More Than one Decade with Development of Common-Rail Diesel Engine Management Systems: A Literature Review on Modeling, Control, Estimation and Calibration

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Abstract

Diesel engines are becoming more popular due to their low fuel consumption and emissions. The performance and emissions of diesel engines are strictly influenced by injection pattern and induced air quality. Utilization of diesel engines with mechatronic systems altogether with advent common-rail (CR) injection systems -which promotes the flexibility of injection control- has further increased diesel engine favorability and decreased the level of relevant emissions and noise. Development of mechatronic systems is a hieratical procedure; especially in the case of CR diesel engine control, the extent and diversity of involved topics leads to a complex multi-stage development procedure. Many researches have been carried out and a rich literature has been formed in the field, which addresses different aspects of diesel engine management systems (EMS) development procedure. Investigation of the existing literature will help researchers in the field to have a better understanding of whole diesel EMS development procedure and make them familiar with new trends, state of art technologies and research fields. In this article, the control strategy development of CR diesel EMS is considered using existing literature, i.e. the related literature has been collected and categorized into five main categories of modeling, sensitivity analysis, controller design, estimation and calibration. A brief description of every categories followed by the relevant literature is given in paper and the common methods as well as the state of the arts have been discussed in each section. Finally, the strength and weakness of the existing methods and the potential for further promotions have been mentioned for each stage of EMS development and a roadmap for CR diesel EMS development has been presented.

Keywords: Common Rail Diesel Engine; Engine Control; Electronic Diesel Control; Electronic Control Unit; Automotive Mechatronics;
1 Introduction

Diesel engines are being paid more attention due to their natural high efficiency and low fuel consumption. On the other hand, the diffuse type of combustion occurs in diesel engines leads to generation of emissions and noise. It has been proved that diesel engine emissions depends on fuel injection specifications such as injection pressure, timing and quantity (1). Application of mechatronic systems into diesel engines increases the ability of designers to reduce emissions, fuel consumption and diesel noise. Increase of sensors and actuators leads to a complicated and time-consuming design procedure. Nevertheless, the advantages of employing electronic engine management systems in improvement of diesel engine performance and emissions make it an attractive topic to both industries and universities. Different branches of engineering and science are involved in design and development of EDC, which results in a rich literature in the field. Due to diversity of engine management system analysis and design procedure, a comprehensive study helps researchers to have a better understanding of whole area of the diesel engines control development procedure and its sequences.

Some of the authors try to consider the whole diesel engine management design and describe the procedure. Isermann and Müller considered the whole engine control design procedure (2). They introduced application of the model based control design in diesel engines. They believed that model based calibration methods can reduce the time and cost of controller design and calibration to a high extent. In their paper, the both software and hardware development are considered and different types of simulation are discussed. They have categorized the different simulation-based design methods to three main categories of software in loop (SiL), rapid control prototyping (RCP) and hardware in loop (HiL).

However, other steps might be used like model in loop (MiL) and processor in loop (PiL). Guzzella and Onder mentioned the internal combustion engine control from primary controller design view point (3). They described the different control oriented modeling methods and then discussed the fundamental approaches of controller design. They have categorized different methods of engine modeling to mean value models (MVM) and discrete event models (DEM). Internal combustion engines (ICE) phenomena involve the fast ones with minor constants and others, which have long time constants. In MVM, the fast phenomena such as combustion process are assumed to be static processes and the slower phenomena like manifold processes and engine inertia are considered as dynamic processes. For static processes, their mean value over 6-10 engine cycles are considered in the model. Hafner et al. also mentioned the mechatronic approach for modeling the diesel engine controller (4). In their paper, they have discussed the software/hardware environment for a mechatronic design approach of engine control systems. They considered RCP and HiL in diesel engine controller development procedure. Kiencke and Nielsen mentioned internal combustion engine modeling and different approaches for designing the engine controllers. Different control methods i.e. classic, modern and soft computing controllers are discussed and samples from each control approaches are mentioned.

Despite of the existing literatures, the common rail diesel EMS design procedure has not been considered in comprehensive way using the available literatures. In this article, the procedure of designing CR management systems is addressed from thermo-fluid modeling to optimization and controlling issues. In each category, the state of art technologies and researches are presented using the available literature in a rational sequence. The article leads to a road-map outlined by the sequence of contents on how to develop the common rail diesel engines control systems.

The paper begins with a brief description of methodology of gathering the papers and their classification, after which the papers will be presented in a categorized manner in the next parts. A brief description of engine modeling is discussed and different methods of engine control oriented modeling will be introduced first. Sensitivity analysis and input selection method will be presented latter. The controller architecture is mentioned; the high level and low-level controllers are considered and different methods of controller designing are investigated. After which a comprehensive discussion on estimation methods in diesel engines will be done. The paper ends with a brief discussion of optimization and calibration methods in common rail diesel engines. The sequences of presented categories are shown in Table 1.
Table 1 The sequence of involved categories in CR diesel engine mechatronics system development literature review

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
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<tr>
<td>Diesel Engine Modeling</td>
<td>Control Oriented Modeling</td>
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<td></td>
<td>Thermodynamic Modeling</td>
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<td>Injection System Modeling</td>
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<td>Real-Time Capable Engine Modeling</td>
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<td>Sensitivity Analysis</td>
<td>Sensitivity Analysis</td>
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<td>Observer Design</td>
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<td>Fuel Path Controller Design</td>
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<td>Optimization and Calibration</td>
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2 Recent Researches in Common Rail Diesel Engine Management Systems

A comprehensive literature review is done based on journal and conferences papers and published books. The related papers and books are collected and reviewed by authors and a data-base is developed, which contains authors names, affiliation, country, year of publication, journal or conference name, key words and paper abstracts. The papers and books were filtered for their publication year to be newer than 2000. The papers are categorized to four main classes of modeling, system analysis, controller design and optimization. Some papers describe the whole EDC design procedure, which have been presented in introduction.

2.1 Diesel Engine Modeling

ICE modeling is employed extensively in primary phases of engine design. Engine modeling is usually based on physical and empirical models of phenomena occur inside the cylinder and other engine components. The approach of modeling directly depends on the aim of designer. There is a variety of methods for engine modeling; thermodynamic modeling, fluid flow modeling and dynamic modeling are among them. The proper model for engine control takes into the consideration the dynamic behavior of engine. The dynamic models with detailed combustion modeling may also be used for calibration aims. The control-oriented models (COM) should be simple enough to run fast while accurate enough to be reliable. Grondin et al. made a comprehensive study on different methods of control oriented engine modeling (5). They also considered different methods of engine controller development and introduced some professional software in engine modeling field.

2.1.1 Dynamic and Control Oriented Engine Modeling

The engine COMs take into account the phenomena, which cause the engine to behavior dynamically. This category of engine modeling is used in procedure of engine controllers design, calibration, implementation and verification. The COMs make dynamic relation between the engine inputs (actuators) and engine outputs (emission and performance). Based on the aim of modeling both the non-real-time and real-time dynamic models are developed. As shown in Figure 1, a modern common rail diesel engine comprises of inlet/exhaust systems, which are coupled by a variable geometry turbine (VGT) and exhaust gas recirculation (EGR) path. Two intercoolers are usually employed to cool the compressed air and EGR.
gas. The inlet air path is sometimes provided with a throttle valve, which is used for accurate EGR control, i.e. difference in manifold pressure is not sufficient to drive desired exhaust gas flow into inlet manifold for EGR rate increasing. The core of model is the in-cylinder model, which investigates the gas exchange as well as torque generation and emission models. The fuel injection sub-system is also of importance.

![Diagram of proposed turbocharged diesel engine](image)

**Figure 1** The components of proposed turbocharged diesel engine

Inertial parts of engine such as inlet and exhaust manifold processes, fuel rail and pump, turbocharger (TC) inertia and engine rotating inertias need to be modeled in different ways. The dynamic models can be categorized to phenomenological based models, which use governing physical equations to describe the systems dynamics (6) and empirical models, which are based on identification of engine input-output data.

The phenomenological dynamic models consider the inlet and exhaust systems and the other modules, which cause the dynamic behavior of engine. Two main approaches are used for dynamic modeling of engines (3):
- mean value modeling (MVM)
- discrete event modeling (DEM)

MVM is the state of art modeling approach for engine dynamic behavior modeling (7). MVM neglects the discrete cycles of engine and assumes the mean value of 5 to 10 cycles properties of each state instead of their instantaneous values. This method is rapid enough to be used as high level control purpose models. On the other hand, DEM needs more time to run. They are used for calibration and design of time dependent control aims.

The MVM models divide the engine to some sub-systems and assume that whole diesel engine behavior can be modeled by interaction of these sub-systems. The schematics of whole diesel engine sub-systems and their interaction is shown in Figure 2. The whole system is assumed to be composed of 5 main sub-systems of: fuel delivery system (FIS), air induction system (AIS), emission exhaust system (EES), mechanical inertial system and last but not least, the in-cylinder process (ICP). MVM models can be developed using physical models or solely based on input-output data for each mentioned sub-systems. In the latter case, soft computing methods as well as classic identification methods are used.
In the case of ICP, due to relatively fast cyclic process, it can be assumed to be a semi-static process in comparison to other processes. In the other words, ICP can be assumed a nonlinear memory-less procedure while its inputs are obtained by other dynamic systems. The ICP is responsible for prediction of torque generation, emission prediction and gas exchange process. The combustion data is usually being taken into account by look-up tables or interpolated algebraic equation (6). This method is rapid enough to be used for high-level control purposes but they have rarely been considered for modeling the emissions due to their weaknesses in prediction of transient mode emissions and performance indices [15]. Nevertheless, some efforts to implement emissions models as tabulated look-up tables or algebraic polynomial expression (based on engine speed and load) into MVM models can be found in literature (8), (9), (7). Application of steady state data test with not sufficient inputs into MVM leads to inefficient models; usually correction factors are used to compensate for transient prediction errors (8). On the other hand thermodynamic crank angle based modeling has also been implemented directly in MVM models. This type of modeling is computationally inconsistent with real time applications (10). A comprehensive discussion of different types of ICP modeling will be done in next part.

The AIS and EES include the inlet and exhaust systems and the interconnecting systems such as turbochargers and EGR valves. These sub-systems are modeled using appropriate physical equations. Usually combinations of continuity, orifice airflow model, ideal gas and energy equations are used to model the AIS and EES; the pressure and temperature of manifolds are calculated as follows:

**Equation 1**

\[ \dot{p}_{cv} = \frac{\gamma R}{V_{cv}} \left( \sum_{i} T_i \dot{m}_i - \sum_{e} T_e \dot{m}_e \right) \]

**Equation 2**

\[ \frac{d}{dt} m_{cv} = \sum_{i} \dot{m}_i - \sum_{e} \dot{m}_e \]

**Equation 3**

\[ T_{cv} = \frac{V_{cv}}{R m_{cv}} \rho_{cv} \]

Where \(cv, i\) and \(e\) indices stand for control volume (manifold), inlet and exhaust respectively. Turbochargers are modeled using a combination of 1D gas dynamic equations and energy equations. Usually static maps are used to describe the compressor and turbine efficiencies and other performance parameters. The static maps developed for describing compressors operation usually report compressor
efficiency in medium to high speed of compressor operation; as a result extrapolation methods are usually used for lower speeds. Standard methods of extrapolation usually fail to predict compressor efficiency in low TC speeds (11). The same problem exists for turbine. Dinescu and Tazerout used dimensional analysis to overcome this problem (11).

The other engine dynamic modeling approach is empirical modeling; it contains both classical methods and modern soft computing methods. Experimental data in time series format is employed to identify the models, which in turn increase the dependency to costly time-consuming tests. However, in some researches the model based data generation is used to generate sufficient data for identification aims (12), (13). This approach can decrease the cost and time of identification process to some extent.

