TESTING, ANALYSIS AND EFFICIENCY OPTIMIZATION OF A SMALL ELECTRIC MOTORCYCLE

AHMAD SYAZLI BIN MOHD KHALIL

UNIVERSITI SAINS MALAYSIA

2012

TESTING, ANALYSIS AND EFFICIENCY OPTIMIZATION OF A SMALL ELECTRIC MOTORCYCLE

BY

AHMAD SYAZLI BIN MOHD KHALIL

Thesis submitted in fulfillment of the
requirements for the Degree of
Master of Science

April 2012

ACKNOWLEDGEMENT

In The Name Of Allah,

The Most Beneficent, The Most Merciful.

Firstly, I would like to express my gratitude and dedicate this dissertation to my beloved mother, ***Zainun Abdullah*** and my beloved late father, ***Mohd Khalil Sheikh Haji Ahmad***, who inspired me in furthering my study and always being supportive throughout the study period. I will always forever indebted to them, and also not to forget, to all my beloved siblings and family members for their prayers and encouragements.

Secondly, I would like to thank my supervisor, Professor Horizon Walker Gitano-Briggs for his guidance and assistance for making this project successful. This project was funded by Research University Grant (1001/PMEKANIK/814009) and APEX Research and Innovation Grant (1002.335.AUSM.ARSP3001).

And lastly but not the least, to all the technicians especially Mr. Mohd Zalmi, Mr. Khomaruddin, Mr. Mohd Sani, Mr. Baharom, Mr. Azhar, Mr. Kamarul Zaman and Mr. Mohd Shawal, who helped me in some critical parts of my project such as design, fabrication and testing work. And also to all my friends who were involved either directly or indirectly in this project.

I really appreciate all the helps that I received during my study. Thank you very much.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BEV	battery electric vehicle
CO	carbon monoxide
CO_2	carbon dioxide
DAQ	Data acquisition
EV	electric vehicle
H_2	hydrogen gas
H_2O	water or steam
HC	unburned hydrocarbons
HEV	hybrid electric vehicle
HFCV	hydrogen fuel cell vehicle
F_{acc}	acceleration force
F_{ad}	aerodynamic drag
F_{cr}	climbing resistance force
F_{rr}	rolling resistance force
FCV	fuel cell vehicle
GPS	global positioning system
IC	internal combustion
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
Mtoe	million tons oil equivalent
N_2	nitrogen gas
NO_X	nitrogen oxides
RFB	redox flow battery

PENGUJIAN, ANALISA DAN PENGOPTIMUMAN KECEKAPAN MOTOSIKAL ELEKTRIK BERKUASA RENDAH

ABSTRAK

Apabila bahanapi petroleum semakin berkurangan, sektor kenderaan akan lebih tertumpu kepada teknologi berkuasa elektrik. Salah satu dari masalah utama dengan kenderaan elektrik generasi terkini ialah jarak pemanduan yang terhad yang disebabkan oleh kapasiti bateri yang tidak mampu bersaing dengan cecair hidrokarbon. Meningkatkan jarak pemanduan memerlukan kepada pengurangan prestasi kenderaan atau peningkatan kos kenderaan. Tujuan kajian ini adalah untuk pengoptimuman jarak pemanduan dan prestasi sebuah motosikal elektrik. Jarak pemanduan dinilai dengan penggunaan aliran elektrik dimana aliran yang tinggi akan mengurangkan kapasiti keluaran bateri. Prestasi kenderaan ujian dinilai berdasarkan kepada ciri-ciri kecekapan semasa pengujian tak tetap kenderaan. Nisbah gear akhir, voltan and kitaran pemanduan akan dikaji kesannya terhadap prestasi and jarak pemanduan motosikal elektrik. Kendaraan ujian pada mulanya diuji untuk prestasi tetap di atas dinamometer dan parameter kajian akan dianalisa untuk hubungkaitan bagi membentuk satu model simulasi dalam menjangka prestasi tak tetap kendaraan. Kendaraan ujian kemudiannya diuji di atas sebuah dinamometer berdasarkan kitaran pemanduan ECER40 pada nisbah gear berlainan. Pada nisbah gear yang lebih besar, kenderaan ujian menunjukkan prestasi yang lebih baik berbanding pada nisbah gear yang lebih rendah. Untuk kenderaan ujian yang mempunyai sistem voltan berlainan, system voltan yang lebih tinggi menyebabkan pengurangan penggunaan aliran dan lebih cekap berbanding kendaraan bervoltan rendah. Kajian telaga-ke-tayar dan pencemaran menunjukkan motosikal elektrik mempunyai kecekapan keseluruhan yang lebih baik dan pengeluaran CO_2 yang lebih rendah berbanding kepada motosikal berkapasiti 110cc untuk kajian dalam Malaysia.

