ADVANCED EFFICIENCY SOLUTIONS FOR HYBRID ELECTRIC VEHICLES (HEVS)

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ABSTRACT

Advanced Efficiency Solutions for Hybrid Electric Vehicles (HEVs)

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As an alternative to conventional vehicles (CVs), hybrid electric vehicles (HEVs) are touted to be a practically attractive measure to create an energy-wise and sustainable society. By employing electric energy as one of the traction energy sources, HEVs are able to reduce costly fuel consumption as well as greenhouse gas (GHG) emissions. There are some commercially available HEVs in the market, employing various drive train configurations; however, their drive trains and control strategies are not optimally designed. In this thesis, parametric and power component stage based efficiency analysis methods are introduced to assess the overall drive train efficiencies for different HEV configurations. Hence, it is possible to find the key parameters that significantly affect the overall drive train efficiency. A mid-sized sport utility vehicle (SUV) is modeled in different hybrid configurations within the Advanced Vehicle Simulator (ADVISOR) software. Simulations are carried out based on the modeled SUV over varied load demands. The thesis also defines regenerative braking efficiency and the term "hybridization factor" for series and parallel HEVs. In addition, a method to analyze and calculate regenerative braking efficiency is also introduced. Finally, the thesis focuses on optimizing system control strategies for series and parallel HEVs, to enhance their regenerative braking efficiency. The optimized fuzzy logic and electric assist control strategies are simulated and tested in ADVISOR, thus providing the data for eventually designing a novel control strategy, to improve the overall drive train efficiency.

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LIST OF ACRONYMS

ADVISOR	Advanced Vehicle Simulator
AC	Alternating Current
Ah	Ampere-Hour
ANN	Artificial Neutral Network
AV	Advanced Vehicle
CD	Charge Depleting
CS	Control Strategy
CV	Conventional Vehicle
DC	Direct Current
EUDC	Extra-Urban Drive Cycle
ESS	Energy Storage System
FESS	Fly-wheel Energy Storage System
EV	Electric Vehicle
FC	Fuel Converter
FCV	Fuel Cell Vehicle
ft	Feet
FTP	Federal Test Procedure
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HF	Hybridization Factor
HWEFT	Highway Fuel Economy Test

ICE	Internal Combustion Engine
IM	Induction Machine
ISA	Integrated Starter/Alternator
L	Liter
Li-Ion	Lithium-ion
mpg	Miles per Gallon
mph	Miles per Hour
NiCd	Nickel-Cadmium
NiMH	Nickel Metal Hydride
PHEV	Plug-in Hybrid Electric Vehicle
PM	Permanent Magnetic
PV	Photovoltaic
SOC	State of Charge
SRM	Switched Reluctance Motor
SUV	Sports Utility Vehicle
UC	Ultra-capacitor
UDDS	Urban Dynamometer Driving Schedule
UPS	Uninterruptible Power Supply
V	Volt
VA	Volt-Ampere
W	Watt
WVU-SUB	Western Virginia Suburban
ZEV	Zero Emission Vehicle

LIST OF PRINCIPAL SYMBOLS

C	Capacitance
C_{rated}	Rated capacitance of individual capacitor
M_v	Vehicle Mass
n_p	Number of parallel strings of capacitors
n_s	Number of series capacitors in each string
$fc_{\_pwr}$	New fuel converter size
$fc_{\_pwr\_\min}$	Required minimum fuel converter size to meet the vehicle performance
$fc_{\_pwr\_\max}$	Required maximum fuel converter size to meet the vehicle performance
f_g	Grading Resistance
F_{trac_front}	Traction force from the frontal tires
F_{trac_rear}	Traction force from the frontal tires
f_{resis_front}	Rolling resistances of front tires
f_{resis_rear}	Rolling resistances of rear tires
f_w	Aerodynamic Drag
η_{REGEN}	Regenerative braking efficiency
$E_{neg.trac}$	Negative traction energy
E_{regem}	Regenerative braking energy recovery
$I_{battery.regen}$	Electric current flowing to the battery pack due to regenerative braking
I_{acces}	Electric current used by the vehicle accessories
t	Time

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Conventional vehicles (CVs), which use petroleum as the only source of energy, represent majority of the existing vehicles today. As shortage of petroleum is considered as one of the most critical world-wide issues, costly fuel becomes a major challenge for CV users. Moreover, CVs emit green house gases (GHG), thus making it harder to satisfy stringent environmental regulations. As one of the major elements of the world economy, the transportation industry plays an important role in daily life, which has effects on, but not limited to, the worldwide environment, global GHG emissions, and recreation and lifestyle issues. Since the early 1900s, the rudimental model of modern transportation changed the world. It is well-known that transportation is a petroleum-based human activity, which consumes approximately more than 21% of the total energy usage. Since 1998, the usage of petroleum in transportation exceeded that compared to other industries. For example, as shown in Figs. 1-1 and 1-2, transportation consumes almost two-thirds of the petroleum used in North America, and similarly, in case of carbon dioxide emissions, the transportation sector contributes to more than half the total emissions. Moreover, assuming some developing countries will mature in forthcoming decades, the overall vehicle population is expected to increase tremendously in the next 15-20 years, becoming five times larger than the current vehicle population [1]-[8]. The serious environmental issues have been brought to the attention of the community. In

recent decades, automobile manufactures and researchers have focused their attention on developing an energy-wise, pollution free, and safe land vehicle. The electric vehicle (EV) is believed to be the ultimate category of advanced vehicle (AV). However, due to immature battery technology, the performance of an EV is greatly restrained by its equipped electric energy. Hence, at least for the next few years, hybrid electric vehicles (HEVs) present a practical alternative to the current vast number of CVs.

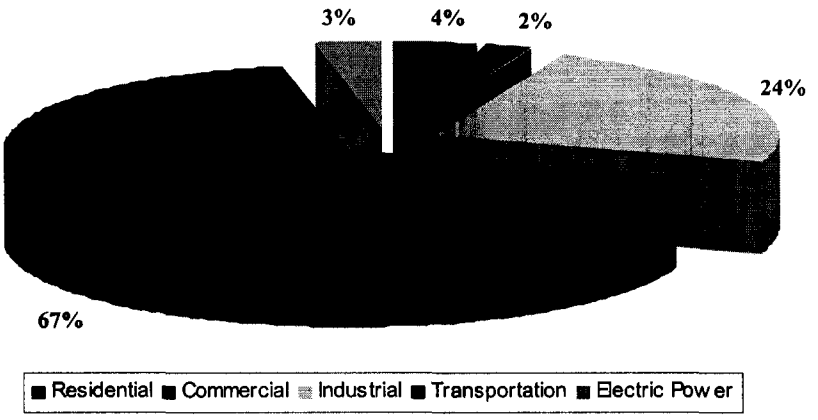


Fig. 1-1 Breakdown of oil usage by sector, 2006 [6], [7]

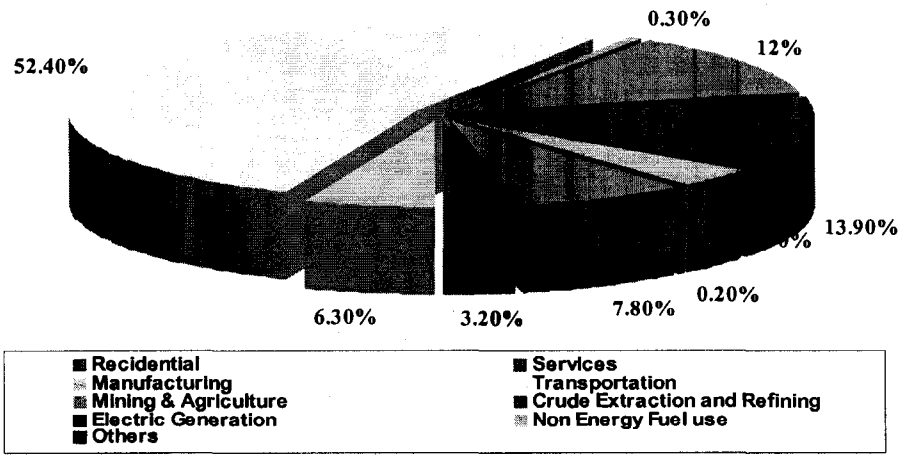


Fig. 1-2 Carbon dioxide emissions, 2006 [6], [7]

1.2 HEV FUNDAMENTALS

1.2.1 CONCEPT OF HEV

Different types of alternate vehicles (AVs) exist, such as EVs, HEVs, and fuel cell vehicles (FCVs). However, HEVs are found to be the most practical and efficient substitutes for CVs in the near future. This is because the characteristics of an electric motor are found to be more favorable, compared to the characteristics of an internal combustion engine (ICE). Different combinations of energy sources exist, for example, electric and mechanical (fly-wheel) energy sources or electric and chemical (fuel cell) energy sources. However, the combination of fuel energy and electric energy sources is found to be the most acceptable, due to the combined usage of mature ICE techniques and well-established modern power electronics.

An HEV is defined as a vehicle whose propulsion energy is usually acquired from more than 2 types of energy sources, one of them being electric. In addition, an HEV electric drive train employs bidirectional power follow to re-capture the heat losses occurring during braking events, which would otherwise be lost in case of a CV. The history of HEVs is surprisingly found to be as old as the automobile itself. However, the initial purpose of employing an electric motor was not to reduce fuel consumption, but to merely help the ICE propel the vehicle. More recently, the purpose of using hybrid drive trains are plentiful:

- To provide sufficient energy to satisfy the required driving range;
- To supply sufficient torque to meet the needs of vehicle performance;

- To achieve higher efficiency compared to CVs and to reduce fuel consumption and GHG emissions as much as possible.

1.2.2 WORKING PRINCIPLE OF AN HEV DRIVE TRAIN

As mentioned in the above section, the electric drive train of an HEV usually illustrates bidirectional power flow. Fig. 1-3 depicts the concept and power flow of a typical HEV. As is clear, the HEV can choose a particular path, in order to combine power flows liberally, to meet the required load demands. The control strategy of an HEV can be designed for different purposes, based on the varied combinations of power flows.

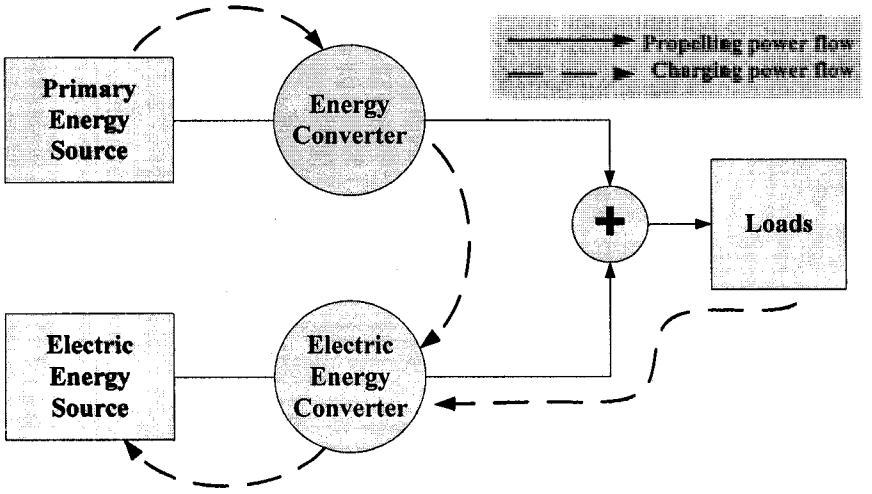


Fig. 1-3 Illustration of power flow within the hybrid drive train

As illustrated in the above figure, considering the drive train is a combination of fuel energy and electric energy, the HEV can work in the following pattern [9]:

- Fuel drive train propels the load alone;
- Electric drive train propels the load alone;
- Both fuel and electric drive trains propel the load at the same time;
- Electric drive train is being charged from load (regenerative braking);

- Electric drive train obtains power from fuel drive train (ICE charging battery);
- Electric drive train is charged by ICE and regenerative braking;
- ICE delivers power to electric drive train, to charge the battery, and propels the vehicle at the same time;
- Fuel drive train deliver power to electric drive train and the electric drive train propels the vehicle (series HEV);
- Fuel drive train propels the load, and load delivers power back to electric drive train.

This freedom of choosing a suitable combination of power flows creates enormous flexibility compared to a single drive train, which has been used so far in CVs. However, such an operational characteristic introduces an interesting series of efficiency issues, which entail properly designing the fuel drive train as well as the electric drive train. In essence, the most appropriate and favourable design of the overall system control strategy is of paramount importance.

1.3 Simulation Platform: The Advanced Vehicle Simulator (ADVISOR) Software

There are many existing software packages for modeling HEV drive trains. Most of these packages exist in the Matlab/Simulink environment with either forward or inverse dynamic solution capabilities. However, the Advanced Vehicle Simulator (ADVISOR) combines forward/backward modeling, which allows monitoring the performance of different drive train components, with fairly accurate dynamic solutions [10]-[12].

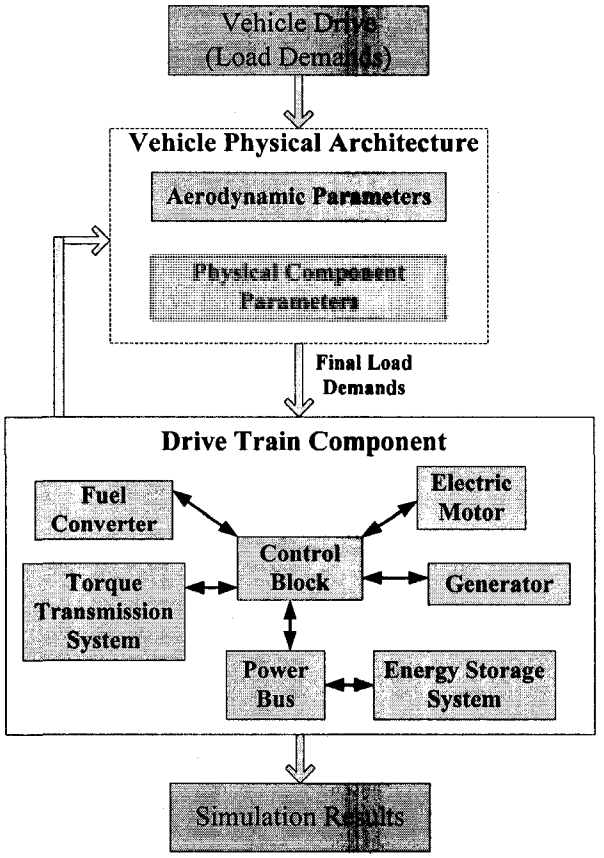


Fig. 1-4 Block diagram of simulation data flow

ADVISOR models the vehicle by integrating the physical architecture model and the drive train component model, as shown in Fig. 1-4. It is primarily used for the analysis of vehicles rather than vehicle design. The pre-summarized vehicle drive is used as a reference to calculate various outputs by analyzing other user-defined input variables, such as the motor size, fuel converter size, and accessory power.

Modeling is performed to accurately simulate the aerodynamic performance of the vehicle. Thus, the vehicle force can be estimated from the vehicle dynamic equation as shown in Equation 1-1. It is clear that the vehicle dynamics involves the calculations of required traction as well as the wheel slip model. In order to find out the grade resistance,

f_g, some important aerodynamic parameters such as vehicle mass, M_v, frontal area, coefficient of aerodynamic drag, and vehicle wheelbase need to be defined.

$$M_V \frac{dV}{dt} = (F_{trac\_front} + F_{trac\_raer}) - (f_{resis\_front} + f_{resis\_raer} + f_w + f_g) \quad (1\text{-}1)$$

The required vehicle speed is predefined by the vehicle drive cycle. The dynamic equation of a conventional vehicle, thus, can be used as the basis for vehicle movement. F_{trac_front} and F_{trac_rear} are traction forces from the frontal and rear wheels, respectively. The terms f_{resis_front} and f_{resis_rear} are the rolling resistances of the front and rear tires, and f_w is the aerodynamic drag.

The overall modeling of an HEV drive train is a complicated process. In ADVISOR, the drive train components are modeled based on efficiency maps, whose data are pre-tested and saved in multi-dimensional tables. The modeling contains procedures, which include component testing, data acquisition, result analyses, and definition. Finally, the acquired data from tests is analyzed or described by mathematical formulation that can be recognized by the program.

1.4 CONTRIBUTION OF THE THESIS

The major contributions of this Thesis include:

(a) Defining hybridization factor (HF) for both series and parallel HEVs.

(b) Defining regenerative braking efficiency.

(c) Development of a novel algorithm that can be used to calculate regenerative braking efficiency and to analyze the motor-inverter efficiency.

(d) Optimization of the fuzzy logic based fuel-economy mode control strategy and the electric assist control strategy that are currently being used in

commercially available HEVs, in order to improve the regenerative braking efficiency as well as motor-inverter efficiency.

(e) Validation and testing of the optimized control strategies.

1.5 THESIS OUTLINE

The contents of this Thesis are organized into 6 chapters. Chapter 1 gives a brief introduction to the project as well as the concept, history, and future development trends of HEVs. It also summarizes the major contribution of the Thesis.

Chapter 2 reviews the HEV efficiency improvement techniques. As groundwork for possible future investigation, this chapter provides sufficient background knowledge to carry out the research. It gives insights into the drawbacks of current HEVs and points out the research direction adopted in the ensuing chapters.

Chapter 3 introduces the efficiency assessment method used in this research. The chapter introduces the power component stage based efficiency analysis and the parametric analysis method. Thereby, the efficiencies of a series HEV and a parallel HEV are compared in this chapter. Also, based on the efficiency analyses, this chapter formulates new efficiency improvement techniques.

Chapter 4 carries on from the conclusion from the previous chapter, to a more specific focal point, regenerative braking efficiency. A novel control algorithm is designed and implemented, by calculating and analyzing regenerative braking efficiency over varied load demands. Eventually, employment of this optimized control strategy results in vastly improved regenerative braking efficiency.

Chapter 5 focuses on optimizing the existing fuzzy logic and electric assist control strategies for HEVs. The optimized control strategies are then simulated and validated. The final results show significant efficiency gains.

Chapter 6 summarizes the research conducted in the Thesis and delivers the overall conclusion. Based on the conclusions of this Thesis and in terms of current automotive industry concerns, appropriate future research directions are finally suggested.

CHAPTER 2

REVIEW OF HEV EFFICIENCY IMPROVEMENT TECHNIQUES

2.1 INTRODUCTION

When terms such as global warming, emissions, and renewable energy frequently come up in daily life, it is time to seriously consider worldwide environmental degradation. However, one day when serious consideration has been achieved, the lifestyle and life quality of human beings will change drastically. Being one of the major elements of world economy, the transportation industry plays an important role in daily life, which has effects on, but not limited to, the worldwide environment, global GHG emissions, and recreation and lifestyle issues. Since the early 1900s, the rudimental model of modern transportation has changed the world. Today, approximately 2,000,000 satisfied HEV customers all over the world, and even more potential users, are changing the world oil consumption structure again.

Together with the environmental pressure and economy reasons, automobile manufactures and governments are driven to explore the commercialization of HEVs and other AVs. As one of the two major international automotive manufacturers, with several years experience in North America, Honda developed the *Insight*, the first HEV to be sold in the North American market. Earlier, in Japan, Toyota also introduced its HEV product, the *Prius*, in late 1997. After several years, Toyota currently has its own HEV product line, extending the implementation of the hybrid drive train to gas-guzzling sport

utility vehicles (SUVs), which incidentally represent about 30% of the total automobiles sold in North America.

Furthermore, automobile manufactures constantly aim to keep up to pace with stringent environmental regulations and ever-growing comfort requirements of customers, to earn their market shares. Toyota lately launched its concept zero emission vehicle (ZEV), the *Hybrid X*, promising that "Fitting with the ecological technology at the core of Toyota's vision of the future, the *Hybrid X* offers not only an environmentally advanced driving experience, but a completely innovative way of providing comfort" [13].

