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STUDY OF CHALLENGES IN TECHNOLOGY DEVELOPMENT AND MARKET PENETRATION OF HYBRID ELECTRIC VEHICLES IN CANADA

By

Mariam Khan

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ABSTRACT

Growing concerns of the economic and environmental impact of petroleum combustion by on-road transportation have accelerated the development of alternative fuel vehicles; of these, the hybrid electric vehicle (HEV) is currently the most commercially successful technology. It integrates an electric drivetrain to the internal combustion engine for optimized engine operation giving significantly higher fuel efficiency and lower emissions. However, despite their well recognized benefits, Canadian consumers have shown reluctance in adapting HEVs so far.

This thesis discusses the immediate need for Canada to adopt more efficient and eco-friendly transportation systems and analyzes the cost effectiveness and tailpipe emissions of HEVs that offer a suitable alternative. The factors inhibiting market acceptance of hybrids are have been reviewed and a set of comprehensive policy guidelines and measures have been proposed to provide financial incentives, enforce emission regulations and support technology development of hybrid vehicles. As part of the highlighted target, challenges in key areas of HEV technology have been discussed and one such challenge is addressed by proposing a more robust electric motor drive for vehicle traction.

DEDICATION

To My Parents

ACKNOWLEDGEMENT

I am thankful to God Almighty for giving me the opportunity to pursue Masters program and the strength and patience to see it through. I am grateful to my wonderful parents whose love, encouragement and sacrifice has made me what I am today.

I wish to express my sincere gratitude to my advisor Dr. Narayan Kar for his assistance at every step of the way. His guidance has had an immense influence on my professional growth and without his technical expertise, reviews, and criticism it would not have been possible to shape this thesis. I would also like to thank my committee members Dr. Minaker and Dr. Wu for their valuable suggestions and guidance in the completion of this work.

I would like to show my appreciation for my thoughtful brother, adorable sister and my dear friends who made strenuous times seem easy and turned stressful days into fun. Their love and support will always be invaluable.

In the end, I want to thank my fellow graduate students in the Electric Machines and Drives Research Lab for their support and encouragement. Working in their friendly company was a memorable experience.

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NOMENCLATURE

Generally symbols have been defined locally. The list of principle symbols is given below.

ψ_{dr}, ψ_{qr}	:d- and q-axis rotor flux respectively
ψ_{ds}, ψ_{qs}	:d- and q-axis stator flux respectively
i_{ds}, i_{qs}	:d- and q-axis stator current respectively
i_{dr}, i_{qr}	:d- and q-axis rotor current respectively
v_{dr}, v_{qr}	:d- and q-axis rotor voltage respectively
v_{ds}, v_{qs}	:d- and q-axis stator voltage respectively
L_m	:Mutual inductance
$L_s, L_r,$	:Stator and rotor inductance respectively
L_{ss}, L_{rr}	:Stator and rotor leakage inductance respectively
R_s, R_r	:Stator and rotor resistance
ω_s, ω_r	:Synchronous speed and rotor speed respectively
T_m	:Mechanical load torque
T_e	:Electromagnetic torque
i_T	:Torque producing current
i_f	:Field producing current
H	:Combined inertia of rotor and load

1 INTRODUCTION

1.1 Background

In the last several decades, excessive combustion of fossil fuel across the globe and its impact on the global economy and environment is beginning to raise serious concerns. Transportation is one of the highest consumers of fossil fuels and the largest contributor of greenhouse gas (GHG) emissions. With a worldwide trend of increase in population, economic growth and rapid urbanization and industrial development, particularly in the developing nations, the demand for transportation is on the rise. Due to the dependency of the transport sector on fossil fuels, the consequent consumption of petroleum is also increasing exponentially. In 1971, the global consumption of petroleum was close to 49 million barrels per day, 33 percent of which was consumed by transport sector. This share increased to 48 percent of the 77 million barrels per day consumed in 2002. According to an estimate by the International Energy Annual, the global oil demand will spike up to 121 million barrels per day by 2030, 54 percent of which will be consumed by transportation alone [1]. It is noteworthy that amongst all modes of transportation, light-duty vehicles consume the largest quantity of fuel. In 2002, petroleum demand by light-duty vehicles was close to 18 million barrels a day which is estimated to increase significantly to about 32 million barrels per day by 2030.

Fossil fuel dependency of the rapidly growing transport sector, particularly on-road transportation, and massive increase in its petroleum demand is a source of concern as fuel reserves continue to deplete at an alarming rate. The rate of depletion of these reserves is likely to further increase sharply with the industrialization of developing countries. This calls for the search for alternative fuel vehicle technology to gradually displace gasoline driven vehicles by those powered by more sustainable and environment-friendly fuel options. Moreover, erratic fluctuations in gas prices are also creating a burden on the global economy as end users suffer from high cost of travel, transport and the price of all other commodities and services.

A yet more grave consequence of the combustion of petroleum, particularly in on-road transportation is the emission of toxic pollutants including carbon monoxide, nitrous oxides and unburned hydrocarbon particles. These pollutants not only degrade the air quality with a long lasting damaging effect on the environment but also pose risk to public health. Nitrous oxides can exacerbate asthma, damage lungs and increase susceptibility to respiratory diseases. They can react with atmospheric water to produce acid rain that kills vegetation and fauna. Carbon monoxide acts as a poison to humans and animals that inhibits the ability of blood to carry oxygen and can cause damage to nervous system. Unburned hydrocarbon particles, similarly, are responsible for smog, damage lung tissue and cause lung cancer. There are several other impurities and chemical additives in petroleum that produce emissions with sulfur and lead content, both hazardous to human, plant and animal life. Vehicular emissions are also a source of carbon dioxide, the principle greenhouse gas, responsible for global warming that is continuing to cause ecological changes and natural disasters.

Realization of the severe effects of extensive fuel combustion has motivated researchers to improve the efficiency of today′s on-road transportation. Conventional vehicles powered by internal combustion engines (ICEs) have been in extensive use for over 100 years and although efforts continue to improve their fuel efficiency, the long term solution to vehicular emissions and dependence on petroleum products will rely on the development of renewable energy sources and alternative fuel vehicle technologies. Alternative fuel vehicles refer to the class of vehicles that are partially or solely powered by sources of energy other than fossil fuels such as biofuels, electricity or hydrogen. The target of all such vehicles is to minimize vehicle emission, increase sustainability and reduce strain on the environment.

1.2 Alternative Fuel Vehicles

1.2.1 Battery Electric Vehicles (BEVs)

The concept of battery powered electric vehicle was first proposed as early as 1834 [2]. In electric vehicles, traction is provided by an electric motor, typically powered by a battery that is the only source of energy on-board. The batteries are recharged by plugging into a power source though an on-board or external charger. The electric motor is controlled by an electronic motor controller that signals to a power electronic drive to run the motor [3]. The motor can also act as a generator during braking to regain part of the kinetic energy and store it in the battery as electrical energy. This operation is called regenerative braking. BEVs do not require gasoline and, thus, in the absence of fuel combustion, they have no tailpipe emissions. They offer high efficiency and smooth and quiet operation.

Initial prototypes of battery electric vehicles were developed shortly after the invention of the first DC motor in 1831, and up until the early 1900s, BEVs outnumbered gasoline vehicles. However, with the improvement in the production of ICE driven vehicles and the reduction of their cost from $850 in 1909 to $260 in 1925, BEVs became a more expensive choice and began to disappear from the market [4]. They started to resurface, however, in the 1960s as environmental concerns began to arise. General Motors (GM) introduced its electric vehicles Electrovair with a 115 hp three-phase induction motor powered by a 512 V silver-zinc battery. Around the same time period "The Great Electric Car Race" cross-country competition between an EV from Caltech and an EV from MIT stirred an excitement for electric vehicle technology in USA. However, the BEV technology, especially in terms of energy storage was not mature enough to support commercial production. The energy crisis in the 70s, followed by the dramatic increase in oil prices made BEVs once again the focus of automotive research. In the coming two decades, development of high frequency semiconductor switching devices and microcontroller technology led to the improvement in power converter devices for efficient control of electric motors in electric vehicles. During the last decade of the 19th century, a number of companies produced battery powered electric vehicles in USA, Britain, and France.

BEVs however have a crucial limitation of short driving range due to the limited capacity of batteries and the absence of any on-board charging source. They have a high initial cost, long charging time and smaller capacity. This is why today BEVs are mainly used for small vehicles and short distance applications. Nickel-metal hydride batteries, most commonly used in automotive applications at present, do not have sufficient storage capacity and energy density to allow wide-scale mass production of BEVs. However, lithium-ion batteries are under research that is expected to provide specific energy and storage capacity higher than any other commercially available battery to provide a much more extended range for battery dependent automobiles.

1.2.2 Fuel Cell Vehicles (FCVs)

Since the specific energy and energy density of batteries are much lower than that of gasoline, the development of fuel cells to generate power for electric vehicles has accelerated in recent years. FCVs are similar to BEVs in their electric propulsion except, in addition to a chemical battery for energy storage, they use fuel cells to generate electricity by an electrochemical reaction between electrodes in the presence of an electrolyte. Unlike batteries, fuel cells consume their reactants and do not store energy but only generate it as long as the fuel supply is maintained [5]. This fuel can be hydrocarbons or alcohol, but hydrogen that can either be stored in pure form on-board or produced from on-board hydrogen carriers that feed directly to the fuel cells is most typically used. A fuel cell system in an FCV serves as the primary energy source to generate electricity that is then either used to propel the vehicle or stored in a battery that does not need any external charging. The battery serves as a storage device for energy generated by fuel cells and also improves the low power density of fuel cell systems that, when used alone, would require a more bulky construction [6]. Furthermore, fuel cells have a slow response that increases the startup time of the vehicle. Fuel cell vehicles offer a much longer driving range than BEVs and almost zero emissions.

The concept of the fuel cell was discovered by Sir William Grove in 1839, and was first engineered in 1889. A limited amount of research was carried out to develop carbon or coal based fuel cells in the early 1900s; however, it lost focus with the popularity of gasoline driven vehicles. The first successful fuel cell was produced in 1932. It consisted of a hydrogen-oxygen cell using alkaline electrolytes and nickel electrodes. Although fuel cell technology faced several challenges, it was used in space programs including Apollo and Gemini in the late 1950s. In 1959 a practical 5 kW fuel cell system was produced, followed by the first ever 20 hp fuel cell-powered tractor. More recently, several leading auto makers have initiated research on fuel cells for use in automotive applications with the aim to displace conventional power sources. Honda developed the FCX, which became the first fuel cell vehicle to be approved by US Environmental Protection Agency (EPA) and California Air Resources Board (CARB) for commercial use and has been certified as a zero emission vehicle by EPA and CARB.

The 2008 Honda FCX offers a fuel economy of 124 km/kg and 108 km/kg for city and highway driving respectively.

Although the fuel cell is an emerging technology with immense potential to significantly reduce petroleum combustion and harmful emissions, high cost and fixed lifecycle of the fuel cell, and storage, production and transportation of hydrogen are huge challenges that need to be addressed before FCVs can become feasible for commercial production [7].

1.2.3 Hybrid Electric Vehicles (HEVs)

Hybrid electric vehicles were designed to overcome the disadvantages of gasoline powered and battery electric vehicles. HEVs combine the conventional ICE driven mechanical drivetrain with a motor propelled electric drivetrain. Electric power to the motor in a hybrid vehicle is usually provided by a chemical battery. The presence of an on-board electric motor allows optimized operation of the engine in its maximum efficiency region, thus giving higher fuel efficiency than ICE vehicles (ICEVs) while the use of the ICE to charge the battery allows a much more extended driving range than BEVs. The electric motor also enables regenerative braking and shutting down the engine during idling, further increasing the efficiency of the vehicle [8].

The two drivetrains in an HEV can be integrated in various configurations that give varied operational and performance characteristics. In a series HEV, the ICE propels an electric generator to produce electrical energy either to charge the battery or to propel the vehicle by an electric motor [9]. In parallel HEVs both the ICE and the motor are coupled to the drive shaft of the wheels, allowing power to be delivered in dual, ICE alone or motor alone mode [10]. Series-parallel is a more complex design in hybrids that combines the advantages of both series and parallel configurations. Due to the optimized operation of the ICE and regenerative braking, maintenance requirements for oil changes, exhaust repairs, and brake replacement are significantly reduced.

The first hybrid car design is reported as early as 1899 by Pieper establishment of Liège, Belgium. It was a parallel hybrid with lead acid batteries that were charged by the engine during coasting or idling. The electric motor, in addition to regenerative braking, assisted the engine in high power demands. The same year, Vendovelli and Priestly Electric Carriage Company of France presented a series hybrid with a tri-wheel design with electric motors on the two rear wheels and a fractional horsepower gasoline engine that did not propel the vehicle but instead was coupled to a 1.1 kW electric generator. Dr. Ferdinand Porsche's second car was also a hybrid that used an ICE to power a generator which in turn powered electric motors located in the wheel hubs.

The aim of these early HEVs was to assist the rather weak gasoline engines. But as Henry Ford overcame many of the challenges in ICEs including noise and vibration, and mass production of self starting gasoline engines gained pace in 1920s, like all other alternative fuel vehicles, HEVs saw a sharp decline. The control of electric machines in the absence of advanced power switching devices was also a hurdle that discouraged the use of electric motors in cars. This is why HEVs did not attract attention until the 1970s as the converter technology began to evolve and Arab oil embargo and consequent energy crisis triggered the development of alternate fuel vehicles including HEVs.

The status of hybrid vehicles took a drastic turn with the commercial launch of Toyota Prius in 1997 which has since sold over a million units. Two years later, the Honda Insight was introduced in North America and was soon followed by the Honda Civic Hybrid. There are now several hybrid vehicles offered by some of the prominent automakers around the world that have together raised annual sales of hybrid units in North America from around 62,000 in 2002 to almost 400,000 in 2006. These sales have proven that hybrid cars not only offer a much better fuel efficiency than ICEVs but are commercially the most viable technology at present, despite their comparatively higher purchase cost. Most of these mass produced hybrid models are available in Canada, but despite their well recognized environmental benefits and fuel savings, and government incentives to promote their sales, consumer acceptance of HEVs remains low throughout the country. With growing awareness of deteriorating air quality and the economic burden of fluctuating gas prices, it has become essential to determine the inhibitors that are retarding market diffusion of hybrid electric vehicles in order to devise systematic strategies to produce hybrid vehicles that satisfy consumer demands and help encourage buyers to consider HEVs in their choice of vehicles.

1.3 Research Objectives

Hybrid electric vehicles are currently recognized as the most viable technology amongst alternative fuel vehicles that offer significant reduction in fuel consumption and vehicular emissions while maintaining vehicle performance, design requirements and affordability within reasonable range. Many auto manufacturers from around the world are producing commercial hybrid vehicles that are available throughout Canada. However, despite their availability and increasing awareness of the harmful impact of fuel combustion in ICEVs, Canadian buyers are reluctant to choose hybrids due to several reasons, high initial cost being the primary cause. The coming chapter will show that despite their savings on fuel cost, some hybrids take seven to ten years to reach the breakeven point. Consumers are also looking for improvement in driving and operational performance of hybrids where they can aggressively compete with the conventional vehicles.

The aim of this research is to devise strategies and propose a set of comprehensive policies, based on the present scenario in Canada, that are urgently needed to promote hybrid vehicles. The proposed policies consist of guidelines formulated to target the following three areas that can provide a thrust to sales of hybrid cars:

- Smart allocation of financial incentives,
- Stringent emission regulations and
- Support for research and development of HEV technology

As a part of the target themes, this thesis discusses in detail the challenges in technology development of some key areas in HEV designs and addresses one such challenge by designing a more robust induction motor drive for electric propulsion system of an HEV

1.4 Thesis Outline

This thesis is organized as follows:

Chapter 2: This chapter demonstrates the increase in petroleum consumption by on-road transportation in Canada and discusses the effect of fossil fuel dependency on the economy, environment and public health. Some of the currently available hybrid cars have been briefly reviewed to demonstrate their improvement in fuel economy with respect to ICEVs, making them a logical alternative for eco-friendly transportation. The results of comparative cost analysis of hybrids and their non-hybrid versions have been presented to determine the financial implications of owning a hybrid vehicle.

Chapter 3: This chapter discusses some of the main reasons why Canadian consumers hesitate to adopt hybrid vehicles and government efforts for the development and promotion of high performance, fuel-efficient hybrid drivetrains systems. The chapter proposes long-term and short-term policies that the government further needs to adapt, to educate consumers, help boost market penetration of HEVs and support their technology development.

Chapter 4: In this chapter key areas of interest in HEV technology development, from an electrical design perspective, are identified as drivetrain configuration, energy management systems, battery technology, and electric motor drive. Challenges in the development of each of these areas that need to be resolved to achieve the common goal of maximizing the utilization of the electric motor for reduction in gasoline consumption while improving the driving performance of the vehicle are discussed. A brief review of electric machines considered suitable for vehicle traction is also presented.

Chapter 5: Induction machines are discussed in detail as a highly suitable candidate for HEV propulsion. The chapter discusses their construction, operating principle and mathematical modeling in detail and demonstrates the parameter sensitivity of the conventional field oriented speed control of an induction machine. The chapter will introduces a proposed fuzzy logic-based vector control strategy for induction machines that exhibits lower sensitivity to parameter changes expected in traction environment.

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2 HEVS FOR SUSTAINABLE AND ECO-FRIENDLY TRANSPORTATION

Growth in on-road transportation is closely associated with the development of the global economy. Due to the present worldwide trends of population increase, expansion in international trade and economic development, the demand for heavy and light-duty vehicles is on the rise. With close to 600 million vehicles on the road today, over the next forty years 800 million more people are expected to own cars around the world. In 2002, light-duty vehicles alone accounted for 23% of the total 77 million barrels per day of oil consumption in the world, and is expected to go as high as 32 million barrels per day by 2030 [1], making them one of the major users of energy. This absolute dependence of on-road transportation on the unsustainable resource of fossil fuels is beginning to raise serious concerns. With the current growth in industrial development and transport demands, especially in the developing countries, the finite fuel reserves are depleting at an alarming rate and will eventually run out. Another cause of concern is the soaring gas prices that have increased exponentially over the last few years due to rapid industrialization of growing economies, depletion of fuel reserves, political factors and speculations. This high fuel cost not only influences the direct expense on transport but also has a cascading effect on prices of all other commodities and services, creating stress on the economy. Another hazard of fossil fuel combustion in vehicles is the expulsion of harmful emissions including carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons. Emission levels of CO_2, the principle greenhouse gas associated with global warming, have steadily escalated corresponding to the increasing fuel consumption particularly in the transport sector. Figure 2.1 shows the trend of worldwide CO_2 emissions in the past three decades [2].

These pollutants from fuel combustion are not only held responsible for climate change, but they also degrade the air quality that has a far reaching impact on human health. Air pollution is linked to cardiovascular and respiratory diseases and is a major environment-related health threat especially to children. An assessment by World Health Organization associates more than 2 million premature deaths due to air pollution [3].

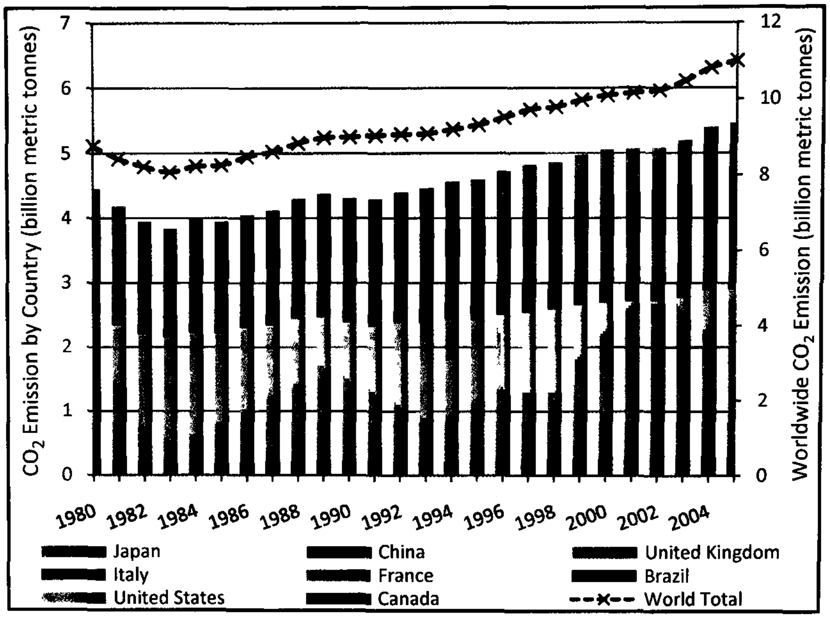


Fig. 2.1. Worldwide CO$_2$ emission from petroleum consumption.

Canada is facing a similar trend of increase in fuel consumption due to a rapidly growing transport sector and the consequent damaging impact on its economy, environment and public health. The coming sections will discuss the effect of growing fuel consumption by on-road transportation in Canada and the economic and environmental feasibility of hybrid vehicles as an alternative.

2.1 Impact of Growth in Petroleum Demand by On-Road Transportation in Canada

Canada spreads over 9,984,670 km^2, making it the world's second largest country by total area. Canada's road network spans more than 1.4 million km over its ten provinces and three territories. It is home to the seventh largest auto industry in the world, which employs well over half a million people associated with automotive assembly, component manufacturing, distribution and aftermarket sales and services. The industry produces about 2.7 million vehicles every year and is a major contributor to the Canadian economy with a share of nearly 13% of its current manufacturing GDP of 176 billion dollars. In the midst of its progressive expansion in international trade, economic development and population growth, the country is now facing a sharp rise in the demand for on-road transportation, particularly light-duty vehicles. In 2007, 1.6 million light-duty vehicles were sold in Canada, increasing the total number of light-duty vehicle registrations to more than 19 million from 16.8 million in 2000 as demonstrated in Fig. 2.2 [4]. Although this drastic growth in the transport sector is an indicator of a thriving economy, it has also grown to become the largest consumer of petroleum. The number of vehicles on the road today, though higher than ever before, cannot be blamed entirely for high fuel consumption by the country's transport sector. Canada's vast road network compels people to travel longer distances between its widespread cities. According to Canada Vehicle Survey, light-duty vehicles travelled close to 300 billion kilometres in 2007. As a result, motor gasoline sales have reached 42 billion litres [5] which constitutes 41% of the country's total domestic petroleum sales as shown in Fig. 2.3. Weather conditions in Canada also influence the amount of fuel consumption in automobiles. While the coastal regions enjoy milder temperatures, most parts of the country, particularly the interior and Prairie provinces, experience harsh winters forcing vehicle engines to burn more gas.

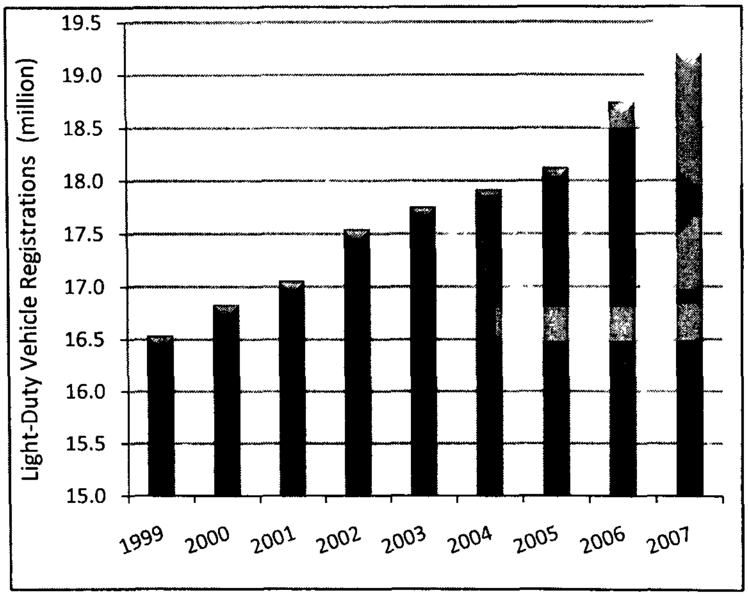


Fig. 2.2. Light-duty vehicle registrations in Canada.

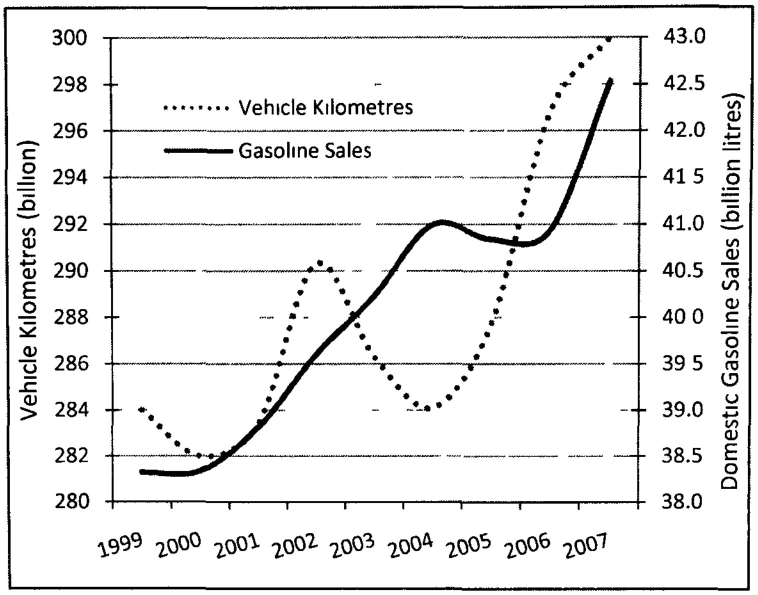


Fig. 2.3. Annual vehicle kilometres and motor gasoline sales in Canada.

