Introduction to Modeling and Control of Internal Combustion Engine Systems

Lino Guzzella and Christopher H. Onder

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Prof. Dr. Lino Guzzella
ETH Zürich
Institute for Dynamic Systems & Control
Sonneggstr. 3
8092 Zürich
ETH-Zentrum
Switzerland
E-mail: lguzzella@ethz.ch

Dr. Christopher H. Onder
ETH Zürich
Institute for Dynamic Systems & Control
Sonneggstr. 3
8092 Zürich
ETH-Zentrum
Switzerland
E-mail: onder@ethz.ch

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Preface

Who should read this text?

This text is intended for students interested in the design of classical and novel IC engine control systems. Its focus lies on the control-oriented mathematical description of the physical processes involved and on the model-based control system design and optimization.

This text has evolved from a lecture series held during the last several years in the mechanical engineering (ME) department at ETH Zurich. The target readers are graduate ME students with a thorough understanding of basic thermodynamic and fluid dynamics processes in internal combustion engines (ICE). Other prerequisites are knowledge of general ME topics (calculus, mechanics, etc.) and a first course in control systems. Students with little preparation in basic ICE modeling and design are referred to [64], [97], [194], and [206].

Why has this text been written?

Internal combustion engines represent one of the most important technological success stories in the last 100 years. These systems have become the most frequently used sources of propulsion energy in passenger cars. One of the main reasons that this has occurred is the very high energy density of liquid hydrocarbon fuels. As long as fossil fuel resources are used to fuel cars, there are no foreseeable alternatives that offer the same benefits in terms of cost, safety, pollutant emission and fuel economy (always in a total cycle, or "well-to-wheel" sense, see e.g., [5] and [68]).

Internal combustion engines still have a substantial potential for improvements; Diesel (compression ignition) engines can be made much cleaner and Otto (spark ignition) engines still can be made much more fuel efficient. Each goal can be achieved only with the help of control systems. Moreover, with the systems becoming increasingly complex, systematic and efficient system design procedures have become technological and commercial necessities. This text addresses these issues by offering an introduction to model-based control system design for ICE.

What can be learned from this text?

The primary emphasis is put on the ICE (torque production, pollutant formation, etc.) and its auxiliary devices (air-charge control, mixture formation, pollutant abatement systems, etc.). Mathematical models for some of these processes will be developed below. Using these models, selected feedforward and feedback control problems will then be discussed.

A model-based approach is chosen because, even though more cumbersome in the beginning, it after proves to be the most cost-effective in the long run. Especially the control system development and calibration processes benefit greatly from mathematical models at early project stages.

The appendix contains a brief summary of the most important controller analysis and design methods, and a case study that analyzes a simplified idle-speed control problem. This includes some aspects of experimental parameter identification and model validation.

What cannot be learned from this text?

This text treats ICE systems, i.e., the load torque acting on the engine is assumed to be known and no drive-train or chassis problems will be discussed.

Moreover, this text does not attempt to describe *all* control loops present in engine systems. The focus is on those problem areas in which the authors have had the opportunity to work during earlier projects.

Acknowledgments

Many people have implicitly helped us to prepare this text. Specifically our teachers, colleagues and students have helped to bring us to the point where we felt ready to write this text. Several people have helped us more explicitly in preparing this manuscript: Alois Amstutz, with whom we work especially in the area of Diesel engines, several of our doctoral students whose dissertations have been used as the nucleus of several sections (we reference their work at the appropriate places), Simon Frei, Marzio Locatelli and David Germann who worked on the idle-speed case study and helped streamlining the manuscript, and, finally, Brigitte Rohrbach and Darla Peelle, who translated our manuscripts from “Germlish” to English.

Zurich, May 2004

Lino Guzzella
Christopher H. Onder

Preface to the Second Edition

Why a second edition?

The discussions concerning pollutant emissions and fuel economy of passenger cars constantly intensified since the first edition of this book was published. Concerns about the air quality, the limited resources of fossil fuels and the detrimental effects of greenhouse gases further spurred the interest of both the industry and academia to work towards improved internal-combustion engines for automotive applications. Not surprisingly, the first edition of this monograph rapidly sold out. When the publisher inquired about a second edition, we decided to seize this opportunity for revising the text, correcting several errors, and adding some new material. The following list outlines the most important changes and additions included in this second edition:

- restructured and slightly extended section on superchargers, increasing the comprehensibility;
- short subsection on rotational oscillations and their treatment on engine test-benches, being a safety-relevant aspect;
- improved physical and chemical model for the three-way catalyst, simplifying the conception and realization of downstream air-to-fuel ratio control;
- complete section on modeling, detection, and control of engine knock;
- new methodology for the design of an air-to-fuel ratio controller exhibiting several advantages over the traditional H_∞ approach;
- short introduction to thermodynamic engine-cycle calculation and some corresponding control-oriented aspects.

As in the first edition, the text is focused on those problems we were (or still are) working on in our group at ETH. Many exciting new ideas (HCCI combustion, variable-compression engines, engines for high-octane fuels, etc.) have been proposed by other groups. However, simply reporting those concepts without being able to round them off by first-hand experience would not add any benefit to the existing literature. Therefore, they are not included in this book, which should remain an introductory reference for students and engineers new to the topic of internal-combustion engines.

Acknowledgements

We want to express our gratitude to the many colleagues and students who reported to us errors and omissions in the first edition of this text.

Several people have helped us improving this monograph, in particular Daniel Rupp, Roman Möller and Jonas Asprion who helped preparing the manuscript.

Zurich, September 2009

Lino Guzzella
Christopher H. Onder

Contents

1

Introduction

In this chapter, first the notation used throughout this text is defined. It further contains some general remarks on electronic engine control systems and introduces the most common control problems encountered in spark ignition (Otto or gasoline) and compression ignition (Diesel) engine systems. The intention is to show the general motivation for using control systems and to give the reader an idea of the problems that can be tackled by feedforward and feedback control systems for both SI and CI engines.

The emphasis in this chapter is on qualitative arguments. The mathematically precise formulation is deferred to subsequent chapters. Those readers not familiar with modern electronic sensors, actuators, and control hardware for automotive applications may want to consult either [7], [108], or [125].

1.1 Notation

The notation used in this text is fairly standard. The *derivative* of a variable $x(t)$, with respect to its independent variable t, is denoted by

$$\frac{d}{dt}x(t)$$

while the notation

$$\dot{x}(t)$$

is used to indicate a *flow* of mass, energy, etc. Both variables $\frac{d}{dt}x(t)$ and $\dot{x}(t)$ have the same units, but they are different objects. No special distinction is made between scalars, vectors and matrices. The dimensions of a variable, if not a scalar, are explicitly defined in the context. Input signals are usually denoted by $u_{\ldots}$ and output signals by $y_{\ldots}$, whereas the index $\ldots$ specifies what physical quantity is actuated or measured.

