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Introduction

Customer needs and requirements from society have, together with a fierce competition among automotive manufacturers, had a tremendous effect on the development of our vehicles. They have evolved from being essentially mechanical systems in the early 1900s to the highly engineered and computerized machines that they are today. An important step has been the introduction of computer controlled systems that accelerate the development of clean, efficient, and reliable vehicles. Two trends are especially interesting for the scope of this book:

- Increased computational capabilities in vehicle control systems.
- New mechanical designs giving more flexible and controllable vehicle components.

These development trends are intertwined, as the development of new mechanical systems relies on the availability of more advanced controllers that can handle and optimally use these new systems. As a consequence, the design of vehicles is really evolving into co-design of mechanics and control. The tasks for such improved designs are numerous, but the main goals to strive for are:

- High efficiency, leading to lower fuel consumption.
- Low emissions, giving reduced environmental impact.
- Good driveability, providing predictable response to driver commands.
- Optimal dependability, giving predictability, reliability, and availability.

The goal of this book is to give insight into such new developments, and to do it in enough depth to show the interplay between the basic physics of the powertrain systems and the possibilities for control design. Having set the goals above, it is impossible to cover the field in breadth too. The text has to be a selection of important representatives. For example, two-stroke engines are not covered, since the usual four-stroke engine illustrates the general principles and by itself requires quite some pages to be described sufficiently.

Control systems have come to play an important role in the performance of modern vehicles in meeting goals on low emissions and low fuel consumption. To achieve these goals, modeling, simulation, and analysis have become standard tools for the development of control systems in the automotive industry. The aim is therefore to introduce engineers to the basics of internal combustion engines and drivelines in such a way that they will be able to understand today's control systems, and with the models and tools provided be able to contribute to the

Modeling and Control of Engines and Drivelines, First Edition. Lars Eriksson and Lars Nielsen.

Companion Website: www.wiley.com/go/powertrain

development of future powertrain control systems. This book provides an introduction to the subject of modeling, analysis, and control of engines and drivelines. Another goal is to provide a set of standard models and thereby serve as a reference material for engineers in the field.

1.1 Trends

Modern society is to a large extent built on transportation of both people and goods and it is amazing how well the infrastructure functions. Large amounts of food and other goods are made available, waste is transported away, and masses of people commute to and from work both by private and public transportation. Transportation is thus fundamental to society as we know it, but there is increasing concern about its effects on resources and the environment. This is also stressed when considering the increasing demands in developing countries. To meet these demands there are many efforts toward making vehicles function as efficiently and cleanly as possible, and some of the major trends are

- downsizing
- hybridization
- driver support systems
- new infrastructure.

These will be briefly introduced below, after a section on the societal drive for care of our resources and environment.

1.1.1 Energy and Environment

Different standards and regulations have been the most concrete results that have come from concern for the environment. A perfect combustion of hydrocarbon fuels will result in CO_2 and water, whereas a non-perfect combustion results in additional unwanted pollutants. This means that the amount of CO_2 is a direct measure of the amount of fuel consumed, and a standard formulated in terms of CO_2 thus aims at restricting the use of fossil fuels. Worldwide standards are illustrated in Figure 1.1, illustrating that society is pushing the development of more fuel efficient vehicles. Standards and measures of control differ between regions, the USA, for example, uses a Corporate Average Fuel Consumption (CAFE) for manufacturers, while cars in Europe have a CO_2 declaration that is used for taxation of vehicles.

Another type of regulation is used to limit the emissions of important harmful pollutants. Examples are emissions of particulate matter (also called soot) and the gases carbon monoxide (CO), nitrogen oxides (NO and NO_2, collectively called NO_x), and hydrocarbons (HC). Legislators have made the levels that vehicles are allowed to emit increasingly stringent and Figure 1.2 shows the evolution for passenger cars in the USA.

