

## Module 8: Design of Hybrid and Electric Vehicles

### Lecture 27: Design Principles of HEVs I

#### Design Principles of HEVs I

In this lecture the different types of the hybrid electric vehicles are presented. The following topics are covered in this lecture:

- Definition of hybridness
- Hybrid design philosophy
- Hybridness: parallel hybrid, series, mixed and range extender (plug-in) hybrids
- Range extender
- Optimization and hybridness
- Battery power and electric motor power

#### DEFINITION OF HYBRIDNESS

The definition of hybridness,  $H$ , is

$$H = \frac{\text{Sum of power of all traction motors}}{\text{Sum of traction motor+Engine power}} \quad (1)$$

Some hybrids have more than one motor/generator (M/G). Hybrids with motor-in-the-wheel and all-wheel-drive (AWD) have more than one motor. The definition uses the sum of all traction motors. The name, hybridization, is occasionally used for  $H$ .

As an example of hybridness consider a light delivery van with the propulsion:

Diesel engine: 110 kW at 3000 rpm

Electric motor: 23 kW; maximum torque 243 N-m at 500 rpm

$$H = \frac{23kW}{23+110kW} = 0.17 = 17\% \quad (2)$$

As will be seen,  $H = 17\%$  is a mild hybrid. As a note of caution, the sum of component power  $23 + 110 \text{ kW} = 133 \text{ kW}$  is not the maximum hybrid power. The maximum electric motor torque and engine torque occur at different rpm.

$H$  defines micro, mild, and full hybrids. The domain of the plug-in hybrid is defined by a range of values of  $H$ .

Morphing of series hybrids, which is done by varying  $H$ , leads to mixed hybrids.  $H$  can be an independent variable in an equation for hybrid performance. One example, which is range extension, is discussed below.

### **HYBRID DESIGN PHILOSOPHY**

By considering the major factors for hybrids, an understanding of the various values of  $H$  is gained. The basic efficiency of the gasoline engine is low. A typical value is 25%. The efficiency of MGs is higher. Typical values are above 90%.

Battery efficiency is moderate; energy is lost putting energy into the battery and again removing energy. Round trip in/out efficiency is typically 70%–80%. Because of the inefficiency, the batteries must be cooled. Overall hybrid design philosophy has three parts:

- Operate electric motor first (less emissions/less fuel consumed).
- Add gasoline engine only when needed.
- Operate gas engine at the best rpm and throttle setting, that is, operate on minimum fuel consumption line in engine map.

### **HYBRIDNESS: PARALLEL HYBRID**

**Figure 1** demonstrates the utility of hybridness,  $H$  for parallel hybrid vehicle. Some parts are not shown, like the battery. Five different values of  $H$  that are illustrated in **Figure 1** are:

- For  $H = 0\%$ , the vehicle is solely powered by a conventional gasoline engine.
- For  $H = 25\%$ , the hybrid electric vehicle (HEV) has an electrical traction motor with 25 kW and an engine with 75 kW. Both engine and motor shafts are inputs to a three-way transmission. This is the region for a mild hybrid. Mild hybrids are a good solution for certain vehicles. The cost/benefit ratio is highly favorable.
- For  $H = 50\%$ , the HEV has both electrical traction motor and an engine with equal power of 50 kW. As is the case for a parallel hybrid, both engine and motor shafts are inputs to a three-way transmission. This is the region for a full hybrid.
- For  $H = 75\%$ , the HEV has a very large M/G compared to the engine power. To supply the electrical power for the M/G, a large heavy battery is required. This is the region for a plug-in hybrid. Also this is the region for the range extender

vehicle. For  $H = 75\%$ , if the M/G runs for an hour, the energy consumed would be 75 kWh. The engine/generator requires 3 h to recharge the battery.

- For  $H = 100\%$ , the vehicle is a pure electrical vehicle (EV). All electrical power comes from either the battery or regenerative braking. Energy stored in the battery is supplied by charging stations.

Except for  $H = 0\%$  and  $H = 100\%$ , each hybrid has the same architecture. The M/G and engine are inputs to a three-way, or three-shaft, transmission.

A series hybrid by its definition has a value of  $H$  near 50%. For values of  $H$  away from 50%, different classes of hybrids are found (**Figure 2**). The diagram assumes no losses; all components have 100% efficiency. The shafts, which are identified by an ellipse indicating torque, are a mechanical connection between parts.

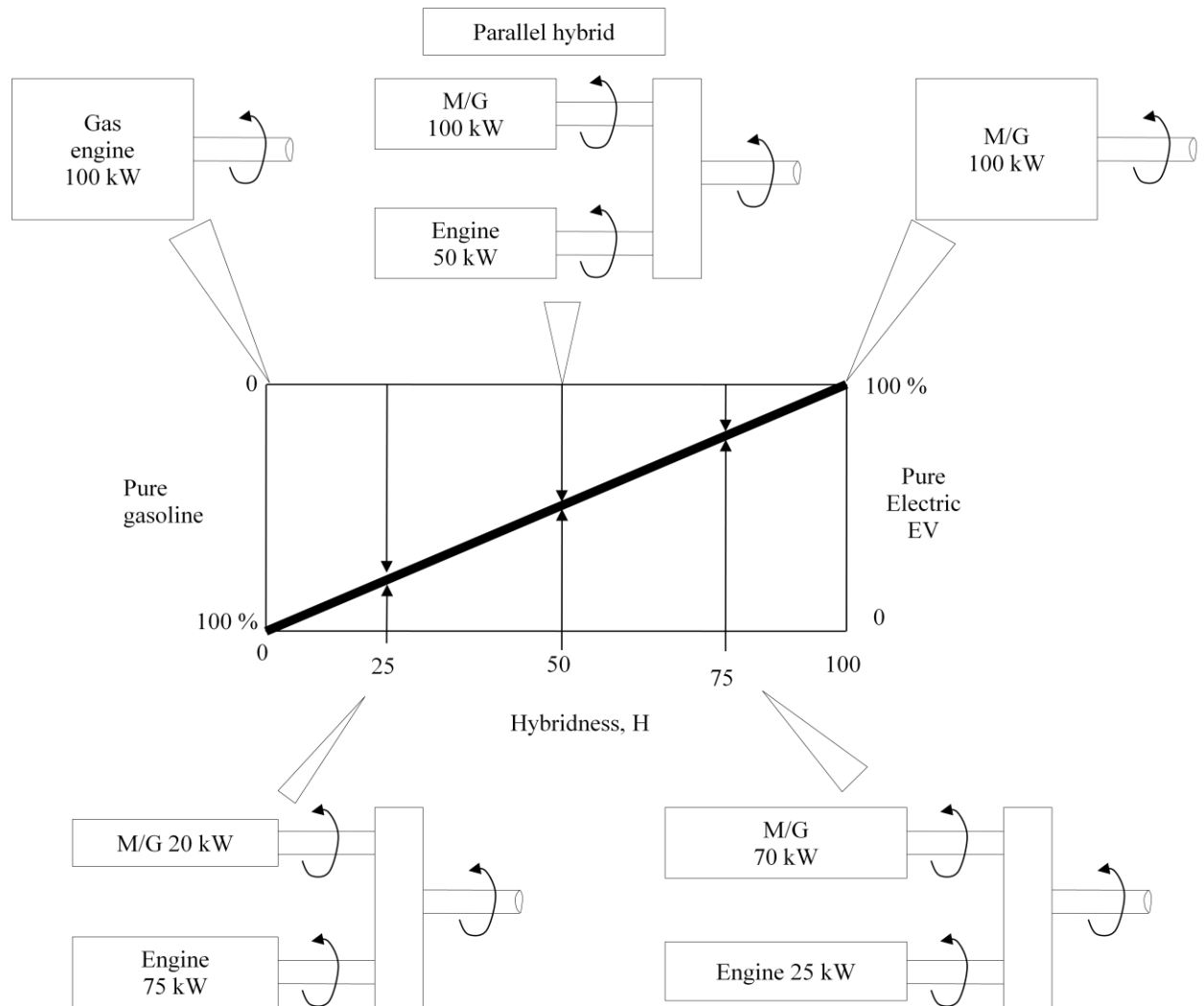


Fig.1. Illustration of component sizes for parallel hybrid designs with varying hybridness. [1]

## **HYBRIDNESS: SERIES, MIXED, AND RANGE EXTENDER (PLUG-IN) HYBRIDS**

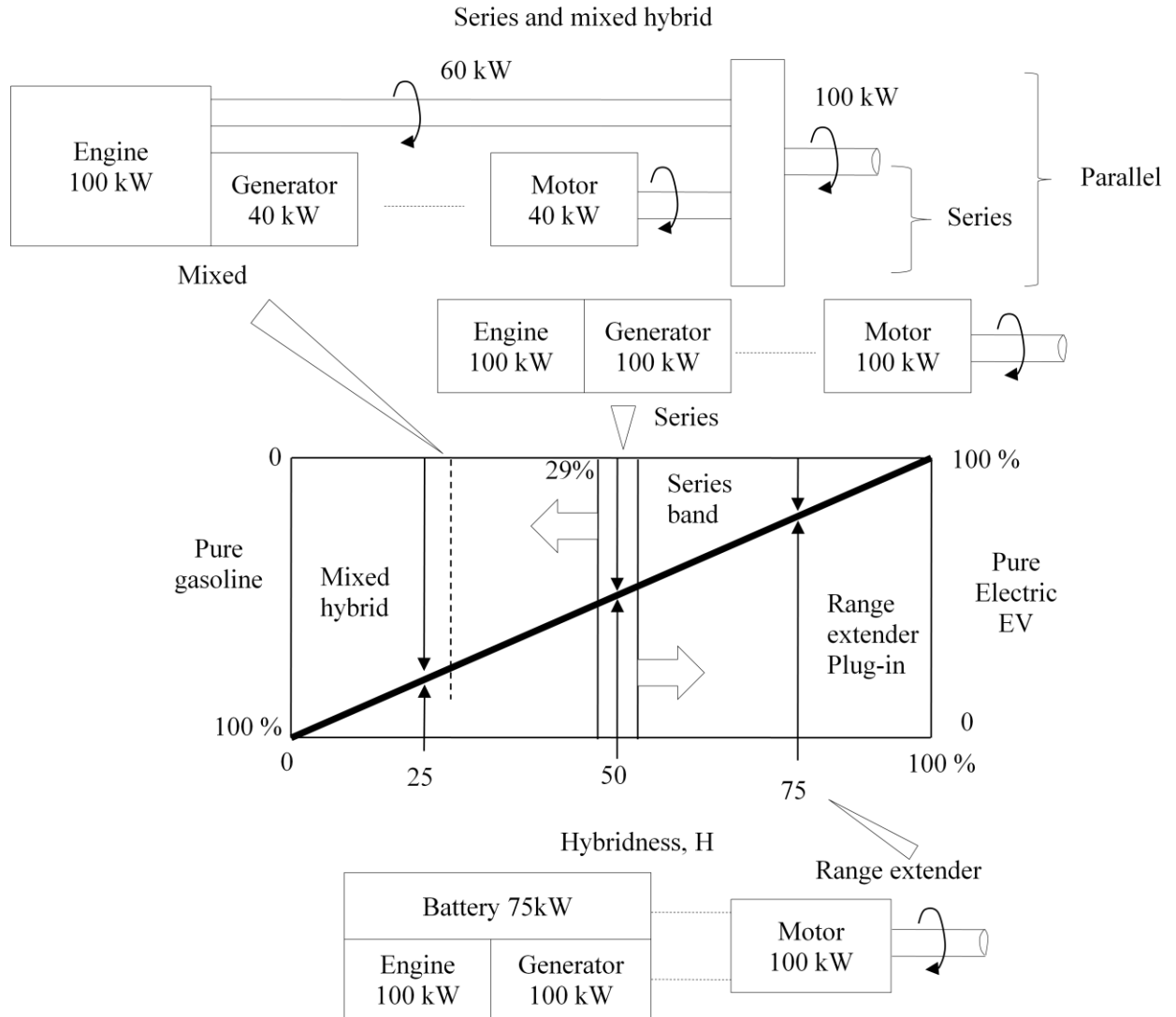
The series hybrid has motor power approximately equal to engine power; hence, the series hybrid exists in a band near  $H = 50\%$ . Outside that band, the series hybrid changes into either mixed hybrid or plug-in hybrid.

### **RANGE EXTENDER**

The range extender, which has large value for  $H$ , is shown in **Figure 2**. An almost infinite number of either parallel, mixed, series or plug-in designs can be made for a hybrid. The equations discussed below apply to one plug-in or range extender hybrid design. The assumptions for the equations are as follows:

1. When it runs, the generator always runs at full power.
2. Power to cruise, which depends on cruise speed, is greater than the generator power.
3. Battery power supplements engine (generator) power.
4. At the end of cruise at maximum range,  $R$ , the battery is “dead” and the fuel tank is empty.

