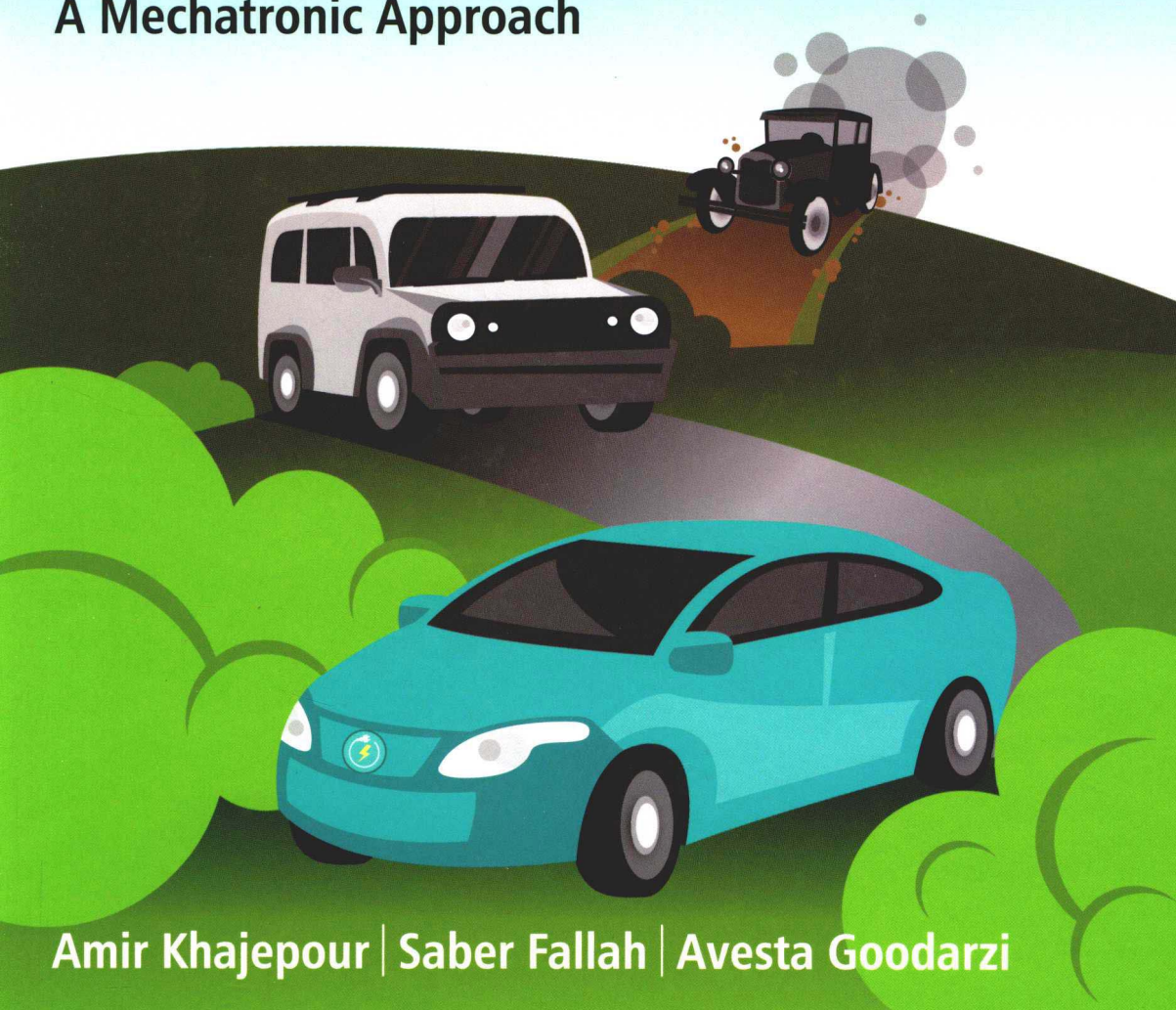


ELECTRIC AND HYBRID VEHICLES

**Technologies, Modeling and Control:
A Mechatronic Approach**



Amir Khajepour | Saber Fallah | Avesta Goodarzi

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TECHNOLOGIES, MODELING AND CONTROL: A MECHATRONIC APPROACH

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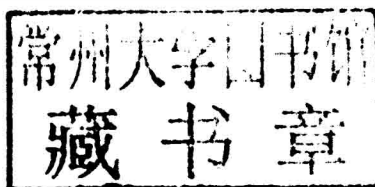
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ELECTRIC AND HYBRID VEHICLES

*To our students, whose enthusiasm and hard work are a
constant source of inspiration, and to our families,
without whose endless patience and support, this
book might never have been written.*

Preface

Concerns over the environment, public health and the availability of fossil fuels have forced the establishment of aggressive emissions regulations, such as the U.S. 2020 CAFE Standards, and have triggered momentous changes in global automotive strategies. New technologies and products are now required to enhance fuel efficiency and reduce harmful emissions, without sacrificing performance, cost-efficiency and safety.