Regulations like these in Figures 1.1 and 1.2 have been, and continue to be, drivers for better vehicles and have a decisive impact on technological development within the automotive area.

1.1.2 Downsizing

There are many ongoing developments to meet legislative requirements like those above, and one major trend in the search for solutions is downsizing. Downsizing has two meanings,

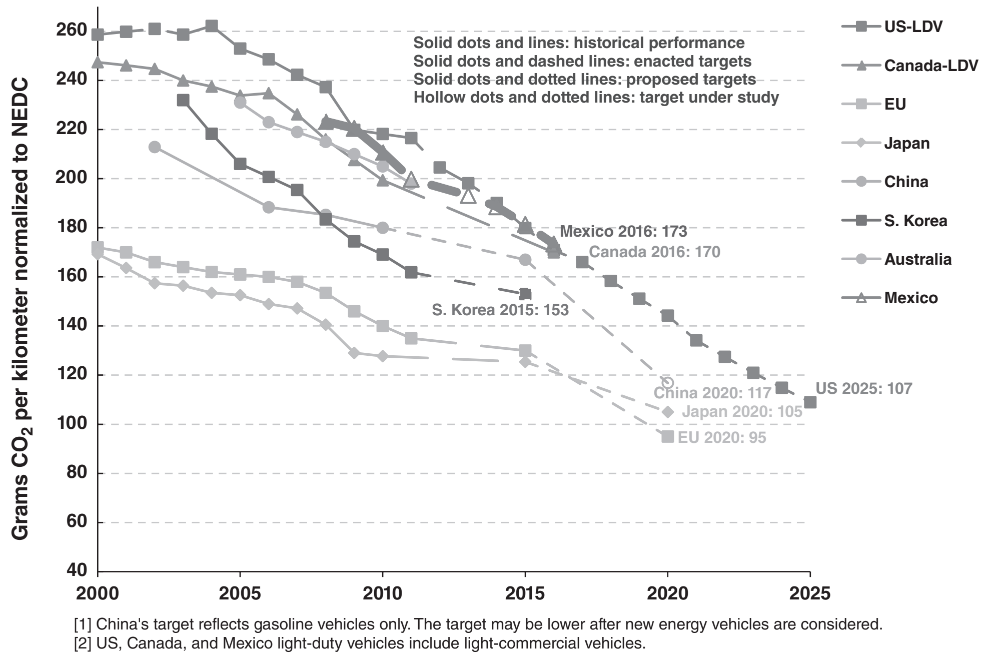

Figure 1.1 Global CO_2 emissions, historical data, and future standards. Reproduced with permission from The International Council On Clean Transportation

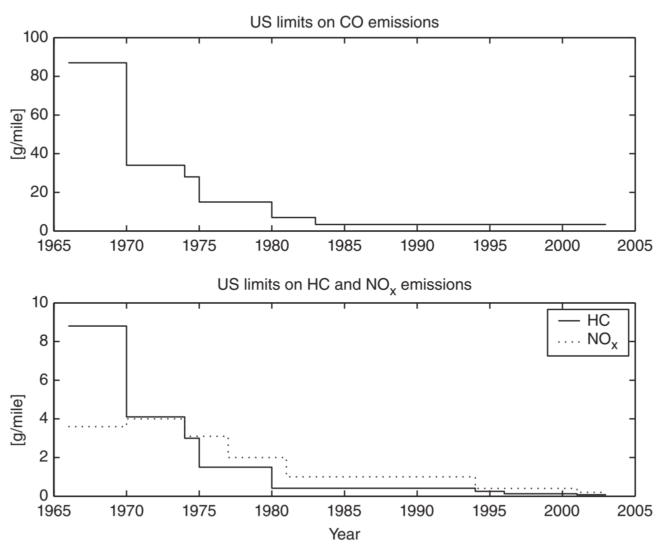

Figure 1.2 The evolution of federal emission regulations for carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) of passenger cars in the USA. At model year 2004 the Tier 2 standards started, specifying 10 bins where the manufacturers can place their vehicles, provided that they fulfill fleet average regulations. No data is plotted after 2004 due to the diversity of limits in the bins