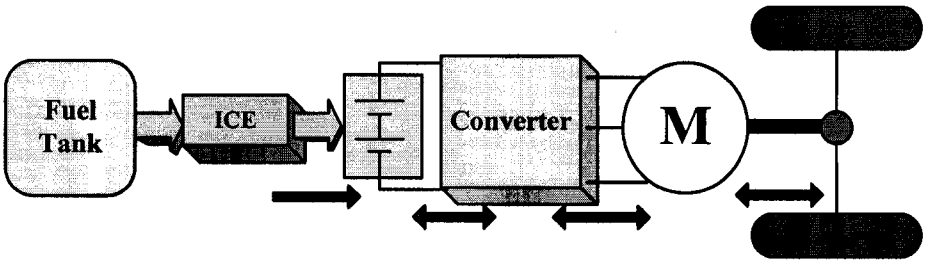
2.2 Basic HEV Drive Train Configurations

As the name suggests, the propulsion energy of an HEV comes from more than 2 types of sources, and one of them must be an electric source. In addition, combining an electric motor with the internal combustion engine (ICE) is the most feasible means of realizing a hybrid topology, before the pure EV eventually becomes commercial. Based on different combinations of electric traction and mechanical traction, HEV drive trains are usually divided into 3 basic arrangements: series, parallel, and series-parallel combined hybrids, as shown in Fig. 3, 4, and 5, respectively [14].

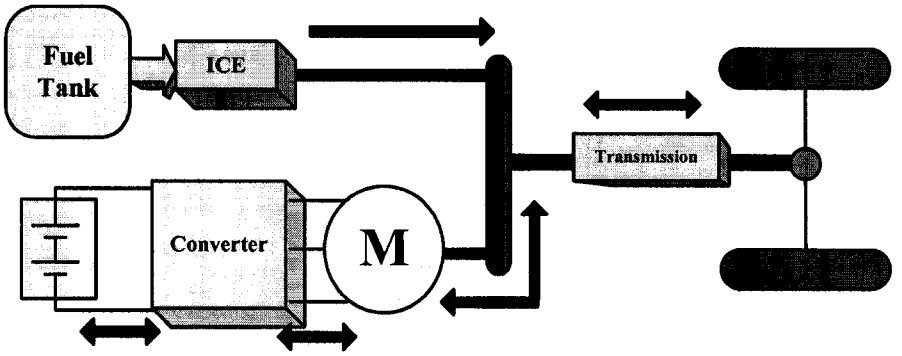
For the series HEV configuration, as shown in Fig. 2-1 (a), 2 different energy sources are combined in series. It is important to note here that the electric motor offers the only traction, making it an electric-intensive vehicle, which is more suitable for city driving. The ICE works at its optimal operation points as an on-board generator, maintaining the battery charge, by meeting the state of charge (SOC) requirements [15].

The overall efficiency of a series HEV is usually around 24%, because of the low efficiency of the ICE and other technical constraints, such as battery capacity and drive train mass.

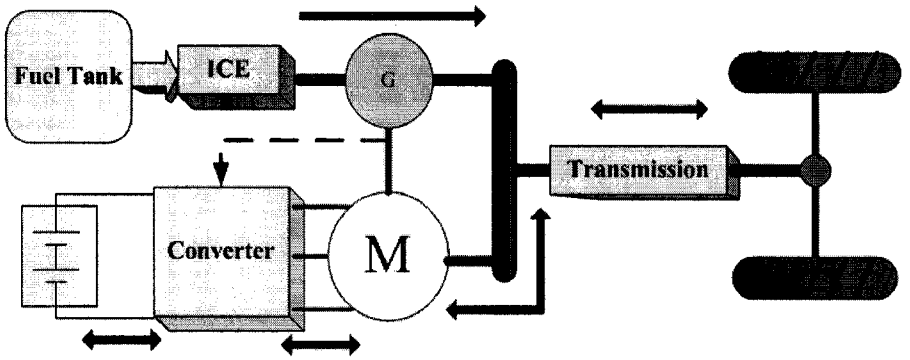
For the parallel HEV configuration, as is clear from Fig. 2-1 (b), the vehicle has 2 traction sources, both electric and mechanical. This type of configuration offers freedom to choose a combination of traction sources. By combining the 2 different traction sources, a smaller engine can be used. In addition, a parallel HEV arrangement requires a relatively smaller battery capacity compared to a series HEV, which results in the drive train mass to be lighter. Therefore, higher efficiency ranges, between 40-50% are easily achieved [16]-[19]. It is a common notion that a higher overall efficiency for a parallel HEV drive train configuration is easily achieved. However, because of the electric-intensive structure of series HEVs, it is more suited for urban driving. On the other hand, parallel HEVs are more suited for highway driving.



(a) Series HEV drive train configuration



(b) Parallel HEV drive train configuration



(c) Series-parallel combined HEV drive train configuration

Fig. 2-1 Schematics of different types of HEV drive train configurations

Furthermore, by adding a mechanical unit between the generator and the electric motor, the series-parallel hybrid HEV combines the features of a series HEV as well as a parallel HEV, as shown in Fig. 2-1 (c). Although it has the advantages of both series and parallel configurations, it also has the drawbacks of these 2 configurations. In addition,

the technical complexity of the general design and development of the combined HEV drive train and its precise control strategy is a major challenge.

It is possible to integrate more than 2 types of drive trains into one vehicle; however, an HEV drive train usually consists no more than 2 power trains. In fact, by integrating 2 drive trains into one vehicle, the complexity of the drive train design increases, and at the same time, the overall control strategy design becomes more difficult. This, in turn, increases the cost.

2.3 Overview of HEV Energy Storage Systems

One of the biggest obstacles for HEV manufacturers is improving system efficiency, and at the same time, reducing the vehicle price (mainly the battery price). From lead-acid (PBA) to nickel-metal hydride (NiMH) batteries, and from ultra-capacitors to flywheels, for years, many battery manufactures have tried to improve energy storage system (ESS) efficiency and energy density. Also, optimized energy-management systems for HEVs have been developed to make good use of limited electric energy stored in the vehicle. Currently, batteries have been developed to range from 20-90 Ah [20]. However, in order to have better performance than those of conventional vehicles, HEVs need more powerful batteries, with power capabilities exceeding 2-4 kW/L. Consequently, the price issue can not be neglected.

Fortunately, with the rapid development of lithium-ion (Li-Ion), Ni-MH, and nickel-cadmium (Ni-Cd) battery technologies, price reductions of 4-6 times is possible. It is commonly understood that these batteries will most probably become the most suitable and promising energy storage devices for future passenger cars. Moreover, the excellent

life cycle characteristics of Li-Ion and Ni-MH batteries can perfectly meet the requirements for future power-intensive HEVs. Furthermore, although the Ni-MH battery has lower efficiency during charging and discharging cycles, compared to Ni-Cd, it demands less in terms of power electronics and electric motors.

In addition, both Li-Ion and Ni-MH batteries are suited to battery-submissive control strategies, which are designed to use the full strength of batteries. For example, the popular charge depleting (CD) HEV control strategy is one of them. By using this control strategy, the overall efficiency is improved approximately up to 5% compared to the multi-speed parallel HEV launch control strategy, which is considered as one of the most efficient control strategies. It is worth mentioning that the Li-Ion and Ni-MH batteries are reasonably maintenance-free, they do not contain toxic heavy metals, and are totally recyclable. These environmentally-friendly characteristics set trends for future battery development. On the other hand, for heavy-duty HEVs, new ESS technologies bring immense hope to the auto industry. Ultra-capacitors (UC) and flywheels are potential promising substitutes for high-power batteries.

The UC is also known as the "double-layer" capacitor. It has a typically small value of resistance, with high energy density. The capacitance usually ranges between 400-3000F. A simplified equivalent model of an UC is shown in Fig. 2-2. This model can be connected with a DC/DC converter, which is equivalent to a constant power load for the UC. The overall value of the capacitance can be expressed by the following equation:

$$C = n_p \frac{C_{rated}}{n_s} \tag{2-1}$$

C is overall value of capacitance; C_{rated} is the capacitance of individual capacitor; n_p is the number of parallel strings of capacitor, and n_s is the number of series capacitors in each string.

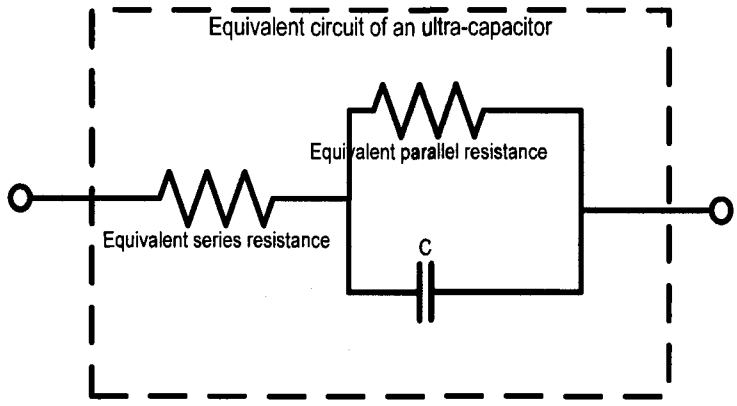


Fig. 2-2 Equivalent circuit of an ultra-capacitor

Constructed by non-environment-harmful materials, the flywheel energy storage system (FESS) offers great characteristics of high energy density, long cycle-life, and high reliability, which are well suited for heavy-duty vehicles and urban transit buses. In recent years, due to the considerable improvement in volumetric density, the FESS is also a promising alternative for small cars. Advanced FESS' have been demonstrated to achieve high rotating speeds, in the range of about 40,000-50,000 r.p.m, and could generate 800-1000 W-hrs., at power ratings of 150-200 kW. An equivalent electric circuit of a FESS is shown in Fig. 2-3. The physical parameters such as friction, rotor inertia, and system inertia, are emulated using passive circuit components [21].

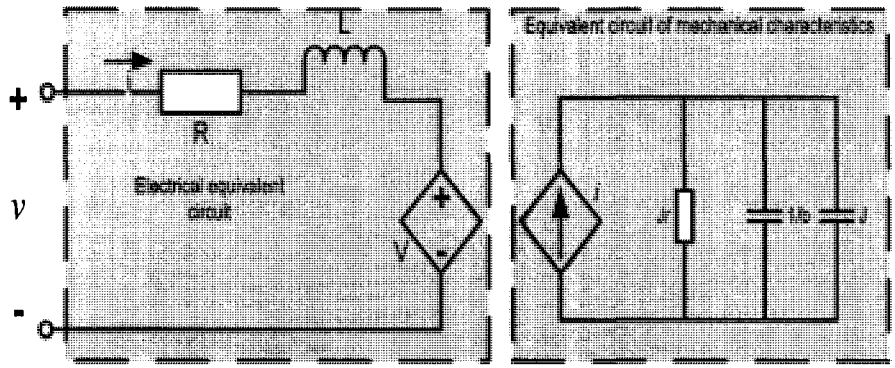


Fig. 2-3 Electrical equivalent circuit of a flywheel energy storage system

Auxiliary energy storage systems, combining the UC and a suitable DC/DC converter, can be easily realized. For an HEV running in an urban drive cycle, almost 30% power economy improvement (in terms of km/kWh), have been demonstrated, with the help of suitable UC/FESS hybrid combination. In addition, by using an UC/FESS hybrid arrangement, the peak power requirements of heavy-duty hybrid electric vehicles and extra high-voltage demands of the hybrid electric military vehicles can also be appropriately satisfied [22]-[24].

It is worthwhile mentioning here that well-designed energy-management strategies and advanced microcontroller techniques make HEVs highly practical. Currently, major research focus is being placed on intelligent control strategies, such as fuzzy logic control strategy, adaptive control strategy, and neutral network based control algorithms. An optimized energy-management system minimizes the energy requirement of the HEV and also maintains best performance under varied load (driving) conditions. Even when the vehicle demonstrates incapability in accepting additional useful energy from regenerative braking, by employing a well-designed artificial neutral network (ANN) energy-management system, reasonable amount of regenerative energy can be recuperated.

2.4 POWER ELECTRONICS AND ELECTRIC MOTOR SELECTION

The biggest challenge for HEV development, apart from bringing existing and future technologies together, is to have the most stable, most reliable performance, and at the same time offer the most comfortable driving experience at a reasonable cost. Advanced power electronic devices and electric motors play major roles in bringing HEVs to the market with the aforementioned excellence, reliability, and affordability [25]. Especially, in the future, when HEVs develop towards a more electric-intensive structure, an even higher amount of power electronic devices will obviously be involved. Therefore, the efficiency issue, reliability issue, and designing compact power electronic devices become major challenges.

Advanced power electronic converter designs and control techniques are implemented into HEV drive trains, in order to overcome numerous technical challenges. As a well-known efficiency improvement technique, soft switching topologies are utilized for HEV power electronic DC/DC as well as DC/AC converters, to reduce switch stresses and to lower the overall switching losses. The results from studies of combinations of soft-switching techniques with different types of motors indicate that soft switching is recommended for an EV or electric-intensive (series HEVs or parallel HEVs, with an electric-intensive control strategy). HEVs running in urban driving schedules have demonstrated energy savings of up to 5%. Conversely, when soft-switching is implemented into regular HEVs/EVs running on the highway, a mere 1% energy saving is not justified compared to the implementation complexity and cost [26].

Therefore, more recently, concentrated research related to novel DC/DC and DC/AC converter designs, and their applications to HEV electric drive trains, have

become a popular topic. Targeted on-board power electronic converters should have features, such as high efficiency (at least >90%), small volume, bidirectional power flow, high voltage rate, and built-in power management, to meet the needs of a more environmentally friendly, electric-intensive HEV. For example, in case of prospective plug-in HEV (PHEV) applications, the arrangement is shown in Fig. 2-4 [27]. Based on the above-mentioned features, multi-level DC/DC converters, featuring clamped-capacitor technology, definitely make low-cost, inductor-free converters a distinct possibility.

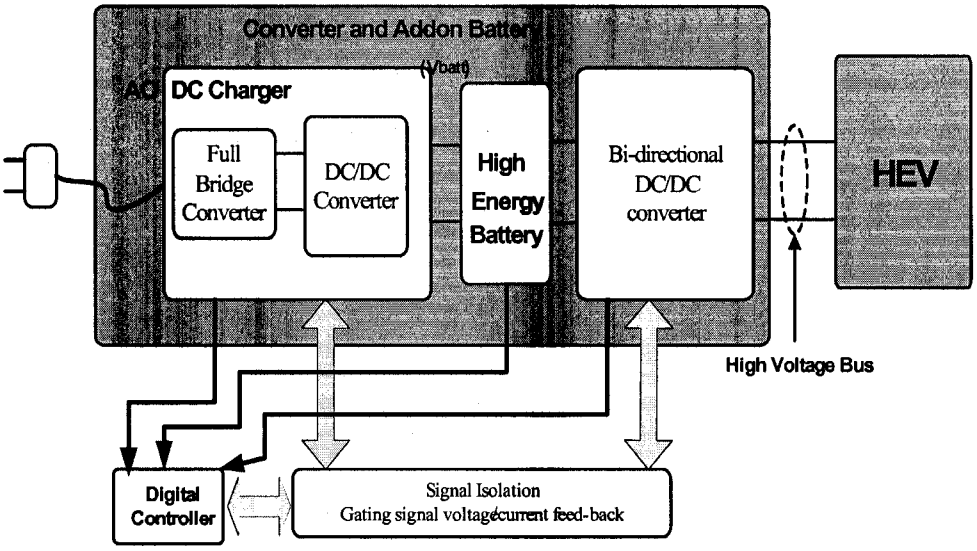
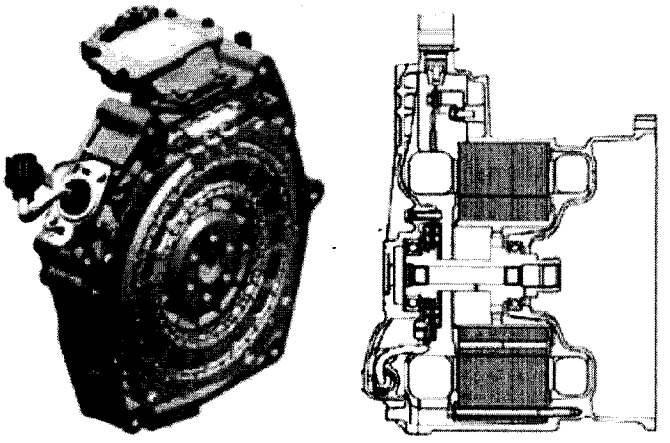


Fig. 2-4 Block diagram of the power system of a PHEV

It is a well-understood fact that the electric propulsion motor is the heart of every HEV system. Currently, there are at least 4 popular types of electric motors in the market. These include the DC motor, the popular AC induction motor (IM), permanent magnet (PM) brushless motor, and the switched reluctance motor (SRM). Selection of an appropriate HEV electric propulsion system requires serious consideration. Recent studies point out that the AC induction motor (IM) and PM motor are the 2 popularly

adopted candidates. The IM is an obvious choice, because of its reliability, low maintenance, low cost, and operating capabilities in aggressive environments. PM brushless motor, however, is popularly utilized in modern HEV designs, due to its light weight, smaller volume, higher efficiency, and rapid heat dissipation. A cross sectional view of a typical PM brushless motor design, more specific for HEV applications, is shown in Fig. 2-5.



10 kW motor for Honda *Insight* 50 kW motor of Toyota *Prius*

Fig. 2-5 Cross sectional view of a PM brushless motor [28], [29] (*Courtesy: Honda Motor Co., Inc., and Toyota Motor Corporation*)

Some series HEV designs use a PM machine as an on-board generator, operating at a pre-designed, optimized operation map, in order to achieve higher efficiency. Considering the extended speed range ability, motor volume, and energy efficiency, however, making a selection between the IM and PM brushless technologies, poses a challenge to auto manufacturers [30], [31].

Device packaging and interconnection are also imperative issues that need to be addressed, when dealing with future automotive power electronics and motor drives [25]. Although the integrated starter/alternator (ISA) has been around for a while, power

electronics has not yet evolved to a stage, where fully-packaged drives can be realized. Optimal packaging of electromechanical and power electronic subsystems is a practical issue, which constantly worries auto manufacturers. Furthermore, numerous difficulties also exist in integrating various sensors and control subsystems, in order to entirely realize high performance electric motor drives [32].

2.5 CURRENT AND FUTURE HEV TOPOLOGIES

Currently, keeping an environment friendly and a more efficient HEV in mind, any striking progress in the HEV industry is possible. From typical HEV drive train configurations to in-wheel motors, fuel economy improvements and GHG emission reductions are easily achievable. For example, in order to improve drive train efficiency, modified planetary gear systems have been successfully designed and tested, whereby the shaft is placed inside the motor, in order to avoid losses occurring during mechanical power transmission. Although such a trivial change might improve the drive train efficiency with less cost, research is constantly being done, in order to find innovative drive train configurations, which can integrate overall features of completely making use of the motor power and reducing mechanical losses.

With the advent of the in-wheel motor technology, wherein the electric traction motor is constricted into the wheels, in order to reduce the energy lost in the transmission, HEV design and development is perceptibly moving towards a more efficient future [33]. However, for the in-wheel motor HEV design, some issues need to be taken care of. For example, to realize a 4x4 drive, 4 in-wheel motors will be needed, which would increase the overall drive train mass. Moreover, the synchronization of 4, or even more motors, will introduce increased complexity of controller design and on-board power electronics.