Note that when voltage supplied to the motor is equal to the battery open circuit voltage, the battery neither supplies nor absorbs electrical energy.



**Figure 2.** Series hybrid and its derivatives related to hybridness,  $H$ . For  $H$  less than 50%, the series hybrid morphs into the mixed hybrid. For  $H$  greater than 50%, the series hybrid transforms into the range extender, electric, vehicle.  $H$  greater than 50% is also the region for the plug-in hybrid. The dashed line (----) is an electrical connection. For  $H = 29\%$ , the part attributed to series is shown as well as the part which is parallel.  $H = 29\%$  is a mixed hybrid. [1]

The symbols and equations are

$$R = \frac{R_0}{H} \quad (3)$$

where  $R_0$  is the range without engine/generator,  $R$  is the range with engine/generator which extends range and  $H$  is the hybridness factor. The increment in range,  $\Delta R$ , is defined by Equation 11.4

$$\Delta R = R - R_0 = R_0 \frac{1-H}{H} \quad (4)$$

The typical SOC versus Range curve for a range extender is shown in **Figure 3**. The numerical values assumed for the curve shown in **Figure 3** are  $R_0=240\text{km}$ ,  $H=75\%$  and  $R=240\text{km}/0.75=320\text{km}$

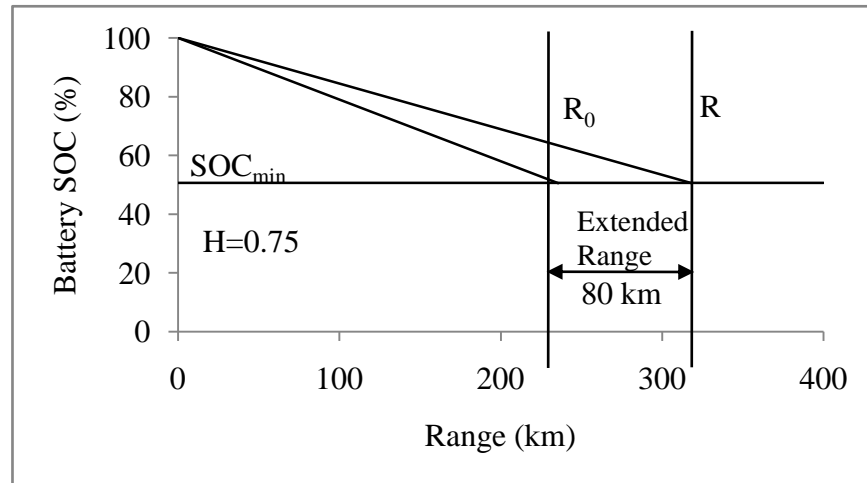


Figure 3. Extension of range due to a small gasoline-powered generator recharging the battery. [1]

The gain in range is

$$\Delta R = R - R_0 = 240\text{km} \left[ (1 - 0.75) / 0.75 \right] = 80\text{km}$$

## OPTIMIZATION AND HYBRIDNESS

For small hybridness, that is  $H$  much less than 50%, the optimum hybrid operates near the best specific fuel consumption line on the engine map. Small  $H$  corresponds to mild hybrids. For a band of hybridness near 50%, the efficiencies of both electrical and engine components affect the optimum operating points. Values of  $H$  larger than 40% are termed full hybrids. For large values of  $H$ , that is, near 100%, hybrid optimization focuses on the M/G, battery, and power electronics.

## BATTERY POWER AND ELECTRIC MOTOR POWER

To begin, a few features of batteries are stated. Battery size is determined by

$$\text{Battery energy} = (\text{power of M/G})(\text{run time})$$

This equation assumes that the battery power equals the power of the M/G. By a property of the battery known as specific energy (Wh/kg), battery energy can be changed to battery mass. Specific energy of the battery has units of (battery energy)/ (mass) and the run time is the time required for the battery to become dead.

The trends in the variation of battery power and energy are shown in **Figure 4**. The battery power and electric motor power must be matched. For examining the trends, battery and motor powers are assumed equal **Figure 4**. is divided into two regions with

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Mild and full hybrids  $0\% < H < 50\%$

Plug-in hybrids  $50\% < H < 100\%$

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The battery variation with increasing  $H$  depends on the region.

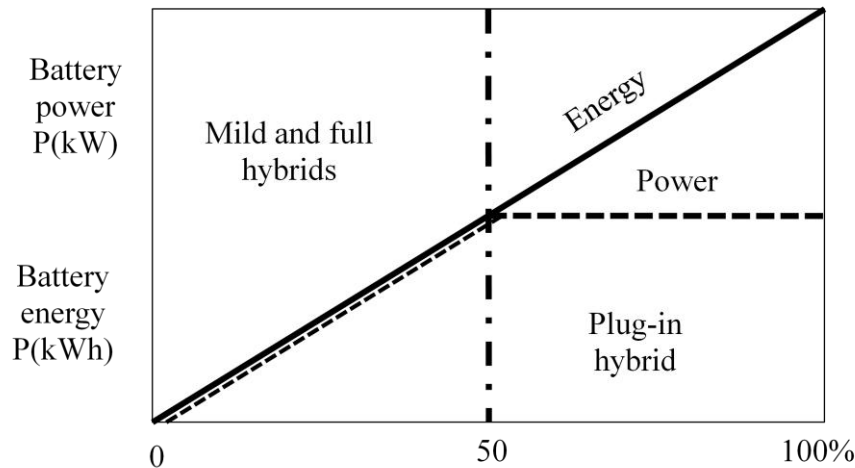


Fig.4.Variation of battery power and battery energy as a function of hybridness. [1]

**TABLE I**  
Qualitative Aspects of Battery Size Small Big

Small	Gig
Engine runs too often	Too much weight to haul around
Little loss of mpg due to excess weight	Allows lots of electric-only operation
Insufficient for electric-only operation	Suitable for plug-in operation

For mild and full hybrids, as  $H$  increases, the battery power and battery energy increase hand in hand. From the equation Battery energy = (Power of M/G)(Run time), the run time remains fixed in this region. Refer to the definition of  $H$  in the opening paragraphs of this chapter.

An increase in M/G power increases  $H$ . Also a decrease in engine power, that is, downsizing the engine, increases  $H$ . Battery energy ( $E$ ), and power ( $P$ ); grow to match the growth in M/G. The increase of  $H$  in this region is due mainly to growth of M/G power.

For the plug-in hybrid, the M/G power no longer needs to grow. The M/G has sufficient power to move the vehicle. The battery power need not grow; however, battery energy must grow to gain more range. **Figure 4.** shows the parting of the ways of battery  $E$  and  $P$  in the plug-in region.

Battery  $E$  continues to increase while battery  $P$  remains constant at a value equal to M/G power. In this region, since M/G power is fixed, increases in  $H$  are due to shrinking engine power compared to M/G power.

Batteries can be designed so that power remains fixed while energy increases. What is the link that relates the power of the M/G to battery size or weight? Table I provides some qualitative comments on battery size.

$$\text{Desired run time} = \frac{\text{Energy stored in battery}}{\text{Power of M/G}} \quad (5)$$



**References:**

- [1] A. E. Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*, CRC Press, 2009

## Lecture 28 Design Principles of HEVs II:

### Design Principles of HEVs II

In this lecture the different types of the hybrid electric vehicles are presented. The following topics are covered in this lecture:

- Interpretation of Ramps
- Techniques to enhance hybrid performance
- Mild or micro hybrid features
- Plug-in hybrid
- All-wheel drive hybrid

### INTERPRETATION OF RAMPS

The interpretation of the ramps is discussed here. The example used in **Figure 1** applies to the capability of hybrids to exploit regenerative braking.

For a mild hybrid,  $H = 15\%$ , regenerative braking is possible but only about 38% of kinetic energy can be recovered. The calculation is  $15/40 = 38\%$ , which is the height of the ramp at  $H = 15\%$ .

The limitation is due to the small generator. The ramp ends at  $H = 40\%$  for which a hybrid has a generator large enough to enable high-efficiency regenerative braking.

For a full hybrid,  $H = 50\%$ , more than enough generating capability exists for regenerative braking. As denoted by the fl at bar, the span of  $H$  from 40% to 100% allows full regenerative braking.

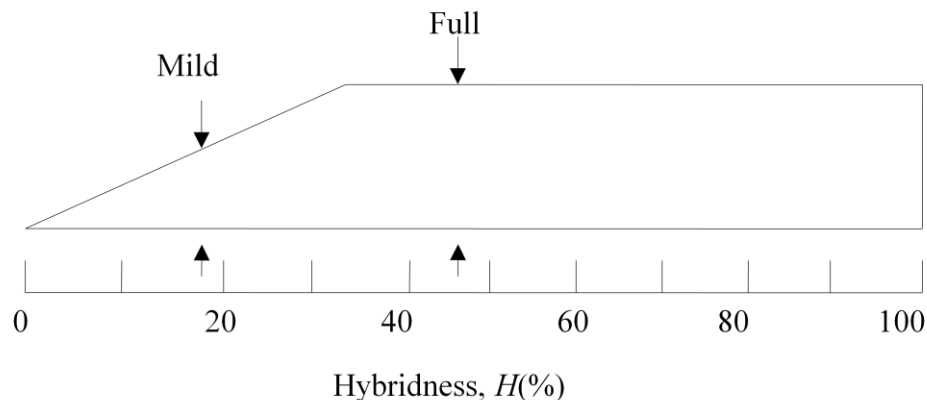


Fig.1. Interpretation of the ramps [1]

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**TABLE 1****Effect of Low Charge on Vehicle Performance**

<b>Acceleration</b>	<b>Full Charge</b>	<b>Partial Charge</b>
Time 0–60 mph, s	10.8	12.3
Standing quarter mile (s)	18.3	19.1
Speed at quarter mile (mph)	78	75

*Note:* Data are for a 2006 Honda Civic Hybrid as compiled from various sources.

## **TECHNIQUES TO ENHANCE HYBRID PERFORMANCE**

As a summary to the hybridness discussion, various techniques to enhance hybrid performance are arrayed with hybridness in **Figure 2**.

### **Start–Stop**

Engine-off during stops in traffic affords a saving in fuel. The usual 12 V starter does not have the power to restart the engine without delay, noise, and vibration. With the more powerful electrical motors, even in mild hybrid, the engine rpm can be quickly increased. Once smoothly and quickly up to starting rpm, the fuel injection can be activated.

### **Damping Driveline Oscillations**

Another way that fuel consumption can be reduced is to shut off fuel flow whenever brakes are applied. Abrupt turn off of fuel can cause shudder and unpleasant oscillations of the engine and of driveline. Damping by the electrical motor can decrease the unpleasantness to an acceptable level.