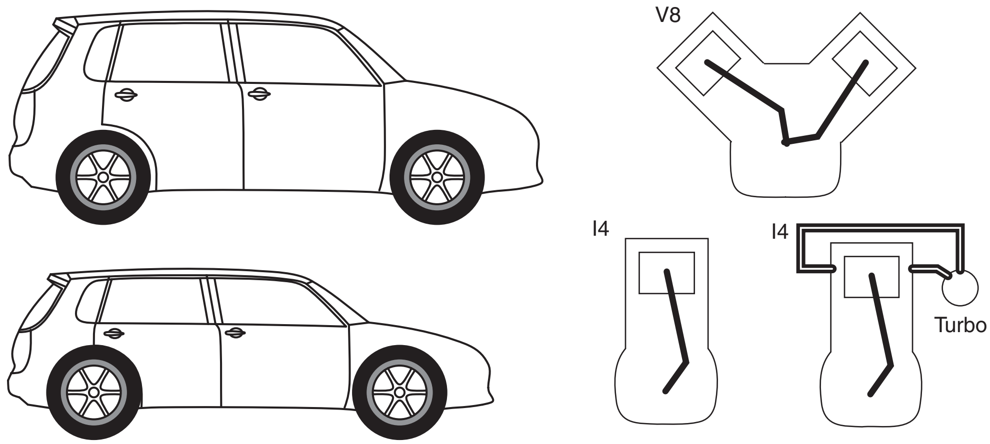

Figure 1.3 Downsizing of cars and engines to increase fuel efficiency

where one is that smaller and more lightweight cars need less fuel. The trends in this area cover new materials and new construction principles as well as customer acceptance of smaller cars. Another interpretation concerns the engine, where downsizing refers to having a smaller engine in the car that consumes less fuel. Downsizing is often used with turbocharging, where the smaller engine gets a boosted performance to come closer to that of a larger engine and improve customer acceptance. Both these ideas are depicted in Figure 1.3. The principle of downsizing engines is an important part of this book, see especially Chapter 8.

1.1.3 Hybridization

Downsizing is one path that leads to less fuel consumption and fewer emissions. Another path is hybridization, where there is an additional energy storage and retrieval in the car. Several ideas exist for storing and retrieving energy, and some candidates are to store energy as rotational energy in a fly-wheel, as pressure in an air tank, or as pressure in a hydraulic system. However, for now, electrification is the main line of development, where energy is stored electrically in a battery or in a super capacitor, and transformed to motion via electrical motors. Compared to traditional vehicles, hybrid vehicles are more complex since there are more components that should operate in harmony to achieve most of the promise of hybridization. This will be expanded on in Chapter 3, and a main theme is that, at the core of the solutions, the torques and velocities are the main variables to model and control; which means that the models and methodologies in this book can be directly applied to simulate and analyze hybrid systems.

1.1.4 Driver Support Systems and Optimal Driving

Fuel consumption and the amount of emissions are highly dependent on how a vehicle is driven. The fuel savings when driving optimally can be substantial compared to energy-unaware driving, so therefore there is a strong interest in systems that help the driver, or even replace the driver, when it comes to propulsion.

