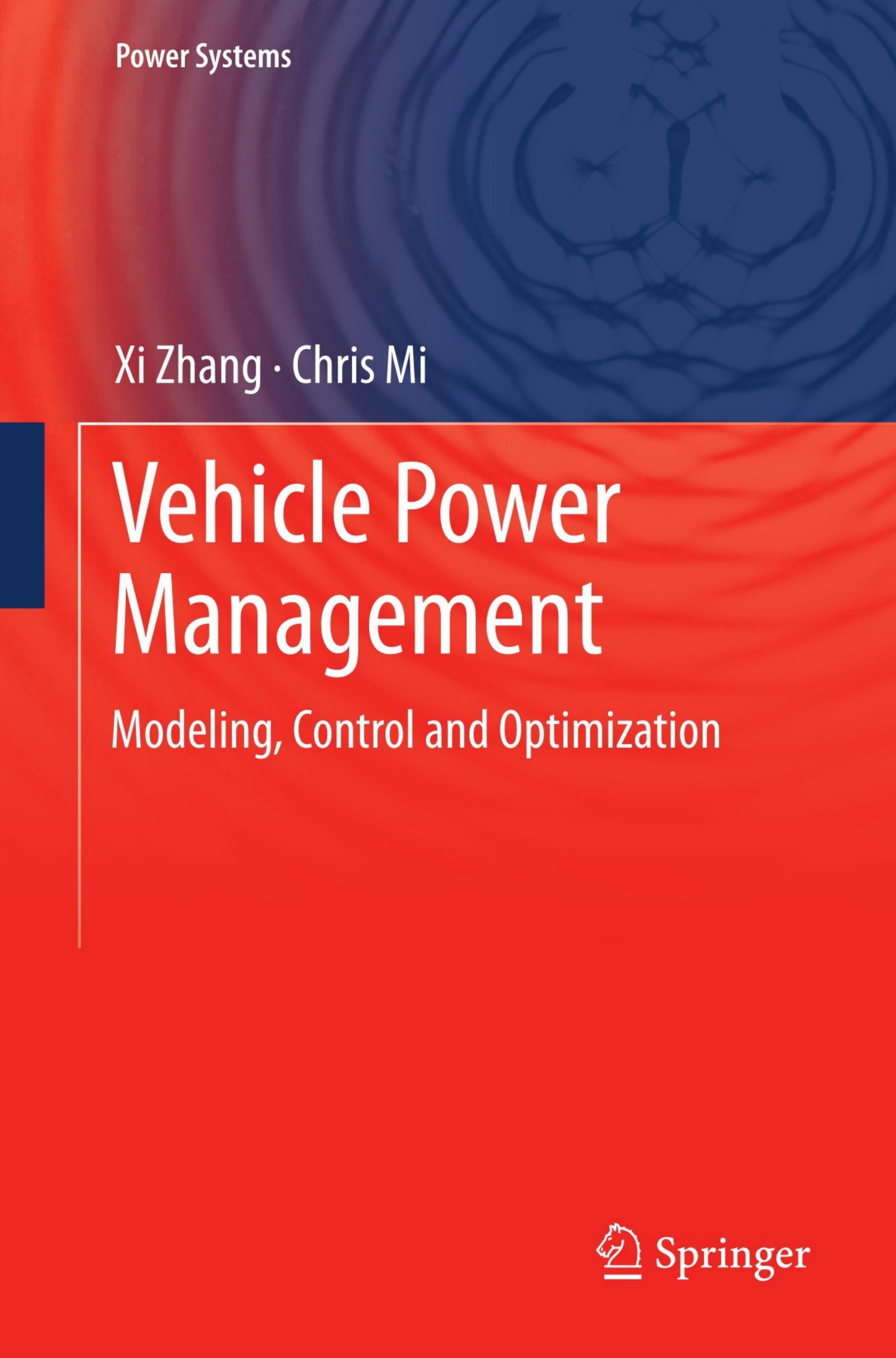

Power Systems

Xi Zhang · Chris Mi

Vehicle Power Management

Modeling, Control and Optimization

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Preface

The world faces two important challenges nowadays: increased energy demand and serious environmental concerns. Global climate change due to green house gas emissions has brought worries about sea-level increase and severe climate damages that are afflicting people. However, the fact is that the vexations are brought about by the human-beings ourselves. The blind deforestation, large-scaled urbanization, and exponentially expanded consumption of fossil-fuel are key contributors to these social and environmental problems. Fortunately, we are more and more aware of these challenges and in the process of developing effective measures to tackle and mitigate these problems. The Kyoto Protocol, Copenhagen Accord, and Cancun Agreements are good proofs.

Automobiles as a major contributor for air pollution and greenhouse gases emissions are under deep innovation and brand-new definitions. Meanwhile the global energy shortage also offers new demands on alternative fuel applications to the automobile industry. Under such a background, development of electric vehicles, hybrid electric vehicles, plugin hybrid electric vehicles, and fuel cell vehicles has been the hottest topic across the automobile industry. New energy sources and energy storage systems (ESS) such as lithium-ion batteries, hydrogen fuel cell and ultra-capacitors are introduced to the design and production of electric and hybrid electric vehicles. Besides, high-performance alternators, electric motors and mechanical transmissions are incorporated in various hybrid architectures (e.g. parallel, series, series-parallel, complex, etc.).

Historically, studies have been concentrated on modeling, control and optimization of vehicle powertrain structure and components with the aim of fuel economy improvement, pollutant emission reduction, lifetime extension of ESS, vehicle drivability and reliability enhancement for various types of electric and hybrid electric vehicles. In the past two decades, new ideas about vehicle power management have been emerging exponentially, including dynamic programming (DP), analytical approaches and intelligent system approaches. Additionally, satisfactory test results when applied to real vehicles are considerable.

Unfortunately, although reasonable amount of literature exists in the area of vehicle power management, there always exists a feeling that the research results are dispersive and not systematic. With such a consideration, the authors decide to write a book to systematically define, analyze and summarize the vehicle power management technology. Thus, this book is born.

