TOWARDS ARTIFICIAL INTELLIGENCE BASED DIESEL ENGINE PERFORMANCE CONTROL UNDER VARYING OPERATING CONDITIONS USING SUPPORT VECTOR REGRESSION

by

Ravi Kumar NARADASU [a*], ***Jyothirmai SRINATHU*** [b], **and *Ramesh RAMAKRISHNAN*** [b]

[a] Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, India
[b] Centre for Intelligent Manufacturing Automation, Department of Mechanical Engineering, MVGR College of Engineering, Vizianagaram, India

Original scientific paper
DOI: 10.2298/TSCI120413218N

Diesel engine designers are constantly on the look-out for performance enhancement through efficient control of operating parameters. In this paper, the concept of an intelligent engine control system is proposed that seeks to ensure optimised performance under varying operating conditions. The concept is based on arriving at the optimum engine operating parameters to ensure the desired output in terms of efficiency. In addition, a support vector machines based prediction model has been developed to predict the engine performance under varying operating conditions. Experiments were carried out at varying loads, compression ratios and amounts of exhaust gas re-circulation using a variable compression ratio diesel engine for data acquisition. It was observed that the support vector machines model was able to predict the engine performance accurately.

Key words: *variable compression ratio, diesel engine, support vector machines, performance, exhaust gas re-circulation*

Introduction

Diesel engines have been a mainstay prime mover in the automobile industry for several years now. While initially not a very efficient power generation concept, extensive research has metamorphosed the traditional diesel engine into a very cost-effective and efficient energy source for most state-of-the-art automobiles. The features offered by diesel engines are inimitable over other fuel driven engines such as the ability to develop high power, reduced cost, reduced fuel consumption, higher torque generation, *etc*. These engines will therefore continue to be used in several automobile applications such as three wheelers, four wheelers as well as heavy-duty vehicles like buses and trucks, power generation applications, locomotives, *etc*. However, diesel engines also suffer from certain nagging issues such as reduced mechanical efficiency and thermal efficiency and also the release of highly polluting organic emissions. Critical evaluation of diesel engine performance therefore plays a crucial role in estimating the degree of success in terms of conversion of chemical energy contained in the fuel into mechanical work. Certain basic performance parameters such as specific fuel consumption, brake mean effective pressure, mechanical efficiency, *etc*. are to be carefully considered in the evaluation of engine performance. The performance of the engine can be improved only when all these parameters are controlled properly. Engine designers are constantly on the lookout for methods to

* Corresponding author; e-mail: naradasuravi@gmail.com

enhance performance through manipulation of the basic operating parameters to improve one or the other of these performance metrics. Despite such attempts, the control of all these parameters and achieving a desired performance in all of these metrics is a very complicated task. Therefore, there is great need for the development of a system that can understand the intricacies of diesel engine performance and efficiently alter the operating parameters such that the desired overall performance is achieved. Despite extensive research into the theoretical basis and performance characteristics of diesel engines, a complete mathematical description of the relationship between the operating parameters and the performance characteristics is still to be clearly understood because of the great complexity in their interrelationship. It is thus necessary to first of all understand and model this complex relationship and thereafter develop a methodology for achieving the desired performance by adjusting the operating parameters suitably. In this paper, an attempt has been made to propose the concept of an automated, intelligent engine control system for the automatically controlling the engine operating conditions to achieve the desired engine performance such that optimum output is produced as well as minimum emission levels are achieved. In addition, as a first step, a model has been developed for the prediction of diesel engine performance under varying operating conditions through conduct of several experiments on a variable compression ratio (VCR) diesel engine.

Literature review

Study on diesel engine performance

Diesel engine performance study has been one of the most significant issues in the engine design and manufacturing industry with special focus on the performance of single cylinder, multi cylinder, and VCR engines and engines fitted with exhaust gas re-circulation (EGR) systems. Subramanian *et al.* [1] studied and compared the performance and emission characteristics of hybrid fuel blends of biodiesel with diesel in a multi cylinder, naturally aspirated, direct injection diesel engine to reduce hydro carbon emissions. Lou *et al*. [2] investigated theoretically the effects of gasoline fumigation on single-cylinder diesel engine performance and emissions to reduce smoke and increase engine output and also coupled the system with EGR to reduce NO_x emissions. Deepak *et al*. [3] studied the effect of EGR on vital engine parts, especially piston rings, in a two cylinder, air cooled, and constant speed direct injection diesel engine to reduce emissions of hydro carbons in NO_x as well as exhaust gas temperature. Muralidharan and Vasudevan [4] investigated and compared the performance, emission and combustion characteristics of a single cylinder, four stroke, VCR multi-fuel engine when fueled with waste cooking oil methyl esters and with standard diesel to obtain optimum compression ratio, longer ignition delay, maximum rate of pressure rise and also to reduce CO and HC emissions.