Concentrations of chemical species C are denoted by $[C]$, with units mol/mol, with respect to the reference substance. The concentrations are therefore limited to the interval $[0, 1]$. The concentration of pollutant species are often shown in plots or tables using *ppm* units (part per million), i.e., by using a amplification factor of 10^6. For mass storage and transportation models it is advantageous to use mass fractions, which are denoted by ξ having units [kg/kg].

In general, all variables are defined at that place in the text where they are used for the first time. To facilitate the reading, some symbols have been reserved for special physical quantities:

α	$[\frac{W}{m^2 K}]$	heat-transfer coefficient
A	$[m^2]$	area
c_x	$[\frac{J}{kgK}, \text{-}]$	specific heat capacities ($x = p, v$), concentration of x
ε	[-]	compression ratio, volume fraction
η	[-]	efficiency
ϕ	$[^\circ, rad]$	crank angle
γ	[-]	gear ratio
H	$[J]$	enthalpy
κ	[-]	ratio of specific heats
λ	[-]	air-to-fuel ratio, volumetric efficiency, Lagrange multiplier
m	$[kg]$	mass
M	$[\frac{kg}{mol}]$	molar mass
N	[-]	number of engine revolutions per cycle (1 for two-stroke, 2 for four-stroke engines)
ν	[-]	stoichiometric coefficient
p	$[Pa, bar]$	pressure
P	$[W]$	power
Π	[-]	pressure ratio
Q	$[J]$	heat
r	$[m, \frac{mol}{s}]$	radius, reaction rate
ρ	$[\frac{kg}{m^3}]$	density
R	$[\frac{J}{kgK}]$	specific gas constant
$\mathcal{R}$	$[\frac{J}{molK}]$	universal gas constant
σ_0	[-]	stoichiometric air-to-fuel ratio
t	$[s]$	time (independent variable)
τ	$[s]$	time (interval or constant)
ϑ	$[K, ^\circ C]$	temperature
θ	[-]	occupancy
T	$[Nm]$	torque
Θ	$[m^2 kg]$	rotational inertia
u, y	[-]	control input, system output (both normalized)
V	$[m^3, l]$	volume
ζ	$[^\circ]$	ignition angle
ω	$[\frac{rad}{s}]$	rotational speed or angular frequency
ξ	[-]	mass fraction

Similarly, some indices have been reserved for special use. The following list shows what each of them stands for:

α, a, β	ambient air
c	compressor or cylinder
e	engine
eg	exhaust gas
egr, ε	exhaust-gas recirculation
f, φ, ψ	fuel
γ	engine outlet
l	load
m	manifold or mean value
seg	segment
t	turbine
ξ	combustion
ζ	timing (e.g. of ignition or injection)

In a turbocharged engine system, the four most important locations are designated by the indices 1 for "before compressor," 2 for "after compressor," 3 for "after engine," and 4 for "after turbine."

In general, all numerical values listed in this text are shown in SI units. A few exceptions are made where non-SI units are widely accepted. These few cases are explicitly mentioned in the text.

The most commonly used acronyms are:

BDC (TDC)	bottom (top) dead center (piston at lowest (topmost) position)
BMEP or p_{me}	(brake) mean-effective pressure
bsfc	brake specific fuel-consumption
CA	crank angle
CI	compression ignition (in Diesel engines)
CNG	compressed natural gas
COM	control-oriented model
DEM	discrete-event model
DPF	Diesel particulate-filter
ECU	electronic (or engine) control unit
IEG	induction-to-exhaust delay
IPS	induction-to-powerstroke delay
IVC (IVO)	inlet-valve closing (opening)
EVC (EVO)	exhaust-valve closing (opening)
MBT	maximum brake torque (ignition or injection timing)
OC	oxidation catalyst
ODE	ordinary differential equation
ON	octane number
PDE	partial differential equation
PM	particulate matter

SCR	selective catalytic reduction
SI	spark ignition (in Otto/gasoline/gas engines)
TPU	time-processing unit
TWC	three-way catalytic converter
VNT	variable-nozzle turbine
WOT	wide-open throttle

1.2 Control Systems for IC Engines

1.2.1 Relevance of Engine Control Systems

Future cars are expected to incorporate approximately one third of their parts value in electric and electronic components. These devices help to reduce the fuel consumption and the emission of pollutant species, to increase safety, and to improve the drivability and comfort of passenger cars. As the electronic control systems become more complex and powerful, an ever increasing number of mechanical functions are being replaced by electric and electronic devices. An example of such an advanced vehicle is shown in Fig. 1.1.

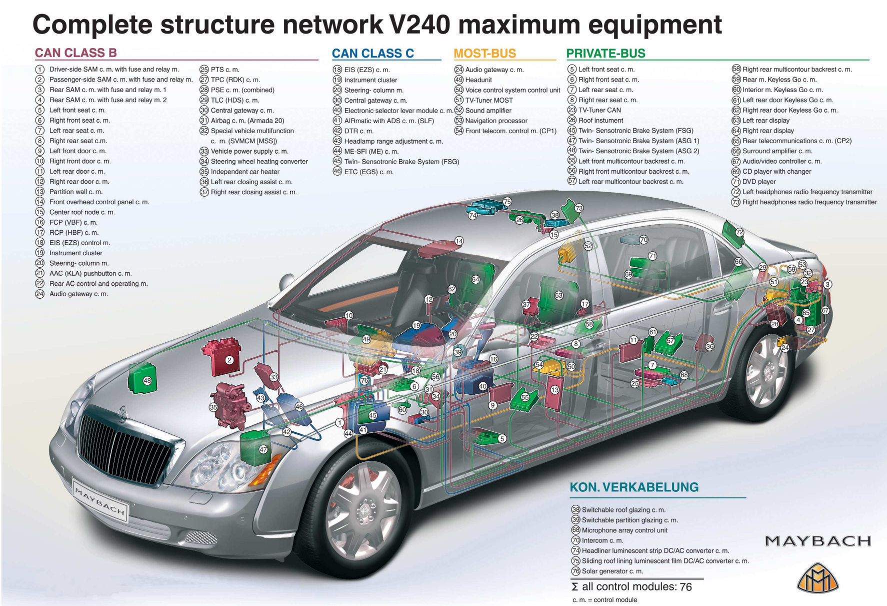


Fig. 1.1. Wiring harness of a modern vehicle (Maybach), reprinted with the permission of Daimler AG.