2.6 CONCLUSION

In this chapter, an overview of HEV efficiency improvement techniques was reviewed and discussed in detail. In addition, a comprehensive discussion on current and future HEV drive train configurations, energy storage systems, power management strategies, motor selection issues, power electronic converter designs, and new technology applications, more specific to HEV drive trains, was presented. By comparing the advantages and disadvantages of the various aforementioned technologies, major HEV commercialization issues were also highlighted in this chapter.

As a fast developing industry, it is hard to give an explicit conclusion to the HEV technology, in general. However, huge potentials in North America, Europe, and Asia certainly represent a promising future for advanced electric propulsion based vehicular technologies. It is predicted that future vehicular technologies will most definitely incorporate hybrid propulsion systems to a great extent. It is hard to say that, maybe, the pure electric propulsion (EV) system is the ultimate vehicle of the future, but the HEV has its own mission in the current era. The future is hard to predict, but it is promising.

CHAPTER 3

EFFICIENCY ANALYSIS OF SERIES AND PARALLEL HEVS

3.1 INTRODUCTION

In order to assess, analyze, and cross-compare efficiencies of HEVs, a true drive train analysis needs to be executed. Generally, the drive train efficiency can be simply yielded out by calculating the losses at each power stage in a series or parallel drive train structure. However, the power component stage-based analysis is a practically deficient method. In order to have a fair efficiency comparison, some parameters that directly affect fuel consumption, such as drive train mass and control strategy should be taken into consideration. This chapter aims at modeling both the series and parallel HEV drive trains, and computing their definite drive train efficiencies, which can be used as a comparative scale for various other HEV topologies. The ADVISOR software is used for modeling, simulation, and parametric analysis of series and parallel HEV drive trains.

In recent years, research results state that vehicle drive train efficiency is considered as an accepted measurement to evaluate and analyse the fuel economy among different types of HEV [33]-[35]. There exist two popular approaches to calculate drive train efficiencies. One of the methods focuses on the losses occurring at individual drive train components. This loss-oriented analysis is termed as power component stage based analysis. On the other hand, few other analyses concentrate on the influence of critical drive train parameters, such as vehicle mass (glider weight), control strategy, and drive train mass, on the overall fuel economy. These comprehensive analyses are imperative, in

order to perform accurate advanced vehicle research, and present a fair comparison between different types of HEVs.

In this chapter, efficiency studies are carried out based on series and parallel HEVs. In order to meet the needs for the required torque, series HEVs usually employ a relatively powerful on-board battery pack and electric motor, which tends to increase the overall drive train mass. However, such an electric-intensive structure liberates the ICE, and allows it to operate at its optimal efficiency points, as an on-board generator. The parallel HEV configuration combines the electric traction with the combustion traction; therefore, the system has the freedom to choose the appropriate propulsion system combination, in order to achieve best efficiency as well as satisfy the load requirement.

This chapter analyzes and compares the drive train efficiencies of series and parallel HEVs by using two different concepts; power component stage based analysis and parametric analysis. Thus, the drive train efficiencies for series and parallel HEV arrangements are fully analyzed and contrasted from the overall efficiency and system performance standpoint.

3.2 COMPONENT STAGE BASED EFFICIENCY ANALYSIS

As the name suggests, the power component stage-based drive train efficiency calculation is based on the number of power component stages in a particular drive train. As depicted in Figs. 3-1 and 3-2, the dark arrows indicate the direction of power flow transmitted along the drive train. Bidirectional arrows stand for two power component stages; therefore, there are six power component stages for a series HEV drive train and nine stages for a parallel HEV drive train. The maximum possible component efficiencies

were considered for the stage based analysis, the data of which was obtained from practical manufacturer data sheets, which include practical de-rated efficiency of each component.

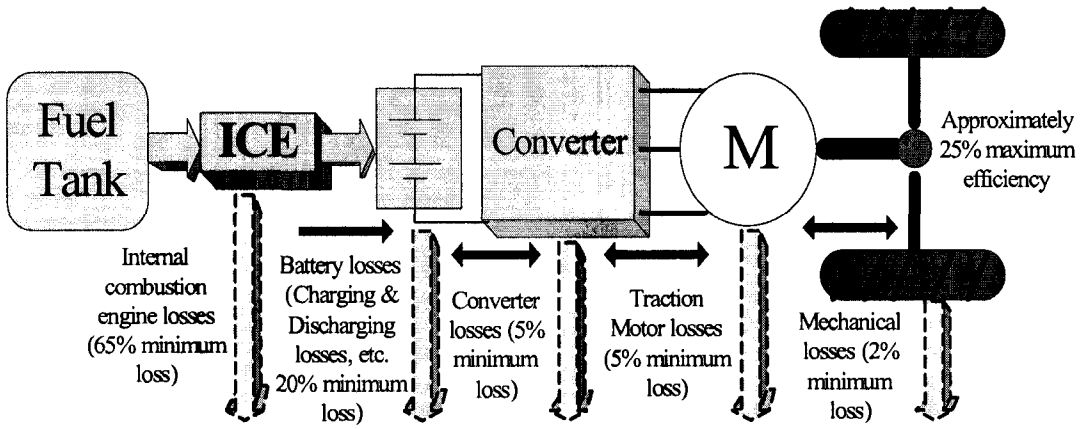


Fig. 3-1 Approximate calculation of maximum theoretical drive train efficiency for series HEVs based on power component stage analysis

For a commercially available battery and power electronic converter, the maximum efficiency is typically around 80% each [15]-[17]. The approximate maximum theoretical drive train efficiency for a typical series HEV is about 25%, which is yielded out by simply multiplying the efficiencies of the corresponding power component stages. Fig. 3-2 shows the losses occurring at each stage of a parallel HEV drive train.

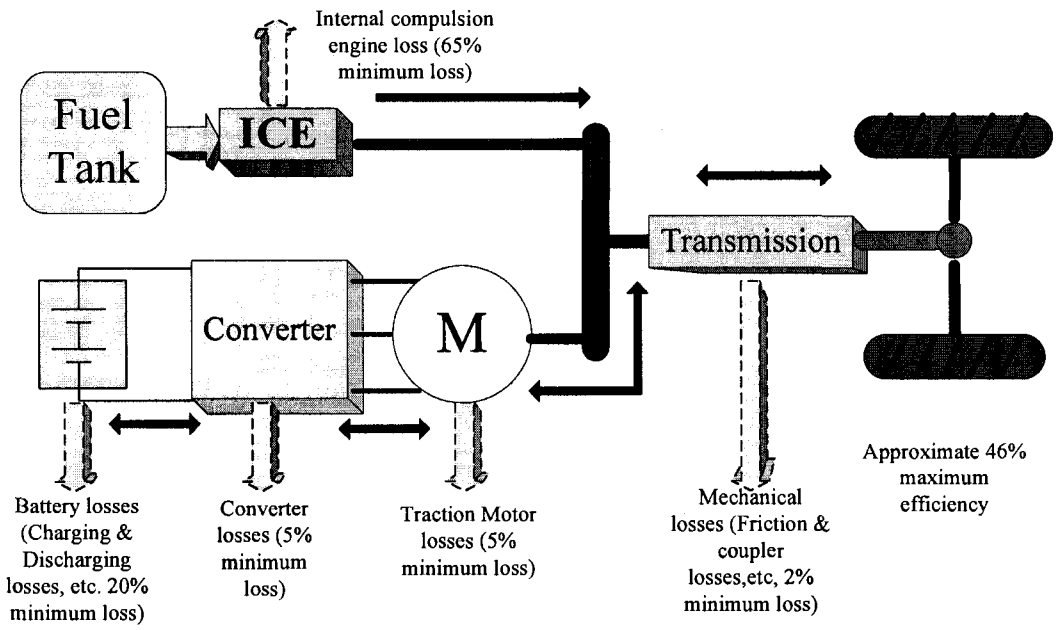


Fig. 3-2 Approximate calculation of maximum theoretical drive train efficiency for parallel HEVs based on power component stage analysis

In order to compare the efficiencies of two different HEV configurations, all the power components used in the representative parallel HEV are assumed to be the same as those used in the series configuration. Considering there are 2 independent power flow channels (via electric traction and via mechanical traction) for the parallel configuration, the calculated drive train efficiency can be theoretically multiplied by a factor of 2. This is because an HEV uses the traction motor alone at low speeds and at starts and stops. When extra power is needed, a combination of both, the traction motor and the ICE, is used. This design utilizes the advantages of the electric motor and the ICE and combines them to form a more fuel-efficient vehicle, thus resulting in efficiencies double that of a conventional vehicle (CV). Thus, based on the power component stage analysis, the approximate maximum theoretical drive train efficiency for a representative parallel HEV is around 45%.

3.3 COMPREHENSIVE PARAMETRIC ANALYSIS

It is clear that the above theoretical efficiency analysis is derived from the system point of view. Although the power component based efficiency computation method simplifies the process of analysis to some degree, the fact is that, sometimes, the fuel economy is significantly influenced by few critically dominant drive train parameters [34], [35]. When investigations concerning the correlation between fuel economy and some other drive train characteristics are carried out, the limitations of the power component stage based analysis become distinct. Therefore, a detailed parametric analysis is needed to deal with the possible uncertainties in efficiency calculation, which is caused by key drive train parameters, such as drive train mass, control strategy, and battery pack.

parallel HEV configurations. The overall analysis mainly examines the influence of 3 critical parameters, namely the influence of different control strategies, drive train mass, and varied battery types. In this chapter, the ADVISOR software is used for modelling, simulation, and test purposes. ADVISOR uses a combined backward/forward modelling approach. This distinct approach allows the monitoring of various drive train component performances during simulations. At the same time, it also offers detailed drive train variables.

3.3.1 PARAMETRIC ANALYSIS OF PARALLEL HEV DRIVE TRAIN

The tested parameters for the parallel drive train configuration are shown in Table 3-1. In this case, the same mid-sized SUV is tested by employing two different control strategies. For Parallel I, CD control strategy is utilized; for Parallel II, the multi-speed

parallel HEV launch control strategy is used. The above-mentioned strategies are found to offer relatively high overall efficiencies under various test conditions. Primarily, a charge depleting control strategy provides a wide envelope between the maximum SOC value and minimum state of charge value, for example between 0.3-0.8. It is designed to make use of the full strength of electric traction, by subtly surrendering the charge of the on-board battery pack. On the other hand, the multi-speed parallel HEV launch control strategy uses the motor for additional power when needed by the vehicle and maintains charge in the battery pack. The SOC envelope, in this case, is set between 0.45-0.95. Also, when the vehicle is at low SOC and its speed is below 54 km/h, the vehicle operates as a pure electric vehicle. In addition, the vehicle also operates as an all-electric vehicle when the SOC is high, and its speed is below 90 km/h. It is worth mentioning here that the lower this speed is set, the better efficiency the vehicle reaches [10].

The simulation studies will also help understand and solve a problem that was identified during the implementation of the experimental set-up. The integrated gate drive circuit of the IGBTs of the inverter present a relatively large dead-time, for avoiding short-circuits through an inverter leg, leading to distortions in the ac side current. This phenomenon is modeled in the simulation circuit, to allow a quantitative analysis of the distortion as a function of the dead-time and also to verify the effectiveness of a well-known compensating method.

Table 3-1 Parallel SUV Parameters

Parameters	Values
Coefficient of drag	0.34
Frontal Area (m^2)	3.15
Wheelbase (m)	2.72
Vehicle Mass (Kg)	2837

The defined SUV chassis is simulated under the urban dynamometer drive schedule (UDDS) for five drive cycles. Fig. 3-3 shows the energy usage during the powering mode for both Parallel I and Parallel II configurations. Since the chassis and the power system are the same, the energy usages in wheel/axle, aero, and energy storage are the same. In case of the Parallel II configuration, the fuel converter (IC engine, ICE) energy usage is apparently more than that of Parallel I. Also worth noticing is that the energy usage in the motor/controller is slightly different in each case. The Parallel I configuration uses the electric motor more than the Parallel II configuration. This energy usage chart reaffirms the fact that by using the CD control strategy, the vehicle is more like an electric vehicle.

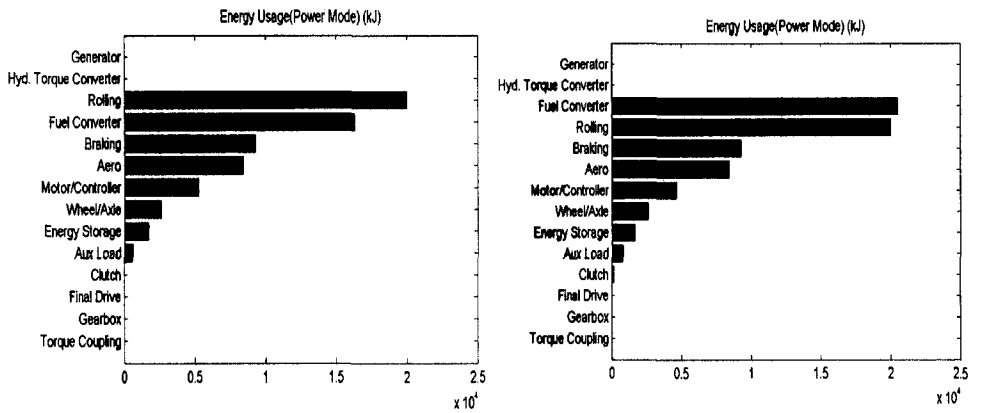


Fig. 3-3 Energy usage during powering mode for parallel 1 (left) and parallel 2 (right) configurations

The defined SUV chassis is simulated under the UDDS for five drive cycles. Fig. 3-3 shows the energy usage during the powering mode for both Parallel I and Parallel II configurations. Since the chassis and the power system are the same, the energy usages in wheel/axle, aero, and energy storage are the same. In case of the Parallel II configuration, the fuel converter (IC engine, ICE) energy usage is apparently more than that of Parallel I. Also worth noticing is that the energy usage in the motor/controller is slightly different in each case. The Parallel I configuration uses the electric motor more than the Parallel II configuration. This energy usage chart reaffirms the fact that by using the CD control strategy, the vehicle is more like an electric vehicle. Fig. 3-4 shows the fuel converter efficiency operation points of both Parallel I and Parallel II configurations.

By using the advanced CD and multi-speed parallel HEV launch control strategies, the ICE operation is usually optimized. Although the ICE operates at a high efficiency (almost 40%), the Parallel II uses its fuel converter more frequently than Parallel I; thus, the prolonged usage of the ICE might lead to a low overall efficiency in

powering mode of operation. This assumption can be confirmed by observing Fig. 3-5, which depicts the fuel converter operation maps.

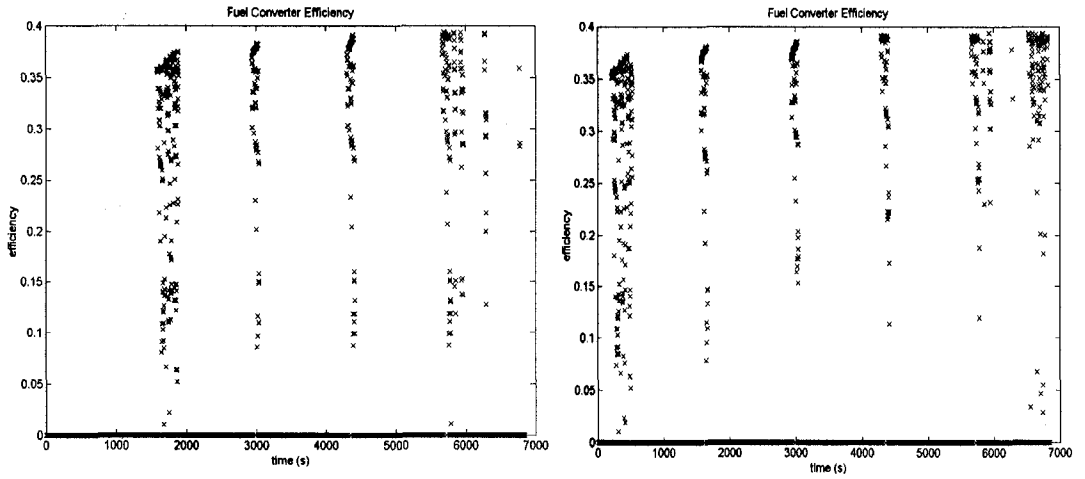


Fig. 3-4 Fuel converter efficiencies of parallel 1 (left) & parallel 2 (right) configurations

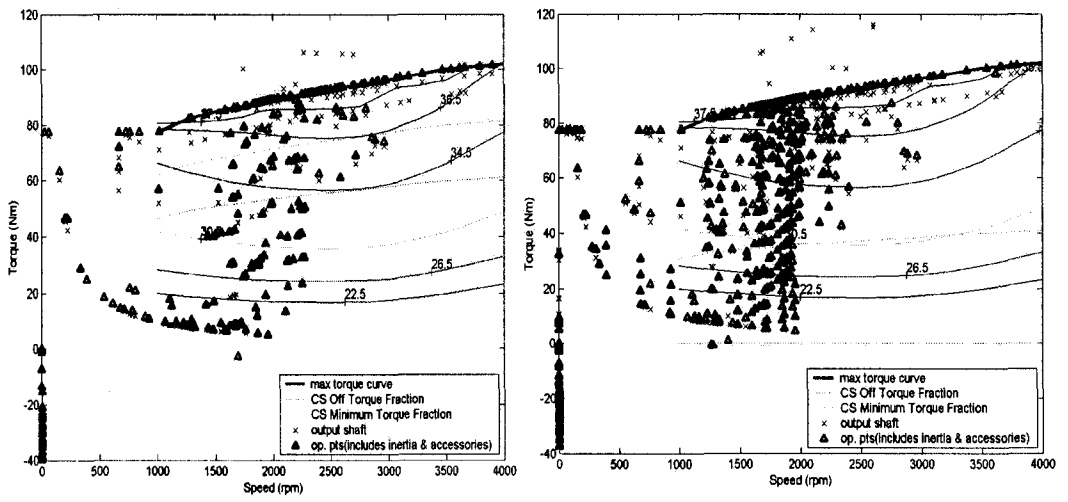


Fig. 3-5 Fuel converter operating points for parallel 1 (left) & parallel 2 (right) configurations

The operation points of Parallel I are closer to the maximum torque curve than those of Parallel II configuration. This implies that the CD control strategy has a slightly higher efficiency compared to multi-speed parallel HEV launch control strategy.

The average speed of the UDDS driving schedule is about 50 km/h. When the simulation runs under UDDS, the SOC of Parallel II maintains an average value of 0.5; therefore, most of the time, Parallel II operates like an electric vehicle. For Parallel I, due to the nature of the CD control strategy, the motor operation map presents a more centralized nature, as shown in Fig. 3-6.

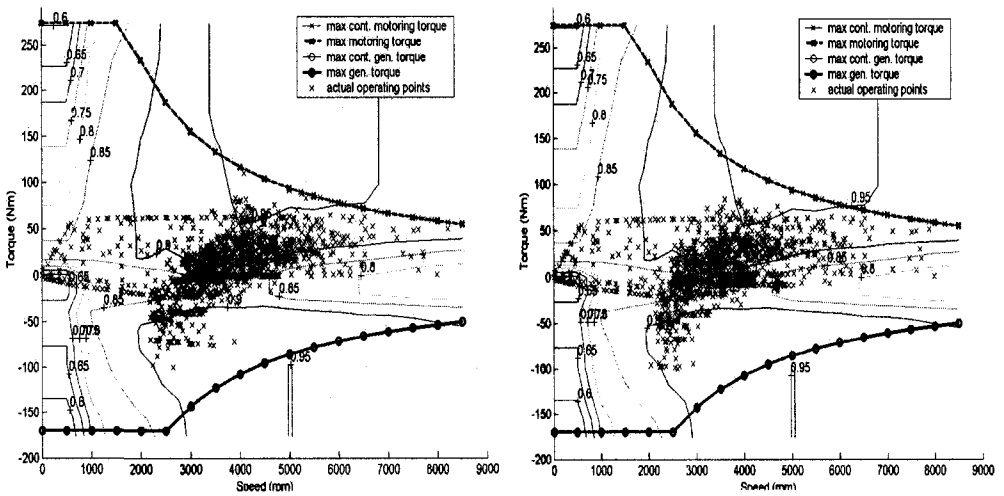


Fig. 3-6 Motor/controller operating maps for parallel 1 (left) & parallel 2 (right) configurations

It is important to note that in case of Parallel I operation, most of the points are within the 90% efficiency envelope, tending to be more efficient than Parallel II. The above analyses, based on the simulation results, lean to the fact that the CD control strategy is more efficient than multi-speed parallel HEV launch.