In the classic approach, such methods as nonlinear auto-regressive moving average with exogenous inputs (NARMAX) (14), subspace method, (12) and linear parametric varying (LPV) (13) are used to identify a dynamic model for diesel engine. The NARMAX method can predict a model for whole engine operation, on the other hand the subspace method can model the engine around an specific operating point. In LPV method, the engine dynamic behavior in whole its operational space is modeled by a state space equation, which its matrices are a function of enigne states. Salcedo and Martinez developed a LPV model for a turbocharged diesel engine. They first derived sufficient number of local linear models around engine operation points and then used the least square method to fit a LPV model based on the mentioned local linear models. They used frequency response comparison to check the validity of model. The diesel engines are highly nonlinear dynamic systems and soft computing methods are best suited for engine modeling. Soft computing methods are intelligent methods, which are used for identification, modeling, control and optimization purposes. A large number of soft computing methods such as fuzzy (15), (16), adaptive network fuzzy inference system (ANFIS) (17), local linear model tree (LOLIMOT) (18) and recurrent artificial neural network (RANN) (19) methods are used to identify diesel engine models. Qiang et al. considered the different approaches of engine dynamic modeling and developed a dynamic model of diesel engine using ANFIS (17). ANFIS is a neural network, which is based on Takagi–Sugeno fuzzy (T-S Fuzzy) inference system. In addition, some researchers used artificial neural networks (ANN) for modeling and identification of engines. Hafner et al. employed LOLIMOT method to model engine dynamics (18). Ouladsine et al. employed neural networks to model the diesel engine dynamics (19). Their model comprises three interconnected sub-models. Experimental data was used to train the ANN. They also used the neural network techniques to design a controller for diesel engine. Zhang and Lan developed a fuzzy model of diesel engine for controlling purposes (15). Due to nonlinearity of engine, they divided the engine operating space to several segments. In every segment, they identified model as a three-order equivalent linear model using correlation analysis-least square method. The results show good accuracy when compared with experimental results.

In addition, special modeling packages are developed to model engine dynamics such as AMESim (20), GT-Power, AVL-Boost and ASCET-MD, which are used in controller development. Recently, a library is developed to be implemented in Matlab/Simulink for engine modeling aims (21).

2.1.2 In-Cylinder Process Modeling (Thermo fluid modeling)

As stated earlier ICP is the core of engine model. Many efforts have been done to model the thermodynamic aspects of compression ignition (CI) engines as well as the gas dynamics involved in the engines. The core of ICP modeling is combustion process. The modeling maybe done without caring the geometric combustion flame propagation (zero dimension), or taking into account the geometric aspects by dividing the chamber into two zones of burned and unburned (two-zone) and lastly assuming multi zones for studying the combustion (multi-zone). From the other point of view, combustion can be studied in one-dimensional space using two-zone or multi-zone approach or analyzed in a three-dimension space using multi zone approach. The thermodynamic models are a variety of application, however, in the case of controller design they are employed in both dynamic model development and engine pre-calibration phases.
A variety of publications can be found which focus on the different approaches of thermodynamic modeling and comparing them. Rakapoulos and Giakoumis considered the different methods of thermodynamic modeling of diesel engines (10). Torkzadeh et al. considered different types of diesel combustion modeling methods (22). They compared different models and mentioned the weakness of zero-dimensional models in prediction of emissions. Finally, they made some comments on how to model the injected fuel jet inside the cylinder.

A major specification of diesel engine combustion models are their ability of emission prediction. Rakapoulos et al. employed two-zone modeling approach to simulate diesel engine operation (23). Their model was able to model fuel jet and its mixing with turbulent air flow inside the cylinder which, enhanced the ability of model to predict the emissions. The model was able to predict emissions using chemical kinetic equations. They also used a model for prediction of soot. Park et al. made a comprehensive study on development of fuel spray inside the cylinder of direct injection (DI) diesel engines (24). They used a macroscopic model for modeling the spray and validate their model with experimental results. They also used a hybrid model for simulating the spray breaking, composed of primary and secondary breakages. The model could predict multiple injection effects on performance and emissions of engine. Aithal et al. developed a model to predict NOx production in diesel engines (25). The model is developed based on physical phenomena and can simulate the combustion rapidly. It predicts NOx production in 8 stages and using 6 different species. HIDECS is a phenomenological model, which has been used for modeling of combustion in direct injection diesel engines. In HIDECS, the spray injected into the combustion chamber from the injection nozzle is divided into many small packages of equal fuel mass with no intermixing between them. The spray characteristics are defined by the empirical equations of spray penetration. The combustion occurs inside the packages may occur in two ways: evaporation-rate-controlled combustion and entrainment-rate-controlled combustion. The occurrence of these types relates to conditions of packages. The concentration of NOx is calculated by using the extended Zeldovich mechanism. The formation of soot is calculated by assuming first-order reaction of fuel vapor. The detailed discussion of model can be found in (26).

The tradeoff between the model accuracy and computational burden of modeling are also of interest of researchers in field. Asprion et al. developed a fast method to simulate NOx production in engine dynamic operation (27). Using a simplified model, which is able to extrapolate the NOx, generation makes it possible to speed up the calculation 500 times faster than real time. The NOx would then be calculated using 10 inputs of engine speed, injected fuel-mass. The model requires the cylinder-charge, its composition, and the start of combustion with the corresponding pressure and temperature as inputs. Some researches have also been carried out to model the effects of multiple injection on performance and emissions of combustion. Barbara et al. developed a non-dimensional model for a common rail high-speed diesel engine (28). Their model was able to predict the effects of multi injection process on performance and emissions. Due to simplicity of their model, it was computationally fast enough to be used for calibration purposes. Seyken et al. developed and validated a model to predict NO and soot in diesel engines (29). Their aim was to limit the computational effort while maintaining the physical/chemical basis in modeling. The input to model is mainly injection pressure pattern and in-cylinder gas condition. Since the majority of fuel is burned in diffuse phase, the NO model considers NO production solely in this phase. The soot production model is based on zero dimensional soot models with some modifications. The whole model is finally validated by test data.

In addition, the transient modeling of diesel engines are getting more attentions. These types of modeling investigate the effects, which cause cycle-by-cycle variation in transient engine operation. Galindo et al. developed a transient thermodynamic model of diesel engine. The transient models take into account the dynamic aspects of engine, caused by gas dynamics and combustion dynamics (30). They used a one-dimensional gas dynamics model accompanied by a neural network for modeling of combustion. Rakopoulos et al. also developed a model for prediction of emissions of a turbocharged diesel engine under transient load conditions (31). They employed a two-zone model for prediction of thermodynamic aspects of the engine. Their model was able to model the NO and soot in transient conditions. 11 chemical species were solved using four atomic balance equations with seven equations for chemical equilibrium.
The engine dynamic aspects were mainly modeled by turbocharger and crankshaft dynamics. The results shows good accuracy of modeling.

Commercial software developed by engine design companies or original equipment manufacturers (OEM) and open source codes such as KIVA is recently extensively being used for simulation of engine behavior. The modeling software provides a pre-designed and verified structure for modeling aims. The user will then select the appropriate modules and tune the regarding parameters according to some limited tests. Shaylar and et al. developed a combustion model of common rail diesel engine using KIVA code to study the effect of split injection on engine soot and NOx (32). They validate the model using experimental test results. Some software packages such as GT-Power and AVL-Boost employs zero dimensional or two-zone combustion modeling approaches (33), (34), (35), (36), (37). This software used a 1D gas dynamic model for modeling the inlet and exhaust systems. In addition, CHEMKIN as a chemical kinetic modeling tool is used altogether with in-cylinder flow pattern simulator to predict the emission generation process inside the cylinder. Pang et al. also used 3D computational fluid dynamics (CFD) to model the influence of injection pattern on engine emissions (38). They linked CHEMKIN-CFD into ANSYS FLUENT to model the combustion inside the cylinder. They used a reduced chemical mechanism comprised 112 reactions with 46 species.

Since utilization of common rail diesel engines, the number of controllable influential parameters on diesel combustion has increased significantly. These new possibilities in engine control increase the demands for thermodynamic models, which can predict the effects of modern actuators such as modern injectors with multiple injections, controllable EGR rate and boost pressure on emissions and performance of engine. The emerging model based calibration (MBC), which will be discussed later needs fast while accurate models, so a tradeoff between model accuracy and complexity will be of interest in engine control field.

### 2.1.3 Injection System Modeling

The common rail diesel engine injection system comprises pump, high-pressure pipes, fuel rail and injector and is an important system in engine operation modeling. Injection system modeling is employed in development of rail pressure controllers and injection controller development. The modeling includes a broad area of system modeling from hydraulic systems to electromagnetic models for driving the injectors.

Varieties of researches are done to model the rail pressure and injector dynamics. Moresseli et al. used energy method to model the injection system components (39). Due to importance of injector behavior on possibility of multiple injection, Bianchi et al. did a research for better modeling the injection system (40). They developed a model, which comprises three main sub-models of electronics, mechanical and hydraulic systems. The inputs to model are the injector geometry, feed pipe pressure, engine chamber pressure, physical properties of the liquid fuel and the current profile. A combined electro-magnetic equation is used to model the current-voltage relation in driving circuit. Also the mass-damper-spring modeling is employed for modeling the mechanical behavior of different phenomena occur in the injector such as internal elastic and viscous actions, impact actions, electro-magnetic actions, external elastic actions and hydraulic actions. They used mass conservation besides Bulk module for modeling the fluid behaviors of injector inside the chamfers and discharge coefficient for modeling the flow between the chambers. The pressure waves inside the rail were neglected in modeling. They used the derived model in the process of developing an open loop driver circuit for injectors (41). They mostly concentrated on decreasing the dwell time between two successive injections in multiple injections. Since any decrease in this time will result in better performance and pollutions of engine, they tried to decrease the time period to 300 μs.

AMESim is recently being increasingly employed for modeling the injection systems (42), (43), (44). Seykens et al. also developed a dynamic model for simulation the injection system in a common rail diesel engine (43). They employed AMESim to model the hydraulic system. The model includes a chain of restrictive and capacitive elements. The capacitive elements are used for predicting the pressure and temperature while the resistive ones are used to estimate the flow rate. The model can predict the

The fluid acceleration and deceleration leads to a pressure wave inside the fuel rail which subsequently affects the injection quantity. Due to importance of pressure wave actions inside the rail, CFD models are employed to simulate the fuel flow inside the rail and pipes and the subsequent pressure variation inside the rail due to pressure waves (45).

### 2.1.4 Real-Time Capable Engine Modeling

A class of diesel engine models is the real-time modeling, which are used in controller implementation phase. The real-time engine models should simulate the engine operation so fast that are synchronous to real engines operation. Usually these real-time engine models are used in HiL test. HiL is one of the final tests done on electronic control unit (ECU) prototypes. In HiL tests, an engine simulator is put in the loop with the real control unit. Using HiL, the faults in control algorithms as well as hardware problems in signal conditioning circuits and output drivers could be found and debugged. Depends on the type of HiL test, sometimes the real actuators and sensors are used in the loop. The most critical specification of HiL models are the execution time of model. Usually, special high performance real time processors are used for execution of engine models on the other hand the models, which are used in HiL, are developed to be run with the least possible computational burdens. Figure 3 illustrates the configuration of a HiL test hardware. The real ECU are connected to virtual engine. Data acquisition modules convert the ECU commands to suitable signals, which can be used by engine simulator. On the other hand, signal conditioner changes the model variables to suitable signals for ECU inputs (voltage and current amplitude and signal shape).

![Virtual Engine For HiL test](image)

**Figure 3 Hardware in the Loop simulation components**

The core of HiL oriented real-time models are a COM model, usually some modifications are done on the model to make it suitable for real time executions. Kohl and Jeminat from dSpace company consider the increasing demands of electronic control systems in automotive industry (46). They mentioned the design time period as a key factor in designing new systems and introduced the model based control system development besides HiL test as a suitable method to decrease the demanded time for design aims.