In such a system, the engine is only one part within a larger structure. Its main input and output signals are the commands issued by the electronic control unit (ECU) or directly by the driver, and the load torque transmitted through the clutch onto the engine's flywheel. Figure 1.2 shows a possible substructure of the vehicle control system. In this text, only the "ICE" (i.e., the engine and the corresponding hardware and software needed to control the engine) will be discussed.

Control systems were introduced in ICE on a larger scale with the advent of three-way catalytic converters for the pollutant reduction of SI engines. Good experiences with these systems and substantial progress in microelectronic components (performance and cost) have opened up a path for the application of electronic control systems in many other ICE problem areas. It is clear that the realization of the future, more complex, engine systems, e.g., hybrid power trains or homogeneous charge compression ignition engines, will not be possible without sophisticated control systems.

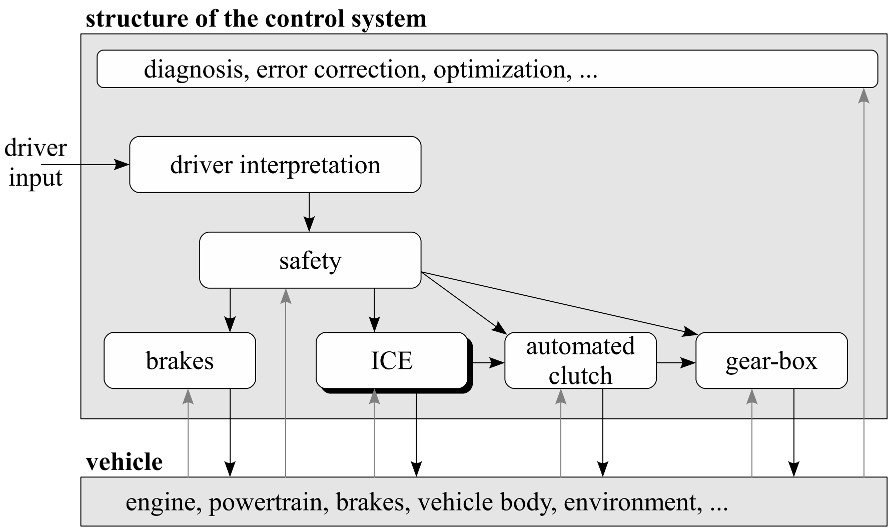


Fig. 1.2. Substructure of a complete vehicle control system.

1.2.2 Electronic Engine Control Hardware and Software

Typically, an electronic engine control unit (ECU) includes standard microcontroller hardware (process interfaces, RAM/ROM, CPU, etc.) and at least one additional piece of hardware, which is often designated as a *time processing unit* (TPU), see Fig. 1.3. This TPU synchronizes the engine control commands with the reciprocating action of the engine. The synchronization of the ECU with the engine is analyzed in more detail in Sec. 3.1.3.[1] Notice also that clock rates of ECU microprocessors are typically much lower than those of desktop computers due to electromagnetic compatibility considerations.

ECU software has typically been written in assembler code, with proprietary real-time kernels. In the last few years there has been a strong tendency towards standardized high-level programming interfaces. Interestingly, the software is structured to reflect the primary physical connections of the plant to be controlled [70].

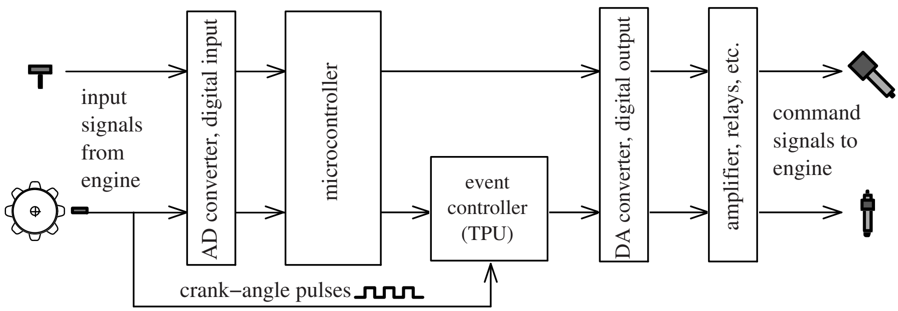


Fig. 1.3. Internal structure of an electronic engine control unit.

1.3 Overview of SI Engine Control Problems

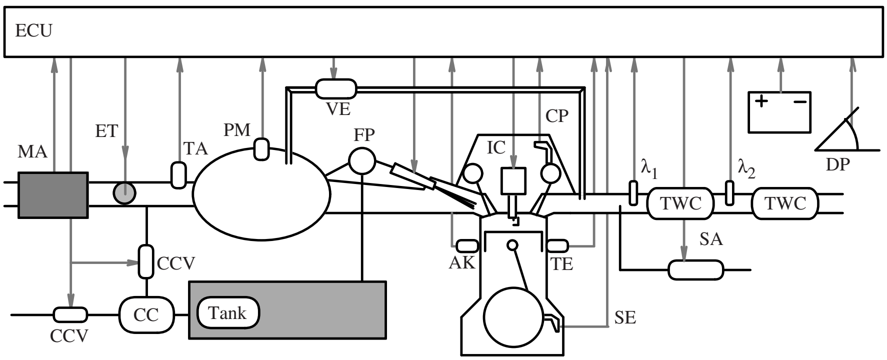
1.3.1 General Remarks

The majority of modern passenger cars are still equipped with port (indirect) injection spark-ignited gasoline engines. The premixed and stoichiometric combustion of the Otto process permits an extremely efficient exhaust gas purification with three-way catalytic converters and produces very little particulate matter (PM). A standard configuration of such an engine is shown in Fig. 1.4.

The torque of a stoichiometric SI engine is controlled by the quantity of air/fuel mixture in the cylinder during each stroke (the quality, i.e., the air/fuel ratio, remains constant). Typically, this quantity is varied by changing the intake pressure and, hence, the density of the air/fuel mixture. Thus, a throttle plate is used upstream of the combustion process in the intake system. This solution is relatively simple and reliable, but it produces substantial "pumping losses" that negatively affect the part-load efficiency of the

[1] The reciprocating or *event-based* behavior of all ICE also has important consequences for the controller design process. These problems will be addressed in Chapters 3 and 4.

engine. Novel approaches, such as electronic throttle control, variable valve timing, etc., which offer improved fuel economy and pollutant emission, will be discussed below.