TESTING, ANALYSIS AND EFFICIENCY OPTIMIZATION OF A SMALL ELECTRIC MOTORCYCLE

ABSTRACT

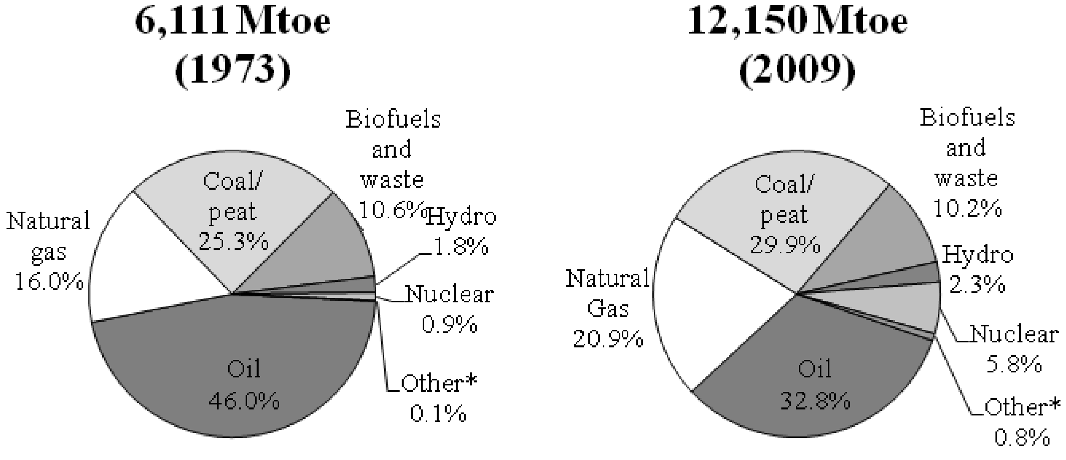
As liquid petroleum fuels deplete, transportation will shift increasingly to electric propulsion technology. One of the main problems with the current generation electric vehicles is limited range because the batteries do not have the energy storage capacity afforded by liquid hydrocarbons. Maximizing the range of electric vehicle requires a reduction in performance or an increase in cost of the system. The goal of this study is to optimize the range and performance of an electric motorcycle. The driving range of the experimental vehicle is justified by the current consumption rate where higher current rate significantly reduces the battery discharge capacity. The performance of the experimental vehicles is justified based on the efficiency characteristic during vehicle transient testing. Final gear ratio, voltage, and drive cycle are investigated for their effects on the electric motorcycle performance and range. The experimental vehicles were initially tested for steady-state performance on a chassis dynamometer and the studied parameters are analyzed for correlationship to formulate a simulation model in predicting the vehicle transient performance. The experimental vehicles were then tested on chassis dynamometer based on ECER40 at different gear ratio. It was found that at higher gear ratio, the experimental vehicles performed better than in the lower gear ratio. For the experimental vehicle with different voltage system, it was found that higher voltage will results in lower battery current consumption and better efficiency than the vehicle with lower voltage. Well-to-wheel energy and emission analysis shows that electric motorcycle has better overall efficiency and lower CO_2 emission compared to a 110cc motorcycles for case study in Malaysia.

CHAPTER 1

INTRODUCTION

1.1 Research background

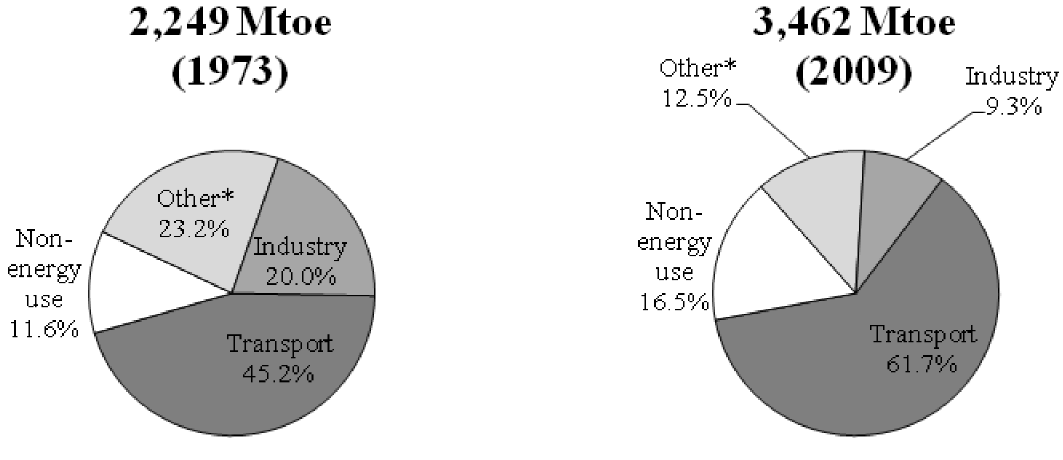
Energy security is one of the most important concerns of many countries in the world**.** The dependency on petroleum fossil fuels is a devastating threat to some nations especially with the growing import dependence, risks of supply disruptions, peaking of oil production, high energy prices and infrastructure reliability (McPherson et al. 2005). Another concern regarding the consumption of these fuels is the adverse effects on the environment including air pollution, acid rain, global warming and certain human diseases. These issues become are becoming more important in the developing world due to increasing energy demand.



*other includes geothermal, solar, wind, heat etc

Figure 1.1 World total primary energy supply by fuel (EIA 2011b)

In the last 40 years, the world's share of energy supply has become less dependent on petroleum oil but the amount of the energy supply has increase by almost 100% between 1973 and 2009 with 41.8% increase in the oil consumption, as shown in Figure 1.1, and the oil consumption has become more concentrated on transport sector as shown in Figure 1.2. For road transportation sector, internal combustion engine vehicles (ICEVs) are the most common vehicle in the world. Unfortunately, the typical automotive engine efficiency is at best about 20%-30% and produces very harmful emissions. The ICEVs are expected to be dominant vehicles for several more decades as there is no competitive technology ready for immediate replacement. In South East Asia, most countries have very high number of motorcycles on the road. This transportation mode is preferred for daily commute purpose mostly due to their small size which enables user to bypass the road traffic congestion and the overall low cost including ownership cost, maintenance cost, and energy cost. Even though the motorcycles consume less fuel compared to passenger cars due to their significantly small size, these small engine vehicles are less efficient in terms of liters of fuel and produce more pollution than passenger cars (Vasic & Weilenmann 2006; Chan et al. 1995).



*other includes agriculture, commercial and public service, residential, and non-specified other.

Figure 1.2 World petroleum oil consumption by sector (EIA 2011b)

In order to become independent of petroleum oil, the use of ICEV needs to be eliminated or substantially reduced. Electric vehicles (EVs), hybrid electric vehicle (HEVs) and fuel cell vehicles (FCV) are potential replacements of this conventional vehicle. The EVs have the best energy conversion efficiency and the biggest potential in reducing the negative environmental impacts especially in the developing countries due to its high energy-efficient system and the absence of tailpipe emission (Chan 2007; Doucette & McCulloch 2011). However due to several limitations such as cost, complexity, weight and reliability, this technology may not be viable for powering two-wheeled vehicle.

1.2 Problem statement

Internal combustion engines have relatively low peak energy efficiency and the peak efficiency only covers small fraction of overall operation. Their efficiency worsens during idling and deceleration where there is no useful power produced. The efficiency of ICEVs varies greatly at different driving conditions, and due to poor overall efficiency, high emission and high concentrations of vehicles, they cause significant deterioration of urban air quality especially the small engine vehicle such as motorcycles (Fatumata & Gordon 2009).