Lee et al. developed a real-time model to run on PC (47). The HiL configuration was essentially based on PC and commercial off-the-shelf boards. The developed system has the following component: 1-host computer, 2-target computer (real-time computing system), 3-signal interface, sensors and actuators, 4-ECU. The Simulink model were developed on host computer and compiled to be run on target computer.
which is suitable for running real time codes. They used Real-time Workshop® of Matlab® package for compiling the model to real time codes. The engine model was a simple MVM model which was provided with some I/O functions which were responsible for synchronizing the engine model with real ECU. The model is partitioned into an engine subsystem, an analogue I/O subsystem and a timing I/O subsystem. The analog signals are easily used by ECU using simple analog to digital convertors (ADC) modules. Stateflow® is used to make proper event based and timing signals such as speed sensor signals. Finally they employed the developed HiL for designing an Air-Fuel Ratio (AFR) control system. Schulze et al. in dSpace company also developed a crank based model with the ability of modeling engine crank angle depended phenomena (48). They believed that MVM models were not suitable for modern diesel engine management systems, which operate based on in-cylinder pressure. They modified the well-known MVM model by employing heat release functions and developed a complicated model to predict the cylinder pressure in both steady and transient operation. Shaylar et al. developed a real time model of a V type 6 cylinder diesel engine (49). They developed their model in Simulink and compiled the code for running in dSpace. The Simulink models are usually not suitable for high-speed executions, which are needed in real time mode. The dSpace devices have enough capacity to run complicated models with real time constraints. Therefore, the engine is first modeled in Simulink and then compiled to dSpace compatible codes. It seems that HiL modeling is a critical and demanded topic in ECU development process due to the volume of researches done by industries and research centers.

2.2 Sensitivity Analysis and Input Selection

2.2.1 Sensitivity Analysis

In order to design an engine control system, deep understanding of the effects of various inputs variation on engine outputs is required. From a system engineering point of view, modern diesel engines are coupled multi input-multi output (MIMO) systems, i.e. variations of input parameters affect all the outputs of engine to some extent, some of which has favorable effects on a special output and negative effect on the others. As a result, comparing and ranking the influences of different operational parameters on engine emission and performance in different engine conditions will be needed for optimal engine control. In order to do so, sensitivity analysis is done either analytically or experimentally. Although the experimental methods are precise and reliable, but are too expensive and time consuming to be employed in sensitivity analysis. In analytical methods, precise models are of most importance. Many researches have been done to study how variation in diesel engine operational parameters can affect engine performance and emission (outputs). The quality and quantity of effects is identified either analytically or experimentally. In the experimental based studies the required time and cost of experiments is a limiting factor. Carlucci et al. also tried to find the influence of injection parameters such as main injection timing, pilot injection timing and pilot injection duration on level of engine noise and emissions (50). They tested the engine and used analysis of variance (ANOVA) to evaluate the influence of operational parameters variables on engine noise. They found that main injection timing influences the noise generation more than other parameters while the influence of pilot injection timing and duration depends on main injection quantity. Agrawal et al. also tried to investigate the influence of injection pressure and injection timing on engine performance and emissions experimentally (51). The experiment was done in constant speed for two different injection pressure and different start of injection timings. They found that decreasing injection pressure would increase the cylinder maximum pressure and rate of heat release. Also, brake thermal efficiency, brake mean effective pressure (BMEP) and exhaust gases temperature will increase with increasing the injection pressure and advancing injection timing. The effects of injection parameter varying on emissions were also investigated in their research. They found that carbon dioxide and hydrocarbons decrease with increasing injection pressure while nitrogen oxide will decrease. In addition, it was found that advancing the injection timing will decrease CO₂ and hydrocarbons (HC) emissions while increasing NOx. Kannan and Udayakumar considered the effects of injection pressure on efficiency and emissions of diesel engine (52). They found that injection pressure...
has different effects on performance and emissions depend on state of engine operation. They shows that increasing the rail pressure decreases emissions in expense of fuel consumption increase. Gomes et al. used experimental methods to analyze the effects of load, speed, injection timing and swirl ratio on engine emissions such as particulate matters, NOx and HC (53). By analyzing the measured data they find the effects of air and fuel mixing process, flame properties and combustion chamber wall temperature on diesel particulate generation. Tanin et al. studied the effects of injection timing and boost pressure on emissions and performance of a diesel engine using experimental results (54). They first developed a map, which shows the trade-off between NOx and soot in constant start of injection timing. They also studied the effects of boost pressure on engine output emissions. They showed that for constant brake specific NOx generation, the particulate matter (PM) generation would first decrease with increasing the manifold pressure, but after a specified value the PM generation will increase. They also found that brake specific fuel consumption (BSFC) will generally decrease with increasing the inlet pressure.

Although the experimental method is more precise and reliable, they are too expensive and time consuming. As a result, a limited sensitivity analysis is possible in experimental tests i.e. only one or two parameters are usually considered in test procedures. Model based sensitivity analysis is another approach, which is gaining more attention due to its simplicity and its capability for doing sensitivity analysis. The precise models are the core demands for doing such sensitivity analysis; usually a mathematical approach will be used to analyze the influence of operational parameters on model outputs. Many papers can be found in literature, which addresses the development and employment of models for model based sensitivity analysis (28), (22), (55), (56), (57). Shenghua et al. developed a multi zone thermodynamic model of engine to study the engine performance from thermo-fluid aspects (57). They used an upgraded multi-zone model to study the effects of boot shape and split fuel injection characteristics on diesel engine emissions. They implemented air swirl in bowl-in-piston and spray impingement models into available models to predict the effects of induction swirl and spray impingement on the combustion emissions. After developing the model, they analyzed the model and found that boot shaping can affect the emissions more than split injection. They found that the more fuel injected in boot (low mass flow rate part) will result in lower NOx and higher soot. They also recommended that increasing the pressure in second part of boot shape can decrease the NOx generation. They showed that in the case of split injection, the longer splitting time (dwell time) will result in more soot and less NOx production. Wang et al. studied the effects of super high pressure injection with fine hole injectors on performance and emissions of diesel engines (58). They increased injection pressure to 3000 bar and used injectors with 80 µm diameter holes. According to their research results, increasing the injection pressure tends to decrease soot generation. Jayashankara et al. developed a CFD model for diesel engine cycle process modeling to investigate the effects of intake pressure and injection timing on engine performance and emissions (59). They simulate the model for different conditions of inlet pressure and injection timing in constant engine speed. They found that retarding the injection timing increases the cylinder pressure and temperature and NOx emissions. The soot generation is reported to have a non-uniform behavior while time injection is varied. It will first increase due to advancing and after a specified angle it will decrease. Shaylar et al. employed CFD technique to investigate the effects of split injection on diesel engine performance and emissions (60). They tried to find the effects of four parameters of pilot to main injection quantity ratio, start of main injection, the interval of two injections and EGR rate on engine outputs. Jeftic et al. studied the effects of injection pattern on engine emissions (61). They found that post injection will increase CO and decrease NOx and soot of engine.

The results of commercial engine modeling packages are also being used for sensitivity analysis. In literature, many papers can be found which use the results of the mentioned software for sensitivity analysis. KIVA III is extensively used for modeling the engine behavior and considering the effects of varying engine input parameters (62), (63). Furthermore, some software packages such as GT-Power and AVL-Boost are also used for investigation of input parameter influence on engine emissions and performance. Voicu and Chiriac used AVL-Boost to investigate the effects of injection timing on engine emissions and performance (34). They developed a model, based on engine geometry and components
specifications and validated it using experimental data. They tested the model for different injection strategies and used diagrams to compare the effects.

The result of engine models are used for sensitivity analysis based on algebraic, statistical and recently soft computing methods. ANN is a powerful tool for modeling the engines based on the input-output data. It can also be used for analyzing the engine behavior. Al-Hinti et al. studied the effects of inlet air pressure on diesel engine IMEP, performance and BSFC in a single cylinder diesel engine (64). They tested the engine outputs in different speeds and inlet pressures, after which they employed ANFIS as an efficient method to make a model out of the collected experimental data. Uzun used neural network to model a turbocharged diesel engine emission and performance (65). In his research, the effect of three operational parameters including engine speed, load and start of injection on engine BSFC is investigated. Galindo et al. employed neural network to model the combustion of a high-speed direct injection diesel engines in transient regime (66). Along with experimental tests, they developed a phenomenal combustion model to study the effects of EGR rate on engine emissions. A large category of sensitivity analyses is done based on thermodynamic modeling. Parlak et al. employed ANN for modeling engine exhaust temperature and BSFC as a function of BMEP, engine speed and injection timing (67). For gathering the required data, they tested the engine in constant speeds and varied the load. They tested the procedure for four different engine speeds and measured the BSFC and exhaust temperature. The results show ANN ability to model the engine behavior in static conditions. Tennison and Reitz studied the effects of variation of different injection parameters such as injection sequence number, injection pressure, injection start time and injection duration on engine performance and emissions (68). Using experimental methods, they considered and analyzed the effects of parameter variation in a well fashion. According to their research, increasing the injection pressure from 600 to 800 bar can reduce soot up to 50% in late injections. They also found that multiple injections will increase soot production.

Carlucci et al. considered the effects of pilot injection on engine noise and vibration using experimental (69). According to their research results, the early injection will increase noise and vibration in diesel engines. In addition, they found that increasing injection duration in idle speed would increase noise level. They found that fuel injection duration and injection timing have a considerable effect on engine noise level. Badami et al. considered the effects of pilot-pilot-main injection and pilot-main-post injection (70).

Zheng and Kumar studied the effects of multiple injections on NOx and soot generation (71). They believed that increasing the injection sequences up to 8 times would result in a homogenous-similar combustion. Hillion et al. studied the effects of injection timing on engine performance and emissions in order to develop a control scheme (72). Finally using a dynamic model of manifolds and combustion, they could design and implement a control scheme, which was able to put the half of combustion point in desirable set point angle. Payri et al. studied the effects of injection pattern on combustion in idle speed after cold start (73). They employed engine modeling and experimental results to optimize the injection pattern. They also studied the effects of injection pattern on combustion stability. Shihie et al. considered the injection pattern on combustion and performance parameters (74). Using optimization method they could decrease the exhaust gas temperature to 50°C and also engine noise to 15 dB. Nikzadfar and Shamekhi investigated the relative importance of diesel engine inputs on emissions and performance (75). They modeled the diesel engine in-cylinder process using AVL-Boost and trained an ANN using the generated data. After which they used a statistical perturbation method to investigate the relative importance of combustion inputs on torque, BSFC, NOx and soot quantitatively. They found that the relative importance of inputs varies by engine speed and equivalence ratio. In the other application of ANN in modeling the engine Parlak et al. used the model to investigate the effects of engine operational condition on engine NOx (76).

### 2.2.2 Input Selection

Input selection is an important stage in procedure of control development. Increasing level of applied technologies usually results in increase of input variables. Usually, sensitivity analysis is used to find the
most effective parameter and input parameters. The following parameters are among the common manipulated control inputs in today common rail diesel engines:

### Table 2 Common manipulated control inputs in today common rail diesel engines

<table>
<thead>
<tr>
<th>Air Path</th>
<th>Fuel Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>- EGR valve</td>
<td>- Rail pressure (Rail valve or delivery valve)</td>
</tr>
<tr>
<td>- Waste gate valve position</td>
<td>- Number of Injection events</td>
</tr>
<tr>
<td>- Turbine blades position (VGT)</td>
<td>- Duration of each injection event</td>
</tr>
<tr>
<td>- Valve actuation</td>
<td>- Start of every injection events</td>
</tr>
<tr>
<td>- In cylinder flow pattern (Swirl control)</td>
<td>- Rate of injection</td>
</tr>
<tr>
<td></td>
<td>- Shape of injection</td>
</tr>
<tr>
<td></td>
<td>- Cold start heater plug</td>
</tr>
</tbody>
</table>

In 2001 Wal and Jager did a comprehensive review on different methods of input selection for control systems (77). They relate the suitable input selection to the number and position of sensors and actuators. They offer the following methods for selection of input parameters:

- Availability
- State observability and controllability
- Right hand side poles
- Input-output controllability
- Performance of selection of estimating and controlling parameters
- Robust control and nominal performance
- Robust performance

Deignan et al. in Purdue University employed the information theory techniques to better select the inputs (78).