AK	knock sensor	PM	manifold pressure sensor	VE	EGR valve
CP	camshaft sensor	ET	electronic throttle	SA	secondary air valve
IC	ignition command	TA	intake air temperature sensor	TWC	3-way catalyst
MA	air mass-flow sensor	TE	cooling water temperature sensor	ECU	controller
SE	engine speed sensor	CC	active carbon canister	CCV	CC control valves
FP	fuel pressure control	$\lambda_{1,2}$	air/fuel ratio sensors	DP	driver pedal

Fig. 1.4. Overview over a typical SI engine system structure.

A simplified control-oriented substructure of an SI engine is shown in Fig. 1.5. The main blocks are the fuel path P_φ and the air path P_α, which define the mixture entering the cylinder, and the combustion block P_χ that determines the amount of torque produced by the engine.

Other engine outputs are the knock signal y_ζ (as measured by a knock sensor P_ζ) and the engine-out air/fuel ratio y_λ (as measured by a λ sensor P_λ mounted as close as possible to the exhaust valves). The engine speed ω_e is the output of the block P_Θ, taking into account the rotational inertia of the engine, whose inputs are the engine torque T_e and the load torque T_l.

The four most important control loops are indicated in Fig. 1.5 as well:

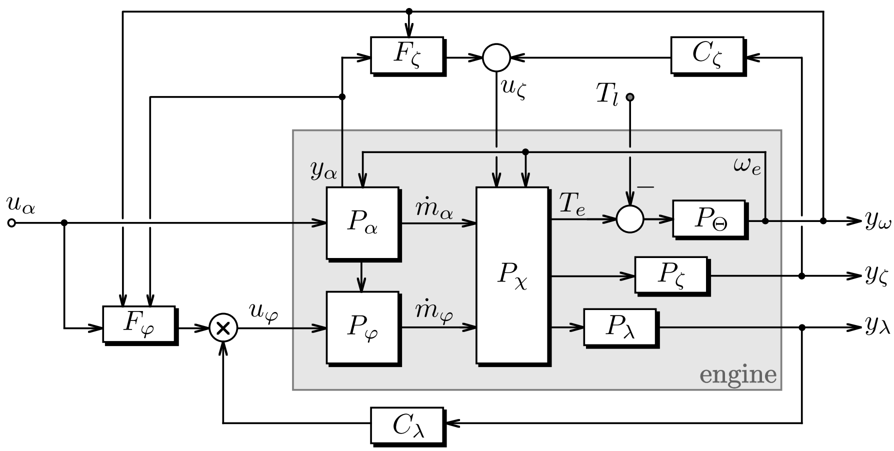
- the fuel-injection feedforward loop;
- the air/fuel ratio feedback loop;
- the ignition angle feedforward[2] loop; and
- the knock feedback loop.

In addition, the following feedforward or feedback loops are present in many engine systems:[3]

[2] Closed-loop control has been proposed in [60] using the spark plug as an ion current sensor.

[3] Modern SI engines can include several other control loops.

- idle and cruise speed control;
- exhaust gas recirculation (for reducing emission during cold-start or for lean-burn engines);
- secondary air injection (for faster catalyst light-off); and
- canister purge management (to avoid hydrocarbon evaporation).



C	feedback controller	α	air	λ	air/fuel ratio	u	input signal
F	feed-forward controller	φ	fuel	ζ	ignition	y	output signal
Θ	inertia	χ	thermodynamics	ω	engine speed	T_l	load torque

Fig. 1.5. Basic SI engine control substructure.

1.3.2 Main Control Loops in SI Engines

Air/Fuel Ratio Control

The air/fuel ratio control problem has been instrumental in paving the road for the introduction of several sophisticated automotive control systems. For this reason, it is described in some detail.

The pollutant emissions of SI engines (mainly hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x)) greatly exceed the limits imposed by most regulatory boards, and future emission legislation will require substantial additional reductions of pollutant emission levels. These requirements can only be satisfied if appropriate exhaust gas after-treatment systems are used.

The key to clean SI engines is a three-way catalytic converter (TWC) system whose stationary conversion efficiency is depicted in Fig. 1.6. Only for a very narrow air/fuel ratio "window," whose mean value is slightly below the stoichiometric level, can all three pollutant species present in the exhaust

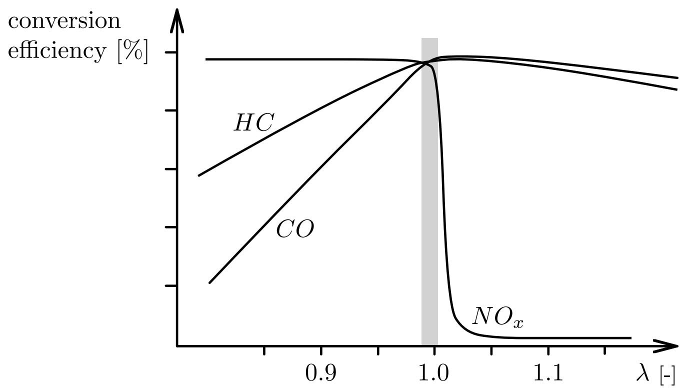


Fig. 1.6. Conversion efficiency of a TWC (after light-off, stationary behavior).

gas be almost completely converted to the innocuous components water and carbon dioxide. In particular, when the engine runs under lean conditions, the reduction of nitrogen oxide stops almost completely, because the now abundant free oxygen in the exhaust gas is used to oxidize the unburned hydrocarbon and the carbon monoxide. Only when the engine runs under rich conditions do the unburned hydrocarbon (HC) and the carbon monoxide (CO) act as agents reducing the nitrogen oxide on the catalyst, thereby causing the desired TWC behavior.

The mean air/fuel ratio can be kept within this narrow band only if electronic control systems and appropriate sensors and actuators are used. The air/fuel ratio sensor (λ sensor) is a very important component in this loop. A precise fuel injection system also is necessary. This is currently realized using "sequential multiport injectors." Each intake port has its own injector, which injects fuel sequentially, i.e., only when the corresponding intake valves are closed.

Finally, appropriate control algorithms have to be implemented in the ECU. The fuel-injection feedforward controller F_φ tries to quickly realize a suitable injection timing based only on the measured air-path input information (either intake air mass flow, intake manifold pressure, or throttle plate angle and engine speed). The air/fuel ratio feedback control system C_λ compensates the unavoidable errors in the feedforward loop. While it guarantees the mean value of the air/fuel ratio to be at the stoichiometric level, it cannot prevent transient excursions in the air/fuel ratio.

Ignition Control

Another important example of a control system in SI engines is the spark angle control system. This example shows how control systems can help improve fuel economy as well.