To reduce petroleum consumption and emissions from these conventional motorcycles in the countries where these vehicles are the most common, replacement with electric two-wheelers in highly populated area such as in the urban centers is a possibility (Weinert et al. 2008). Due to the limitations of current battery technologies, the EVs are not the best alternative for normal driving and only suitable for short range commute purposes. The range of EVs is generally specified at certain constant speed. However, in practice, the vehicle is almost never driven at a constant speed and driving characteristics are mostly influenced by the geographical location such as urban, rural and highways area.

With the torque-speed profile of electric motors closer to the ideal engine, the use of single gear ratio transmission is sufficient to meet the vehicle performance requirement, and the gear sizing are mostly depends on vehicle top speed and acceleration requirement (Husain 2003). However improper gear sizing will reduce the overall efficiency of the vehicle, increasing the battery discharge current rate for the same drive cycle, and consequently leads to efficiency loss of battery and electric motor. In order to fully optimize the range and performance of BEVs, it is necessary to study the EVs based on a practical driving cycle, rather than constant speed test.

1.3 Objectives

The objectives of this research are as follow:

1) To develop electric motorcycles with different power ratings and voltage systems.
2) To measure the steady-state performance characteristics of the experimental vehicles and to develop a model to predict the transient vehicle characteristic based on the ECER40 drive cycle.
3) To test the electric motorcycle based on transient ECER40 drive cycle using chassis dynamometer at various gearing ratios, and optimize for range and performance.
4) To determine the well-to-wheel energy efficiency and emission of conventional motorcycle and the experimental electric motorcycle.

1.4 Scope of research

The scope of this research are as follow:

1) The electric motorcycles developed must be sufficient for commuting purpose using conventional EV components i.e. brushless DC motor as the propulsion and lead acid battery as the energy storage.
2) The steady-state performance characterization of the experimental vehicles is measured on a chassis dynamometer by varying the throttle setting at different constant speed points to obtain the speed-torque characteristics of the vehicles. A simulation model can then be established based on the studied parameters from the steady-state performance characteristics to predict and optimize the experimental vehicles for transient performance characteristics based on ECER40 drive cycle.
3) The experimental vehicle is further tested based on transient ECER40 drive cycle at different gearing ratio and optimize for performance and range based on the lowest battery current consumption at given minimum requirement of vehicle performance such as minimum vehicle speed and acceleration.
4) The well-to-wheel analysis is performed to compare the energy efficiency and CO_2 emission of an 110cc gasoline motorcycle with the experimental motorcycle for case study in Malaysia

CHAPTER 2

LITERATURE REVIEW

2.1 Energy scenario

The world still largely consumes fossil fuels i.e. oil, coal and natural gas, in satisfying the energy need due to the fact that these fuels are currently the cheapest of all energy resources. Even though the world share of primary energy supply is becoming more diverse, the amount of energy supply almost doubled from 1973 as shown in Figure 1.1. The world energy consumption in 2009 is shown in Figure 2.1, where the difference between these figures is the energy losses during transformation process from primary energy source into secondary energy source e.g. crude oil is refined and then transformed into electricity by thermal power plant.

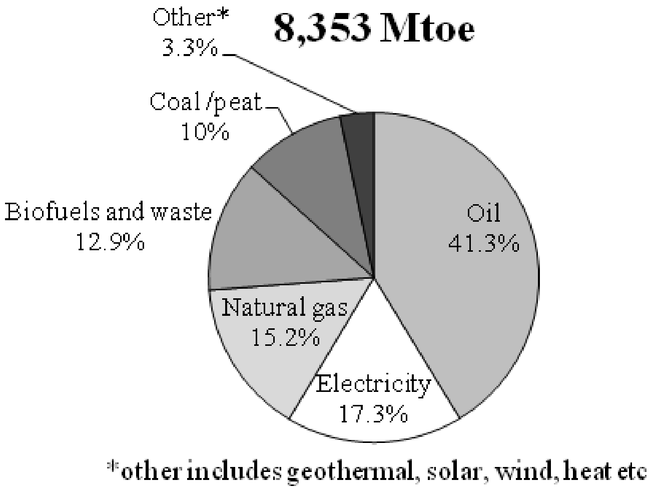
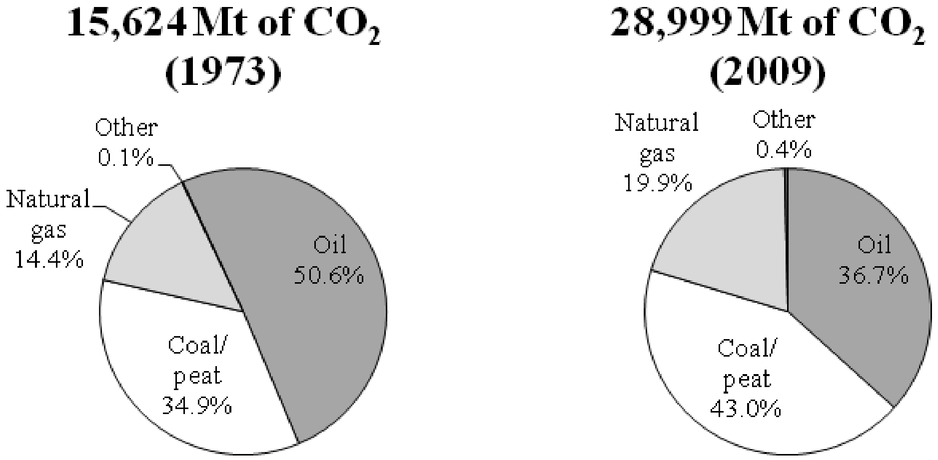


Figure 2.1 World total final consumption by fuel in 2009 (EIA 2011b)

2.1.1 Environmental impacts

CO_2 and water vapor are among the gases responsible for the greenhouse effect which is the ability to trap some of the reemission of solar energy from the planet. The greenhouse effect is a necessary component in providing some level of heat to support life on earth (Wuebbles & Jain 2001). It was discovered that during the past 1,000 years the CO_2 concentration was relatively constant until the 19th century as a result of fossil fuel burning and forest clearing (Gautier 2008). The world CO_2 inventory from fuel combustion in 2009 has increased by 87% compared to the CO_2 inventory in 1973 as shown in Figure 1.1. This can be explained by the increasing of world energy supply as shown in Figure 1.1. A number of different analyses strongly suggest that the global temperature rise over the last few decades is a direct consequence of the increasing atmospheric concentrations of greenhouse gases (IPCC 2007; Wuebbles & Jain 2001). This warming of the climate system is also evident from observations of the global sea level rise, and widespread melting of snow and ice.