### 2.3 Observers and Estimators

Along with development of advanced engine management systems, demands for estimation of the new parameters, which are not easy to measure increased. For instance, instantaneous brake torque, (79), (80), (81), (82), (83), (84), (85), indicated torque (86), (80), (92), in-cylinder air charge and air flow (87), (88), (89), (90), in-cylinder instantaneous pressure (91), EGR rate (92) and some special emission species (81), (93) need expensive sensors to be measured; on the other hand, they are important in control of engine operation and fault diagnosis aims. Although special sensors are used in industry, they are expensive and unreliable to be used in automotive powertrain. Usually model based approaches such as Kalman filters or extended Kalman filters (90), (92), nonlinear observers (80), (89), (85), (94), sliding-mode observers (91), (92), (84) frequency based estimation (83), input observers (87), unknown input observers (UIO) and also some non-model based soft computing observers (79), (86), (93) are employed to estimate these hard to measure parameters. Since software signal processing is used to estimate the desired parameters from measured parameters, these methods are called “soft sensor”. Either closed loop dynamic observers or open loop static look-up tables are used to estimate the parameters.

Development of automotive dynamic control systems increase demands to integrated automotive control systems, which take into account both engine and chassis control systems. These all lead to development of torque based engine management systems. As a result, the load torque of engine should be available to control unit. On the other hand, the instantaneous torque generation is useful in the fault detection systems. Usually the engine brake torque is estimated using look-up tables; however, their estimations are not reliable in transient modes, so estimators are used extensively to estimate the torque in transient modes. Many researches are done to estimate the torque based on engine speed, (79), (80), (81), (82),
The crank-slider mechanism of reciprocating engine makes a dynamic relation between gas force and crankshaft speed. This kinetic-kinematic nonlinear relation is suitable to be used in nonlinear estimation of engine instantaneous torque and in-cylinder pressure (91). The fundamental dynamic equation of torque estimation is as follows (84):

\[ J_{\text{tot}}(\theta)\ddot{\theta} = T_i(\theta) - T_m'(\theta, \dot{\theta}) - T_f - T_l \]

Where \( J_{\text{tot}} \) is the crank shaft, piston and connecting rod inertia, \( T_i \) is the instantaneous indicated torque, \( T_m \) is the mass torque for piston and connecting rod inertia, \( T_f \) is the friction torque and \( T_l \) is the load torque.

The \( T_m' \), which is the demanded torque to accelerate the piston and connecting rod masses based on engine speed, is calculated using the crank-slider mechanism relations. Falcone et al. used the sliding mode estimators to estimate the indicated torque (84). They defined the \( S \) as the difference between estimated measured crank shaft speed \( \hat{\theta} \) and the calculated speed \( \tilde{\theta} \):

\[ S = (\hat{\theta} - \tilde{\theta}) \]

They used the following equation as the estimator:

\[ \dot{\tilde{\theta}} = \frac{1}{J_{\text{tot}}(\theta)}[-k \cdot \text{sign}(S) - T_m'(\theta, \dot{\theta}) - T_f] \]

The \( T_1 \) can be found from transmission by an error of 50% and \( T_m'(\theta, \dot{\theta}) \) can be calculated using the dynamic relations, the switching function estimates the difference between indicated and friction torque, which is desirable for engine control. Lypanov theorem is used to find the appropriate gain for \( S \). The comparison of experimental results shows that the estimator can estimate the brake torque with desirable accuracy in transient modes.

Zweiri and Seneviratne developed a nonlinear robust observer for estimating the engine indicated torque and load torque (80). The engine was connected to a dynamometer using a flexible coupling, which enhanced the estimation capabilities. The developed observer used the flywheel and dynamometer rotational speed signals to estimate the engine indicated torque. This model-based observer was based on a nonlinear torque generation model of engine. In addition, the effects of variable inertia of powertrain are taken into account. In order to decrease the chattering in estimation an adaptive gain is used. Brahma et al. used a first law based model and linear regression to develop a torque estimator algorithm (82). They used the estimator as a part of TBCS. In addition, the frequency analysis is used to correlate the engine speed to engine indicated torque (83). Linear observers have also been used for estimation of engine torque. Chauvin et al. designed a Kalman observer for the engine (92). Since the effective inertia of engine part varies by engine angle, they used a time varying Kalman estimator for estimation of instantaneous torque. Zweiri used a neural network to estimate generated torque based on engine speed signals (86). He used a dynamic model as feedback and the neural network as the feed-forward parts. Due to use of neural network the scheme is able to be employed in real time systems. The structure of estimator is illustrated in Figure 4.

![Figure 4 Torque estimator structure (86)](image-url)
As stated earlier, the in-cylinder pressure is recently being employed for control and diagnosis aims. However, the suitable sensors to measure the in-cylinder pressure exist; they are so expensive to be used in economical products. Usually estimators are used to estimate the in-cylinder pressure out of engine instantaneous speed. Al-Durra et al. designed a sliding mode observer to estimate the in-cylinder pressure based on variations in engine speed (91). They used a dynamic model of engine to predict the pressure trace out of engine speed. A state space equation with pressure and speed states was formed based on thermodynamic equation for pressure and Euler equation as follows.

Equation 7

\[
\begin{bmatrix}
\frac{d\omega}{d\theta} \\
\frac{dp_{cyl}}{d\theta}
\end{bmatrix} = \begin{bmatrix}
A_{11}(\omega) & A_{12}(\omega) \\
0 & A_{22}(\omega)
\end{bmatrix} \begin{bmatrix}
\omega \\
p_{cyl}
\end{bmatrix} + \begin{bmatrix}
H(\theta, \omega) \\
N(\theta)
\end{bmatrix}
\]

In which the elements of matrices are found from thermodynamic and Euler equations and \(p_{cyl}\) is a vector containing the pressure of each cylinder. Sliding mode estimator is then employed to found the states.

The following state estimator dynamics is used:

Equation 8

\[
\begin{align*}
\frac{d\hat{y}}{d\theta} &= A_{11}\hat{y} + A_{12}\hat{x}_2 + H(\theta, \omega) + V \\
\frac{d\hat{x}_2}{d\theta} &= A_{22}\hat{x}_2 + N(\theta) + LV
\end{align*}
\]

In addition, the error model is defined as follows:

\[
\begin{align*}
\frac{d\tilde{y}}{d\theta} &= A_{11}\tilde{y} + A_{12}\tilde{x}_2 - K \text{ sign}(\tilde{y}) \\
\frac{d\tilde{x}_2}{d\theta} &= A_{22}\tilde{x}_2 - LK \text{ sign}(\tilde{y})
\end{align*}
\]

A variable “K” factor is used to decrease the chattering based on crank angle. Sliding mode estimator is then employed to find the states. This pressure estimator works well for each cylinder when the valves are both closed; in order to estimate the pressure in induction and exhaust phases, an augmented state is employed which predict the torque generated by prior cylinders. The results show good agreement with real pressure data sets.

The air charge of engine cylinders is the other parameter, which should be estimated. Usually MAF sensors are employed to sense the flow of induced air into engine. Since the diesel engine should operate in lean regime, it is important to know how much air is induced in the cylinder, so that over injection, which will result in soot is avoided. The MAF however cannot measure how much air is induced into cylinder especially in transient operations. Usually open loop estimators are used to estimate the induced air, which take into account the pressure and temperature of inlet manifold and volumetric efficiency that is a function of engine speed and load as follows:

Equation 9

\[
m_{tot} = \eta_v \frac{P_i}{RT_i} n V_d i
\]

Where \(P_i, T_i, V_d\) are pressure and temperature of inlet manifold and displacement volume respectively, “n” is engine speed and \(i=0.5\) for a 4 stroke engine. \(\eta_v\) is the volumetric efficient and is a function of engine speed and load, also some paratemers such as air temperature affects it, which are usually taken into account using the correction factors. However, the error of estimation in transient is still a problem due to relatively complex dynamics of turbocharger and the importance of exhaust pressure in obtaining
the volumetric efficiency in diesel engines (89). Many researches are done to develop an estimator, which can estimate the engine induced air in transient regimes (87), (88), (89), (90). In order to estimate the air charge in diesel engine, these methods have been used: directly using the MAF sensor, simultaneously employment of MAF/ MAP sensors with an observer, using an extended Kalman filter altogether with MVM with fusion of different sensor sets i.e. MAP, coolant temperature and exhaust manifold pressure, using an exhaust lambda sensor and injection signal for estimating the air mass flow (90).

Stotsky and Kolmanovsky in Ford Company considered the different algorithms of input observers (87), (95). Input observers are a category of observers that estimate the input signals using the measured output and state signals. Different estimation methods such as high gain observers, dirty differentiation observer, sliding mode observer, and higher order observers are discussed. They used input observers to estimate the manifold pressure and inlet airflow. Desantes et al. also developed an estimator to predict the airflow using in-cylinder pressure (88). They first described the usual methods to measure induced air in diesel engines with and without EGR and then described the Δp method which estimates the induced air by comparison of in-cylinder presser in two specific points in compression stroke as follows:

**Equation 10**

\[
\text{m}_{\text{ive}} = \frac{\Delta p V_a}{RT_a \left( \frac{V_a}{V_b} \right)^k - 1}
\]

In which \(m_{\text{ive}}\) is the induced mass when inlet valve is closed and “a” and “b” are two points in compression stroke also V and T are the volume and temperature respectively. Δp is the difference of pressure in “b” and “a”. In Δp estimator, the only parameter to estimate is \(T_{b}\). They compared their proposed method with usual “volumetric efficiency” in which \(\eta_p\) should be calibrated and tried to find the appropriate function to estimate \(T_b\) based on inlet manifold pressure, exhaust to inlet pressure ratio, wall temperature, injected fuel and engine speed. They also consider the effects of EGR on their estimator.

Storset et al. also developed an adaptive estimator to estimate the induced air in engines with low EGR rate (89). Poloni et al. also used a MVM model of engine along with an extended Kalman filter (EKF) to measure the air charge of engine (90). They mentioned that MVM models use the steady state maps to model subsystems of torque generation, volumetric efficiency and turbine and compressor. As a result, there will be some errors in transient modeling. They tried to compensate errors by augmenting the model with bias parameters to be identified on-line by the observers. The number of augmented states (bias) is limited to the number of sensors, which can sense the states. They tested the different configurations for biases and showed that with correctly selection of bias parameters, the accuracy of prediction promotes.

Precise control of burned gas fraction in inlet manifold can decrease the NOx production to high extent without violating the soot limits. The engines, which are provided with an EGR valve, employ estimators to estimate the burned gas fraction (or fresh air fraction) in the inlet manifold. In estimation of air fraction in inlet manifold, EGR mass flow rate is a demanding factor: The EGR mass flow rate can be directly estimated using the orifice’s mass flow rate equation by measuring the pressure before and after the EGR valve and the upstream temperature of the EGR valves. In addition, the opening area of the EGR valve should be provided. However, the open-loop estimation of EGR rate is not reliable and feedback observers are being used. Usually inlet manifold pressure and air flow sensor (AFS) is used to estimate the EGR mass flow rate. The AIS, EES and EGR valve besides ICP form a dynamic system, which contains air fraction in each manifold as states. Since the temperature in inlet manifold is not sufficient for activation of Nernst effects, universal exhaust gas oxygen (UEGO) is used to measure the air fraction in exhaust manifolds as a measurable state. Based on which, a model-based estimator is developed to estimate the air fraction in inlet manifold (92), (147).