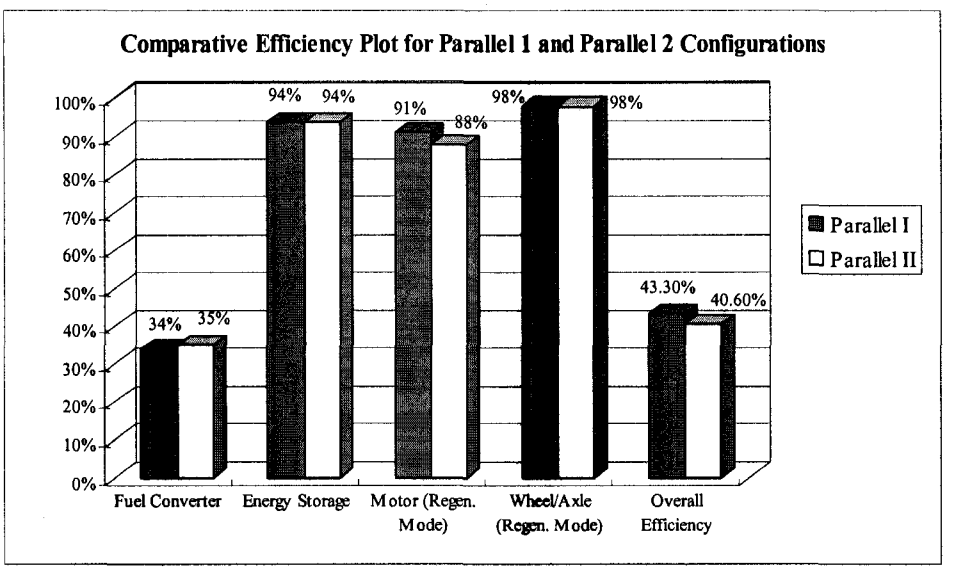


Fig. 3-7 Comparative efficiencies for parallel 1 & parallel 2 configurations

Fig. 3-7 gives a brief comparison of some major parameters between Parallel I and Parallel II. As is observable, in both the powering as well as regenerative breaking mode, the control strategy vastly influences the overall fuel economy.

3.3.2 PARAMETRIC ANALYSIS OF SERIES DRIVE TRAIN

In this section, the mid-sized SUV is modelled in a series configuration, in order to investigate the influence of varied control strategies and battery pack mass on the overall fuel economy. The parameters of three simulated series SUVs are shown in Table 3-2.

Table 3-2 Series SUV Parameters

Parameters	Series I	Series II	Series III
Drag Coefficient	0.34	0.34	0.34
Frontal Area (m^2)	3.15	3.15	3.15
Wheelbase (m)	2.72	2.72	2.72
Vehicle Mass (kg)	2955	2955	2943
Control Strategy	Chrg Depltng	Thermo	Thermo

For Series I and Series II, the chassis are the same except for the control strategies. In case of Series III, the control strategy is the same as that of Series II, but the generator is different from the other two models, which results in a significant difference in drive train mass, which in turn eventually leads to varied test results, as will be seen in this investigation.

3.3.2.1 INFLUENCES OF CONTROL STRATEGY

In order to examine the influence of control strategies, the Series I and Series II HEVs are simulated under UDDS driving schedule by using the CD control strategy and series thermostat control strategy, respectively. The operating principle of CD control strategy is almost the same as the CD control strategy for parallel HEV, as described in the earlier section. The series thermostat control strategy uses the generator and fuel converter to generate electrical energy for use by the vehicle. It primarily uses the ICE to maintain charge in the battery. The fuel converter turns ON, when the SOC reaches the low limit, and turns OFF, when the SOC reaches the high limit. Moreover, as far as possible, the ICE tries to operate at the most efficient speed and torque level. Fig. 3-8

below shows the energy usage during powering mode for both Series I and Series II configurations.

Again, since the chassis and power system are the same, the energy usage in the wheel/axle, aero, and energy storage are the same. As is clear in Fig. 8, one significant difference is that the ICE energy usage for the Series II configuration is almost twice that of Series I. Although the thermostat control strategy makes sure that the ICE operates at the most efficient speed and torque level, the high losses of the ICE are still a major contributor to the overall losses in the complete drive train. The fuel converter operation maps of Series I and Series II drive train arrangements are shown in Fig. 3-9.

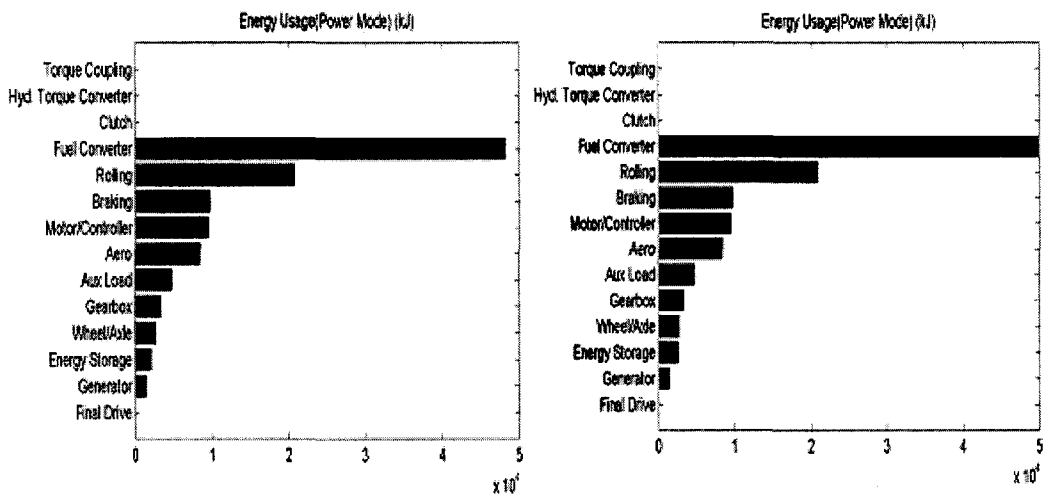


Fig. 3-8 Energy usage during powering mode for series 1 (left) and series 2 (right) configurations.

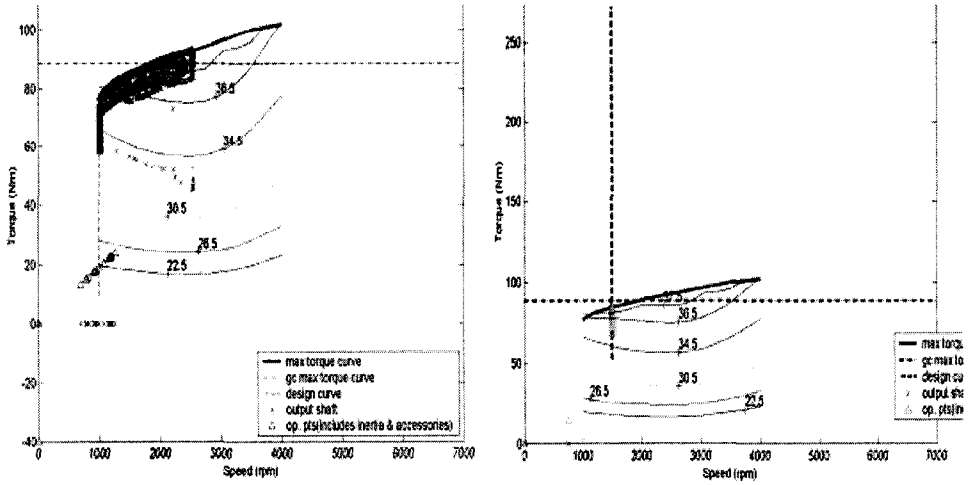


Fig. 3-9 Fuel converter operation maps for series 1 (left) and series 2 (right) configurations

For Series I, its fuel converter operates at various speeds and close to the maximum torque curve. For Series II, contrarily, its fuel converter operates around a constant speed, because the control strategy requires the fuel converter running at the most efficient speed and torque level.

It is worthwhile noting here that, because of the fact that the series HEV is an electric-intensive configuration, and the electric motor is the only traction source, the motor efficiency has a significant contribution to the drive train efficiency. Fig. 3-10 shows the motor/controller operation maps of Series I and Series II configurations. Both the drive train models use a 75kW AC induction motor.

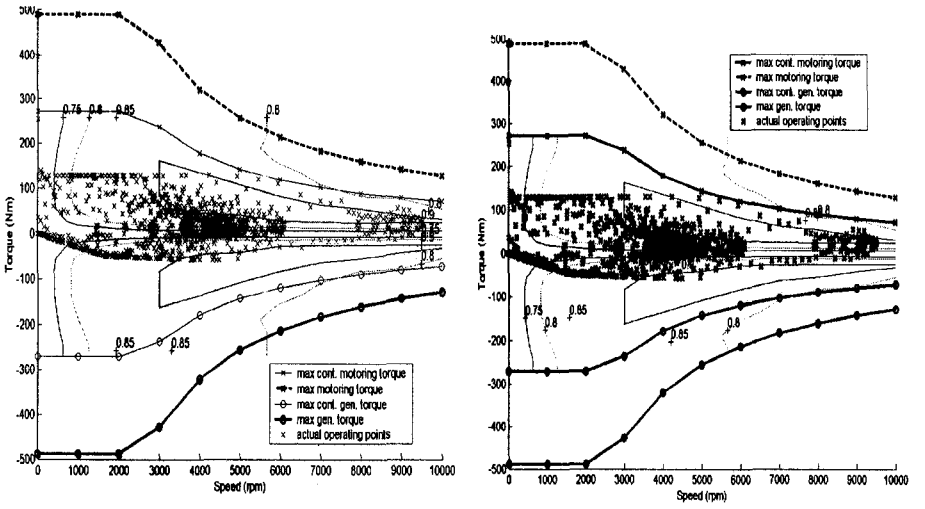


Fig.3-10 Motor/controller operation maps for series 1 (left) and series 2 (right) configurations

The motor-controller operating map for the Series I drive train is distributed intensively around the central area, which is similar to the case of Series II. Such a central distribution of the operation points show that the AC motor operates at an acceptable efficiency.

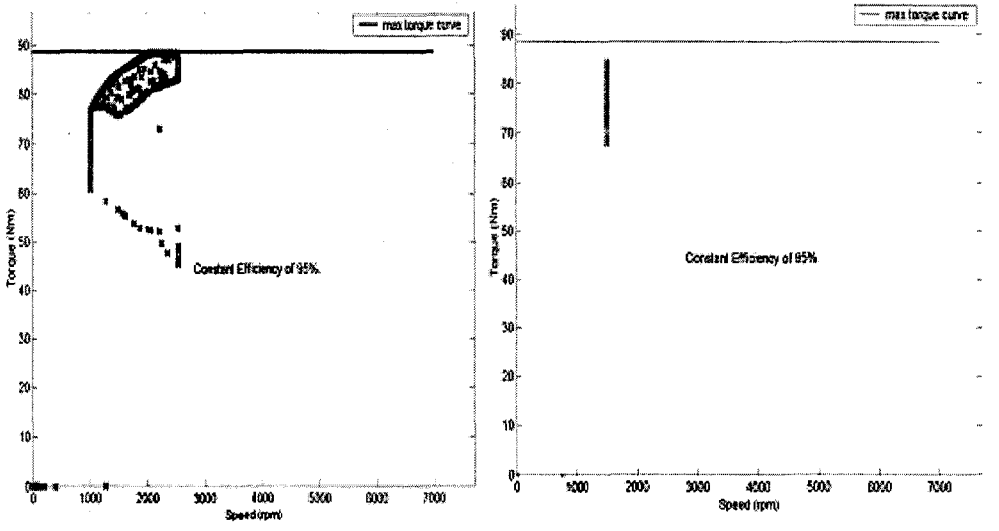


Fig.3-11 Generator/controller operation maps for series 1 (left) and series 2 (right) configurations

An interesting observable fact for both Series I and Series II is that they keep the generator operating at a constant efficiency for which it has been pre-designed. Fig. 11

shows the generator operation points of Series I and Series II, maintaining a constant efficiency of 95%.

3.3.2.2 INFLUENCE OF VEHICLE MASS

It is a well-known fact that the HEV drive-train mass has a direct influence on fuel economy [36]-[38]. For a series HEV, in order to supply the desired load torque, and to have the same capability as that of a parallel HEV, it may demand the usage of a relatively larger electric motor. In addition, due to its electric-intensive nature, the series HEV power system components also require relatively higher power ratings, in order to achieve attractive performance, which leads to heavier battery packs. Moreover, battery mass is one of the major parameters contributing to overall vehicle weight. As shown in Fig. 3-12, the battery mass covers almost 25% of the overall weight of a typical medium sized SUV [37]-[38].

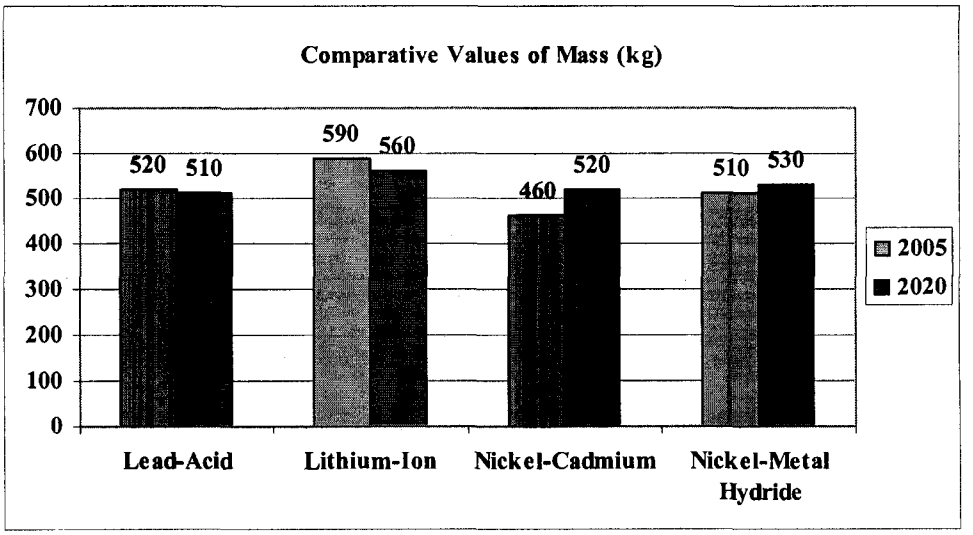


Fig. 3-12 Current (2007) and projected (2020) mass values for HEV battery candidates

The Series III configuration is used for a simple simulation, in order to test the sensitivity of the drive train mass. In Series III, the power of the on-board generator is

reduced to 65 kW, which is less than the nominal value of the 75 kW AC motor. Although the power of the on-board generator is reduced to less than the nominal power of the AC motor, the simulation results show that the overall efficiency is slightly increased. This result implies that the series SUV is highly sensitive to the drive train mass. Even with a small reduction in drive train mass, the overall efficiency can be increased up to 0.2%. This fact necessitates the usage of batteries with high power density characteristics.

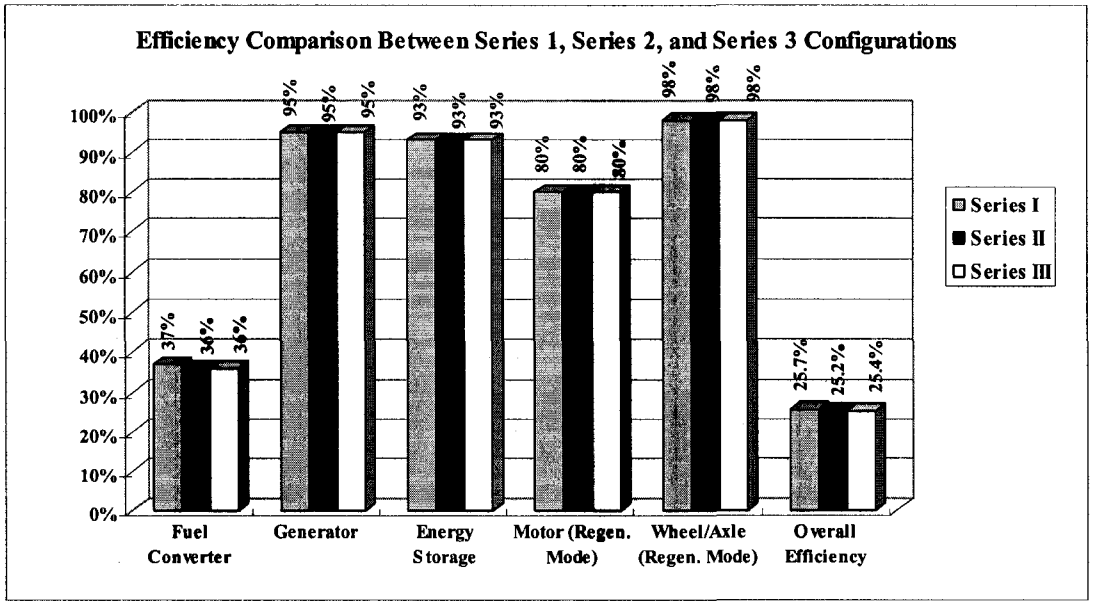


Fig. 3-13 Efficiency Comparisons of Series 1, Series 2, and Series 3 configurations

Fig. 3-13 gives a visual comparison of efficiencies of the three series configurations. The efficiency differences among the three configurations are not as observable as those of parallel one. This is most likely because of its electric-intensive structure, since this structure is not so sensitive to HF.

3.4 COMPARATIVE ANALYSES OF SERIES AND PARALLEL SUV DRIVE TRAINS

From the above analyses, Parallel I and Series I are the most efficient configurations amongst their own categories. Thus, some additional tests were carried out, in order to have a complete comparison between the Parallel I and Series I configurations, the results of which are summarized in this section. Fig. 14 presents the acceleration test results and Fig. 15 depicts the comparison of the GHG emissions.

Fig. 16 below summarizes the drive train component efficiencies as well as the overall drive train efficiency for both the Parallel I as well as Series I configurations. Consistent with the results from the power component stage based analysis; the parallel HEV configuration again depicts a significantly higher efficiency than the series configuration.