Thus, due to the growth in Canadian transport sector and the vast and diverse geography with long distances and harsh weather, transportation draws the largest share of oil, making per capita fuel consumption in Canada higher than most industrialized nations.

2.1.1 Economic Impact of Fossil Fuel-Based Transportation

With the world's second largest oil reserves of 179 billion bbl [6] and a production rate of 3.3 million bbl per day [7] as shown in Table I, Canada may not have to worry about depletion of fuel reserves for decades, but dependence of its transport sector on fossil fuel is beginning to raise serious concerns as Canadians face the impact of worldwide escalation in oil prices. Rapid industrial development and urbanization of growing economies, depletion of global fuel reserves, political factors and speculations are amongst the many reasons why oil prices in Canada have almost tripled in the last 10 years. In the current scenario of global economy, the price of gasoline, shown in Fig. 2.4, saw a sudden decline as far low as 2004 level. This exponential increase or sudden fluctuation in fuel cost not only influences the expenditure on transportation, producing financial strain on vehicle owners, but also has a cascading effect on the prices of all other commodities and services, creating economic stress and financial uncertainties.

TABLE 2.1
STATUS OF GLOBAL OIL RESERVES AS OF 2007

Country	Reserves (billion bbl)	Production (million bbl/d)
Saudi Arabia	262	10.7
Canada	179	3.3
Iran	136	4.1
Iraq	115	2
Kuwait	102	2.7
UAE	98	2.9
Venezuela	80	2.9
Russia	60	9.7
Libya	42	1.8
Nigeria	36	2.4
USA	22	8.2

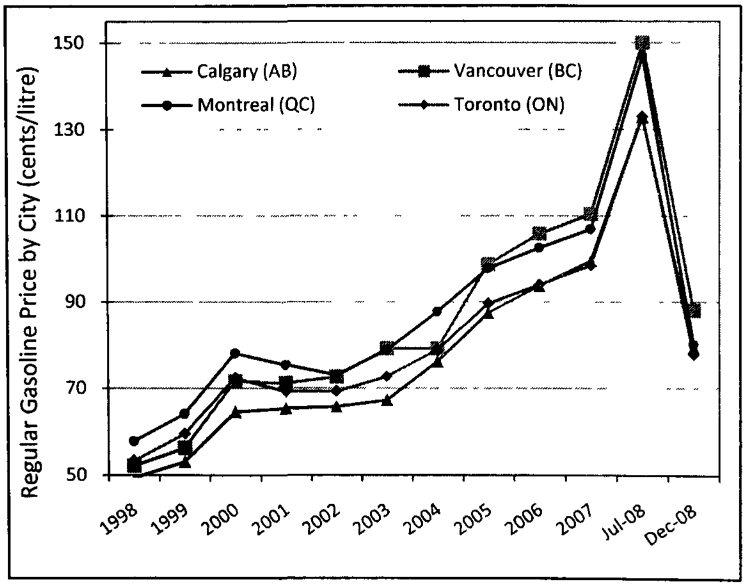


Fig. 2.4. Regular unleaded gasoline retail price by cities in Canada.

2.1.2 Degradation of Air Quality Due to Vehicular Emissions

An equally alarming consequence of petroleum combustion in transportation is the emission of CO_2, and toxic pollutants including CO, NO_x, hydrocarbons and particulate matter that are known to produce adverse health effects. Canada is amongst the ten highest CO_2 producing nations in the world with a per capita annual emission close to 22 tonnes.

In an effort to reduce these emissions, Canada is systematically replacing coal based electricity generation by hydro and nuclear power plants. However, rapidly increasing passenger transportation and consumer trend shifting towards minivans, sport utility vehicles and small trucks have led to an increase in fuel consumption. These heavier vehicles with lower fuel efficiency emit on average 40% more greenhouse gases per kilometre than passenger cars [8], playing a pivotal role in continued deterioration of air quality. Figures 2.5 and 2.6 show that transport sector is the single largest source of greenhouse gas in Canada, accounting for about 25% of total emissions within which light-duty vehicles are the highest contributor to air pollution, emitting more than 11% of the total CO_2 in Canada [9]. Despite preventive efforts, emissions from transport sector alone rose by about 44 megatonnes, or 32%, in the last fifteen years with a huge 24 megatonne increase in the emissions from light-duty gasoline trucks [10]. In December 1997, Canada and other developed countries negotiated the Kyoto Protocol at the United Nations Framework Convention on Climate Change. The protocol commits Canada to reduce its greenhouse gas emissions to 6% below 1990 level, indicated in Fig. 2.7, during the five-year period from 2008 to 2012. However, if the current emission trend by transportation continues, greenhouse gas emissions in Canada are expected to exceed 1990 level by 38.5% by 2010 and 58.2% by 2020 [9].

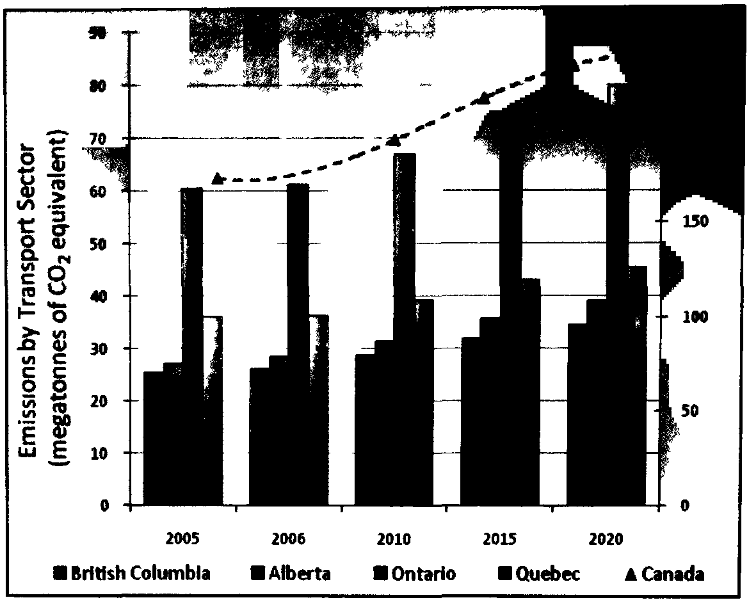


Fig. 2.5. Projected annual CO_2 emissions by province.

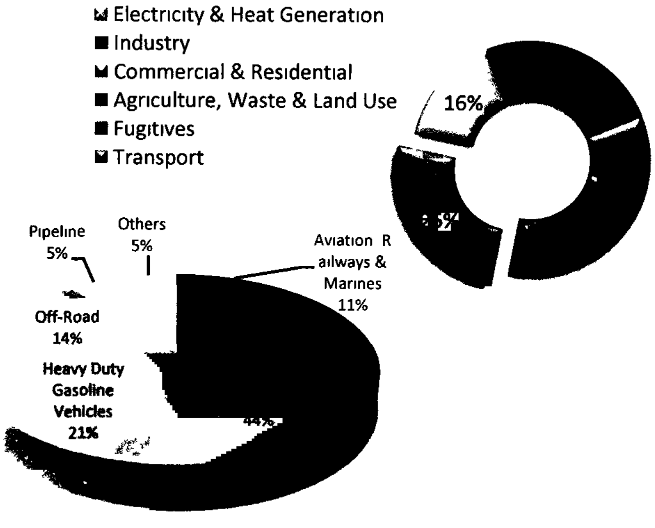


Fig. 2.6. CO_2 emission by transport sector (2005).

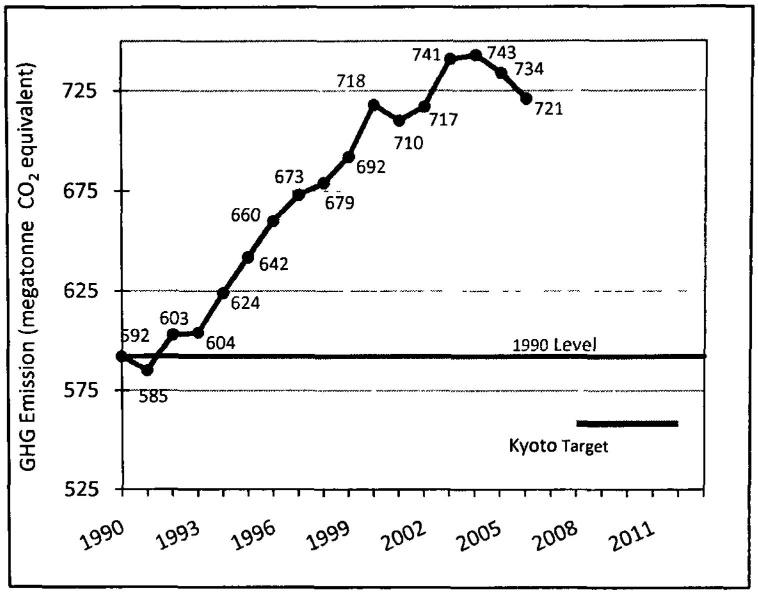


Fig. 2.7. Annual GHG emissions in Canada.

2.1.3 Health Risks Associated with Vehicular Emissions

Toxic emissions from fossil fuel combustion particularly in vehicles are not only linked to climate change but also have a significant impact on air quality and health, resulting in increased hospital admissions, respiratory illnesses and premature deaths, especially in urban areas. Carbon monoxide is known to inhibit the ability of blood to carry oxygen and may cause damage to central nervous system, nitrous oxides exacerbate asthma, affect the lungs and increase susceptibility to respiratory infections, and emissions of un-burnt particulate matter cause shortage of breath, worsen cardiovascular diseases and cause lung cancer. The Canadian Medical Association (CMA) has recently released data that predicts the annual death toll caused by air pollution to reach 21,000 in 2008. The CMA warns that 710,000 more people will lose their lives by 2031 due to long-term exposure to air pollution and the count for acute short-term effects will reach 90,000 deaths. Children are particularly vulnerable since they breathe faster than adults and inhale more air per pound of body weight. Air pollution is known to exacerbate the condition of people with respiratory and cardiovascular diseases that are among the leading causes of hospitalization and almost 80,000 deaths every year [11]. Canadians are also suffering the economic impact of air pollution as higher health care expenditures, non-attendance of ill workers and several other factors have cost the country more than $10 billion this year and according to the CMA, the cumulative total between 2008 and 2031 is expected to reach $300 billion. People are now recognizing the economic constraints of fossil fuel-based vehicles and the grave impact of fuel combustion on the Canadian environment and public health.

Attention is, therefore, focused towards the development and promotion of advanced vehicular technology and alternative fuels that can reduce dependency on fossil fuels in order to de-link transportation demand from fuel consumption and emissions. Amongst several possible alternatives, hybrid vehicle technology has proven to be the most commercially viable solution to conventional transportation.

2.2 Hybrid Electric Vehicles as a Fuel-Efficient Alternative

Hybrid electric vehicles offer an environment-friendly and fuel-efficient alternative to gasoline fueled vehicles by combining an electric motor based drivetrain to the conventional internal combustion engine (ICE) driven propulsion. This gives HEVs significantly higher fuel economy and lower emission compared to ICEVs with an extended range and better performance than electric vehicles. These benefits have prompted the leading car manufacturers around the world to develop hybrid vehicles, most of which are available in Canada today. As the leading names in auto industry compete to market high performance hybrid vehicles, Canadian consumers now have a wide selection of hybrid models from to choose. The availability of the Toyota Prius and hybrid versions of the Toyota Camry, Chevy Malibu, Nissan Altima and Honda Civic, sports utility vehicles (SUVs) such as the Ford Escape, Toyota Highlander and GM's Saturn Vue, and even luxury cars such as the Lexus GS 450h is an indication that hybrid technology is now ready to serve all types of consumer expectation.

2.2.1 Toyota Prius

It is the first mass-produced HEV with global sales of over 1 million units since its launch in 1997, nearly 60% of which have been in North America. The Prius, shown in Fig. 2.8(a), has sold over 13,000 units since the launch of its generation I in Canada in

2001. Its series-parallel powertrain integrated a 1.5-litre engine with a 33 kW motor that was later upgraded to 50 kW in the generation II introduced in 2004. The 2004 model featured a hatchback design, a lighter 201.6 V NiMH battery, higher system voltage of up to 500 V and improved fuel economy of 4.9/5.2 L/100 km for city/highway driving. It is now a part of the taxi fleet in Victoria and Vancouver in British Columbia (BC). The third generation Prius is expected to have faster acceleration, improved fuel economy, a 1.8 L engine and net drivetrain power of 119 kW

2.2.2 Toyota Camry Hybrid

Acknowledged as the 2007 Canadian Car of the Year by Automobile Journalists Association of Canada, the Toyota Camry Hybrid sold 5,802 units in 2007, accounting for 20% of all Camry sales in the country. It is the most fuel-efficient sedan available today, giving a fuel economy of 7.12 L/100 km for city and 6.92 L/100 km highway driving. With a 108 kW motor and a 244 V NiMH battery on board, this full hybrid, shown in Fig. 2.8(b), can accelerate from 0 to 100 km/h in 8.4 s with 80-120 km/h passing move at 6.8 s. It is this combination of rapid acceleration, good fuel economy and spacious interior that make Camry Hybrids widely popular.

2.2.3 Ford Escape Hybrid

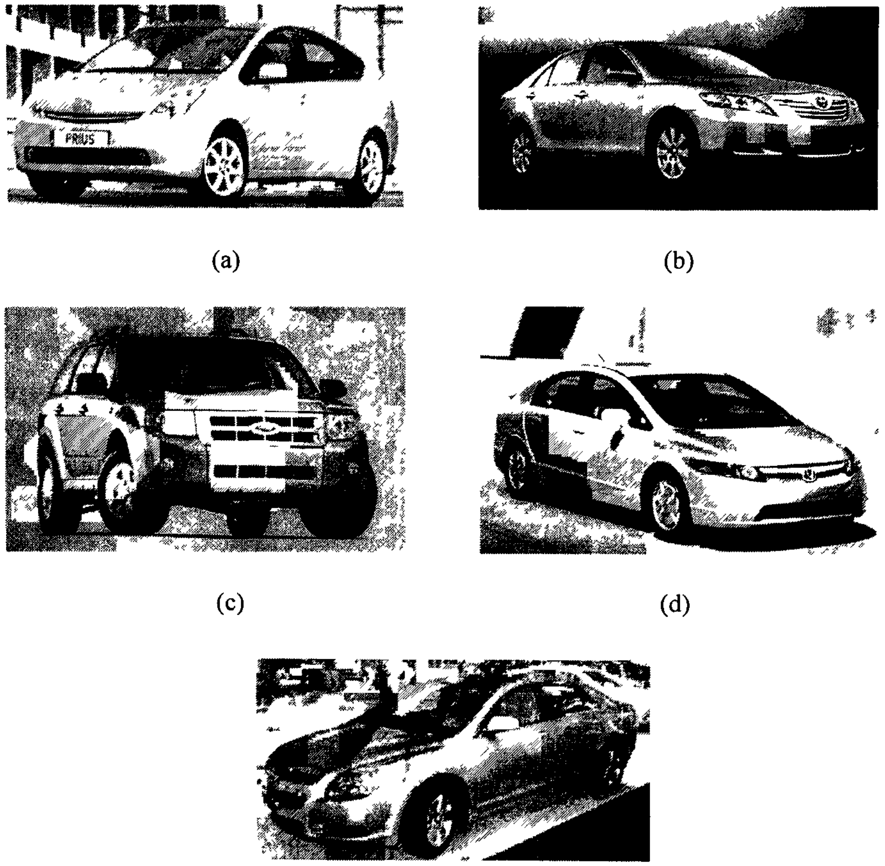
The escape hybrid, shown in Fig. 2.8(c), was launched in 2004 and is considered to be the most fuel-efficient SUV in Canada. A powerful 99 kW engine in this full hybrid is coupled with a 75 kW motor to enable high acceleration resulting in a quality driving experience similar to the standard Escape, yet maintaining a fuel economy that even beats many subcompact gas-powered vehicles. Improved drivetrain management software in the recent Escape Hybrid ensures a smooth drive and the vehicle boasts of a smarter, more comfortable interior than earlier models. However, the driver's side window in the cargo area is smaller to accommodate a ventilation slot for the high voltage battery.

2.2.4 Honda Civic Hybrid

This mild hybrid, shown in Fig. 2.8(d), was introduced in Canada in 2006. It features idle-stop, regenerative braking and an Integrated Motor Assist system that couples a 1.3-litre gasoline engine with a 15 kW motor. The motor provides assistance to the engine in high vehicle power demand under acceleration and drives the vehicle on its own at low speeds after which the engine takes over. Although slightly sluggish with an acceleration time of 14.9 s from 0 to 100 km/h, they are highly fuel-efficient and are now part of the courier fleets in Vancouver.

2.2.5 Chevy Malibu Hybrid

The Chevy Malibu's mini hybrid in Fig. 2.8(e) employs a relatively small 2.5 kW motor during idling where the engine is shut off and for regenerative braking. As a result, the vehicle size and performance resembles its non-hybrid version and there is little improvement in fuel economy and a high emission rating for a hybrid.



(a) (b)

(c) (d)

(e)

Fig. 2.8. Hybrid vehicles on the Canadian market. (a) Toyota Prius. (b) Toyota Camry Hybrid. (c) Ford Escape Hybrid. (d) Honda Civic Hybrid. (e) Chevy Malibu Hybrid.

2.3 Emission and Cost Saving Analysis of Hybrid Cars

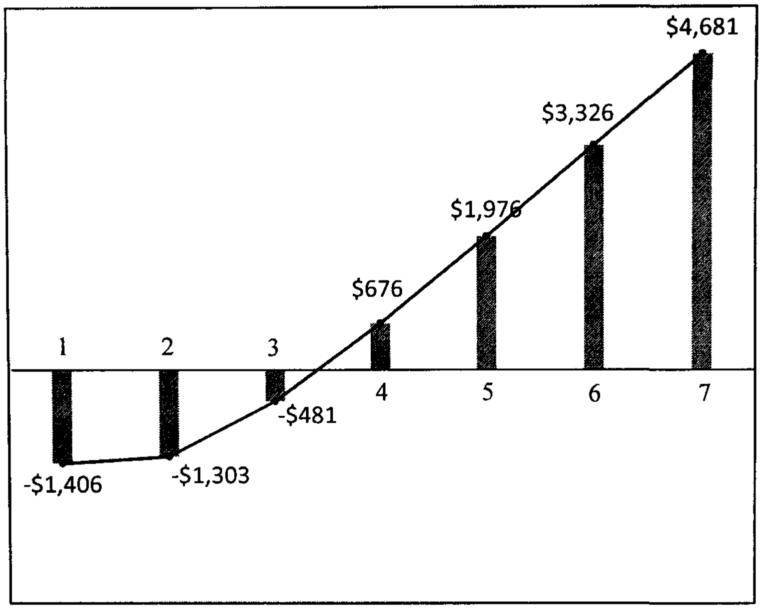
To examine the cost effectiveness and emission levels of HEVs, a comparative assessment of hybrid cars with their corresponding standard counterparts was conducted. The aim of this study is to determine the amount of emissions that vehicle owners can save by driving a hybrid car. The study also evaluates the effective cost of owning and driving a hybrid car to determine the number of years it takes for HEV models recoup their high initial cost. The analysis was conducted for a vehicle life of seven years, assuming it travels 24,000 kilometres every year, 55 percent of which was covered in city driving and 45 percent on the highway.

2.3.1 Cost Savings by Hybrid Vehicles

The lifetime cost analysis evaluates the expenditure on purchasing, operating and maintaining a 2008 hybrid model and its non-hybrid counterpart to determine the hybrid car's breakeven point. The estimate encompasses the purchase price of the vehicles in Canada, taking resale value into account, expected maintenance charges and total fuel expense at the end of vehicle life. The base price of the hybrid models were taken from the manufacturer's suggested retail price (MSRP) in Canada. The price of vehicles, including hybrid versions are higher in Canada in comparison to United States. The Alternative Fuels and Advanced Vehicles Data Centre (AFDC) under the US Office of Energy has developed estimation models to determine the resale value of vehicles in successive years. Since hybrid vehicles are new in the market and their technology is rapidly evolving, it is difficult to make an accurate prediction of what their resale values will be several years in the future. However, it is possible to determine a good estimate based on the initial price, years in use and annual mileage. This estimation model was used to calculate the resale values of hybrid cars in Canada for seven successive years. Maintenance cost on commercial hybrids was obtained from a maintenance history of test results from fleet data issued by US Department of Energy. Since the gasoline prices have fluctuated drastically in the last few months, the annual fuel cost spent on vehicles has been calculated for gasoline price of Cdn \$1.35/litre and Cdn \$0.80/litre, which were the official retail price of gas in Canadian cities in September and December 2008 respectively. Table II shows the base price of vehicles in Canada and their fuel economy and annual fuel cost. From these values of retail vehicle price, resale value for every consecutive year and annual maintenance and fuel expenditure, the total cost of owning and driving conventional vehicles and their hybrid versions was determined. Figures 2.9 through 2.13 show the progressive difference in the cumulative spending for successive years on HEVs and conventional cars from some of the leading automakers. Since calculations are made by subtracting annual cost on a conventional car from that of its hybrid version, a positive number indicates the amount of savings made by an HEV compared to its counterpart. The Prius and Camry Hybrids, due to their exceptionally good fuel economy and smaller difference in cost from their non-hybrid versions, reach breakeven within three to four years. The Ford Escape Hybrid, on the other hand, due to a much larger price difference from its non-hybrid version does not start paying back even after seven years.

TABLE 2.2
MSRP AND ANNUAL FUEL COST OF VEHICLES

Manufacturer	**2008 Model**	**MSRP (Cdn$)**	**Fuel Economy city/hwy (l/100 km)**	**Annual Fuel Cost at $0.80/l (Cdn$)**	**at $1.35/l (Cdn$)**
Toyota	Yaris	14,945	8.1/6.7	1,442	2,439
	Prius	27,600	4.9/5.2	972	1,645
Ford	Escape	25,000	10.1/7.2	1,701	2,878
	Escape Hybrid	35,000	5.8/6.4	1,158	1,960
Honda	Civic	20,700	9.4/6.5	1,563	2,644
	Civic Hybrid	27,000	5.8/5.2	1,076	1,820
Toyota	Camry	25,900	11.2/7.6	1,844	3,120
	Camry Hybrid	32,000	7.1/6.9	1,355	2,292
Nissan	Altima	25,000	10.2/7.6	1,741	2,946
	Altima Hybrid	34,000	5.6/5.9	1,103	1,866



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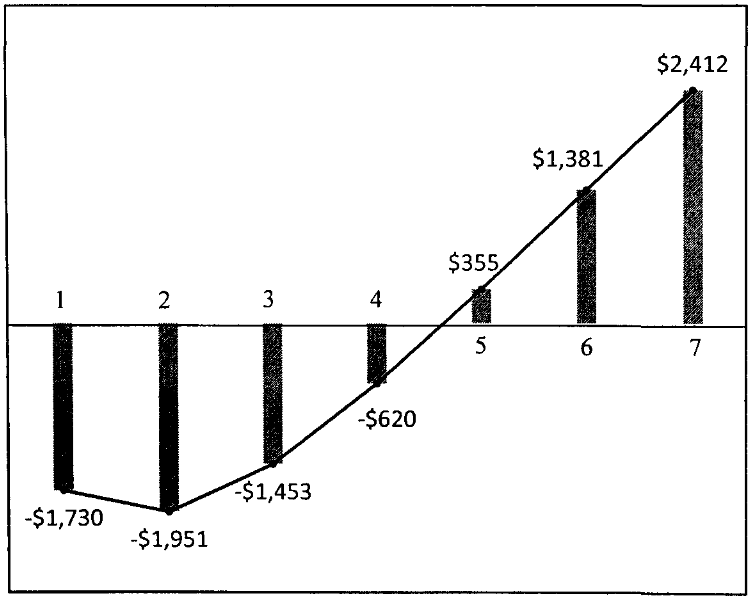

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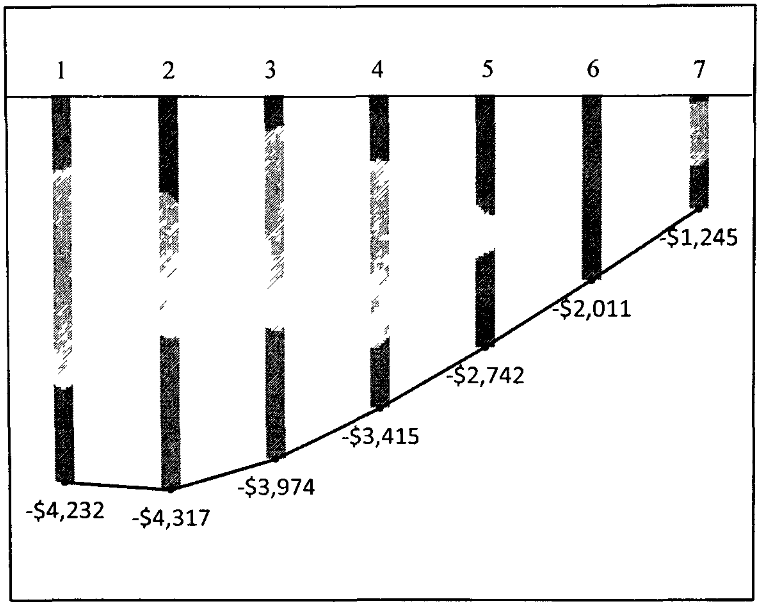
Fig. 2.9. Cumulative annual savings for Toyota's Prius over Yaris. (a) Gas price Cdn $1.35/l. (b) Gas price Cdn $0.8/l.