Castillo et al (92), developed a simultaneous observer to estimate both the air fraction and the EGR rate in a dual EGR loop diesel engine. They employed sliding mode observer to estimate the EGR rate based on inlet manifold pressure and AFS sensor. Also a robust linear parameter varying Kalman filter is developed to estimate the air fraction in inlet manifold based on linear matrix inequality (LMI).
Recent control algorithms take into account the individual cylinders for control i.e. every injector is controlled individually. Therefore, the estimators that can predict the situation of cylinders distinctively are of importance. Chauvin et al. developed an estimator to estimate the AFR in each cylinder separately using only an oxygen sensor in exhaust manifold (94).

Engine emissions are recently being employed in control purposes. Since the sensors to measure the emission are expensive, emission estimators are recently being paid more attentions. The underlying physical phenomena of emission generation are complex; as a result, ANN can be used in estimation. On the other hand, if in-cylinder pressure is available to control systems, it will promote the estimation process, since some information from ICP is available. Henningsso et al. developed an estimator to predict the emissions based on in-cylinder pressure using ANN (93). They used a principal component analysis (PCA) to decrease the size of pressure information (p) and then merged them with other engine information such as engine speed and injection timing (v) and then they trained an ANN to predict soot and NOx based on the “v” information. The estimating approach is shown in Figure 5.

Locally linear estimators are also used for prediction of non-measurable parameters. Brahma et al. employed a nonlinear mean value model of engine for estimation of brake torque and NOx emissions (81). They linearized the model is some operating points in whole engine operational space and developed linear observer based on them. The proposed observer could predict torque and NOx based on measured inlet airflow and inlet pressure.

### 2.4 Controller Design

#### 2.4.1 Controller Structure

Diesel engines as multivariable complex systems comprise a variety of internal states and output variables. The output variables such as performance and emissions level of engines are strictly related to values of internal states of engine. Usually a hieratical-type controller structure is used to optimally control the engine as depicted in Figure 6 (96), (97). As depicted in Figure 6, the high level controller receives the signals from sensors and obtains the set points for the sub-controller which are responsible for obtaining the situation of actuators.
The controllers used in hierarchical engine management systems can be classified into two main classes of controllers:
- Output variable controllers: upper level controllers (ULC)
- Internal state controllers: lower level controllers (LLC)

ULC’s or supervisory controllers are those which are responsible for tuning the engine output variables such as speed, torque and emissions; on contrary, some controllers are employed for tuning the intermediate parameters. On the other hand, LLCs or internal state controllers, tune such parameters as pressure rail, air boost pressure and EGR rate. The structure of diesel engine management system is depicted in Figure 7. The accelerator pedal signal obtains the required torque. The situation of systems and required set points for attaining the required torque are obtained by ULC. The LLCs are then responsible to control the actuators in such a way that the required set points -which are defined by ULC- are attained, which in turn guarantees the required torque in both steady and transient modes.

The entire modern engine control systems can be assumed to be composed of a global ULC which includes LLC’s as internal loops. Open loop controllers (OLC) and closed loop controllers (CLC) are two main approaches used in implementation of ULC and LLC systems. Omran et al. mentioned the development of control structure in their research on optimization of control parameters in diesel engines (98). They categorized the controllers in EMS to two main categories of CLC and OLC. The OLCs often determine the optimal input variables based on the engine operating point (usually engine speed and load) and correct them regarding the ambient conditions. The dynamic correctors are also used in transient operation modes. The OLC values would then be applied directly to actuators or as a set point for CLC’s. The open loop calculations are usually done by look-up tables. The OLC structure and corresponded ambient condition compensators are depicted in Figure 8. The dynamic correctors are the functions based on time, which varies the outputs in a pre-defined time interval to obtain the final state.
A large number of controllers involved in engine control systems are feed-forward controllers. Due to expense of some sensors, feed-forward controllers are vastly used in engine control schemes. The feed-forward controllers usually determine the set points for engine operation, some of which are directly applied on actuators while the others are used as set point generators for feedback controllers. Pressure, timing and duration of injection are among injection properties, which are determined using feed-forward controllers. These controllers are in the simplest form implemented statically using look-up tables (3). Usually the main inputs are considered in look-up tables while the less important affective parameters such as ambient temperature and pressure are taken into account in the form of 1D-lookup table correction factors. A simple block diagram of effects of correction factor in compensating for ambient variations is depicted in Figure 9.

In the traditional control algorithms, simple feed-forward controllers are used as the base of engine control algorithms. Feed-forward controllers obtain engine essential operating parameters such as injection timing, duration and pressure as well as air boost pressure and EGR rate. One of the most important feed-forward controllers involved in ECU is the ULC torque generation controller. The input to the controller is demanded torque required by driver via accelerator pedal. Using a 2D lookup table, the pedal position along with engine speed is mapped to demanded torque. The feed-forward controller obtains the optimal values of injection start point and duration as well as boost pressure and EGR rate. The feed-forward controller also takes into account ambient conditions in the form of correction factors and compensate for dynamic aspects of engine operation using appropriate dynamic correction factors. Nowadays, using generated torque estimators, it is possible to control the generated torque accurately and in an optimal way.

CLC structures are the other type of controllers, which are used extensively in structure of engine management systems. The set points for closed loop control systems are generated using appropriate static and dynamic maps as illustrated in Figure 10.

The CLCs are used to control different parameters such as boost pressure, EGR rate, trapped air mass, rail pressure, injector needle position, engine speed and recently generated torque. Usually PID controllers are used for CLCs; however, the other control methods such as fuzzy, neural network, robust and adaptive approaches have been used for closed loop design which will be discussed later. Since the precise operation of engines is provided by employing feedback controllers, the closed loop feedback controllers are increasingly being used in automotive and powertrain industries. The diesel engine closed loop control systems can be categorized in to three main classes as follows:

- Engine outputs control loop (ULC)
- Air path control loop (LLC)
- Fuel path control loop (LLC)

Every class of feedback controllers includes some CLCs, which are shown in Table 3.

### Table 3 Classification of diesel engine management CLCs

<table>
<thead>
<tr>
<th>Control Level</th>
<th>ULC Category</th>
<th>Air path</th>
<th>Fuel path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque control</td>
<td>EGR control</td>
<td>Rail Pressure</td>
<td></td>
</tr>
<tr>
<td>Speed control</td>
<td>Boost Pressure</td>
<td>Injected mass rate</td>
<td></td>
</tr>
<tr>
<td>Emission control</td>
<td>Air mass control</td>
<td>Needle valve position</td>
<td></td>
</tr>
<tr>
<td>Engine smoother</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lambda control</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Different control approaches such as PID controllers, optimal control (125), (104), (126), fuzzy (109), (122), neural networks control (19), robust control (127), MIMO (112), (113) adaptive and nonlinear controllers (116), (114), (114) are used for designing the CLCs.

#### 2.4.2 Engine Outputs Controller Design

Engine output controller is a major class of diesel engine controller, which is usually being used as supervisory controllers. Torque control strategy, engine speed controllers and the emission control systems are the most important types of ULCs, among them torque based control systems (TBCS) attracts attention of engine developers.

TBCS is a modern supervisory control strategy, which is used in engine management systems (99). In TBCS, the demanded torque is estimated using accelerator pedal position and its rate as well as antilock brake systems (ABS), traction control systems (TCS) and electronic stability program (ESP) torque requirement signals transmitted via controller area network (CAN) (3). In this case other systems such as chassis control systems can send their torque demand to engine ECU by appropriate signals. The desired torque is then provided by lower LLCs, which employ appropriate manipulated variables such as air and fuel quantity and injection pattern considering emissions and the fuel consumption limitations. A simple mapping between required torque and input variables are illustrated in Figure 11.

![Figure 11 Mapping between required torque and manipulated values (3)](image)

Since torque is not measured directly, the generated torque should be estimated using suitable torque estimators. Many approaches have been used to control the engine-generated torque; classic, fuzzy, neural network, robust and adaptive controllers are among them. Benz developed an optimal controller to minimize the emissions of a diesel engine (125). A model of diesel engine was developed with capabilities of raw emission prediction in transient modes based on extended quasi-static approach. Six main inputs are selected for the engine, comprises VGT position, EGR position, injection timing, rail
pressure, load torque and injected fuel mass. The dynamics of engine (both performance and emission) are stated as a nonlinear equation as follows:

**Equation 11**

\[ x = f(x, u) \]

Where \( x \) is the state of systems (contains performance, fuel consumption and emission indices) and \( u \) is the input to systems. Since fuel mass considerably affects the engine torque, a feed-forward controller is developed for injected fuel mass; a cost function is then defined which takes into account the emissions of engine based on five remained inputs (\( \vec{q} \) vector) as shown in **Equation 12**.

**Equation 12**

\[ J = \int_{t_0}^{t_f} L(x(t), \vec{q}(t), t) \]

Since the model is a nonlinear with discontinuities and time delays, a nonlinear optimization problem is formed which should be solved numerically. Among different numerical methods, sequential quadratic programming (SQP) is selected due to its robustness and fast convergence capabilities. The SQP algorithm requires values of the gradient of the cost function with respect to the control input parameters \( \vec{q} \). The nonlinear model is then discretized using step discretization method. The results show considerable decrease in output emissions. They defined different cost function based on test scenario and optimized the input pattern based on them.

Engine speed controllers are the other type of high-level controllers, which are able to control engine speed. Ouladsine et al. used neural network to control the speed of diesel engine with lowest possible emissions (19). They developed an ANN model of engine and estimated its parameters using engine experimental data. The model comprised distinct multi input-single output neural networks for modeling engine emissions and speed. Five states of engine speed, the intake manifold pressure, the inlet airflow, the fuel flow and the opacity of the exhaust gas are modeled. The aim of controller is to reduce the opacity (soot) peaks in acceleration mode. They used the indirect control method for designing the neural network controller as shown in **Figure 12**. In indirect ANN control method, an ANN is first developed which mimic the behavior of main systems. The error between system outputs and derided value are then used to train the controller.

![Figure 12 Training architecture of ANN controller (19)](image)

A cost function is defined based on deviation from desired speed and opacity, which is shown in **Equation 13**.

**Equation 13**

\[ J(W) = \frac{1}{2} \sum_{k=1}^{N} \left( (R_{ref}(k) - R(W, k))^2 + \eta_{Op}(O_{p_{ref}}(k + d - 1) - O_{p}(W, k + d - 1))^2 \right) \]

Where \( R_{ref} \) and \( O_{p_{ref}} \) are reference speed and opacity factor respectively and \( \eta_{Op} \) is the weighting factor which obtains the degree of importance of opacity in comparison to speed deviation from desired value. The training procedure is done to tune the controller parameters (the weights of neural network
controller) in such a manner that minimizes the cost function. Since the inputs are most of the time unknown, finding the Jacobian matrix, which is needed in training procedure is impossible. The problem is overcome by employing the direct method, i.e. using a neural network model of engine. A recursive algorithm is used to tune the neural controller parameters just like adaptive control. The controller was able to track the desired speed constrained to minimum soot generation.

A problem involved in diesel engines is the difference between torque generation in different cylinders or successive cycles of one specific cylinder. Petterson et al. designed a feedback controller to compensate for torque variations and automatically regulate the engine speed (100). Their aim was to cancel the natural frequency of powertrain system. In a similar research, Ostman and Toivonen developed a feedback controller to compensate for vibration effects of reciprocating parts of engine (101). The main source of engine speed variation is the uneven torque generation in different cylinders due to variation in injection and combustion process. They used the temporally engine speed signal after each combustion and compare it with average speed to compensate the injection of each cylinder separately. The resulted controller is able to reject the effects of uneven torque generation and regulate the output speed of engine. In addition, robust controller is employed to withstand the speed variations in diesel engines.