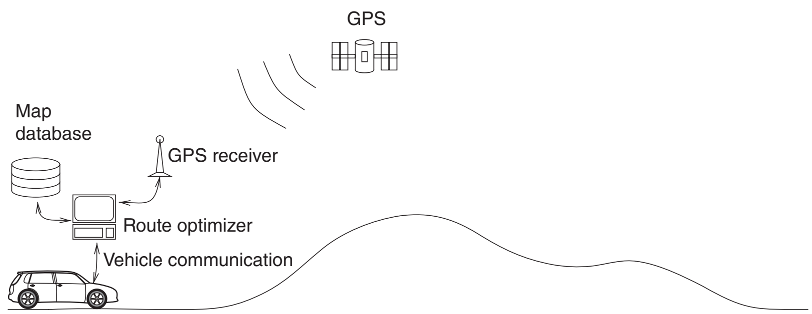

Figure 1.4 Depiction of a system for optimal driving regarding the upcoming topography of the road

A driver support system proposes speed and gear selections to the driver, and can also evaluate and educate a driver. There are also systems that can plan a fuel-optimal driving based on the topography of the road, that is using knowledge of the upcoming slopes of the road, as illustrated in Figure 1.4. The basis for such a system is positioning the vehicle using GPS, a map database used to read the upcoming road slopes, and on-board optimization algorithms that take control over propulsion. A number of names are given to these systems, such as Optimal driving, Look-ahead control, and Active prediction cruise control. The latter name reflects the fact that it is a natural extension of a conventional cruise control system.

New Infrastructure

Optimal driving as regards topography was made possible by the technological development of GPS and map databases. It would, of course, also be highly beneficial if driving could be optimal relative to all other circumstances like, for example, the traffic situation, other vehicles, and weather. To approach these potential benefits there is active development of vehicle-to-vehicle communication, road-side information systems, traffic systems, and on-line teleservices, such as weather and traffic reports. Such a situation is depicted in Figure 1.5. Some acronyms used are V2V for vehicle-to-vehicle, V2R for vehicle to road-side, and V2X as a generalization to any connection.

In addition to the infrastructure, the vehicle has its own sensors. These are both internal, regarding powertrain and vehicle motion dynamics, and external, like radars and cameras.

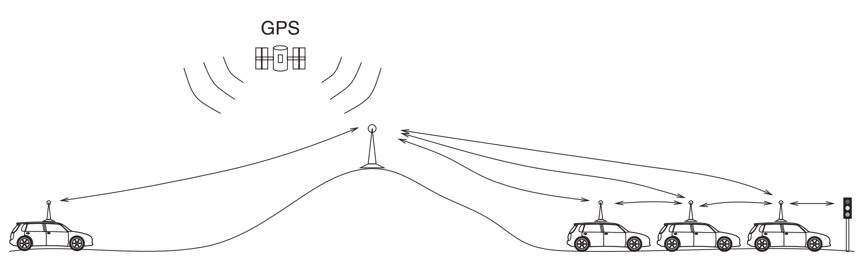

Figure 1.5 Illustration of a situation where each vehicle is provided with information from other vehicles, from road-side systems, and from teleservices such as GPS and weather information

In the future, the aim is to have superb situation awareness and planning potential within each individual vehicle, and the engineering task will be to utilize this potential in the best possible way. There is another benefit, with a system as sketched in Figure 1.5, besides making driving optimal. Information from other vehicles and from infrastructure providing road-side information, on-line weather, and traffic information, can also improve safety.

Integrated Propulsion and Powertrain Control

The situation in Figure 1.5 will make new functionality possible. One example, not far away, is platooning, where vehicles can drive close to each other to reduce the losses from air drag, see Section 2.2.3, and other more autonomous functionality will follow.

Eventually, all the aspects above will be part of truly integrated powertrain control based on the actual state within the powertrain, that contributes to a system that at every time instant can behave optimally.

1.1.5 Engineering Challenges

To sum up, transportation is crucial to society, but limited resources and environmental concerns have led to the need to find transportation solutions of the future. Luckily, new technological possibilities and developments have given many new possibilities, so there are now many trends constituting a vast plethora of challenging and interesting engineering tasks.

The full picture requires more than one book to cover, but one perspective is that all aspects come together in the question of optimal propulsion. The main scope of this book is to give the understanding and engineering tools for the powertrain that transforms energy to motion. The goal is to do this such that the systems of today are treated, but also so that a foundation is laid for approaching the engineering challenges of many years to come. To do this, a certain level of depth is needed, and our hope is that the reader will share a feeling of excitement about the challenges and the fun involved in exploring and developing future solutions.