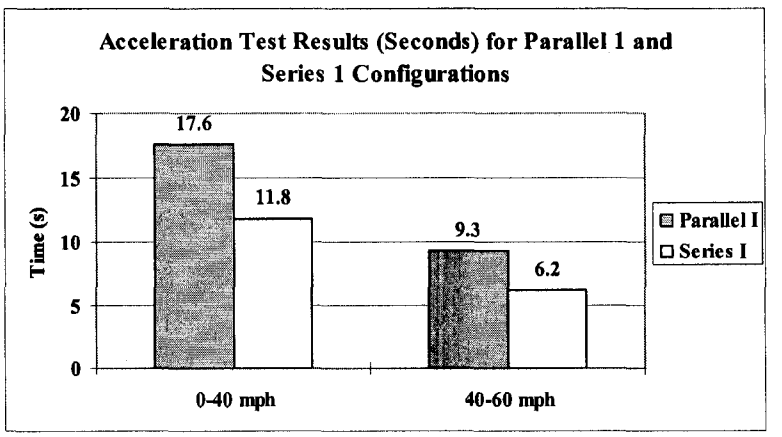


Fig. 3-14 Acceleration test results for simulated parallel and series SUVs

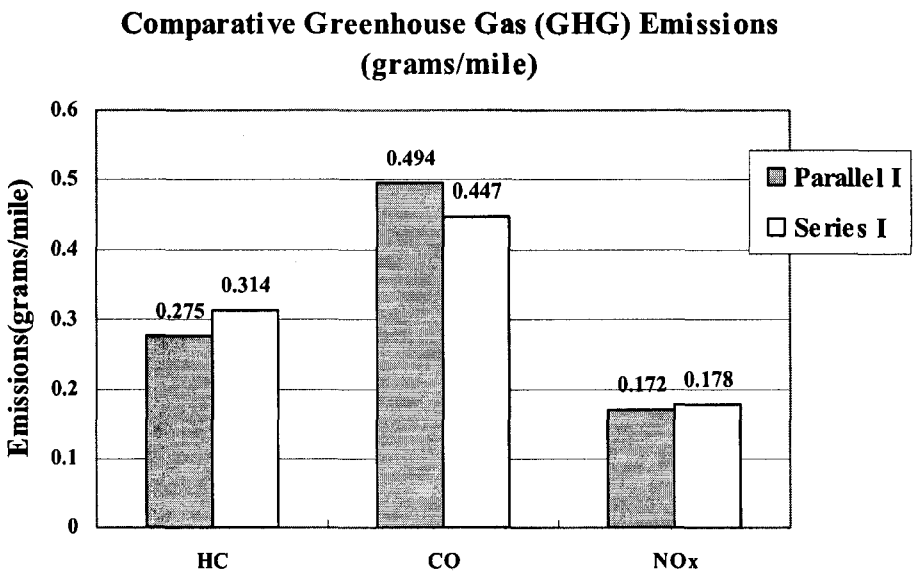


Fig. 3-15 Comparative GHG emissions for simulated parallel and series SUVs

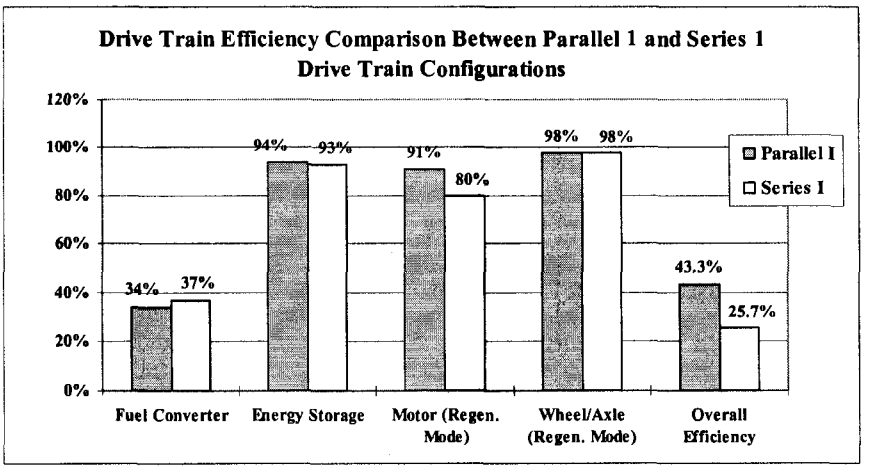


Fig. 3-16 Overall efficiency comparison between parallel 1 and series 1 drive train configurations

Although the results of the power component stage based analysis and the parametric analysis are not exactly the same, the slight differences do not change the consistency of the results. In addition, through the investigation carried out in this work, is found that the series HEV is less affected by varying and optimizing its control strategy. This is due to the fact that an intelligent control strategy for a parallel HEV monitors the battery SOC and coordinates the operation of the fuel converter and motor, to decide the

exact mode of operation of the vehicle, in order to obtain the best efficiency. In another words, the best efficiency in a parallel HEV can be easily maintained by modifying the hybridization factor (HF) [38]. For a series HEV, the only energy source is from the fuel converter which is a low efficiency system. Therefore, it can be safely concluded that a series HEV is less sensitive to its control strategy, but more influenced by its drive train mass.

3.5 CONCLUSION

Based on the detailed analyses conducted in this chapter, it can be concluded that for parallel HEV configurations, the HF plays a vital role in optimizing the overall drive train efficiency. However, for a series HEV configuration, the drive train operates at a relatively lower overall efficiency, because of the maximum efficiency limitation of the fuel converter. Nevertheless, by improving the performance of on-board power generation, battery operation, smarter usage of the regenerative braking property of the traction motor, and using the most suitable control strategy, even higher efficiencies can be achieved in case of series HEVs.

It is also worth mentioning here that a critical deduction of this chapter is that the results from the power component stage based analysis prove to be consistent with those of the detailed parametric analysis. Therefore, it is safe to conclude that both the methods display practicable measures to evaluate HEV drive train efficiencies. However, the theoretical back-of-envelope calculations, performed in the power component stage based method, are not as accurate. Thus, as long as all the parameters that influence the fuel

economy are taken into consideration, an effective technique of improving HEV drive train efficiencies can be established.

CHAPTER 4

EFFECT OF VARIED LOAD DEMANDS ON DRIVE TRAIN EFFICIENCY

4.1 INTRODUCTION

It is a well-understood fact that power electronic converters and electric propulsion motors are extremely critical for every HEV system. It is essential that the traction motor must meet demands of varied driving schedules, and at the same time, it should run at its most optimal operating points to achieve higher drive train efficiency. Therefore, modeling the motor-inverter losses/efficiencies over typical city and highway driving schedules is the key to observe and analyze practical drive train efficiency and vehicle performance.

Currently, land vehicles are transiting from pure gasoline-fuelled to gasoline-electric combined HEV. In fact, there exist about 1,500,000 satisfied HEV users around the world. This number is constantly increasing, based on a yearly rate of roughly about 40%. A major increase is noticeable in light-duty hybrids, such as passenger cars and SUVs [39], [40]. Majority of these vehicles are used for personal transportation, typically driven in the urban area or on a highway. Therefore, HEVs are not just run in particular routes, but in varied driving patterns. As a complex system, the automobile features vast mobility and variation. It is hard to measure its efficiency by using a simple measurement [41]. Thus, well-rounded measurements, such as well-to-wheel efficiency and tank-to-wheel (drive-train) efficiency are employed to fairly evaluate its efficiency.

However, it is a fact that HEVs cannot be optimally designed for all driving patterns. Various control parameters and efficiency data over particular driving schedules are required to optimize the control strategies for HEVs. Fortunately, because of commuters' regular routes, most of the driving patterns are predictable. In addition, automobile manufactures are tending to design HEVs that can use the electric propulsion motor over all range of load demands. Thus, a motor with high torque density, high efficiency, excellent controllability, and accuracy is needed. Therefore, the efficiency of traction motor-inverter drive system needs to be specifically studied and analysed on the basis of varied load demands [4].

Keeping the above-mentioned constraints in mind, the major focal point of this chapter is to model the traction inverter and motor losses/efficiencies over typical driving patterns. Efficiency maps are usually used to describe total efficiency of traction motors with respect to certain speed/torque combinations. The overall HEV drive train efficiencies are determined by the resultant traction motor-controller efficiency maps during simulation. Consequently, by using efficiency maps, an HEV motor drive can be represented as a "black box" that provides a known output when certain input is applied. The modeling concept is shown in Fig. 1. Thus, the traction motor can be studied at all possible torque/speed combinations within the motor's operating envelope by analyzing its operating efficiency.

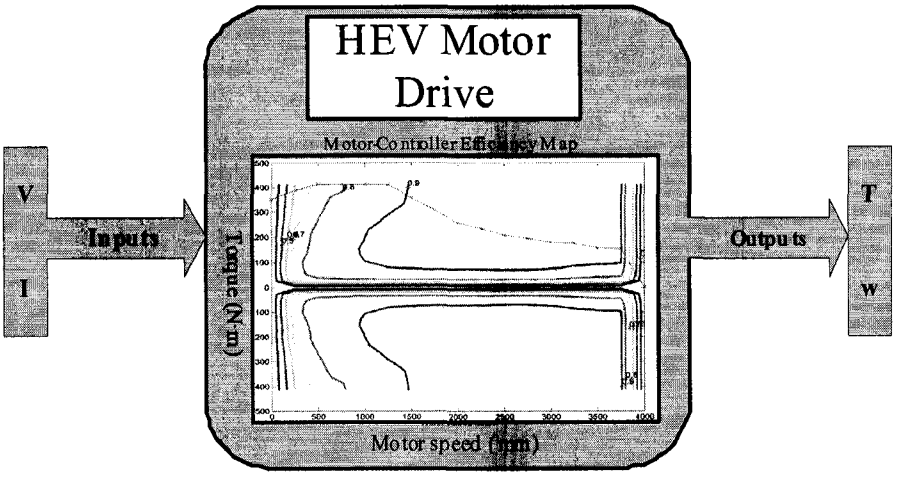


Fig. 4-1 HEV motor drive efficiency modeling concept based on operating efficiency maps

In this chapter, optimal control strategies are used for parallel HEVs, based on the UDDS driving pattern, which generally represents an average urban driving model. Based on the simulation results, a comparative analysis is carried out for 6 selected different driving patterns, which show varying results in terms of overall drive train efficiency, vehicle performances, and overall emissions.

4.2 VEHICLE SPECIFICATION AND MODELING

In this chapter, a typical mid-sized SUV is selected to represent the most popular vehicle in the market. The major dimensions and weights of the tested SUV chassis are summarized and revised for simulation purpose based on current commercially available SUVs. The physical parameters of the tested SUV are shown in Table 4-1.

As aforementioned, a parallel HEV drive train configuration is chosen for simulation purposes. Fig. 2-1 (b) shows the block diagram of the modeled parallel SUV. It is clear that a parallel HEV structure is a combined traction source arrangement [19]-

[43]. Thus, the hybridization factor (HF), which is defined as the ratio of the total electric power to the total propulsion power, plays an important role in the overall efficiency.

Table 4-1 Physical parameters of tested parallel hybrid SUV

Parameters	Value
Dimensions	
Coefficient of drag	0.34
Frontal Area (m^2)	3.15
Wheelbase (m)	2.72
Overall Length (m)	4.71
Vehicle Mass	
Vehicle Weights (kg)	2701
Cargo Weight (kg)	156

The fuzzy logic drive train control strategy is selected for simulation purpose and it is optimized based on UDDS, by adjusting its SOC and HF to have better city-driving efficiency. The tested drive train components were optimized by using the auto-size routine, which employs a bisection method to optimize the component size, based on the required vehicle performance. For the simulated parallel SUV, first the entire energy storage system size is minimized, and then its minimum fuel converter (FC) size is determined, according to the vehicle performance criteria. Finally, the FC size is fixed by a suitable HF, based on the following equation.

$$fc\_pwr = fc_{\_pwr\_\min} + HF * (fc_{\_pwr\_\max} - fc_{\_pwr\_\min}) \tag{4-1}$$

Here, fc_pwr = new fuel converter size; min_fc_pwr = required minimum fuel converter size to meet the vehicle performance; max_fc_pwr = required maximum fuel converter size to meet the vehicle performance; HF = hybridization factor.

Once the FC size has been determined, the routine resizes the energy storage once again, to meet the acceleration requirements. The UDDS driving pattern, which is equivalent to the first 2 cycles of the Federal Test Procedure (FTP-75) driving schedule, represents general city driving conditions. Thus, UDDS is selected as a reference, for optimizing the drive train components [44]. The optimized drive train components are listed in Table 4-2.

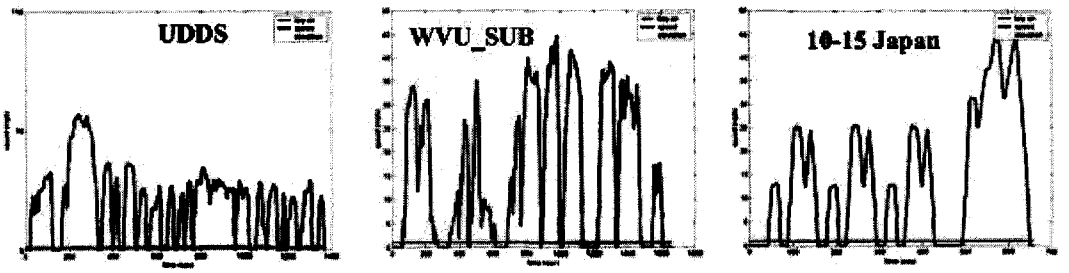
The selected drive train was tested over 6 different driving schedules, which include 3 stop-and-go type low-speed driving patterns and 3 high-speed driving patterns. The driving patterns include the West Virginia Suburban (WVU-SUB), the Urban Dynamometer Driving Schedule (FUDS), 10-15 Japan driving schedule, the Highway Fuel Economy Test (HWFET), US06 Highway Driving Schedule (US06 HWY), and the Extra-Urban Drive Cycle (EUDC) [12]. The speed profile versus time for each of the above-mentioned 6 driving schedules and their detailed characteristics are summarized in Fig. 4-2 and Table 4-3, respectively.

Table 4-2 Summary of parallel HEV drive train components

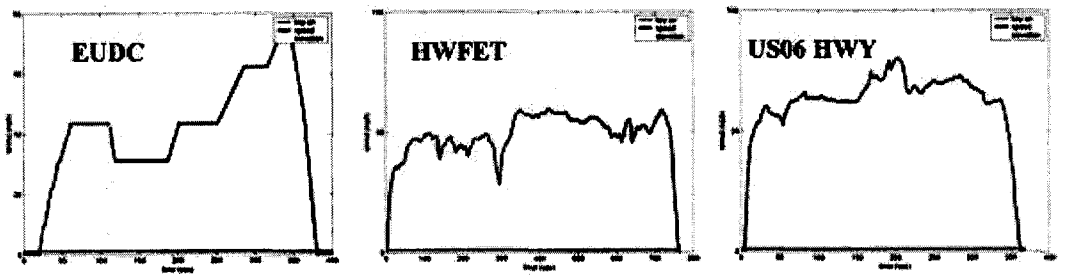
Parameters	Value
Fuel Converter	
Max. Power	17kw @ 4000rpm
Max. Torque	45Nm @ 4000rpm
Fuel Converter Mass	70 kg
Battery (Nickel-Metal Hydride)	
Single Module Voltage	12 V
Number of Modules	25 modules
Nominal Capacity	60 Ah
Peak Power (10s pulse @ 50% DOD @ 35 deg. C)	4.9 kW
Mass	290 kg
Motor-Controller (PM)	
Continuous Power	48 kW
Peak Torque	370 Nm
Motor-Controller Mass	58 kg
Maximum Speed	4000 rpm

Table 4-3 Summary of the 6 different driving schedules

Driving Cycle	Dist.	S	Max. Spd.	Ave. Spd.	Max. Accel.
UDDS	7.45 miles	17	56.7 mph	19.58 mph	4.84 ft/s^2
WVU-SUB	7.44 miles	9	44.8 mph	16.7 mph	4.25 ft/s^2
10-15 Japan	2.61 miles	14	43.96 mph	14.24 mph	3.89 ft/s^2
HWFET	10.26 miles	1	59.9 mph	48.2 mph	4.69 ft/s^2
US06 HWY	6.24 miles	1	80.3 mph	60.84 mph	10.12 ft/s^2
EUDC	4.32 miles	1	74.56 mph	38.8 mph	3.46 ft/s^2



a. City driving patterns.



b. Highway driving patterns.

Fig. 4-2 Simulated driving schedules for test purposes

The modeled mid-sized hybrid SUV is simulated over 3 reiterations of each driving schedule. The overall efficiency and vehicle performance will be compared in the ensuing sections, which are directly influenced by the different driving patterns.

4.3 Overall Efficiency Comparison Based on Varied Driving Patterns

As aforementioned, the ADVISOR software is used in order to determine the overall efficiency based on above-mentioned driving schedules. The comparative overall efficiencies of different driving schedules are shown in Fig. 4-3.

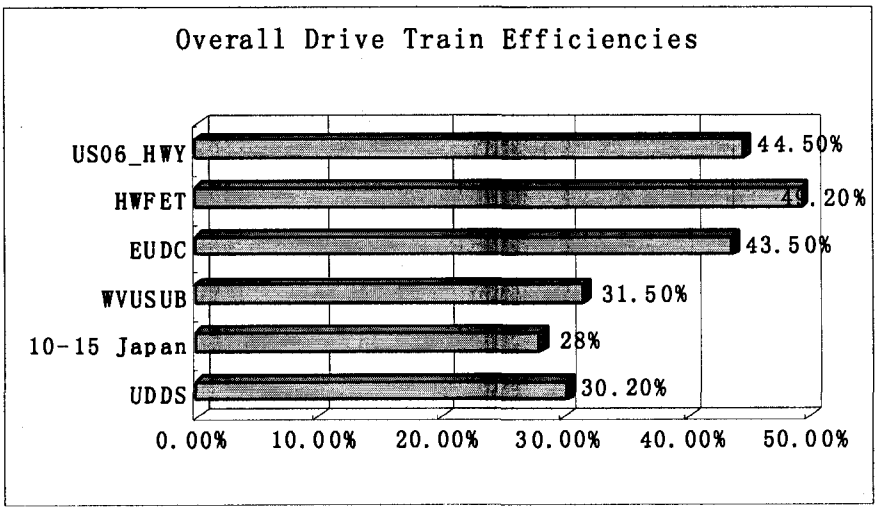


Fig. 4-3 Overall drive train efficiency over different driving schedules

As explained earlier, a parallel HEV is the combination of different traction sources, and hence, the system has the freedom to choose the suitable propulsion system combination. For city driving, the number of stops and starts is 10 times more than that in case of highway driving. Thus, the ICE is more frequently used in city driving patterns than highway driving patterns, which results in a lower efficiency. Moreover, steep decelerations are harmful for regenerative braking energy recovery. Especially in the case of 10-15 Japan, there are 14 stops-and-starts in only 2.61 miles, as shown in Table 4-3, and the average deceleration is the greatest amongst the 3 city driving patterns. Therefore, less energy is recovered from regenerative braking and the overall drive train

efficiency over 10-15 Japan is the lowest, although the driving distance and acceleration is much less compared to other city driving schedules [45].

The overall fuel economy over the designated 6 driving schedules is shown in Fig. 4-5. It can be easily observed that the overall drive train efficiency is not necessarily proportional to fuel economy. For example, the fuel economy under 10-15 Japan driving conditions is higher than that under UDDS conditions, but the overall drive train efficiency is lower. The higher fuel economy of 10-15 Japan is because it possesses lower average speed as well as maximum acceleration, which leads to less usage of the ICE and leads to higher motor-controller efficiency. In the case of drive train efficiency, UDDS has a higher efficiency, because of the efficient usage of regenerative braking. As is clear from Table 4-3, there are a total of 51 stops in UDDS, but only 42 stops in 10-15 Japan. The simulation data also shows that the energy generated by regenerative braking under UDDS conditions is 2% higher than that of 10-15 Japan, which indicates that more energy is saved in the drive train, as shown in Fig. 4-6. In addition, the electric motor is more frequently used in UDDS, which leads to a higher efficiency.

Moreover, it is easy to notice that a single cycle distance of UDDS is 3 times greater than that of 10-15 Japan. Since the simulation is carried out over 3 repetitions for each driving schedule, the simulated distance of UDDS is approximately 9 times longer than that of the 10-15 Japan. On the other hand, the tested SUV runs as an electric vehicle because the high (80%) initial SOC. The ICE starts working when the SOC decreases to a designated value. For these reasons, the SUV tested over 10-15 Japan is more likely to stay in electric mode longer than UDDS, which contributes a higher fuel economy. This

result also suggests that a higher fuel economy can be obtained by maintaining the ESS in its high SOC range and driving the vehicle for shorter distances.