Idle speed controller (ISC) is the other important feedback controller employed in internal combustion engines. The ISC keeps the engine speed in a pre-defined speed set point, regardless of external and internal load variations. Idle speed has significant effect on vehicle fuel consumption especially in urban traffic. In ISC, the demanded torque is estimated and required torque is generated providing appropriate inputs to the engine. Zhengmao Ye did a comprehensive review on modeling, identification and design of ISC for both gasoline and diesel engines (102). The related papers have been reviewed and application of feed-forward controllers, conventional PID, linear quadratic, optimal control, L1 controllers, robust synthesis, adaptive control, gain scheduling and soft computing methods have been discussed in his paper.

Recently a class of controllers are developed which employs in cylinder pressure signal as feedback (108), (128), (129). However the scheme requires expensive fast pressure sensors, they can probe the in-cylinder process and provide valuable information about the combustion properties. Direct pressure information are usually processed in combustion process analysis module (CPAM) and then employed for subsequent decisions and control functions as depicted in Figure 13 (108).

![Figure 13 Schema of injection control with CPAM and cylinder pressure sensor (108)](image)

Bienek developed an advanced pressure based diesel engine control system. The fuel heat release and a simple wall heat transfer model are used to calculate the heat release rate from pressure signal. The Equation 14 shows the relation between heat release and pressure signal.

**Equation 14**

\[
\frac{dQ_{\text{fuel}}}{d\theta} = \left(1 + \frac{\sum m_i c_{vi}}{\sum m_i R_i} \right) P_{\text{cyl}} \frac{dV_{\text{cyl}}}{d\theta} + \left( \frac{\sum m_i c_{vi}}{\sum m_i R_i} \right) V_{\text{cyl}} \frac{dP_{\text{cyl}}}{d\theta} - \frac{dQ_w}{d\theta}
\]

In which \(dQ_{\text{fuel}}\) is heat release, \(P_{\text{cyl}}\) is cylinder pressure, \(m_i\) is mass of charge, \(V_{\text{cyl}}\) is instantaneous cylinder volume, \(c_{vi}\) is specific heat of charge in constant volume and \(R_i\) is gas constant. A controller is
then used to tune the heat release rate to target heat release based on engine operational point (108). HaiFeng et al. developed a controller for diesel engine based on in-cylinder pressure signal processing (128). They found that there is a tight dependence between signal properties and engine torque generation, fuel consumption and NOx generation. They first mapped the in-cylinder pressure signals to an index parameter using radial basis function (RBF) technique, then they used the index as a feedback signal for closed loop control of engine. Using this approach, significant decrease in engine NOx generation is obtained.

AFR is another important factor, which should be controlled in diesel engines. AFR influences emission (Soot and NOx) significantly. Smoke limiter is a type of AFR control systems, which is used to prevent diesel engines to fall in rich zones, especially in accelerating conditions. Stefanopoulou et al. developed a controller to limit the soot generation while minimizing NOx generation with simultaneous control of EGR and VGT (130). They showed that an increase in EGR rate would generally increase smoke generation. They first found the optimal sets of EGR rate and $\lambda$ as a function of engine speed and fuel rate. Then a nonlinear feed-forward and an optimal $H_\infty$ gain schedule feedback controller was developed to keep engine in optimal set points in transient mode.

Fengjun tried a new control scheme for controlling the AFR of diesel engine (105). He used air and fuel path simultaneously to control the AFR in engine transitions. In his research, he employed active and rapid fuel injection timing and mass adjustments for fuel path control while two loops of EGR and VGT were used to compensate for air path dynamics in engine transient modes. Alfier et al. also developed a model-based controller for controlling the AFR of diesel engine, which was provided with a lambda sensor (106). The proposed controller used only EGR valve to control the AFR. They used $H_\infty$ and internal mode control to develop gain schedule feedback controller while two feed-forward controllers were developed to promote the tracking. Inversion method is used to design the feed-forward method, where engine speed, desired $\lambda$, inlet manifold pressure and temperatures are inputs to nonlinear feed-forward controller and EGR valve position is the only output of controller as depicted in Figure 14.

![Figure 14 The scheme of EGR valve nonlinear feed-forward controller (106)](image)

The control scheme they used in their research is depicted in Figure 15. The control scheme compromise estimator and disturbance compensator. Two different methods are used to design feedback controllers, 1) A linear parameter varying (LPV) of engine is developed based on first-order low-pass filter with a time delay element and a schedule for the element parameters; internal mode controller (IMC) is then employed to develop the controllers to force the local system to have the same loop form for every engine operational condition. 2) Locally linear models of engine in a grid space are identified, a common structure model is defined and then $H_\infty$ is employed to design the feedback controller.
Tschanz et al. made a new controller which was able to take NOx and particulate matter (PM) into feedback controller (107). They used model-based observer for compensating the slowness in dynamics of sensors. They also used a novel controller for controlling the engine using emission feedback.

2.4.3 Air Path Controller Design

Air boost pressure, inducted charge mass, air mass fraction (burnt gas fraction) and EGR rate are widely being used in modern common rail diesel engines for power and emission control aims (air path control). The typical control structure employed in these engines compromises a multivariable controller, which simultaneously controls EGR rate and boost pressure based on to the desired set points, which is provided by the torque based optimal coordinator. VGT blade angle, EGR valve position, waste gate valve position and recently throttle valve are the most important manipulated variables, which are employed for air path control. The air system is a nonlinear cross-coupled system. Usually PID controllers are used distinctly (114); the problem is the natural interference due to natural couple of EGR rate and pressure in air system. Nowadays MIMO controllers are used, which can solve this problem to some extent (109), (112), (113).

The aim of EGR control is to regulate the burned gas fraction in the inlet manifold. Two distinct control schemes are used for EGR control in diesel engines. In the simpler scheme, since the burned gas fraction is not measured directly, the EGR demand is translated to EGR mass flow rate set-points and the corresponding fresh inducted air mass measured by AFS (146, 147). The controller regulates the EGR mass flow rate and fresh air flow using the EGR valve, VGT, wastegate and throttle valve. In the next control scheme, the air mass fraction is estimated using UEGO sensor and the air fraction (or burned gas fraction) is directly controlled instead of EGR mass flow rate (92). The second control approach is more precise and takes into account the air fraction in exhaust manifold in the lean regimes of engine operation.

Wanga et al. developed a MIMO controller for simultaneous control of air boost pressure and air flow rate (112). Since the air system is a nonlinear dynamic system with variable system dynamics in whole engine operational space, a controller system composed of feed-forward path, feedback controller and actuator saturation is employed. Due to nonlinearity of system, PID with gain-scheduled controller is used for feedback controller design. In order to avoid instability, a preserved robustness margin is critical when each PID controller is designed for a selected operating point. In order to design the controller, the system is identified using proper random signals. Quantitative feedback theory (QFT) is used to design the controller. The QFT method is a robust frequency-based method for controller design, which is employed for both linear and nonlinear systems. The QFT is best suited for the nonlinear systems, which are described by different linear systems around their operating points. This control design technique guarantees the stability and performance criteria for a class of linear systems using a unique lead-lag or PID controller. The control scheme used in developing the controller is illustrated in Figure 16. As depicted the optimal parameters of inlet circuit is included in the model using 2D lookup tables and are used as the set points for feedback (FB) and feed-forward (FF) controllers.
Rajamani designed a MIMO controller to simultaneously control EGR rate and exhaust gas excess air (\( \lambda \)) (113). A hieratical controller is employed to control the turbine air mass and EGR flow rate. Feedback linearization is used to control the system. The developed controller is able to decrease NOx and PM of engine.

Garcia Neito et al. developed a nonlinear predictive controller based on local model network to control the air flow into engine (114). They developed a MVM model of engine and then used two independent controllers to control the inlet manifold pressure and inlet airflow. Depend on engine speed, the developed controller used EGR and VGT position actuators to control the engine; in both regimes, PI controller is employed. In low speeds, both EGR and VGT are used while in the low speed regime only VGT is used. Arnold et al. developed a fuzzy controller for controlling air path of diesel engines (109). The developed controller was able to control the mass airflow (MAF) and inlet air pressure (MAP) simultaneously. The fuzzy controllers do not need accurate system models and system identification. As depicted in Figure 17, MAF control is implemented as a fuzzy-PID controller while MAP controller is implemented as a P-Fuzzy controller. The VGT position, EGR valve and throttle are controlled based on fuzzy controller, however for better tracking in transient regime, VGT position is also provided with a feed-forward path.

Nieto et al. used the parallel-distributed control (PDC) for control of the air system of a diesel engine (16). The proposed method assumes that a nonlinear dynamic system can be described by a system of locally linear state space equations, after which the suitable controller such as state vector feedback control (SVFC) is used for designing linear controller for every linear systems. The linear matrix inequality method (LMI) can be used for stabilizing the control systems. They identified a diesel engine air system.
using the T-S fuzzy method. The T-S fuzzy models are used for the nonlinear systems, which can be described by a number of locally linear state-space systems. The if-then rules will be used to describe whole the system by appropriate state space equations. They tested a diesel engine based on Euro IV test procedure and used the result for system identification. A fuzzy clustering method is then used to find appropriate rules base, which used to make a T-S fuzzy system. Finally, they used LMI to design the local controller for every state space systems, which minimize the decay rate of system and guarantee the stability of whole system.

Capobionco used a two input controller which employed EGR valve position and waste gate valve position to optimally control the turbocharged engine (110). Wijetunge et al. shows that lowering exhaust pressure will decrease the soot generation in transient (111). They used the exhaust manifold pressure to control the turbine blades angle. Using this signal, they could control the soot generation in transient mode and also stabilize the inducted air mass in steady state operation of engine. Sassano et al. also employed optimal control to control the air dynamics (126). They first identified a NARX model of engine and then developed a state space model out of it. After which they made an optimal regulating rule for inlet manifold pressure.

Ferreau et al. employed the model predictive control (MPC) to control the diesel engine. They used online active sets to speed up the required calculations. Using this method causes the calculation to be done in a time order of milliseconds (116). Ahmed Ali et al. tried a nonlinear sliding mode controller to control the EGR rate and AFR (115). They believed that using nonlinear controller instead of usual PID controller would decrease the demand of controller calibration.

2.4.4 Fuel Path Controller Design
An important aspect of diesel engines is the injection circuit and its control process. In the common rail diesel engines, regulation of rail pressure as well as precise metering of injected fuel quantity and timing are of most importance. The rail pressure must be able to be varied typically from 230 bar up to 1600 bar within a tolerance of 1% and steep gradients (e.g. up to 3000 bar/s) (118). Solenoid and piezo-electric injectors, both are stimulated using electronic signals, which in turn drive a hydraulic system to move the needle and inject the high-pressure fuel in a fraction of milliseconds. Usually feed-forward controllers are used to control the injection process, however recently using needle motion sensors, feedback controllers found their place in control of injection such as I-Art technology dedicated by Denso. Rail pressure is one the most important disturbance parameters, which should be taken into account in feed-forward controller design. A feedback controller is employed to control the rail pressure based on predefined optimal rail pressure set point. Many researches have been done to model and control the injection circuit. A brief description of them is considered here.

Tanabe et al. designed a new injection system for common rail diesel engines (119). They employed two low and high-pressure rails for injection. Using this scheme, it is possible to shape the injection rate profile accurately. The shape of injection rate is an effective method to decrease engine pollutions. Lino et al. modeled and designed a controller for common rail injection systems (120). They developed a model of injection system in AMESim and designed a controller in Simulink. They used slip mode controller to regulate the rail pressure. The slip mode control is best fitted to hydraulic systems due to the solenoid properties. Yang and Wang designed a controller for tuning the rail pressure (123). The controller could identify the effects of injection in an online mode using oxygen concentration sensor signals. After processing the data, controller could control the injection. Shuman et al. developed a high speed controller which could trigger up to 10 injection phenomena in one cycle (124). They employed MCF5235 microprocessor for controlling aims.
2.5 Optimization and Calibration

Optimization of engine control strategy and calibration of control maps are among the final stages of engine controller development. As stated earlier, the controller structures usually involve look-up tables which store the steady states situation of actuators or set point of CLC systems as 2D functions of engine speed and load (98). These look-up tables also store the gain values for adaptive gain scheduled PID controllers. The process of fulfilling these look-up tables with values, which guarantee an optimal operation of engine in both steady and transient modes, is called calibration. Many methods have been developed for calibration of engines in both steady and transient regimes. In this part experimental calibration, model based steady calibration and dynamic calibration will be investigated.