1.2 Vehicle Propulsion

As seen in Section 1.1, there are many developments in transportation solutions for the future, and to be able to cope with these challenges the main focus in this book is the fundamental issue of efficiently transforming energy to motion without unwanted side effects such as pollution. This transformation is performed by the powertrain, which is the group of components that generate power and deliver it to the road. Illustrations of powertrains are shown in Figures 1.6, 3.1, 3.5, and 13.1, and they may include the engine, electrical motor, battery, transmission (or gearbox), driveshafts, differential, and wheels. As will be seen, the powertrain is a complex system in itself, and as described in Section 1.1 road-side information or interaction with other vehicles adds to the complexity. Handling this complexity in an optimal way is a strong motivation for modeling and control, and this is given some background and motivation in the following sections. Thereafter, a more detailed outline of the book is given in Section 1.3.

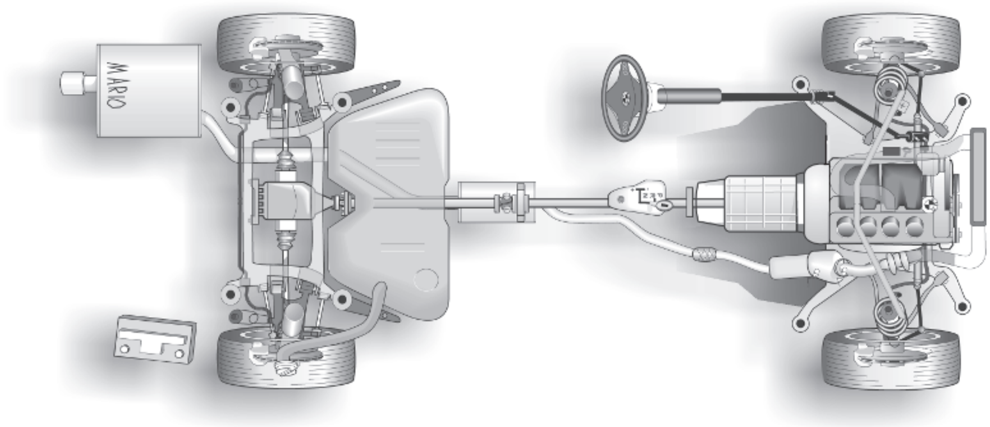

Figure 1.6 A sketch of a BMW 520D, touring, automatic, -08, that includes the driveline. This powertrain includes the engine, transmission (gearbox), propeller shaft, differential with final-drive, drive shafts, and wheels. Other components are: fuel tank, exhaust system, steering wheel, and suspension systems. Reprinted with permission from Mario Salutskij

1.2.1 Control Enabling Optimal Operation of Powertrains

The powertrain, with its components and with its external interactions, has to be coordinated into a single operational unit fulfilling a complex set of requirements. Hence, the need for control is natural, and potential and advantage is found in at least the following areas

- fulfilling legal requirements
- achieving performance
- handling complexity
- enabling new technology.

From the discussion above it should be clear that control is a strong enabler for the first three items. Regarding the fourth item, it is interesting to ask ourselves why so many advanced concepts, like supercharging, turbo, variable valve actuation, variable compression engines, and gasoline direct injection, are surfacing as commercial products. In fact, none of these concepts are new, even if they are sometimes presented so, but the novelty is instead that they can now with proper **control** achieve competitive functionality and performance. A well-known example is now used to illustrate this point.