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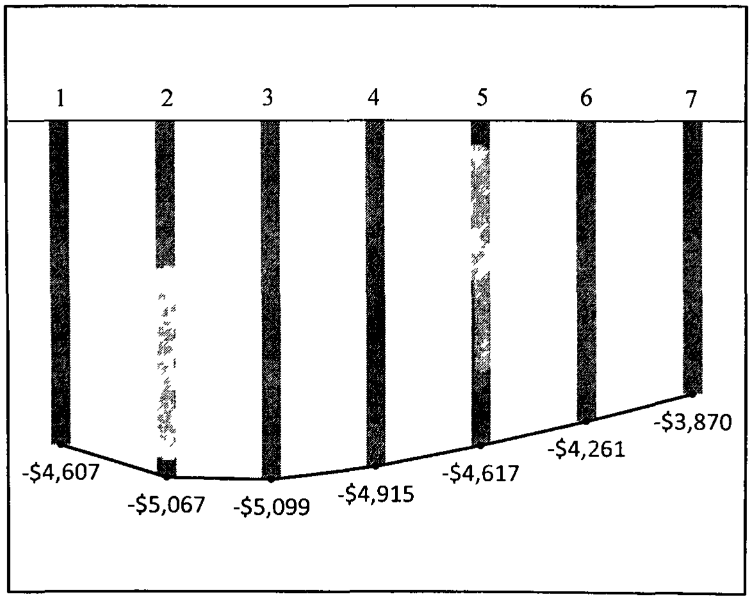

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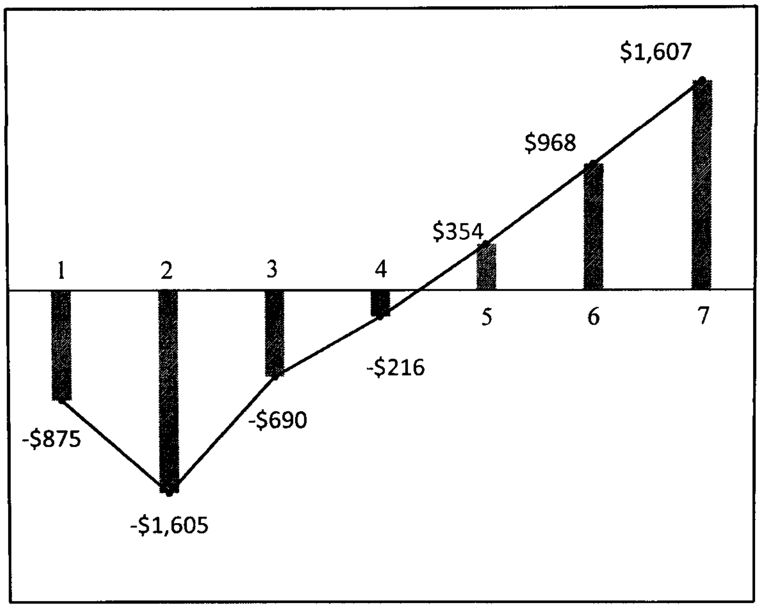
Fig. 2.10. Cumulative annual savings for Ford's Escape Hybrid over Escape. a) Gas price Cdn $1.35/l. (b) Gas price Cdn $0.8/l.



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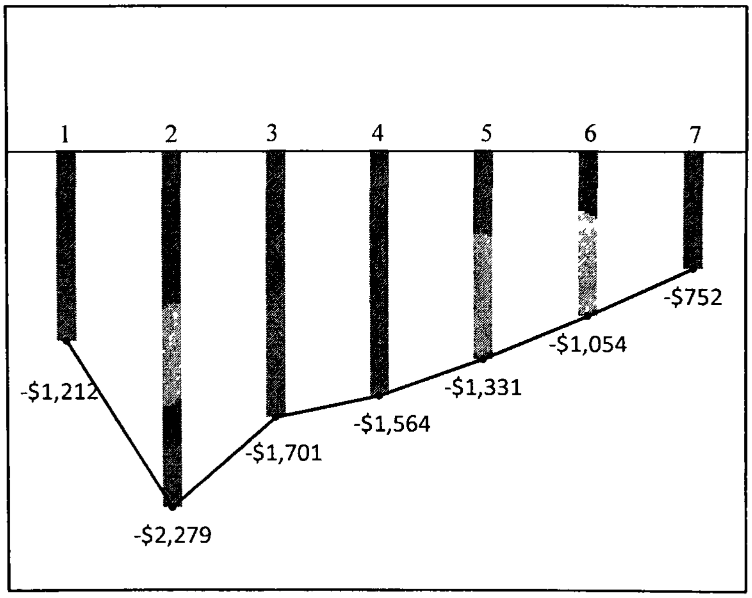

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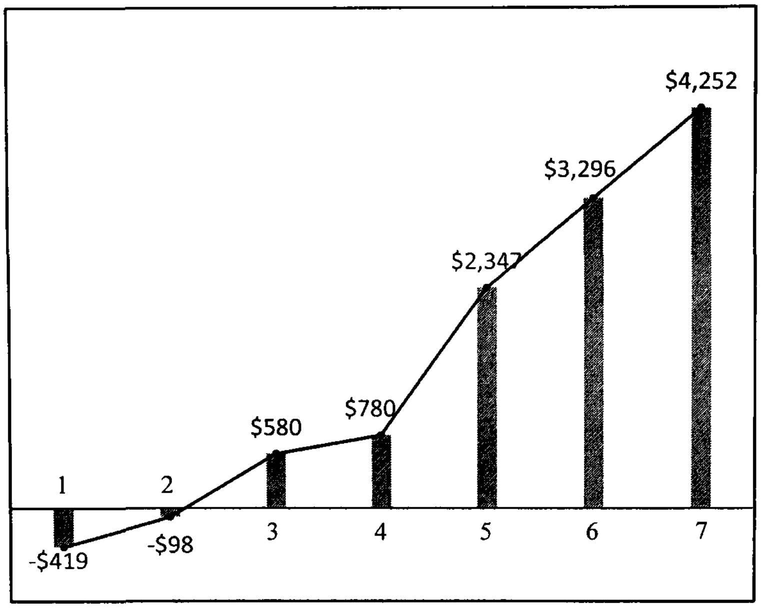
Fig. 2.11. Cumulative annual savings for Honda's Civic Hybrid over Civic. a) Gas price Cdn $1.35/l. (b) Gas price Cdn $0.8/l.



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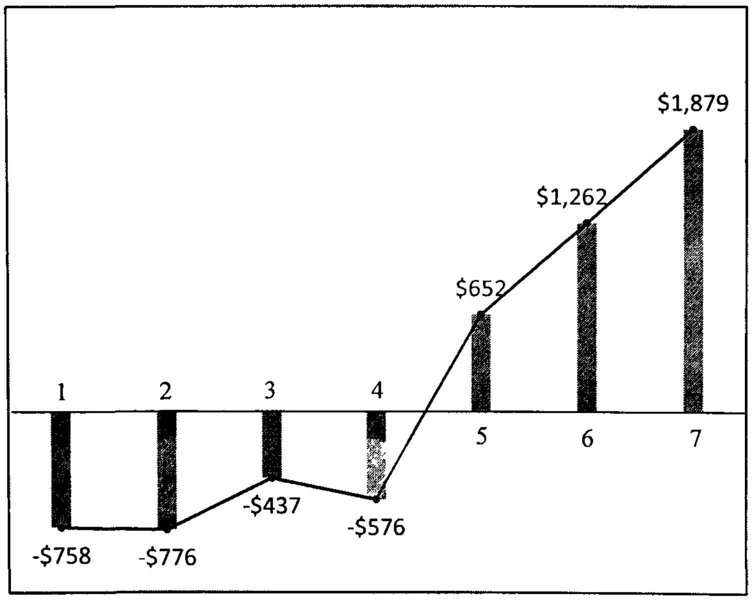

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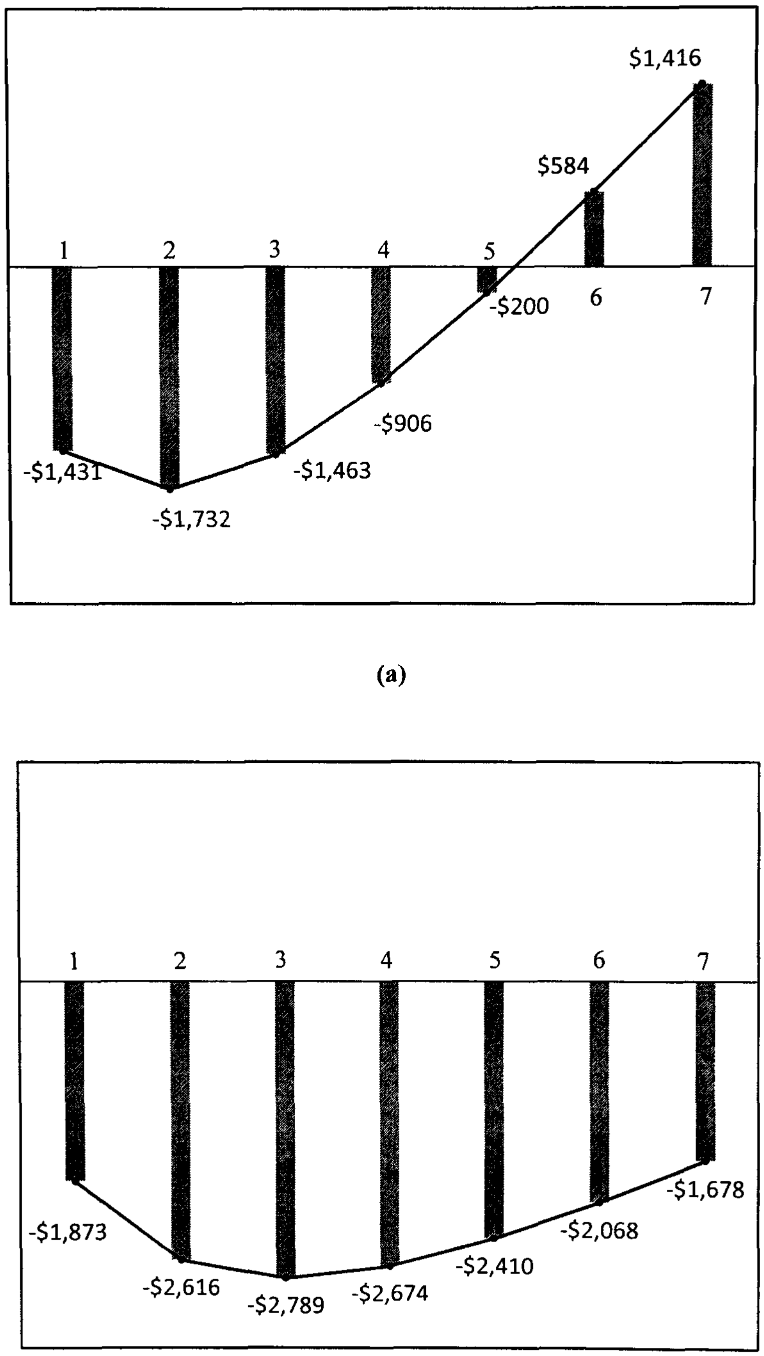
Fig. 2.12. Cumulative annual savings for Toyota's Camry Hybrid over Camry. a) Gas price Cdn $1.35/l. (b) Gas price Cdn $0.8/l.



(a)

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Fig. 2.13. Cumulative annual savings for Nissan's Altima Hybrid over Altima. a) Gas price Cdn $1.35/l. (b) Gas price Cdn $0.8/l.

It can be seen from Figs. 2.9 to 2.13 that if fuel economy is the motivation, consumers have several hybrid options to chose from that can give considerable savings on fuel cost to overcome the initial high cost of hybrid between five to seven years. On the other hand, larger high performance hybrids may give the driving experience that drivers demand, but such hybrids tend to deliver lower fuel economy by hybrid standards and have much higher cost than their standard counterparts.

Determining the payback for the incremental cost of hybrid vehicles involves a number of parameters, some of which are variable. The fuel cost is one such parameter. With unpredictable fluctuation in gas prices, the number of years before the vehicle hits breakeven may vary. Base price of hybrid cars also varies depending on technology advancement and market demand; and the fuel economy of the car is affected by the driving habits of vehicle owners. Financial incentives at the federal and provincial level in the form of tax cuts and rebates also influence the payback period of hybrid cars by bringing down their purchase price. It is notable that several factors influence the accuracy of this analysis. One such factor is identifying the direct hybrid comparison. Some hybrid cars such as the Toyota Prius do not have a direct basis for comparison. The Toyota Yaris is the closest non-hybrid car manufactured by Toyota that is comparable to the Prius, and is therefore used in the comparative assessment. Even hybrids with standard versions, such as the Camry and its hybrid, are not identical in features and accessories, which affects the cost of these vehicles. These variables have to be kept in consideration while drawing any conclusion from the analysis discussed above.

2.3.2 Lifetime Emission Savings by Hybrid Vehicles

Irrespective of their cost, the most important feature that hybrid vehicles offer is the drastic reduction in vehicular emissions. In order to determine the emission savings that can be achieved in a lifetime of seven years with annual mileage of 24,000 km by replacing conventional vehicles with hybrids, emissions from hybrids and gas powered vehicles were calculated for 55 percent city and 45 percent highway driving based on their respective fuel economies. Since combustion of one litre of gasoline emits 2.4 kilograms of carbon dioxide (CO_2) [12], the consequent emissions from vehicles in their lifetime were evaluated and are summarized in Table III.

TABLE 2.3
LIFETIME EMISSION SAVINGS BY HYBRID VEHICLES

Manufacturer	2008 Model	Fuel Economy city/hwy (l/100 km)	Annual Emissions (kilograms)	Lifetime Emissions (tonnes)	Emission Savings (tonnes)
Toyota	Yaris	8.1/6.7	4,206	29.44	9.59
	Prius	4.9/5.2	2,837	19.86	
Ford	Escape	10.1/7.2	5,079	35.55	11.24
	Escape Hybrid	5.8/6.4	3,473	24.31	
Honda	Civic	9.4/6.5	4,560	31.91	9.95
	Civic Hybrid	5.8/5.2	3,139	21.97	
Toyota	Camry	11.2/7.6	5,380	37.66	9.95
	Camry Hybrid	7.1/6.9	3,952	27.66	
Nissan	Altima	10.2/7.6	5,080	35.56	13.04
	Altima Hybrid	5.6/5.9	3,218	22.52	

The emission calculations show that high fuel efficiency of hybrids not only means less spending on gas but also translates into reduced CO_2 emission. The analysis indicates that at the end of seven years, all hybrids exhibit much lower emissions. The Honda Civic Hybrid, for instance, emits 1,421 kg, or 31%, less CO_2 than the standard Civic. This means that displacement of gas driven cars by hybrid vehicles can have a significant impact on the air quality in Canada. In 2006, close to 870,000 passenger cars were sold country wide. Amongst these, Honda Civic alone sold 70,028 units. If these Civic units were to be replaced by their hybrid version, Canada could save 100 kilotonnes of CO_2 every year. Hence, while hybrid vehicles might not return the financial investment soon enough, they have a huge impact in controlling vehicle emissions countrywide to improve the air quality that can ensure a safer environment to safeguard public health.

Despite this significant benefit of HEV technology, sales of hybrid units in Canada continue to remain low. Close to 900,000 passenger cars were sold countrywide in 2007 out of which HEVs could penetrate the market with a share of merely 1.6%. There are several reasons associated with the slow market diffusion of hybrid technology High initial cost, presumably poor acceleration, limited cargo and passenger space, availability of spare parts and technicians and long waiting periods for vehicle delivery are some of the causes of consumer hesitation in adapting HEVs. Overcoming these barriers is a challenging task that calls for a well devised approach that not only requires the formulation, regulation and implementation of policies, incentive strategies and promotional campaigns to support and encourage hybrid vehicles but also requires strenuous efforts towards the technological development of hybrid drivetrain systems so that the drive performance and operational features of hybrid cars can compete with the already established and matured technology of conventional vehicles.

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3 DEVELOPMENT OF POLICIES AND STRATEGIES TO PROMOTE HEV SALES IN THE MAINSTEAM MARKET

Transportation has always been critical to the development and growth of the Canadian economy and now, more than ever before, efficiency and sustainability are becoming the top objectives, particularly in on-road transportation. Hybrid technology has been recognized as a commercially viable, fuel-efficient alternative to conventional transportation that can help cut down fossil fuel dependency and reduce toxic and greenhouse gas emissions. Although there are several varieties of HEVs manufactured by some of the leading automakers around the world, most of which are available in Canada today, market diffusion of hybrid cars continues to remain slow.

3.1 Factors Affecting Consumer Acceptance of Hybrid Vehicles

There are several factors influencing hybrid vehicle sales in Canada. These factors that can broadly be categorized into three areas discussed in this section.

3.1.1 Financial Limitations

The high initial cost of hybrids is main cause of low sales. Most hybrids cost seven to ten thousand dollars more than their non-hybrid versions or vehicles of the same class. This increase in cost is attributed to low demand and higher cost on additional electric components, particularly the battery. The Ford Escape Hybrid, for example costs approximately $35,000 compared to the standard Escape that costs approximately $25,000. In some cases this sharp difference in initial price makes it difficult for hybrids to payback this cost differential through fuel savings even after ten years. Car prices in are higher in Canada compared to United States and the additional cost increase in hybrids discourages consumers to choose HEVs. Moreover, consumers are concerned about the expected maintenance expenditure. They are under the impression that battery replacement can cost them up to $3,000.

These financial limitations compel buyers to shy away from the purchase of hybrid cars since many people are reluctant to pay the price just for better emission standards. Efforts are therefore not only required at the development stage to bring down the component cost, but also to provide financial incentives, rebates and tax exemptions to lower the differential cost between hybrids and non-hybrids.

3.1.2 Consumer Lack of Information

There are many misconceptions associated with the fairly new hybrid technology that misleads consumers. One such misconception is the high maintenance cost on batteries. Although battery replacement can cost $2,000 to $3,000, most manufacturers now offer 8-10 years/240,000 km warranty and in coming years, with the progress in battery technology, this warranty is expected to go up to vehicle life.

Another reservation towards hybrid vehicles is their failure to deliver the fuel economy numbers verified by Environment Protection Agency in the United States or by EnerGuide labels in Canada. Vehicle owners need to be made aware of the effect of driving habits on fuel economy. Fast acceleration of a motor vehicle from a start, speeding, sudden braking and flooring the gas at traffic signals all adversely affect the vehicle's fuel economy.

Some consumers also do not recognize the wide-ranging operational performance and fuel efficiency of hybrid cars designed for varied requirements. Not all hybrid cars give a high fuel economy. The Chevy Malibu Hybrid, for instance, is a mini hybrid that gives a competitive driving experience but only features idle-stop and regenerative braking, and thus gives very little improvement in fuel economy over its non-hybrid version. The Honda Civic Hybrid, on the other hand, shows an improvement of 3.6 and 1.3 L/100 km for city and highway driving respectively over the conventional Civic. Speculations that hybrids are sluggish in performance also need clarification as hybrid models such as the Camry can now compete with any gas driven vehicle of its class.

Buyers, therefore, need to be educated on the wide-ranging vehicle performance and fuel savings offered by HEVs available in the market to help them make informed decisions.

3.1.3 Technology Challenges

The addition of electrical components to the vehicle drivetrain makes the design and control of hybrid electric vehicles a challenging task. Drivetrain components have to be designed specific to HEV applications such that the vehicle performance can compete with all other available automobiles in the market. In this regard, hybrid vehicles have several challenges to overcome, particularly in the design and control of its electric drivetrain for enhanced driving performance, advancement in battery technology for longer life, lighter weight and higher power density, and the improvement in the exterior design and spaciousness of the vehicles to satisfy consumer expectation.

While the above mentioned are the most dominant inhibitors to market diffusion of hybrid vehicles, there are several other noticeable issues. Availability of technicians and maintenance equipment for hybrid cars is still not common in many Canadian cities. Delivery of hybrid vehicles can take up to six months from the time of order due to low production which also discourages many consumers. Moreover, unlike several states in the United States and other countries around the world, federal and provincial governments in Canada have not enforced strict emission regulation, which could potentially compel buyers to opt for more fuel-efficient cars.

3.2 Need for Strategies to Promote HEVs in Canada

To overcome consumer hesitation to hybrid technology, the above mentioned barriers need to be addressed by improving HEV technology to satisfy consumer needs, providing financial motivation and promoting environment-friendly transportation. To achieve this, while the automotive industry has to find ways to cut down cost on the vehicle components, The Canadian public needs to be educated with the financial implications of owning an HEV, its positive impact on the environment and latest development in hybrid technology available commercially today that fits the design, performance and fuel consumption requirements of vehicle owners. It is unquestionably a challenging task that calls for a three-pronged effort by the government, auto manufactures and the civic community to interact with each other and all other stake-holders, as shown in Fig. 3.1, and develop a systematic strategy that facilitates and encourages sustainability through

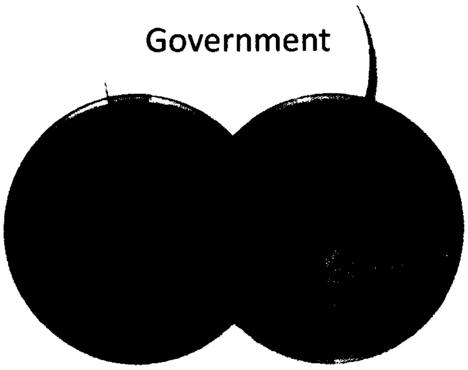

Fig. 3.1. Collaboration amongst major stake-holders to promote HEVs for sustainable transportation.

hybrid technology and raises awareness for the need for an environment-friendly transportation. The Canadian government has the most important role to play in this endeavor. It not only needs to promote green technology in transportation through showcase programs, tax reduction and financial incentives for people but can also aid auto manufacturers and research organizations in developing cutting-edge automotive technology by setting emission standards and providing research funding, subsidies and infrastructure support. This will, in turn, allow the industry to cut production cost, making hybrid cars a more accessible option for transportation. However, the success of any such new technology will eventually depend on consumer acceptability. Canadians have to recognize their responsibility to foresee and prevent the economic, environmental and health hazards associated with conventional vehicles and adopt more sustainable alternatives. Increase in HEV demand by consumers will not only strengthen automakers' confidence on this fairly recent technology but will also help increase production and, hence, their immediate availability, bringing down cost of hybrids and allowing readily available maintenance and technical assistance.

Transportation is typically required to be efficient, competitive, cost effective, safe and reliable. But now, more than ever before, sustainability and eco-friendliness are becoming the top priority in Canada's transport sector. The Government of Canada has initiated programs for promoting public awareness, setting emission standards, identifying provincial and federal incentives and rebates, and encouraging Canadians to consider fuel efficiency and consumption in their personal vehicles.

3.3 Existing Federal Programs and Public Policies

The federal government is beginning to recognize the urgency of encouraging fuel-efficient vehicles in an effort to control GHG emissions in the country. Within the federal government, several departments have the responsibility for transportation and the environment, particularly Transport Canada, Environment Canada, and Natural Resources Canada. They are dedicated to improving the quality of Canada's environment, especially by reducing emissions from transportation through rebates and national programs some of which have will be discussed in this section.

3.3.1 ecoAUTO Rebate Program

The ecoAUTO rebate is an initiative under the ecoTRANSPORT Strategy that aims to reduce greenhouse gas and air pollutant emissions from the transportation sector. Under this initiative, to encourage Canadians to adopt more fuel-efficient vehicles, the federal government of Canada offers rebates of up to $2,000 on the purchase or long-term lease of fuel-efficient vehicles, including most hybrids that meet the required fuel economy standards. The rebate is valid on eligible 2006, 2007 and 2008 models purchased between March 20, 2007 and December 31, 2008. Generally cars getting Combined Fuel Consumption Rating (CFCR) of 6.5 L/100 km or better and light trucks getting 8.3 L/100km or better qualify [1]. CFCR is determined by adding 55% of the vehicle's city fuel consumption rating to 45% of the vehicle's highway fuel consumption rating.

3.3.2 ecoTECHNOLOGY for Vehicles Program

With $15 million in funding, the ecoTECHNOLOGY for Vehicles (eTV) program conducts in-depth testing and evaluation of safety and environmental performance of a range of innovative technologies used in vehicles. Results of these studies are showcased across the country to provide information on the potential of emerging technologies to help reduce the damaging impact of vehicles on the environment.

Under this umbrella, eTV evaluates different categories of advanced environmental vehicle technologies which are:

- *Alternative Fuels*: The eTV program is currently evaluating a number of vehicles that use alternative fuel technologies including bio-fuel vehicles, biodiesel, cellulose, ethanol, clean gasoline and diesel, compressed natural gas and liquefied petroleum gas
- *Battery, Electric, Hydrogen and Hybrid Vehicles*: The program is currently conducting research on a number of different advanced vehicle technologies to evaluate their performance in Canada, including hydrogen, electric and hybrid electric vehicles.
- *Engine/Power Train Design and Emissions Control:* Advanced engine/power train design refers to technologies that can help improve vehicle fuel economy by achieving greater efficiencies while emissions controls include all technologies that monitor and control the air pollutants released from a vehicle. The eTV tests technologies such as, but not limited to, 42-volt electrical architecture, engine control units and advanced transmissions, to improve power train design and emissions control systems, balanced against the need for performance and safety.
- *Vehicle Design and Aerodynamics*: Under this program tests are being conducted to support research on improving aerodynamics of the vehicle.

