Discrete-event models (DEM) of selected engine subsystems are the subject of this chapter. The input and output signals of these systems either are not defined or are not relevant continuously, but only at certain discrete instances. Thus, the system behavior associated with the sampling of the signals, the delays caused by the timing relations, and the interaction with the ECU (which operates in a discrete-time way as well), become important.

Crank-angle based representations are often used for IC engine models. This change in the independent variable from time $t$ to crank angle $\phi$ has advantages for certain control problems. Specifically, the feedforward action of the air/fuel ratio control system needs this special representation because it must be realized with the maximum bandwidth achievable. It is thus very sensitive to any errors in modeling the delays and the timing relations.

The following items are discussed in this chapter:

- When are DEM required?
- Various ECU operation modes and time scales.
- Precise timing of injection and ignition commands.
- DEM of torque production in IC engines.
- DEM of the air flow in IC engines.
- DEM of the fuel flow in IC engines.
- DEM of back-flow dynamics of CNG engines.
- DEM of residual gas dynamics.
- DEM of exhaust pipe dynamics.
- DEM based on measurements data of the cylinder pressure.

Most of these models are control-oriented models. Only the last model represents a first step toward thermodynamically more detailed ones.

One fundamental assumption that underlies the derivation of all of these models is that the engine speed does not significantly change during one engine cycle. This assumption has been justified in Sect. 2.5.2. Therefore, the models, although being defined in the crank-angle domain, are formulated on the basis of constant sampling times.
3.1 Introduction to DEM

3.1.1 When are DEM Required?

A model of an engine system always includes continuous-time and discrete-event subsystems. Examples of the continuous-time subsystems are the intake manifold dynamics, the acceleration of the crankshaft, the turbocharger speed dynamics. Subsystems that often are modeled as discrete-event systems are the torque production, the gas exchange of the individual cylinders, the injection and the ignition processes, etc.

The ECU is another part of the complete system that is best described using a discrete-time approach. In fact, modern ECUs are always microprocessor systems running various tasks with different sampling times. Section 3.1.3 provides a short overview of the software structure implemented in such ECUs.

The derivation of continuous-time mean-value models for the various engine subsystems is shown in Chap. 2. The discrete working principles of the subsystems must be considered in the following cases:

- When the system representation, and therefore the subsequent controller realization, is simpler in the crank-angle domain.
- When the control system has to achieve bandwidths that make it necessary to take into account the synchronization problems. This is often the case for feedforward control action, since this type of controller usually requires maximum bandwidth attainable.
- When cylinder-individual effects have to be analyzed, e.g., single-cylinder air/fuel control, misfire detection with engine speed measurements, the interpretation of cylinder-pressure measurement data, etc.

Note that it is usually not possible to know at the outset which approach is better suited. A robustness analysis can help to decide whether a time or a crank-angle discretization achieves the best performance. Moreover, the available CPU power does not allow the calculation of control tasks in the so-called “synchro mode” (synchronized with the engine’s crank angle, i.e., using a discrete-event approach) unless it is mandatory to do so.

3.1.2 Discrete-Time Effects of the Combustion

Due to its reciprocating action, an internal combustion engine by its very nature is a discrete-event system. The focus of this chapter is on four-stroke spark ignited (SI) engines. Almost identical models can be derived for two-stroke gasoline engines and Diesel engines.

A cylinder-pressure trajectory and the scaled valve-lift curves are depicted in Fig. 3.1. The timing of the different strokes is indicated as well. As the diagram clearly shows, a single-cylinder engine produces torque every two engine revolutions. This torque acts on the crankshaft during approximately