An Illustrative Example – The Three-Way Catalyst

One important historic milestone was the introduction of the three-way catalyst that constituted a breakthrough in the reduction of emissions from a gasoline engine. The key step for successful application was the introduction and integration of a control system that continuously monitors the air–fuel mixture and modifies the fuel injection. This was necessitated by the catalyst, which requires a very precise mixture of air and fuel for optimal operation that could only be achieved by means of a control system. Together with proper controls the three-way catalyst now removes more than 98% of the emissions. This control problem will be treated in more detail in the engine-related chapters in the book. However, the main point here is that this is one example that clearly illustrates how control systems have become crucial components in the development of clean and efficient vehicles.

Another Illustrative Example – Energy Management in Hybrids

One more example is used to illustrate the importance of control. The torque of an electrical motor and an internal combustion engine have different characteristics, as shown in Figure 1.7. Proper control can be used combine the best elements from their respective characteristics.

High Ambitions Need Models

The ambitions for powertrain control are already high, and the demand for care in energy utilization and environment preservation will continue to develop toward optimal powertrain control. These societal drives are strong, and lead to striving to find really good designs from a performance perspective. To be able to handle these increasingly better and more complex systems, strong physical knowledge will be required, but it will also be necessary that this physical knowledge is provided in an efficient form for analysis and design. For this purpose, models are needed.

1.2.2 Importance of Powertrain Modeling and Models

This book covers modeling, control, and diagnosis of powertrains, with its main focus on models and model-based methods. In particular, much attention is given to modeling and models, and this choice has been made for two more reasons than its obvious use in model-based control.

Virtual Sensors

A first additional motive is seen by looking at the powertrain as the group of components that generate power and deliver it to the road, and the torque is thus fundamental to control.

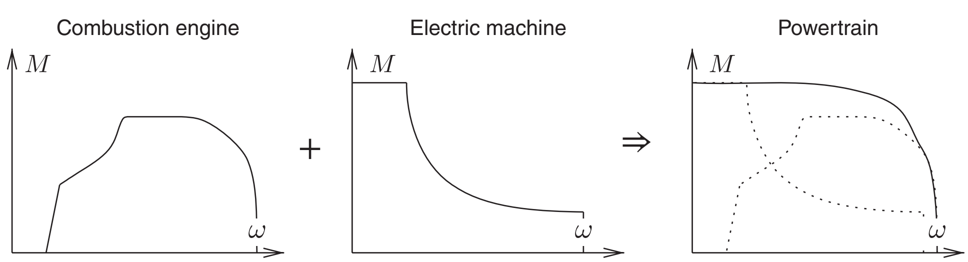

Figure 1.7 Illustration of control as an enabler for new functionality. Here, the example is about finding the best combination of an electrical motor and an internal combustion engine in a hybrid vehicle

One notes that the powertrain torque is not measured in current production systems, even though it is such a central variable. Thus, to be able to control this system, it is necessary for the system to have models that calculate (or estimate) the torque at various positions in the powertrain and especially the torque production from the engine. This generalizes to an important issue in mass produced vehicles: sensors cost money and cutting the cost of both the total system and of each component is of utmost importance. An additional sensor is not mounted unless it delivers a necessary input to the control system and, at the same time, is really worth its price. Models are therefore utilized to a high degree, instead of sensors, for determining interesting quantities in the system.

Systematic Build-Up of Knowledge

Secondly, models provide a foundation that can also be utilized in the development of future systems, one can say that they in a sense form a scientific basis for the control system design. Controllers and control architectures will change in the future, since these depend on the technical development of, for example, sensors and actuators. As an example, a particular control problem and its design to a large extent depend on what sensors and actuators are utilized, and if new better options become available and competitive the controller structure and control design can also be fundamentally changed. However, the physics of the energy conversion system does not change substantially, for example they follow Newton's and thermodynamic laws. Therefore, models that describe these system will also in the future provide a basis for analysis of system properties and future control designs.

1.2.3 Sustainability of Model Knowledge

Major constituents of modeling have developed since the introduction of the microprocessor in the 1970s and 1980s, but have developed with increased pace over the last 20 years. Many of the models presented in this book have received thorough experimental verification and have proved their usefulness in many existing designs. Therefore, it is our belief that these models, perhaps in new combinations but still comprising the same model components, will be the foundation for analysis and design for many years to come.

