_{wheel} is the total tractive torque acting on the wheels

T_{ring} is the output torque from the planetary gear unit and is a torque generated by ICE (T_{ice}) and the EM (T_{em})

i_{rw} is the gear ratio from the ring gear to the driven wheels

i_{mw} is the gear ratio from the traction motor to the driven wheels

η_{rw} is the transmission efficiency from the ring gear to the driven wheels

η_{mw} is the transmission efficiency from the traction motor to the driven wheels

The total traction torque request on the driven wheels, which is commanded by the driver through the accelerator pedal can be met by the torque outputs from the ring gear and the traction motor. In **Figure 8** an example of drive train with full ICE throttle opening and full traction motor load is shown. The control strategy that is used to obtain **Figure 8** is:

- At low speeds the ICE operates at constant speed and the EM operates with positive speeds
- At medium speeds the EM is locked to the vehicle frame and the engine speed linearly increases with vehicle speed.
- At high vehicle speeds the ICE again operates with a constant speed and the EM operates with a negative speed (rotating in opposite direction of the ICE).

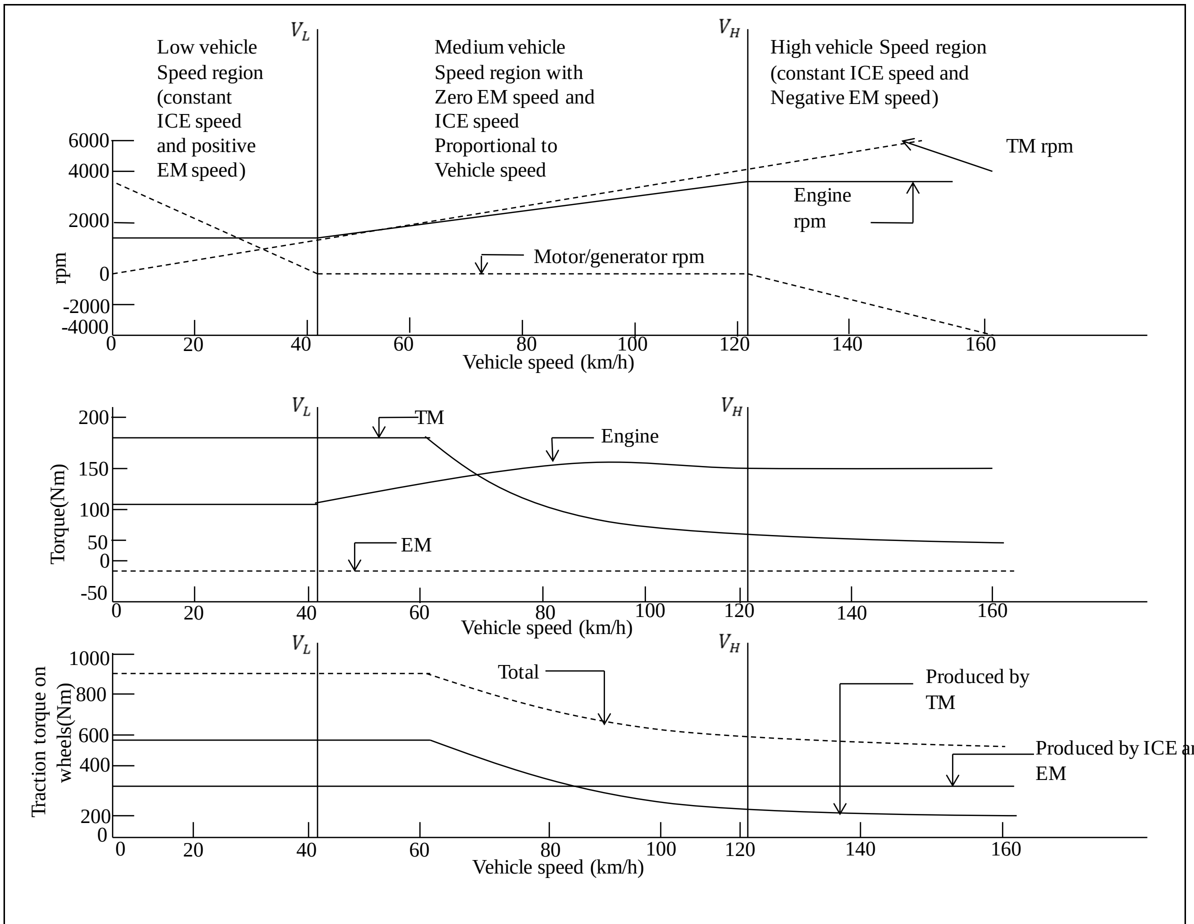


Figure 8: Torque and speed of ICE, TM, EM and Vehicle [1]