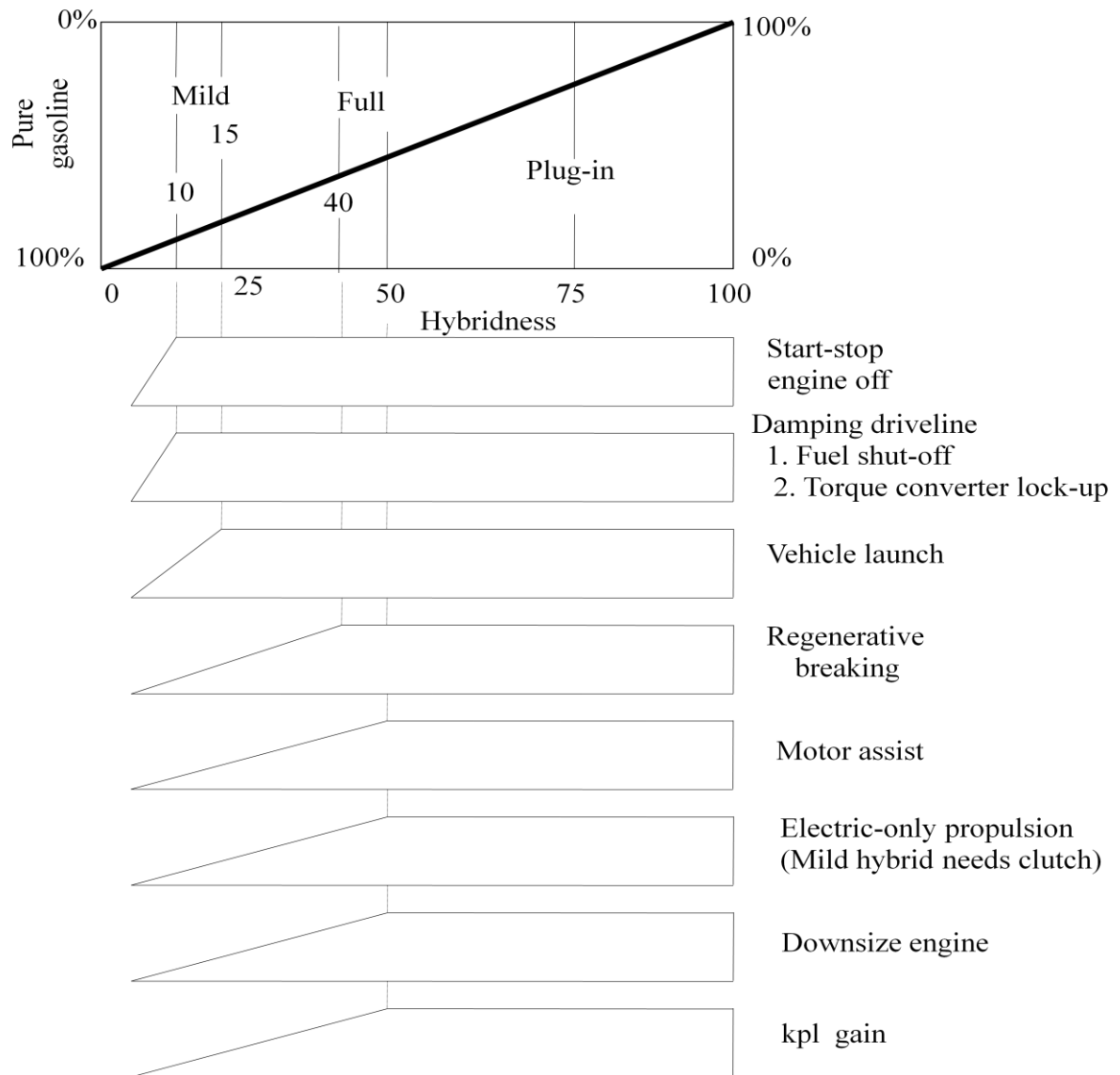
For a hybrid that uses an automatic transmission, some losses in the torque converter can be reduced by locking the torque converter eliminating slippage.

Under some conditions, when the torque converter is locked, driveline oscillations are excited; these oscillations are disagreeable to the customer. Once again, damping by the electrical motor can decrease the unpleasantness to an acceptable level.

## Vehicle Launch

An engine at low rpm has little torque. At launch, torque is essential. An electric motor, even a small one, has high torque at low rpm.

The motor fills in the torque hole at low rpm. A small motor can contribute significantly to the initial launch.



**Fig.2.** Availability of various techniques to enhance hybrid performance as a function of hybridness and resulting mpg gain. The bar below the hybridness graph has a ramp which extends from  $H = 0\%$  to a value of  $H$  for the particular technology. For start-stop, the ramp ends at  $H = 10\%$ . The flat bar beyond indicates that for all values of  $H > 10\%$ , that feature is available to the hybrid designer. [1]

### **Regenerative Braking**

For small values of  $H$ , which implies small generator, the Motor/Generator (M/G) set cannot absorb the kinetic energy of the vehicles forward motion in a rapid stop.

Although modest regenerative braking is possible and is used at low  $H$ , regenerative braking can only be fully exploited when  $H$  is about 40%.

### **Motor Assist**

Vehicle launch is part of motor assist, but applies to very low speed. Motor assist covers a broader range of speed and vehicle operations such as hill climbing and driving in snow. More power and a larger electric motor are required.

Hybridness,  $H$ , of 50% yields enough power from the electrical motor to overcome the power deficiencies of the downsized engine.

### **Electric-Only Propulsion**

Electric-only propulsion means the gasoline engine is shut down and does not consume fuel. Electric-only operation improves mpg.

To achieve performance goals, the motor must have adequate power. At  $H = 50\%$ , the traction motor is as large as the engine. Alone, the traction motor yields the desired performance.

Another reason that electric-only operation is desirable is the fact that emissions are zero or near zero. Stringent emission requirements may be met by electric-only operation. However, cool-down of the catalyst during idle-off is a problem to be solved.

### **Kilometer per liter gain**

*As hybridness increases, up to about 50%, mpg (1 mile per gallon = 0.425143707 kilometers per liter) also increases. This is a result of a balance between power required and power available. The increase in mpg possible by plug-in is not shown. Plug-in requires energy from charging stations.*

## **MILD OR MICRO HYBRID FEATURES**

As a result of being a mild hybrid, certain features follow. The M/G may be belt or chain driven. Alternatively, the M/G may be part of the flywheel. The M/G serves as the starter/alternator combined.

Mild hybrids have limited regenerative braking. The battery and installed M/G may be large enough to provide low speed motor assist or to provide low speed launch assist. For the rare case of a diesel/hybrid, the M/G in M-mode can provide cold start of the diesel.

For a mild hybrid, other possible design features include fuel cutoff at deceleration, idle shutoff, and torque converter lockup where applicable.

## **PLUG-IN HYBRID**

The plug-in hybrid can be viewed as an EV but with a small engine to extend range. Features of a plug-in hybrid include a large, heavy, expensive battery. The comparison with a full hybrid is a battery of a few 45.36 kg instead of the typical 45.36 kg in a full hybrid.

Additional equipment is needed to connect to external “wall plug” electrical source for recharging. Since batteries are high voltage, the voltage of the charging source must be even higher. Inductive rechargers prevent exposure to high voltage. The plug-in will likely have small gasoline engine driven generator for on-board charging; this engine separates the plug-in hybrid from the EV.

For people willing to undertake the recharging chore, the plug-in offers fantastic mpg. To gain the benefits, the range of hybridness for a plug-in is  $50\% < H < 100\%$  with  $H$  likely to be closer to 100%.

## ALL-WHEEL DRIVE HYBRID

For the subsequent discussion, some definitions are necessary: AWD = All-wheel drive, 4WD = Four-wheel drive, 2WD = Two-wheel drive, FWD = Front-wheel drive and RWD = Rear-wheel drive. In the discussion to follow, AWD is used for either AWD or 4WD.

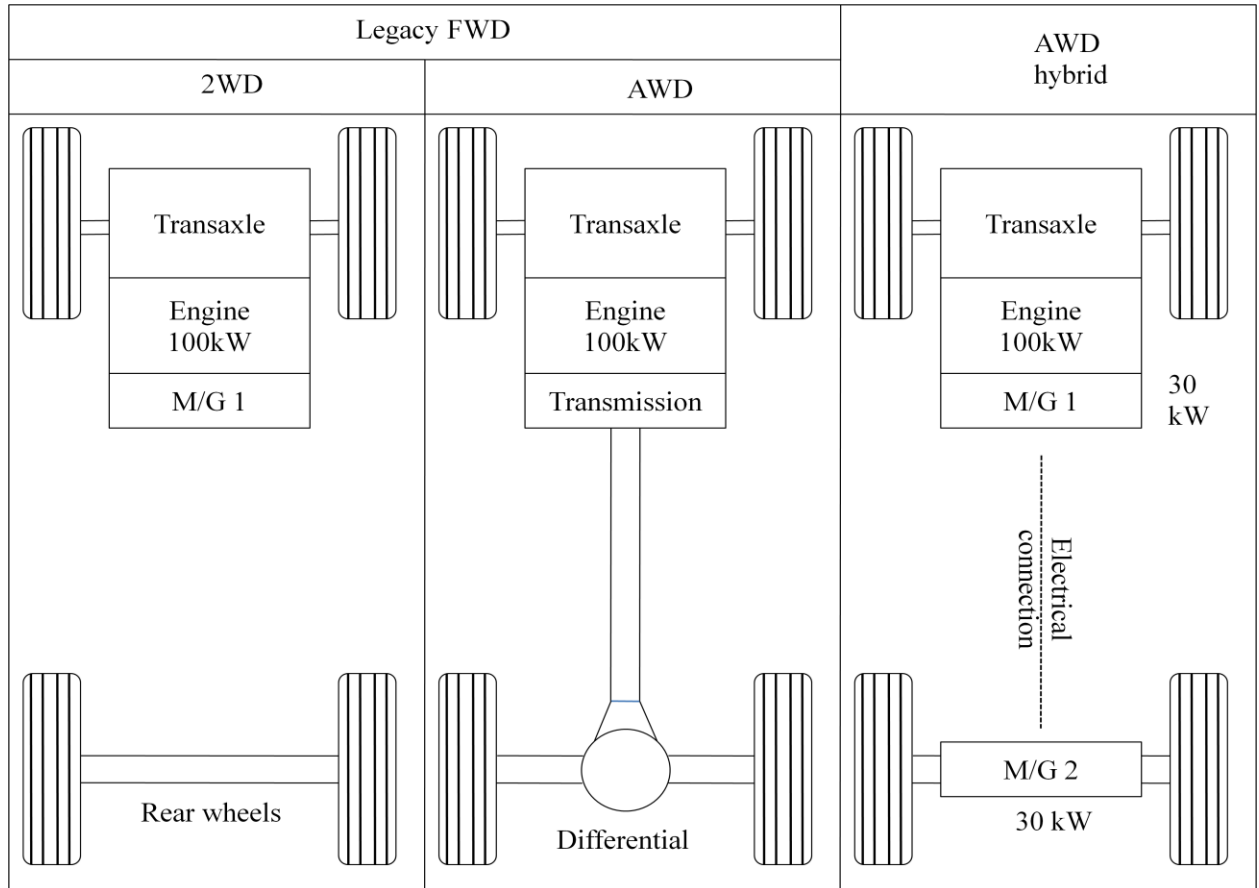


Fig.3. AWD hybrid design starting with an FWD legacy vehicle. The three drawings are 2WD, the conventional AWD, and hybrid AWD. [1]

The design for an AWD hybrid vehicle depends on whether the starting point is a conversion of an existing AWD vehicle or starting with a clean sheet of paper. With conversion of an existing design, the starting point is called the “legacy design.” Many conventional AWD vehicles are sold with the optional choice of either 2WD or AWD. The 2WD is less expensive than the AWD and provides better mpg. The optional 2WD versions may be either FWD or RWD. The 2WD on the left side of Fig.7 starts as FWD. The 2WD on the left side of **Figure 4** starts as RWD.

The legacy design affects the loading for the front and rear tires. With FWD, the front tires have three loads:

- cornering
- braking or traction
- steering.

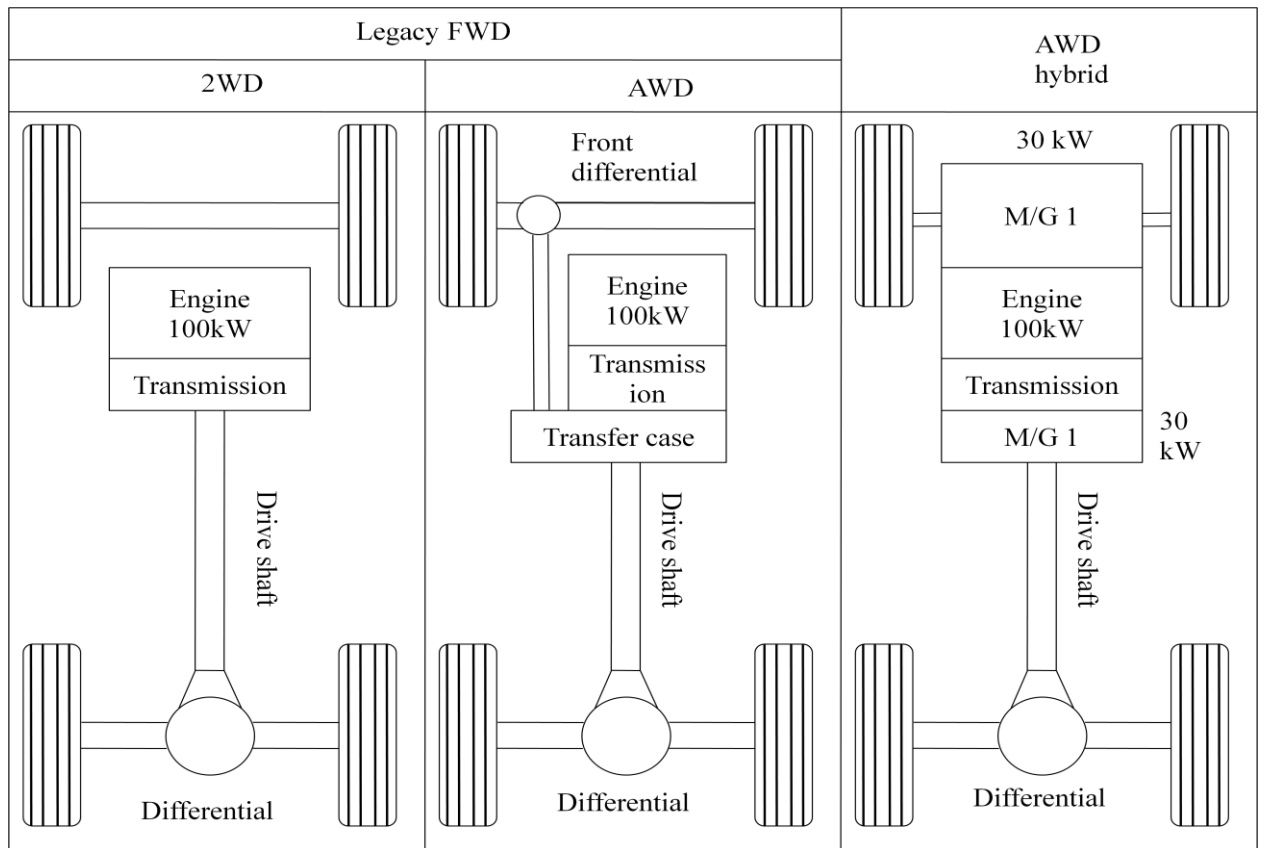
Tires have a load limit. Loads are additive. The rear tires carry, at most, two loads:

- cornering
- braking or traction.