Note: CO_2 emissions are from fuel combustion only.
*Other includes industrial waste and non-renewable municipal waste.

Figure 2.2 CO_2 emission by fuels in year 1973 and 2008 (EIA 2011b)

Apart from the greenhouse gases, the combustion of fossil fuels also emits air pollutants that are potentially hazardous to human health. Table 2.1 summarizes the causes and effects from the primary air pollutants produced from fuel combustion activities.

Table 2.1 Primary air pollutant from fuel combustion (Sher 1998)

Pollutant	**Causes**	**Known or suspected effects**
Carbon monoxide (CO)	Fuel-rich and stoichiometric combustion mainly from motor vehicle.	Reduces oxygen-carrying blood by combining with hemoglobin, thus deprives tissues of O_2.
Nitrogen oxides (NOx)	High temperature combustion mainly from motor vehicles.	Cause the irritation of eye, throat and lung. Primary pollutants producing photochemical smog, acid rain, and destroy ozone.
Particulate matter (PM)	Burning of coal, waste, and fossil fuels.	Breathing difficulties and cardiopulmonary deceases.
Sulfur dioxide (SO_2)	Coal combustion, petroleum refineries, and diesel engine.	Causing irritation of eye, throat and lung. Primary pollutant that produces acid rain.
Ozone (O_3)	Product of photochemical reactions in photochemical smog.	Causing irritation of eye, throat, and long, and impairs lung function.
Carbon dioxide (CO_2)	Combustion of fossil fuels and wood.	Partly responsible for the greenhouse effect.
Unburned hydrocarbons (HC)	Incomplete combustion.	Primary pollutants that produce photochemical smog and partly responsible for greenhouse effect.

2.1.2 Energy security

Petroleum has been used since the beginning of civilization and it is derived from the bodies of ancient organisms. Industrial evolution and the invention of internal combustion engine were major factor in increasing the importance of petroleum via mass consumption. Unfortunately, petroleum fuels are not unlimited and its extraction/production flow can be explained by the well-known theory called “peak oil”. The theory states that the maximum production of the oil will be accomplished when approximately half of the existing resources have been extracted (Hubbert 1956). After this point, the extraction process will gradually decline to the point where the cost to maintain or increase the production is uneconomic (Höök et al. 2010). Hubbert’s prediction was proven when he predicted that the US oil production will peaks between year 1965 and 1970, as shown in Figure 2.3 and Figure 2.4. However not everyone agrees that oil is a finite resource. This speculation is often based on the “abiotic” oil formation theory (Höök et al. 2010). There are two geological explanations of petroleum formation which are called the biogenic and abiotic models. The biogenic theory states the petroleum originated from remains of biological matter (theory of fossil fuels), while the abiotic theory claims that petroleum is derived from non-biological processes and the abiotic oil could lead to potentially everlasting available of petroleum. Although scientific evidence and supporting observations can be found for both models, the amount of evidence for the biogenic origin is overwhelming and there has never been commercial quantities of abiotic petroleum is ever found. So, the abiotic theory is largely irrelevant and the peak oil is generally accepted along with the result that it is impossible to extract larger amount of petroleum than the nature has created.

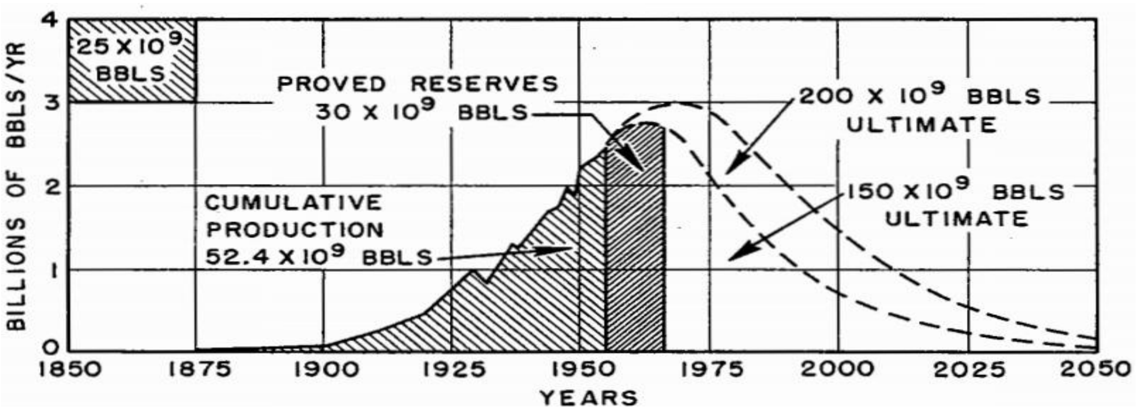


Figure 2.3 Hubbert’s curve predicting US peak oil based on different assumed initial reserve volumes (Hubbert 1956)

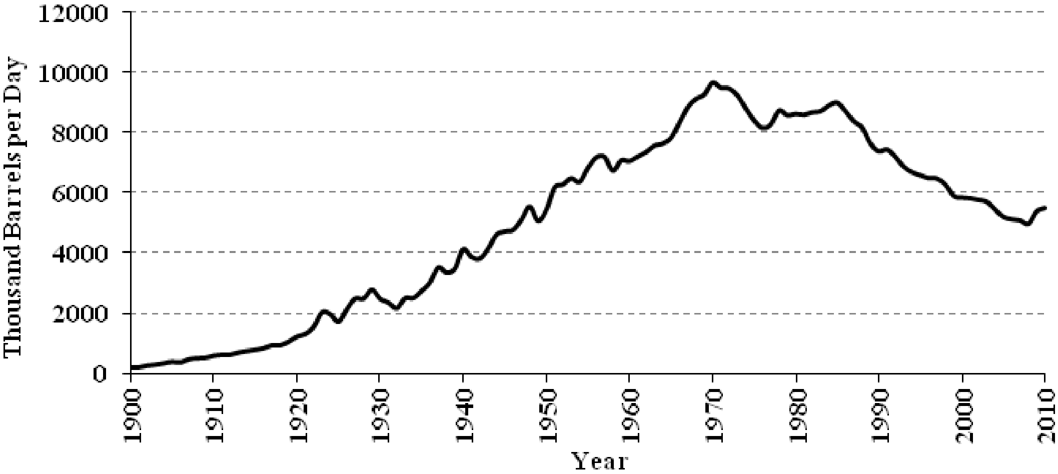


Figure 2.4 Annual U.S. crude oil production (EIA 2011a)