Modeling of engine parameters to predict engine performance

As seen from the above trend of investigative attempts, several different operating conditions in terms of fuel type, engine type, running condition, *etc*. and several performance characteristics in terms of emissions, output and efficiency present a complex interrelationship that needs to be carefully understood in order to achieve best possible performance. Given the complex nature of this interrelationship, arriving at a suitable mathematical or thermodynamic model of this relationship is certainly a non-trivial task. Artificial intelligence techniques that have been a major area of research in the computational field are being increasingly applied to the solution of complex problems in various domains of mechanical engineering with the same finding its way into the field of engine performance as well. Several studies have been on-going in the use of artificial neural networks (ANN) for predicting the performance and emission control of diesel engines. Jahirul *et al.* [5] developed a prediction model using ANN to evaluate the performance of a retrofitted automotive compressed natural gas (CNG) engine. Abhisek *et al*. [6] developed linear models using ANN for control of emissions in heavy duty vehicles such as buses. Hari Prasad *et al*. [7] developed a model for the study of emissions in diesel engines using methyl esters of fish oil. Obodeh and Ajuwa [8] evaluated the capabilities of ANN as a predictive tool for multi-cylinder diesel engine to predict NO_x emissions under various operating variables. Berber *et al.* [9] investigated the characteristics of a four-stroke diesel engine using ANN. Kiani *et al*. [10] developed an ANN model for predicting the brake power (BP), torque and CO, CO_2, HC and NO_x emissions of the engine in relation to input variables such as engine speed, engine load and fuel blends. Antonio *et al.* [11] developed a thermal network model for the simulation of the transient response of diesel engines. Yan *et al.* [12] described the use of ANN for modeling the diesel engine emission performance based on experimental data. Abhisek *et al.* [13] developed an optimum ANN architecture to reduce HC and NO emissions. All of these attempts indicate that there is sufficient scope for the application of artificial intelligence techniques in the understanding and predicting the performance of an engine under various operating conditions as these methods are capable of modeling complex interrelationships using a data driven approach.

Intelligent engine control systems

In order to improve engine performance as also to obtain better control of automobiles, several different attempts have been made to integrate electronic systems with vehicle operation and control. As such, the use of a range of sensors and associated electronic transducer systems are increasingly taking over manually controlled vehicle operations. Several engine control systems have been developed in diesel engines to control engine performance parameters such as a diesel particulate filter (DPF) device designed to remove diesel particulate matter (or soot) from the exhaust of diesel engines. Recent trucks and care have been designed with electronic diesel injection control, a fuel injection control system for the precise metering and delivery of fuel into the combustion chamber of the diesel engine. In addition, at the research front, Chen *et al.* [14] analyzed, in a low-speed marine diesel engine, the relationship of emission with the combustion process, fuel injection, exhaust re-circulation, *etc*. Diesel engines are also established with fuel injection system with the high-pressure common rail and the test system based on the emission control optimization and matching technology for the diesel engine's emission performance. Shen and Su [15] proposed a fuzzy-PID control method in the speed control of a marine diesel engine to realize online adjustment of parameters and also improve the system dynamic performance, reduce system oscillation and improve the response speed. Chen *et al.* [16] performed strength and fatigue analysis of the engine body, bending and torsion fatigue analysis of the crankshaft, thermal fatigue and mechanical fatigue analysis of the cylinder head-piston, wear analysis of the valve-seat, and structural-thermal coupling analysis based on finite element methods in a high-power low-speed diesel engine.The objective was to optimize the structure of the diesel engine. Ji *et al.* [17] proposed a PID controller based on radial basis function (RBF) neural network model in a high pressure common rail diesel engine system for better dynamic response. Barghi and Safavi [18] designed a predictive recurrent neuro-fuzzy network (RNFN) controller based on non-linear inverse dynamics in the fuel injection control of a spark ignition system to avoid the costly and time-consuming calibration efforts required in conventional fuel injection control strategies. These efforts have paved the way for better control of engine operation and performance as well as extended the scope of application of electronic systems in the optimized performance of the automobile.