With these notes, about seeing modeling as the foundation for future development, it must also be mentioned that it is still important to analyze and understand current systems and controllers. This is because they give insight into current system designs and constitute design examples of how powertrain demands are formulated as control problems and how these are solved. Another aspect that this visualizes is the interesting interplay between thermodynamics, mechanics, and control that is seen in modern cars, and this is an interesting and dynamic area.

1.3 Organization of the Book

The core topics in this book are the modeling and control of powertrains, their components, and the interplay between these components. Models are provided for each system and for the integration between systems that are needed for successfully engineering a complete vehicle powertrain. In addition, it is also highlighted that systems should be designed such that they can be maintained and diagnosed over the vehicle lifetime, which is also an important engineering task in the development of control systems.

The text is organized into five parts: vehicles and powertrains, engine fundamentals, engine modeling and control, drivelines, and diagnosis. In the presentation of these subjects, measurements on real processes are used early in the treatment of different systems, and it is then shown how models are used as approximations of reality. For example: the process in the cylinder of a real gasoline engine (Otto engine) does not follow the ideal Otto cycle exactly, but the Otto cycle gives valuable insight into the engine's characteristics and properties. The main contents in each part will now be outlined in the following paragraphs.

Vehicle – Propulsion Fundamentals

The first part of the book gives an overview of vehicles and powertrains to set the framework for the rest of the chapters. The performance of a vehicle, regarding the motions coming from accelerating, braking, or ride, is mainly a response to the forces imposed on the vehicle from the tire–road contact. Chapter 2, Vehicle, gives sufficient background in these matters by providing models, so an engineer can study engines, motors, and drivelines in an complete vehicle setting. In Section 1.1 it was clear that there are many expectations of well-behaved vehicles, and in Chapter 2 this is further quantified by presenting legislative requirements and measures for consumer demands. Whereas Chapter 2 looks at the vehicle from outside, the following chapter, Chapter 3, Powertrain, continues the treatment by going inside the car to give a first overview of possible solutions. Already here there is a preliminary discussion on control structures for powertrain control.

Engine – Fundamentals

This second part summarizes important properties and basic operating principles of engines with respect to overall performance, limitations, and emissions. Chapter 4, Engine – Introduction, introduces basic engine geometries and quantities that are used to characterize the engine operating conditions and performance. Many of these appear as components or parameters in the models that are developed in later chapters.

Chapter 5, Thermodynamics and Working Cycles, covers the basics of the work production in a four-stroke engine operation and develops thermodynamic models for the process based on a thermodynamic foundation. The first sections are devoted to simplified thermodynamic processes, developing equations that both give insight into operating characteristics and can be used in models. Finally, Section 5.4 develops more detailed models that are often used for analyzing the effects of different design or control actions and optimizing set points for the controls.

Chapter 6, Combustion and Emissions, treats the combustion processes in spark ignited (gasoline) engines and compression ignited (diesel) engines as well as their characteristics. Further, the engine-out emissions and their treatment is summarized, giving a background for understanding the control goals for the engine with respect to emission.

Engines – Modeling and Control

Chapters 5 and 6 in the preceding part deal with work and emission production in the cylinder, and thus involve quantities that vary under one cycle, and the resolution of interest is in the region of one crank angle degree. The chapters in Part 3 on modeling and control treat the engine block, with the cylinders, as a system and develop component and system models that have longer time constants.

Chapter 7, Mean Value Engine Modeling, has as its theme *mean value engine modeling* and develops models for different components that are found in an engine. The timescales of these models are in the order of one to several engine cycles, and the variables that are considered are averaged over one or several cycles (i.e., the quantities are mean values over a cycle, giving the name mean value engine models). These models describe the processes and signals that have a direct influence on the control design. Another strong trend in engine development, namely downsizing and supercharging of engines, is treated in Chapter 8, Turbocharging Basics and Models, which gives a fundamental treatment of turbocharging and other variants of supercharging. The chapter leads to models for turbochargers and collects two complete turbocharged engine models, one gasoline and one diesel.