With the mass consumption of the depleting petroleum resources and the adverse impacts on human and environment, the dependency on petroleum has proven to be a possible threat to national security. Main areas of concern in terms of energy security can be summarized as follows (McPherson et al. 2005):

1) Growing import dependence in major parts of the world: Import dependence is expressed as fraction of the net fossil fuels import for primary energy use i.e. the reliance on foreign source of energy. For instance, China was almost 40% dependant on oil imports in 2002 and the imports grew by 30% in 2003. The global economy is expected to continue to rely heavily on oil and gas for next twenty to thirty years.

2) Geopolitics, terrorism and associated risks of supply disruptions: Politics have played major role in the market and become important when the production of petroleum fuels is concentrated in politically instable countries or regions. War, economic sanctions, general strikes, terrorist attacks on ships and pipelines, and facility sabotage are among of the risks that can disrupt the fuel supply.

3) Finite resources and associated concerns on peaking of oil and gas: Concerns that world production of oil and gas could peak in the near future, leading to the fuel shortage and spikes in energy prices.

4) Barriers to investment: With the most of the remaining fossil fuel resources in the less developed countries especially in Middle East and Former Soviet Union, there are doubts whether such countries will allow the required level of investment to expand the supply in parallel with the global demand.

5) High and volatile energy prices: This situation may result from the reduced margin of spare capacity in fossil fuel production, processing and political instabilities. To some extent it may reflect a deliberate strategy to keep the markets tight and production profits high.

6) Infrastructure reliability: Concerns about the reliability of the ageing infrastructure and impacts from the increasing global energy demand, where the increasing fossil fuels production would require external capital and new technology.

2.2 Conventional vehicles

Engines or motors are used in motor vehicles for propulsion. Every type of engine or motor has different energy conversion efficiency rating. Most engines used in the present automotive technology are internal combustion engines (ICE), basically a type of heat engine that converts thermal energy into mechanical work. A heat engine can never achieve the energy conversion efficiency of 100% and this fact is based on the Kelvin-Planck statement of the second law of thermodynamics. A heat engine must exchange heat from a high temperature source to a low temperature sink i.e. it requires a temperature difference, to keep operating (Cengel & Boles 2006). Table 2.2 shows some of common heat engines with their respective efficiencies. Nowadays, most of conventional road vehicles are using either gasoline or diesel engines for their propulsion. They are heat engines that burn liquid fuels to produce mechanical energy.

Table 2.2 Efficiency of different engines (Schwaller 2004)

Engine type	**Efficiency**
Gasoline engine	28-32%
Diesel engine	35-40%
Aircraft gas turbine	33-35%
Liquid fuel rocket	46-47%
Rotary engine	22-25%
Steam locomotive	10-12%

2.2.1 Powered two-wheelers

Motorcycles are the most common means of transportation in Asia because of their small size and related costs including ownership cost, maintenance cost and operational cost. The number of motorcycles increased by more than 100% between

1996 to 2003 in China and India, and is still growing. Motorcycles with displacements of 50-125 cm^3 are far more popular than the heavy-duty motorcycles (displacement more than 250 cm^3) in most countries in Asia. These motorcycles are significant source of air pollution in their respective countries (Yao et al. 2009). In Malaysia, there were more than 8 million motorcycles registered for road use in 2009, including 441,545 units registered in the same year (JPJ 2010). This number covers 47.0% of all road vehicles in Malaysia as shown on Figure 2.5. Most of these motorcycles are carbureted and many have inefficient two-stroke engines.

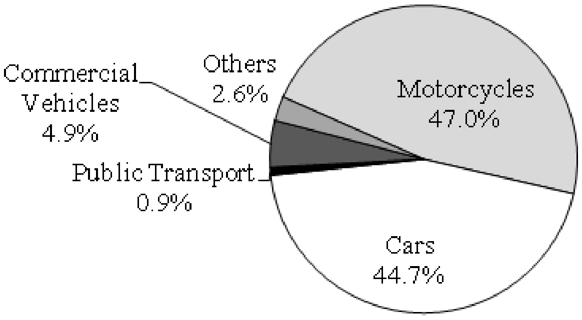


Figure 2.5 Cumulative registered road vehicle in Malayia as of 2009 (JPJ 2010)

Even though the powered two-wheelers consume significantly lower amounts of fuel compared to common passenger cars, the efficiency of the engine is lower and emissions level of the two-wheelers is relatively higher. The efficiency of the engine decreases with decreasing engine size due to elevated impact of friction and heat loss per cycle (Heywood 1988). A study comparing emission between 8 two-wheelers and 17 passenger cars concluded that the two-wheelers produce significantly higher emissions levels of CO, HC and NO_x than the passenger cars except for CO_2 emission which is direct consequence of fuel consumption rate (Vasic & Weilenmann 2006). For in-use two-wheelers, some emissions such as HC, CO, and some species of VOCs are higher from the new vehicles (J.-H. Tsai et al. 2000).

Another factor that effecting engine emissions is the cold-start driving where the emission factors of HC and CO were found to be greater than hot-start driving especially in the passenger cars which may be attributed to high fuel consumption in cold-start driving (Yao et al. 2009).