In fact, the efficiency of SI engines is limited, among other factors, by the knock phenomenon. Knock (although still not fully understood) results from an unwanted self-ignition process that leads to locally very high pressure peaks that can destroy the rim of the piston and other parts in the cylinder. In order to prevent knocking, the compression ratio must be kept below a safe value and ignition timing must be optimized off-line and on-line.

A first optimization takes place during the calibration phase (experiments on engine or chassis dynamometers) of the engine development process. The nominal spark timing data obtained are stored in the ECU. An on-line spark timing control system is required to handle changing fuel qualities and engine characteristics. The key to this component is a knock sensor and the corresponding signal processing unit that monitors the combustion process and signals the onset of knocking.

The feedforward controller F_ζ, introduced in Fig. 1.5, computes the nominal ignition angles (realizing maximum brake torque while avoiding knock and excessive engine-out pollution levels) depending on the engine speed and load (as measured by manifold pressure or other related signals). This correlation is static and is only optimal for that engine from which the ignition data was obtained during the calibration of the ECU. The feedback control system C_ζ utilizes the output of the knock detection system to adapt the ignition angle to a safe and fuel efficient value despite variations in environmental conditions, fuel quality, etc.

1.3.3 Future Developments

Pollutant emission levels of stoichiometric SI engines are or soon will be a "problem solved" such that the focus of research and development efforts can be redirected towards the improvement of the fuel economy. The most severe drawbacks of current SI engines are evident in part-load operating conditions. As Fig. 1.7 shows, the average efficiency even of modern SI engines remains substantially below their best bsfc[4] values. This is a problem because most passenger cars on the average (and also on the governmental test cycles) utilize less than 10% of the maximum engine power.[5] Not surprisingly, cycle-averaged "tank-to-wheel" efficiency data of actual passenger cars are between 12% and 18% only. The next step in the development of SI engines therefore will be a substantial improvement of their part-load efficiency.

Several ideas have been proposed to improve the fuel efficiency of SI engines, all of which include some control actions, e.g.,

- variable valve timing systems (electromagnetic or electrohydraulic);
- downsizing and supercharging systems;
- homogeneous and stratified lean combustion SI engines;

[4] Brake-specific fuel consumption (usually in g fuel/kWh mechanical work).

[5] Maximum engine power is mainly determined by the customer's expectation of acceleration performance and is, therefore, very much dependent on vehicle mass.

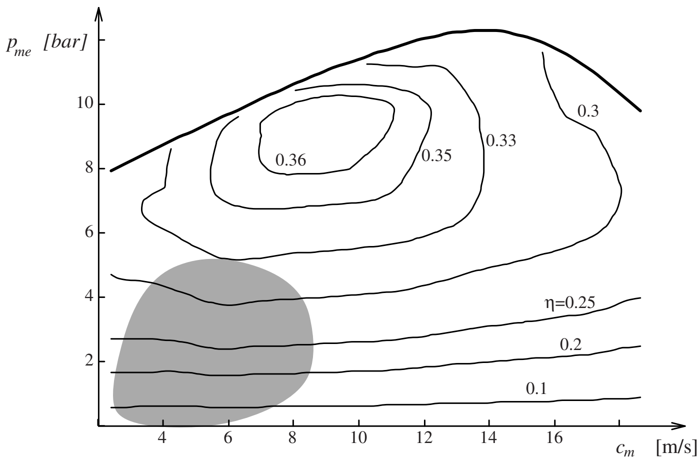


Fig. 1.7. Engine map (mean effective pressure versus mean piston speed) of a modern SI engine, gray area: part-load zone, η =const: iso-efficiency curves. For the definition of p_{me} and c_m see Sect. 2.5.1.

- variable compression ratio engines; and
- engines with improved thermal management.

These systems reduce the pumping work required in the gas exchange part of the Otto cycle, reduce mechanical friction, or improve the thermodynamic efficiency in part-load conditions.

Another approach to improving part-load efficiency is to include novel power train components, such as starter-generator[6] devices, CVTs[7], etc. As mentioned in the Introduction, these approaches will not be analyzed in this text. Interested readers are referred to the textbook [81].

1.4 Overview of Control Problems in CI Engines

1.4.1 General Remarks

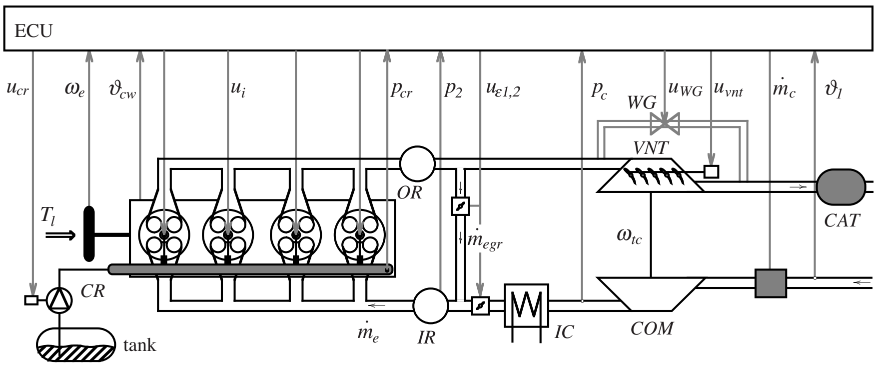
Diesel engines are inherently more fuel-efficient than gasoline engines (see Appendix C), but they cannot use the pollutant abatement systems that have proved to be so successful in gasoline engines. In fact, the torque output of Diesel engines is controlled by changing the air/fuel ratio in the combustion

[6] These advanced electric motors and generators typically have around 5 kW mechanical power and permit several improvements like idle-load shut-off strategies or even “mild hybrid” concepts.

[7] Continuously variable transmissions allow for the operation of the engine at the lowest possible speed and highest possible load, thus partially avoiding the low efficiency points in the engine map.

chamber. This approach is not compatible with the TWC working principle introduced above.

In naturally aspirated Diesel engines, the amount of air available is approximately the same for all loads, and only the amount of fuel injected changes in accordance with the driver's torque request. In modern CI engines the situation is more complex since almost all engines are turbocharged. Turbochargers introduce additional feedback paths, considerably complicating the dynamic behavior of the entire engine system. Additionally, pre-chamber injection has been replaced by direct-injection systems. The injection is thereby realized using either integrated-pump injectors or so-called common-rail systems, of which particularly the latter introduces several additional degrees of freedom.