A comprehensive description of classic calibration methods can be found in (131). They categorized the whole steady state calibration workflow to three phases of choosing operation point (OP), optimization of OP based on emission and fuel consumption targets and finally fulfilling the look-up tables with a smoothing process between the optimal values. The second step in the most important step, which needs many tests and is time consuming. This phase consists: defining the domain of parameter variations, development of test matrix, testing the engine according to defined matrix, development of a response model based on the test results, optimizing the engine based on the developed model.

In the classic method of calibration, factorial tests are done to fulfill the look-up tables (131), (132) which means that a large number of test should be done for calibration. By development of mechatronic systems, the number of actuators increased from 3 in 1998 to 15 in 2010 which in turn increased the number of required look-up tables significantly. If the factorial optimization method is employed to optimize the modern engine look-up tables, more than $10^7$ testes will be needed which make calibration process an expensive time consuming process for engine designers (133). Different approaches are used to decrease the number of demanded tests for calibration (131), (134), (132), (135), (136). Design of experiments (DOE) technique is a statistical method, which can decrease the number of required tests to 90% (137). DOE is a statistical method for the sampling the data, where a high level of modeling accuracy can be obtained with a small number of data points (135). Using the DOE a matrix of test points is generated to explore the behavior of engine in a specific zone. The test data will then be used to determine a model of engine, which can predict the performance and emissions of the engine, based on the independent parameters. DOE investigates the effects of more than one of the factors at a time by designing a matrix of test points. Since a single matrix test point can involve several variables being changed once, the interactions between the factors quantified in addition to the singular effects of individual factors. The main benefits include significant reductions in the number of initial tests required, quantification interactions between factors, and predictions of responses to factor settings and variations. (138).

Many researches have been done to calibrate engines using the minimum possible number of tests. Brroks et al. calibrated a diesel engine using DOE. The 14 points new European drive cycle (NEDC) were used and 5 points out of them where selected to calibrate the engine around them. They used MBC in Matlab for DOE. Using MBC they found the interaction between factors (inputs) and responses (outputs) and found the most effective parameters; based of them some experiments where planned to find the NOX-soot tradeoff in constant BSFC. Using the tradeoff plots it was possible to calibrate the engine. Many methods have been used to promote DOE. Soft computing methods, response surface method and Taguchi statistical method are among of them. Rissi et al. employed GA method to optimize the injection sequences of a diesel engine based on experimental tests (134). They first described the limitations of engine models to predict the engine performance and emission and then described their method to implement the micro genetic algorithm ($\mu$GA) to find the optimal parameters of injection. They used European driving cycle (EDC) to find the operating point, around which they calibrated the engine. They defined distinct cost function based on NOx, particulate matters, fuel consumption and also a penalty function for noise, finally a test was done on engine based on $\mu$GA. These results were used to find the correlation between engine inputs and outputs statistically. Finally, the NOx cost function where plotted against the soot cost function and optimal setting where selected for calibration. Also soft computing methods have been used for DOE. Nazaki et al. found a method to calibrate the ECU free parameters based on experiments (135). DOE decreases the design zone based of the relative influence of parameters of...
responses. They drafted calibration rules in accordance with operating parameters and physical engine phenomena, and developed a logic enabling automatic calibration using a search based on these rules based on fuzzy logic. The results show a 50% saving in calibration procedure in both aspects of time and cost. Langouet et al. developed a new approach called multi-objective covariance matrix adaptation evolutionary strategy method (MOCMAES) for optimization of engine maps. In this approach an evolutionary multi objective optimization process is developed which make new generation based on current generation to reach the optimal point (131). They also used LOLIMOT for smoothing the optimal values in ECU maps. Zwin et al. used the response surface methodology (RSM) to find the optimal inputs of engine (132). RSM is a mathematical-statistical method that models the input-output process by planar approximation models. They used the mentioned method with least square to find the coefficient of planar model. After which, they used goal programming and minimax programming method to find the optimal inputs to system. Nataraj et al. used Taguchi orthogonal array DOE method for optimization of diesel engine emissions (136). Conventional method of DOE is based on averages only; Taguchi method on the other hand, takes into account the average and as well variability using the signal to noise parameter. Taguchi method employs the orthogonal array to decrease the number of demanded test. Taguchi method consists of following steps: defining the goals, selecting the parameters, selecting the orthogonal array, running the tests, statistical analysis, finding the optimal setting, prediction of emission in optimal setting and running the confirmation tests.

Recently MBC are attracting more attention due to their lower requirement for experimental tests. MBC employ engine models to predict the emission and performance of engine. Therefore, the role of suitable models, which can predict the engine outputs with desirable accuracy in suitable time, is of importance. Using the MBC will decrease the time and cost of calibration significantly. Rask and Sellnau did a research on simulation based calibration procedure and described the tools and methods of calibration (139). They used the tools for calibration of a variable valve actuation (VVA) system. Hessel and Reitz also optimize the boost pressure, EGR rate, start of injection and injection rate shape of a diesel engine to minimize emissions and fuel consumption in four operating points which are derived from EPA federal test (140). They employed KIVA 3V code to model engine performance and emissions in the operational points. The multivariable problem of optimization of emission and performance is converted to a single object using the defined cost function:

Equation 15

\[
f(X) = \frac{1000}{\left(\frac{NOx + HC}{W_1(NOx + HC)_m}\right)^2 + \left(\frac{PM}{W_2PM_m}\right)^2 + \frac{ISFC}{ISFC_m}}
\]

Where \(W_1\) and \(W_2\) are two weighting factors and the parameters, which are indexed by “\(m\)” are the nominal parameters which are used for normalization. \(X\) is the vector of inputs containing boost pressure, EGR rate and split fuel injection parameters such as timing and quantity of injection. GA is then used to optimize the above cost function. The single objective GA is an evolutionary optimization algorithm to find the value of \(X\), which minimize the function \(f(X)\). The GA is simply defined in (141) as follows: First "individuals" are generated through random selection of the parameter space (inputs to model) for each control factor a "population" is then produced from the set of individuals. In the next step a cost function is used to evaluate the fitness of each individual. The fittest individuals are allowed to reproduce, "resulting in a new generation" through combining the characteristics from two sets of individuals. "Mutations" are also allowed through random changes to a small portion of the population. The fitness criterion thins out the population by "killing of" less suitable solutions. The characteristics of the individuals tend to converge to the most fit solution over successive generations. In the other research, Hiruyasu et al. used the phenomenological model of a diesel engine called "HIDECS" to optimize the engine. They used multi-objective optimization (MOO) based on GA (26). They tuned EGR rate and multiple injection parameters for optimal operation of engine in sense of emissions and fuel consumption using GA MMO. The MMO problem is a problem of minimization or maximization of multiple evaluation criteria that conflict with each other instead of a single cost function (142). In MOO, there is not a unique
solution for optimization problem. Instead a set of optimal solution called "Pareto optimal front" which is a set of solution is used. Different GA based MOO methods are introduced. Hiruyasu et al. introduces different method of MOO containing SPEA2+, SPEA2 and NSGA-II and compared them in optimization of diesel engines (142). Furthermore, some other optimization method such as gradient-based optimization methods is considered for diesel engine optimization in steady state modes (143). The gradient based optimization is computationally more efficient but only can be used if the cost function satisfies certain convexity conditions on the parameter space. In gradient-based methods, a total cost function is minimized by determining a sequence of pivots at which the search directions are determined by a descent strategy, and the next pivot is obtained by a line-search along which the cost function is minimized.

The pre-mentioned calibration methods take into account the steady state operation of engines. A significant of engine operation occurs in transient mode. The mentioned calibration procedure is not suitable for dynamic optimizations. Some efforts have been done to find a way to optimize the transient operation of diesel engines (137), (144), (133). Model based calibration is extensively being employed in transient calibration of diesel engines. The model-based calibration of diesel engine consists of modeling phase and calibration phases. The model should be able to predict the emissions and performance of diesel engine in transients.

Omran et al. calibrate a diesel engine in transient modes with aim of minimizing engine emissions and fuel consumption under new European driving cycle (NEDC) (98). They described the control algorithms of diesel engine for both steady and transient modes and then developed a procedure to calibrate the engine in dynamic modes. Their proposed method consists of two main steps of pollutant modeling and optimization procedure as depicted in Figure 18. In the first phase, they tested the vehicle on the chassis dynamometer and derived data of emissions and performance and other engine operational parameters while the vehicle forced to follows the NEDC. The derived data then were used to train a recurrent (dynamic) ANN and its validation. In the next phase the data were used to model the angular speed of engine, after which dynamic minimization method were used to optimize the control parameters based on GA. After all the smoothing method were used to smooth the obtained results. The input parameters to optimize were fresh air flow rate, engine boost pressure, start of the main injection, quantity of the Pilot fuel injection, dwell time, the total quantity of fuel injection and the rail pressure.

![Figure 18 Modeling and Optimization procedure in Omran et al. research (98)](image_url)

They discretized the cost function and defined the cost function as follows:

\[ \text{Equation 16} \]
Where the “max” index stands for maximum reachable quantity of emission. GA is then used to optimize this optimization function. Atikson and Mott also did a similar research for calibration of diesel engine under transient condition in FTP test (137), (133).

The ordinary calibration of engine controller takes into account a predefined driving cycle, however new structures of engine controller make it possible to optimize the engine regardless of driving pattern. In ordinary calibration, the parameters are tuned to minimize the total fuel consumption and emissions in a pre-defined driving cycle. Recently some efforts have been done to calibrate engine online. Malikopoulos et al. calibrate engine without taking into account any special driving cycle (145). They treat engine control system as a stochastic system and engine operation as Markov decision process. Engine calibration is formulated as a centralized decision-making problem under uncertainty. The engine controller is a smart system and will learn from driver style how to optimally control the engine. Recently some researchers have used the direct control design for optimization of engine operation. Stewart and Borrelli employed Model Predictive Controller (MPC) to compensate for automatically optimize the engine operation (97). In MPC controller, the future behavior of the system is predicted using a model, then an optimal input for next time interval is obtained which optimized a pre-defined performance index. They showed that MPC controllers can meet the requirement emerged in diesel engine control such as system nonlinearity, time varying properties and computational requirements.

3 Results and Discussions

In this part, the key points in the procedure of common rail diesel engine management systems development are investigated from point of view of the existing literature and finally a workflow is mapped. The whole EMS development process is divided to modeling and identification, sensitivity analysis, controller design, estimator and observer and finally calibration and optimization. In every section the existing method, state of arts and weaknesses and strengths of different methods are briefly discussed.

- **Modeling and identification**

  Different modeling approaches, which are used in engine management procedure, have been classified to dynamic COM, ICP modeling and fuel FIS modeling. The COM models contain ICP and FIS as well as IES models. Two important specification of COM is their accuracy and fast computation capabilities. The soft computing method i.e. ANN and Fuzzy systems are being extensively used in engine dynamic modeling and identification, due to their relatively fast computation speed and ability to learn the nonlinear systems. It was found that the approach of turbocharger modeling is changing from simple look-up table based modeling to non-dimensional modeling due to their ability to cover whole turbocharger operational range. It seems that the COM models, which can predict the emissions in transient modes with enough accuracy and with low computation burdens are demanded for further development in model based designs. Application of ANN and RANN for modeling the ICP can provide the existing MVM models with this capability. With advent of modern CR systems, the injection process are being more flexible, so the models which can predict engine emission and performance with multiple injection and variable rail pressure is highly demanded. On the other hand, the modern controllers and estimators need the models, which can predict the cylinder pressure and speed of engines in an angle based rather than the usual MVM models, which predict the mean value of parameters.