Drive Train Control Strategies

The distinct features of the series parallel drive train are:

i. The ICE speed and torque can be decoupled completely or partially from the driven wheels through speed coupling or torque coupling
ii. It has much more flexibility than the series or parallel drivetrains in the choice of active operation mode thus providing more potential for the improvement of drive train efficiency and emissions

To enable the flexibility of operation suitable control strategies have to be developed and the objective of the control strategies should be:

i. high overall fuel utilization efficiency
ii. low emission.

The control strategy should meet both the condition under following constraints:

i. Always meeting the driver's torque command
ii. Always maintaining the state of the charge (SOC) of the energy storage system (batteries and/or supercapacitors) around 70% and never below 30%.

The control strategies used in the series-parallel drivetrain can be divided into two broad categories, namely:

i. ICE speed control strategies
ii. Traction torque control strategies

ICE Speed Control Strategy

From **Figure 8** and **9** it can be seen the vehicle speed is divided into three regions, namely:

- Low speed region
- Medium speed region
- High speed region

The vehicle speed $V_{vehicle\_low}$ is determined by the lowest ICE speed allowed with zero EM speed and can be written as

$$V_{vehicle\_low} = -\frac{\pi r_{wheel} n_{ice\_\min}}{30 i_{rw}} \frac{n_b}{1-n_b} \tag{7}$$

where

r_{wheel} is the radius of the wheel [m]

$n_{ice\_\min}$ is the minimum ICE speed [rpm]

In the low vehicle speed region the EM has to be operated with a positive speed which is given by (**equation 4**)

$$n_{em} = \frac{n_b}{1-n_b}\left[\frac{n_{ice\_\min}}{n_b} - i_{rw} n_{wheel}\right] \tag{8}$$

The speed of the wheel in rpm (n_{wheel}) is given in terms of vehicle speed (V) as

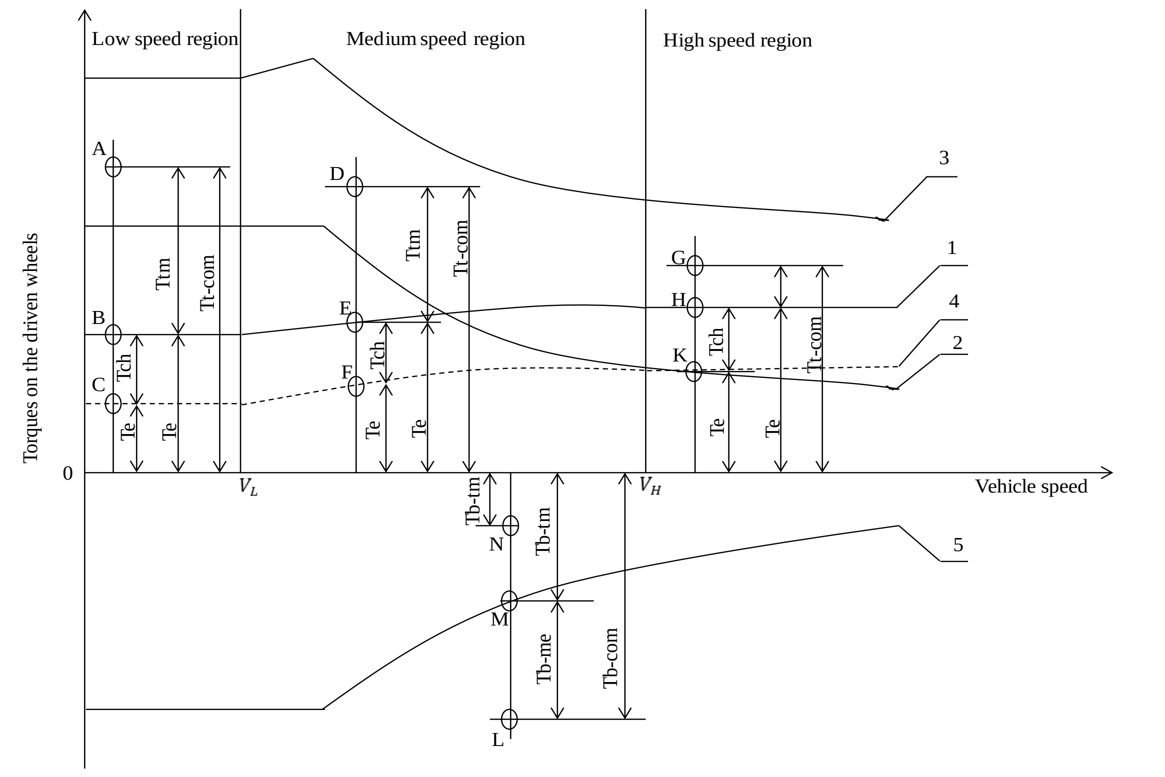
$$n_{wheel} = \frac{30V}{\pi r_{wheel}} \tag{9}$$