Vehicle electrification and hybridization have been increasingly recognized as the most promising road transportation solutions to both the global energy crisis and the increasingly stringent requirements related to environmental protection and vehicle safety. However, the electrification of automotive systems presents significant design challenges, specifically related to drivetrain systems, chassis design and layout, multidisciplinary power management and optimization, system integration, and vehicle dynamics and control.

Electric and hybrid electric vehicles (EVs and HEVs) are complex mechatronic systems; their design requires holistic consideration of vehicle and tire dynamics, powertrain, electric motors and batteries, and control and estimation modules that are integrated through millions of lines of computer code. Several books have already been published that outline very well the electrical aspects of EV and HEV platforms. In this book, we have expanded upon these early works to present a more comprehensive perspective that combines electrical, control, and dynamics in systems-level design. It places new emphasis on how dramatically vehicle dynamics and, subsequently, our understanding of conventional vehicle design is changed by electrification.

This book is structured to address both senior undergraduate and graduate level courses, and can serve as an excellent reference for anyone with a background in dynamics, electrical, and control engineering. The content is sufficiently broad to allow course instructors the opportunity to tailor the material according to students' backgrounds. Several introductory chapters provide important background information on vehicle technologies in propulsion, powertrain, body and chassis, and the evolution of automotive technology design from conventional vehicles to the HEV and EV models we see on the road today. Students with electrical and control engineering backgrounds, but limited experience with automotive and mechanical engineering applications will benefit from these initial chapters, while students with stronger automotive backgrounds will benefit from later chapters that focus on HEV and EV power management optimization and vehicle control.

In this book we have tried our best to ensure students are presented with a balance between building a solid conceptual understanding and developing procedural skills related to automotive design. Examples are presented throughout that encourage students to apply their theoretical knowledge to real EV and HEV design challenges and considerations specific to these vehicles. End-of-chapter problems are provided for further practice and to facilitate a better understanding of the materials.

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1

Introduction to Vehicle Propulsion and Powertrain Technologies

The advent of the internal combustion engine has significantly influenced human life. As the main propulsion technology used in vehicles, the internal combustion engine has become an integral part of modern life. However, as internal combustion engine vehicles increase in number, they constitute one of the largest sources of air pollution and greenhouse gas emissions. This chapter introduces currently available propulsion technologies, as well as their advantages and disadvantages. The chapter begins by providing a brief history of internal combustion engine vehicles, then reviews the environmental challenges associated with combustion engine emissions. The rest of the chapter discusses the benefits of emission control technology, alternatively-fueled propulsion, and advanced powertrain technologies.

1.1 History of Vehicle Development

Vehicles have a long and varied history. In this section, we highlight few key events [1–5]. In 1769, Nicolas-Josef Cugnot and M. Brezin designed and built the first self-propelled vehicle, a steam-powered motor carriage capable of a maximum speed of 6 km/hr. However, even when modified for faster speeds, its heavy mass hindered the vehicle's performance. In 1807, the invention of the internal combustion engine (ICE) by François Isaac de Rivaz created new possibilities. This engine generated propulsion energy by using a mixture of hydrogen and oxygen. Several other engineers developed designs for the ICE, all of which were commercially unsuccessful because they lacked the fuel necessary to safely facilitate internal combustion.

Jean Joseph Etienne Lenoir invented the first successful gas engine 53 years later. After numerous modifications and improvements on Lenoir's design, the brothers Charles and Frank Duryear built the first gasoline-powered car in 1893, a design that was ready for road trials. In 1901, the German engineer Ferdinand Porsche manufactured a car that was powered by an internal combustion engine and hub-mounted electric motors (Figure 1.1). This was one of the first hybrid vehicles on record.