Too much torque to the front wheels may overload the front tires. An overload adversely affects vehicle handling in extremis.

To avoid overloading the front tires, a torque split between front/rear is satisfactory with 50/50 or with a bias on the rear wheels of approximately 30/70 F/R.

The torque split need not be precisely equal to the numbers 50/50 and 30/70; values near these values are satisfactory.



**Fig.4. AWD hybrid design starting with an RWD legacy vehicle. The three drawings are 2WD, the conventional AWD, and hybrid AWD. [1]**



Table I, which is coordinated with **Figure 3** and **4**, shows the front and rear power loading for legacy FWD and legacy RWD. The traction motors are limited in power due to battery limitations. For discussion purposes, each M/G has a realistic 30 kW and the engine is 100 kW.

In motor assist, the battery must supply 60 kW, which is 30 kW for each M/G in M-mode (**Figure 3**). With a legacy FWD, the M/G is on the rear axle. This means the traction load on the rear axle is limited to 30 kW (**Figure 3**). With a legacy RWD, the M/G is on the front axle. This means the traction load on the front axle is limited to 30 kW, which is favorable in regard to loading of the tires.

**Figure 3** shows a legacy design of FWD for the optional 2WD. When the 2WD version of unmodified vehicle is FWD, then a hybrid conversion will undoubtedly have an electric traction motor driving the rear wheels. Front/rear torque bias will likely be reversed 70/30 F/R, which is usually unfavorable.

**Figure 4** shows a legacy design of RWD for the optional 2WD. If the 2WD version of the unmodified vehicle is RWD, then a hybrid conversion will undoubtedly have electric traction motor driving the front wheels. Front/rear torque bias will likely be a favorable 30/70 F/R.

AWD hybrid vehicles operate in the 2WD cruise mode of Table II. In the motor assist mode, both M/G are in M-mode providing traction. Hence

$$H = 60kW / (100 + 60kW) = 37.5\%$$

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TABLE II				
Power and Load to Front and Rear Wheels for Two Hybrid AWD Designs Using Either Legacy FWD or Legacy RWD				
Operational Mode	M/G 1	M/G	Power to Wheels	
			Front	Rear
<i>Legacy Design: FWD</i>				
2WD cruise	Off	Off	100	kW
0 kW				
4WD cruise	G-mode, 30 kW	M-mode, 30 kW	70 kW	30 kW
4WD motor assist	M-mode, 30 kW	M-mode, 30 kW	130kW	30 kW
<i>Legacy Design: RWD</i>				
2WD cruise	Off	Off	0 kW	
100 kW				
4WD cruise	M-mode, 30 kW	G-mode, 30 kW	30 kW	
70 kW				
4WD motor assist	M-mode, 30 kW	M-mode, 30 kW	30 kW	
130 kW				

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### References:

[1] A. E. Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*, CRC Press, 2009

## **Lecture 29: Drive cycle and its detailed analysis**

### **Drive cycle and its detailed analysis**

#### **Introduction**

The topics covered in this chapter are as follows:

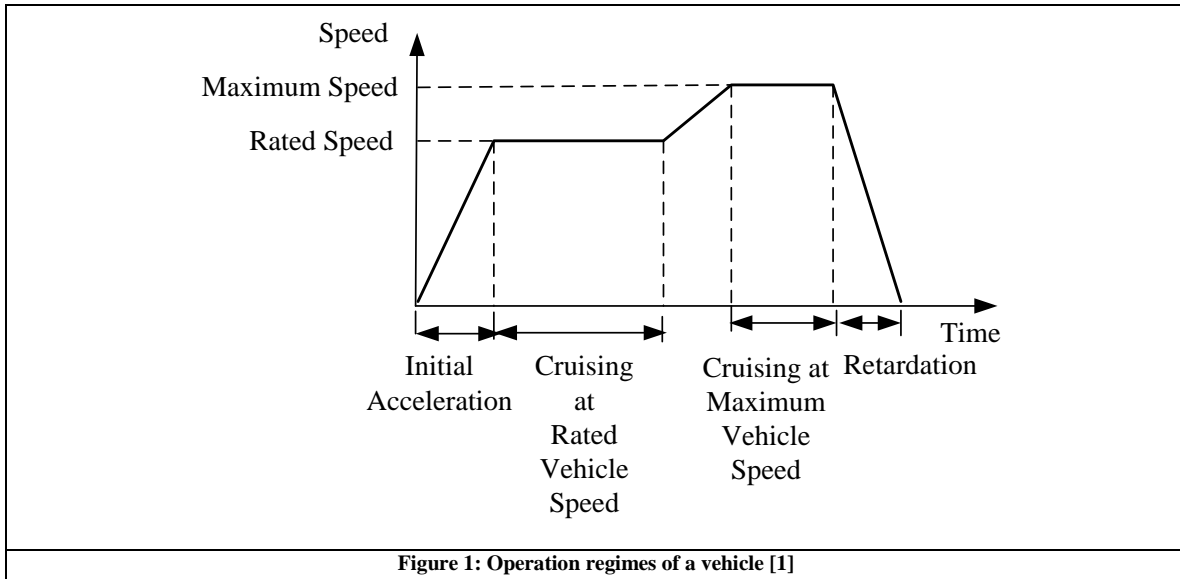
- Power Train and Drive Cycles
- New York City Cycle (NYCC)
- Japanese (JP-10-15)
- Extra Urban Driving Cycle (EUDC)
- Federal Test Procedure (FTP-75)
- New European Driving Cycle (NEDC)

#### **Power Train and Drive Cycles**

The power train of EVs and HEVs consists of Electric Motor (EM) and the Internal Combustion Engine (ICE). The first step towards the design of the power train is to determine the power ratings of the motor used in the EV and HEV drivetrain is to ascertain the motor specifications. These specifications are determined making use of the drive cycle the vehicle operates on and the vehicle dynamic equation for tractive force calculation. The design constraints set on the drivetrain like the initial acceleration time, the value of the cruising at rated vehicle speed, and the value of the cruising at maximum vehicle speed affects the specification of the induction motor. Finally, the tractive force required to propel the vehicle to the drive cycle chosen gives the necessary motor specifications used in the drivetrain.

The design constraints of power train of the vehicle are listed below and the vehicle operating regions are shown in **Figure 1**.

- i. Initial acceleration.
- ii. Cruising at rated vehicle speed.
- iii. Cruising at maximum vehicle speed.
- iv. Retardation.



Hence, in order to size the components of the vehicle properly, it is necessary to understand the drive cycle properly. The various drive cycles used are:

- **New York City Cycle (NYCC)**
- Japanese JP-10-15 Drive Cycle
- Extra Urban Driving Cycle (EUDC)
- Federal Test Procedure
- Federal Test Procedure (FTP-75)
- Inspection and Maintenance (IM-240)
- Highway Fuel Economy Test (EPAHWFET)
- Air-conditioning Supplemental (FTP SC03)
- Heavy Duty Urban Driving Cycle (HUDDSCOL)
- Unified Cycle Driving Schedule (UCDS) LA-92

The dynamic equations of the vehicle (refer **Lecture 3**) are used to analyse the impact of drive cycle on the vehicle performance. The dynamic equations of the vehicle give the force required to move the vehicle and this force is given as:

$$F_{\text{resistance}} = Mg f_r \cos(\alpha) + \frac{1}{2} \rho A_f C_D V^2 + Mg \sin(\alpha) + \lambda M \frac{dV}{dt} \quad (1)$$

In **equation 1**, the first term refers to **rolling resistance** ( $F_r$ ), the second term is the **aerodynamic drag** ( $F_w$ ), the third term is the **grading resistance** ( $F_g$ ) and the last term is the acceleration resistance ( $F_a$ ). Hence, the **equation 1** can be written as

$$F_{resistance} = F_r + F_w + F_g + F_a \quad (2)$$

The sizing of the components of HEVs and EVs is usually done in terms of **power**. The power can be determined from **equation 2** as

$$P_{resistance} = P_r + P_w + P_g + P_a \quad (3)$$

where

$$P_r = F_r V, P_w = F_w V, P_g = F_g V, P_a = F_a V$$

$V$  = speed of the vehicle in m/s

In the following sections the analysis of the some of the drive cycles (marked in bold and italicized) using the dynamic equations is done. The parameters of the vehicle that are used for the analysis are given in **Table 1**.

**Table 1: Parameters of the test vehicle**

Mass of vehicle [Kg]	5300
Coefficient of rolling resistance	0.01
Gravitation acceleration constant [m/sec <sup>2</sup> ]	9.81
Air density [kg/m <sup>3</sup> ]	1.3
Aerodynamic drag coefficient of vehicle	0.5
Frontal area of vehicle (m <sup>2</sup> )	5.65
Road angle [degrees]	0
Radius of the wheel [m]	0.21

### New York City Cycle (NYCC)

The New York City Cycle (NYCC) is a standard test drive cycle for the city traffic as is shown in **Figure 2**.