Intelligent system design

Despite extensive research carried out in this domain, there appears to be significant scope in two major areas namely the modeling of engine performance under wide ranging operating conditions as well as the development of an intelligent vehicle control system incorporating such a model to enhance vehicular performance. In this paper, an attempt is made to propose the concept of an intelligent engine control system for the dynamic, automatic control of engine operating conditions in order to achieve desired performance and emission levels under real-time road conditions. At the heart of such a system is an artificial intelligence based model that maps the operating conditions with engine performance and emission characteristics. As a first step towards the development of such a system, in this paper, a support vector machines (SVM) based model is also developed for engine performance prediction under varying operating conditions.

Proposed concept

On-road vehicular conditions are highly dynamic, terrain dependent, and influenced by other road traffic elements making the control of engine operation subject to constant variation. Achieving optimum performance of the engine under such conditions is certainly a non-trivial task and requires in-depth understanding of the relationship between the operating variables and the performance parameters. In order to develop a fully automated intelligent engine control system, critical decision-making tasks need to be integrated into the system and adjustment or compensation carried out to ensure that the engine operating conditions are as required to achieve the desired performance. Such a closed loop control system requires monitoring of operating conditions, prediction of engine performance under these conditions based on a model developed a priori and adjustment of the control variables through suitable actuation systems. Being a real-time task, this requires development of a closed loop control system that can execute all the above tasks. Since real-time prediction of performance is also involved, such a system will require a dedicated, digital signal processing (DSP) based central processing unit (CPU) at its core to handle these activities. Given the highly complex nature of the interrelationship between the operating parameters and performance variables, a first-principles approach to building a mapping model is certainly very complicated necessitating the development of an artificial intelligence based prediction model. The proposed concept of the intelligent engine control system is illustrated in fig. 1.

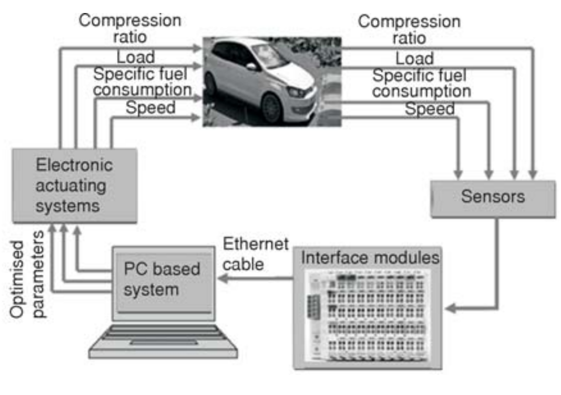

Figure 1. Intelligence based diesel engine performance control system

The vehicle is envisaged with additional capabilities having sensors monitoring the variables, interface with an on-board computer control unit, a software-based control system, and an electronic actuation system to effect change in parameters. Typical operating parameters include engine speed, compression ratio (CR), degree of EGR, *etc*. The effective control of these parameters determines the performance, mileage, and emissions produced by the vehicle. Sensors mounted on the vehicle can monitor these operating parameters constantly. The information from the sensors is routed to the on-board CPU through the interface modules. The CPU estimates the performance of the vehicle using an a priori software-based mapping model. This mapping model predicts the performance, compares the same with the pre-defined performance expected of the vehicle and computes the optimum operating conditions necessary to achieve that performance. Once the optimum operating conditions are identified, the same can be supplied to the electronic actuator system that dynamically effects changes to the operating parameters through electronic servo-controlled actuators. The control of these servo devices can be accomplished through a fully software-based open architecture control system that is installed in the same CPU. The CPU thus serves as the common backbone computational platform that collects data from the sensors, processes the data to compute desired operating conditions and effects change in the operation conditions by suitably commanding the servo drive system controlling the actuators.