The material of the book composition is mainly derived from many years of research experience of the authors and several colleagues and students. Some ideas from published references are introduced and quoted with their permissions. Three aspects for vehicle power management with modeling, control and optimization involved are focused on. Definitions, objectives, mathematical models, development tools, cases studies, and prospects related to vehicle power management are covered by the book. In addition, the system-level and component-level methodologies are both discussed. The book consists of 11 chapters, and reasonable configurations and stratified descriptions will bring in fresh and comprehensive understanding to the vehicle power management technology.

Similar to most publications, the book starts with an introduction in Chap. 1. An overview of application fields and necessity of vehicle power management is provided in this chapter.

Chapter 2 focuses on fundamentals and basic concepts of vehicle power management, including effects on vehicle performance, drive cycles and power demands, major applied software tools and so on.

In Chap. 3, uniform model representations for vehicular components (i.e., energy sources, ESS, electric machines and mechanical devices) existing in the vehicle powertrain are described in detail.

Chapters 4–7 describe the theoretical fundamentals and applications of state-of-the-art vehicle power management strategies. The analytical approach, dynamic and quadratic programming, and intelligent system approach employed for vehicle power management have already existed in various publications. However, the authors extend some new thoughts to their applications. These three strategies are introduced in Chaps. 4, 6 and 7, respectively. The wavelet-based power management approach for multiple on-board energy sources and ESS is depicted in Chap. 5. The theoretical system for applications of the wavelet technology on various types of vehicles is established, and the real-time analysis for employment in real vehicles is also given.

The battery is an essential factor for development of alternative fuel vehicles. At some point of view, the cost, volume, charging convenience and lifetime of the battery determines the marketization process of hybrid electric and all-electric vehicles. Consequently, the book specially gives one chapter's space to the management of energy storage systems with main focus on batteries. Chapter 8 focuses on the energy management strategies for the purpose of battery lifetime extension and precise estimation of the battery status for powertrain controls.

Type selection, configuration, and design optimization of powertrain components in the early development stage for hybrid vehicles will represent significant impacts to running vehicles on dynamic performance, fuel economy and emissions. Therefore, Chap. 9 discusses the component optimization issues for avoiding unnecessary losses on these aspects.

Hardware-in-the-loop (HIL) and software-in-the-loop (SIL) are delineated in Chap. 10 since they can substantially lower the cost and the time for delivery of a vehicular product to market.

Chapter 11 paints magnificent application prospects of vehicle power management for readers, and points out potential problems to be faced. Also, some advanced technologies of alternative fuel vehicles and accordingly powertrain components are introduced in this chapter.

The book can be used as a textbook to educate undergraduate and graduate students majoring in automotive engineering. Students majoring in mechanical engineering, electric engineering, and computer science and engineering may find this book useful when dealing with vehicle related design, optimization and control development. Besides, the book can be used as a reference for designers and engineers working in the automobile industry. Abundant case studies are beneficial for development of alternative fuel vehicular systems.

The authors wish to extend sincere thanks to several colleagues who made signification contributions for the successful publication of this book. In particular, Mr. Mengyang Zhang, a specialist in HEV, lent his idea to the authors to form the basis of Chap. 4, Analytical Approaches for Vehicle Power Management. Students in the research group of Professor Chris Mi provided the original material and helped draft the manuscript of a few chapters: Dr. Zheng Chen for Sects. 6.1 to 6.2, and Sect. 7.5, Zhiguang Zhou for Sect. 6.3 and Sect. 7.6, Bingzhang Zhang for Sects. 4.1 and 9.1, Yan Yang for Sect. 4.2, Dr. Wenzhong Gao for Sect. 9.2. Without their great efforts, the book would not have been possible.

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Contents

Chapter 1
Introduction

The objects under consideration in this book are automobile or motor cars, i.e., wheeled motor vehicles for transporting passengers or goods, which also carry their own engines or electric motors. Nowadays, most vehicles running on the road are propelled by spark-ignition (SI) or compression-ignition (CI) internal combustion engines (ICEs) that use gasoline or diesel as fuels.

Limited oil reserves, increased demand and costs for oil-based fuels, as well as air pollution and greenhouse emissions, are challenging the automobile industry. With fuel and emission reduction as the main objectives, alternative power systems for hybrid electric vehicles (HEV), electric vehicles (EV) and fuel cell vehicles are under development and production. Nevertheless, energy losses in vehicle operation and replacement of aged power sources, and pollutant emissions (in HEV) also exist in these new technologies. Regardless of the type of vehicles, it is essential to improve energy efficiency, reduce emission and extend lifetime of power sources without sacrificing vehicle performance, safety, and reliability.

First of all, to help readers comprehend the urgency of vehicle research for energy saving and emission reduction, we will start with the introduction to the above global problems which the automobile manufacturers are facing today.

1.1 Energy and Environmental Challenges

Gasoline and diesel used for vehicle propulsion are both refined from fossil oil. In 2008, the world oil reserves were 1.342 trillion barrels [1] and the daily consumption was about 85 million barrels [2]. Around 60% of the total oil consumption goes to transportation. Meanwhile, the world's population continues to grow at a quarter of a million per day [3], increasing the transportation demand and consequent oil consumption. The United States Energy Information Administration predicted that world daily oil consumption would increase to 98.3 million

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barrels in 2015 and 118 million barrels in 2030 [4]. By using the Hubbert peak theory [5–7], the oil depletion situation can be predicted based on prior discovery rates and anticipated production rates. The American Petroleum Institute estimated in 1999 that the world's oil supply would be depleted between 2062 and 2094 [8]. Oil depletion curves are depicted in Fig. 1.1. The oil shortage will result in severe social and economic problems such as transportation and food crisis.

ICE powered vehicles rely on gasoline and diesel combustion during operation. Pollutions are generated during the combustion process inside the ICE. In addition, unburned fuel evaporates which forms the basis for another type of pollution-volatile organic compounds (VOC).