where

$V \le V_{vehicle\_low}$

Hence, **equation 8** can be written in terms of vehicle speed as

$$n_{em} = \frac{n_b}{1-n_b}\left[\frac{n_{ice\_\min}}{n_b} - \frac{30 i_{rw} V}{\pi r_{wheel}}\right] \tag{10}$$



1-Traction torque developed by ICE with optimal throttle opening

2-Traction torque developed by TM

3-Traction torque developed by ICE and TM

4- Traction torque developed by ICE with partial throttle opening

5-MAXIMUM BRAKING TORQUE DEVELOPED BY tm

Figure 9: Maximum SOC control strategy [1]

The ICE and the EM are connected to the yoke and sun gear respectively. Hence, the torque produced by the EM, applied to the sun gear of the planetary unit, has the direction opposite to its speed. Thus, in this case, the EM absorbs part of the ICE power to charge the batteries. The power on the EM shaft (ignoring the losses) is

$$P_{em} = \frac{2\pi}{60} T_{em} n_{em} \tag{11}$$

Substituting n_{em} from **equation 10** into **equation 11** gives

$$P_{em} = \frac{n_b}{1-n_b}\left[\frac{2\pi}{60}\frac{T_{em} n_{ice\_\min}}{n_b} - \frac{i_{rw} V T_{em}}{r_{wheel}}\right] \tag{12}$$

In **equation 12** the first term on the right hand side is the power that the engine produces and the second term is the power that is delivered to the driven wheels.

When the vehicle speed is higher than $V_{vehicle\_low}$ but lower than the maximum speed $V_{vehicle\_high}$, that is $V_{vehicle\_low} \leq V_{vehicle} \leq V_{vehicle\_high}$, the following actions are taken by the controller:

i. the EM is de-energised and the sun gear (the shaft of the EM) is locked to the stationary frame of the vehicle.

ii. The drivetrain operates in the torque-coupling mode and the ICE speed is proportional to the vehicle speed.

The speed $V_{vehicle\_high}$ is determined by the maximum ICE speed allowed $n_{ice\_\max}$. Beyond the $n_{ice\_\max}$ operating efficiency of ICE may reduce. When the vehicle speed is higher than $V_{vehicle\_high}$, the ICE speed is kept constant at $n_{ice\_\max}$ and the EM starts working again with a negative speed to compensate for the ICE speed. The speed $V_{vehicle\_high}$ is given by

$$V_{vehicle\_low} = -\frac{\pi r_{wheel} n_{ice\_\max}}{30 i_{rw}} \frac{n_b}{1-n_b} \tag{13}$$

where

$n_{ice\_\max}$ is the maximum ICE speed [rpm]

When the vehicle speed is higher than $V_{vehicle\_high}$, for limiting the ICE speed below the maximum ICE speed ($n_{ice\_\max}$), the EM has to be operated in the direction opposite to the ICE speed, which as be expressed as

$$n_{em} = \frac{n_b}{1-n_b}\left[\frac{n_{ice\_\max}}{n_b} - \frac{30 i_{rw} V}{\pi r_{wheel}}\right] \tag{14}$$

The EM is in motoring mode and the power delivered by it is given by

$$P_{em} = \frac{n_b}{1-n_b}\left[\frac{i_{rw} V T_{em}}{r_{wheel}} - \frac{2\pi}{60}\frac{T_{em} n_{ice\_\max}}{n_b}\right] \tag{15}$$

The first term in **equation 15** is the total power delivered to the driven wheels and the second term is the power that the ICE produces. In this mode of operation the EM takes power from the batteries.