2.3 Electric vehicles

In the last few decades, there has been an increase in the demand for personal transportation parallel with the growth of human population especially in developing countries such as China and India. The demand trend has a direct influence on the world oil supply. With issues such as air pollution, global warming and petroleum depletion, there is a need for alternative vehicles which reduce reliance on petroleum oil. Electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell vehicles (FCV) are among some of the potential solutions proposed in providing cleaner alternative vehicles (Chan 2007). EVs or sometimes called battery electric vehicles (BEVs), are the best solution as they could eliminate dependency on the fossil fuel resource because of their high performance and energy efficiency, which can be charged by electrical power thus producing no tailpipe emission. The main disadvantage of this technology is the high cost and weight of batteries, making the vehicle very expensive and not viable for long range driving. HEVs, combining the technologies of ICEs and EVs, are becoming a popular choice of alternative vehicle at the moment and in the near future. The major disadvantages of the HEVs preventing this technology from dominating the market are high cost (although cheaper than EV) and inherent weaknesses arising from the requirement of maintaining both an ICE and an EV technology as well as high cost of the battery technology and continued dependence on liquid fuel as its primary energy source. For FCV, the issues of high cost and short lifetime of the fuel cells, hydrogen storage, production and transportation for polymer electrolyte membrane fuel cell type, and low power density and efficiency of direct methanol fuel cell type, making FCV far from viable technology for near future. Table 2.3 compares the major characteristics of ICEVs, EVs, HEVs and FCVs.

In Asian cities, the growing population density, road congestion and relatively low incomes make the powered two- and three wheelers an attractive option for personal transportation. However the large number of these vehicles is partly responsible for road congestion (Fatumata & Gordon 2009). The road congestion causes higher fuel consumption and air pollution especially during vehicle idling where no useful power produced. In China, one of the world largest countries, electric two-wheelers (E2Ws) are gaining widespread acceptance; it is arguably the most successful electric-drive market in the world (Weinert et al. 2008). If E2W success continues, it may accelerate the development of battery and larger EVs.

Table 2.3 Characteristics of ICEVs, BEVs, HEVs, and FCVs (Chan 2007)

Type of EVs	ICEV	Battery EVs	Hybrid EVs	Fuel cell EVs
Propulsion	• IC engine only	• Electric motor only	• Electric motor and/or IC engines	• Electric motor only
Energy storage system	• Gasoline or diesel tank	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit • Liquid fuel tank	• Fuel cells • Need battery/ ultracapacitor to enhance power density for starting
Energy sources and infrastructure	• Gasoline stations	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (for plug-in hybrid)	• Methanol • Hydrogen • Hydrogen production and transportation infrastructure
Characteristics	• Mature technology • Dependant on crude oil • Long driving range • Low fuel economy • Low initial cost • Commercially available	• Zero emission • Low energy density • Low energy cost • Independence from crude oil • Relatively short range • High initial cost • Commercially available	• Very low emission • Higher fuel economy as compared to ICE vehicles • Long driving range • Dependence on crude oil (for non-plug-in hybrid) • Higher cost as compared with ICE vehicles • The increase in fuel economy and reduce in emission depending on the power level of motor and battery as well as driving cycle • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence from crude oil (if not using gasoline to produce hydrogen) • Satisfying driving range • High cost • Under development
Major issues	• Increasing fuel cost • High emissions	• Battery life • battery management • Charging facilities • Cost • Range	• Multiple energy sources control, optimization and management • Battery sizing and management	• Fuel cell cost, cycle life and reliability • Hydrogen infrastructure

The EV is not a breakthrough invention. In fact, it has been around since approximately the same time as ICEV (Ehsani et al. 2010). The first EV was built by Frenchman Gustave Trouvé in 1881. It was a tricycle powered by a 0.1 hp DC motor fed by lead acid batteries. However, the technology was not mature enough to compete with horse and carriage until the 1894. The following 20 years were an era which EVs competed with ICEVs. The limited range of EVs was not a problem until there was a rapid expansion of paved roads favoring ICEVs. The EVs began to disappear because of several reasons such as the high cost, limited driving range and poorer performance compared to ICEVs. During the 1960s and 1970s, concerns about the environment triggered some research on EVs but their range and performance were still the major obstacles to widespread implementation. The progress has been slow since then and it became clear during early 1990s that EVs of that period could not compete with ICEVs mostly due to very low energy density compared to the gasoline.

EVs use one or more electric motor for traction, and electrical energy sources such as chemical battery, fuel cells, ultracapacitors, and/or flywheels. EVs have several major advantages over conventional internal combustion engine vehicle (ICEV) such as the absence of tailpipe emission, high efficiency, independence from fossil fuel, multiple energy sources, quiet and smooth operation. The major differences between EVs and ICEVs are the energy sources, propulsion system and transmission requirement. There are two methods of constructing an EV (Ehsani et al. 2010). First is to convert an existing ICEV by replacing the engine and fuel tank with the electric propulsion system and battery pack while keeping all the other components intact. However this method may create drawbacks such as heavy weight, lower flexibility and performance degradation. Another method is to manufacture the frame that satisfies the structure requirements of EV and this considered to be the modern way of producing EVs.

2.3.1 Electric vehicle propulsion system

A modern electric drive train consists of three major subsystems: electric motor propulsion, energy source, and auxiliary as shown in Figure 2.6 (Ehsani et al. 2010).

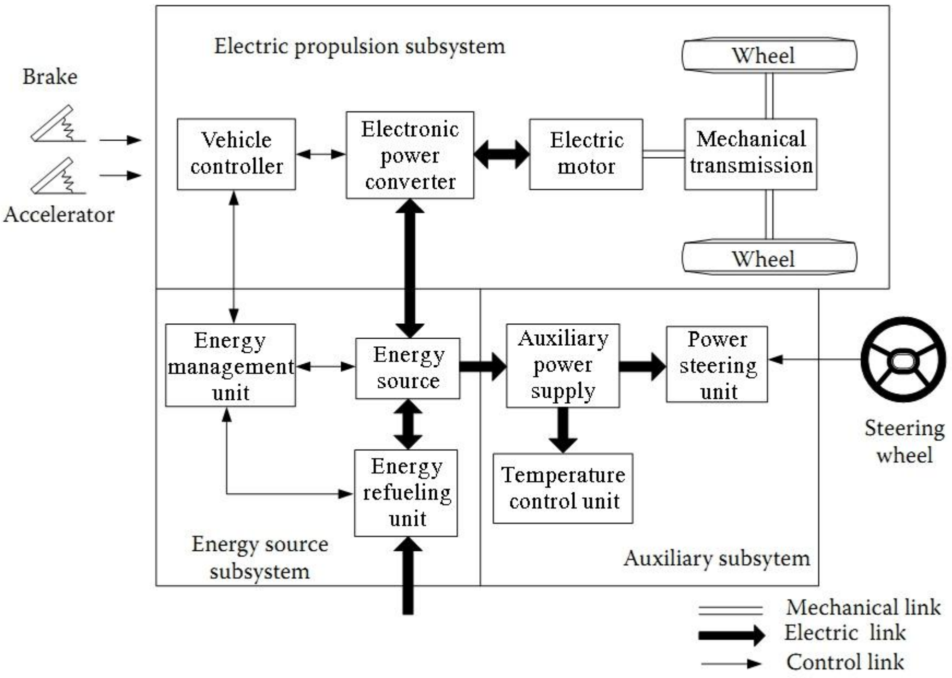


Figure 2.6 Conceptual illustration of general EV configuration (Ehsani et al. 2010)