In 1904, Henry Ford developed the first assembly line manufacturing plant for gas-powered vehicles. As the twentieth century progressed, the automotive industry began to develop

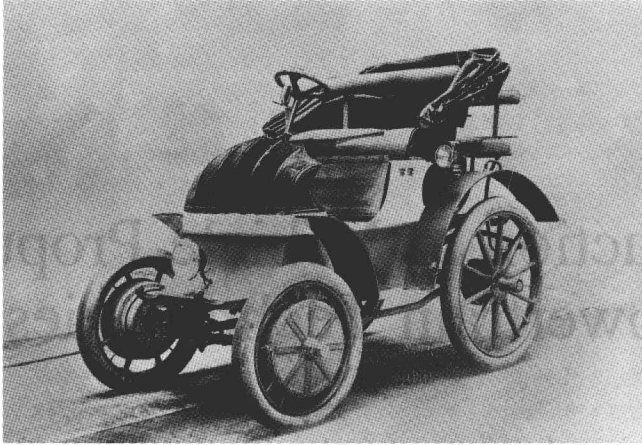


Figure 1.1 The early 1900's Lohner-Porsche, the first hybrid vehicle on record. *Source:* Reproduced by permission of Porsche Cars North America, Inc.

rapidly, and motor vehicles were soon available in steam, electric, and gasoline versions. While gas-powered vehicles are prevalent in our world today, electric vehicles (EVs) were more popular than other vehicle alternatives in the early 1900s. The primary reason for its popularity at this time was functionality. Unlike gasoline vehicles, electric vehicles were without the engine-related vibration, smell, and noise. However, gasoline vehicles require manual gear shifting, which was regarded as a difficult component of driving at the time. Likewise, EVs were also preferable to steam-powered vehicles because they were capable of longer ranges on a single charge, and were more convenient during colder weather. Under similar weather conditions, steam-powered vehicles suffered from start-up times of up to 45 minutes.

The electric vehicles continued to be attractive until the 1920s, with peak production occurring in 1912. However, improvements in intercity road quality propelled the need for ICE vehicles, which were capable of operating at longer distances. At the same time, the discovery of oil reduced the price of gasoline, making internal combustion vehicles more affordable to consumers. Moreover, the invention of the electric starter made the use of the internal combustion vehicles more convenient, whereas the long recharge time of electric vehicles and the expensive large battery packs made the electric vehicles less attractive to consumers. As a result of these developments, the market for EVs gradually disappeared by the 1930s.

Moving forward in time, cars became less of a luxury and more of a necessity for everyday life. While the increased use and development of internal combustion vehicles have changed city landscapes and lifestyles, scientists began to worry about the long-term environmental effects of ICE exhaust emissions. Most concerns related to the influence of vehicle emissions on the onset of global warming and excessive greenhouse gas production. Furthermore, oil prices began to rise around this time, along with increased public awareness of the limited supply of oil resources. This led to a pressing need for alternatively-powered vehicles, which began to surface in the 1970s.

The afore-mentioned issues also led governments to take several legislative and regulatory actions to moderate oil production dependency and reduce the causes of air pollution. Likewise, several organizations from around the world began to work with vehicle

manufacturers to create conditions more favorable to the development of electric vehicles. As a result of these changes, the automotive industry began to renew their attempts to develop electric vehicles.

In 1974, the American company, Sebring-Vanguard, designed the CitiCar, the first mass-produced electric car, and continued its production until 1977. From 1977–1979, General Motors Company spent over \$20 million in electric car development and research, with a stated objective to produce electric vehicles by the mid-1980s. Similarly, Peugeot and Renault designed an electric vehicle that could drive at 100 km/h, with a travel range of 140 km. In 1989, Audi unveiled the first generation of the experimental Audi Duo, a petrol engine/electric hybrid concept vehicle. This car had rear wheels driven by a 12.6 hp electric engine, and front-wheel drive powered by a 2.3 litre 5-cylinder engine with a 136 hp output. In 1996, General Motors designed and developed an electric motor vehicle called the EV1, which had a top speed of 130 km/h and a range of 130 km.

Improvements in electric vehicle performance motivated the automotive industry to develop and market mass-produced electric vehicles. However, the electric vehicle market could not achieve success with consumers, and was largely failing by the end of the 1990s. The primary reason for the failure of EVs was their limited performance capability as compared to gasoline-powered vehicles. Moreover, the low price of oil at the time, as well as the EVs' high initial costs, high maintenance costs, and infrastructure shortage contributed to their commercial lack of success.

However, a new type of motorization appeared in the late 1990s: hybrid technology, which combined the internal combustion engine with an electric motor. Toyota made the Prius, the first mass-produced hybrid electric vehicle (HEV), which was launched successfully in Japan in 1997. Shortly after, in 1999, the Honda Insight was launched in both the United States and Japan. These two vehicles pioneered the hybrid vehicle concept, and led to a shift in the market perception of alternative fuel vehicles.