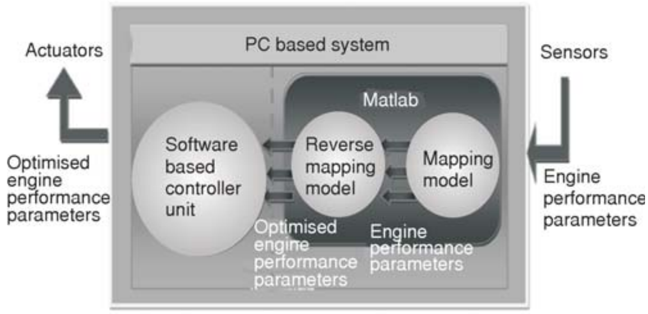

Figure 2. Parameter mapping and control system framework

The heart of the system is the central computing unit that performs the tasks of mapping the input variables with the performance parameters as well as controls the actuator system to effect changes in the operating conditions. The parameter mapping and control system framework is illustrated in fig. 2. The engine operating parameters are sent to the software-based forward mapping model that has been built to map the relationship between the operating variables and performance parameters. For the given operating conditions, the forward mapping model predicts the performance. The desired optimum performance is defined for the engine so that the engine always operates under these conditions. This is achieved by linking the artificial intelligence based reverse mapping model with the forward mapping model. The reverse mapping model estimates the optimum operating parameters from a range of candidate solutions that satisfy the requirement. This optimised solution is then sent to the software-based controller that controls the actuators and ensures that the engine operates under these optimum conditions. Such a set up constantly monitors engine performance and ensures that real-time control of the engine operating conditions is achieved.

Despite extensive attempts at improving engine performance and control, a conventional engine control system affords the end-user little scope for communicating specific requirements that the engine can automatically ensure. This framework presented herein would significantly help the driver to achieve effectively optimum performance of the engine under real-time, on-road conditions.

Experimental work

In an attempt to work towards the system concept proposed above, an engine performance model was first developed using SVM. Experiments were conducted on a fully computerized, single cylinder, direct injection, VCR, high speed diesel engine test rig shown in fig. 3.

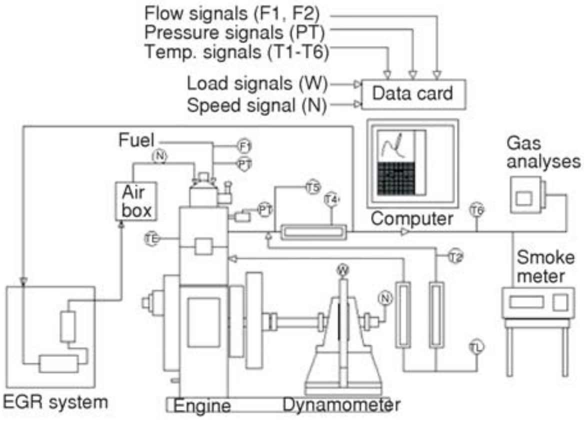

Figure 3. Experimental set-up of variable compression diesel engine

Table 1. Specifications of the engine

Bore and stroke	80 × 110 mm
Brake horse power	5
Speed	1500 rpm
Loading	Eddy current dynamometer
Compression ratio	16.5:1
EGR [%]	0-15
Fuel injection	230 bTDC
Fuel injection pressure	200 bar

Specifications of the engine are given in tab. 1. At the rated speed (1500 rpm), the engine develops approximately 4 kW power output. The engine is coupled to an eddy current dynamometer. A mass flow sensor is used to find the mass flow rate of air entering into the cylinder. A non-contact PNP sensor is used to measure the engine operating speed. The PNP sensor gives a pulse output for each revolution of the crankshaft. The frequency of the pulses is converted into voltage output and connected to the computer. Torque is measured using a load cell transducer which is basically a strain gauge. The output of the load cell is connected to the load cell transmitter which is in turn connected to the computer. The fuel consumption is measured by help of optical sensors. These optical sensors are capable of detecting any liquid and give an electrical output signal. The system consists of a burette fitted with two optical sensors one detecting the high level and the other detecting the low level. As the fuel passes across the higher-level optical sensor, the sensor gives a signal to the computer to start the time clock. Once the fuel reaches the lower-level optical sensor, the sensor gives a signal to the computer to stop the time clock and refill the burette. The time taken for consumption of fuel for a fixed volume is calculated.