CAT	oxidation catalytic converter	$u_{\varepsilon 1,2}$	EGR valve(s) command	p_c	pressure after COM
COM	compressor	u_{cr}	CR pump command	p_2	intake pressure
CR	common-rail system	u_i	injection command	p_{cr}	CR injection pressure
IR	intake receiver	u_{vnt}	turbine nozzle command	$\dot{m}_c$	intake air mass flow
OR	outlet receiver	u_{WG}	WG command	ϑ_1	intake air temperature
IC	intercooler	T_l	load torque at the flywheel	ϑ_{cw}	cooling water temperature
VNT	variable nozzle turbine	ω_{tc}	turbocharger speed	ω_e	engine speed
WG	waste-gate (alternative to VNT)	$\dot{m}_e$	total engine-in mass flow	$\dot{m}_{egr}$	exhaust gas recirculation

Fig. 1.8. Overview of a typical system structure of a Diesel engine.

Compression ignition, or Diesel engines, have been traditionally less advanced in electronic controller utilization due to cost, reliability, and image problems in the past. However this situation has changed, and today, electronic control systems help to substantially improve the total system behavior (especially the pollutant emission) of Diesel engines [79].

Figure 1.8 shows an overview of a typical modern Diesel engine as used in passenger cars. The main objective for electronic Diesel-engine control-systems is to provide the required engine torque while minimizing fuel consumption and complying with exhaust-gas emissions and noise level regulations. This requires an optimal coordination of injection, turbocharger and exhaust-gas recirculation (EGR) systems in stationary and transient operating conditions.

From a control-engineering point of view, there are three important paths which have to be considered: fuel, air and EGR. Figure 1.9 shows a schematic overview of the basic structure of a typical Diesel-engine control-system, clearly pointing out these three paths (for more details on the inner structure of the Diesel engine, see Sect. 2.1). Notice that a speed controller is standard in Diesel engines: The top speed must be limited in order to prevent engine damage whereas the lower limit is imposed by the desired running smoothness when idling.

The fuel path with the outputs torque, speed, and exhaust-gas emissions obtains its inputs from the injection controller. The control inputs to the fuel path are start of injection, injection duration, and injection pressure. With common-rail systems, new degrees of freedom, such as the choice of a pilot injection, main and after-injection quantities with different dwell times in-between, are added. The injected fuel mass is, if necessary, adjusted by the speed controller and has an upper boundary often called the smoke limit: Using the measurement of the air mass-flow into the engine, the maximum quantity of injected fuel is calculated such that the air/fuel ratio does not fall below a certain (constant or operating-point dependent) value. This prevents the engine from producing visible smoke as often seen on older vehicles during heavy acceleration.

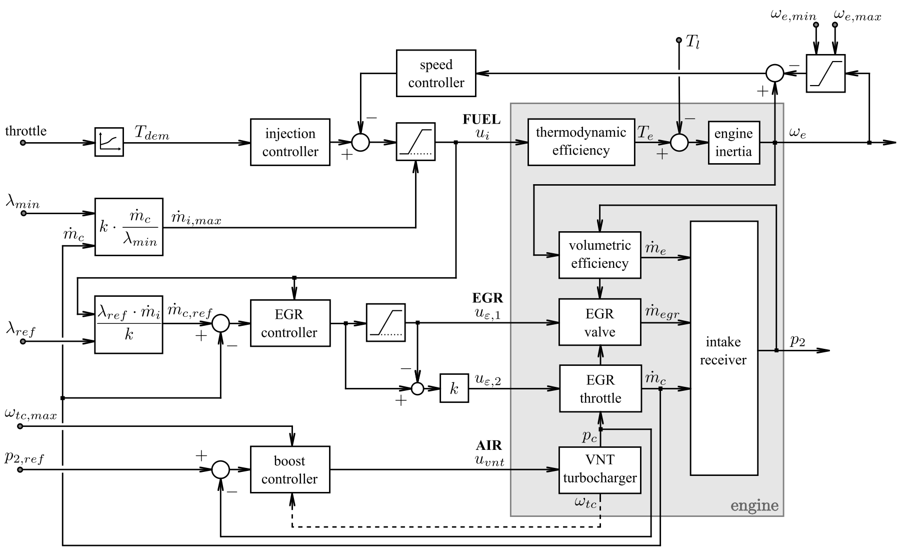


Fig. 1.9. Basic Diesel-engine control-system structure, variables as defined in Fig. 1.8.

The turbocharger dominates the air path. Especially in applications with heavy transient operations, turbocharger designs with small A/R ratios (nozzle area over diameter of the turbine wheel) are chosen to get a good acceleration performance of the supercharging device. Unfortunately, at high loads the small-sized turbocharger works inefficiently and creates high back pressure increasing the pumping work of the engine. Therefore, a substantial fraction of the exhaust gas has to bypass the turbine through a waste gate and at a certain point, not enough enthalpy can be extracted from the exhaust gas, leading to a lack in boost pressure and thus constraining the entire engine system. Besides this, the turbocharger speed has to be limited in order to prevent mechanical damage, further restricting the maximum power output of small-sized turbines.

With the expectations of good acceleration performance and high turbocharger efficiency over the whole range of operation, instead of waste-gate systems variable nozzle turbochargers (VNT) are used. They overcome the trade-off between acceleration performance and sufficient power output at high loads by adjusting the nozzle area as needed. Another approach is two-stage charging, combining a small and a large turbocharger in serial configuration. The former accelerates quickly and ensures good driveability, while the latter provides high boost pressures at high mass flows when needed.

Turbochargers are typically controlled using a closed-loop approach where the measured output is the boost pressure. However, special care has to be taken to keep them from reaching dangerously high rotational speeds.[8]

1.4.2 Main Control Loops in Diesel Engines

With emission legislation becoming ever more stringent, exhaust-gas recirculation is needed for NO_x reduction. A closed-loop control system takes care of the EGR path. Even if the objective is EGR control, the closed loop takes the measured air mass-flow as the feedback variable. A Diesel engine produces smoke if the air/fuel ratio falls below a certain value. The air/fuel ratio with the best NO_x reduction under the boundary condition of no increase in smoke generation is mapped over the quantity of fuel injected and the engine speed. Together with the quantity of fuel injected, which is known from the injection table, the reference air mass-flow can be derived. The EGR valve position is determined from the difference between reference and measured air mass-flows. The EGR flow heavily affects the air mass-flow through the states of the intake and outlet receiver. Additional devices, such as throttles, must be used to maintain a pressure difference over the EGR valve.