- **Sensitivity analysis**

  The increasing number of actuators has increased the number of affective parameters on engine performance and emissions. The sensitivity analysis is extensively being used to explore the influence of different inputs such as air and fuel path parameters on engine emissions and performance. The
fuel injection parameters such as injection pressure, multiple injection properties such as timing, quantity and shape of each injection event have vastly been investigated in literature. Both experimental based methods and model-based methods are used to study the effects of engine inputs on engine performance and emissions. The later decrease the cost due to lower demanded test, but need accurate models. The statistical methods as well as soft-computing methods have been used to investigate the relative importance of each input on engine outputs.

- **Controller design**

The common methods of engine control, which employ the simple FF controller in the form of lookup tables are investigated in the paper, however due to emphasis of obligations on transient mode emissions, they cannot meet the new standard. The modern CR diesel EMS should be able to optimally control the diesel engines in transient modes using dynamic controllers. Since the CR diesel engines are highly nonlinear, modern approach of control such as LPV, PDC, adaptive and robust controller are gaining more attention to be employed for control aims. The hierarchical controller design are extensively being used to develop the CR diesel EMS controlling strategies, which use a supervisor control for managing the fuel and air path controllers. However, some efforts have been done to implement the integrated MIMO controllers, which promote synergic use of all input paths for optimization of engine. The TBCS, which control the output torque are recently gaining more attention due to the ease of integration with other control unit in automotive. TBCS also pave the way for further optimizations in CR diesel engines. The soft computing based controllers such as ANN controller, fuzzy and adaptive fuzzy controller are recently being paid more attention to be used in diesel engine controllers. They have shown good results in decreasing the output emissions especially in transients. On the other hand, the in-cylinder pressure contains valuable information of combustion process, which can promote the capabilities for further optimality. Although they have been rarely considered for general production due to expense of relevant sensor, it seems that the next generation of EMS will benefit from them.

- **Estimator and Observers**

The emerging modern controllers need some output and signals, which cannot be measured by common sensors. The indicated torque, induced air charge, in-cylinder pressure and emission are from which. The classic methods as well as modern soft computing methods have been used to estimate these parameters. Furthermore, the ANN and RANN are increasingly being used for estimation of emissions in both steady state and transient modes. The literatures shows that instantaneous engine speed and in-cylinder pressure signals contain valuable information for estimation of torque, emission, trapped mass and many other states of engine.

- **Optimization and Calibration**

The calibration procedure is an important step in meeting the obligations and emission standards. In this paper, both classic and modern methods of engine calibration were described. Three different calibration methods can be found in literature: classic experimental based calibration, model based steady calibration and model based dynamic calibration. The classic methods employed a large number of tests for optimization of engine. Since the number of actuators have been increasing significantly in modern EMSs, the classic methods are not suitable in calibration of today engines. The DOE is used to decrease the number of demanded test for calibration. DOE is an approach, which decrease the number of demanded test by modeling the engine input-output relations. In order to further decrease the cost and time of calibration, MBC is employed. The MBC used the model of engine instead the real engine. GA as a global optimization algorithm is extensively being used for optimization procedure in MBC. The GA is used in both single objective and multi objective form. In the case of single objective a cost function based on emission and fuel consumption is defined and optimized by GA. Usually the steady state calibration is done based specific driving cycles; that is
some OP are found and calibration is done to find the optimal inputs. Recently some efforts have been done to calibrate the engine regardless of any specific driving cycle. On the other hand, the transient optimization is recently gaining more attention due to emphasis of obligations on transient mode emission. In the case of transient calibration a model of emission generation in transient is developed based on test results of standard driving cycles. The ANN is then employed to model the emission and performance in transient. The GA or other algorithms are then used for optimization. Some efforts are being done implement the optimization directly into control algorithms by adaptive optimal control of engines.

- **Workflow**

Finally a schematic workflow is drawn as depicted in Figure 19. The procedure starts with definition of existing obligations and level of desired standard. The limitations on emissions and fuel consumption and the key points of control design such as the emphasis on transient modes are defined in this stage. Regarding the last phase a proper model should be developed. The model should meet the speed and accuracy demands. Usually the COM model are developed by integration of ICP, FIS and IES models. However, ICP model will also distinctively be needed for sensitivity analysis in which the most effective parameters is selection for control aims. The COM will be used in controller design phase, where hieratical control is of interest in recent approaches of control design. Both FF and FB controllers are used in controller design. In new scheme of EMS some hard to measure parameters such as torque and trapped air are demanded for control aims. The estimator will then be used for estimating these parameters. Finally the free parameters, lookup tables and controller gains should be calibrated to guarantee an optimal operation of engine in both steady and transient modes.

![Figure 19](image-url) The flow work of CR diesel EMS development

### 4 Conclusion

- The development procedure of common rail diesel engine management system is investigated using the existing literature; the whole procedure is divided into modeling, sensitivity analysis, controller design, estimator design and calibration.
- The model-based methods are being paid high attention in different phases of design, which in turn, increased the need of more accurate models with emission prediction capabilities. Since the CR engines have the most flexible injection capabilities, development of models which can predict the emissions and performance in multiple injection will have the most importance.
- Modern controller development demands the MVM model, which can predict the emissions in transient modes. For that, the ANN and RANN can be used. On the other hand, the traditional MVM models are being promote to be able to model instantaneous speed, torque and in-cylinder pressure for control aims.
- Soft computing methods such as ANN, RANN, GA, MOO-GA and fuzzy methods are being extensively used in different development phases; such as application of ANN, RANN and fuzzy systems in
modeling, GA and MOO-GA in calibration, application of ANN and RANN in estimations and application of ANN and fuzzy systems in control.

- The hierarchical controllers are extensively being used in engine control as supervisory controllers, which control the LLCs. However, it seems that the integrated MIMO controllers—which can control both the air and fuel paths in transient modes—have more potential for lowering the emissions and therefore, will replace the existing controllers.

- PID gain schedules controllers are widely being used in EMS for closed looped control of parameters such as ISC, boost control and torque control. Recently, fuzzy controllers as well as ANN controller are being employed for feedback control of parameters which result in more optimal control of engines as nonlinear dynamic systems.

- The in-cylinder pressure signals have valuable information about the situation of in-cylinder phenomena. There is a high tendency for employing the controllers that operate based on in-cylinder pressure signals.

- Howbeit the valuable signals are hard to measure; they can greatly promote the control. It seems that they can be obtained from "soft sensor" considering the advances in microprocessors.

- The model-based calibration is receiving more attention due to its capabilities in lowering the required time and cost of calibration in both steady and transient modes. In MBC, the evolutionary optimization techniques such as GA are used for optimization of accurate models of engines.

- The existing method of calibrations take into account the standard driving cycles and define the OPs based on them; this approach however guarantees an optimal operation only in a specific driving cycle. Recently, some effort are being done to optimize the engine, free of driving cycle, based on adaptive online optimization which takes the individual driving style into consideration.

- Finally, a workflow for CR diesel EMS is drawn depicting the sequences of different steps of development.

### 5 Abbreviation

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Antilock Brake System</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Convertor</td>
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<tr>
<td>AFR</td>
<td>Air-Fuel Ratio</td>
</tr>
<tr>
<td>AIS</td>
<td>Air Induction System</td>
</tr>
<tr>
<td>ANFIS</td>
<td>Adaptive Network Fuzzy Inference System</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Networks</td>
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<tr>
<td>ANOVA</td>
<td>Analysis Of Variance</td>
</tr>
<tr>
<td>BMEP</td>
<td>Brake Mean Effective Pressure</td>
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<tr>
<td>BSFC</td>
<td>Brake Specific Fuel Consumption</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>CI</td>
<td>Compression Ignition</td>
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<tr>
<td>CLC</td>
<td>Closed Loop Controller</td>
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<tr>
<td>COM</td>
<td>Control Oriented Model</td>
</tr>
<tr>
<td>CPAM</td>
<td>Combustion Process Analysis Module</td>
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<tr>
<td>CR</td>
<td>Common Rail</td>
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<tr>
<td>DEM</td>
<td>Discrete Event Modeling</td>
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<tr>
<td>DI</td>
<td>Direct Injection</td>
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<tr>
<td>DOE</td>
<td>Design Of Experiments</td>
</tr>
<tr>
<td>DOE</td>
<td>Design Of Experiment</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>EDC</td>
<td>Electronic Diesel Control</td>
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<td>EDC</td>
<td>European Driving Cycle</td>
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<td>EES</td>
<td>Emission Exhaust System</td>
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<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
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<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
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<td>ESP</td>
<td>Electronic Stability Program</td>
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<td>FB</td>
<td>Feedback</td>
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<tr>
<td>FDS</td>
<td>Fuel Injection System</td>
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<tr>
<td>FF</td>
<td>Feed forward</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
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<tr>
<td>HC</td>
<td>Hydro Carbons</td>
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<tr>
<td>HiL</td>
<td>Hardware in the Loop</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>ICP</td>
<td>In-Cylinder Process</td>
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<tr>
<td>IMC</td>
<td>Internal Mode Controller</td>
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<tr>
<td>IMEP</td>
<td>Indicated Mean Effective Pressure</td>
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<td>ISC</td>
<td>Idle Speed Controller</td>
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<tr>
<td>LLC</td>
<td>Lower Level Controller</td>
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<tr>
<td>LMI</td>
<td>Linear Matrix Inequality</td>
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<td>LOLIMOT</td>
<td>Local Linear Model Tree</td>
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<tr>
<td>LPV</td>
<td>Linear Parameter Varying</td>
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<td>MAF</td>
<td>Mass Air Flow</td>
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<td>MAP</td>
<td>Manifold Air Pressure</td>
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<td>MBC</td>
<td>Model Based Calibration</td>
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<td>Mil</td>
<td>Model in the Loop</td>
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<tr>
<td>MIMO</td>
<td>Multi Input Multi Output</td>
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<tr>
<td>MOCMAES</td>
<td>Multi-Objective Covariance Matrix Adaptation Evolutionary Strategy</td>
</tr>
<tr>
<td>MOO</td>
<td>Multi Objective Optimization</td>
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<td>MPC</td>
<td>Model Predictive Control</td>
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<td>MVM</td>
<td>Mean Value Modeling</td>
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<tr>
<td>NA</td>
<td>Natural Aspirated</td>
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<tr>
<td>NARMAX</td>
<td>Nonlinear Auto-Regressive Moving Average with Exogenous inputs</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturers</td>
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<tr>
<td>OLC</td>
<td>Open Loop Controller</td>
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<tr>
<td>OP</td>
<td>Operation Point</td>
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<td>PCA</td>
<td>Principal Component Analysis</td>
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<td>PDC</td>
<td>Parallel Distributed Controller</td>
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<td>PID</td>
<td>Proportional Integral Derivative</td>
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<td>Processor in the Loop</td>
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<td>PM</td>
<td>Particulate Matters</td>
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<td>QFD</td>
<td>Quantitative Feedback Design</td>
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<tr>
<td>RANN</td>
<td>Recurrent Artificial Neural Network</td>
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<td>RBF</td>
<td>Radial Basis Function</td>
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<td>RCP</td>
<td>Rapid Control Prototyping</td>
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<td>RSM</td>
<td>Response Surface Methodology</td>
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<td>Selective Catalyst Reduction</td>
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<td>Software in the Loop</td>
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<td>Sequential Quadratic Programming</td>
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<td>State Vector Feedback Control</td>
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<td>TBCS</td>
<td>Torque Based Control System</td>
</tr>
<tr>
<td>TCS</td>
<td>Traction Control Systems</td>
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</table>
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