The emissions from the combustion include carbon dioxide, VOC, nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO). These exhaust emissions occur during the following two modes [10, 11]:

- Cold Start—during cold weather, the catalyst which is used to control tailpipe emissions will not work until they have been warmed up to a certain temperature. Hence, starting and driving a vehicle in the first few minutes result in higher emissions.
- Running Exhaust Emissions—emissions are formed during normal operation of the vehicle-driving and idling.

Through the fuel evaporation, the VOC leaves for the ambient air, which occurs in four ways as follows:

- Running Losses—During vehicle running, the gasoline is vaporized in the hot engine and exhaust system.
- Hot Soak—The engine remains hot for a while after the vehicle is turned off, and gasoline evaporation continues when the car is parked while cooling down.
- Diurnal Emissions—Even when the vehicle is parked for long periods of time, gasoline evaporation occurs due to the high ambient temperature.
- Refueling—While the tank is being filled, gasoline vapors escape from the vehicle's fuel tank and the refueling tubes.

In the United States, vehicles contribute 25 and 33% of the total VOC and NO_X respectively which combine to form ground-level ozone. Additionally, the combined direct and indirect contribution of vehicles amounted to 49 and 55% of national PM_{10} and $PM_{2.5}$ (both belong to particulate matter) emissions, respectively [12]. Unfortunately, ozone and particulate matter are identified as contributors towards worsening the health of people with asthma and other related public health impacts, e.g. increases in medication use, doctor and emergency room (ER) visits, and hospital admissions. Moreover, the possible contribution of vehicle pollution to the development of asthma, frequent respiratory infections and potential long-term effects of retarded lung growth and reduced lung function in children (which can lead to chronic lung disease later in life) may even have greater long-term public health significance [13].

Besides, vehicles play a disgraceful role in global climate change. Burning of fossil fuels contributes to the increase of carbon dioxide (CO_2) in the atmosphere.

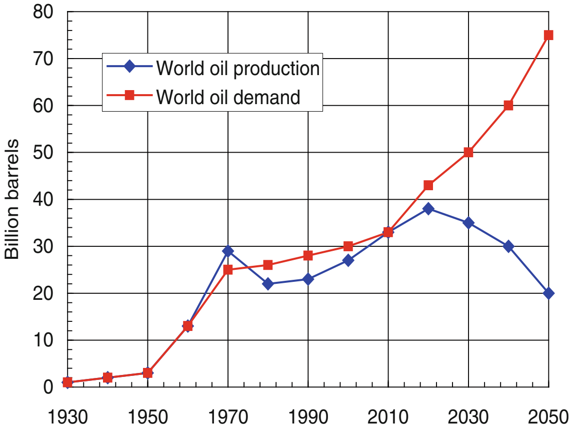

Fig. 1.1 World oil demand and production. *Source* [9]

This will result in increased thickness and density of the atmosphere due to the action of carbon dioxide and other greenhouse gases (i.e., water vapor, ozone and methane) in the atmosphere. The thicker and denser atmosphere will trap heat inside the atmosphere to form the basis of the greenhouse effect [14–16]. It may increase the global air temperature and introduce global climate change due to disturbance to the eco system. The Intergovernmental Panel on Climate Change (IPCC) concluded in 2007 [17] by stating that: "Most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." The consequences including the widespread melting of snow and ice and rising global average sea level will bring disasters to the earth particularly to the maritime countries. Other consequences include increase flood and drought and extreme weathers in certain parts of the world which can cause disasters to many areas.

The global fossil carbon emissions and global air temperature since the nineteenth century are shown in Figs. 1.2 and 1.3, respectively. It can be observed from Fig. 1.2 that petroleum contributes the most fossil carbon emissions while most of the petroleum consumption comes from automobiles. Through contrast between Figs. 1.2 and 1.3, we can see that there really exists a relation between carbon dioxide emission and air temperature increase, as approved by most ecologists.

1.2 Energy Conversion Chain for Vehicle Energy Consumption

No matter what power sources are applied for vehicle propulsion, there exist at least three energy conversion processes [20]. The energy conversion chain from the primary energy sources to the eventual thermal energy generated in the vehicle

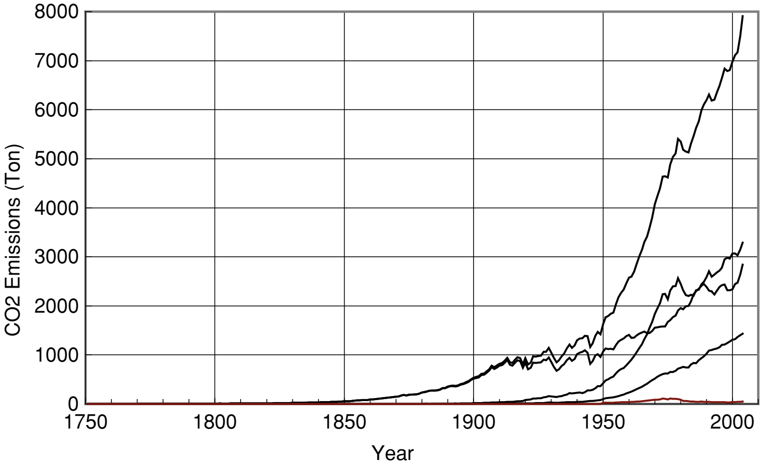

Fig. 1.2 Global fossil carbon emissions from 1800 to 2004 [16]. From top to bottom: total CO_2; CO_2 from oil; coal; cement production; other