The cylinder pressure is calculated using a piezoelectric transducer. The temperature of gases and water at various points are calculated using "K" type thermocouples. The experimentation was carried out at different loads, CR ranging from 15 to 20, and EGR quantities varying between 0 and 10%. For each of these conditions, performance parameters such as specific fuel consumption (SFC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE) and mechanical efficiency (ME) are estimated.

Results and discussion

In order to evaluate performance of a diesel engine, the BTE, ME, volumetric efficiency (VE), brake specific fuel consumption (BSFC), BMEP, indicated mean effective pressure (IMEP), SFC, maximum pressure (MP), combustion duration (CD). and ignition delay (ID), *etc*. were measured. The experimentation was done at constant speed and different loads while also varying the CR. The data related to performance, combustion and emissions was simultaneously recorded and the results obtained from experimentation were plotted. It is observed that with increase in CR, the BTE increases as seen in fig. 4. At CR 15 the BTE is 15.6% whereas at CR 19 the BTE increases to 16.97%. Similarly, with increase in CR the ME also in-

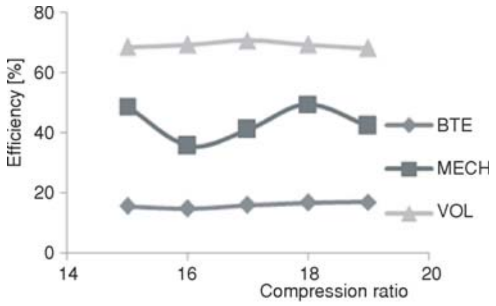

Figure 4. Effect of CR on BTE, ME, and VE at 25% load

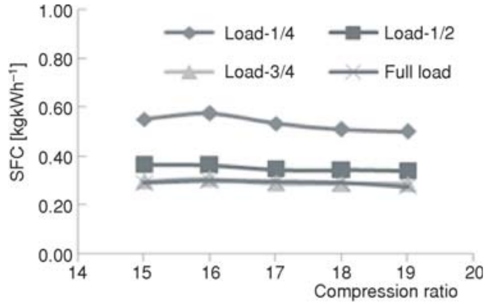

Figure 5. Effect of CR on SFC at different loads

creases obtain maximum of 49.4% at 25% load with CR 18 and then decreases. The SFC at various loads and CR are presented in fig. 5. At part loads, with increase in CR the decrease in SFC is considerable. With increase in load the decrease in SFC is less. Overall, with increase in CR the SFC decreases irrespective of the load except at CR of 16.

This trend is also observed from individual graphs between SFC and CR plotted earlier.

Figure 6 illustrates the change in maximum pressure with CR. The maximum pressure increases with increase in CR because of more ignition delay. The maximum pressure at CR of 15 is 60.1 bar which increases to 71.2 bar at CR of 19. The combustion duration slightly changes with respect to the CR. Figure 7 explains the effect of CR and percentage of EGR on NO_x emissions. With increase in percentage of EGR the NO_x emissions decreases due to reduced combustion temperature and effective combustion. At CR of 19 with 10% EGR, the NO_x emissions are reduced to 62.8%.The percentage decrease in NO_x emissions is more at higher CR (18 to 20) compared with CR 15 to 17. The combined influence of CR and EGR on SFC for varying values of CR and EGR at half load is shown in fig. 8. As seen from these surface plots, the SFC appears to be at local minima for CR in the range of 18 to 19 and EGR of 0 and local maxima for CR in the range of 16 to 18 and EGR of 0 to 10.