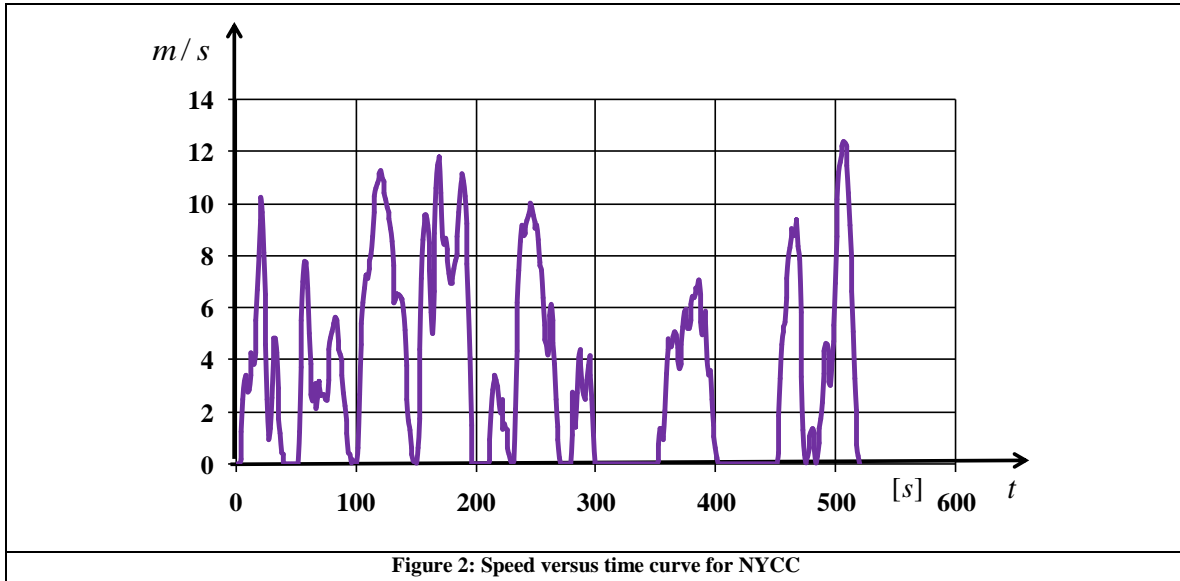


Figure 2: Speed versus time curve for NYCC

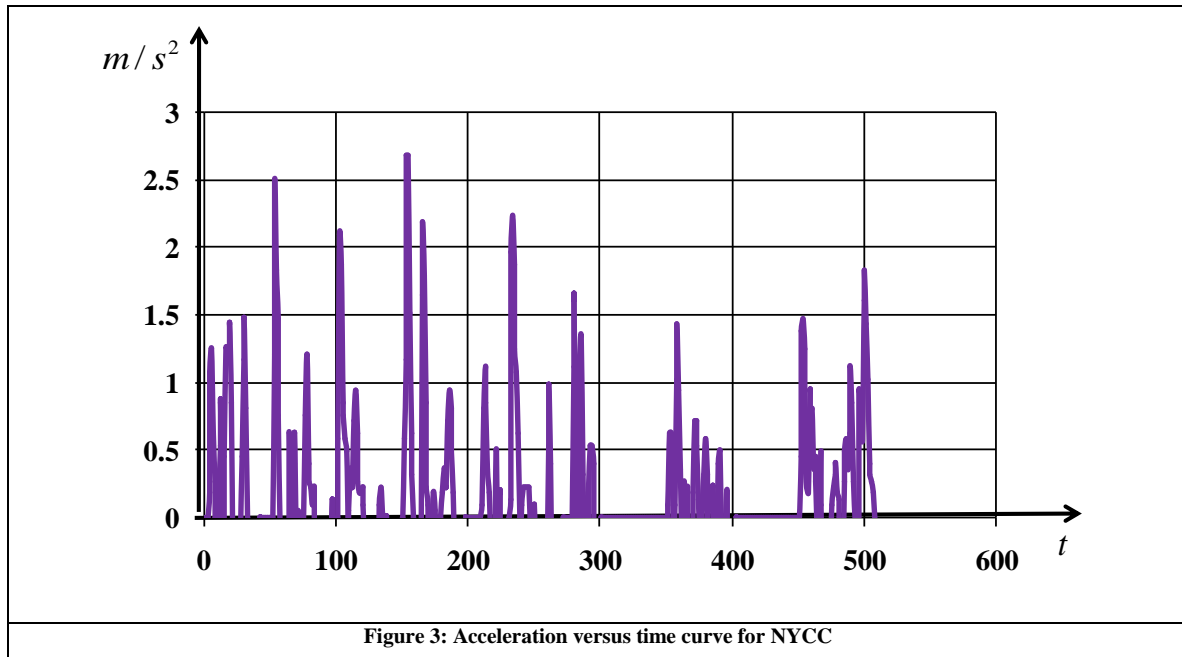
The NYCC is an aggregate of representative urban stop–go driving and its parameters are shown in **Table 2**.

Table 2: Parameters of NYCC

Average speed	3.63 [m/s]	Maximum deceleration	2.6 [m/s <sup>2</sup> ]
Maximum speed	12.4 [m/s]	Maximum power	85 [kW]
Maximum acceleration	2.7 [m/s <sup>2</sup> ]	Maximum braking power	89 [kW]

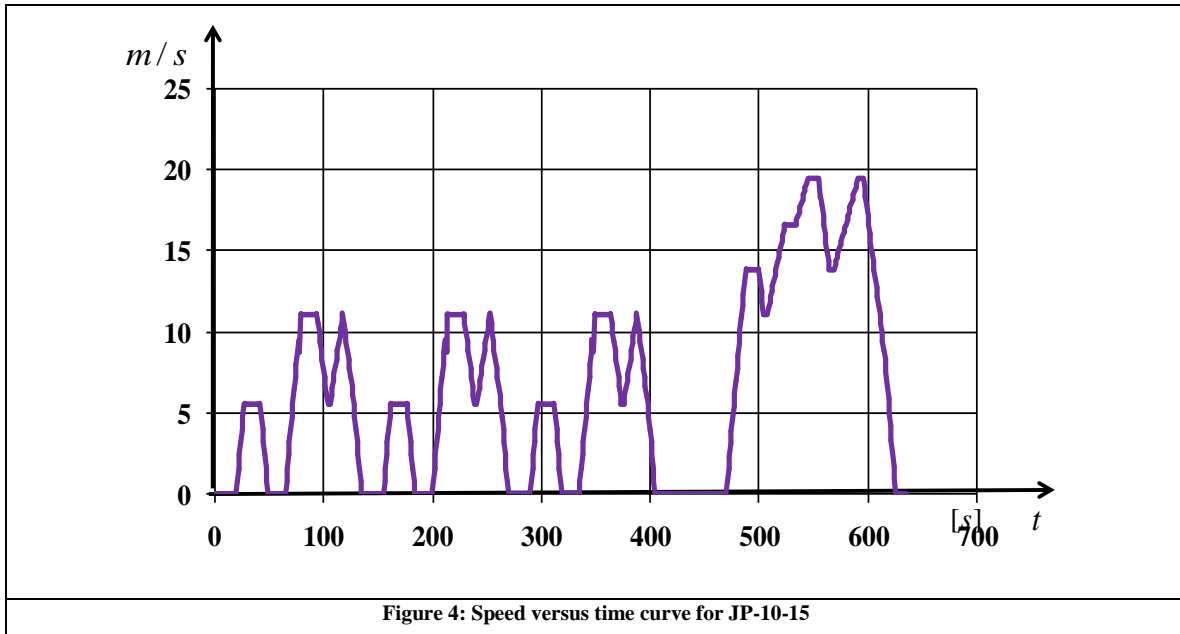
From the **Table 2** the following conclusions can be drawn:

- The maximum power required to move the vehicle on this drive cycle is about 85kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 89kW and a fraction this power can be recovered by using regenerative braking.
- The maximum and minimum acceleration that the vehicle experiences are  $2.7\text{m/s}^2$  and  $2.64\text{m/s}^2$ . EMs are better suited for such rapid acceleration because the torque produced by the EMs have higher overloading factor compared to ICEs, hence, a smaller EM will be sufficient.
- Moreover, from **Figure 2** and **3** it can be seen that the vehicle is subjected to frequent start-stop. Since the ICEs tend to be very fuel inefficient for such frequent start-stop operation, it is wise to use only EM as the prime mover.



### Japanese (JP- 10-15)

The Japanese JP- 10-15 test cycle is currently used in Japan for emission certification and fuel economy for light duty vehicles. It is derived from the 10 mode cycle by adding another 15-mode segment of a maximum speed of 70 km/h. The distance of the cycle is 4.16 km, average speed 22.7 km/h, duration 660 s (or 6.34 km, 25.6 km/h, 892 s, respectively, including the initial 15 mode segment). The Japanese JP- 10-15 test cycle is as shown in **Figure 4** and in **Figure 5** the acceleration versus time curve is given.



The driving cycle parameters for Japanese JP- 10-15 test cycle are as shown in **Table 3**.

Table 3: Parameters of JP-10-15

Average speed	6.53 [m/s]	Maximum deceleration	0.8 [m/s <sup>2</sup> ]
Maximum speed	15.2 [m/s]	Maximum power	108.8 [kW]
Maximum acceleration	2.3 [m/s <sup>2</sup> ]	Maximum braking power	46 [kW]



From the **Table 3** the following conclusions can be drawn:

- The maximum power required to move the vehicle on this drive cycle is about 108.8 kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 46 kW and a fraction this power can be recovered by using regenerative braking.
- The maximum and minimum acceleration that the vehicle experiences are  $2.3\text{m/s}^2$  and  $0.8\text{m/s}^2$ . EMs are better suited for such rapid acceleration because the torque produced by the EMs have higher overloading factor compared to ICEs, hence, a smaller EM will be sufficient. For regions where there is constant acceleration, the required power can be supplied by a combination of ICE and EM.
- Moreover, from **Figure 4** and **5** it can be seen that the vehicle is subjected to frequent start-stop however, there are time intervals where the vehicle travels at constant speed. Since the ICEs tend to be very fuel inefficient for such frequent start-stop operation, it is wise to use only EM as the prime mover. In the constant speed regions only ICE can be used to deliver the required power.

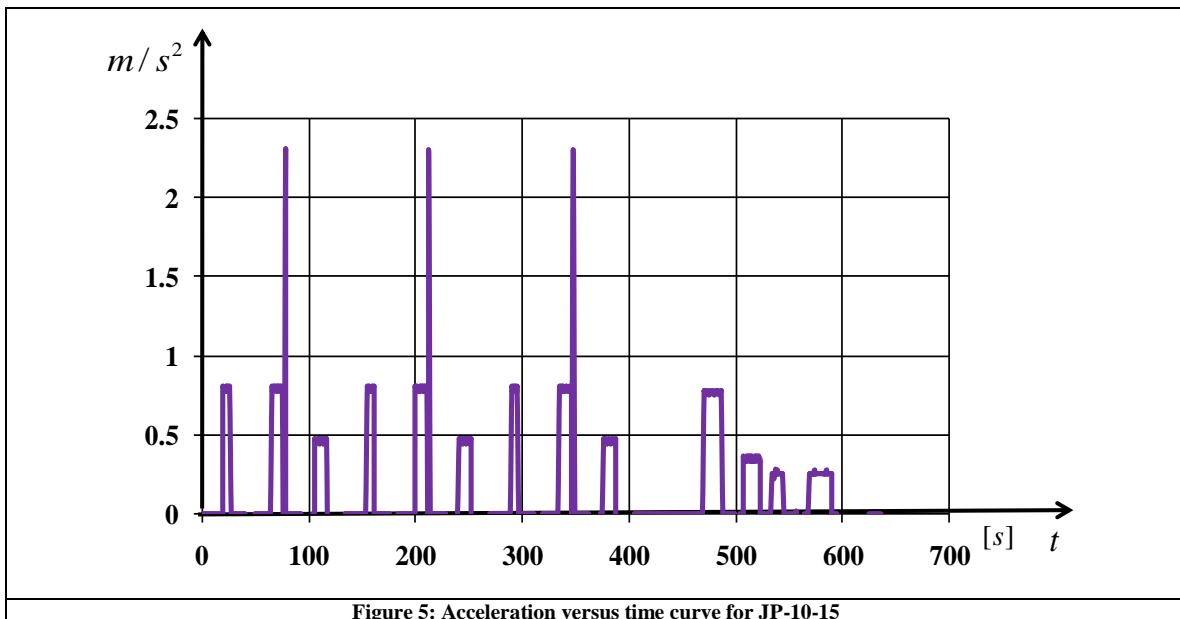
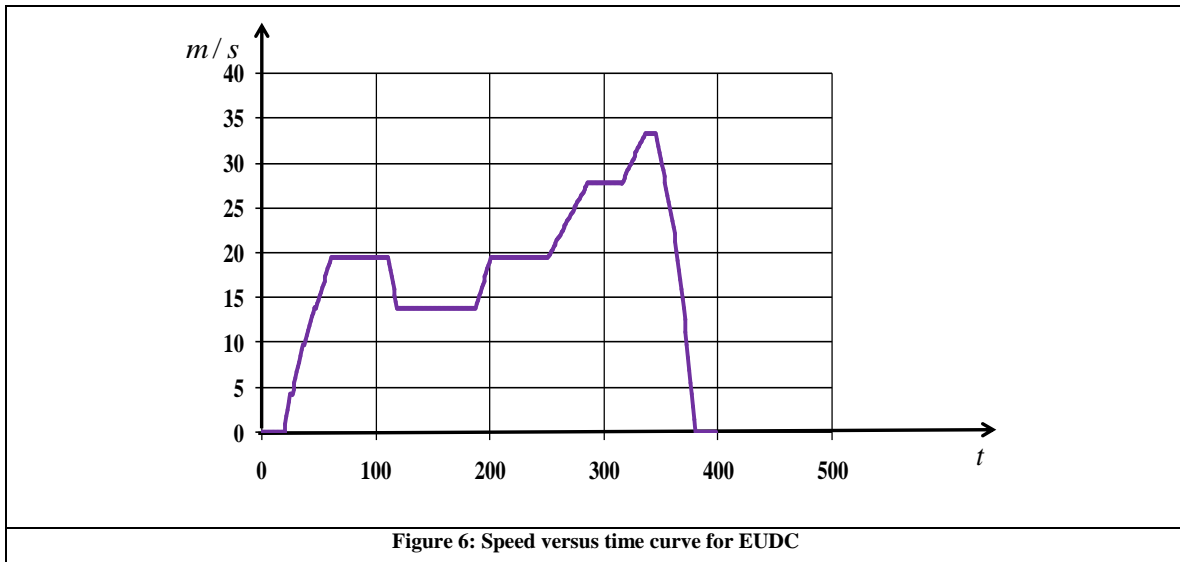


Figure 5: Acceleration versus time curve for JP-10-15

### Extra Urban Driving Cycle (EUDC)

The European drive cycle is composed of the ECE (Urban Driving Cycle) and a recently introduced Extra Urban Drive Cycle. For emissions certification, the ECE is repeated 4 times and then the EUDC once. The EUDC (Extra Urban Driving Cycle) segment has been added after the fourth ECE cycle to account for more aggressive, high speed driving modes. The maximum speed of the EUDC cycle is 120 km/h. An alternative EUDC cycle for low-powered vehicles has been also defined with a maximum speed limited to 90 km/h. The Extra Urban Driving Cycle EUDC is as shown in **Figure 6**.