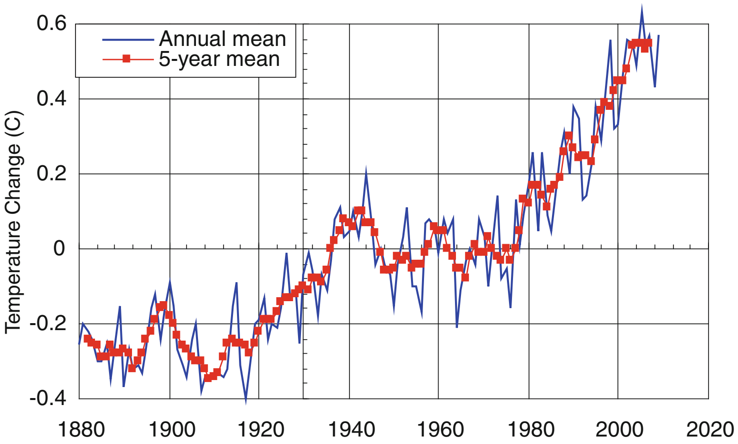

Fig. 1. 3 Global air temperature since the year of 1850. *Source* [19]. *Courtesy* NASA Goddard Institute for Space Studies

operation is illustrated in Fig. 1.4. In the first step, the primary energy sources (chemical energy in fossil hydrocarbons, solar energy for generation of bio mass or electric energy, nuclear energy, etc.) transit energy to onboard energy carriers (battery, gasoline, hydrogen, etc.) in vehicles. Then the vehicle propulsion system transfers the energy from these energy carriers to mechanical components as the form of kinetic or potential energy in vehicles. Eventually, the mechanical energy is dissipated to thermal energy which is deposited to the ambient.

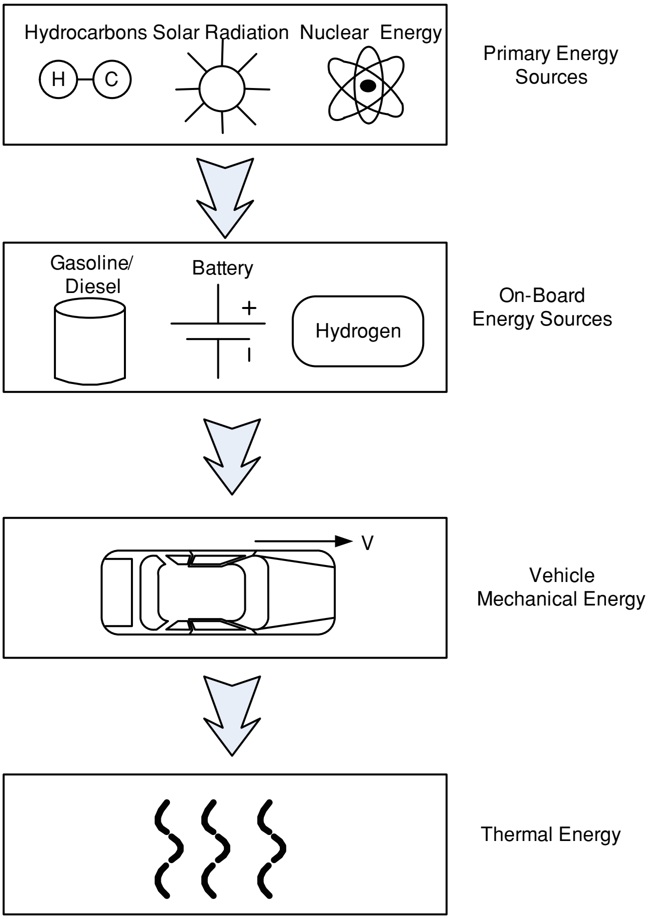

Fig. 1.4 Energy conversion steps for vehicle energy consumption

There exist energy losses in every junction of the energy conversion chain. Although the energy conversion efficiency and pollutant emissions in the first step have a great impact on the entire energy saving and environmental protection, large power plants, refineries, or other process engineering systems are beyond the scope of this book. The vehicle power management concept arises for the second energy conversion step (i.e., on-board energy carriers to vehicle mechanical energy) aimed at improving fuel economy, reducing pollutant emissions and maintaining power sources working properly, while the performance and safety are not impacted at all. For the ultimate step, energy conversion is natural and uncontrollable in a fixed driving profile, except that vehicle functional topology changes ahead of vehicle operation. In summary, the second energy conversion step, where vehicle power management strategies are embedded, acts as the main emphasis of this book.

1.3 Fuel Efficiency

Fuel efficiency of automobiles refers to the energy efficiency of a vehicle in terms of fuel consumption or fuel economy. In the United States, fuel economy is defined as the total distance travelled for a given amount of fuel, i.e., miles per gallon of fuel (MPG). In Asia and Europe, fuel consumption is defined as the amount of fuel required to move a vehicle over a given distance, whose unit is liters of fuel per 100 km (L/100 km), or (L/km). Since fuel consumption is reciprocal of fuel economy, to convert MPG to L/km or L/km to PMG, one first needs to convert them into the correct units and then take the reciprocal. From MPG to L/km:

$$xMPG = x\frac{1.608\,\text{km}}{3.785\,\text{L}} = \frac{x}{2.35}\ (\text{km/L}) \Longrightarrow \frac{2.35}{x}\ (\text{L/km})$$

From L/km to MPG:

$$yL/km = y\frac{0.2642\,\text{Gallon}}{0.6219\,\text{miles}} = \frac{y}{2.35}\ (GPM) \Longrightarrow \frac{2.35}{y}\ (\text{MPG})$$

Hence one can convert MPG to L/km by dividing 2.35 by the MPG numbers. Similarly one can covert L/km to MPG by dividing 2.35 by the L/km numbers. For example, to convert 33 MPG to L/km, one divides 2.35 by 33 to get 0.0712 L/km. To convert 7.5 L/100 km to MPG, one divides 235 by 7.5 to get 31.3 MPG.

Since different road conditions and driving patterns require different amount of fuel for a given distance, fuel economy or fuel consumption has to be evaluated upon different driving scenarios, also known as driving cycle tests, as further explained in Chap. 2.