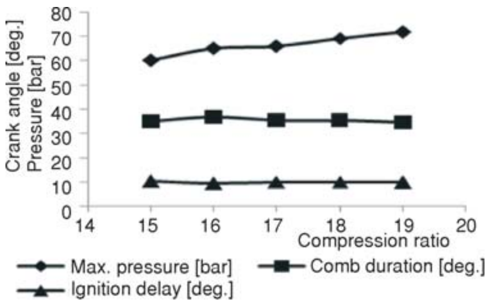

Figure 6. Effect of CR on MP, CD, and ID

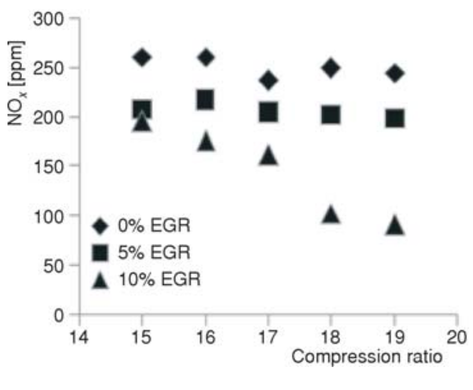

Figure 7. Variation of NO_x with % of EGR and CR

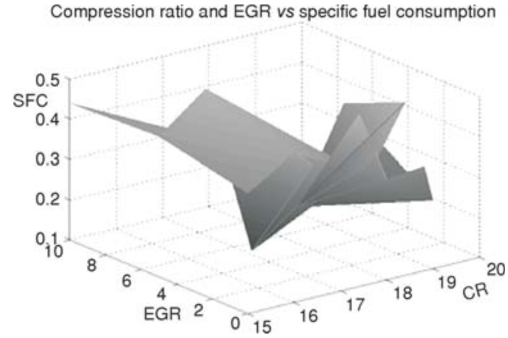

Figure 8. EGR and CR *v/s* SVM predicted SFC

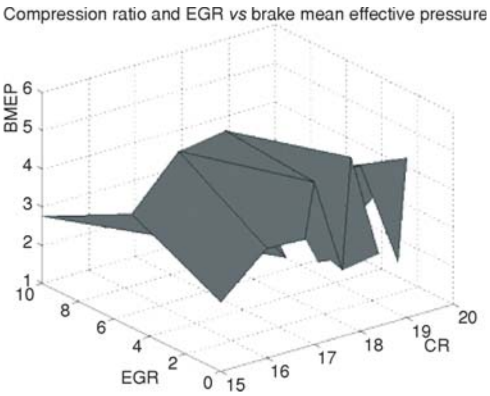

Figure 9. EGR and CR *v/s* SVM predicted BMEP

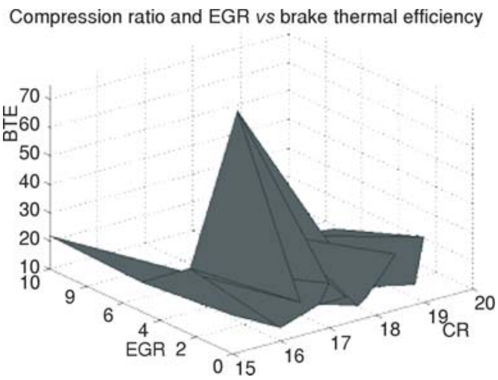

Figure 10. EGR and CR *vs*. SVM predicted BTE

The combined influence of CR and EGR on mean effective pressure for varying values of CR and EGR at half load is shown in fig. 9. As seen from these surface plots the mean effective pressure appears to be at local minima for CR 17 and EGR of 5 and at local minima for CR 19 and EGR of 0 to 5. This trend is also observed from individual graphs between mean effective pressure and CR plotted earlier. The combined influence of CR and EGR on BTE for varying values of CR and EGR at half load is shown in fig. 10.

As seen from these surface plots the BTE appears to be at local maxima for CR 19 and EGR of 0 to 5 and local minima for CR 16 and EGR of 0 and10. This trend is also observed from individual graphs between mean effective pressure and CR plotted earlier. Based on the results obtained from the experiments on the VCR engine, it appears that optimum performance can be achieved by operating the 5 horse power engine in the range of CR18 to 19. Automobile engine manufacturers however generally design their engines for CR in the range of 16 to 18 which, for a given engine, is always fixed. In addition, as seen from the above analysis, achieving a desired performance in terms of engine output as well as emission levels needs careful adjustment of several different factors. A very complex relationship exists between these factors and engine performance especially when all the factors vary simultaneously. Herein arises the need for an intelligent system that can dynamically vary the engine operating parameters to achieve the desired performance.