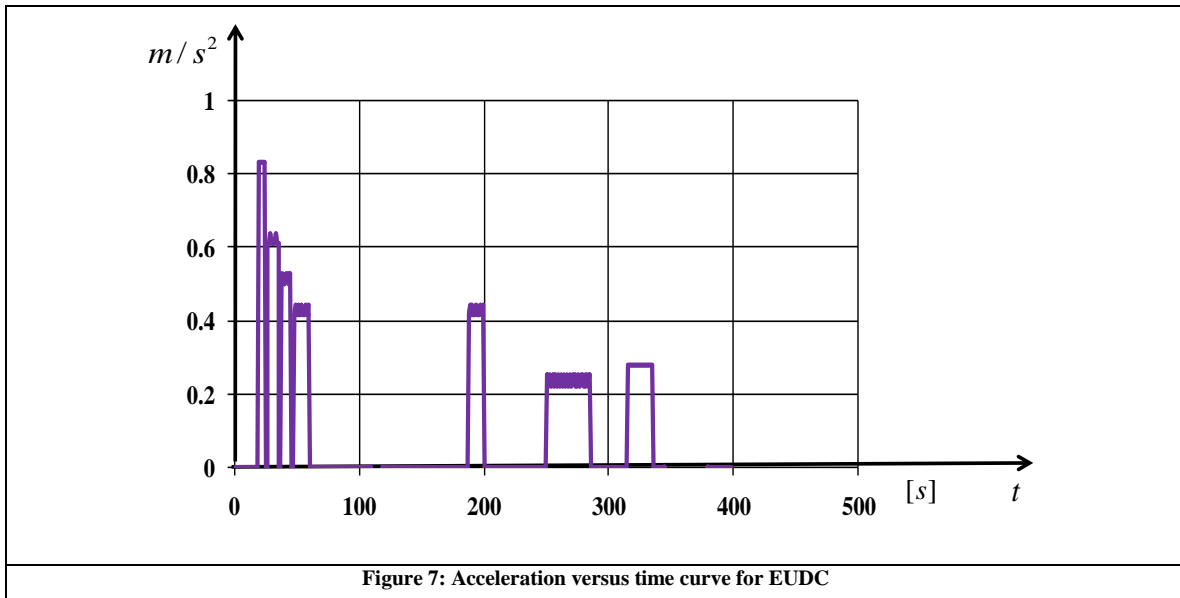
The driving cycle parameters for Extra Urban Driving Cycle EUDC are as shown in **Table 4**.

**Table 4: Parameters of EUDC**

Average speed	6.53 [m/s]	Maximum deceleration	1.33 [ $\text{m/s}^2$ ]
Maximum speed	33.33 [m/s]	Maximum power	115 [kW]
Maximum acceleration	0.83 [ $\text{m/s}^2$ ]	Maximum braking power	101 [kW]

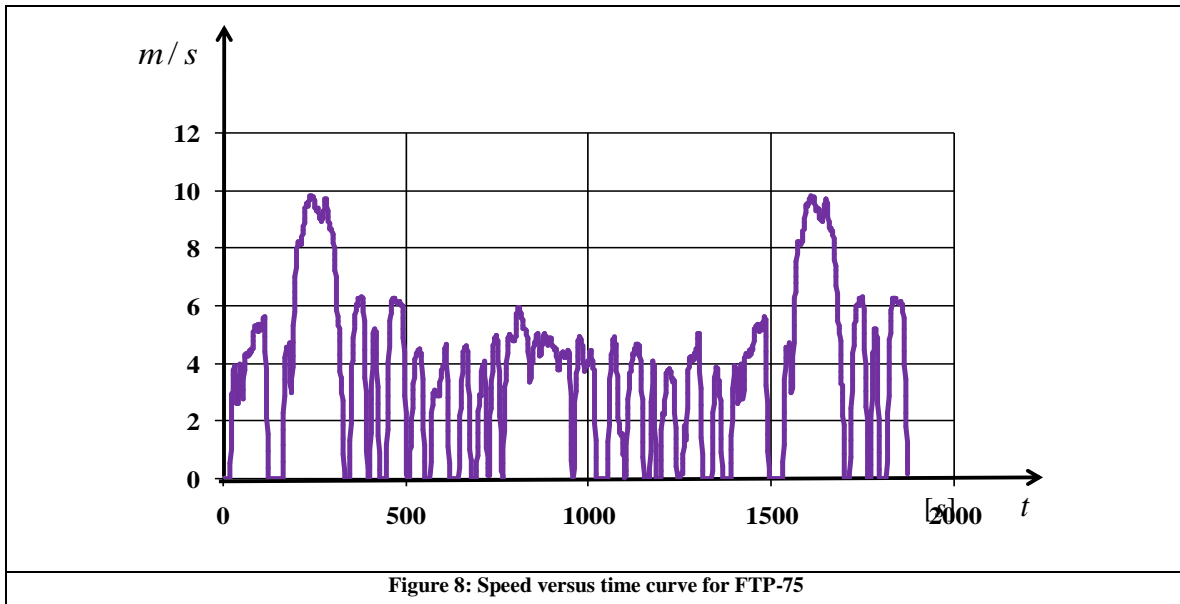
From the **Table 4** the following conclusions can be drawn:

- The maximum power required to move the vehicle on this drive cycle is about 115 kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 101 kW and a fraction this power can be recovered by using regenerative braking.
- The maximum and minimum acceleration that the vehicle experiences are  $0.83 \text{ m/s}^2$  and  $1.33 \text{ m/s}^2$ . Since this drive cycle does not involve start-stop operation, the ICE can be used to supply the required power.
- Moreover, from **Figure 6** and **7** it can be seen that the vehicle is subjected to high acceleration in the initial periods. During these periods, the power required to accelerate the vehicle can be obtained, in case of HEVs, from the combination of ICE and EM.



### Federal Test Procedure (FTP-75)

The FTP-75 (Federal Test Procedure) has been used for emission certification of light duty vehicles in the U.S. The FTP-75 cycle is derived from the FTP-72 cycle by adding a third phase of 505s, identical to the first phase of FTP-72 but with a hot start. The third phase starts after the engine is stopped for 10 minutes. Thus, the entire FTP-75 cycle consists of the following segments cold start phase, transient phase, hot start phase. The following are basic parameters of the cycle i.e. distance travelled is 11.04 miles (17.77 km), duration: 1874s, average speed is 21.2 mph (34.1 km/h). The FTP-75 cycle is known in Australia as the ADR 37 (Australian Design Rules) cycle. Federal Test Procedure FTP-75 drive cycle is as shown in **Figure 8**.



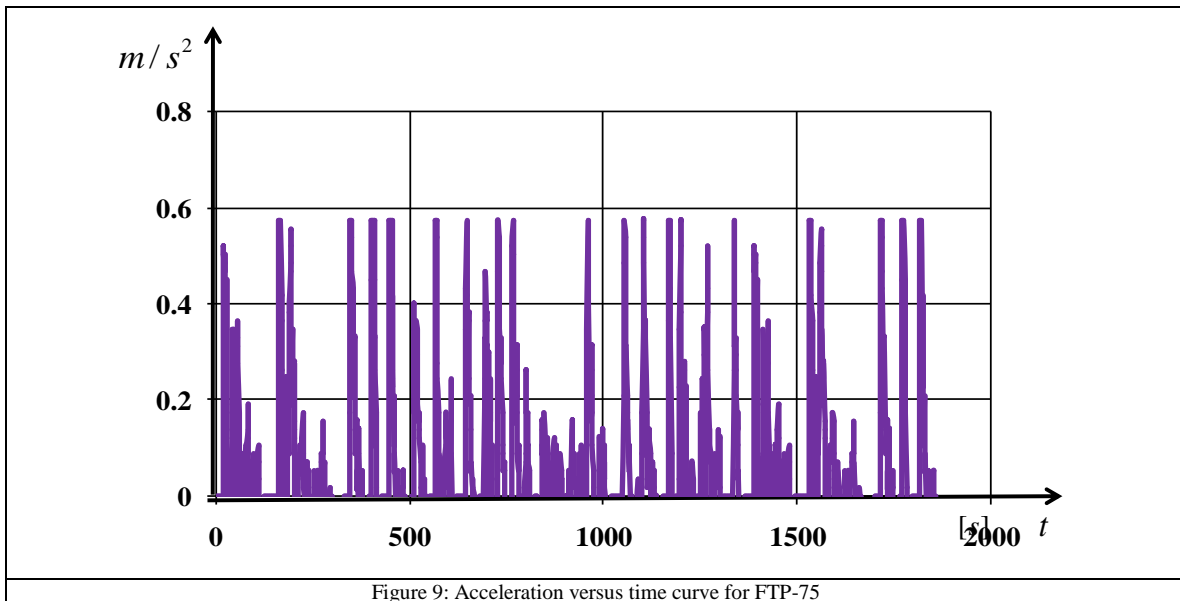
The driving cycle parameters for Federal Test Procedure FTP-75 are as shown in **Table 5**.

**Table 5: Parameters of FTP-75**

Average speed	3.7 [m/s]	Maximum deceleration	0.57 [m/s <sup>2</sup> ]
Maximum speed	9.8 [m/s]	Maximum power	15 [kW]
Maximum acceleration	0.57 [m/s <sup>2</sup> ]	Maximum braking power	15 [kW]

From the **Table 5** the following conclusions can be drawn:

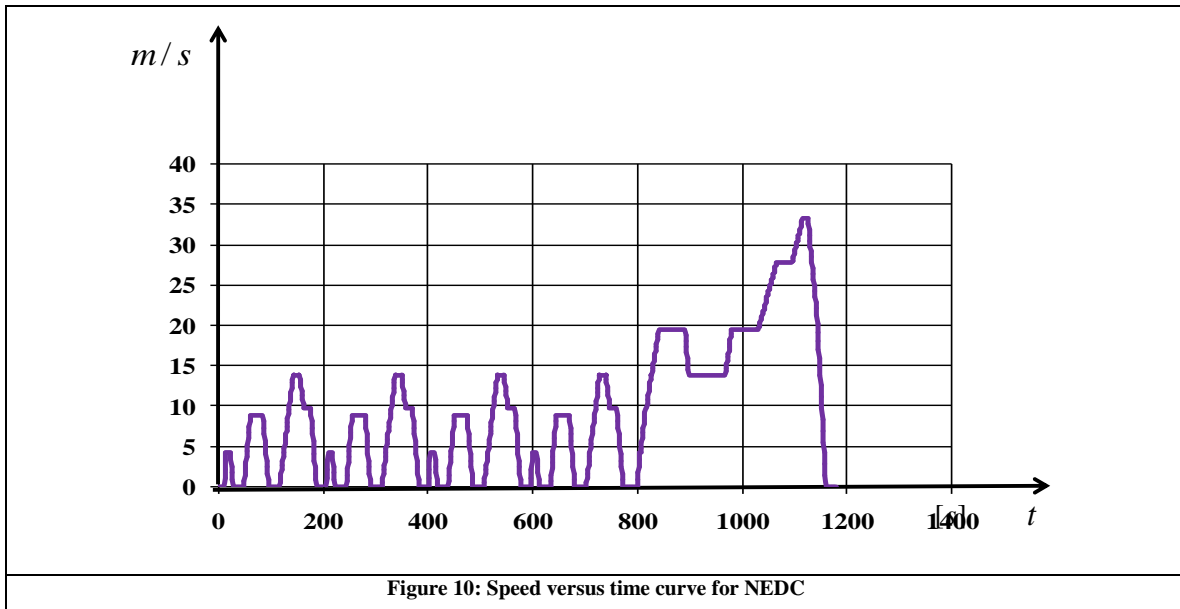
- The maximum power required to move the vehicle on this drive cycle is about 15 kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 15 kW and a fraction this power can be recovered by using regenerative braking.
- The maximum and minimum acceleration that the vehicle experiences are  $0.57 \text{ m/s}^2$  and  $0.57 \text{ m/s}^2$ . Since this drive cycle does not involve start-stop operation, the ICE and EM both can supply the required power.



### New European Driving Cycle (NEDC)

The New European Driving Cycle is a driving cycle consisting of four repeated ECE-15 driving cycles and an Extra-Urban driving cycle (EUDC). The NEDC is supposed to represent the typical usage of a car in Europe, and is used, among other things, to assess the emission levels of car engines. It is also referred to as MVEG cycle (Motor Vehicle Emissions Group). Effective year 2000, that idling period has been eliminated, i.e., engine starts at 0 seconds and the emission sampling begins at the same time. This modified cold-start procedure is also referred to as the New European Driving Cycle or NEDC.