The eTV program also works in cooperation with the automotive industry and consumers to identify and remove barriers to the introduction of advanced technology vehicles in Canada.

3.3.3 Excise Tax

The federal budget for 2007 proposed a vehicle efficiency incentive aimed to encourage the purchase of fuel-efficient vehicles in Canada through rebates for highly fuel-efficient vehicles, neutral treatment for vehicles of average fuel efficiency and a new green levy on fuel-inefficient vehicles based on fuel economy ratings. This excise tax, starting at $ 1,000, will be payable by the automobile manufacturer or importer at the time of vehicle delivery The tax will, however, not apply to vehicles manufactured in Canada or exported to other countries.

3.3.4 ecoENERGY for Personal Vehicles

The Ministry of Natural Resources announced $21 million in February 2007 for this program that provides fuel consumption information and decision-making tools such as vehicle labels, guides and interactive websites. Under this umbrella several tools were developed to assist consumers in making informed decision on vehicle purchase. EnerGuide label for vehicles are issued with all new passenger cars, light-duty vans, pickup trucks and special purpose vehicles not exceeding a gross vehicle weight of 3855 kg (8500 lb) that indicate city and highway fuel consumption ratings and an estimated annual fuel cost for that particular vehicle. The program offers teaching tools, on-line resources and publications by providing vehicle owners with information and resources that will help them save fuel and protect the environment through their buying, driving and maintenance habits.

Under this program, the annual ecoENERGY for Vehicles Awards are presented by Natural Resources Canada's Office of Energy Efficiency for the most fuel-efficient vehicles sold in Canada to encourage automakers to manufacture low emission vehicles.

3.3.5 Motor Vehicle Fuel Efficiency Initiative

It aims to improve fuel efficiency of light-duty vehicles by 25% by 2010 through voluntary agreements with the automakers. It also includes the Advanced Technology Vehicles Program that provides information on fuel-efficient technologies such as advanced powertrains and emission controls.

3.3.6 Moving on Sustainable Transportation

The Moving on Sustainable Transportation (MOST) Program was launched by Transport Canada to support projects that create awareness and develop analytical tools that can increase sustainable transportation options for Canadians. The program fulfils a commitment made by Transport Canada's first *Sustainable Development Strategy* in 1997 and has three major goals [2]:

- Development of innovative tools, approaches and practices for increasing the sustainability of Canada's transportation system and the use of sustainable modes of transportation
- Realize quantifiable environmental and sustainable development results on Transport Canada's sustainable development priorities
- Provide Canadians with practical information, tools and opportunities for better incorporating sustainable transportation options into their daily lives

The MOST program was launched in 1999 with a budget of $1 million over three years. The program was later extended with an additional $2.5 million in funding. The MOST program has committed funding to innovative projects across Canada involving more than 500 environmental groups, community associations, academic institutions, business groups and professional associations. With financial support from MOST, these organizations are promoting education and awareness, conducting advanced research, testing new approaches, and developing needed tools to promote sustainable transportation.

3.3.7 Fuel Consumption Program

The Fuel Consumption Program was established in 1975 to promote energy conservation in the transportation sector through the design, manufacture and sale of fuel-efficient light-duty vehicles. The main objective of the program is to promote public awareness of vehicle fuel efficiency through fuel consumption labels on new vehicles. This information is also published in the annual Fuel Consumption Guide booklet.

The program also monitors fuel consumption of new vehicle fleet in Canada, collects detailed vehicle fuel economy and engine technology data, and tests selected new models. The program sets annual company average fuel consumption (CAFC) goals for the automotive industry so that manufacturers and importers attempt to meet the CAFC goals. Additional incentives are also provided to the auto industry to increase the production of vehicles which operate on alternative fuels.

3.3.8 Urban Transportation Showcase Program

The Urban Transportation Showcase Program (UTSP), an initiative by Transport Canada under the Government of Canada's Action Plan 2000 on Climate Change, is expected to continue through 2009. Its aim is to test and measure the impacts of strategies designed to reduce urban GHG emissions from transportation. Under this program, the following objectives have been identified [3]:

- Support the development and integration of strategies, transportation planning tools and best practices so as to reduce GHG emissions
- Demonstrate, measure and monitor the effectiveness of a range of integrated urban GHG emissions strategies
- Evaluate the effects of these strategies for other important policy objectives to build strong cities (smog reduction, congestion relief, improved public transit infrastructure)
- Establish a comprehensive and pro-active national network for the dissemination of information on successful GHG emissions reduction strategies for sustainable urban transportation.

The program supports innovative projects such as transit and pedestrian priority measures and hybrid buses, to attract Canadians to sustainable transportation options. The UTSP emphasizes on the measurement of benefits. Supported projects are required to identify performance measures such as transit ridership, operating costs and GHG emissions, establish baseline data, set targets and monitor results.

3.4 Existing Provincial Initiatives to Encourage HEVs

In addition to the federal programs, several provinces have also taken initiative to promote sales and use of efficient vehicles including HEVs, in their jurisdiction in an effort to combat greenhouse gas emissions.

3.4.1 Ontario

Ontario offers a rebate of the 8% sales tax paid on alternative fuel vehicles to a maximum of $2,000. The Government of Ontario is also considering special license plates which would entitle high occupancy vehicle lanes and parking discounts to owners of fuel-efficient cars. Various cities in Ontario including London and Windsor are incorporating hybrid public transits in their fleet.

3.4.2 British Columbia

Hybrid and other fuel-efficient vehicles in British Columbia (BC) are eligible for a maximum rebate of $2,000. British Columbia is also the first jurisdiction in North America to introduce a carbon tax of $10/tonne beginning July 2008 which will rise by $5 a year until 2012. The BC government already operates a fleet of 584 hybrid vehicles, and since 2007 has had a policy of only leasing or purchasing HEVs for government use. Under the Ecotaxi Initiative, hybrid taxis have been incorporated into the regular fleet. The number of hybrids in the taxi fleet has been steadily increasing and constitutes 36% of all taxis in Victoria.

3.4.3 Prince Edward Island

The provincial sales tax rebate for fuel-efficient vehicles in Prince Edward Island is $3,000, the highest among all Canadian provinces.

3.4.4 Saskatchewan

Saskatchewan provides a 20% rebate on registration fees and basic insurance premiums paid for 2007 on fuel-efficient vehicles.

3.4.5 Alberta, Manitoba and Quebec

Alberta, Manitoba and Quebec also provide a rebate of $2,000 on fuel-efficient vehicles.

3.5 Proposed Guidelines to Accelerate Market Diffusion of Hybrid Electric Vehicles

Hybrid vehicle technology has, without a doubt, established itself as a reliable alternative and a promising future for sustainable transportation. But, like any new technology, consumer response to hybrid cars is inevitably slow and calls for an organized effort that mobilizes policies to price greenhouse gases and supports technology development for HEVs. Although such measures are fundamental for the advancement of hybrids in Canada, they face several barriers and market imperfections in the form of hidden and transaction costs including the cost of time to plan new investments, lack of information on available options, capital constraints, misaligned incentives as well as behavioral and organizational factors affecting economic rationality in decision-making. Such limitations may hinder the anticipated outcome of policies and actions towards sustainability. Thus, the challenge lies in identifying the obstacles and developing targeted strategies for regulation, information, technology development and financing in order to overcome the market barriers that affect the demand for HEVs.

Although such measures have begun to take place in the Canadian government at the federal as well as the provincial level, sales of hybrid units continue to share a fractional portion. This slow market penetration of hybrids calls for more effective and well devised strategy with long-term and short-term plans to encourage consumers to adapt this eco-friendly vehicular technology.

3.5.1 Economic Policies and Financial Incentives

The Canadian government needs to recognize the significance and urgency of taking pro-active steps towards providing serious alternatives to the community as the means to reduce carbon inputs. A solution can only be found through a tiered approach, ranging from increased hybrid vehicle usage to a national sustainable transportation plan addressing the needs of all Canadians. One of the most effective ways to prevent deterioration of air quality by on-road transportation is to support and promote the market arrival of HEVs. Exempting duty on both personal and commercial scale imports of hybrids can ease the inflow of hybrids into Canada. The government can also accelerate market arrival of HEVs by signing advanced purchasing agreement through soft orders. A soft order is a commitment that the city would give the purchase of hybrid vehicles a serious consideration. All federal funding provided to provinces, cities and institutions can be made conditional to the display of evidence of carbon reduction and possibly the purchase of hybrid vehicles.

Scale-based rebates on the purchase of efficient vehicles should also be increased up to $5,000 to bring down the price differential between hybrid and non-hybrid cars. It is also noteworthy that consumers respond more to direct price cuts at the time of purchase instead of rebates that require following application procedures for reimbursements. Hence making the rebates effective at the time of purchase can also be a motivating factor for buyers. The federal government's ecoAUTO rebate program is set to expire in March 2009. The government should consider extending it until consumer confidence can be built on hybrid technology and hybrid vehicles become well established in the mainstream market.

3.5.2 Regulation of CO_2 Emission

Federal government needs to strengthen its commitment to working with auto manufacturers, provinces and other stake-holders and develop a sustainable vehicles strategy for significant reduction in emission levels. Setting penalty for owning inefficient cars can be an effective motivation to adopt low emission vehicles. Carbon tax, for example, is an indirect environmental tax on emissions of carbon dioxide and other green-house gases, under which motorists pay a few extra cents per litre at the pump. British Columbia was the first province to introduce carbon tax and the Green Party of Canada suggests these taxes be imposed countrywide with an immediate price of \$50/tonne of CO_2 equivalent (CO_2e). With continuous monitoring on their impact on target reduction, these taxes can be increased up to \$100/tonne of CO_2e which has been determined to be the price put on the cost of climate change by 2020 according to the

Stern Review. With 2.34 kg of CO_2 emitted from combustion of every litre of gas, a tax of $50/tonnes implies an additional 12 cents per litre that vehicle owners will have to pay at the gas station. Revenues from this carbon tax can be used to reduce income taxes and shift to pollution-based taxation to offset any negative impact on low- and middle-income Canadians.

California has the most strict emission standards for any jurisdiction in North America. Canada can adopt California emission standards for light-duty vehicles requiring a 30% reduction in CO_2 emission/mile from new vehicles by 2016, 50% reduction by 2020 and as much as 90% by 2025. This will motivate the auto manufacturers to build low and zero emission vehicles and help create fuel-efficiency standards in Canada that are in line with the US states leading in emission regulation.

3.5.3 Support for Technology Development

The efforts to promote green transportation should not only emphasize on accelerating market diffusion and building consumer confidence, but should also focus on overcoming technological challenges that hybrids face today. All commercially available hybrids consume gasoline to some extent, raising the question of partial dependence on fossil fuel. Since ethanol emits 85% less GHGs than gasoline, the federal government needs to support and assist research and development to produce cellulosic ethanol from wood, grasses, or non-edible parts of plants. The government should establish corn, cellulosic and advanced ethanol and biodiesel standards to displace gasoline and eventually phase out the use petroleum with 100% ethanol and biodiesel standards. Auto manufacturers need to create more skilled technicians and equip service stations for the repair and maintenance of hybrid cars.

Canada also needs to the build partnerships, such as the Hybrid Consortium in United States, to help bridge the gap in research and development between auto makers and part suppliers and original equipment manufacturers and to accelerate the development of critical components. Such collaborations can build political support and secure funding to help automakers build HEV prototypes using new technology from its members. They can help develop vehicle system designs and start the commercial production of hybrid vehicles in Canada. Municipal and provincial governments, and environmental, consumer and business organizations can actively participate in such initiatives to assure vehicle makers that a market for hybrid vehicles exists today. The benefits of becoming a member of this partnership may include:

- Access to information and data on technical and infrastructure support and operational matters of HEVs to assist in planning
- Help from partners in improving the effectiveness and overall competitiveness of their products and services
- Becoming a pioneer in discovering low emission vehicle solutions for the community
- Boost in the demand for hybrid vehicles in support of the municipality's action plan on climate change
- Access to current information for members to develop strategies in successfully managing their business

These measures altogether can form a comprehensive solution-based approach to build consumer confidence on hybrid electric vehicles and prepare Canada's transportation network for a green economy. Canada now has the opportunity to renew its commitment towards a greener and sustainable world, and the transport sector can take the first step towards achieving this goal.

3.6 References

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4 DEVELOPMENT OF HYBRID DRIVETRAIN TECHNOLOGY

While formulation, regulation and implementation of active public policies and introduction of financial incentives are crucial to accelerate market diffusion of hybrid vehicles, automakers also face the challenge of the necessity to improve the performance of HEVs and build consumer confidence in this fairly new technology. For successful marketing, hybrids need to demonstrate enhanced vehicle characteristics that can compete with the well established conventional vehicles. However, the integration of electrical and mechanical drivetrains makes the development of HEVs a complex task of multidisciplinary nature. This increased complexity magnifies the challenge to produce reliable vehicles that meet stringent emissions, fuel economy, and performance criteria. Design of hybrid drivetrain architectures, energy management systems and particularly battery and electric motor drive technology are key areas where operational characteristics of drivetrain components need to be drastically improved to enable hybrid cars to deliver the vehicle performance and fuel economy that consumers demand.

4.1 HEV Design Concept

The Technical Committee 69 of Electric Road Vehicles defines HEV as a vehicle in which the propulsion energy is available from two or more kinds or types of energy stores, sources or converters at least one of which can deliver electrical energy [1]. Hybrid electric vehicles today typically integrate a gasoline or diesel-fueled internal combustion engine (ICE) with a battery powered electric motor drive. The presence of on-board electric motor gives the flexibility to operate the ICE only in its maximum efficiency region to improve the overall vehicle efficiency. Based on the hybrid drivetrain architecture, the motor can either utilize the power generated by the engine to charge the battery or provide additional power to assist the driving if the engine cannot provide the required traction power. Moreover, bidirectional flow of electric energy between the motor and battery in the vehicle allows part of the braking energy to be recaptured rather than dissipated as heat in conventional vehicles. Optimized operation of the ICE in a hybrid vehicle and its capability of regenerative braking allow drastic improvement in fuel economy and considerable reduction in vehicular emissions. These features also help reduce maintenance cost on oil changes, exhaust repairs and brake replacement [2].

4.1.1 Optimized Operation of Internal Combustion Engine

Fuel consumption of an internal combustion engine is measured as the mass flow per unit time and is called the flow rate. The flow rate per output power of the engine is called the *specific fuel consumption* (*sfc*), expressed in g/kWh, that measures how efficiently the engine uses the fuel supplied to produce work.

$$sfc = \frac{m_f}{P} \tag{4.1}$$

where m_f is the fuel flow rate and P is the engine power. If the engine power is measured as the net power from the crankshaft, the specific fuel consumption is called *brake-specific fuel consumption* (*bsfc*) [3]. Figure 4.1 shows that fuel consumption of the vehicle increases at high speeds to overcome the aerodynamic resistance of the vehicle governed by the equation:

$$F_w = \frac{1}{2}\rho A_f C_D (V + V_w)^2 \tag{4.2}$$

where V is the vehicle speed, V_w is the component of the wind speed on the vehicle's moving direction, ρ is the air density, C_D is the aerodynamic drag coefficient and A_f is the vehicle frontal area. The consequent increase in engine power output to overcome the resistance power of the vehicle is given as:

$$P_e = \frac{V}{\eta_t}\left(F_f + F_w + F_g + M_v \delta \frac{dV}{dt}\right) \tag{4.3}$$

where η_t is the well-to-wheel driveline efficiency F_f is the tire rolling resistance, F_g is the grading resistance, M_v is mass of the vehicle and δ is the mass factor that can be calculated from the values of mass moment of inertia of all rotating parts or estimated

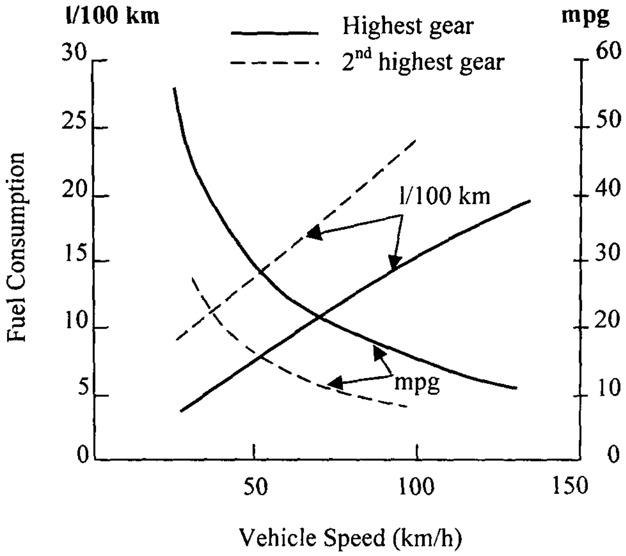


Fig. 4.1. Fuel economy characteristics of a typical vehicle at constant speed.

using empirical formula. Figure 4.1 also shows an improvement in fuel economy of the vehicle with high-speed gear due to reduced engine speed for a given vehicle speed.

The ICE is the primary source of power in hybrid electric vehicles. However, its operation widely differs from that in a conventional automobile. In an HEV, the engine is run for a longer time at high power with infrequent demand for change in its delivered power. The fuel consumption characteristics of an engine vary widely with engine speed and load. Typical fuel economy characteristics of a gasoline engine are shown in Fig. 4.2. The optimal operating region of the engine, where, fuel consumption is minimal, is generally located near the centre of the speed range, corresponding to the maximum torque [3]. It is close to the full load operation where the percentage of losses to the total power is small. Thus in vehicle design, the engine operation needs to be kept close to this region to achieve high operating fuel economy This is made possible by the hybridization of the ICE with an electric motor that governs the vehicle traction such that the engine need only run in the region of its optimum efficiency.

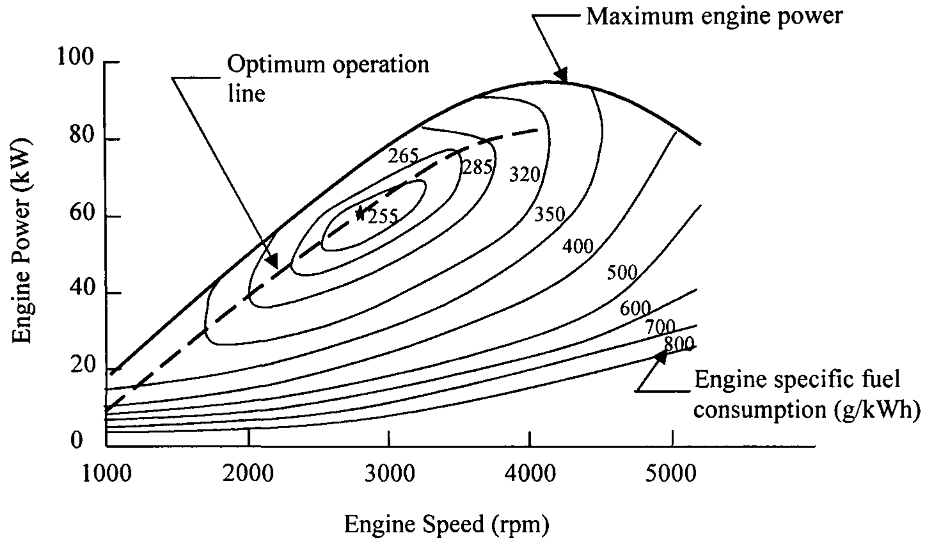


Fig. 4.2. Fuel economy characteristics of a typical gasoline engine.

4.1.2 Regenerative Braking

The braking performance is one of the key features that determine the safety of the vehicle. In urban driving a significant amount of energy is lost during driving due to frequent braking, resulting in high fuel consumption. The integration of an electric drivetrain in an HEV that enables the vehicle to recapture this energy during braking is one of the most significant characteristics of a hybrid electric vehicle. The electric motor serves as a generator during braking to convert kinetic energy of the vehicle into electrical energy that can be stored in the battery through a bidirectional converter. Braking energy in a typical urban driving pattern may reach up to 25% of the total traction energy. Thus, the effective recovery of this energy and its conversion to electrical power by the motor has a significant impact on the fuel economy of automobiles [4].

When the driver hits the brake pedal in an ICEV, the brake pad is pressed against the brake disc, developing a frictional torque on the brake plate. This braking torque results in a braking force in the contact area between tire and ground, causing the vehicle to slow down and eventually stop. The braking force increases with the increase in braking torque until it reaches a maximum braking force after which it will no longer increase irrespective of the braking torque, i.e., the tire skids. The braking power and braking energy consumed by the front and rear wheels are associated with the braking forces on the front and rear wheels. Figure 4.3 shows the ideal and actual braking force distribution curves. The ideal braking force distribution curve, called *I* curve, is a non-linear hyperbolic curve. If it is desired for the front and rear wheels to lock up at the same time on the road, the braking force on the front and rear axle should follow this curve closely. The actual braking forces, on the other hand, have a fixed linear proportion shown by the β line. Ignoring vehicle drags, the braking forces on the front and rear wheels can be expressed as:

$$F_{bf} = \frac{jM_v}{L}\left(L_b + \frac{h_g}{g}j\right) \tag{4.4}$$

$$F_{br} = \frac{jM_v}{L}\left(L_a + \frac{h_g}{g}j\right) \tag{4.5}$$

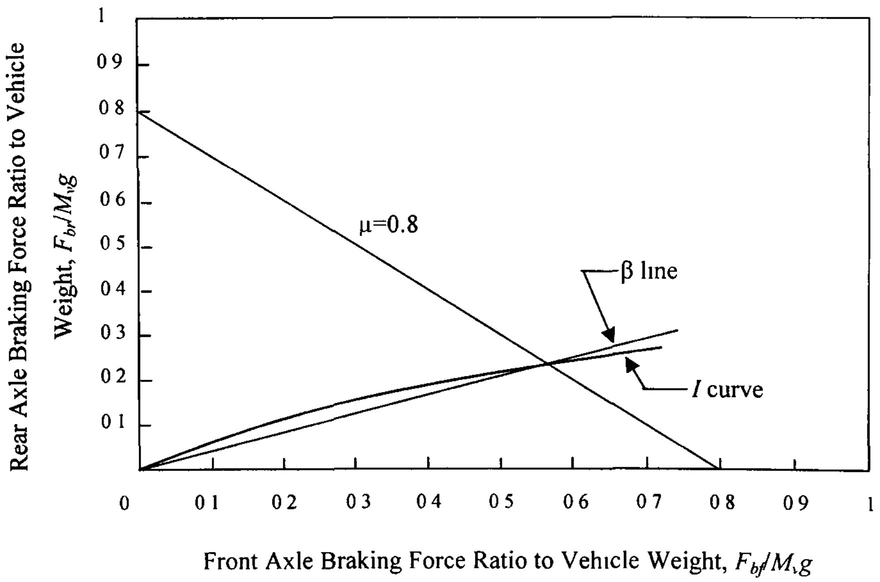


Fig. 4.3. Ideal and actual braking force distribution.

where j is the deceleration of the vehicle in m/s^2, L is the wheel base of the vehicle, L_a and L_b, are the horizontal distances between the vehicle centre of gravity to the centre of gravity of the front and rear wheels respectively, and h_g is the height of the gravity centre of the vehicle to the ground. In order to prevent the rear wheels from becoming locked before the front wheels resulting in unstable braking, the actual braking force on the front wheels is usually greater than that dictated by the ideal distribution curve I.

Regenerative braking in HEVs adds complexity to the design of braking system in the vehicle. The main concern is to distribute the total braking forces between regenerative brake and mechanical brake with maximum possible recovery of kinetic energy. At the same time, the braking forces have to distributed between the front and rear axles to ensure steady braking. The electric motor, thus, has to be controlled accordingly to produce the amount of braking force for recovering energy as much as possible, while the mechanical brake has to be controlled to meet the braking force command by the driver. There are three typical braking control strategies based on the design requirement. The series brake for optimal feel consists of a braking controller that controls the braking forces on the front and rear wheels in order to minimize the stopping distance and driving feel. The series brake for optimal energy recovery aims to recover the braking energy as much as possible while meeting the total braking force demanded for the given deceleration. Both kinds of series braking systems are currently under development. Another control strategy for braking control is the parallel brake which produces both regenerative and mechanical braking forces in parallel and simultaneously. Such a braking strategy has a much simpler construction and control compared to series strategy, however the braking performance of the vehicle and its energy recovery are compromised.

The electric drivetrain consisting of a battery powered electric motor drive is, thus, primarily responsible in improving fuel efficiency of HEVs compared to conventional vehicles by allowing the engine to run in its optimum efficiency region and recovering part of the braking energy. The primary objective in the development of the electric drivetrain of HEV is to select the drivetrain topology and design, size and control its drivetrain components to maximize the utilization of electric motor in the vehicle while sustaining sufficient reserves of electrical energy and maintaining the vehicle performance.

4.2 Hybrid Drivetrain Configurations

The combination of electrical and mechanical drivetrains makes the design and control of hybrid traction system a complicated task. The two drivetrains can be integrated in various drivetrain configurations that result in varied vehicle performance and operation characteristics [5]. Based on the flow of electrical and mechanical power, hybrid vehicles can be classified as series, parallel or series-parallel HEVs.