Prediction model for engine performance

One of the difficulties observed in the study of the performance of the engine as done above is the inability to estimate variation in BTE, IMEP, *etc*., when the load, CR, EGR, *etc*. are varied simultaneously. The computation of these parameters under the combined influence of all the operating conditions is a non-trivial task but one which requires to be correctly modeled in order to estimate the performance of the engine. Artificial intelligence techniques have evolved as a very effective and useful tool to develop models for complex situations such as this based on extensive experimental data. Although ANN has been popularly used, one of the major problems with ANN is the need for a large database of high quality data for the development of the model. In order to generate such data, extensive experimentation will have to be carried out on the engine in several stages. This runs the risk of other effects such as engine overheating, *etc*. contributing to the observed performance. As such, limited number of data points only can be made available with which the model needs to be developed. ANN has been found to be not very effective with sparse data. SVM is a very effective approach that has been found to address many of the difficulties faced with the use of ANN. In this paper, an attempt is made to develop a forward mapping model using SVM to predict the engine performance under varying operating conditions as shown in fig. 11. The SVM model can easily be developed by assigning a few parameters namely the kernel function, the cost function, *etc*. Unlike with ANN where the architecture has to be developed in advance, the SVM model is easy to build and at the same time it generates a unique solution after training. Mukherjee *et al*. [19] SVM based on the structural risk minimisation (SRM) principle shown to be superior to the empirical risk minimisation (ERM) principle employed by conventional ANN. The goal of SVM is to find out a function that gives a deviation of error from the actual given output and at the same time is as flat as possible. This is achieved by mapping the training patterns from the input space to a high dimensional feature space in such a way that the data which could not be separated by a linear function in the input space can be separated in the feature space. Thus, in arriving at a suitable SVM model for the given sparse data, the only parameters that the user deals with and has to specify are the kernel function, type of loss function, the error goal, the constant, and the width of the radial basis function. This makes it convenient to use SVM in the prediction of the output variable for a given combination of input variables especially in a situation where collection of data for training the model is difficult. Wei and Ping [20] attempted application of SVM model to predict engine reliability. They found that numerical results indicate the feasibility and superiority of the SVM model in predicting engine reliability. Chi *et al.* [21] studied prediction of automotive engine power and torque using least squares SVM and Bayesian inference. These few works have attempted to predict engine reliability, power and torque. But the prediction of engine performance parameters in diesel engines using SVM has not received much attention.

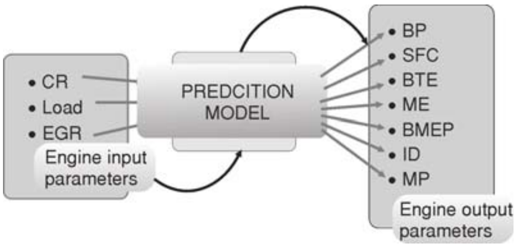

Figure 11. Prediction model using SVM for various engine performance parameters

In this work, an attempt is made to develop a prediction model so that an engine performance prediction system can be developed that could predict engine performance parameters for various operating conditions. Experiments were conducted and the data generated for various test conditions. In order to develop a prediction model, input parameters for the SVM model were taken as CR, load, and EGR and the output parameters were taken as SFC, ME, BMEP, ID, MP, BTE, and BP. A total of 85 data points were obtained from experimentation of which 75 were used to develop the model.

Prediction model performance

The predicted values from the SVM model were found to be very close to the actual values obtained through experimentation. In the case of BTE, it can be observed from fig. 12 that the SVM predicted values and the values obtained from experimentation are fairly close. Out of 21 values given as test values, 11 values have an error less than 1%. Seven values have slightly higher than 1%. Figure 13 shows the compari-

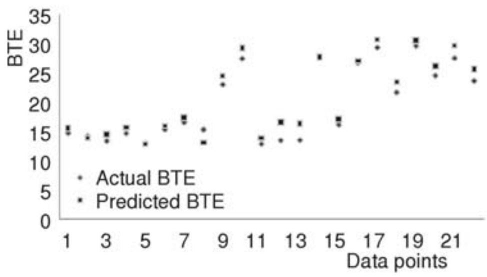

Figure 12. SVM predicted results for BTE

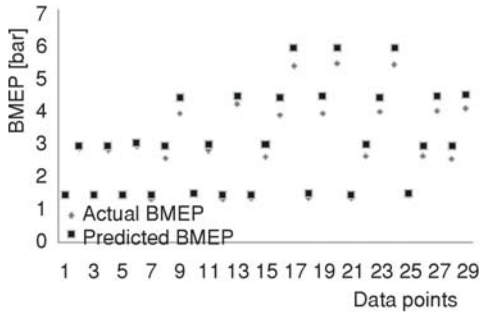

Figure 13. SVM predicted results for BMEP

son of BMEP between the experimental values and SVM predicted values. Out of 29 values given as test input, five values have error less than 0.05 bar and 24 values have less than 0.5 bar. It reveals that the SVM model is able to accurately map the input parameters and the BMEP of the engine.