The New European Driving Cycle NEDC drive cycle is as shown in **Figure 10**.



The driving cycle parameters for New European Driving Cycle NEDC are as shown in **Table 6**.

**Table 6: Parameters of NEDC**

Average speed	9.3 [m/s]	Maximum deceleration	1.33 [ $\text{m/s}^2$ ]
Maximum speed	14 [m/s]	Maximum power	115 [kW]
Maximum acceleration	1.05 [ $\text{m/s}^2$ ]	Maximum braking power	101 [kW]

From the **Table 6** the following conclusions can be drawn:

- The maximum power required to move the vehicle on this drive cycle is about 115 kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 101 kW and a fraction this power can be recovered by using regenerative braking.
- At low speeds (upto 10m/s) the power can be supplied by EM only and between 10m/s and 20m/s the tractive power can be supplied from the combination of EM and ICE.
- Moreover, from **Figure 10** it can be seen that the vehicle is subjected to high acceleration from 800 sec onwards. During these periods, the power required to accelerate the vehicle can be obtained, in case of HEVs, from the combination of ICE and EM.
- For when the vehicle cruises at speeds 15m/s, the tractive power can be delivered only by the ICE.

**References:**

[1] L. Guzzella, A. Sciarretta, *Vehicle Propulsion Systems*, Springer, 2007

## **Lecture 30: Sizing of Electric Machine for EVs and HEVs**

### **Sizing of Electric Machine for EVs and HEVs**

#### **Introduction**

The topics covered in this chapter are as follows:

- Sizing of Electric machine
- Peak Torque and Power
- Constant Power Speed Ratio
- EM Sizing
- Sizing Power Electronics
- Switch Technology Selection

#### **Sizing of the Electric Machine (EM)**

An EM is at the core of HEV drivetrains. The electric energy path of HEV consists of an energy storage unit (such as batteries, supercapacitors or fuel cells), a power processing unit (such as DC-AC converters) and an EM. In **Figure 1** a schematic of hybrid propulsion system is shown. Most EMs used in HEV or EV drivetrains have speed limit of 12000 rpm due to following reasons:

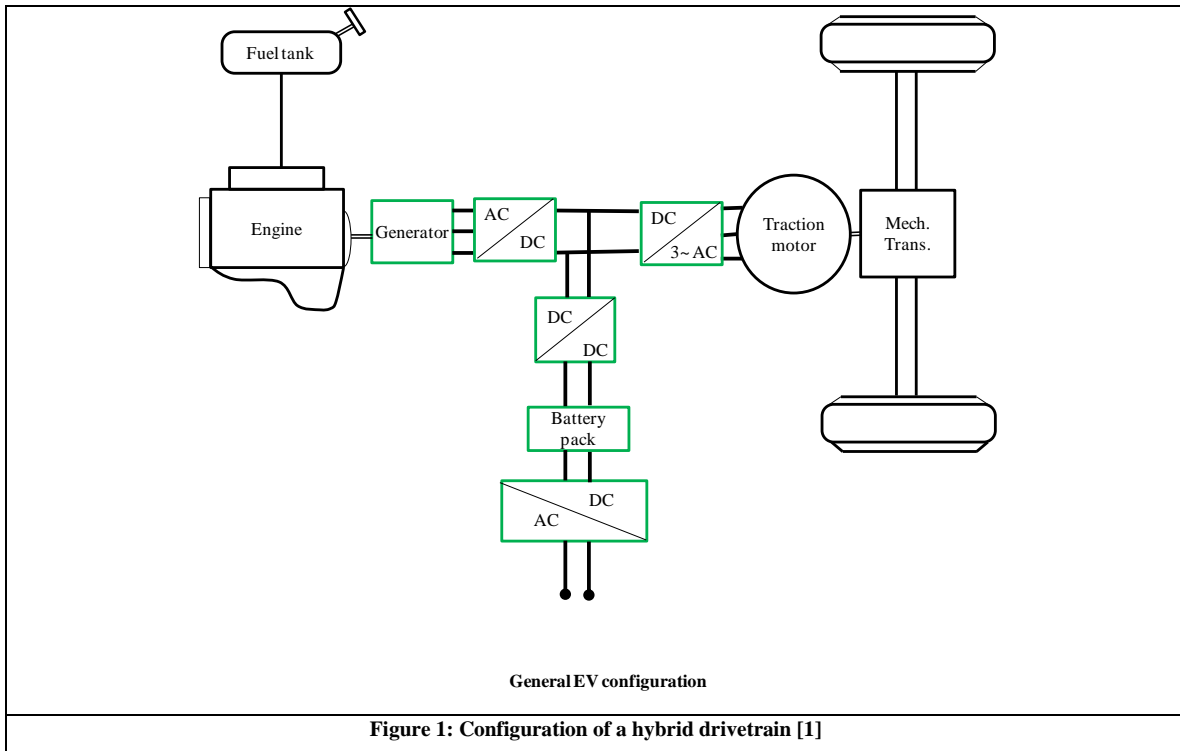
- i. At very high rpm, the centrifugal force acting on the rotor increases and it is possible that the rotor might fail mechanically.
- ii. The control algorithms of the EM involve determination of rotor position and this becomes very difficult at high rotor rpm.

The performance of EM is measured by following quantities:

- i. Torque and Power Capability
- ii. Constant Power Speed Ratio (CPSR)



In the subsequent section these quantities are explained in detail.

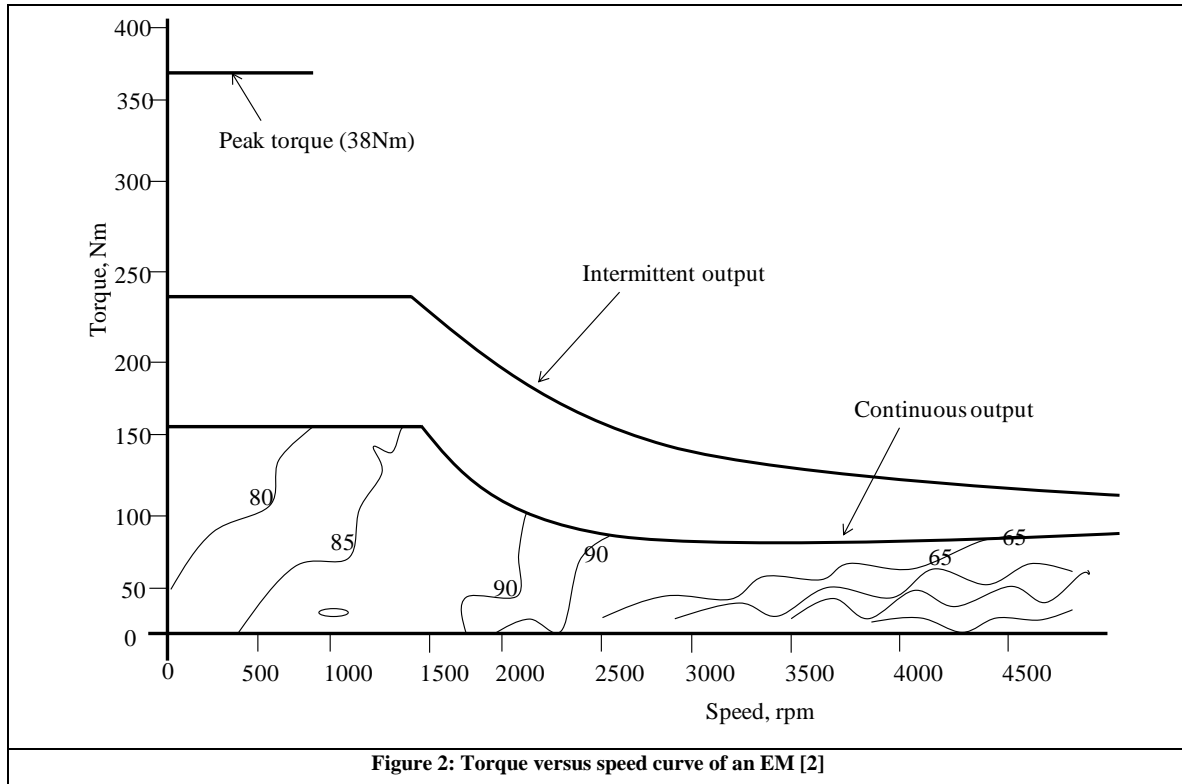


### Peak Torque and Power

The EM capability curves for torque and power define the peak operating capability curve of the HEV.

In **Figure 2** a typical torque versus speed characteristics of an EM is shown. There are three curves shown in **Figure 2** namely:

- i. **Continuous rating:** The EM can be operated within its continuous rated region.
- ii. **Intermittent overload operation:** The EM can operate in this regime for short duration (typically <30s).
- iii. **Peak overload operation:** The EM can operate in this region for a very short duration (typically <1~2s).



From **Figure 2** it can be seen that:

- i. the peak output is about 2.5 times the continuous or rated output
- ii. the intermittent output is about 1.5 times the continuous or rated output

The various operating regions show in **Figure 2** is:

- i. the region the flat torque region is known as the ***constant torque operating region***. In this region the DC-AC converter has sufficient voltage from the dc sources to inject required current into the EM.
- ii. when the machine speed increases and reaches the point **A**, the induced emf in the stator winding increases and the EM enters the constant power regime and flux weakening control is used.

### Constant Power Speed Ratio (CPSR)

In **Figure 3** the operation of EM in different modes is shown. The description of various operation modes is as follows:

1. In the 1<sup>st</sup> quadrant the EM works as a motor and its direction of rotation is clockwise (CW).
2. In the 2<sup>nd</sup> quadrant, the EM operates as a generator and its direction of counter clockwise (CCW)
3. In 3<sup>rd</sup> quadrant the EM operates as motor and its direction of rotation is CCW
4. In the 4<sup>th</sup> quadrant the EM operates as a generator and its direction of rotation is CW

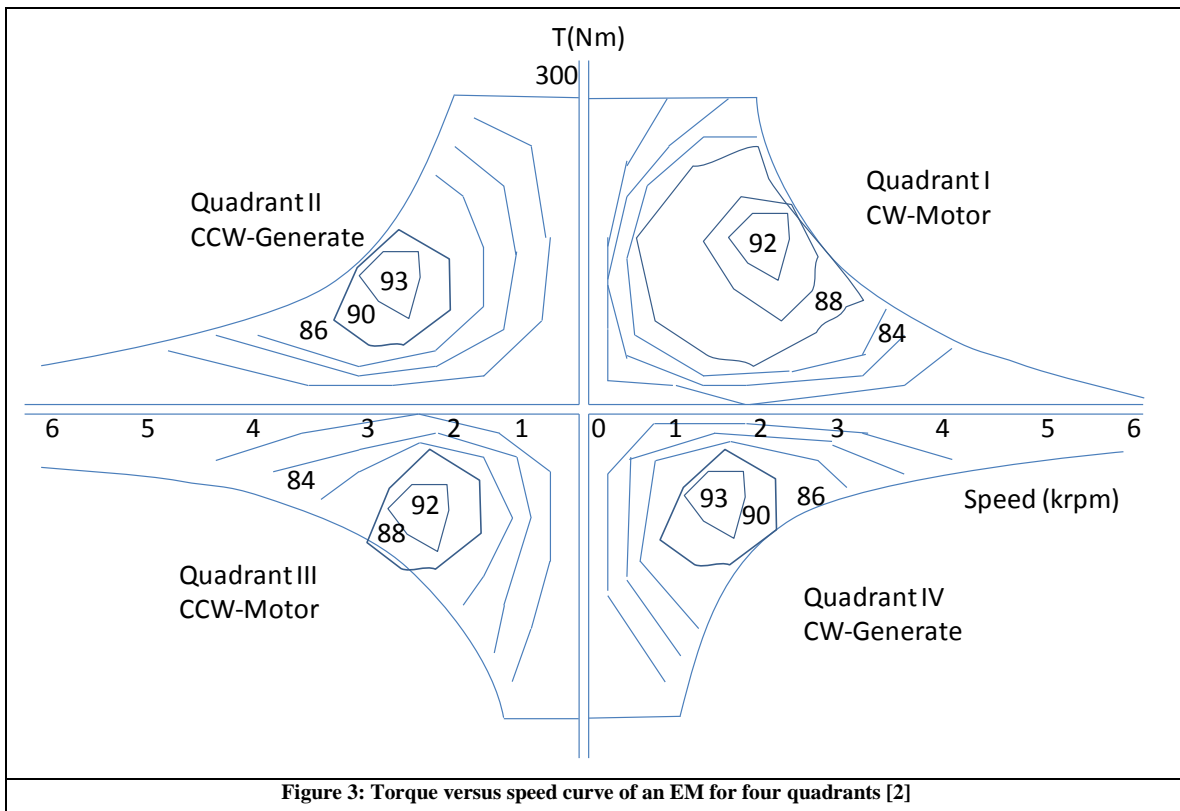


Figure 3: Torque versus speed curve of an EM for four quadrants [2]

In **Figure 3** the efficiency contours for the EM are also shown. A few observations from **Figure 3** are:

- i. The motoring operation of the EM occurs for positive torque and positive speed (CCW)
- ii. For negative torque and negative speed (CW) the motoring action takes place.