While engine performance, dynamic behavior and fuel consumption are important criteria for engine manufacturers, all engine system must comply

[8] Note that it is not sufficient to limit the boost pressure. Depending on the operating point and on the ambient conditions, e.g. high altitude and the corresponding low ambient pressure, the turbocharger speed may exceed critical limits even while the demanded boost is not attained. Measuring the turbocharger speed, as indicated in Figure 1.9, or calculating it on-line by means of an observer in the boost controller is the only way to reliably resolve this problem.

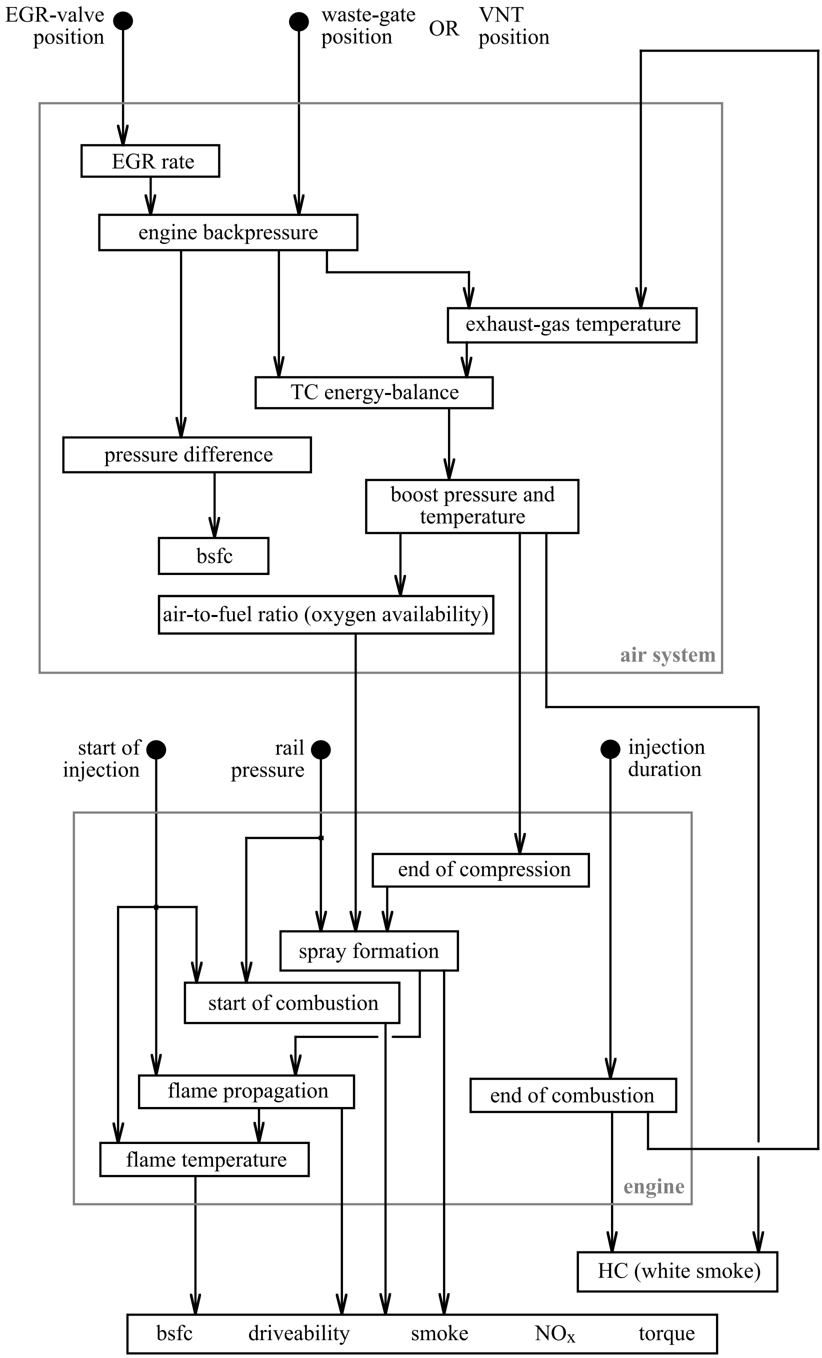


Fig. 1.10. Qualitative input-output relations in a Diesel engine.

with the emission limits. Figure 1.10 summarizes the main input-output relationship and attempts to illustrate the complex network of the underlying physics. In most cases, a single control input affects several outputs.

Three main phenomena are especially important for understanding the key issues of emission control in Diesel engines:

- The thermal efficiency[9] of any combustion process (see Appendix C) depends on the mean combustion temperature ϑ_{com} (determined by the thermodynamic cycle)
$$\eta_{th} = 1 - \frac{\vartheta_{exh}}{\vartheta_{com}} \tag{1.1}$$
where ϑ_{exh} is the mean exhaust temperature. Obviously, the higher the combustion temperature with respect to the exhaust temperature, the better the thermal efficiency and, therefore, the lower the fuel consumption.
- The rate at which NO is produced can be approximated, according to [97], by
$$\frac{d}{dt}[NO] = \frac{6 \cdot 10^{16}}{\sqrt{\vartheta}} \cdot e^{\frac{-69090}{\vartheta}} \cdot [O_2]^{1/2} \cdot [N_2] \tag{1.2}$$
where [.] denotes equilibrium concentrations. The strong dependence of the NO formation on the temperature ϑ of the burned gas fraction in the exponential term is evident. High temperatures and oxygen concentrations, therefore, result in high rates of NO formation.
- Diesel particulate matter consists principally of combustion-generated soot absorbing organic compounds. Lubricating oil contributes to the formation of particulate matter. The amount of particulate matter produced during combustion depends on oxygen availability, spray formation and oxidation conditions towards the end of the combustion process.

These facts raise the question of how the electronic control inputs affect the key parameters mentioned:

- *Brake-specific fuel consumption:* With a given injection amount, the main inputs to improve bsfc are start of injection, rail pressure, and boost pressure. An early start of injection results in a fast heat release around top dead center (TDC). Because of the sinusoidal motion of the piston in this area, the volume of the combustion chamber remains almost constant, which results in high gas temperatures and, thus, a good thermal efficiency. Increasing the rail and boost pressures leads to shorter ignition delays and faster burn rates due to faster fuel evaporation and higher in-cylinder temperatures and pressures, respectively.
- *NO formation:* A late start of injection, combined with EGR, yields low in-cylinder temperatures and therefore reduces the NO_x formation. At the same time, relatively high temperatures during the expansion stroke enhance the reduction of NO being formed. Note that these measures are conflicting the ones stated for improved bsfc above.

[9] Sometimes also called the Carnot efficiency.