4.2.1 Series Architecture

In a series configuration, such as in GM's upcoming Chevy Volt, the electric motor is the only source of traction to drive the vehicle. As shown in Fig. 4.4, the ICE serves to generate mechanical output that drives an electric generator to either charge the battery or power the traction motor [6]. In concept, a series HEV functions similar to an EV with an ICE to extend the driving range. There are six possible modes in a series HEV:

- Battery alone mode: The engine is shut down and the battery alone powers the traction motor
- Engine alone mode: The engine propels the generator to power the traction motor
- Combined mode: ICE driven generator and battery together power the motor
- Power split mode: Power from ICE propelled generator splits to drive the traction motor and charge the battery
- Stationary charging mode: The vehicle is stationary and ICE charges the battery via the generator
- Regenerative braking mode: Traction motor works as a generator to recharge the battery

Since the engine is decoupled from the wheels and is not responsible to drive the vehicle in any mode, series hybrids have the inherent advantage of the ability to operate the ICE in a very narrow optimal region at all times [7], [8]. The electric motor is the only source of traction that simplifies the drivetrain and speed control of the vehicle and provides close to ideal torque-speed characteristics for vehicle propulsion without the necessity of multi-gear transmission. However, such a configuration requires a generator in addition to the engine and a full sized motor to meet the traction demands, thus adding to the weight and cost of the vehicle. This is why such architecture is generally used in heavy commercial vehicles, military vehicles and buses [9]. Moreover, multiple energy conversions from engine to generator and finally to motor reduce the overall efficiency.

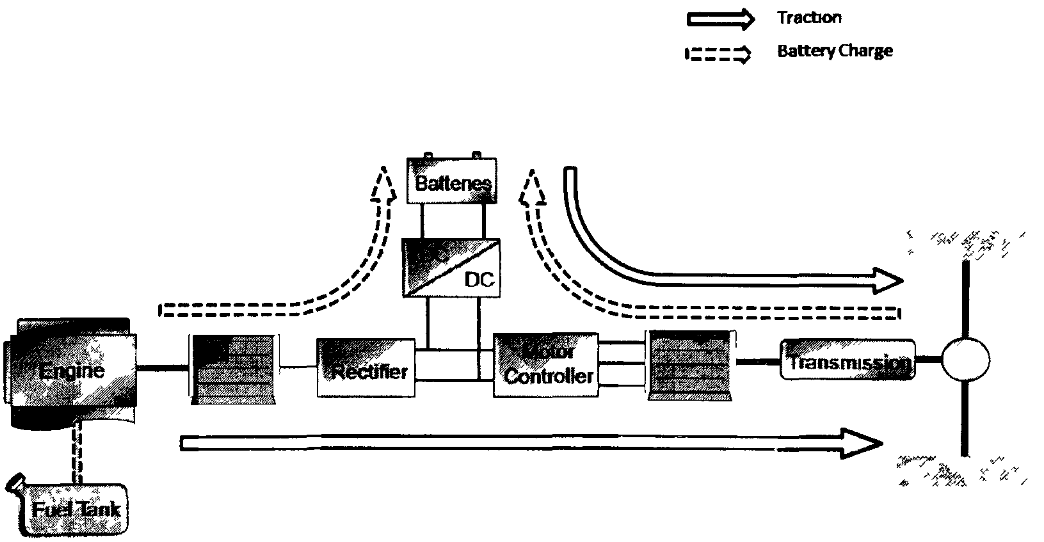


Fig. 4.4. Series drivetrain configuration.

4.2.2 Parallel Architecture

In parallel drivetrain architecture, as demonstrated in Fig. 4.5, both the ICE and the electric motor are mechanically coupled to the drive shaft of the wheels to provide torque for vehicle traction. A parallel HEV is essentially an ICE driven vehicle with an electric motor assist. In the Honda Civic Hybrid it is referred to as the Integrated Motor Assist. The motor complements the engine during high power demand and takes over traction at low speeds, allowing the engine to shut down at low speeds and during idling [10], [11]. The electric motor also functions as a generator during regenerative braking or when driven by the engine to charge the battery. The parallel design operates in the following modes:

- Motor alone mode: Vehicle is only propelled by the motor
- Engine alone mode: Vehicle is only propelled by the ICE
- Combined mode: Both ICE and motor drive the vehicle during high power demand
- Power split mode: For ICE power higher than vehicle demand, engine power is split to drive the vehicle and charge the battery via the motor
- Stationary charging mode: The vehicle is stationary and the engine drives the motor/generator to charge the battery
- Regenerative braking mode: Traction motor works a generator to recharge the battery.

Parallel hybrids need only two propulsion devices, the ICE and the electric motor, the size of which can be reduced since they can function together to meet the vehicle power demand. This helps control the cost, dimension and weight making them ideal for passenger cars. There are fewer energy conversions in parallel drivetrains, making them more efficient than series configuration. But a major drawback of this hybrid design is the inability to fix the operating points of the engine in a narrow region since it is mechanically linked to the wheels for traction. The control strategy of parallel hybrids is more complicated and requires a complex transmission.

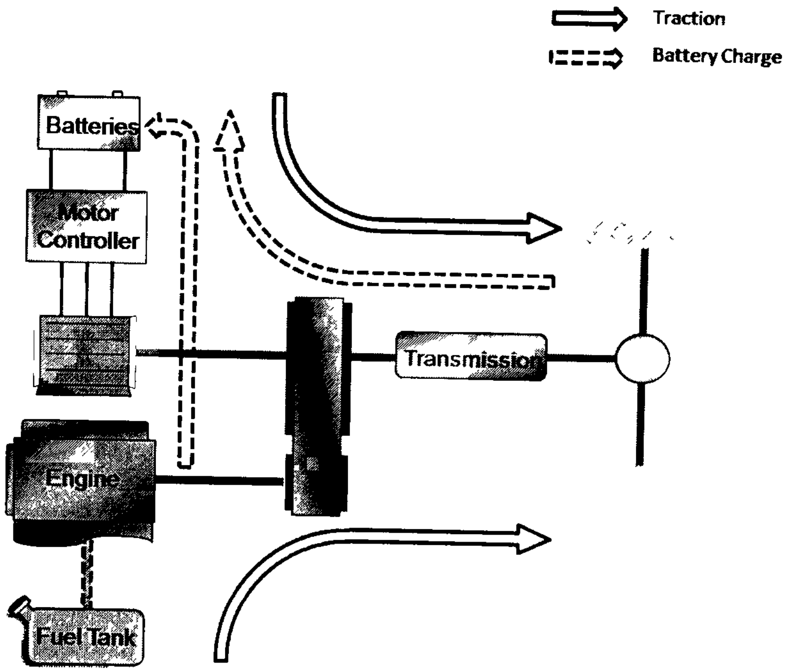


Fig. 4.5. Parallel drivetrain configuration.

4.2.3 Series-Parallel Architecture

Figure 4.6 shows the series-parallel hybrid configuration that takes advantage of the benefits of both series and parallel architectures. It consists of a battery powered electric motor connected to the driveshaft, while the engine, via a power split device, is linked both to the driveshaft as well as to an electric generator that charges the battery [12]. This allows the engine power to be split in into traction force to drive the vehicle and propulsion for the generator to produce and store electric power. Such a topology has an additional mechanical link from engine to the wheels compared to the typical series design, and an additional generator compared to the typical parallel design. During low power demands, the engine can be disconnected from the wheels and together with the planetary gear sets for power split and the generator, it forms a series configuration, operating in a narrow region of maximum efficiency. During high power demand both the engine and traction motor can drive the vehicle. This drivetrain design is more complex and costly, and requires an additional electric machine. Many of the well known hybrid cars including Toyota Prius, and Ford Escape Hybrid employ the series parallel configuration.

There are other possible drivetrain designs that do not qualify as any of the three configurations mentioned above, and are categorized as complex architectures. However, they also face challenges of complexity in design and control along with additional cost.

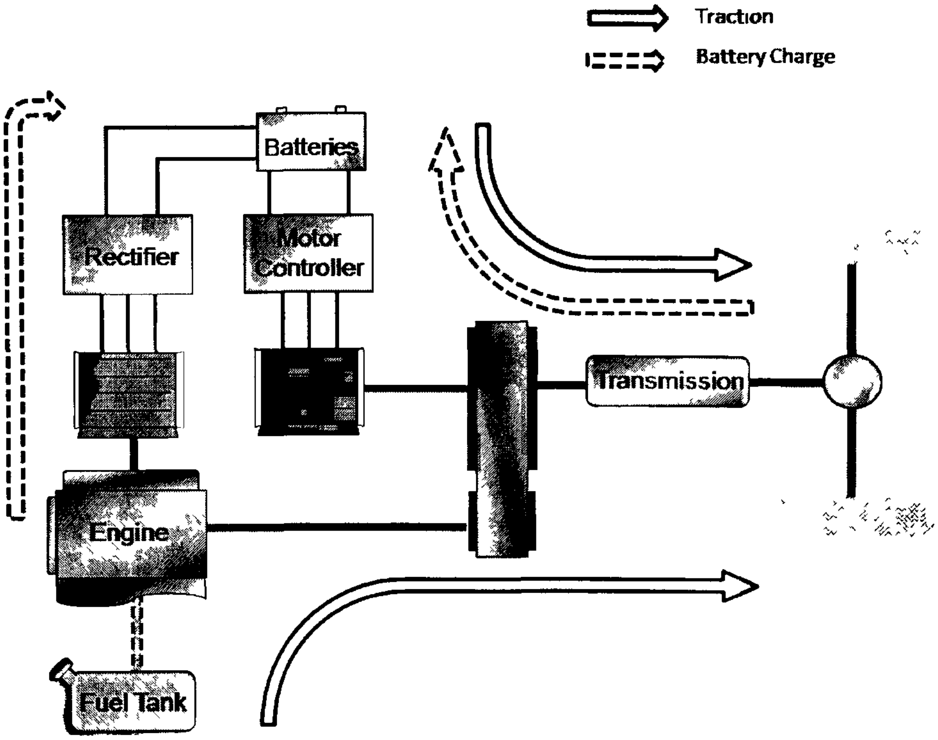


Fig. 4.6. Series-parallel drivetrain configuration.

Based on the function of the electric motor and degree of hybridization, HEVs can also be classified as mini, mild, and full hybrids. A brief description of these hybrids is presented in the following sections.

4.2.4 Mini Hybrids

Mini hybrids such as Chevy Malibu and Smart Fortwo are conventional vehicles with a belt-driven motor serves as an oversized integrated starter/generator (ISG) but that does not propel the vehicle. The ISG, typically rated between 3-5 kW, offers the idle-stop feature that allows the engine to shut down when the vehicle is at rest, hence improving fuel economy for city driving. The ISG can also recharge the battery during vehicle deceleration and braking. With frequent starts and stops in urban driving, the energy saving may reach about 5% to 10% [13]. Due to a very small extent of hybridization and lack of any additional electric drivetrain components, the cost of mini hybrids is only a few percent higher than their conventional counterpart; however they give poor fuel economy by hybrid standards.

4.2.5 Mild Hybrids

In mild hybrids an electric motor rated from 10 to 20 kW at 100 to 200 V, provides the hybrid features of idle-stop and regenerative braking. In addition it can assist the engine in propulsion during high power demands or split engine power to recharge the battery during low power demand [14]. The engine and motor can be down sized in mild hybrids for the same power output since the motor assists the engine for high power requirements. Commercial mild hybrid models include the Honda Civic and Honda Insight. The Honda Insight is not available in Canada at present; however the Honda Civic is one of the most successful hybrid cars in Canada.

4.2.6 Full Hybrids

Full hybrids, such as the Toyota Prius, Ford Escape and Nissan Altima, typically consist of a motor, generator, and ICE, connected in series-parallel or a more complex hybrid architecture where, in addition to idle-stop and regenerative braking, the engine and motor can drive the vehicle mutually or independently such that propulsion can be executed by motor only for start, engine only for cruising at optimum operation region, or a combination of both for sudden acceleration or normal driving when the required propulsion power is less than the engine optimum power range. In such cases, the engine will drive the generator to charge the battery. The corresponding motor and battery ratings are typically 30 kW and higher at 200-600 V Power split devices such as a planetary gear control the power flow among the engine, motor, generator, and battery in order to achieve optimum drive performance at maximum energy efficiency and minimum emission.

Full hybrid vehicles can be further subdivided into synergy hybrid and power hybrid. The Toyota Prius an excellent example of synergy hybrids that produce the optimum combination of drive performance, energy efficiency, and emission reduction with a downsized engine compared to conventional vehicles. The Toyota Highlander, on the other hand, is a power hybrid that aims for enhanced driving performance. The engine is not downsized, and together with the motor, the vehicle offers improved drive performance.

4.3 Energy Management Systems

Any hybrid drivetrain configuration is an integration of electrical and mechanical power producing components and requires a supervisory control strategy to manage the flow of power to and from each component while maintaining sufficient energy reserves in the storage devices. This facilitates an effective and optimum usage of the electric drivetrain to achieve design objectives such as high fuel economy and low emissions while ensuring performance improvement in terms of acceleration and range. The aim of such vehicle supervisory control is to employ conventional and adaptive control theories and optimization techniques to develop energy management systems that address the issues of torque distribution and charge sustenance in HEVs [15].

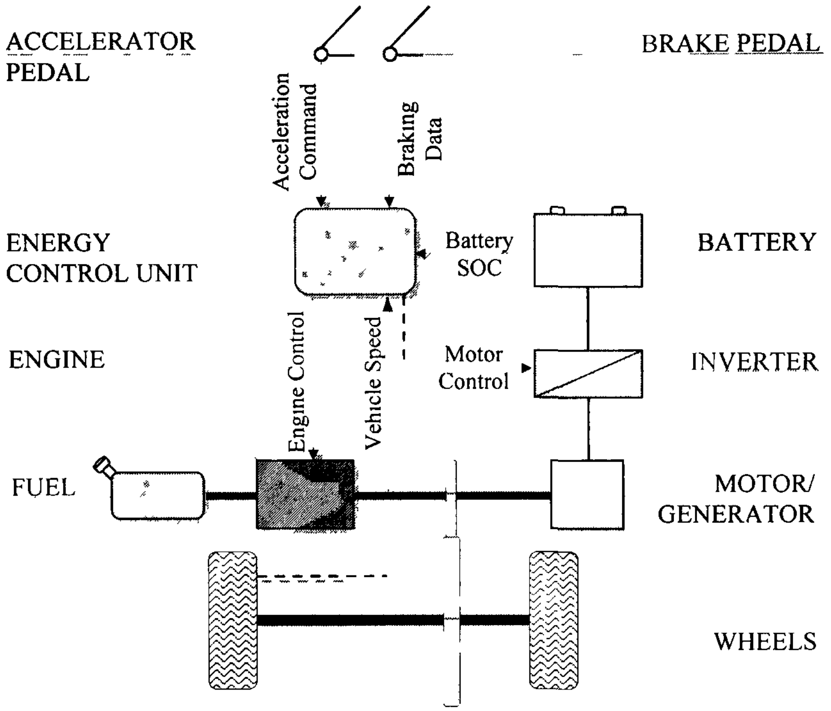


Fig. 4.7. Energy control unit of hybrid drivetrain.

Figure 4.7 shows the energy control unit (ECU) of Toyota's Hybrid Synergy Drive that constantly monitors the operational conditions of drivetrain components including the ICE, motor, generator and battery, braking data through the control network, acceleration demand from the pedal and gear shift position, and energy consumption from accessories such as air conditioning and navigation systems [16]. Based on this information, the ECU generates corresponding command signals that control power flow in the electric and mechanical drivetrain components for optimum performance and maximum fuel efficiency.

A smart energy management system can ensure effective utilization of the available electric power to maximize the use of the electric motor for vehicle traction so that the use of the internal combustion engine can be considerably curtailed consequently improving fuel efficiency, reducing gasoline consumption and lowering emissions from the vehicle [17].

4.4 Battery Technology

The energy storage device is a crucial component of the electric drivetrain in hybrid vehicles, since the utilization of electric motor for traction depends on the availability of electric power. For hybrid vehicles, energy storage systems should be capable of storing sufficient energy, offer high energy efficiency, high current discharge, and good charge acceptance from regenerative braking, and must meet the peak power demands of the vehicle [18]. The storage unit must also meet appropriate cycle and calendar life requirements, exhibit abuse tolerance to ensure safety and provide a cost effective solution for market acceptability. Although many different types of energy storage technologies, including ultracapacitors and fuel cells are under development, batteries are currently used as source of electric power in almost all HEVs.

A battery is composed of modules of unit cells stacked together to convert chemical energy into electrical energy using the basic components of the cell shown in Fig 4.8. The positive and negative electrodes, called the cathode and anode respectively, are the active components of the cell, and are immersed in an electrolyte that serves as a medium to permit ionic conduction between the electrodes. In addition, the cell has non-reactive components such as separators, collectors and a container. Chemical oxidation and reduction take place at the electrodes releasing electrons.

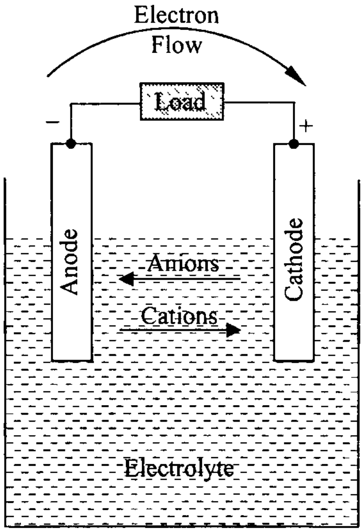


Fig. 4.8. Electrochemical reaction in a cell during discharge.

When the cell is connected to a load, these electrons travel from the oxidized anode, through the external load to the cathode that is reduced. The electric circuit is completed in the electrolyte by the flow of negative ions, called anions, to the anode and positive ions, or cations, to the cathode [19]. Following are the basic parameters that determine the performance of a battery for any given application:

- *Coulombic capacity*. It is expressed in ampere-hours and is the total quantity of electric charge involved in the electrochemical reaction. It can be calculated from the equivalent weight of the reactants.
- *Thermodynamic voltage*. The standard potential of a cell is determined by the type of active materials and can be calculated from oxidation and reduction potentials of the reactants. It is also dependent on concentration and temperature.
- *Specific energy*. This is the capacity per unit weight expressed in Wh/kg. The theoretical specific energy is the maximum energy that can be generated per unit total mass of the cell reactant and depends on the electrode materials. The actual specific energy, however, is only a fraction of the theoretical energy. This is mainly due to the additional weight and volume of inactive components. The theoretical energy of a cell is determined by

  $$Watthour\ (Wh) = Voltage\ (V) \times Ampere - hour\ (Ah) \tag{4.5}$$

  The battery does not discharge at the theoretical voltage due to internal losses and cannot completely deliver the theoretical ampere-hours. This further reduces the practical specific energy of the cell.
- *Specific power* This is the maximum power per unit weight that the cell (or battery) can produce in a short time period and is expressed in W/kg. It mainly depends on the internal resistance of the cell.
- *Energy efficiency*. The energy and power losses during battery discharge appear in the form of voltage loss. The efficiency at a given operating point during discharge is therefore defined as the ratio of the cell operating voltage to the theoretical thermodynamic voltage.
- *Cycle life*: This is defined as the number of complete charge/discharge cycles a

battery can perform before its capacity falls below 80% of its initial rated capacity.

- *Calendar life*. This is the elapsed time before a battery becomes entirely unusable.

Batteries can broadly be classified as 'primary' type that cannot be recharged due to irreversible chemical reactions, and 'secondary' type rechargeable batteries. Hybrid vehicles employ the latter and several options, particularly lead-acid, nickel-metal hydride (NiMH) and lithium-ion (li-ion) batteries, have been under consideration for this application. In electric vehicles the battery does not have access to on-board charging due to the absence of ICE, and thus energy density is of prime importance in its design. However, in hybrid electric vehicles the battery is sized by the peak power demand during vehicle acceleration. Thus, the weight and volume of the battery for an HEV is determined primarily by the required pulse power density of the battery. In most cases, the corresponding energy density of an HEV battery designed for a given power demand, although still lower than EV batteries, is considerably greater than that needed by the vehicle to meet appropriate driving cycles. This additional stored energy permits the battery to operate over a relatively narrow state-of-charge (SOC) range that helps extend battery cycle and calendar life.

Developing a battery technology with an acceptable combination of power, energy and life cycle for HEV application continues to pose a challenge. NiMH batteries have been used in almost all commercial hybrids to date since they offer fairly good energy and power densities, long cycle life and abuse tolerance; however their cell efficiency is quite low with very high self discharge. Their life reduces with high depth-of-discharge cycling and heat production becomes a concern at high temperatures. Lithium ion batteries, on the other hand, although still in the developmental stage, are now seen as the long term solution for automotive application. But concerns of high cost, low cycle life and thermal runaways have to be addressed before they can be used in commercial hybrids.

4.4.1 Nickel-Metal Hydride Batteries

Nickel-metal hydride batteries have dominated the automotive application due to their overall performance and best available combination of energy and power densities, thermal performance and cycle life. They do not need maintenance, require simple and inexpensive charging and electronic control and are made of environmentally acceptable recyclable materials.

NiMH batteries can have a cylindrical or prismatic construction as shown in Figs. 4.9(a) and 4(b) respectively. The low cost cylindrical construction can be manufactured faster and is used in application requiring under 10 Ah. Cylindrical batteries typically have a low to moderate discharge rate, therefore, to provide high discharge demand in HEV traction, a multiple tab current collection is used which consists of current collecting strips on one side of each electrode wound together. Cylindrical batteries are only developed in metal casing such that the casing itself serves as the negative terminal and is electrically connected to the metal hydride electrode. Prismatic construction is used for application requiring higher than 20 Ah, whereas both cylindrical and prismatic configurations can be used for 10 Ah to 20 Ah range. Prismatic batteries consist of electrode stacks of alternating positive and negative electrode with immediate separators. HEV prismatic NiMH batteries are expected to deliver specific power of 500 W/kg or higher, for which the thickness of the electrode is kept small. Unlike cylindrical construction, prismatic design has both a positive and negative terminal at the top cover plate. Both metal and plastic cell cases are common in prismatic batteries for HEV application.

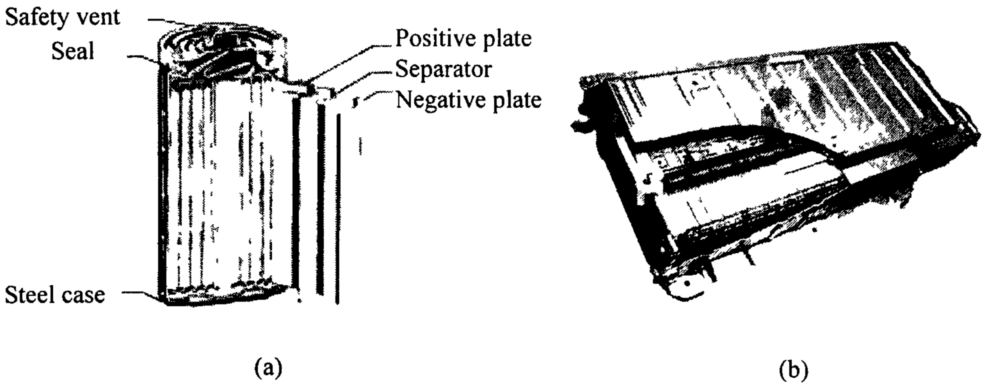
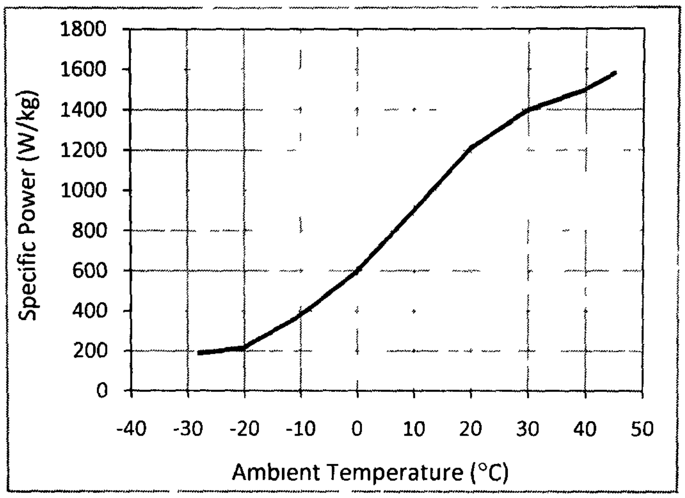


Fig. 4.9. NiMH battery construction. (a) Cylindrical. (b) Prismatic.