Once fuel economy is evaluated on standard driving cycles, they can be combined to form a composite fuel economy. In the United States, the composite fuel economy is evaluated over 55% urban driving (FUDS) and 45% highway driving (FHDS) as the following:

$$\text{composite MPG} = \frac{1}{\frac{0.55}{(\text{MPG})_{\text{FUDS}}} + \frac{0.45}{(\text{MPG})_{\text{FHDS}}}}$$

In this book, we will use fuel economy to evaluate the overall fuel efficiency of vehicles. But we will also refer to fuel consumption as needed when we discuss fuel savings. This is due to the fact that fuel consumption is more appropriate when calculating fuel savings. For example, fuel economy improvement from 30 MPG (0.07833 L/km) to 60 PMG (0.03917 L/km) seem to have 100% improvement in fuel economy but in fact the fuel saving is

$$Fuel\ Savings = \frac{0.07833 - 0.03917}{0.07833} = 50\%$$

1.4 Main Objectives of This Book

Although vehicle power management is familiar to related researchers and designers, this book, addressed to readers at various levels, describes and analyzes the basic concepts with respect to different vehicle configurations. The factors influencing the fuel economy and emissions are also discussed.

Today's advanced vehicles contain a significant number of components which consume a substantial amount of power. For vehicle designers, it's impossible to deal with the optimization of the entire system using heuristic methods. The model-based method has been proved to be the most efficient way for the initial-phase of vehicle design [20] (e.g. determination of vehicle structure and verification of control strategies in simulation). Consequently, this book also introduces the modeling of various devices and components in a vehicle which are involved in the vehicle power management system.

Although reasonable amount of literature exists in the area of vehicle power management [21], there always exists a feeling that the research results are dispersive and not systematic. To the authors' best knowledge, there do not exist comprehensive references that systematically define, analyze, and summarize this topic, which can be meaningfully applied to vehicle applications. This book is intended to bridge this gap. Specific algorithms and strategies including analytical approaches, optimal control, intelligent system approaches, wavelet technology, and optimizations, are theoretically derived and analyzed in this book for realistic applications towards vehicle power management. Optimal control, in particular the dynamic programming (DP) and the intelligent schemes (e.g. fuzzy logic control, neural networks, etc.), are existing popular power management methodologies for the purpose so far, while the wavelet technology is introduced for the first time to vehicle power management.

Electrification of the automobile is the current focus to shift fossil fuel based transportation to alternative energy based transportation. The fuel cell and battery are commonly regarded as two major alternative power sources for vehicle propulsion [22–38]. Equipped with these alternative power sources, various types of vehicles with low or zero emissions, pure electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV), and fuel cell vehicles (FCV), have become research and development emphasis lately, which are within the scopes of this book. Despite of low or zero emissions, the problems of equivalent fuel economy improvement and power source lifetime extension in these alternative fuel vehicles or alternative drive train vehicles are still under consideration. So vehicle power management is beneficial and suitable for the above advanced vehicles.

In addition, the hardware-in-the-loop for vehicle power management research to emulate the realistic conditions is introduced with existing and potential real system designers in mind. Useful tools and devices, as well as some experimental results, can be found in this book to enlighten designers when establishing their own experimental platforms for vehicle power management research.

1.5 Issues in Research on Vehicle Power Management

Automotive industry is focusing on developing affordable vehicles with increased electrical/electronic components to satisfy consumers' needs on safety and comfort, while improving fuel economy and reducing emissions to comply with environmental regulations. With this in perspective, vehicle power management strategy that is employed to control power flow of power sources in vehicles was proposed during the last two decades to meet the above challenges [21].

Hybrid electric vehicles (HEV) are one of the leading technologies aimed towards sustainable mobility, and vehicle power management that is suitable for all types of vehicles has been more intensified by this emerging technology [21].

Mathematical models or human expertise are critical to the development of most of the power management approaches prior to real applications. Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A control problem includes a cost function that is a function of state and control variables. An optimal control is a set of differential equations describing the paths of the control variables that minimize the cost function [39–41]. The optimal control strategy has been the most popular vehicle power management approach since the fuel consumption or emissions or other indexes can be considered as a cost function. The optimal control, especially dynamic programming (DP), has been widely applied to a broad range of vehicle models [42–44]. When using optimal control in vehicle power management, researchers usually assumes that the entire driving cycle is available for analysis and algorithm development. This assumption can only provide off-line solution to the problem. Nevertheless, the off-line results provide a benchmark for performance of control strategies prior to real applications.

Recently, the intelligent system approaches including the artificial neural network (ANN), fuzzy logic, etc. have been introduced into vehicle power management [45–47]. The ANN, composed of artificial neurons or nodes, is a mathematical model or computational model. With the desire to incorporate the fuel consumption or emissions as design criteria, researchers used ANN models for prediction of vehicle behaviors [48]. The ANN models are trained using data from tests or simulations for different driving cycles.

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise [45, 49]. In fuzzy logic, the degree of truth of a statement ranges between 0 and 1. In fuzzy-logic-based vehicle power management strategy, fuzzy rules were developed by researchers for the fuzzy controller to effectively determine the power split between various power sources in vehicles. The fuzzy controllers can be built based on some variables such as the driver command, the SOC of the energy storage system (ESS), the alternator speed, etc. The purpose of obtaining fuzzy rules is to optimize the operational efficiency of different power sources in all types of vehicles.

The analytical approach tries to reduce a system to its elementary elements in order to study in detail and understand the types of interaction between them.

General laws can be inferred to predict the system properties under various conditions. Laws of the additivity of elementary properties have to be invoked to guarantee the possibility of this prediction [50]. The analytical approach can take on the responsibility of meeting the objective (i.e., fuel consumption minimization) of the plug-in hybrid electric vehicle (PHEV). The simplified or unified analytical power solution to this optimization problem can be derived on basis of a realistic vehicle model comprised of individual power source components. Usually different PHEV operation modes such as the pure electric mode and blended mode need to be involved in discussion.