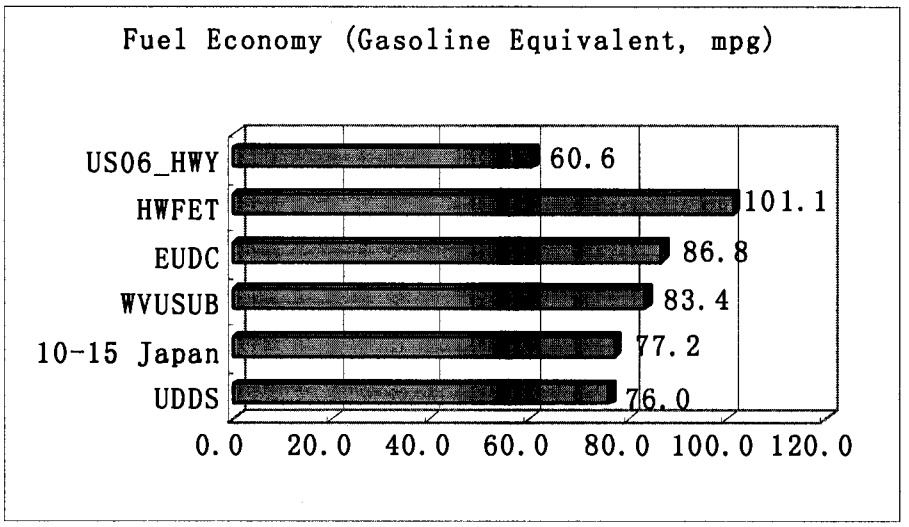
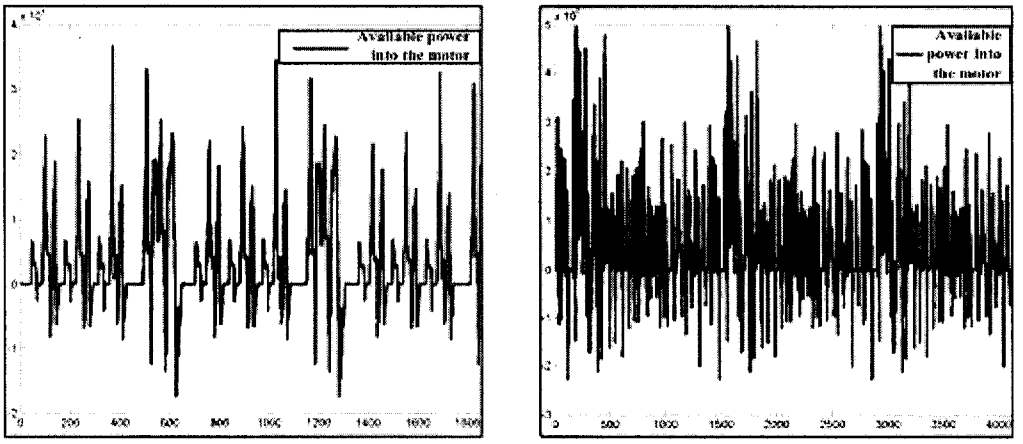


Fig. 4-4 Fuel economy over different driving schedules



10-15 Japan driving schedule **UDDS**

Fig. 4-5 Comparison of available power into the motor under UDDS and 10-15 driving patterns

According to the simulation results, it is easy to see that the parallel drive train system is more suitable for highway driving. Both the fuel economies as well as the overall drive train efficiencies, under highway driving, are comparatively higher than in case of city driving patterns. This is mainly because the ICE nearly reaches its maximum

efficiency (around 40%). When the vehicle is running on the highway, the smooth driving patterns allow either the ICE or the electric motor to operate at its respective optimal operating point. Although the recovered energy from regenerative braking is much less compared to city drive cycles, as a low-efficiency power component, the ICE running at its most efficient operating points is a significant factor in improving the drive train efficiency.

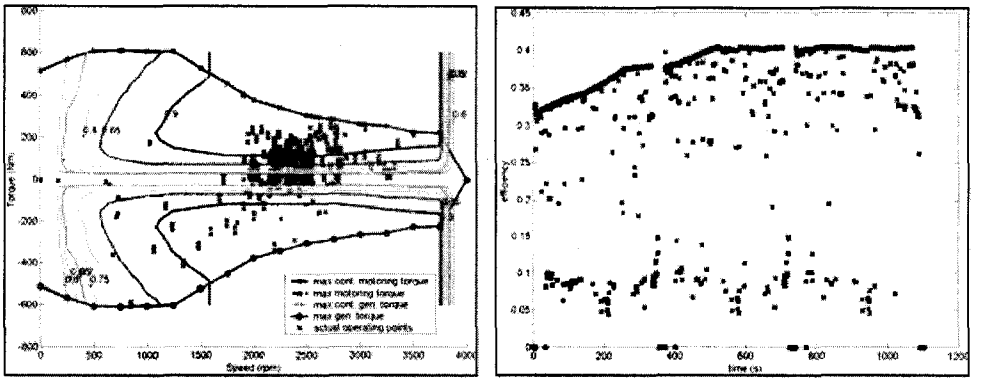
4.4 Operating Characteristics of the Motor/Inverter System

As a critical component of the HEV drive train system, the motor-inverter efficiencies were also thoroughly analyzed in this chapter. As mentioned earlier, in order to determine the efficiency of a motor drive, it is essential to understand how each loss component changes with vehicle speed (over the specific driving pattern). Fortunately, the major motor losses include core, copper, or mechanical losses, which are common in certain regions of the torque/speed curve and present efficiency maps that show this general trend [46].

In this section, the motor-inverter efficiency map, generated over the 6 driving patterns, are presented and contrasted. In addition, the efficiency behavioral trend of the ICE is compared with that of the motor-inverter, to form the basis for overall efficiency analysis. Figs. 7-12 depict the motor-inverter operating points and engine efficiency maps for US06_HWY, HWFET, EUDE, WVUSUB, 10-15 Japan, and UDDS, respectively.

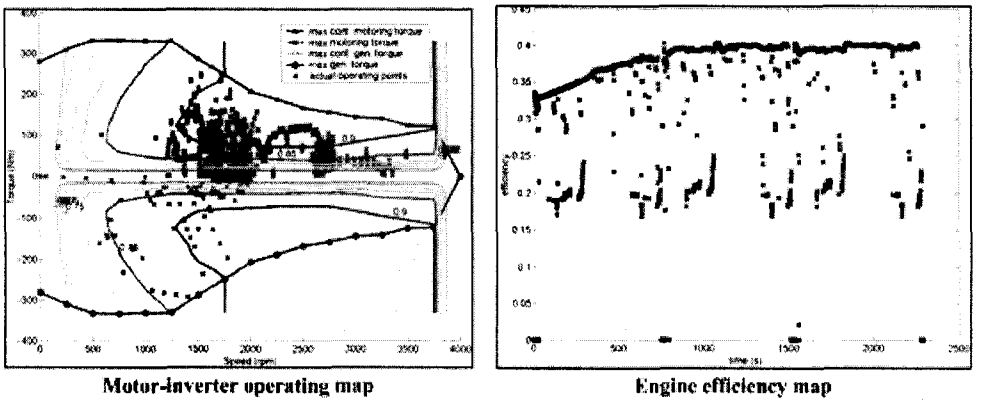
As is obvious from the first 3 sets (highway driving patterns, Fig. 4-6 to Fig. 4-8) of comparison of motor-inverter operating points and ICE efficiency maps, the motor-inverter operating points are more likely to be discovered within the high efficiency

(above 90%) region. Similarly, the ICE efficiency maps prove that the operating points are extensively found in the maximum efficiency region, which suggests that they operate close to their highest efficiency (around 40%) during high speed driving [19].



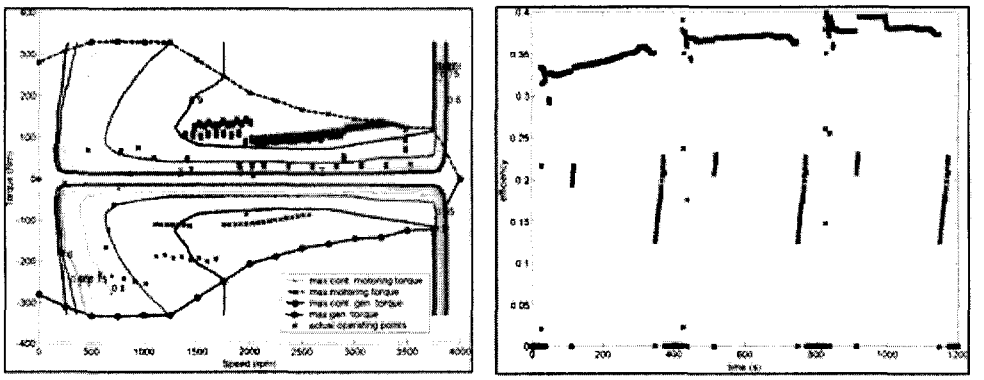
Motor-inverter operating map Engine efficiency map

Fig. 4-6 Traction motor-inverter operating points and ICE efficiency map for US06_HWY drive cycle



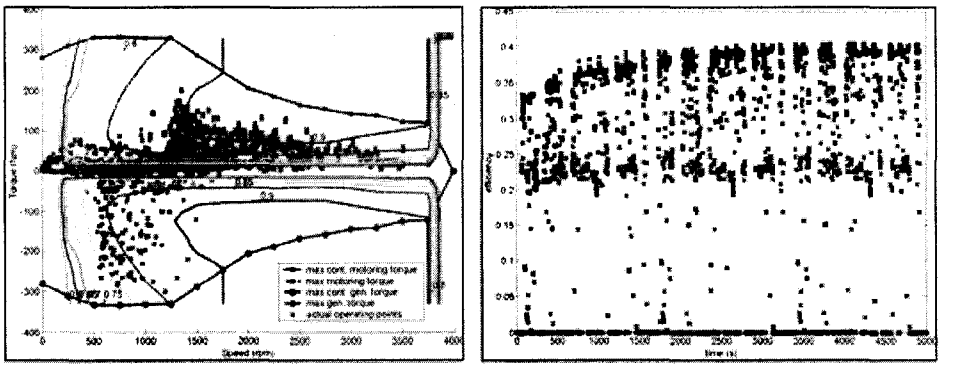
Motor-inverter operating map Engine efficiency map

Fig. 4-7 Traction motor-inverter operating points and ICE efficiency map for US06_HWY drive cycle



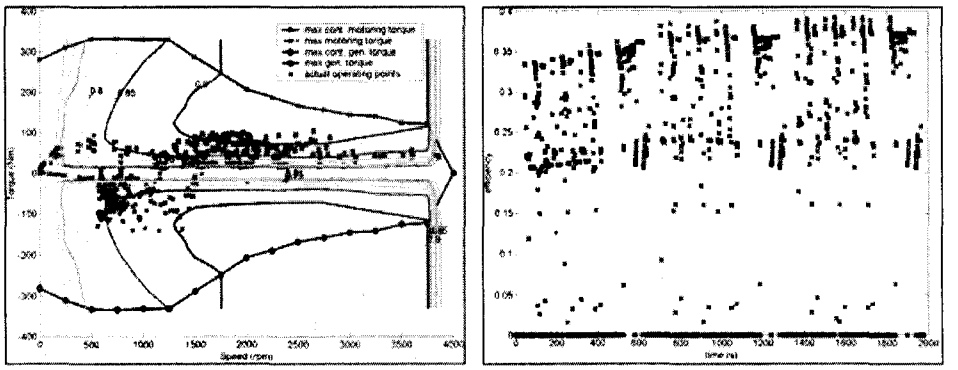
Motor-inverter operating map Engine efficiency map

Fig. 4-8 Traction motor-inverter operating points and ICE efficiency map for EUDC drive cycle



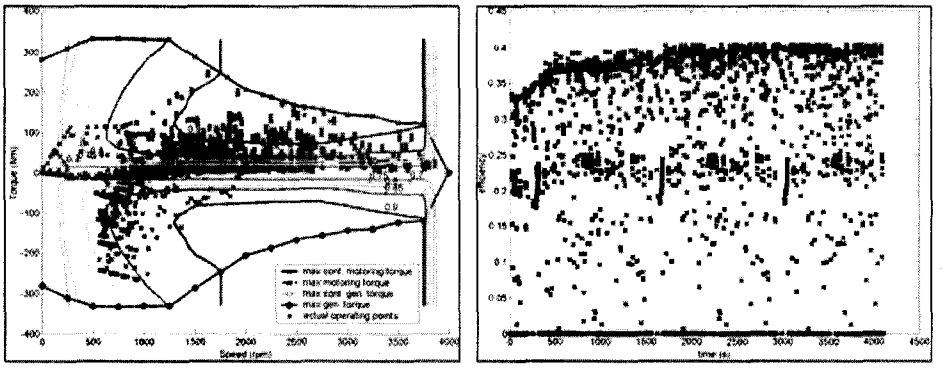
Motor-inverter operating map Engine efficiency map

Fig. 4-9 Traction motor-inverter operating points and ICE efficiency map for WVUSUB drive cycle



Motor-inverter operating map Engine efficiency map

Fig. 4-10 Traction motor-inverter operating points and ICE efficiency map for 10-15 drive cycle



Motor -inverter operating map Engine efficiency map

Fig. 4-11 Traction motor-inverter operating points and ICE efficiency map for UDDS drive cycle

The latter 3 sets of comparative figures (Fig. 4-9 to Fig. 4-11) show operating points of the electric motor and ICE efficiency maps running while operating under city driving patterns. Compared to highway driving patterns, the operating points of the motor drift away from the 90% efficiency region and the ICE efficiency points are scattered away from the maximum efficiency line. This is due to the fact that the stop-and-start nature of city driving requires the ICE to provide extra torque to help the vehicle with acceleration. At the same time, the traction motor operates at a lower efficiency due to the low-speed nature of the city drive cycle. In order to improve the efficiency of a parallel HEV in the city, advanced power electronic converter topologies and control techniques need to be employed, to reduce the losses during starts/stops and recover greater amount energy from regenerative braking. Moreover, combining the usage of a PM machine with cascaded inverter topology, the overall energy storage system losses can be reduced by almost 5%. The power density and low speed torque can also be increased [47]-[49].

4.5 OVERALL VEHICLE PERFORMANCE ANALYSIS

In order to present a complete analysis of the effects of varied driving patterns on the HEV efficiency, some additional tests were carried out to monitor GHG emissions, acceleration, and gradability performance. The GHG emissions (in grams/mile) over different load demands are summarized in Fig. 4-12. Generally speaking, the GHG emissions over city driving patterns are slightly higher than that under highway driving patterns, which can be predicted by analyzing the ICE operating points. Thus, the more inefficient use of the ICE, the greater are the GHG emissions. It is worthwhile pointing out here that the modeled hybrid SUV has the best efficiency and lowest GHG emission under HWFET driving conditions, proving that the electric traction system is proficiently used in this driving schedule [23]-[25].

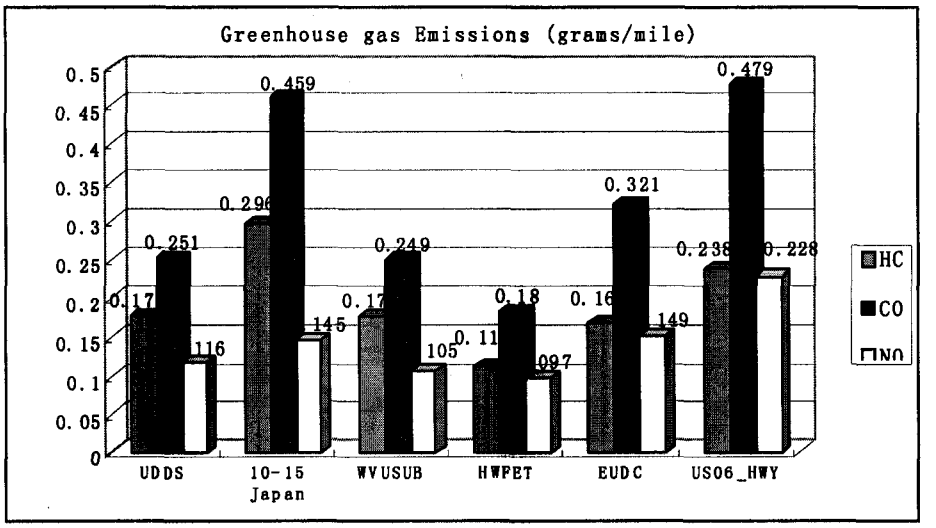


Fig. 4-12 Comparative GHG emissions for modeled parallel SUV

Since the size of the ICE of the modeled hybrid SUV has been optimized in the modeling section, it is important to take a look at the acceleration and gradability performance of the vehicle, which is summarized in Table 4-4.

Table 4-4 Summary of acceleration and gradability performance

	Acceleration performance (sec)			Gradability @ 55 mph
	0-30 mph	30-40 mph	0-60 mph	
Optimized SUV	6.2	4.4	25.4	5.20%
SUV modified for US06_HWY	3.6	2.2	13.1	9.90%

The modified SUV is designed for meeting the acceleration and maximum speed requirements of the high-speed US06_HWY driving pattern. Therefore, its acceleration and gradability is obviously superior to that of the optimized SUV. On the other hand, the price paid for greater vehicle performance is higher GHG emissions, as shown in Fig. 13, and relatively lower drive train efficiency and fuel economy, which were discussed in section 3 of this chapter.

4.6 CONCLUSIONS

The modified SUV is designed to meet the acceleration and maximum speed requirements of the high-speed US06_HWY driving pattern. Therefore, its acceleration and gradability is obviously superior to that of the optimized SUV. On the other hand, the price paid for greater vehicle performance is higher GHG emissions, as shown in Fig. 4-13, and relatively lower drive train efficiency and fuel economy, which were discussed in section 3 of this chapter.

This chapter thoroughly studied the effects of different load patterns on the HEV motor-inverter system efficiency and consequent effects on the overall drive train

efficiency and vehicle performance, more specific to a parallel hybrid SUV. Through the simulation results presented in this chapter, it is clear that the varied driving patterns have influential effects on the motor/inverter efficiency. An appropriate speed, modest acceleration/deceleration, and suitable number of starts and stops within a driving cycle are the major parameters that contribute to higher drive train efficiencies under city driving conditions. The overall HEV efficiency was further studied by analyzing the traction motor operating points and ICE efficiency maps. The inefficient use of the ICE is a major contributor to low overall drive train efficiency.

In addition, it is noteworthy that for a parallel HEV drive train configuration, the traction motor and the ICE losses are much higher in the city compared to those in the highway. Using advanced converter topologies, switching techniques, and/or advanced semiconductor materials will help reduce HEV traction inverter losses. With future development of energy storage devices inevitable, it would be possible to further optimize HEV hybridization levels, which in turn offers the flexibility to use more favorable HEV control strategies, in order to achieve higher motor/inverter efficiencies as well as electric drive train performance.

CHAPTER 5

MOTOR-CONTROLLER REGENERATIVE BRAKING EFFICIENCY ANALYSIS AND CONTROL STRATEGY OPTIMIZATION

5.1 INTRODUCTION

A well designed control strategy enables better usage of the fuel converter and traction motor, as well as helps increase efficiency of the storage system. Some important control strategy parameters are elaborated in this chapter for particular driving patterns, in order to achieve overall drive train efficiency improvement. The optimal control strategy design also aims at making most favorable use of regenerative braking. Consequently, the parameter regenerative braking efficiency is introduced in this chapter.

Recently, the auto industry is experiencing a major increment in light-duty vehicle sales, such as passenger cars and SUVs. For instance, SUVs have an approximate share of 26% (in 2006) in the North American light vehicle market [39]-[51]. Therefore, even a modest fuel economy improvement in each SUV will result in a nation-wide influence of energy saving and emission reduction.