Electric propulsion subsystem is the main component of an EV. It consists of an electric motor, vehicle controller, electronic power converter, mechanical transmission and wheels. The electric motor converts electric energy into mechanical energy to propel the vehicle, or vice versa by enabling regenerative braking to recover portions of kinetic energy and convert back into electric energy to recharge the on-board energy storage. The power converter is used to supply the electric motor with proper voltage and current for the required operation. The vehicle controller drives the electric motor by providing accurate control signals to power converter. This controller contains sensory elements, interface circuitry and processor which are responsible for the whole operation of the electric vehicle propulsion system.

The electric motor for EV propulsion system can be divided into two groups: commutator motors and commutatorless motors. The main difference in construction between both motors is the presence of the commutator, which is used with carbon brushes for mechanical and electrical contact between the power converter and the rotor of the motor. This carbon brush will eventually wear out and requiring replacement, making them less reliable and unsuitable for maintenance-free and high speed operation. In addition, winding excited DC motors have low specific power density. Due to its mature technology and simple control, DC motor drives are well-known in electric propulsion systems (Emadi et al. 2004).

For commutatorless electric motor, the advantages includes higher efficiency, higher power density, lower operating cost and maintenance-free operation, making them more reliable than the commutator electric motors. In EV and HEV applications, one of the most promising candidate of the electric motor is the permanent magnet (PM) brushless DC (BLDC) motor drive. The major advantages of BLDC motor drives include (Emadi et al. 2004):

1) High efficiency: BLDC motors are the most efficiency of all electric motors. This is due to the use of PMs for the excitation and the commutatorless configuration.
2) Compactness: The use of high energy density magnet generating very high flux densities which produce high torques, making the motor small and light.

3) Ease of control: The motor can be controller as easily as DC motor because the control variables are easily accessible and constant throughout the operation of the motor.

4) Ease of cooling: Since the winding is on the stator side, it is easier to cool this static part.

5) Low maintenance, great longevity, and great reliability: The commutatorless design suppresses the need for associated regular maintenance. The longevity is therefore only a function of the winding insulation, bearings, and magnet.

6) Low noise emissions: Associated noise of commutator motor design is inexistent and the driving converter switching frequency is sufficiently high so that the harmonics are not audible.

However, BLDC motor drives suffer from disadvantages as follow (Emadi et al. 2004):

1) Cost: Higher cost rare-earth magnets compared to other magnets, which increasing motor cost.

2) Limited constant power range: A large constant power range is essential in achieving high vehicle efficiency.

3) Safety: Large rare-earth PM attracts metallic objects and this is very dangerous during the construction of the motor. Another safety issue is the exposure risk to high motor terminal voltage in case of vehicle wreck where the wheel is freely spinning while the motor is still excited by its magnets.

4) Magnet demagnetization: PM can be demagnetized by large opposing magnetomotive forces and high temperature. Motor cooling is important especially for the compact design motor.

5) Inverter failures: BLDC motors present major risks in case of short-circuit failures of the inverter where the rotating PM rotors induce an EMF in the short-circuited winding, creating very large current circulating in the winding and high torque that could possibly stop the rotor forcefully. The resulting large current can also demagnetize and destroy the PMs.

2.3.2 Electric motor basic operation

The basic concept of permanent magnet motor can be demonstrated by placing a magnet near a current carrying conductor as shown in Figure 2.7 (Hughes 2006). The magnitude of the mechanical force depends directly on the current in the wire and the strength of the magnetic field, and the force is the greatest when the magnetic field is perpendicular to the conductor. The force on a wire length l, carrying a current I and exposed to a uniform magnetic flux density B throughout its length is given by the simple expression below. However, this equation is strictly when the current is perpendicular to the magnetic field (Hughes 2006).

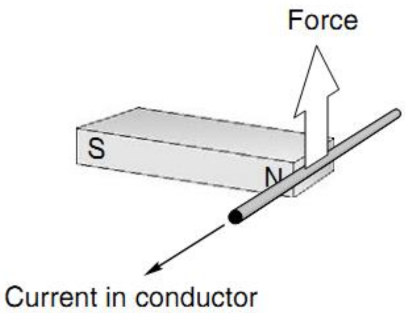


Figure 2.7 Mechanical force produced on a current carrying wire in a magnetic field (Hughes 2006)

$$F(N) = B(T) \times I(A) \times l(m) \tag{2.1}$$

Summation of the tangential force acting on each current-carrying conductor in the magnetic field (Figure 2.8) at rotor radius r produces a twist force called torque, and the equation is given as follows (Hughes 2006):

$$T(Nm) = F(N) \times r(m) \tag{2.2}$$

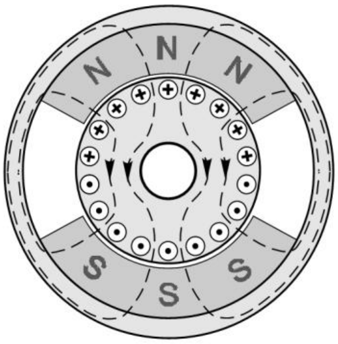


Figure 2.8 Permanent magnet brushed DC motor (Hughes 2006)