Since then, other car manufacturers have designed and produced a variety of fuel-efficient vehicles using vehicle electrification technology. Ford introduced its first hybrid vehicle in 2004 with the Escape SUV hybrid model. Likewise, General Motors introduced the Silverado and the Sierra in 2004 as their first hybrid vehicle models. Currently, countries such as Brazil and China are competing to increase their shares in the worldwide market of EVs and HEVs.

Nevertheless, the share of HEVs worldwide is still quite low when compared to IC engine vehicles. In 2004, the share of HEVs was 0.25% whereas in 2007, the total production of 541 000 HEVs was only 0.8% of the production of light vehicles worldwide. Anticipated production numbers of HEVs predict an increase to 1.7 million by 2014. The increasing share of HEVs overall reflects the accelerating pace towards greater electrification of vehicles, and eventually, the production of zero emission vehicles with better efficiency [6].

1.2 Internal Combustion Engine Vehicles (ICEVs)

Most modern vehicles create propulsion power through an internal combustion engine. An internal combustion engine generates propulsion power from the combustion of fuel and an oxidizer in a confined cylindrical space known as a combustion chamber. The engine then takes the heat energy generated by the combustion process and converts it into mechanical work based on the principle of energy conservation.

The oxidizer of an IC engine is typically oxygen, which is sufficiently available in the Earth's atmosphere. The most common fuels used in an IC engine are gasoline and diesel;

however, other fuels such as hydrogen, methane, and propane are also used. The exothermic reaction of the fuel with the oxidizer results in the production of high-temperature and high-pressure gases. The expansion of these gases applies force to a piston inside the combustion chamber. Subsequently, the linear motion of the piston is transferred to the wheels through the crankshaft and the vehicle transmission system. The advantageous features of IC engines are a high power-to-weight ratio and excellent fuel energy density.

Dutch physicist Christian Huygens first proposed the design concept of a working internal combustion engine in 1680. Almost 130 years later, Swiss engineer François Isaac de Rivaz realized Huygens' vision by inventing an unsuccessful version of the IC engine. His internal combustion engine attempted to propel automobiles by burning a fuel mixture of hydrogen and oxygen for power. While de Rivaz's attempts failed to achieve success, the efforts of English engineer Samuel Brown were successful. In 1826, Brown developed a hydrogen-fueled combustion engine that was industry-compatible. Brown's engine had separate combustion and working cylinders with four hp.

The first functioning and successfully designed gas-powered internal combustion engine was invented in 1860 by Jean Joseph Etienne Lenoir. Fueled by coal gas, this engine was a double-acting, electric spark-ignition capable of running continuously. In 1863, Lenoir further improved this engine model so that it was able to run on petroleum using a primitive carburetor. Following these developments, engineers continued to invent and modify variations of the IC engine. However, the most significant contribution was the invention of the four-stroke engine by Nicolaus August Otto in 1876. The patented "Otto Cycle Engine," a universally implemented, practical four-stroke IC engine was soon in all liquid-fueled automobiles. A four-stroke engine still powers most modern cars and trucks.

In 1885, German engineers and design partners, Gottlieb Daimler and Wilhelm Maybach modified the Otto Cycle Engine by reducing its size while increasing its speed and efficiency. Their engine was small, lightweight, and quick; it used a gasoline-injected carburetor and had a vertical cylinder. In 1886, as a separate work and without any knowledge of Daimler's and Maybach's work, German engineer Karl Benz patented the first gas-fueled automobile powered by a four-stroke engine. Benz's engine designs were the pioneers for modern vehicles. Rudolph Diesel made another key contribution towards improving the efficiency of IC engines by inventing and patenting the diesel engine in 1892.

Currently, gasoline and diesel engines are the main power sources for the majority of road vehicles. Most cars and light-duty vehicles use gasoline engines while heavy-duty vehicles, buses, and some passenger cars use diesel. Diesel engines are more fuel-efficient and more powerful at lower speeds than gasoline engines. However, they are also noisier, heavier, and more difficult to start in cold weather conditions. While gasoline engines have an easier time starting in the cold, they are still prone to problems under extreme conditions.

Both gasoline and diesel engines convert the chemical energy of fuel into motion through a four-stroke process, and are available as either reciprocating or piston engines. A reciprocating engine includes a number of cylinders (combustion chambers), each containing a piston that moves up and down. Each piston connects to the crankshaft (Figure 1.2) through a connecting rod, which rotates the crankshaft by using the reciprocating (up-and-down) motions of the piston. The crankshaft features offset axis sections called crankpins. While the upper end of the connecting rod attaches to the piston with a joint, the bearing offset sections attach to the end of the connecting rod. The design of the crankshaft causes the reciprocating motion of the pistons to translate into a rotary motion. In manual transmissions, the rotary motion of the crankshaft