Generic components and tasks that are found in engine management systems are summarized in Chapter 9, Engine Management Systems – An Introduction. Control loops in spark ignited (SI) engines are treated in Chapter 10, Basic Control of SI Engines, covering both high level controllers, such as torque, air and fuel, and ignition control, and low level servo controllers such as throttle, waste gate, fuel injector, and so on.

Compression ignited (CI) engines are covered in Chapter 11, Basic Control of Diesel Engines, covering both high level controllers such as torque and gas flow control, and low level control, such as injection. Finally, Chapter 12, Engine – Some Advanced Concepts, describes some advanced engine concepts, such as variable valve actuation, variable compression ratio engines, and advanced feedback control. A theme of the topics in advanced concepts is that they rely on control systems in order to reach full utilization of their performance potential.

Driveline – Modeling and Control

From the prime movers (combustion engine or electrical motor) the driveline (clutch, transmission, shafts, and wheels) transmits the power for propulsion and is thus a fundamental part of a vehicle. Since the driveline parts are elastic, mechanical resonances may occur. The handling of such resonances is basic for functionality and driveability, but is also important for reducing mechanical stress and noise. Chapter 13, Driveline Introduction, introduces the nomenclature and defines the area of driveline control as a certain subarea of powertrain control. As a background to the coming chapters, it explains the physical background of unwanted vehicle behavior that results from inadequate driveline control. It clarifies the control tasks at hand, and gives a brief discussion on sensors and actuators. Chapter 14, Driveline Modeling, models the driveline and its components, providing descriptions of both how the engine is coupled to the wheels and how oscillations are caused by the elasticities found in, for example, the driveshafts. When describing the forces and torques on the wheels there is a connection back to Chapter 2, Vehicle, for descriptions of driving resistance. A systematic modeling methodology is used, and a set of driveline system models are developed with the purpose of giving a range of models that are suitable for analyzing different control problems.

Driveline control is treated in Chapter 15, Driveline Control, where, besides a general discussion on control formulations, the two main problem areas of speed control and torque control are given specific attention. Relating back to torque-based powertrain control in Chapter 3, Powertrain, both of these are examples where driveline control intervenes in the torque propagation structure with short-term demands. The two applications chosen to illustrate speed control and torque control respectively are *anti-surge control* and *driveline torque control for gear shifting*. The first application is important for handling wheel-speed oscillations, following from a change in accelerator pedal position or from impulses from towed trailers. The second application is used to implement automated gear shifting.

Diagnosis and Dependability

The availability of computing power in vehicles has also strongly influenced another field, namely diagnosis and dependability. Originally, the main driving force came from legislation requiring diagnostic supervision of any component or function that when malfunctioning would increase tail-pipe emissions by at least 50 %, the well-known On Board Diagnosis (OBD) requirements by the California Air Resource Board (CARB). Basically, there are observed variables or behaviors for which there is knowledge of what is expected or normal. The task of diagnosis is, from the observations and knowledge, to generate a fault decision, that is to decide whether there is a fault or not and also to identify the fault. Once a methodology to find faults or malfunctions has been developed then many new application areas open up. Chapter 16, Diagosis and Dependability, briefly introduces basic diagnostic techniques, and their wider use today is presented where the same techniques are used for safety, machine protection, availability, up-time, dependability, functional safety, health monitoring, and maintenance on demand. The consumer value is, for example, increased profit through dependability, or lower costs through maintenance on demand. Explicit examples of model based diagnosis are given where it is shown how the models that are developed in the book can also be used for diagnosis and dependability. These examples include important automotive examples. Finally an overview of OBDII is given.