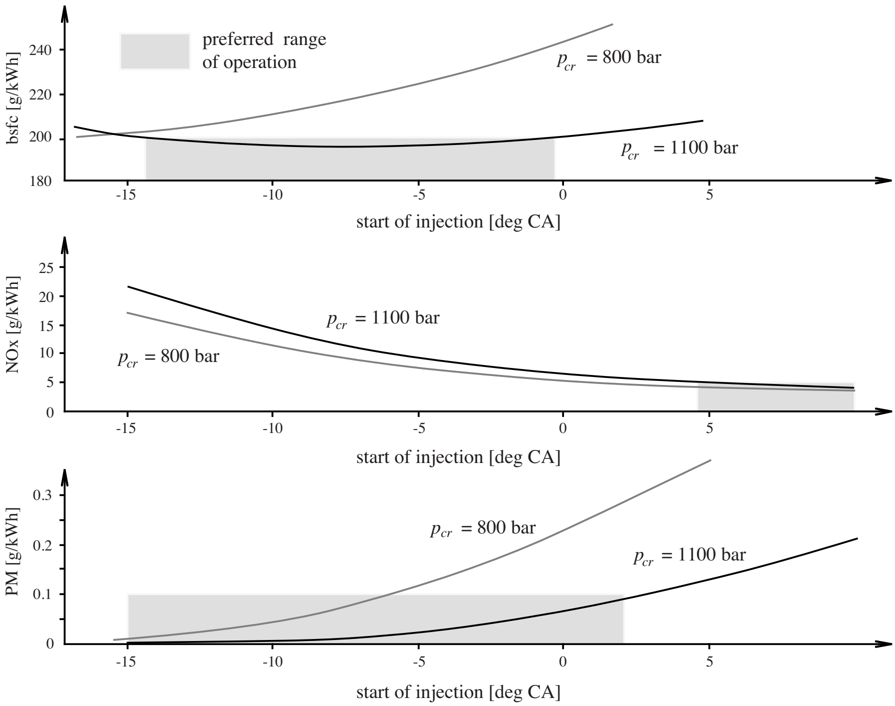


Fig. 1.11. Influence of start of injection on bsfc and on the emission of PM and NO_x, with p_{cr} representing the injection pressure.

- *Particulate matter (PM):* Early start of injection with its fast, hot and complete combustion produces low amounts of particulate matter. Additionally, with an early start of injection, conditions for soot oxidation are good during the long period of the expansion stroke. Due to the good influence on spray formation, high injection pressures also are beneficial for obtaining low amounts of PM. Unfortunately, the high-pressure fuel pump introduces an additional load and thus reduces the engine's overall efficiency.

The tendencies of various input-output relations are summarized in Table 1.1. It shows the difficulty of stating clear control objectives, since nearly every input has a good and a bad effect on the outputs of interest. A well-known method for dealing with the PM-NO_x trade-off is to vary the start of injection from early (e.g., 30 degrees before TDC) to late (e.g., eight degrees after TDC). The optimal injection timing is selected as the one where the trade-off curve crosses the acceptable emission limits defined by the corresponding emission regulations. This approach, however, does not take into account that bsfc should be as low as possible.

Table 1.1. Tendencies in the influence of control inputs on fuel economy (bsfc) and emission quantity.

Control Input	**Result**
early start of injection	good bsfc low particulate matter high NO_x
high rail pressure	increased NO_x low PM slightly improved bsfc
pilot injection(s)	low noise
smaller VNT area	improved bsfc lower particulate matter higher NO_x
increased EGR	lower NO_x danger of higher PM improved noise equal or slightly increased bsfc

The PM-NO_x trade-off is inherently connected to the principle of the Diesel cycle and creates an obstacle that is difficult to surmount. Figure 1.11 shows the influence of injection on bsfc and on the emission of NO_x and PM. The shaded areas indicate where the emission values are within the regulations and where bsfc is below 200 g/kWh. In this case, even with an injection pressure of 1100 bar, there is no starting point for the injection at which NO_x and PM satisfy current emission limits. Especially in Europe, selective catalytic reduction (SCR) technologies are increasingly used to clean the exhaust gas from NO_x, breaking the PM-NO_x trade-off (see Section 2.9).

For concepts not using SCR, the problem is being tackled in the following order: Sophisticated developments are pursued in the areas of the combustion chamber as well as for the injection, air, and EGR systems. The electronic control system must then guarantee the best use of the given hardware under stationary and transient conditions. Regardless of the selected strategy, model-based controller designs play an important role as an enabling technology.

1.4.3 Future Developments

Diesel engines clearly have a high potential to become much cleaner. On one hand, progress in reducing engine-out emissions will continue. On the other hand, several aftertreatment systems are ready to be introduced on a large scale.

In heavy-duty applications, where fuel economy is a top priority, lean de-NO_x systems using a selective catalytic reduction (SCR) approach are an interesting alternative. Such systems can reduce engine-out NO_x by approximately one order of magnitude. This permits the engine to be calibrated at the high-efficiency/low-PM boundary of the trade-off curve (see Fig. 1.11, early injection angle). The drawback of this approach is, of course, the need for an additional fluid distribution infrastructure (most likely urea).

While such systems are feasible in heavy-duty applications, for passenger cars it is generally felt that a solution with Diesel particulate filters (DPF) is more likely to be successful on a large scale. These filters permit an engine calibration on the high-PM/low-NO_x side of the trade-off. Using this approach, engine-out NO_x emissions are kept within the legislation limits by using high EGR rates but without any further after-treatment systems.

Radically new approaches, such as cold-flame combustion (see e.g., [190]) or homogeneous-charge compression ignition engines (HCCI, see [187], [188], [172] for control-oriented discussion) promise further reductions in engine-out emissions, especially at part-load conditions.

In all of these approaches, feedforward and feedback control systems will play an important role as an enabling technology. Moreover, with ever increasing system complexity, model-based approaches will become even more important.

1.5 Structure of the Text

The main body of this text is organized as follows:

- Chapter 2 introduces mean-value[10] models of the most important phenomena in IC engines.
- Chapter 3 derives discrete-event or crank-angle models for those subsystems that will need such descriptions to be properly controlled.
- Chapter 4 discusses some important control problems by applying a model-based approach for the design of feedforward as well as feedback control systems.

In addition to these three chapters, the three appendices contain the following information:

- Appendix A summarizes, in a concise formulation, most of the control system analysis and synthesis ideas that are required to follow the main text.

[10] The term mean-value is used to designate models that do not reflect the engine's reciprocating and hence crank-angle sampled behavior, but which use a continuous-time lumped parameter description. Discrete-event models, on the other hand, explicitly take these effects into account.