Figure 14 shows that the variation in SFC between the SVM predicted values and the experimental values. Out of 29 values given as test input, 26 values have error less than 0.1 kg/kWh and only three values have error between 0.1 and 0.151 kg/kWh. Figure 15 describes the change in ID between SVM predicted values and experimental data. Out of 27 data points given as test input, 15 points have error less than 0.50 and 5 points have error less than 10 and the remaining seven points are between 1 to 2 deg. of crank angle rotation which is an acceptable deviation given that the standard range for ID is 8 to 12 deg. Figure16 shows the variation of error in prediction for the performance parameters namely BP, SFC, and BMEP which is less than 1%. It is observed that the SVM model developed is able to map the relationship between operating parameters and performance attributes very accurately.

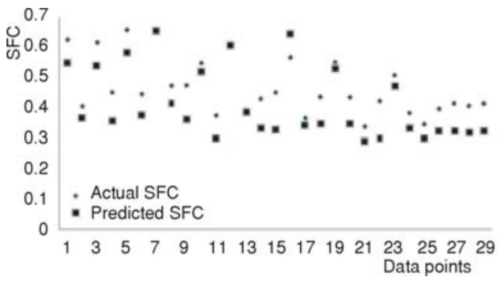

Figure 14. SVM predicted results for SFC

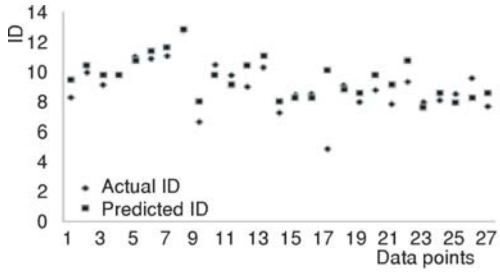

Figure 15. SVM prediction error values for ID

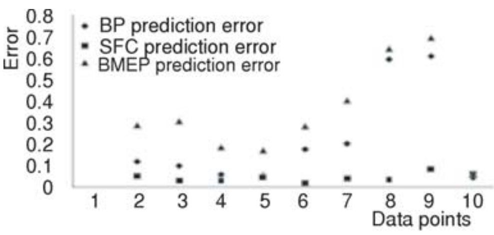

Figure 16. SVM prediction error values for BP, SFC, and BMEP

Conclusions

In the present work, the concept of an intelligent diesel engine performance control system was proposed. At the heart of this system is the SVM forward mapping model that was developed to predict the performance of the diesel engine under simultaneously varying operating conditions. Experiments were conducted on a VCR engine based on which this model was developed. From the experimentation, it was found that with increase in CR, BTE increases, and SFC is decreases. It was also found that when EGR is adopted, the MP in the cylinder and NO_x emissions are reduced. The developed SVM model is able to offer accurate prediction of the performance parameters for a given set of operating values in comparison with actual experimental data with an error of less than 0.8%. Using this model, it is possible to estimate quickly the performance of the engine. With such a model, the difference between the engine output and the set reference can later be used to arrive at the optimsed set of operating parameters for a given engine performance requirement.

Acknowledgment

The authors are thankful to the All India Council for Technical Education (AICTE), New Delhi for their financial support vide project grant, F.NO:8204/RID/BOR/MOD--545/2009-10.

Acronyms

ANN – artificial neural network
BMEP – brake mean effective pressure
BP – brake power
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CD – combustion duration
CR – compression ratio
CPU – central processing unit
EGR – exhaust gas re-circulation
ID – ignition delay
IMEP – Indicated mean effective pressure
ME – mechanical efficiency
MP – maximum pressure
SFC – specific fuel consumption
SVM – support vector machines
VCR – variable compresion ratio
VE – volumetric efficiency

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Paper submitted: April 13, 2012
Paper revised: August 23, 2012
Paper accepted: October 22, 2012