When the sign of either torque or speed are reversed the EM enters generating mode. With modern power electronic converters the EM is capable of operating anywhere within the confines of the torque versus speed envelope shown in **Figure 3**. The shift of EM's operation from one quadrant to the other is generally very fast but it depends on the previous and new operating points. For example:

- i. A transition from motoring at 2500 rpm and 100Nm of torque to generating at 2500 rpm and -100Nm of torque can be achieved a simple change in sign in the controller. Since the EM's transient electrical time constant is much smaller than the mechanical system, the torque change is viewed as occurring nearly instantaneously.
- ii. The driver wishes to overtake some vehicle and at that instant the EM is operating in motoring mode at 2500 rpm and producing a torque of 100Nm. After overtaking the driver slows to re-enter the traffic. When the driver slows, the EM has to decelerate and it acts as a generator and produces -100Nm of torque at a reduced speed, for example, of 1500 rpm. Initially the acceleration started the EM was operating in the field weakening region and during deceleration the EM has to operate in the constant torque region (**Figure 3**). Hence, the controller has to change its action from field weakening to constant torque regime and this process is slower than simply changing torque at constant speed. This changeover takes about 30ms to 100ms and is still much faster than the mechanical system.

### EM Sizing

The EM is physically sized by its torque specification. Since, EM torque is determined by the amount of flux the iron can carry and the amount of current the conductors can carry, and can be expressed as

$$T = kABD^2L$$

where

$k$  is proportionality constant

$A$  is total ampere-turns per circumferential length [A/m] (1)

$B$  is the Magnetic flux density [T]

$D$  is the diameter of the rotor [m]

$L$  is the length of the EM [m]

The two fundamental sizing constraints on the EM are:

- i. Electric loading
- ii. Magnetic loading

The electric loading is determined by the current carrying capacity of copper conductor and it is limited by its thermal dissipation. The bounds on the current density for copper is given by

$$J_{cu} = \left\{ \begin{array}{l} 2 \text{ A/mm}^2 \text{ for continuous operation} \\ 6 \text{ A/mm}^2 \text{ for 3 minutes} \\ 20 \text{ A/mm}^2 \text{ for 30 seconds} \end{array} \right\} \quad (2)$$

The magnetic loading, also defined by  $B$ , for EM is usually about 0.8 Tesla. The EM sizing using **equation 1** gives the first approximation of the size of EM. Once the initial size of the EM is obtained, detailed analysis and modelling techniques such as Finite Element Methods can be used to obtain detailed design.

The EM design is also constrained by a mechanical limit known as the *rotor burst* condition. For this constraint it is common to limit the EM rotor *tangential velocity to less than 200m/s*. At higher speeds the following factors become major concern:

- i. Critical speed flexing
- ii. Rotor retention
- iii. Rotor Eccentricity

### Sizing the Power Electronics

In **Figure 4** a schematic for the HEV drivetrain consisting of on board energy storage system, power processing unit and the EM is shown. The power electronics is an electrical element in much the same manner that a gearbox processes mechanical power to match the ICE to the road requirements.

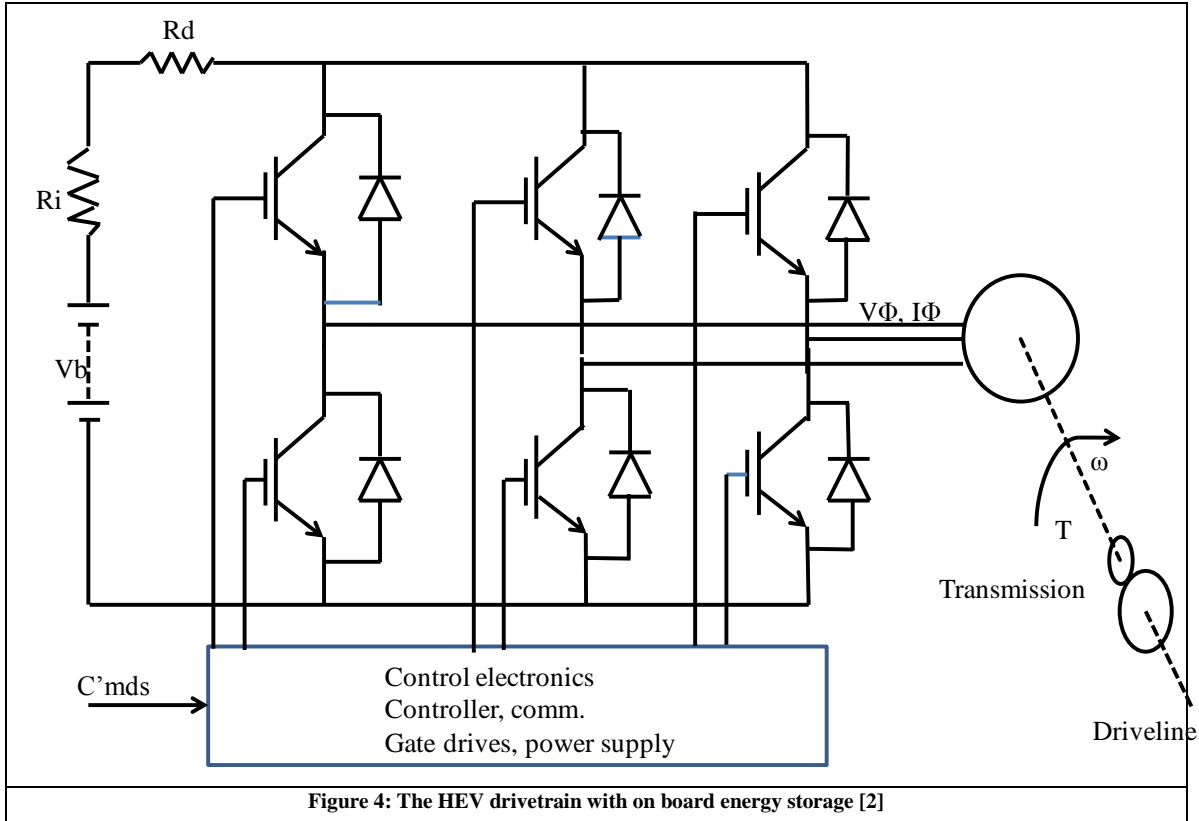
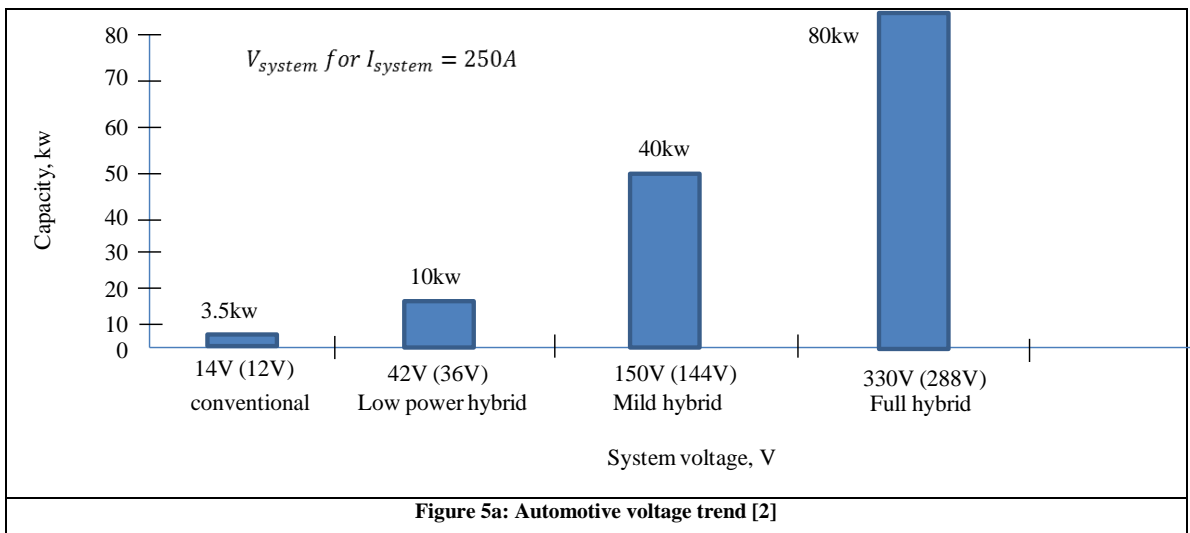


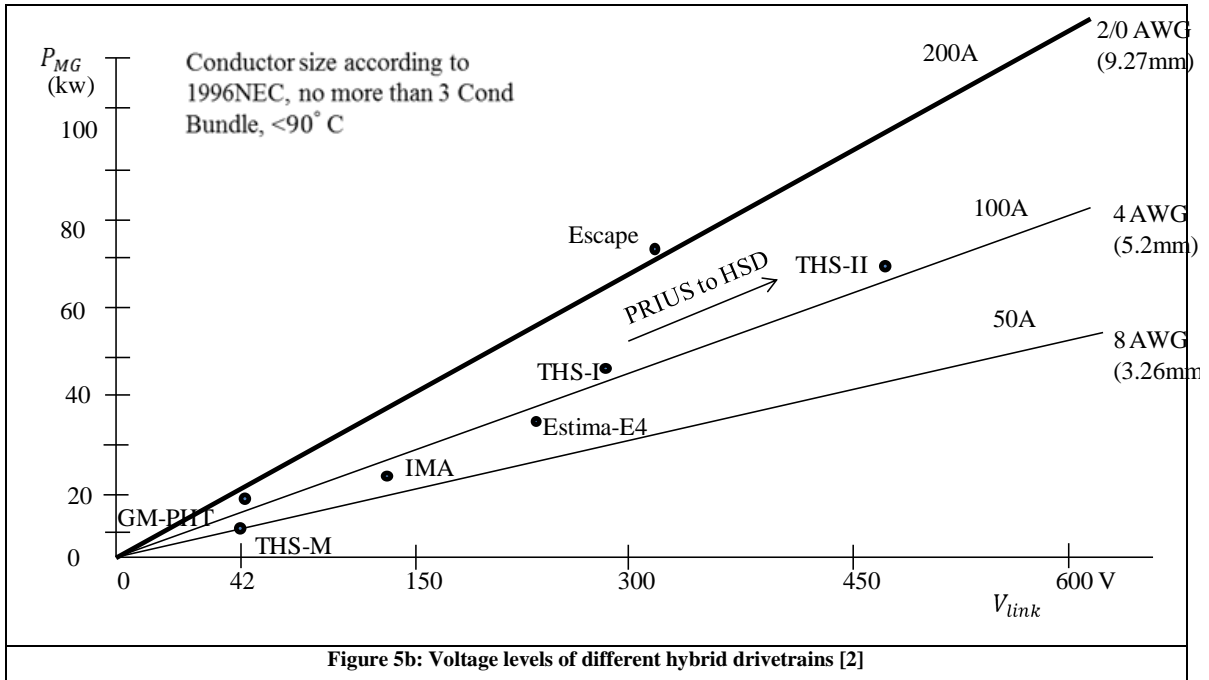
Figure 4: The HEV drivetrain with on board energy storage [2]

The power processing capability of power inverters is directly related to the dc input voltage available. Higher voltage means more throughput power for the same gauge wiring. The throughput power versus the voltage is shown in **Figure 5**. From **Figure 5a** it can be seen that as automotive voltages move towards 42V, the sustainable power level will approach 10kW. For hybrid propulsion the **Figure 5a** shows that voltages in excess of 150V are advisable. With recent advances in power electronic switches it is possible to move to voltage beyond 300V.

The **figure 5b** shows that most of the hybrid propulsion systems such as Toyota Hybrid System, Honda IMA, etc. are clustered along the 100A trend line.

Virtually all power electronics inverters for hybrid propulsion use IGBT device technology. Power semiconductor device range in voltage withstanding capability from 2kV to 6.5kV and current magnitudes from 3kA to 4.5kA. Thyristors have the highest kVA rating but are generally slow switching. The gate turn off thyristor (GTO) is capable of handling 3kA at 4.5kV but can switch at only 700Hz. The IGBTs have made enormous progress in both the voltage and current ratings, with some IGBTs being capable of handling 6.5kV and 3.5kA and have switching frequency up to 100kHz.





### References:

- [1]. M. Ehsani, *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design*, CRC Press, 2005
- [2] A. E. Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*, CRC Press, 2009