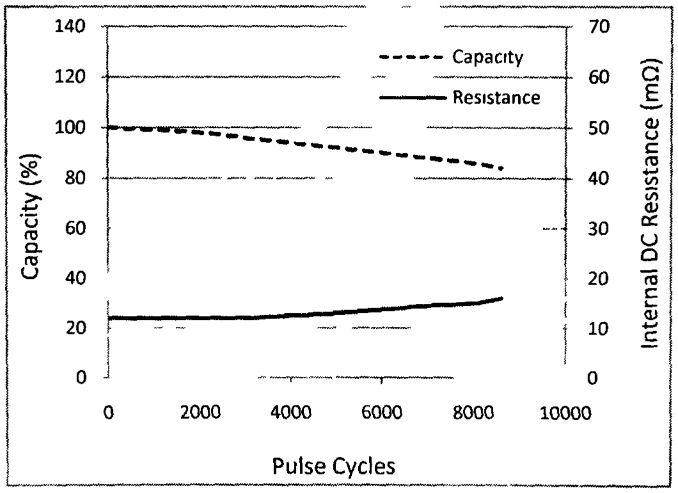
TABLE 4.1
SUMMARY OF BATTERY SYSTEMS FOR AUTOMOTIVE APPLICATION

Battery Type	Specific Energy (Wh/kg)	Peak Specific Power (W/kg)	Efficiency (%)	Cycle Life	Self Discharge (% per 48 h)	Cost (Cdn$/kWh)
Lead acid	35-50	150-400	>80	500-1000	0.6	144-180
Nickel-cadmium	50-60	80-150	75	800	1	300-420
Nickel-zinc	55-75	170-260	65	300	1.6	120-360
NiMH	70-95	200-300	70	750-1200+	6	240-420
Lithium-iron sulfide	100-130	150-250	80	1000+	n/a	130
Lithium-ion	80-130	200-300	>95	1000+	0.7	240

Table IV shows the summary of specifications of various batteries as of 2006. However, Panasonic, the battery supplier for leading hybrid manufacturers such as Toyota, now offers metal case prismatic NiMH batteries for HEVs with specific power up to 1300 W/kg and specific energy of 46 Wh/kg. The Toyota Prius is equipped with a 201.6 V battery pack of prismatic NiMH modules from Panasonic that comes with an 8-10 year/240,000 km warrantee. Each module weighing 1.04 kg, consists of six 1.2 V cells connected in series, a capacity of 6.5 Ah, and has dimensions of 19.6 mm (width) x 106 mm (height) x 275 mm (length). The specific power by Panasonic's NiMH module under varying operating temperatures can be seen in Fig. 4.10(a). The specific power of the module increases at higher temperature due to increase in chemical activity and the battery can deliver up to 1500 W/kg at 40°C. The cycle life of the battery, shown in Fig 4.10(b), is close to 9,000 pulse cycles after which the battery's capacity reduces to 80% of its initial capacity. Within this cycle life, the internal resistance shows a considerably small increase of about 5 mΩ.



(a)



(b)

Fig. 4.10. Performance characteristics of Panasonic NiMH module. (a) Specific power for varying operating temperature. (b) Change in internal resistance over the cycle life.

4.4.2 Lithium-ion Technology

Since their introduction in 1991, lithium-ion batteries have been regarded as a promising alternative due to their relatively higher specific power and energy density, low self-discharge, reduced volume and light weight. Their efficiency and single cell voltages are higher than any other battery technology available on the market. Many manufacturers including SAFT, Panasonic, EnerDel Inc. and Sony are involved in extensive research to develop commercially viable high performance lithium-ion batteries for hybrid vehicles with higher calendar life and reduced cost. A123 Systems have developed lithium-ion batteries for HEVs that exhibit drastic reduction in impedance change even after 250,000 pulse cycles as shown in Fig. 4.11. Li-ion batteries tend to heat when overcharged which may cause failure with shortened life or melting of the battery. Lithium-ion batteries need to be made tolerant to such electrical abuse before they can be used commercially in hybrid vehicle applications. General Motors is targeting a 100 L, 16 kWh Li-ion battery for its upcoming plug-in series hybrid Chevy Volt while BMW is launching Li-ion powered 7-series hybrid, expected to debut in 2009.

A breakthrough in the development of high performance batteries will play a crucial role in the effective usage of the electric drivetrain in a hybrid traction system. This will, in turn, translate into a drastic reduction in fuel consumption due to minimized operation of the IC engine. Thus, the primary consideration while designing a hybrid drivetrain configuration, developing its supervisory control unit and improving the performance of battery packs is to maximize the utilization of the electric motor in the vehicle. The endeavor in the advancement of these technologies is to gradually displace gasoline powered mechanical propulsion with electric propulsion that can lead to extended range HEVs, to plug-in hybrid and finally to battery electric vehicles where electric motor is the only source of traction.

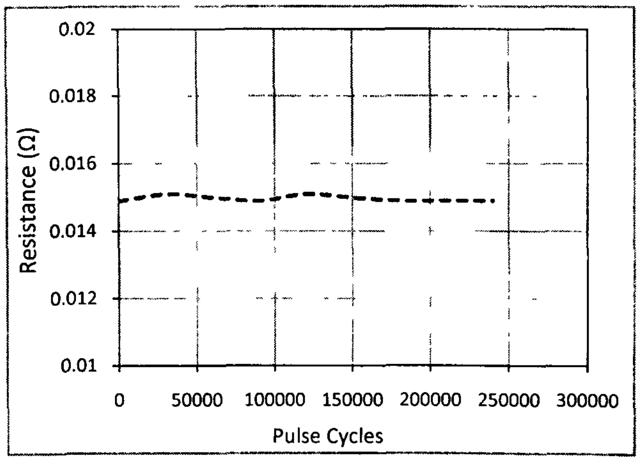


Fig. 4.11. Change of lithium-ion battery impedance after 300,000 cycles.

4.5 Electric Traction Motor

The electric propulsion system is the focal point of hybrid vehicle technology that distinguishes operational features of HEVs from conventional automobiles. It consists of an electric motor, power electronic drive for the motor and electronic controllers. With deeper penetration of hybrid vehicles in the market followed by consumer expectation for improved vehicle performance, auto manufacturers are recognizing that design of next generation hybrid systems will heavily rely on the development of high performance motors for HEV specific application. This will particularly hold true as motors become the primary traction component with the improvement in the all-electric range of vehicles. Although electric motor drive and control is a mature technology, further improvement in efficiency, robustness, weight, cost and noise, vibration and harshness (NVH) of electric motors in HEVs can be achieved, through design modifications and control strategies.

Figure 4.12 shows characteristics of electric motors desired in HEV application. In the constant torque region, the electric motor delivers constant torque from zero to rated speed. Past the rated speed, the torque decreases proportionally with the square of the speed, maintaining a constant rated power output [20]. Selection of an appropriate traction motor is based on efficiency, power density (power output/volume), reliability

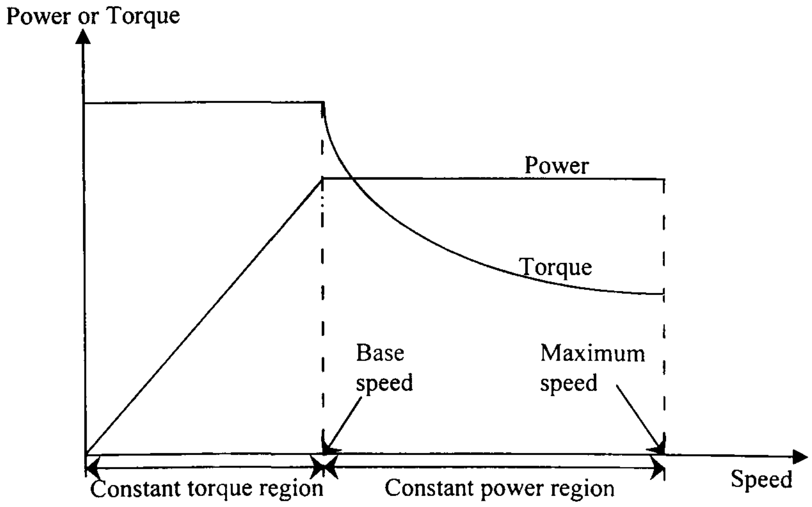


Fig. 4.12. Desired characteristics of electric traction in HEV.

and cost and is a crucial stage in the design of the electric drivetrain. The three main factors that need to be kept in consideration during the selection and design process of motors are a) the driver expectation for the driving profile in terms of acceleration demand, climbing and braking performance, maximum speed and range, b) vehicle constraints of weight and volume based on vehicle type and c) the type and specifications of the energy storage unit. An electric motor for hybrid vehicle traction is typically expected to fulfill the following requirements:

- High instant power and high power density
- Quick torque response
- High torque at low speeds for starting and climbing
- High power at high speed for cruising
- Wide speed range in constant-torque and constant-power regions
- High efficiency, reliability and robustness
- Low cost

Under these criteria, several electric machines are being investigated for HEV application. Although DC motors were the initial choice, induction motors (IMs), permanent magnet synchronous motors (PMSMs) and switched reluctance motors (SRMs) have now gained attention as the most favoured candidates for HEV propulsion.

4.5.1 Induction Motors

Induction motors, particularly squirrel cage IMs have been widely regarded as one of the most suitable options for HEVs. Induction motors are three-phase commutatorless AC machines that are extensively used in industrial applications. They are reliable, cost less, and require very little maintenance. Their ruggedness makes them suitable for operations in the harsh environment of traction drives. Their control and drive technology has well matured and prominent automakers have used IMs in their hybrid cars including the Daimler/Chrysler Durango, the Chevrolet Silverado and the BMW X5. Accurate speed control of induction machines is made possible by vector control techniques and wide speed ranges, generally over two to three time the synchronous speed, are possible through flux weakening.

However, the breakdown torque creates a limitation on the constant power operation of the motor. If run at speeds higher than the critical value, where break down torque is reached, the motor begins to stall [20]. But the more crucial factor that has diverted auto manufacturers away from IMs is their inherently lower efficiency than PMSMs particularly due to copper losses in the rotor. Research is now focused to address these issues through design modification and more effective control methods. A new generation of control strategies are being tested to improve the overall efficiency of induction motors[21] and a multiphase pole-changing IM drive has been developed to extend the constant-power region without oversizing the motor [22], [23].

Rotor resistance variation due to temperature is also a problem in induction motors that can detune the field controller during its operation [24]. Therefore, development of robust parameter insensitive motor control techniques for induction machines is another area that calls for immediate attention to improve the performance of IM drives and make them, once again, the foremost choice in hybrid vehicle application.

4.5.2 Permanent Magnet Synchronous Motors

Permanent magnet synchronous motors use a rotor made of earth magnetic materials to generate magnetic flux. Depending on the arrangement of the magnet, they can be classified as surface-magnet mounted or buried-magnet mounted. Absence of rotor windings gives PMSMs an edge over induction motors in terms of efficiency [25]. They have high power density, fast torque response and comparatively lighter weight, making them the primary choice of leading automakers for most hybrid cars available commercially today.

The absence of field windings makes the flux weakening capability of PMSMs rather constrained, limiting their speed ranges in the constant power region [26]. One method to overcome this limitation is to control the conduction angle of the power converter. An alternative solution is the permanent magnet hybrid configuration where the air-gap magnetic field is obtained through a combination of the magnet and additional field winding. The direction and magnitude of the DC field current can be controlled so as to weaken the flux of the magnet. This arrangement, however, adds to the complexity of design and control.

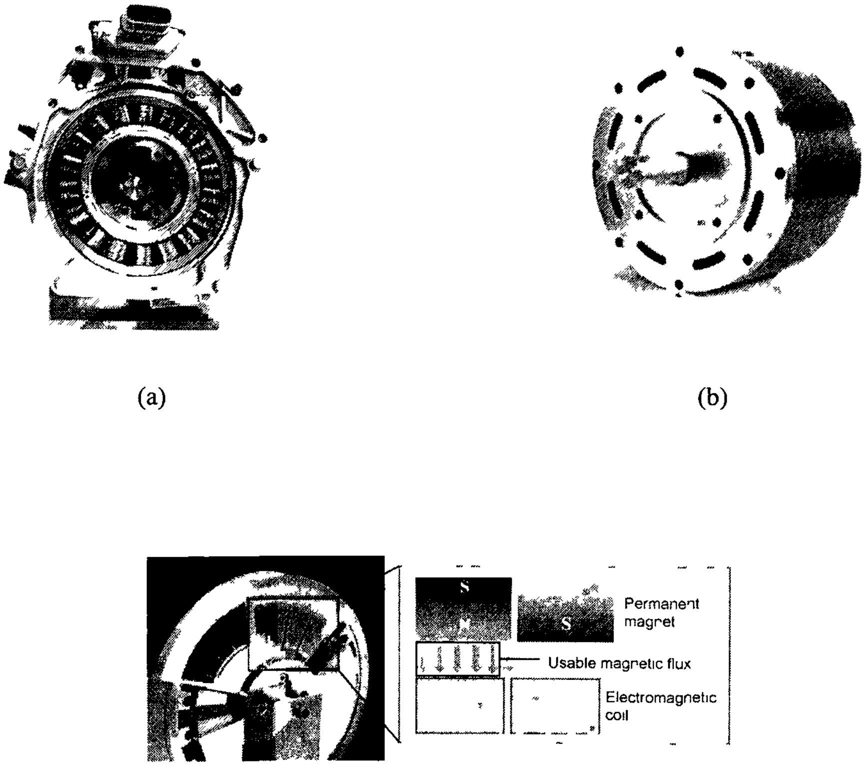
Another downside of using a permanent magnet is its sensitivity to temperature and its demagnetization with age which can affects long term performance of the machine.

4.5.3 Switched Reluctance Motors

SRMs are beginning to gain interest as a potential candidate for HEV propulsion due to their simple and rugged construction, an extremely long constant-power range and high speed operation [27]-[29]. However there are several barriers that need to be resolved before they can be applied in mass produced vehicles [30]. Since SRM control involves successive excitation of poles to align the rotor, torque ripple, vibration and associated acoustic noise are the main concerns in SRM operation [31]. They require a complex converter topology for the drive that makes their control complex and expensive. These issues are critical in vehicle application and research is targeted towards analysis, design improvement and development of excitation schemes and control strategies to reduce these effects.

4.5.4 HEV Specific Motor Designs

The auto industry is also looking for more drastic modifications in terms of material selection, innovative component shapes and designs, and control strategies for electric motors to improve efficiency, cost and NVH (noise, vibration and harshness) while maintaining compact size and light weight. Honda, for example, has developed an exceptionally thin (70 mm) motor for their Civic Hybrid, shown in Fig. 4.13(a), that claims to have achieved a peak efficiency of 97%. Toyota is also experimenting with a new smaller motor for its Lexus RX400h that produces low torque but spins at a much higher speed, producing high output power. This was achieved through reorientation of magnets for better control of magnetic flux and reduction in torque ripple effect. GM's belt alternator/starter system, capable of idle-stop and mild power assist, uses a brushed permanent magnet motor instead of the conventional brushless motor to produce higher magnetic field strength. However, the possible wearing of brushes and inability to apply coolants and lubricants in their presence makes this design unsuitable for larger motors used in full hybrids. Researchers are also developing "hub" style induction motors of much smaller dimensions for the same power output as shown in Fig. 4.13(b). Figure 4.13(c) shows a 3D motor developed by Nissan for HEVs with a modified deign for maximum utilization of magnetic flux. All these efforts are directed towards improving the efficiency and power and torque outputs of motors while maintaining smooth operation, light weight and compact structure, all within a reasonable cost.



(a) (b)

(c)

Fig. 4.13. Special motor designs for HEVs. (a) PMSM in Honda Civic Hybrid. (b) Hub style induction motor. (c) Nissan's 3D PM motor.

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5 INDIRECT FIELD ORIENTED CONTROL OF AN INDUCTION MOTOR

5.1 Introduction to Induction Motor

An induction motor (IM) is singly-fed machine that does not require commutators, slip rings or brushes. The rotor of the machine does not require excitation, instead it produces current through induction, hence the name induction motor. Since a winding that receives its power exclusively from induction is a transformer, hence induction machine is regarded as a transformer whose secondary windings are rotator [1]. Induction machines can be single-phase or poly-phase. Single-phase IMs are preferred in domestic applications for fractional horsepower range whereas poly-phase machines are generally three-phase machines, due to common availability of three-phase supply in industrial setting, and are available in an entire spectrum of horsepower ratings.

5.1.1 Construction

Induction motors consist of an outer, stationary structure called the stator. It is formed by stacking thin laminations of steel, or a cast-iron frame which provides mechanical support to the motor and is not designed to carry magnetic flux. Coils are wound into the slots and connected to form a three-phase winding.

The rotating part of the induction machine, called the rotor, also consists of thin laminations that are pressed onto a shaft. Induction machines can be classified into two types based on their rotor construction, namely, squirrel cage and wound rotor induction motor. In a squirrel-cage construction, the rotor is made of slots of heavy conducting bars welded together to end-rings. On the other hand, in a wound-rotor construction, the rotor has placement of coils similar to the stator. The three-phase windings on the rotor are connected internally to form an internal neutral connection. The other side of the windings is connected to slip-rings and is accessible externally to add resistance in order to allow variable rotor resistance for a more flexible torque control. Wound-rotor motors, however, are more expensive and less efficient than squirrel-cage ones. In this chapter only the squirrel-cage induction motor will be considered for analysis.

5.1.2 Operating Principle

Like all other electric machines, based on the state of their operation, induction machines can serve both as a motor and a generator. In motoring mode, the power source provides a three-phase supply that generates a magnetic field rotating at synchronous speed in the air-gap. For frequency f of the supply current in the stator windings and P number of poles in the stator, the synchronous speed in rpm is given as:

$$N_s = \frac{120f}{P} \tag{5.1}$$

The rotating magnetic field induces electromotive force (emf) in the rotor coil that generates induced current in the coil. A force is exerted on the current carrying rotor bars in the presence of the rotating magnetic field, thus generating torque. With time, in the absence of load, the rotor can achieve a speed very close to the synchronous speed, however it can never run exactly at synchronous speed since in such a case, the rotor will appear stationary to the rotating magnetic field and torque will no longer be produced. This characteristic of the induction motor to run at all speeds other than its synchronous speed has given it the name of asynchronous motor.

The rotor speed changes as the load connected at the motor shaft varies. The relative speed by which the rotor slips behind the rotating stator magnetic field is called the slip speed and is expressed as:

$$N_{sl} = N_s - N_m \tag{5.2}$$

where N_m is the rotor speed in rpm. Slip of the motor is defined as the ratio of its slip speed to the synchronous speed.

$$s = \frac{N_s - N_m}{N_s} \tag{5.3}$$

In radians per second (rad/s) slip is expressed as:

$$s = \frac{\omega_s - \omega_m}{\omega_s} \tag{5.4}$$

Moreover, the frequency of the induced emf or current in the rotor is given in (5.5).

$$\begin{aligned} f_r &= \frac{PN_{sl}}{120} \\ &= \frac{P(N_s - N_m)}{120} = \frac{PN_s}{120}\left[\frac{N_s - N_m}{N_s}\right] \\ &= sf \end{aligned} \tag{5.5}$$

Thus, at standstill, the slip is 1 and the rotor frequency is equal to the frequency of the supply voltage and as slip decreases and approaches zero, the rotor frequency also decreases.

5.1.3 Equivalent Circuit

When three-phase power is supplied to the stator windings, the energy is transferred through the air-gap to the rotor by induction. The frequency of the induced emf in the rotor is proportional to the slip. Since the windings of the motor act like transformer windings coupled inductively, an induction motor resembles a transformer with rotating secondary windings. Figure 5.1 represents the per-phase equivalent circuit of an induction motor where the windings have been combined considering the turn ratio of transformation. The additional resistance $R_2[(1-s)/s]$ is called the load or dynamic resistance that depends on the speed of the motor.

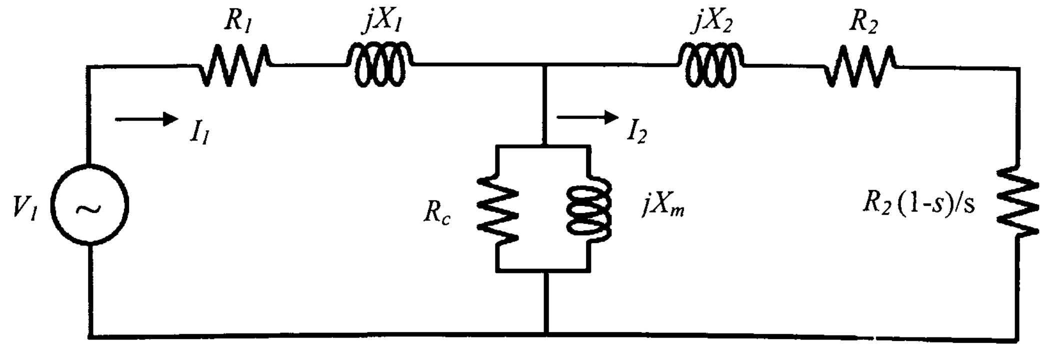


Fig. 5.1. Per-phase equivalent circuit of induction motor.

The parameters of the equivalent circuit are described below on per-phase basis.

V_1	applied voltage
I_1	supply current
R_1	stator winding resistance
X_1	stator winding leakage reactance
I_2	rotor current
R_2	rotor resistance
X_2	rotor winding leakage reactance
I_C	core loss current
X_m	magnetization reactance

5.1.4 Operational Characteristics of Induction Motors in HEV Application

One of the benefits of employing induction motors in variable speed drives, particularly traction applications, is the inherent ability to control their rotor magnetic field for extended speed ranges. For slip greater than zero, power increases corresponding to the increase in rotor speed while torque is kept constant at its maximum value. For an extended speed range over the synchronous speed, to ensure that power does not exceed the rated value, the flux is weakened to reduce torque as shown in Fig. 5.2. This allows the induction motor to deliver speeds generally two to three times higher than the synchronous speed. At further high speeds, however, torque is reduced drastically, and may cause the motor to stall.

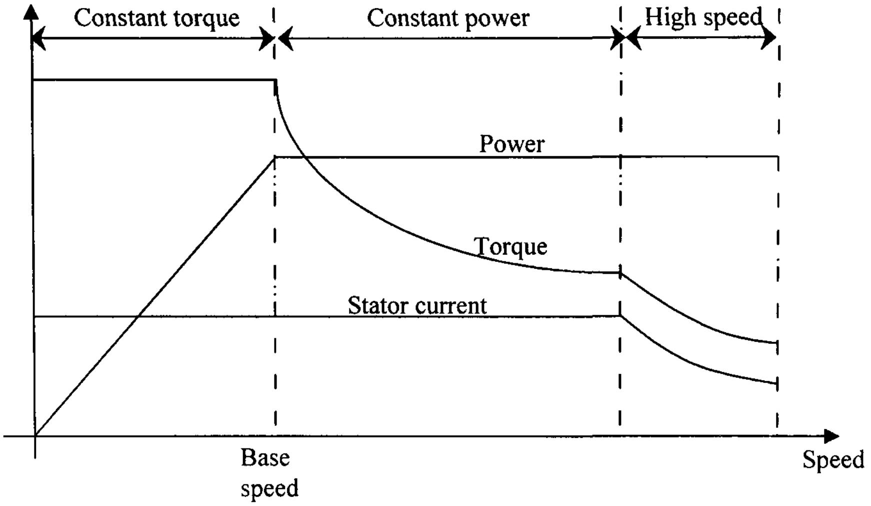


Fig. 5.2. Flux weakening for extended speed range of IMs.

The steady-state torque speed characteristics of the induction machine are shown in Fig. 5.3. The torque produced by the motor is determined by the slip and stator current. The starting torque of the IM is lower than the peak torque the motor can produce which is determined by the rotor resistance [2]. The motor suffers from losses at high slip operation and gives maximum efficiency in the linear region of its torque-speed curve at low slip values. For slip less than 0, the motor is in forward braking mode where the rotor speed is greater than synchronous speed and the rotor produces negative torque. Between slip values of 0 and 1, the induction machine is in forward motoring mode whereas in the region of slip greater than 1, the torque continues to decrease with the increase in slip and the rotor speed is negative from (5.4). This region is called reverse plugging. For higher efficiency and to limit the currents at high slip, IMs are usually operated in the narrow linear region of maximum efficiency at constant voltage, which is not suitable for variable speed traction applications. Most applications of IMs in HEVs require voltage, frequency or other control methods in order to fully utilize the motor through the entire speed range without increasing loss and reducing the efficiency.

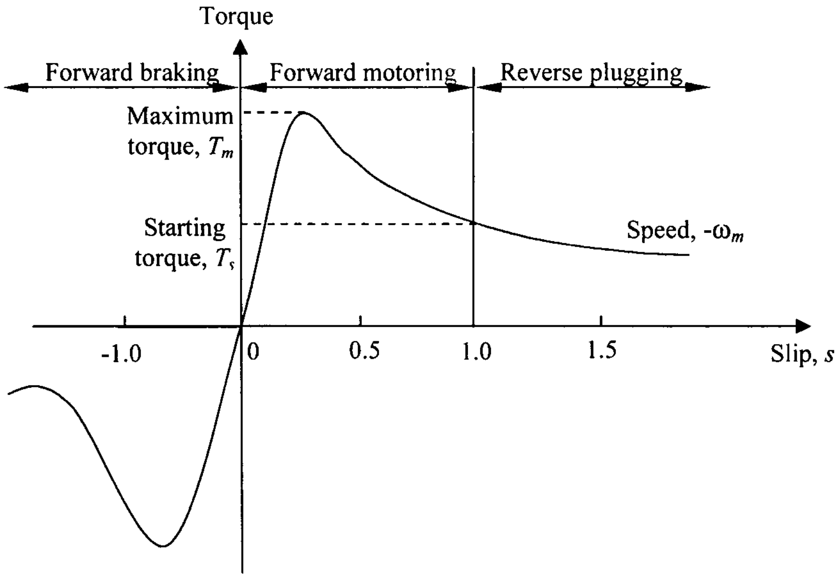


Fig. 5.3. Torque-speed characteristics of IM at fixed voltage and frequency.

5.1.5 Scalar vs. Vector Speed Control Methods of Induction Motors

The earlier methods of controlling induction motors involved the control of voltage magnitude or the frequency of the supply. Such methods, called scalar control strategies, exhibit a poor dynamic response [3]. This is explained by the deviation of air-gap flux linkage from a set value in both magnitude and phase. Since scalar control methods do not control the flux angles along with their magnitudes, the resulting flux deviations cause torque and speed oscillations.