Since HEVs run under varied driving patterns, a universal control strategy (CS) for HEVs running at optimum efficiency cannot be possible using currently available technologies. An optimized control strategy for a particular driving pattern, however, is feasible because the majority of SUVs are found to be used for personal transportation, typically driven in the urban area or on the highway. Thus, certain predictable driving

patterns from commuters' regular routes are employed to optimize the control strategies [51]. In this chapter, 2 control strategies, parallel electric assist control strategy and generalized fuzzy logic control strategy, for parallel HEVs, are optimized, to improve the motor-controller efficiency, more specifically to improve regenerative braking efficiency. In order to lucidly observe the improvement in regenerative braking efficiency, simulation is conducted under the UDDS cycle, which has numerous stops and starts.

The parallel HEV drive train structure is proposed for simulation purpose, since it is a combination of electric traction and combustion traction, which offers freedom to choose the appropriate combination of propulsion system. For this reason, some parameters are allowed to be optimized and be fully realized compared to the series HEV structure. In other words, a parallel HEV offers more freedom and measures for optimizing the control strategies than the series HEV. The selection of parallel electric assist control strategy and generalized fuzzy logic control strategy for parallel HEVs gives the simulation solid theoretical support, since these 2 control strategies aim at making full use of different drive train components. Thus, more convincing simulation results can be presented.

5.2 VEHICLE MODELING AND CONTROL STRATEGY DESIGN

5.2.1 VEHICLE MODELING

A selected vehicle, which must represent current market needs and future market trends, is modeled in this section. According to the market survey, SUVs have the greatest share and sale increment amongst all land vehicles [52]. Fig. 5-1 illustrates a typical parallel drive train configuration of the modeled SUV. Some important physical

parameters of the vehicle chassis are summarized in Table 3-1. As aforementioned, since the parallel structure offers great freedom to choose the appropriate combination of traction sources, hybridization factor (HF) becomes a critical contributor to the overall drive train efficiency. HF is defined differently for parallel and series HEVs. In this case, the definition of HF for a parallel HEV is the ratio of total electric power (motor) to the total propulsion power (ICE + motor). On the other hand, for series HEVs, HF is defined as the ratio of the difference between the power of electric motor and the power of the ICE to the power of the electric motor.

Once the vehicle chassis design is determined, the electric drive train can be modeled. The modeled drive train components were optimized by using the Matlab-based auto-size routine, which employs a bisection method to optimize the component size based on the required vehicle performance. The full details of the method are described in Chapter 4. By using this routine, FC size is eventually fixed by HF. A 40% HF is chosen to calculate the ICE size, signifying a full-hybrid structure. For modeling purposes, the value of HF is revised to 42%, in order to obtain integer values of the ICE size. The optimized drive train components are listed in Table 5-1.

Table 5-1 Summary of drive train components

Parameters	Value
Fuel Converter	
Max. Power	140kw @ 4000rpm
Max. Torque	334Nm @ 4000rpm
Fuel Converter Mass	70 kg
Transimission (5-speed manul)	
Gear Number	5
Gear Ratio	13.45, 7.57, 5.01, 3.77, 2.84
Wheel/Axle	

Wheel Radius	0.343 m
Battery (Nicle-Metal Hydride)	
Single Voltage	12 V
Number of Modules	25 modules
Nominal Capacitor	60 Ah
Peak Power (10s pulse @ 50%DOD @ 35 deg. C)	4.9 kW
Mass	290 kg
Motor-Controller (PM)	
Continuous Power	105 kW
Peak Torque	370 Nm
Motor-Controller Mass	58 kg
Maximum Speed	4000 rpm

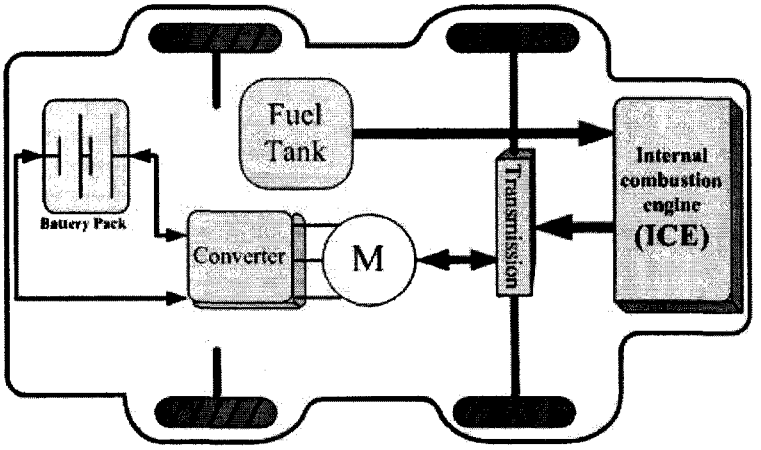


Fig. 5-1 Block diagram of modeled parallel mid-sized SUV drive train

5.2.2 CONTROL STRATEGY DESIGN

The modeled control strategy in ADVISOR is divided into various parts and scattered in different drive train modules, since the vehicle modeling process is power consumption-based and each module stands for a power consumption stage. The modules that contain part of the control strategy are highlighted in Fig. 5-2. The calculation flow within the block diagram starts from left to right.

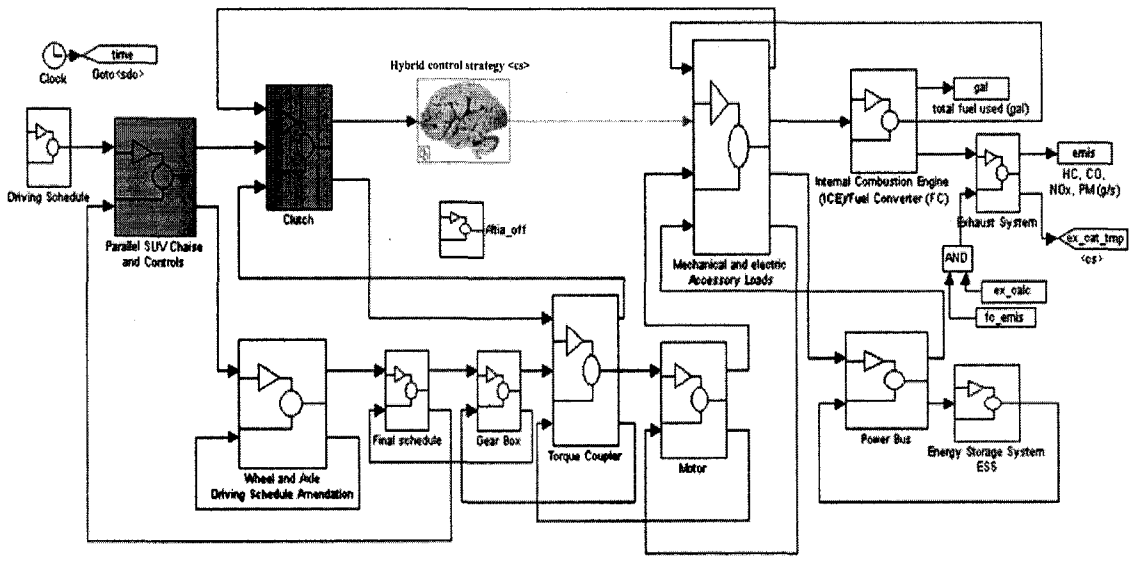


Fig. 5-2 SIMULINK diagram of modeled SUV

In order to formulate a fair comparison, the 2 most popular parallel HEV control strategies are selected for the purpose of optimization and simulation, namely, the parallel electric assist and fuzzy logic control strategy. The major difference between the 2 control strategies is the hybrid control strategy module. Thus, the optimization mainly concentrates on this module.

5.3 CHARACTERIZATION OF OPTIMIZED PARALLEL HEV CONTROL STRATEGIES

Since a universally optimized control strategy is practically impossible to construct, different control strategies only achieve certain goals by sacrificing certain features. Considering the selected 2 control strategies as examples, the parallel electric assist control strategy focuses on the most appropriate use of the electric motor during driving cycles, whereas the fuzzy logic control strategy aims at optimizing the ICE efficiency under efficiency mode of operation. In this chapter, the optimization rationale will focus on the improvement of overall drive train efficiency as well as regenerative

braking efficiency. The characterization of different objectives of the selected 2 control strategies is described in the ensuing paragraphs.

The parallel electric assist control strategy generally aims at using the electric motor for additional power when needed by the vehicle and sustaining the charge of batteries. For example, the electric motor is used when driving torque is below the set value, or it is used to help shift engine operation points to more efficient regions. In this chapter, however, this control strategy is optimized to achieve higher motor-controller efficiency by enhancing regenerative braking efficiency. At the same time, the control strategy also ensures improvement in overall drive train efficiency by appropriately setting the electric motor as torque assist and disengaging the ICE when it operates inefficiently [53], [54]. The efficiency improvement is enhanced by optimizing the hybrid control strategy block and redesigning the braking strategy look-up table within the braking control logic module, for the specific SUV, as shown in Fig. 5-3.

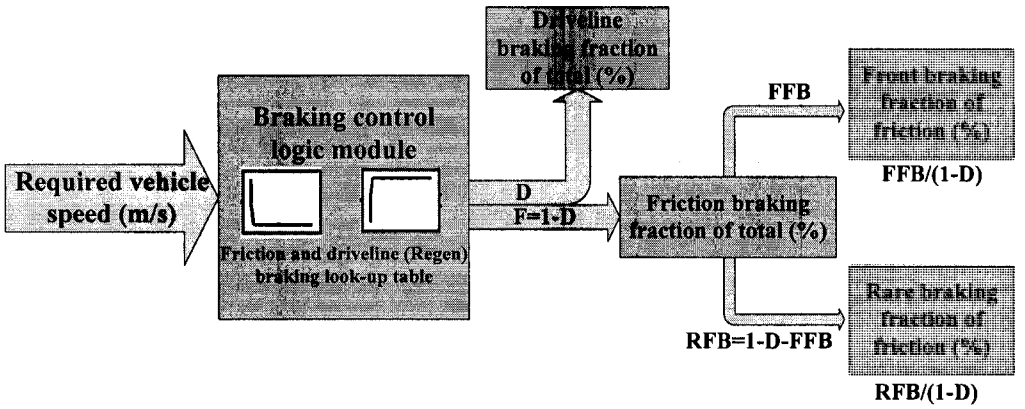


Fig. 5-3 Diagram of braking control logic

Two fuzzy logic control strategies are designed in ADVISOR. The fuel use mode is designed based on a particular value that limits the fuel usage by the ICE; the value can be deliberated from the ICE fuel use map. Another fuzzy logic control strategy is called

efficiency mode, which is built based on the average efficiency of the ICE. Since this chapter focuses on the motor-controller efficiency, hence, for data acquisition purposes, the efficiency mode is preferred. The efficiency mode runs the ICE about its peak efficiency at a particular speed. Therefore, the electric motor is sometimes used as a generator, when the ICE torque surpasses the required driving torque. This helps recover the exceeding torque to electric energy through regenerative braking, which in turn maintains the battery SOC. Thus, regenerative braking functions are more frequently used in the efficiency mode than in fuel mode. Hereafter, the efficiency mode is referred as the fuzzy efficiency control strategy in this chapter. The fuzzy efficiency control strategy for parallel HEV originally aims at setting the internal combustion engine (ICE) operation points in its most efficient region. It is obvious that the overall efficiency can be tremendously enhanced if motor-controller efficiency can be improved at the same time. Fortunately, this viewpoint is consistent with the initial purpose of parallel fuzzy logic control strategy [55]-[57].

As mentioned in the above analysis, since regenerative braking plays an important role in the process of optimization, regenerative braking efficiency is introduced, in order to assess the performance of the drive train system in using the available mechanical traction energy to produce electric energy. Most of the previous work that has been done in this area barely considers regenerative braking efficiency as a key element in the drive train efficiency analysis. Therefore, lack of notion regarding regenerative braking efficiency is perceptible when conducting research in this area.

Regenerative braking efficiency can be defined as the ratio of regenerative braking energy recovered to the total energy used for braking, as shown in Equation 5-1.

In order to compute the regenerative braking efficiency, however, one should characterize the total energy used for braking events first, which is the negative traction energy, as defined in Equation 5-2. Secondly, the energy recovery over regenerative braking events can be computed by retrieving the regenerated current, multiplied by the bus voltage (V_{bus}) and time Δt, which is described in equation 5-3.

$$\eta_{REGEN} = \frac{E_{regen}}{E_{neg.trac}} \bullet 100\% \tag{5-1}$$

$$E_{neg.trac} = \sum_{i=1}^{n} (|P_i| \bullet \Delta t), P_i \prec 0 \tag{5-2}$$

$$E_{regem} = \{I_{regen} \bullet V_{bus}\}\Delta t = \{(I_{battery.regen} + I_{acces}) \bullet V_{bus}\}\Delta t \tag{5-3}$$

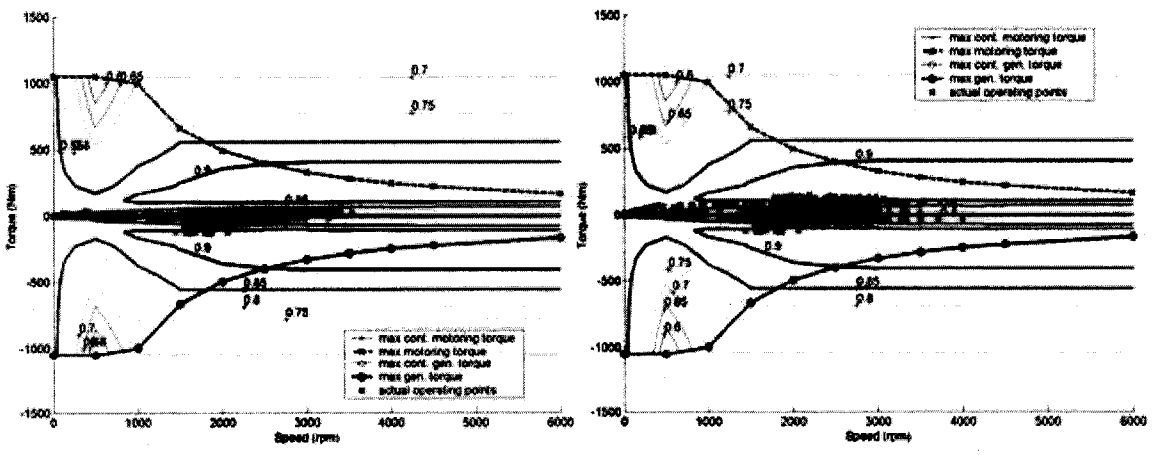
Here, η_{REGEN} is the regenerative braking efficiency, $E_{neg.trac}$ is the negative traction energy, E_{regem} is the regenerative braking energy recovery, $I_{battery.regen}$ is the electric current flowing to the battery pack due to regenerative braking, and I_{acces} is the electric current used by vehicle accessory loads.

5.4 COMPARATIVE MOTOR-CONTROLLER EFFICIENCY RESULTS

As analyzed in Section III, the effectiveness of regenerative braking relies on the driving conditions and driver behavior. As one of the most typical driving conditions, the UDDS cycle is selected for better understanding of regenerative braking efficiency, due to its large number of starts and stops. Thus, regenerative braking can be easily realized during the stops. The optimized control strategies guarantee regenerative braking energy recovery, no matter what the driver behavior is. The simulation tests are conducted over 5

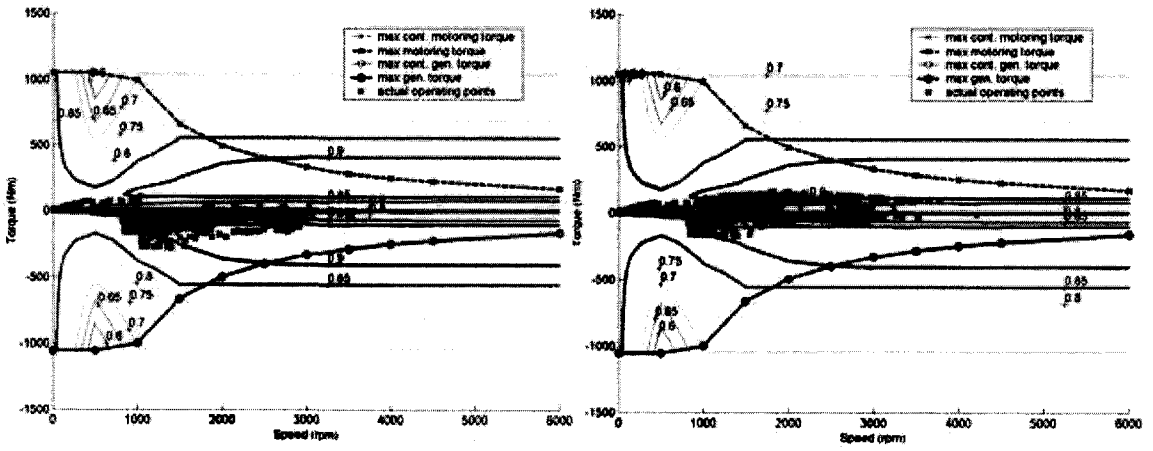
cycles, in order to ensure that the SUV has been driven long enough, so that its operation will cover both high and low SOC modes. This will provide a fair test of the optimized control strategy.

Four sets of simulations are conducted under UDDS. Both original and optimized control strategies are simulated. They are divided into 2 groups. One group is used for parallel electric assist control strategy test, while the other is used for fuzzy logic control strategy test. Figs. 5-4 and 5-5 show the comparative results of the motor-controller operating points over the 2 selected control strategies. It is clear that the motor operating points in powering mode have been noticeably shifted to the extended speed region when the optimized control strategies are employed. These encouraging phenomena posses the undoubted evidence of higher motor-controller efficiency, which is favorable. Nevertheless, when the motor works as a generator, 2 cases come to slightly different results. For the electric assist control strategy, the generator operating points are clearly shifted towards the extended speed region; but are not clear for fuzzy efficiency mode, a conjectured explanation of which is presented in the ensuing paragraph.