So, for the constant magnetic field of permanent magnet and the constant length of conductors the total torque can further be expressed by the following expression (Hughes 2006):

$$T(Nm) = K_T(Nm/A) \times I(A) \tag{2.3}$$

Where K_T is the motor torque constant and I is the armature current. The torque at given rotational speed will produce mechanical power output and the relation between the power output P_{out}, torque T and rotational ω speed is given as follows:

$$P_{out}(W) = T(Nm) \times \omega(rad/s) \tag{2.4}$$

The efficiency of the motor can be determined by simply dividing the power output with the electrical power input. The efficiency η can also be expressed by:

$$\eta(\%) = \frac{T_m \omega_m}{T_m \omega_m + P_{loss}} \times 100\% \tag{2.5}$$

Where T_m = torque of the motor (Nm)

ω_m = speed of the motor (rad/s)

P_{loss} = power losses in electric motor (W)

Power losses in electric motors can be divided into following elements (Pyrhonen et al. 2008):

1) Resistive losses (also known as Joules or copper losses): The resistive losses are the largest losses in electric motors. The relation of the resistive losses in winding with number of phases m, current I (A) and winding resistance $R(\Omega)$ is given by following equation:

$$P_{cu}(W) = mI^2R \tag{2.6}$$

2) Core losses (also known as iron losses): There are two types of core losses: hysteresis losses and eddy current losses. The hysteresis losses are cyclic losses due to magnetization and demagnetization of the core. The eddy current losses are caused by induced current in the core due alternating flux and this current tends to resist change in the flux.

3) Additional losses (also known as stray losses): Additional losses are electromagnetic losses not accounted for in resistive and core losses. It is

difficult to calculate and measure this type of losses. It is assumed to be between 0.1% and 1% of power input depending on electric motor type.

4) Mechanical losses (also known as rotational losses): Mechanical losses in electric motor are caused by bearing friction and windage, which are strong function of rotational speed of motor. The bearing friction losses increase linearly with speed while the windage losses increase by the cube speed.

2.3.3 Electric vehicle transmission

For vehicular applications, the ideal performance characteristic of a power plant is constant power output, resulting in hyperbolic torque curve as shown in Figure 2.9 (Jazar 2008).

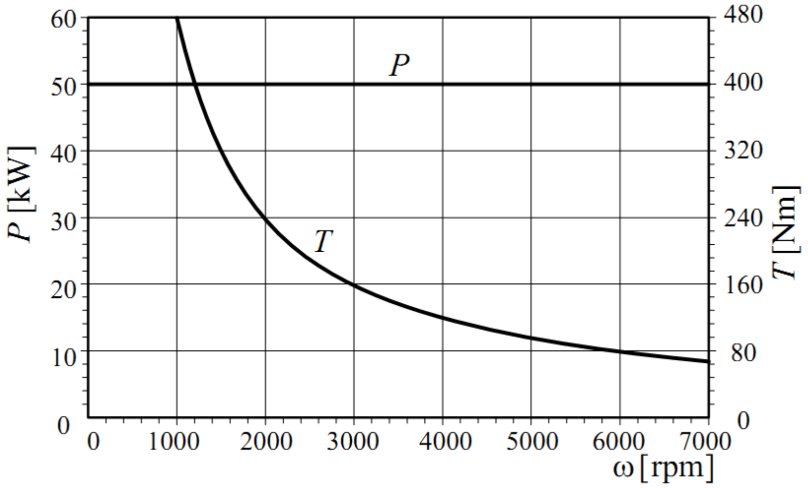


Figure 2.9 Power and torque performance of an ideal engine (Jazar 2008)

However in practice, the torque is restricted at low speed to avoid tyre slip. In the case of IC engine, the performance characteristics are far from the ideal e.g. typical gasoline engine has a relatively flat torque-speed profile, as shown in Figure 2.10. Multigear transmissions are usually employed to meet the power demand of a vehicle by multiplying the torque at low speed, as shown in Figure 2.12. In the case of the electric traction motor, the torque-speed profile is usually is much closer to the ideal, as shown in Figure 2.11. So, single gear transmission can be possibly employed to meet the vehicle performance requirement. Since the electric motor can produce torque from zero speed upward, the use of clutch is not required (Husain 2003). The utilization of electric motor in EV eliminates or reduces the use of transmission requirement common to ICEVs such as clutch and gearbox, thus improving overall efficiency of EV operation and consequently resulting in better mileage.

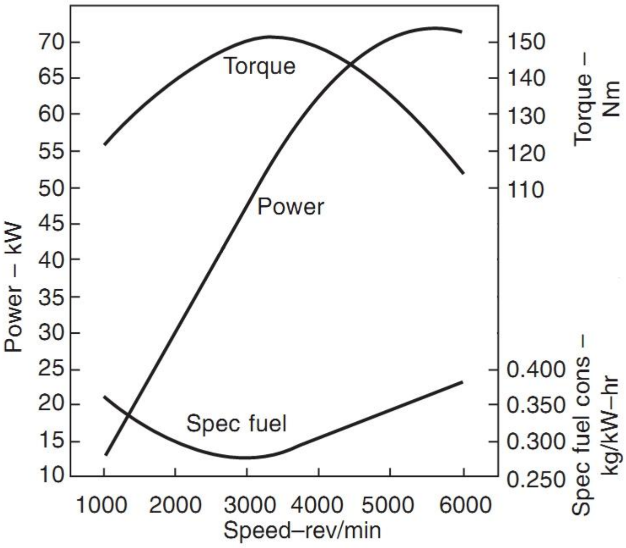


Figure 2.10 Typical performance characteristics of gasoline engines (Garrett et al. 2001)

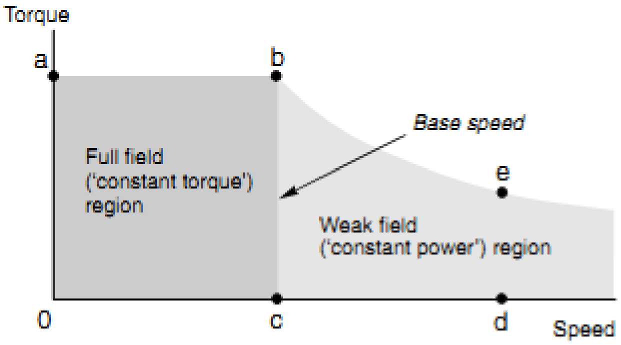


Figure 2.11 Typical performance characteristics of electric motors (Hughes 2006)