To overcome this problem, the vector control method was devised for precision control which previously only DC motors could offer [4]. Separately excited DC motors provide a simple control because they independently control torque and flux, where flux can be kept constant for independent control of torque. Vector control makes it possible to control AC motors using a simple method where the stator current command can be resolved into field and torque producing components independent from each other. This has given induction motors the possibility of improved control, similar to DC motors, with superior dynamic performance and the additional advantages of low cost and low maintenance operation when compared to DC machines. However, as discussed in previous chapter, the conventional design of vector control is subjected to variations in machine parameters. To overcome this problem, a robust control system that can reduce the sensitivity of vector control of induction motors needs to be implemented.

5.2 *d-q* axis Modeling of Induction Motors

The direct- and quadrature-axis representation of electric machines provides a more convenient and comprehensive representation to analyze their dynamic and steady state conditions. Machine parameters vary with change in rotor position with respect to stator, making analysis in the *abc* axis frame complicated. In a *d-q* reference frame the machine parameters become independent of rotor position. Depending on the requirement of the analysis and simplicity the *d-q* frame of reference is assumed to be stationary, or rotating at the rotor or synchronous speed. Any machine parameter such as voltage, current or flux linkage in the *abc* frame can be converted to corresponding d- and q-axis parameters using Parks' transformation as shown in (5.6) where *m* represent an arbitrary parameter.

$$\begin{bmatrix} m_q \\ m_d \\ m_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\theta_f & \sin\left(\theta_f - \frac{2\pi}{3}\right) & \sin\left(\theta_f + \frac{2\pi}{3}\right) \\ \cos\theta_f & \cos\left(\theta_f - \frac{2\pi}{3}\right) & \cos\left(\theta_f + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} m_a \\ m_b \\ m_c \end{bmatrix} \tag{5.6}$$

where m_0 represents the imbalances in the a-, b- and c-phase parameters. Figure 5.4 shows the d- and q-axis equivalent circuits of the induction motor in a synchronously rotating reference frame.

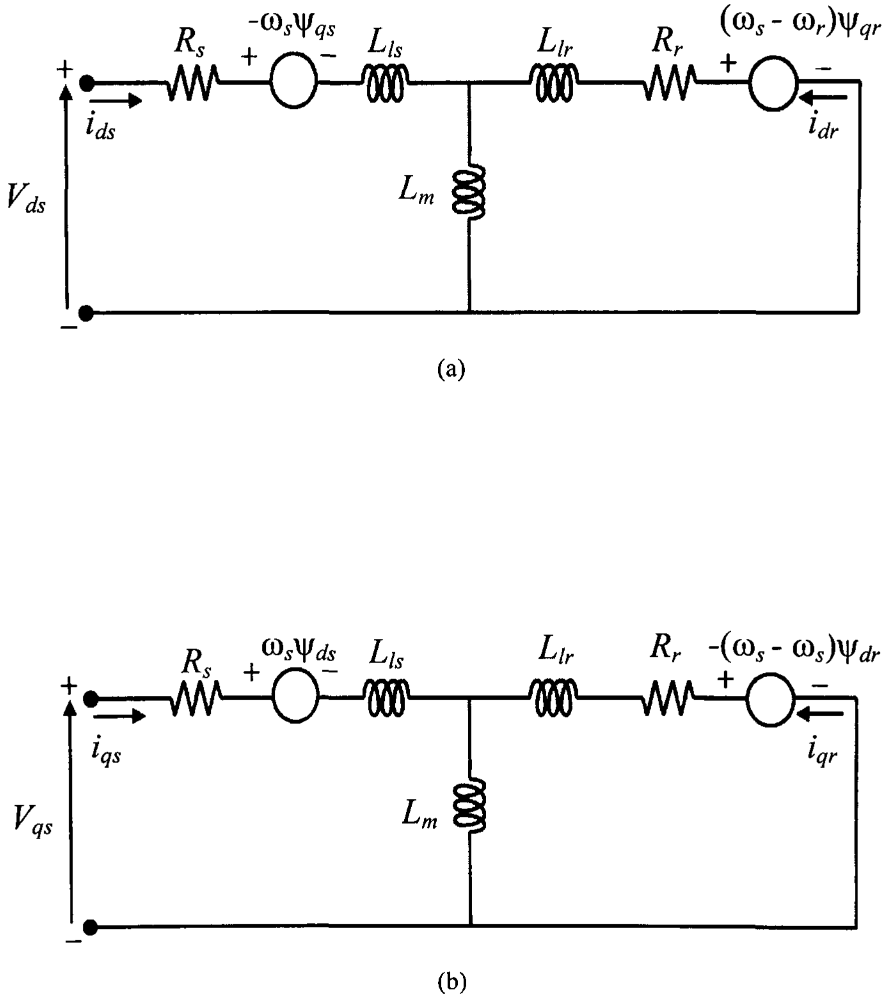


Fig. 5.4. Equivalent circuit of induction motor. a) d-axis. b) q-axis.

The d- and q-axis stator voltage equations of the induction motor in the synchronous frame are given in (5.7) and (5.8).

$$v_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \tag{5.7}$$

$$v_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \tag{5.8}$$

Similarly, the d- and q-axis components of rotor voltage are expressed in (5.9) and (5.10).

$$v_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{5.9}$$

$$v_{qr} = R_r i_{qr} + (\omega_s - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{5.10}$$

The d- and q-axis stator and rotor flux linkage equations are given in (5.11) to (5.14).

$$\psi_{ds} = (L_{ss} + L_m) i_{ds} + L_m i_{dr} \tag{5.11}$$

$$\psi_{qs} = (L_{ss} + L_m) i_{qs} + L_m i_{qr} \tag{5.12}$$

$$\psi_{dr} = L_m i_{qs} + (L_{rr} + L_m) i_{dr} \tag{5.13}$$

$$\psi_{qr} = L_m i_{ds} + (L_{rr} + L_m) i_{qr} \tag{5.14}$$

The mechanical equation representing rotor speed and electromagnetic torque are given as:

$$\frac{d\omega_r}{dt} = \frac{1}{2H}(T_e - T_m) \tag{5.15}$$

$$T_e = \frac{3}{2}\frac{P}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{5.16}$$

Equation (5.16) can be rewritten as:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \tag{5.17}$$

5.3 Vector Control of Induction Motors

5.3.1 Principle of Vector Control

With the vector control method, stator current can be de-coupled into torque and flux producing components that are independent of each other. The flux producing component can be kept constant for a uniform field, while the torque producing component can be varied for variable speed and torque requirements. The principle of vector control is based on the assumption that the position of the rotor flux linkage ψ_r is known to be at an angle θ_f from the stationary reference frame as shown in Fig. 5.5 [5]. Assuming ψ_r to be on the direct axis of the synchronously rotating frame, the stator current i_s can be resolved into its d- and q-axis components i_{ds} and i_{qs} in the synchronous frame. It can be seen that i_{ds} is in phase with ψ_r and is the field producing part of the current i_f. The perpendicular component i_{qs}, therefore, must solely determine the torque generation and is therefore called the torque producing current component i_T.

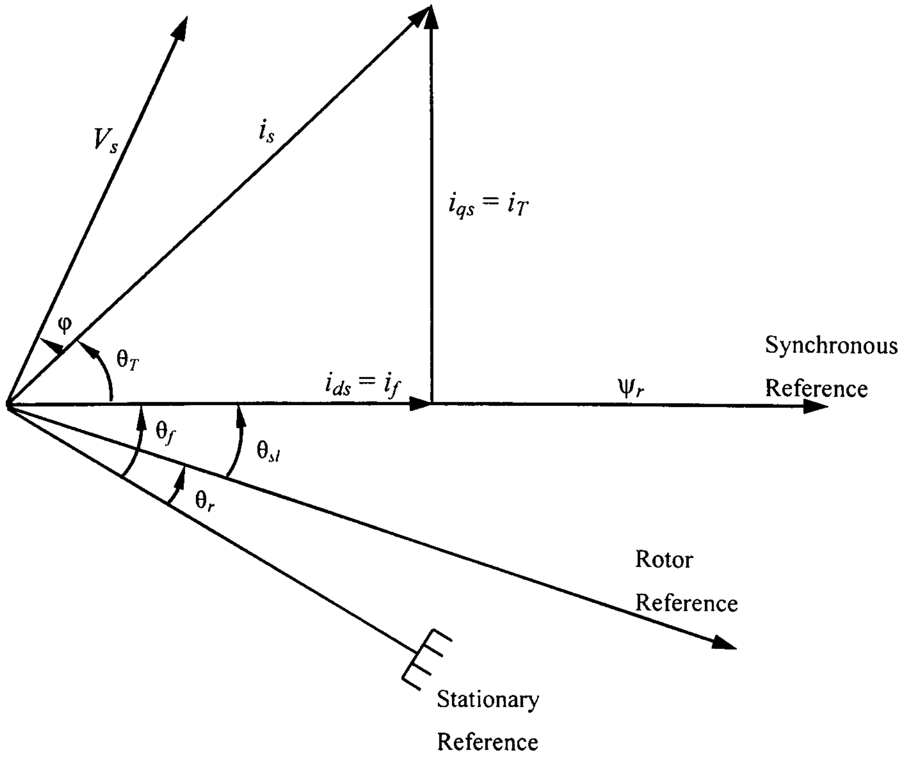


Fig. 5.5. Phasor diagram of vector control.

The knowledge of not only rotor flux magnitude but also its phase angle is crucial for the implementation of this control technique, thus the name vector control. The field angle can be expressed as:

$$\theta_f = \theta_r + \theta_{sl} \tag{5.18}$$

where θ_r is the rotor position and θ_{sl} is the slip angle. In terms of rotor speed ω_r and slip speed ω_{sl} the field angle can be written as:

$$\theta_f = \int(\omega_r + \omega_{sl})dt \tag{5.19}$$

Based on the method of how this field angle is determined, vector control can be classified into two types.

- *Direct vector control.* This method either uses terminal voltages and currents, or Hall sensors or flux-sensing windings to determine the field angle θ_f. Although computation is simplified using this technique, it adds to the design cost due to the requirement of additional sensors.
- *Indirect vector control.* In order to reduce cost and eliminate the need for flux sensors, this method, also called indirect field oriented control (IFOC), uses partial estimation and rotor position measurement using only machine parameters but no other variables such as voltage and current. However this method not only creates additional complexity, but also makes the control system sensitive to any changes in machine parameters, particularly the rotor resistance that is expected to change in the high temperature vehicle environment.

5.3.2 Indirect Field Oriented Controller

This section presents the derivation of an indirect field oriented controller using the dynamic equations of the induction motor in a synchronously rotating reference frame. In a squirrel-cage induction motor, the rotor consists of conducting bars shorted together in a cage-like construction. Hence the d- and q-axis rotor voltage equations in (5.9) and (5.10) can be expressed as:

$$\left.\begin{aligned} 0 &= R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \\ 0 &= R_r i_{qr} + (\omega_s - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \end{aligned}\right\} \tag{5.20}$$

The slip speed is defined as

$$\omega_{sl} = \omega_s - \omega_r \tag{5.21}$$

Since the rotor flux linkage ψ_r is aligned with the direct axis of the synchronous frame, its components are given as:

$$\left.\begin{aligned} \psi_{dr} &= \psi_r \\ \psi_{qr} &= 0 \end{aligned}\right\} \tag{5.22}$$

Applying (5.22) to (5.20), the rotor voltage equations become:

$$\left.\begin{aligned} R_r i_{dr} + \frac{d\psi_r}{dt} &= 0 \\ R_r i_{qr} + \omega_{sl}\psi_r &= 0 \end{aligned}\right\} \tag{5.23}$$

Substituting (5.22) in rotor flux linkage equations from (5.8) and (5.9), and solving for rotor currents:

$$\left.\begin{aligned} i_{qr} &= -\frac{L_m}{L_r} i_{qs} \\ i_{dr} &= \frac{\psi_r}{L_r} - \frac{L_m}{L_r} i_{ds} \end{aligned}\right\} \tag{5.24}$$

Substituting (5.24) in (5.23) the d- and q-axis stator currents can be determined.

$$\left.\begin{aligned} i_T &= i_{qs} = \omega_{sl}\frac{L_r \psi_r}{R_r L_m} \\ i_f &= i_{ds} = \frac{1}{L_m}\left[\psi_r + \frac{L_r}{R_r}\left(\frac{d\psi_r}{dt}\right)\right] \end{aligned}\right\} \tag{5.25}$$

The field and torque producing components determine the magnitude of the stator current.

$$i_s = \sqrt{i_f^2 + i_T^2} \tag{5.26}$$

The phase angle of the stator current θ_s is the sum of θ_f and θ_T where θ_f is determined by the integration of slip speed and rotor speed respectively and using (5.18) and θ_T is given as:

$$\theta_T = \tan^{-1}\left(\frac{i_T}{i_f}\right) \tag{5.27}$$

The stator current magnitude and phase angle are used to calculate the 3-phase current signal as shown in (5.28).

$$\left.\begin{aligned} i_{as} &= i_s \sin\theta_s \\ i_{bs} &= i_s \sin\left(\theta_s - 2\pi/3\right) \\ i_{cs} &= i_s \sin\left(\theta_s + 2\pi/3\right) \end{aligned}\right\} \tag{5.28}$$

Figure 5.6 shows the indirect vector control scheme of an induction motor. A transducer sends the rotor speed signal to a speed controller that generates a torque command based on the deviation from the specified reference speed [6]. The required current component i_T is calculated based on this torque using (5.17). Within the normal range of operation, flux can be kept constant by maintaining a constant field component i_f and is used to calculate the slip speed from (5.25) [7].

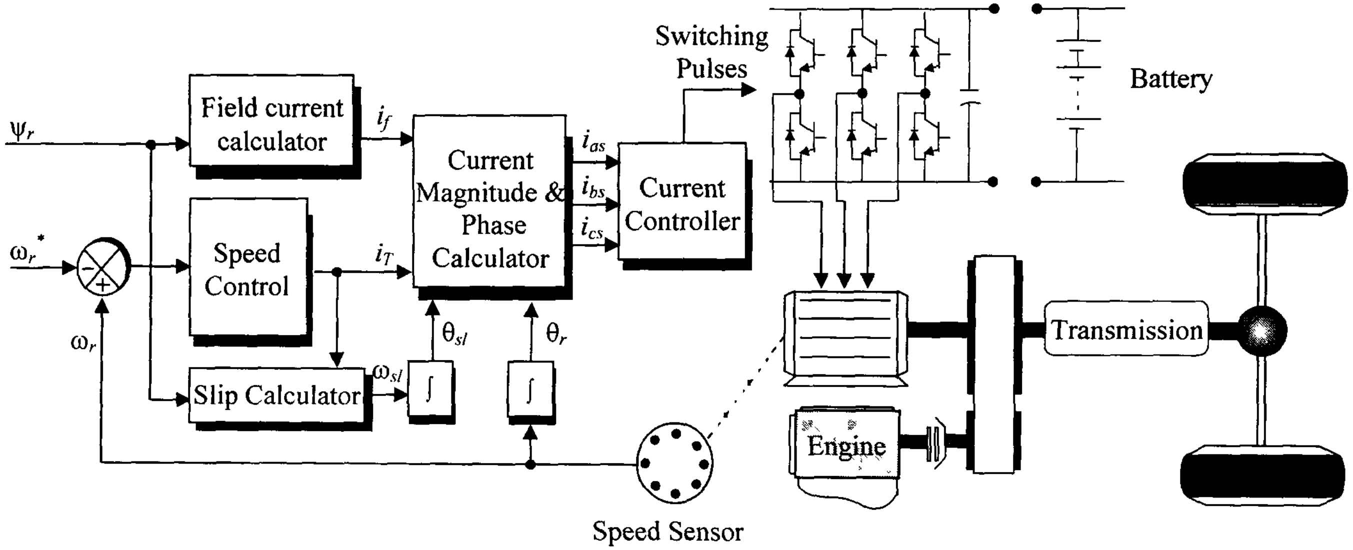


Fig. 5.6. IFOC control scheme for induction motor drives in HEV application.

The field and torque producing components determine the magnitude of the stator current. The rotor and slip speed are integrated to determine the rotor and slip angles, the sum of which provides the field angle θ_f. The field angle and magnitudes of d- and q-axis current components help evaluate a three-phase stator current signal that is sent to a current controller to generate switching pulses to drive the PWM inverter connected to the motor.

In a conventional IFOC implementation, the speed controller uses proportional and integral gains to determine the torque command as shown in Fig. 5.7. Proportional-Integral (PI) is one of the most commonly used control methods due to its simplicity. It depends on the tuning of its proportional gain K_p and integral gain K_i which can be adjusted manually or through tuning techniques such as Ziegler–Nichols method. The PI compensation G_s is given by the equation below.

$$G_c(s) = K_p + \frac{K_i}{s} \tag{5.29}$$

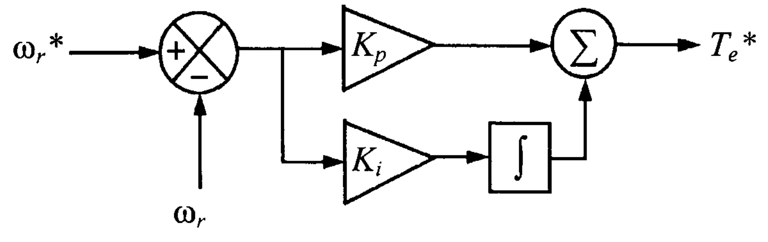


Fig. 5.7. PI controller.

Increasing K_p reduces error and rise time whereas higher K_I values reduce oscillations but increase settling time. Although this control method is reliable and has been used extensively for control systems applications, it lacks the ability of efficient tracking and regulation simultaneously and may require frequent online tuning [3]. Moreover, the complex computation of the IFOC technique and parameter sensitivity is also a concern. The slip speed is calculated using i_T which is a function of rotor resistance. In a hybrid vehicle this resistance is expected to increase as the temperature of the environment rises, resulting in deviation from set speed.

5.4 Fuzzy Logic-Based Indirect Field Oriented Controller

Fuzzy logic offers a linguistic approach to develop control algorithms for any system independent of system equations. Ebrahim Mamdani developed the first inference method in 1975 [8] based on Lotfi Zadeh's fuzzy algorithms for complex systems and decision processes, and since then the Mamdani fuzzy inference method has been applied to fuzzy controllers in a wide variety of applications including motor control, image processing, power system fault diagnosis and many others [9].

5.4.1 Overview on Fuzzy Logic

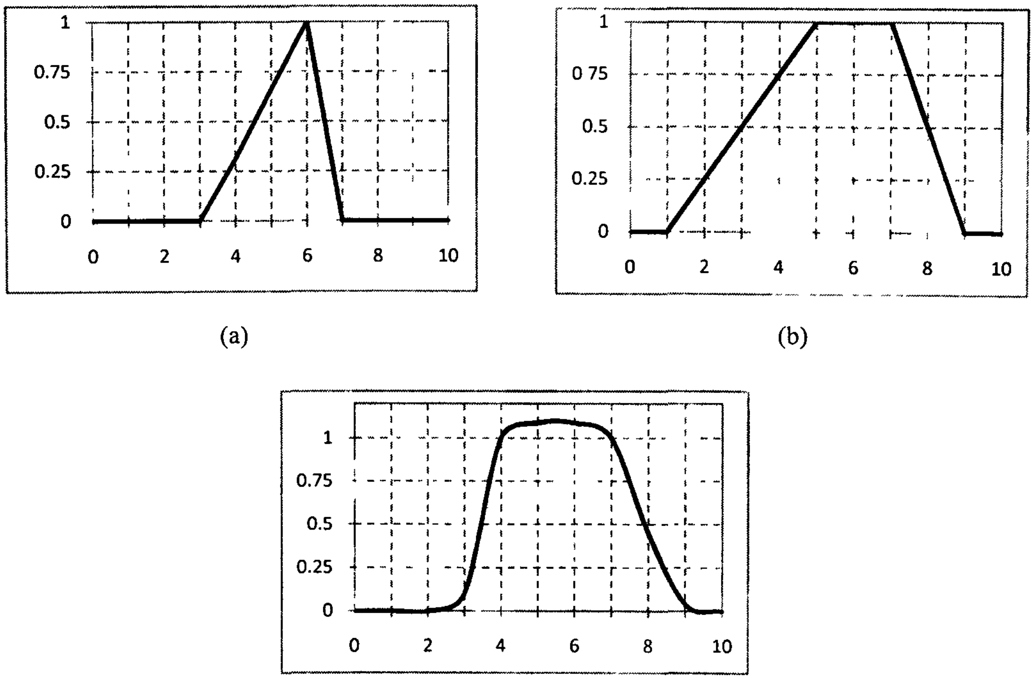
Fuzzy logic incorporates an approach based on *if-then* rules to solve the control problem of a given system rather than modeling it mathematically. All actual parameters from the system environment are mapped on a fuzzy domain where they are evaluated against the predefined rules. The corresponding results determined from these rules are then converted to actual values as a system control output. The two main components of the fuzzy inference system are:

- *Membership functions.* A membership function is a graphical representation of the magnitude of participation of each input by mapping it to a membership value between 0 and 1. The function can be a curve of arbitrary shape such as triangular, trapezoidal or bell as shown in Fig. 5.8. depending on the requirement. Triangular membership functions are most commonly used but the designer of the inference system can also create customized functions.

- *if-then rules.* The rule-base of the inference system is a collection of linguistic rules that describe the control system that assume the form:

if x is A then y is B

where A and B are linguistic values of fuzzy sets for all membership functions. The *if* part of the rule 'x is A' is called the antecedent while the *then* part of the rule 'y is B' is called the consequent. The consequent specifies a fuzzy set to be assigned to the output. The output fuzzy set is then assigned a degree of membership using the *min*, *max* or *not* functions.



(a)

(b)

(c)

Fig. 5.8. Fuzzy membership functions. (a) Triangular. (b) Trapezoidal. (c) Bell shaped.

5.4.2 Implementation of a Fuzzy Logic-Based IFOC of an Induction Motor

The design of fuzzy speed controller for an IFOC of an induction motor is shown in Fig. 5.9. The controller follows a series of steps to determine the current command required to attain desired speed.

- *Fuzzification.* The controller accepts two inputs, error e between the reference speed and rotor speed, and the rate of change of error $\dot{e}$. The speed error is mapped on fuzzy sets with a universe of discourse ranging from -360 to 360, the maximum motor speed in rad/s for given machine ratings while rate of change of error was assigned a universe of discourse from -2 to 2. Fuzzy sets for each input consist of seven membership functions from negative large (NL), negative medium (NM), negative small (NS), zero (ZO) up to positive large (PL) as shown in Fig. 5.10. Similarly, the output has a universe of discourse from -60 to 60. The gain G_{in} is tuned to map the acceleration to the given range of fuzzy sets and G_{out} is tuned to scale the controller output to a corresponding value of i_T.

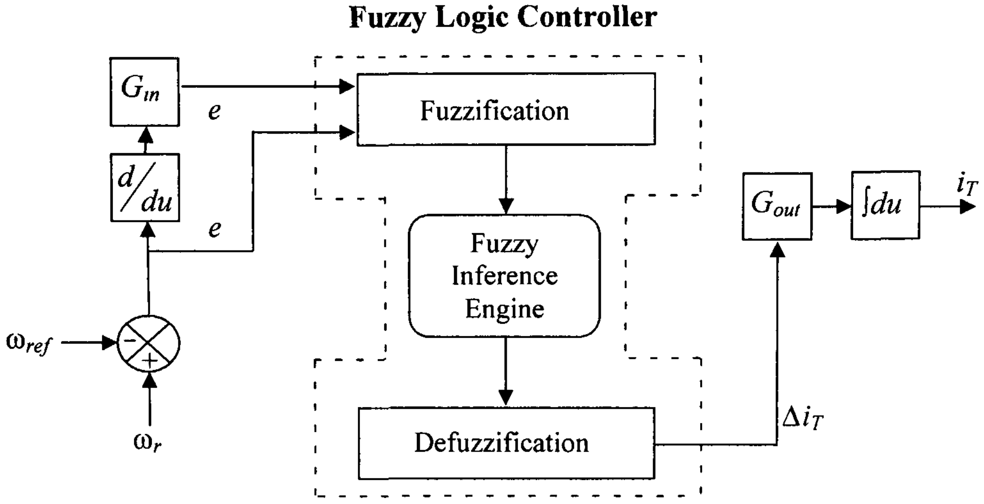
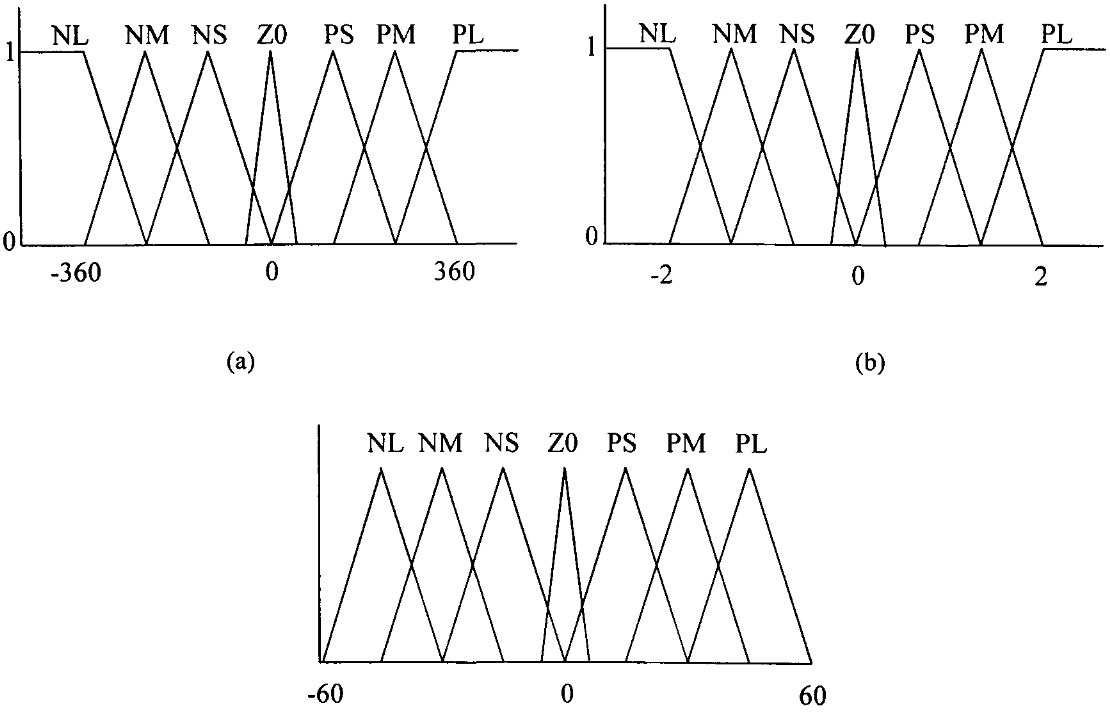


Fig. 5.9. Fuzzy logic-based controller for IFOC.