(a) Before optimization (b) After optimization

Fig. 5-4 Electric assist control strategy based motor-controller operating maps



(a) Before optimization (b) After Optimization

Fig. 5-5 Efficiency mode fuzzy logic control strategy based motor-controller operating maps

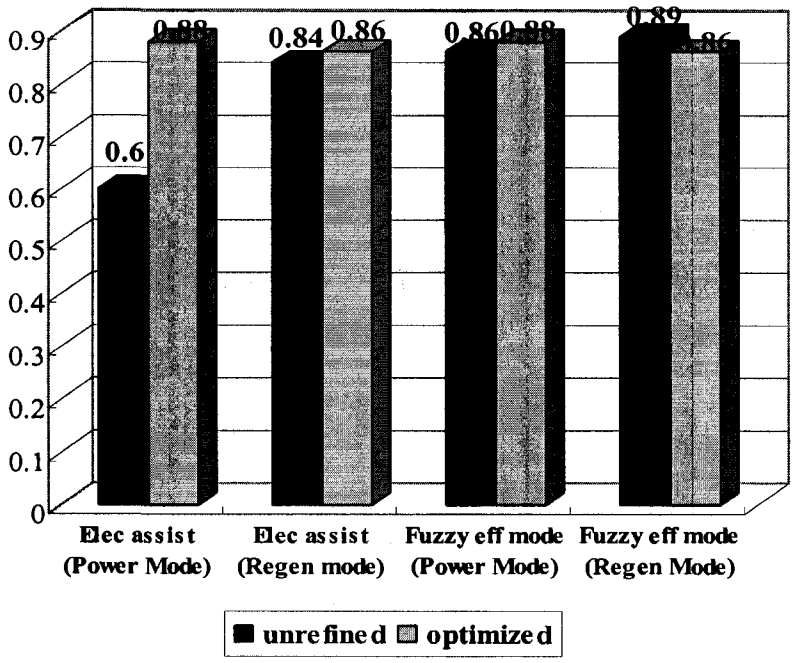
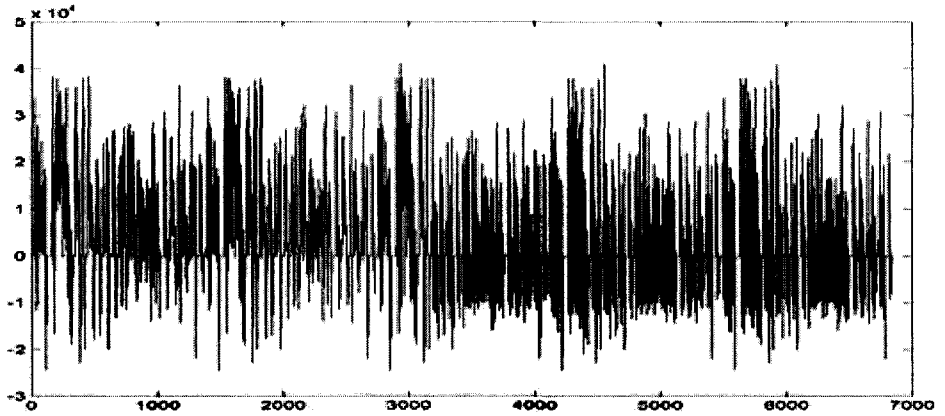
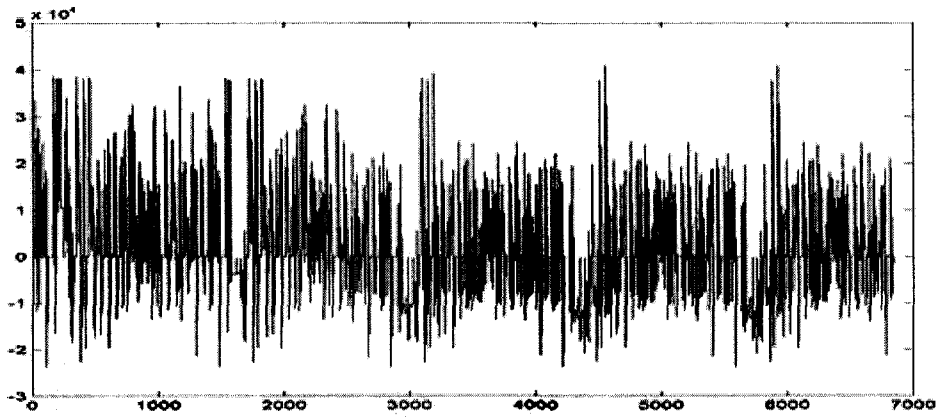


Fig. 5-6 Comparative motor-controller efficiency improvement



a. Electric assist control strategy



b. Fuzzy efficiency mode control strategy

Fig. 5-7 Motor-controller input power over optimized control strategies (Watts)

Fig. 5-6 presents a brief summary to visualize the motor-controller efficiency improvement. In powering mode, both optimized control strategies have significant improvement compared to the unrefined ones, especially, for the electric assist strategy. An interesting fact from Fig. 5-6 that needs to be clarified is the slight generator efficiency decrease, while using optimized fuzzy efficiency mode. This characteristic can be attributed to the principal rationale of fuzzy efficiency control strategy, which is essentially to improve the overall drive train efficiency by enhancing motor-controller efficiency. Thus, when improving the motor-controller efficiency, motor operating criteria were set to run the HEV as a zero emission vehicle, when the speed is below 50 mph and the battery is at high SOC. This means that the vehicle runs in all-electric mode

and the engine is shut down. As a result, the vehicle loses some regenerative braking energy taking place at speeds higher than 50 mph, but achieves higher motor-controller efficiency in return. The lost regenerative braking energy occurs in a high regenerative braking efficiency region, because reasonable deceleration can only be found above 50 mph. As shown in Fig. 5-7, the comparatively higher motor-controller efficiency, experienced when using the electric assist control strategy, can also be proved by plotting the motor-controller input power. Thus, irrespective of operating in either the powering mode or the regenerative mode, the electric motor is used more efficiently when using the electric assist control strategy compared to the fuzzy efficiency mode. Although the motor-controller efficiency when using the fuzzy efficiency control strategy decreases in the generation mode, a noticeable trait from the tests is that the overall drive train efficiency drastically improves, which will be explained in the next 2 sections.

5.5 REGENERATIVE BRAKING EFFICIENCY ANALYSIS

According to the definition of regenerative braking efficiency in the previous section, the regenerative braking efficiency for each control strategy is calculated by retrieving the current that flows into motor for regenerative braking and the energy used by accessory loads, during regenerative braking events. The results are calculated based on equation (5-1) and summarized in Fig. 5-8.

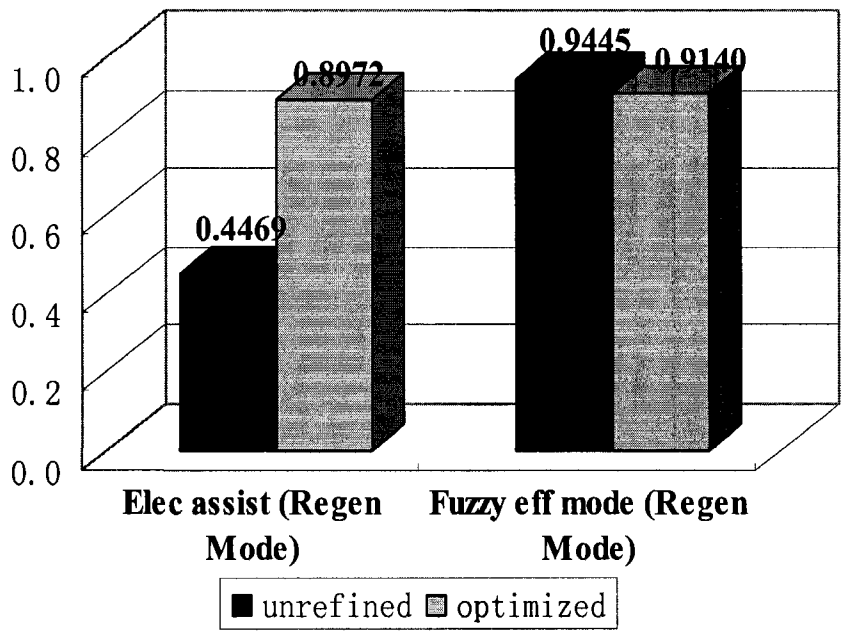


Fig. 5-8 Comparative electric drive train regenerative braking efficiencies

The considerable improvement of regenerative braking efficiency in electric assist mode indicates the flexibility of this control strategy, as it is originally designed to use electric traction, when needed. Therefore, increase of the possibility of using electric traction is allowed. As shown in Fig. 5-3, the modification of regenerative braking control look-up table increases the percentage of regenerative braking usage. A cumulative amount of 20% increment was observed compared to the original case. For the fuzzy efficiency control strategy, due to the preset ZEV condition, the regenerative braking efficiency does not increase. The compromise between regenerative braking efficiency and motor-controller efficiency is made by sacrificing regenerative braking efficiency. This is done principally because in the fuzzy efficiency mode, the motor-controller efficiency has greater priority compared to regenerative braking efficiency, as explained in the previous section.

Moreover, it is clear that the fuzzy efficiency mode is better at using electric traction and regenerative braking than the electric assist control strategy. In addition, high regenerative efficiency does not necessarily mean desirable overall drive train efficiency.

5.6 OVERALL ELECTRIC DRIVE TRAIN EFFICIENCY ANALYSIS

The ultimate purpose of control strategy optimization is to improve the overall drive train efficiency by enhancing motor-controller efficiency. Also, as a key contributor to the overall drive train efficiency, regenerative braking efficiency is also appropriately optimized. Fig. 5-9 shows the comparative overall electric drive train efficiencies over the 4 different control strategies. As is evident, the improvement is approximately 2 times greater than the untreated strategies, which justifies the suitable arrangement and correct proportion of efficiency improvement between the motor-controller efficiency and regenerative braking efficiency.

In general, the fuel economy is proportional to the overall drive train efficiency. However, it is important to note that the rates of increase of fuel economy for the 2 proposed control strategies are slightly different. Consequently, it is easy to see from Fig. 5-10 that the fuel economy increasing rate, when using electric assist control strategy, is larger than that when using the fuzzy efficiency mode. By retrieving the simulation data from the fuel converter and motor-controller, it is straightforward to explain the above-mentioned ambiguity. Since the driving patterns for the 2 control strategies are same, the energy used during the simulated 5 driving cycles is equal as well. However, the employment of electric traction and the effectiveness of regenerative braking are different from each other. Based on the previous analyses, the regenerative braking efficiency, when using the optimized electric assist control strategy, is found to be much higher than

when using the fuzzy efficiency mode. Nearly 6-7% of total fuel consumption is saved due to regenerative braking in the case of electric assist control strategy compared to when using fuzzy efficiency mode.

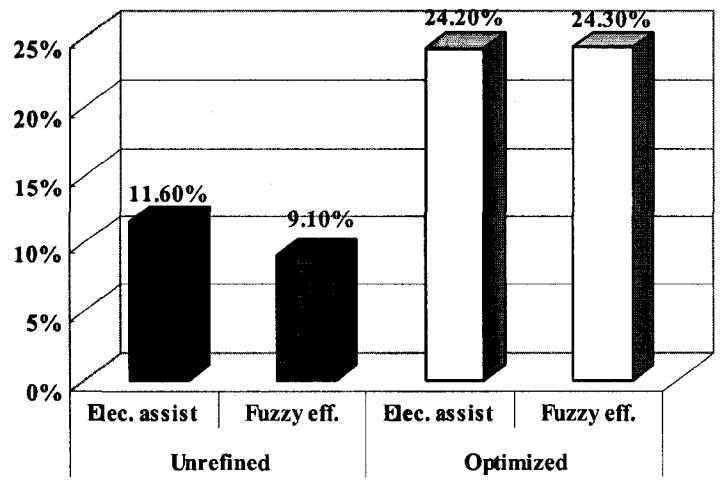


Fig. 5-9 Comparative overall electric drive train efficiencies

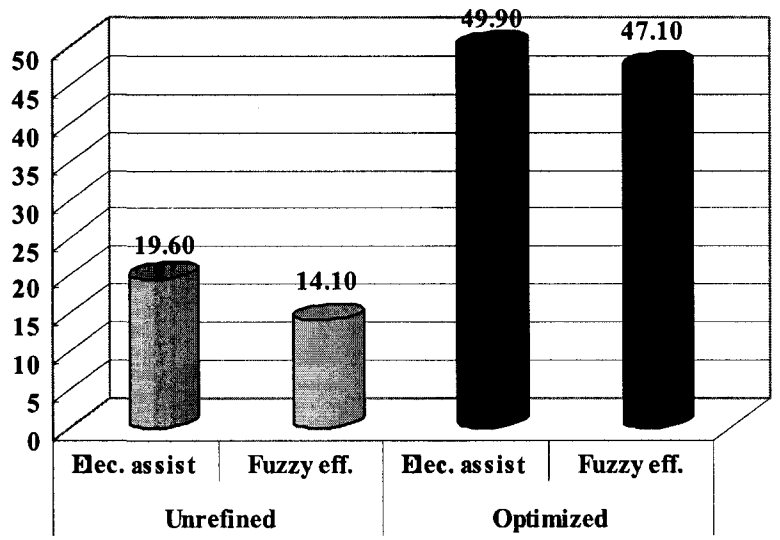


Fig. 5-10 Comparative fuel economies over 4 proposed control strategeis

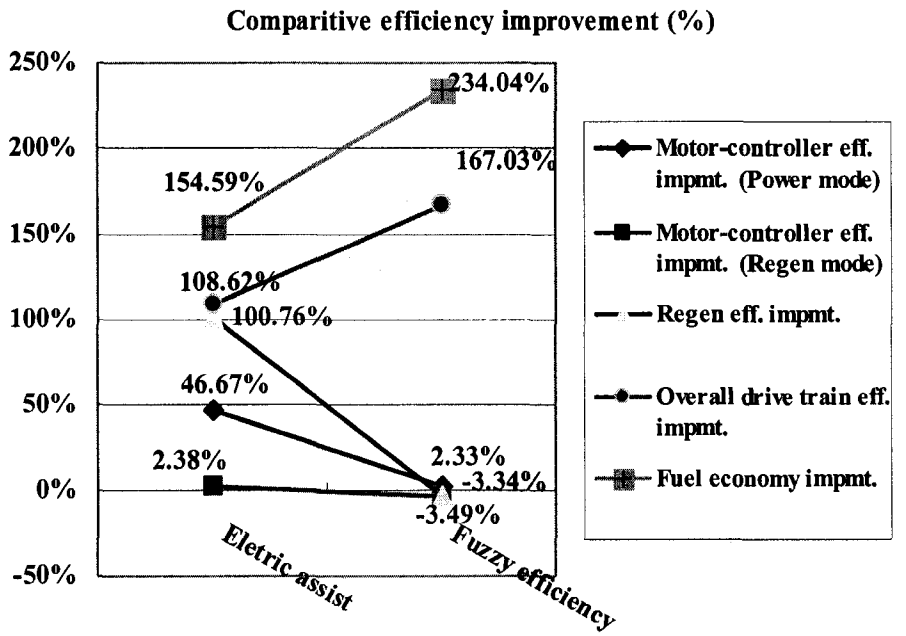


Fig. 5-11 Comparative efficiency improvment

Fig. 5-11 summarizes the efficiency improvement in terms of motor-controller efficiency, in both powering mode as well as regenerative braking mode. Fig. 5-11 also depicts the respective regenerative braking efficiency, overall drive train efficiency, and fuel economy improvements. There are only 2 negative increments, motor-controller efficiency in regenerative mode and the regenerative braking efficiency in fuzzy efficiency mode, which are mainly restricted by the ZEV setting in powering mode, as explained in the previous section. Nevertheless, the increment of overall drive train efficiency and fuel economy, respectively, is more than 100% higher, which justifies that the decrease is correct and proves to be a necessary trade-off.

5.7 CONCLUSION

Based on the comprehensive efficiency analysis and comparison, this chapter provides a strong reference for optimization studies of control strategies, in order to specifically improve motor-controller efficiency. From the simulation results, it can be

suggested that an appropriate speed and modest acceleration as well as deceleration are the major parameters that contribute to higher drive train efficiencies in city driving conditions [58]. Also, as was observed through the results, the electric assist control strategy and fuzzy efficiency mode based optimization require a favorable ratio between the motor-controller efficiency (in powering mode) and the regenerative braking efficiency, which in turn, limits the maximum optimization. Hence, the analyzed control strategies in this chapter may not be the best and most suitable control strategies.

In addition, the current available control strategies focus on either motor-controller and fuel converter efficiency (or vehicle performance, such as acceleration, gradeability, and emissions). Therefore, coming up with a novel control strategy that can make full use of regenerative braking as well as assure maximum overall drive train efficiency and fuel economy will be the focal point of future work. An important part of the future work also includes the validation of the proposed novel control strategy through real-time simulations and dynamometer tests.

CHAPTER 6
CONCLUSION

6.1 SUMMARY

This thesis analyzed the overall drive train efficiencies of popular series and parallel HEVs in detail. Not limited to the system level, the thesis also provided a novel method to calculate regenerative braking efficiency. Hence, this thesis offers the possibility to first analyze the motor-controller efficiency in detail, followed by providing the data to optimize the control strategy, which focuses on the improvement of motor-controller efficiency as well as regenerative braking efficiency.

The thesis also initially reviewed the techniques for improving overall HEV drive train efficiency. Furthermore, the thesis also pointed out the most sensitive parameters that affect HEV drive train efficiency. The second chapter introduced the power electronics as well as motor selection criteria, battery technologies, and control strategies, which are believed to be the key parameters that have great influence on overall drive train efficiency. The chapter also introduced new HEV drive train topologies, which are proposed as possible future research topics.

By analyzing the overall drive train efficiency of series and parallel HEVs, it is discovered that the parallel HEV, in general, depicts a higher efficiency than the series HEV. The higher efficiency is endowed to the fact that the parallel configuration possesses the flexibility to choose the most appropriate torque combination, in order to achieve the highest efficiency. However, selection of proper torque combinations is based on the optimized design of the hybridization factor. By avoiding the inefficient use of the

ICE, more electric energy is involved in vehicle propulsion, which eventually reflects an increased overall efficiency. On the other hand, being an electric-intensive structure, the series HEV presents the potential for future development of advanced electric vehicles. As long as there is enough on-board electric energy, by utilizing an appropriate control strategy, series HEVs can achieve higher efficiencies than those depicted by parallel HEVs. However, being electric-intensive, the major limitation of any series HEV based drive train is its battery life, the industry of which is struggling to find feasible solutions.

In addition, an integral part of the thesis focused on the efficiency of the heart of HEV; the motor-controller efficiency. Based on advanced efficiency map modeling techniques, the motor-controller efficiency is easily analyzed. Hence, through the analyses, 2 important parameters; regenerative braking and control strategy, are considered as the major contributors to motor-controller efficiency. Since the most efficient region of regenerative braking is directly related to the zero-emission boundary speed, efficient use of the motor-controller by some means restrains the regenerative braking efficiency. To solve this problem, 2 alternate measures can be proposed. Finding accurate upper and lower speed boundaries for zero-emission mode of operation will be the most direct way. However, to develop a control strategy that specifically improves regenerative braking efficiency, will be another solution. By integrating the 2 proposed methods, higher motor-controller efficiency can be achieved, which again in turn, will further improve the overall drive train efficiency.

Finally, the thesis also covered the all-important optimization of a novel control strategy. Based on the fuzzy control algorithm and electric assist control strategy, the newly optimized control strategy was modeled and tested exhaustively. The designed

control strategy was run through simulation tests, which were based on practical load demands, and the commercially available *Toyota Highlander* vehicle model. From the simulation results presented in the thesis, it is obvious to note that the motor-controller and regenerative braking efficiency improvement is up to 2.5% and 100%, respectively. More interestingly, in terms of fuel economy, the improvement is as high as 234.04%.

6.2 FUTURE WORK

Few developments that relate to proposed future work have also been performed during the Master's program. The research mainly concentrates on plug-in HEVs (PHEVs). Considered as a sophisticated form of HEVs, PHEVs are equipped with sufficient on-board electric power, to support daily driving (an average of 40 miles/day) in all-electric mode, only using the energy stored in batteries, without consuming a drop of fuel. Similar to the regular HEV, a PHEV can also be divided into the aforementioned 3 configurations. Although the series PHEV topology has been initially targeted as the prime choice for PHEV applications, it is unclear as to whether or not it is indeed the most efficient option [59]. Therefore, one of the future research focal points will target the efficiency and suitability assessment for different PHEV configurations.

PHEVs reduce fuel consumption by charging its batteries from the grid. If the generation, however, is thermal generation, charging from grid cannot essentially reduce the GHG emissions. Moreover, the overall fuel cycle (well-to-wheels) efficiency is considerably poor. In addition, the typical charging time would be between 7 to 8 hours, which might make it hard to accommodate additional loads in the system load curve, without increasing the peak load. Alternatively, smaller power plants, based on renewable energy such as solar or wind energy, can be installed in a fraction of that time on the

distribution system, which is commonly referred to as "distributed generation (DG)." Photovoltaic (PV) presents a modular characteristic and can be easily deployed on a roof-top or on facades of residences and buildings. Therefore, charging PHEVs through solar or wind energy will be an attractive solution. At the same time, PHEVs are able to work as uninterruptible power supplies (UPSs), during power outrages [60]. An initial cost effective investigation and comparative analyses between PHEVs and other alternately fuelled vehicles has been accomplished.

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