Besides, wavelets are introduced in this book for vehicle power management system applications. Wavelet transforms can be considered as forms of time–frequency representation for continuous-time signals, and so are suitable for harmonic analysis [50–52]. High-frequency transients can be identified from the real time power demand of the drive line. With the help of wavelet transform, a proper power demand combination can be achieved for power sources in all types of vehicles. The wavelet-based power management strategy helps improve system efficiency and life expectancy of power sources, usually in the presence of various constraints due to drivability requirements and component characteristics.

Details of the above state-of-the-art technologies for vehicle power management will be described from their fundamentals to specific applications for various types of vehicles in the later chapters of this book.

1.6 Book Organization

The entire composition structure and relations among various chapters are shown in Fig. 1.5.

Chapter 2 introduces the basic concepts of vehicle power management such that readers can have a clear global idea of what vehicle power management is. Due to the importance of modeling to development of vehicle power management strategies during the initial phase, Chap. 3 establishes mathematical or electrical models for vehicle propulsion systems where the internal combustion engine (ICE), battery, ultracapacitor, fuel cell, etc. may exist with respect to various vehicle types. Multiple vehicle power management strategies are described and analyzed in Chaps. 4, 5, 6, 7, 8, 9. Chapter 4 is devoted to the analytical approaches for the power management of hybrid and plugin hybrid electric vehicles. Chapter 5 introduces wavelets to the vehicle power management system. Chapter 6 introduces dynamic programming and quadratic programming for the power management of hybrid and plugin electric hybrid vehicles. Chapter 7 depicts two intelligent system approaches i.e., the fuzzy logic and neural networks, for vehicle power management. Chapter 8 briefly discusses the battery management in EV, HEV and PHEV. Chapter 9 discusses

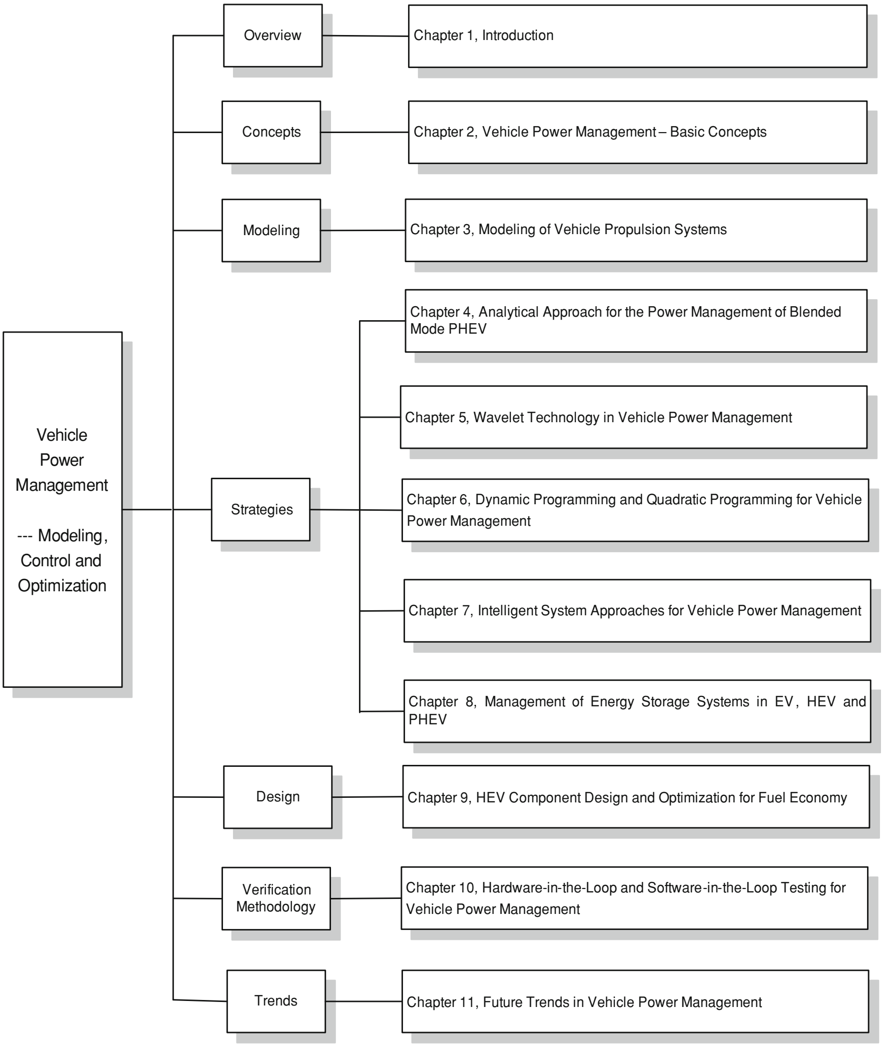

Fig. 1.5 Framework of the book organization

the component optimization which can also result in performance improvement of HEV and PHEV. In order to verify the validity of power management strategies prior to real applications in vehicles, experimental platforms are necessary. Thus Chap. 10 describes the definition and structure of hardware-in-the-loop (HIP), and introduces relevant experimental devices and methodologies to enlighten the readers. Finally, Chap. 11 gives an outlook on trends in future vehicle power management.

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Chapter 2
Vehicle Power Management: Basic Concepts

2.1 Vehicle Configurations

Since all types of vehicles including conventional, electric, and hybrid electric vehicles can be adapted to and benefited from the power management concept for improved fuel economy, reduced emissions, or extended power source life expectancy, a discussion of their configurations is important to help readers better understand how vehicle power management strategies cope with operations of various powertrain configurations and components.