(a) (b) (c)

Fig. 5.10. Fuzzy membership functions. (a) Input error. (b) Input error derivative. (c) Output current change.

- *Fuzzy inference system.* The fuzzified inputs are fed to the inference engine that determines the consequent current signal based on given input data and generates a fuzzy output in terms of current change Δi_T. The decisions of the fuzzy inference engine are based on a set of 49 rules for the 2-input fuzzy system summarized in Table V These rules are *if-then* statements that determine the consequent output current response for a given input condition to attain a desired speed. For example, if e is NL and $\dot{e}$ is NS, it implies that the rotor speed is much slower than the specified reference speed and is continuing to reduce; hence the current Δi_T is increased by a large factor PL. On the other hand if e is ZO and $\dot{e}$ is NM, it implies that although the motor has achieved the set speed however, it is slowing down. The current is, therefore, slightly increased by PM to prevent the motor speed from reducing. Once the inference engine triggers the relevant rules for a given set of inputs, the weight of the output current is computed from the triggered membership functions using *min* aggregation method. The rule base was designed using human experience and then refined with trial and error. 3D curve representation of the rule base is shown in Fig. 5.11. The sharp outer edges of the curve show the ability to make drastic changes in the torque command due to complete decoupling of currents i_T and i_f.

TABLE 5.1
FUZZY RULE BASE

e $\dot{e}$	**NL**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PL**
NL	PL	PL	PL	PL	PM	PM	NS
NM	PL	PL	PL	PM	PS	ZO	NM
NS	PL	PM	PS	PS	NS	NS	NM
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PM	PS	PS	NS	NS	NM	NL
PM	PM	ZO	NS	NM	NL	NL	NL
PL	PS	NM	NM	NL	NL	NL	NL

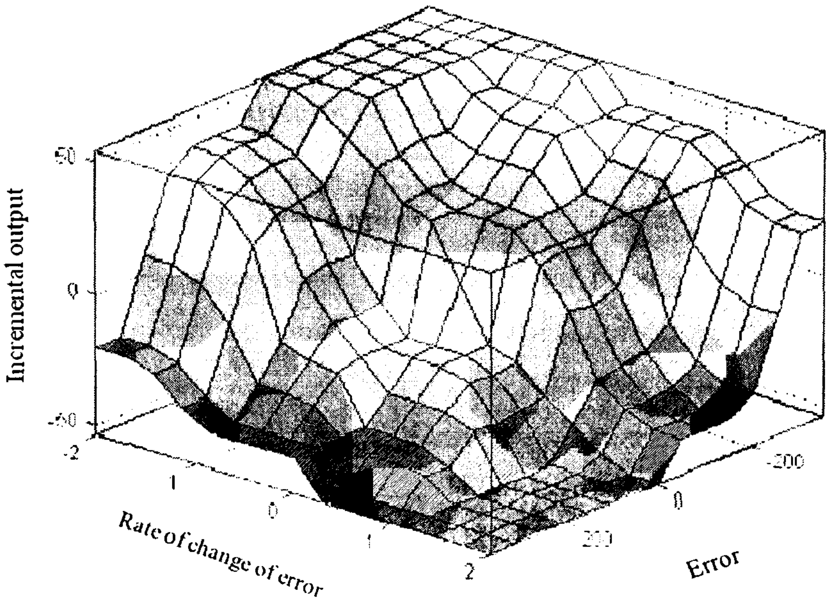


Fig. 5.11. 3D representation of fuzzy rule base.

- *Defuzzification.* The net weight of the output current is computed from the triggered membership functions using a *min* aggregation method. The weighted output is transformed into the required current signal through defuzzification. This is accomplished by the inverse transformation to map the calculated output from the fuzzy domain to a crisp real-time value. The conventional method of defuzzification is the centre of area (COA), which calculates the centre of the area representing the output fuzzy term. The output u of the controller is given by:

$$u = \frac{\int \mu(x_i) x_i du}{\int \mu(x_i) du} \tag{5.30}$$

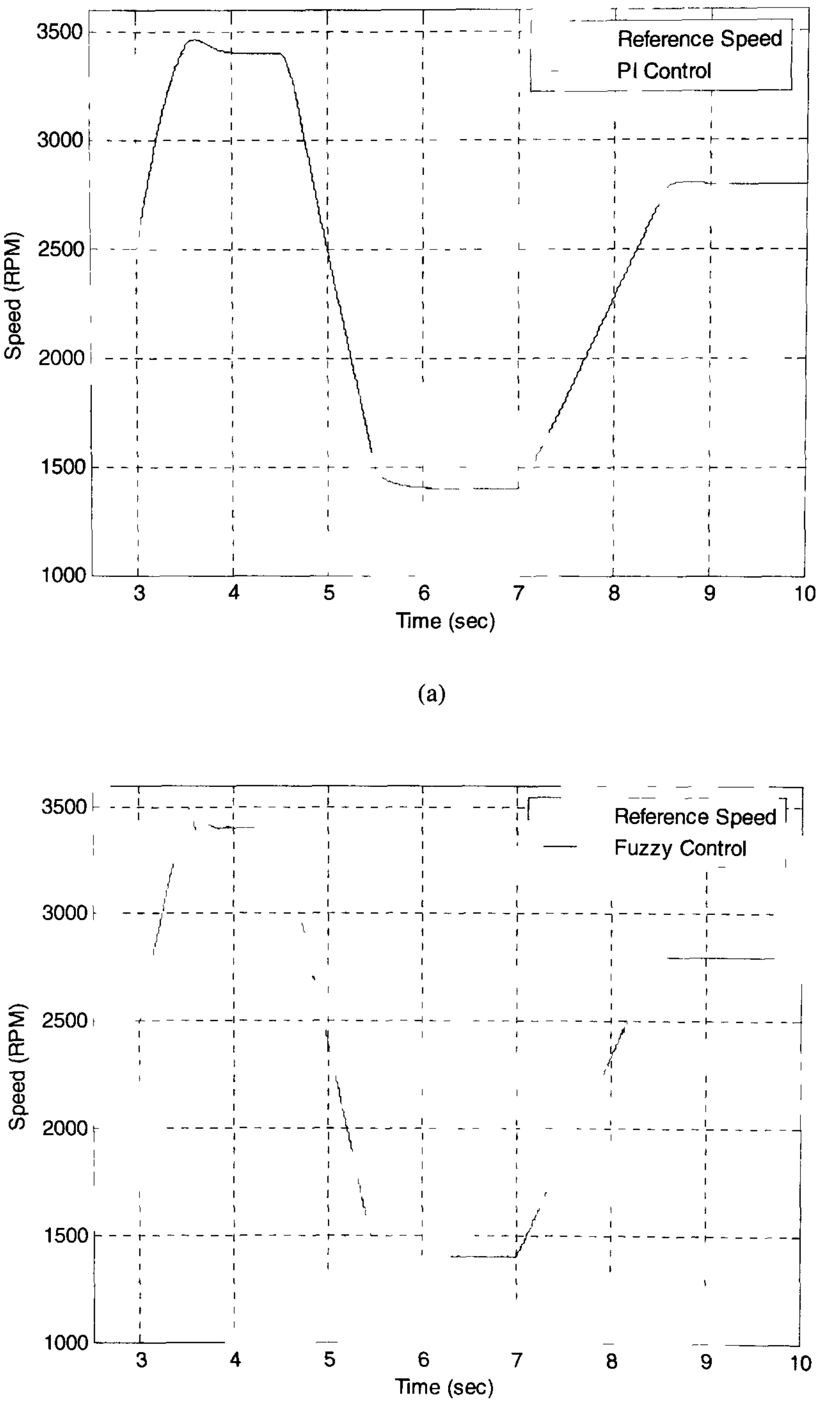
where x_i is a point in the universe of discourse and $\mu(x_i)$ is its membership value in the membership function. Since the effective output from the fuzzy controller is the amount of increment or decrement in current signal, Δi_T, it is integrated to generate the net value for the torque producing current component i_T [10]. This fuzzy based control algorithm was implemented in the Fuzzy Toolbox of Matlab/Simulink. The toolbox allows the user to create multiple inputs and outputs, define the rule base in linguistic terms in the Rule Base Editor and is also capable of displaying which rules are triggered for any given set of inputs to indicate the consequent output generated.

5.5 Simulation Results and Analysis

To analyze the performance of the proposed fuzzy model and compare its robustness to the conventional control techniques, computer simulations were carried out on a 3-phase, 2-pole, 50-hp induction motor to implement speed tracking and acceleration patterns of both PI and fuzzy based IFOC. Moreover, parameter insensitivity of both controllers was determined for changes in load and rotor resistance.

5.5.1 Speed Tracking Performance under Constant Load Condition

Figure 5.12 shows the speed tracking performance of this motor for both PI and fuzzy control systems for a 100 N.m loading condition. For an arbitrary step change in set speed from 2,500 to 3,400 rpm, the PI controller takes 1.3 s to reach steady state.



(a)

(b)

Fig. 5.12. Speed tracking performance. a) PI controller. b) Fuzzy controller.

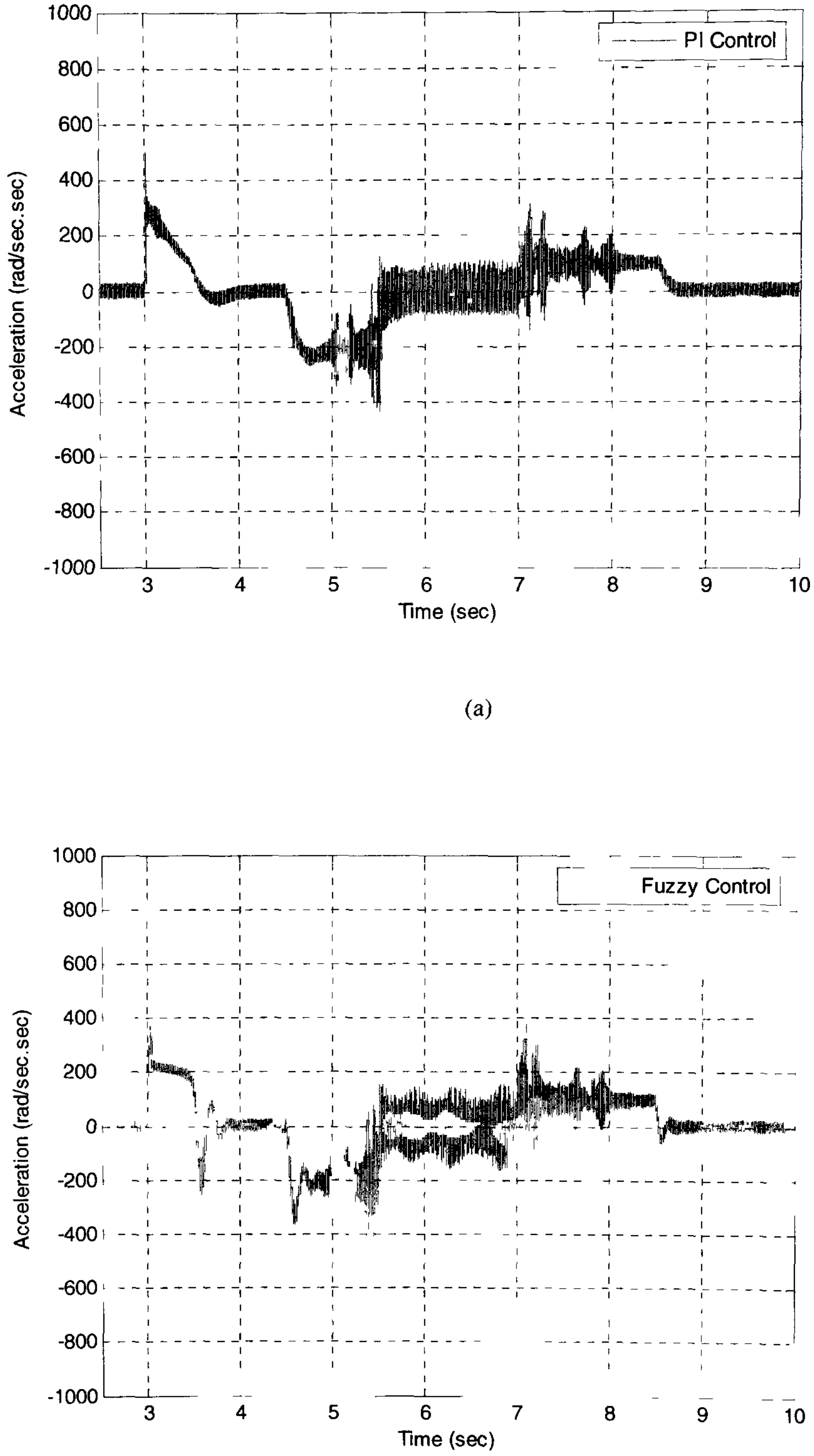
During deceleration from 3,400 to 1,400 rpm, the PI controller appears to struggle in tracking the reference speed signal and reaches steady speed of 1,400 rpm in 1.7 s. Similarly during the acceleration from 1,400 to 2,800 rpm, the PI controller tracks the speed with small steady state error and attains the final reference speed in 2.1 s. The fuzzy controller, under the same loading condition, acquires the step change in speed in less than 0.9 s. It is able to accurately track the reference signal with no steady state error.

5.5.2 Motor Acceleration Performance

The instantaneous acceleration values for PI and fuzzy controllers during this trapezoidal speed tracking are shown in Fig. 5.13. The motor shaft will experience the average value of this instantaneous acceleration. This average value a_{avg} can be calculated using (5.31).

$$a_{avg} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \qquad (5.31)$$

where $a(t)$ is the acceleration function between time intervals t_1 and t_2. For constant speed, the acceleration for either controller is zero. For a decrease in speed from 3,400 to 1,400 rpm, the deceleration of PI controller is smaller with peak value reaching -400 rad/s^2 as compared to the fuzzy controller with its peak deceleration value at -500 rad/s^2 This is explained by the steady state error of PI controller which is seen in terms of a time lag between the actual motor speed and the reference value. Similarly, the acceleration of fuzzy controller is observed to be slightly higher than that of the PI controller during the 7 to 8.5 s time range; however, its improved performance is more evident during the step change in speed where the acceleration remains sustained at 200 rad/s^2 for a longer period of time. This higher acceleration explains the capability of the fuzzy controller to attain desired speed in a much smaller time.



(a)

(b)

Fig. 5.13. Acceleration performance. (a) PI controller. (b) Fuzzy controller.

5.5.3 Effect of Load Change on Motor Performance

To determine the effect of load variation on the motor performance, a step change in load torque was applied from 200 to 400 N.m on both controllers for a constant reference signal of 2,300 rpm as shown in Fig. 5.14. The PI controller deviates by approximately 40 rpm and regains the set speed in 0.7 s, whereas due to its two-input inference system and ability to take preemptive measures to control speed deviation, the fuzzy controller shows a maximum deviation of only 18 rpm with a settling time of 0.3 s.

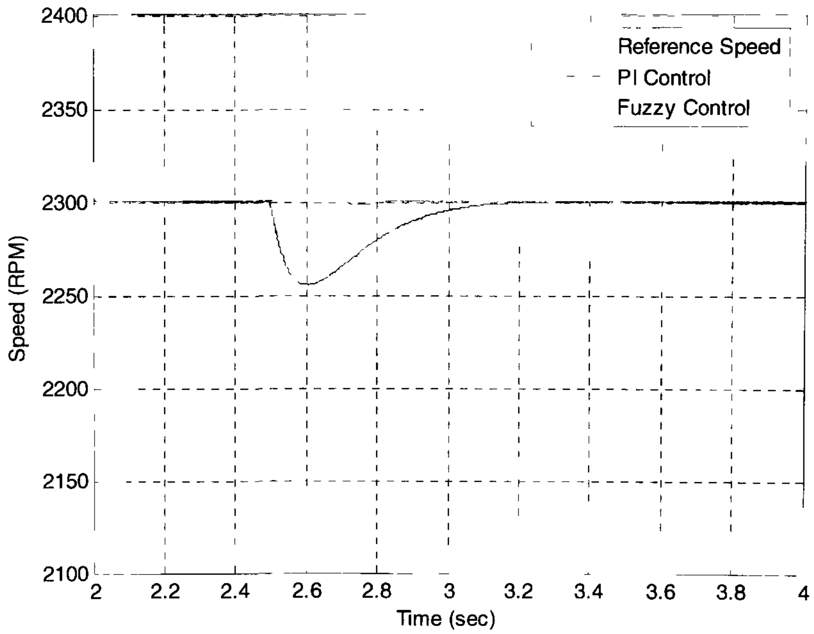


Fig. 5.14. Performance of PI and Fuzzy controllers under step change in load torque.

5.5.4 Effect of Variation in Rotor Resistance on Machine Performance

In Fig. 5.15, the effect of change in rotor resistance on the speed tracking capability of PI and fuzzy control is demonstrated. During a steady state operation at 2,300 rpm, the rotor resistance of the motor is doubled at 2.5 s. In the case of PI control, the speed deviates by 290 rpm and takes 1 s to recover its steady state condition. This deviation occurs since the rotor resistance is employed in calculating both i_f as well as i_T. However, in the fuzzy controller, i_T is independent of rotor resistance. Speed, therefore, deviates only by 115 rpm and returns to set speed value in 0.2 s.

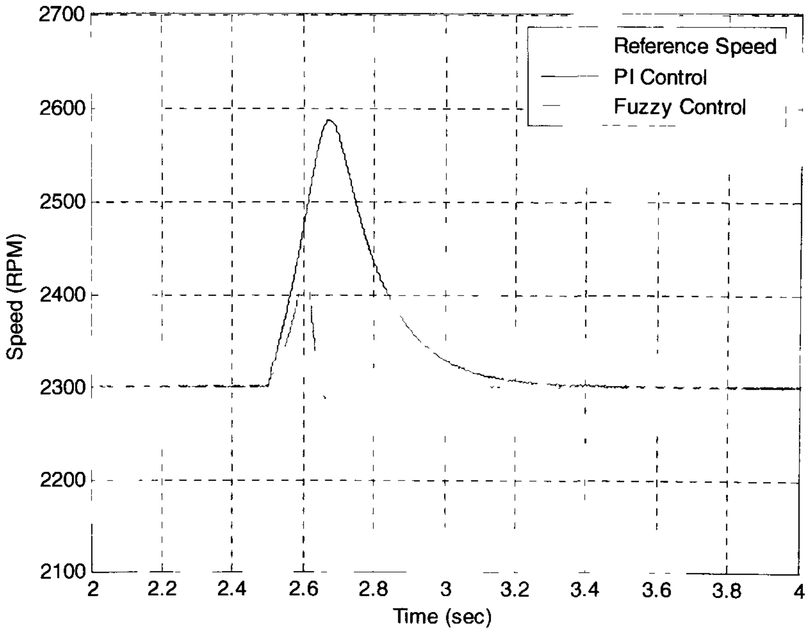


Fig. 5.15. Performance of PI and Fuzzy controllers under step change in rotor resistance.

It was observed that the delay in speed tracking of PI controller can be reduced by selecting a lower value of integral gain K_I, however, this increases oscillations during speed tracking and causes higher deviations due to disturbance in parameter changes.

Thus, the fuzzy logic-based speed controller designed for field oriented control of induction motors offers an enhanced performance in terms of parameter insensitivity and disturbance rejection due to its independence from machine equations. Due to its multi-input inference system that can predict the expected machine behavior in the next simulation cycle, deviations due to disturbance can be controlled preemptively resulting lower oscillations and a shorter time to regain set speed. Moreover, the heuristic approach to control system design based on experience makes the task of developing such a control scheme much less intricate.

5.6 References

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6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

With the growth of Canada's transport sector, an increasing petroleum demand by on-road transportation, particularly light-duty vehicles, is raising concerns due the economic stress of fossil fuel dependency, deterioration of air quality from fuel combustion, and the effect of vehicle emissions on public health. Hybrid electric vehicles offer a suitable alternative for an environment-friendly and sustainable transportation and have been successfully launched commercially by many of the leading automakers. Although HEVs exhibit drastically improved fuel efficiency and can reduce annual tailpipe emissions by up to 35% compared to ICEVs, their market acceptance in Canada remains low. This calls for a systematic effort to develop incentives and policies for the promotion of this technology to encourage sustainable transportation.

This thesis analyses the inhibitors to market diffusion of hybrids and proposes a set of targeted policy guidelines to develop consumer confidence and encourage the development of HEV technology. These guidelines are summarized below.

- Financial incentives are necessary to overcome the major concern of most buyers regarding high purchase price of HEVs. These can be tax exemption on imports and scale-based rebates on the purchase of hybrids. The government's commitment to purchase HEVs and conditional funding to provinces, cities and institutions based on evidence of purchasing hybrids can also boost sales of hybrid vehicles.
- Enforcing strict emissions regulations and charging tax on inefficient cars and vehicle emissions will compel buyers to consider fuel economy in their choice of vehicle. Support for research on biofuels is also essential to displace gasoline by alternative fuels, the combustion of which emits considerably less pollutants.
- Establishing a national consortium to bring together automakers, researchers, businesses and the public is necessary not only to foster collaborative research that will enable Canada to develop its own hybrid prototypes and commercial units, but will also aid in educating buyers about HEV technology and clarify misconceptions to assist them in making informed decisions.

- Financial and infrastructure support for research on HEV technology is crucial to enable the development of hybrid vehicles that can satisfy consumer demands, with drive performance and design specifications comparable to any ICEV

As one of the targeted areas that require focused attention, this thesis discusses challenges in the development of HEV technology. An HEV integrates an electric motor to an ICE to allow optimized engine operation. Induction motors are amongst the candidates considered suitable for vehicle traction, and indirect field oriented control of induction motors allows precise control due to decoupling of torque and current producing components. However, an IFOC conventionally designed with PI gains is sensitive to parameter changes and disturbances. This work proposes an IFOC for IMs employing a fuzzy logic-based inference system. The designed control system provides:

- More accurate speed tracking performance
- Less sensitivity to changes in rotor resistance due to control design independent of machine equations
- Higher disturbance rejection capability due to error derivate input that limits deviation under disturbance such as changes in load torque
- Ease of design due to its linguistic approach based on human knowledge

6.2 Future Work

With the improvement in battery technology, particularly lithium-ion batteries, commercial production of grid-rechargeable plug-in hybrid electric vehicles (PHEVs) has now become a possibility. Plug-in hybrids are hybrid vehicles with an extended all-electric range due to a larger battery pack that can be charged by the ICE or externally through the grid. This year GM will launch its first plug-in hybrid the Chevy Volt this year which promises a 40-mile all electric range. With substantially improved fuel economy, it will be a logical extension of this work to analyze the emissions and cost effectiveness of plug-in hybrids as they enter into the mainstream market and incentives that can be provided in terms of vehicle-to-grid sale of electric power at a lucrative price.

Moreover, to extend the design of fuzzy logic-based IFOC, field weakening can be applied to the induction motor control to obtain extended speed range application beyond the synchronous speed of the motor.

LIST OF PUBLICATIONS

[1] M. Khan and N. C. Kar, “Recent technology development and strategies to promote hybrid vehicles for sustainability in Canada,” submitted to *IEEE Vehicular Technology Magazine*, Paper ID TEC-00481-2008.

[2] M. Khan and N. C. Kar, “Bibliography on the development of design and control technologies for hybrid vehicles,” submitted to *International Review of Electrical Engineering*, Submitted in Jan. 2009.

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APPENDIX

Induction machine parameters:

Nominal power	50 hp
No. of poles	2
Stator resistance (R_s)	0.087 Ω
Rotor resistance (R_r)	0.228 Ω
Stator leakage inductance (L_{ls})	0.8×10^{-3} H
Rotor leakage inductance (L_{lr})	0.8×10^{-3} H
Mutual inductance (L_m)	34.7×10^{-3} H
Inertia constant (H)	1.662 kg-m^2

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