Traction Torque (TM) Control

The control of the TM is divided into three distinct regions, namely:

i. Low vehicle speed region
ii. Medium vehicle speed region
iii. High vehicle speed region

The control action in each of the three regions is explained in the subsequent subsections.

Low vehicle speed region: When the vehicle speed is below $V_{vehicle\_low}$ the following actions are taken:

i. The ICE is made to operate at $n_{ice\_\min}$. The ICE torque is marked **1** in **Figure 9** and this torque is produced with an ICE throttle at which it has maximum fuel utilization efficiency at this speed.
ii. The point **A** in **Figure 9** represents the traction torque command given by the driver and this required torque is greater than the torque that the ICE can produce with optimal ICE throttle as shown in **Figure 9**. Hence, the ICE alone cannot handle this required torque and the additional torque has to be supplied by the TM.
iii. The magnitude of torque that the TM produces depends on the energy level of the batteries. When the SOC of the battery is lower than a specified minimum value of SOC ($SOC_{\min}$), the batteries do not supply energy to TM. In this case the maximum power to the TM is the power generated by the EM governed by **equation 12**.
iv. If the SOC of the battery is greater than $SOC_{\min}$ ($SOC > SOC_{\min}$), the batteries support the TM and it is controlled to produce the required torque.
v. When the required torque is smaller than the ICE torque produced with optimal throttle as shown by point **B** in **Figure 9** and the SOC of the battery is less than $SOC_{\min}$, then the ICE is operated at a speed of $n_{ice\_\min}$. The batteries are charged by the EM (the EM works in generator mode), hence, the torque produced by the ICE is used to drive the vehicle and charge the batteries.

vi. When the required torque is smaller than the ICE torque and the SOC of the battery lies between the $SOC_{\min}$ and $SOC_{\max}$, the ICE and the EM are controlled in such a way so that the ICE operates with at a speed of $n_{ice\_\min}$ and produce the required torque. The TM in this is de-energized.

vii. When the required torque is smaller than the ICE torque and the SOC of the battery is greater than $SOC_{\max}$, then the ICE is turned off and the required torque is provided by the TM.

Medium vehicle speed region: When the vehicle speed is greater than $V_{vehicle\_low}$ and less than $V_{vehicle\_high}$, the ICE provides the required torque and the speed of the ICE is proportional to the speed of the vehicle.

High vehicle speed region: When the vehicle speed is higher than $V_{vehicle\_high}$, the ICE operates at its maximum speed $n_{ice\_\max}$. The following cases are possible in this mode of operation:

i. In case the ICE, operating at $n_{ice\_\max}$, cannot meet the required torque and the batteries have SOC lower than $SOC_{\min}$, then the ICE is forced to operate at speed greater than $n_{ice\_\max}$ to meet the required torque demand and the EM is de-energised.

ii. In case the SOC is greater than $SOC_{\min}$, the ICE speed is controlled at its specified speed $n_{ice\_\max}$, and the remainder torque is produced by the TM.

iii. In case the required torque is smaller than the what the ICE can give operating at optimal throttle position (point **K** in **Figure 9**), and the SOC of the battery is less than $SOC_{\min}$, the ICE is operated at point **K** and the TM works as a generator to charge the batteries. The EM is de-energised in this mode of operation.

iv. If the SOC of the battery is between $SOC_{\min}$ and $SOC_{\max}$ and the required torque is less than what ICE can deliver at optimal throttle position, the ICE alone provides the required torque. The TM and EM are de-energised in this mode of operation.

References:

[1] M. Ehsani, *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design*, CRC Press, 2005