2.1.1 Configuration of Conventional Vehicles

Figure 2.1 shows the configuration of a conventional vehicle. An internal combustion engine (ICE) provides all the vehicle propulsion power [1]. The drivetrain of a conventional vehicle includes clutches, gearbox, and final drive and differential. A speed-torque conversion is provided by the mechanical transmission for proper speed of the front or rear wheels. A multi-speed transmission is required due to the limitations of the ICE, such as incapable of running below 800 rpm, as well as incapable of providing large torque for low speed vehicle operations or maintaining high efficiency under certain operating conditions. Automatic transmissions, such as continuous variable transmission (CVT), automated manual transmission (AMT), dual clutch transmission (DCT) are developed to help transfer torque and power of the ICE to the final drive with better fuel economy and driveability. Many manufacturers capable of producing conventional vehicles exist around the world. On the other hand, conventional vehicles are major contributors to air pollution and green house emissions.

As alternatives to conventional vehicles, the new automobile propulsion technologies under development include electric vehicles, hybrid electric vehicles, plugin hybrid electric vehicles, and fuel cell vehicles.

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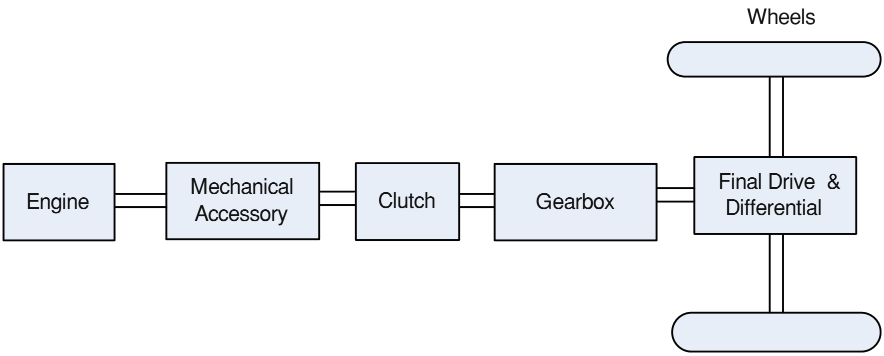

Fig. 2.1 Configuration of a conventional vehicle

2.1.2 Configuration of Electric Vehicles

Unlike a conventional vehicle driven by an ICE, an electric vehicle (EV) is propelled by electricity which is stored in an energy storage system (ESS), such as batteries, ultracapacitors, or flywheels. Electric vehicles are also referred to as pure EV or battery EV (BEV) in case the main energy storage is a battery pack. The configuration of a BEV is shown in Fig. 2.2.

The battery-powered electric vehicle is comprised of a battery for energy storage, an electric motor, and an inverter [2]. The battery is charged through a charger which can be either carried onboard or fitted at the charging point. The inverter is responsible for the direction and amount of power flow to/from the electric motor such that the vehicle speed and moving direction can be controlled. It has to be noted that during the braking process, the battery is charged by regenerative energy. The DC-DC converter is used to match the battery pack voltage and that of the DC bus of the inverter and can be optional. The mechanical transmission shown here is a generic term for gears and speed reduction. In contrast to conventional vehicles, EVs and other advanced vehicles do not have the need for automatic transmission as the case in conventional vehicles.

The limited travel range of BEVs (without recharging) prompted the research and development of fuel cell electric vehicles (FCEV) [3]. The fuel cell-powered electric vehicles have almost the same configuration as a BEV as shown in Fig. 2.3, except for the energy source. Hydrogen fuel is required and stored on board. The FCEV represents a true zero-emission vehicle for a long term. The Honda FCX was the first FCEV to be certified for use in the USA.

The traction motors used in electric vehicles are usually classified into DC motors, induction motors or permanent magnet motors [4]. Disadvantages of DC motors have forced EV researchers to turn their attention to AC motors. The maintenance-free and low-cost induction motors have attracted many EV developers. However, the problems of size and weight for high-speed operation

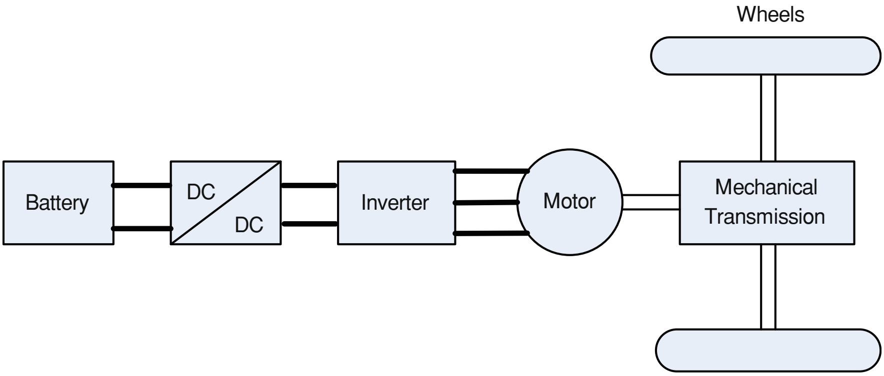

Fig. 2.2 Configuration of a battery-powered EV

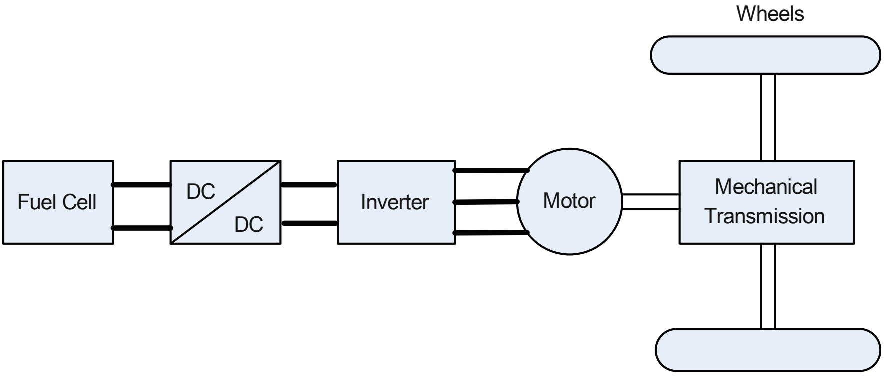

Fig. 2.3 Configuration of FCEV

exist in the meantime. High power density offers a major advantage by permanent magnet motors, which is attractive for EV propulsion solution in spite of the high cost of the motors.

2.1.3 Configuration of Hybrid Electric Vehicles

There are two or more power sources in a hybrid electric vehicle (HEV). Normally an ICE is combined with a battery, an electric motor, and/or an electric generator in the most common types of hybrid electric vehicles. Hybrid electric vehicles can be classified into four different types according to how the powertrain components are arranged: series, parallel, series–parallel, and complex hybrid.

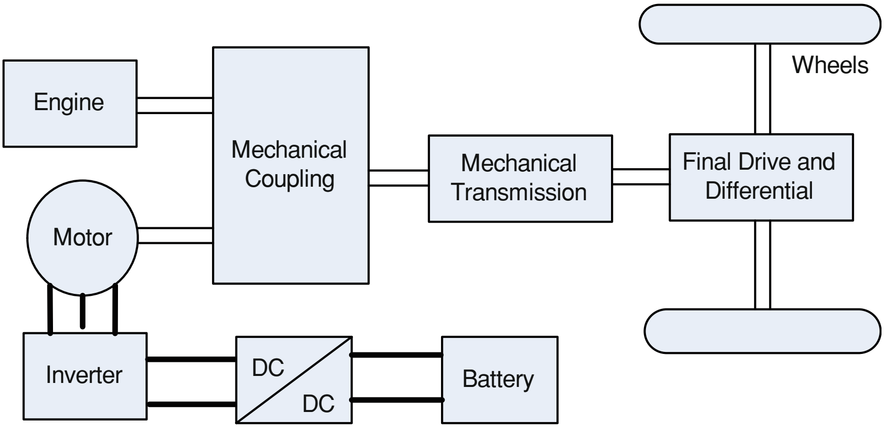

Fig. 2.4 Configuration of a parallel HEV

2.1.3.1 Parallel Hybrid

In a parallel HEV, an electric motor and an ICE are connected to the transmission through a mechanical coupling device, such as separate clutches, so that the vehicle can either be driven by the ICE, or by the electric motor, or by both [5]. The power requirements of the motor in a parallel HEV are lower than that of an EV with similar size. The configuration of the parallel HEV is shown in Fig. 2.4.

The parallel HEV has the following advantages. First, a parallel HEV needs only two propulsion components, ICE and an electric motor. The motor can be operated as a generator and vice versa. Second, the engine and the motor can be rated at reduced power levels for short-distance trips. For long-distance trips, the engine may be designed for maximum power, while the motor/generator may still be rated to half the maximum power. However, the mechanical structure and powertrain control is complex due to the necessity of power coupling for the ICE and the motor. It is also this complexity that gives more freedom for the powertrain control to optimize fuel economy and vehicle performance.

The mechanical coupling is realized through the use of pulleys, gears, clutches, or a common shaft for the engine and motor [5]. Mechanical coupling between motor and ICE can be configured to share a common transmission, or use separate transmissions or even separate axles. The mechanical transmission is also no longer restrained by the traditional automatic transmissions. For example, planetary gear sets have been introduced in parallel hybrids in place of the traditional CVT. The flexibility of configurations in parallel HEV offers the maximum advantage for fuel economy optimization in hybrid electric vehicles.

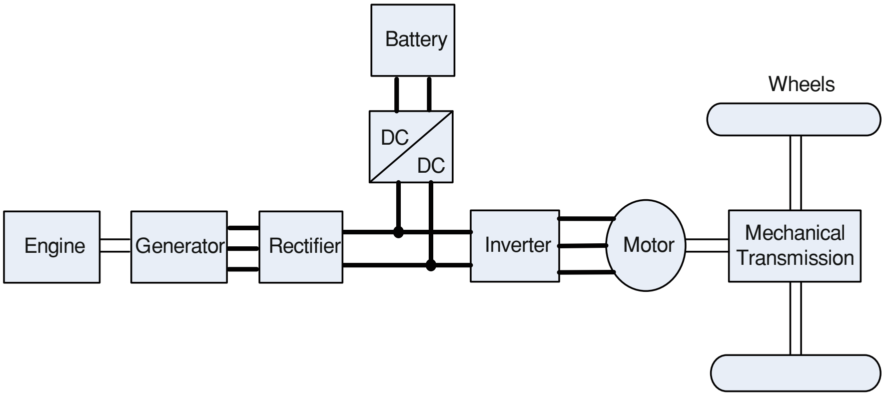

Fig. 2.5 Configuration of a series HEV

2.1.3.2 Series Hybrid

The configuration of a series HEV as shown in Fig. 2.5 is simpler than that of a parallel HEV. Only the electric motor provides all the propulsion power. An ICE on board drives a generator which can charge the battery when the state of charge (SOC) of the battery drops below a certain level [6]. Beyond the ICE and the generator, the propulsion system is the same as in an EV. The series HEV has advantages including flexibility of location of engine-generator set and simplicity of drivetrain, but meanwhile, due to its intrinsic structure, the series HEV needs more propulsion components (i.e., ICE, generator and motor). The fact that no mechanical link exists between the engine and mechanical transmission can have the engine operate in its most efficient region by adjusting its speed and torque. The electric motor has to be designed for the maximum power required by the vehicle. For long-distance missions, the three propulsion components need to be sized for maximum power.

2.1.3.3 Series–Parallel Hybrid

Considering the advantages of both series and parallel configurations, manufacturers and researchers have developed series–parallel hybrid electric vehicles. These HEVs can operate by either using electric motor alone or with the assistance of the ICE [7]. The configuration of the series–parallel HEV is shown in Fig. 2.6. In this configuration, power of the ICE and the electric motor is coupled to drive the vehicle in parallel operation. While power flow from engine to generator and then to the electric motor can be considered series.

There are many choices to design the “mode selection” device. The simplest one is clutches to select which shaft is connected to the ICE, i.e., to connect either the final drive or the electric generator to the ICE. Another choice is to have a