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# Development and validation of a GEP model to predict the performance and exhaust emission parameters of a CRDI assisted single cylinder diesel engine coupled with EGR

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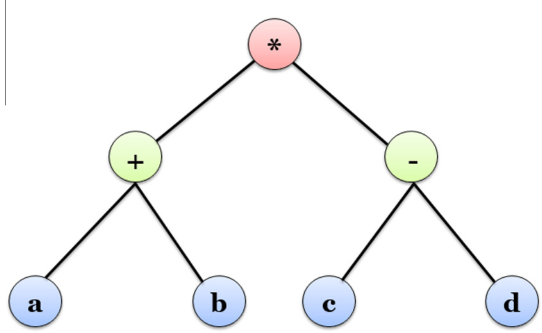
## HIGHLIGHTS

- CRDI/high pressure fuel injection reduces PM and BSFC with the penalty of increase in NOx emissions.
- EGR operation at lowest injection duration case of CRDI operation reduces NOx.
- GEP modelling of BSFC, BTE, $CO_2$, NOx and PM.
- Gene Expression Programming is capable in predicting performance and emission parameters of the experimental engine.
- GEP performed better when compared with ANN.

## GRAPHICAL ABSTRACT

*Equation:* $(a+b)*(c-d)$

*GEP Expression Tree:*

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## ABSTRACT

Gene Expression Programming was employed to express the relationship between the inputs and the outputs of a single cylinder four-stroke CRDI engine coupled with EGR. The performance and emission parameters (BSFC, BTE, $CO_2$, NOx and PM) have been modelled by Gene Expression Programming where load, fuel injection pressure, EGR and fuel injected per cycle were chosen as input parameters. From the results it was found that the GEP can consistently emulate actual engine performance and emission characteristics proficiently even under different modes of CRDI operation with EGR with significant accuracy. Moreover, the GEP obtained results were also compared with an ANN model, developed on the same parametric ranges. The comparison of the obtained results showed that the GEP model outperforms the ANN model in predicting the desired response variables.



*Abbreviations:* ANN, Artificial Neural Network; BDO, baseline diesel operation; BP, brake power; BSFC, brake specific fuel consumption; BTDC, before top dead centre; BTE, brake thermal efficiency; $CO_2$, carbon-di-oxide; CI, compression ignition; CRDI, common rail diesel injection; DI, direct injection; EGR, Exhaust Gas Recirculation; ETs, Expression Trees; FIP, fuel injection pressure; GA, genetic algorithm; GEP, Gene Expression Programming; GP, Genetic Programming; IC, internal combustion; MAPE, Mean Absolute Percentage Error; MSE, Mean Square Error; NOx, oxides of nitrogen; PM, particulate matter; ppm, parts per million; R, correlation coefficient; RMSE, Root Mean Square Error.

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## 1. Introduction

The inspection of the chronology of the diesel engine emission mandates over the past decade resonate the irrevocable fact that each successive evolution of the emission directives have demanded, at each step of its revisions, a greater commitment of the diesel engine manufacturers to significantly reduce its PM and NOx emission footprint simultaneously than its immediately preceding directives [1–3]. Such legislative expectations have been constricting the operational frontiers of the diesel engines to such challenging domains that the inherent paradox of the diesel PM–NOx–BSFC dilemma has been greatly amplified. Diesel engine technology, have undergone a paradigm shift in recent decades in order to remain contemporary to the requirements of the successive emission mandates on one hand and consumer expectations of greater fuel economy on the other. Among the various technical advancements adopted in defining strategic pathways to meet the PM–NOx–BSFC trade-off in diesel engines [4,5], CRDI systems with its characteristic ability to simultaneously provide a significantly reduced PM–TUHC–BSFC footprint as compared to conventional diesel operation have been aptly considered to be a pivotal technical breakthrough to grace the diesel engines of today. That said the very ability of the CRDI systems to decrease PM emissions has been found to be a penalizing precursor for NOx formation which have been observed to paradoxically increase [6–8]. The Exhaust Gas Recirculation technique has been proved in this regard to be a cost effective NOx containing strategy [9–12].

Traditionally, diesel engines have been designed with a perspective of requiring a minimal complexity of control as ruggedness and simplicity of operation has been its primary customer unique selling proposition (USP). However, in order to design an appropriate strategy to meet the present day impasse of emission-performance trade-off expectations of a diesel engine, there has been a steady increase of the parametric degrees of freedom invoked by the new technical adaptations of the day. The available degrees of freedom of the diesel engines of today need to be effectively controlled in order to harness the synergetic benefit of the opportunities provided by the incorporated technical novelties to attain the desired optimal trade-off responses. Initial chapters of IC engine calibration paradigm had been primarily built upon an Engine Control Unit (ECU) embedded, two-dimensional map based interpolative look up table of the calibrated engine operating conditions determined by experimentation. Subsequently, with the steady increase of the dimensional burden of the parametric control variables [13,14] being invoked, such full factorial one-factor-at-a-time (OFAT) based experimental approach to engine calibration became impractical due to the exorbitant and often unjustified running costs of engine test cell facilities and experimentation time. Thus the traditional basis of engine calibration had become redundant in the face of the multi objective necessities of the day and had to undergo a radical shift in its perceptions. A methodology was needed to be adopted wherein the optimal exploration of the design space could be performed without the need to resort to extensive experimentation.

Metamodel based optimization strategy has been observed to provide a viable solution where the relevant engine behaviour is emulated by an appropriate plant model embodying the underlying physics of the problem, so that, the main task of parametric optimization can be accomplished virtually on a computational platform. Compared to conventional calibration methods by real onsite laboratory experimentation, modern day synergy of traditional experimental methods coupled with the ready availability of substantial parallel processing power of the present day computational platforms are being increasingly harnessed to transfer an appreciable proportion of the engineering effort from the actual test cell environment to the computational environment, thus offering significant reductions in costs and time in multi-objective optimization problems. Optimization under such model based paradigms typically induces challenges for the formulation of an acceptable system identification technique to correlate the desired objective responses with the control variables under study.

Studies involving the development of accurate yet computationally cost effective metamodels as a viable system identification tool (SIT) have resulted in the proliferation of various AI based techniques in contemporary IC engine paradigms [15–30]. Among the many facets of the AI paradigms, ANN endeavours with its inherent aptitude to quickly and efficiently emulate nonlinear trends in engine emission data have helped establish it as a credible metamodelling platform in engine optimization and real time control strategies. Consequently, the potential of ANN strategies have been extensively exploited in the field of simulation of engine performance and emission characteristics of IC engines. Based on sigmoid activation functions, the modelled response variables are correlated to the chosen control variables via complex weight matrices which tend to increase in complexity with the increase in the non–linearity of the problem. This in turn induces the pitfalls of over fitting in estimating the responses when presented with untrained data. Further, the optimal design of the ANN topology and the learning algorithm which is of pivotal importance in an ANN based modelling endeavour is susceptible to the expertise of the designer for a given problem under study [31]. At the other end of the spectra, classical polynomial regression based metamodelling techniques employed to establish explicit parametric relationships between the variables are often limited in its applicability by the need to satisfy predefined fitness functions which need to be ascertained beforehand. Thus a need has gradually emerged in contemporary meta-modelling realms to develop such metamodels which can combine the inherent efficiency, robustness and speed of an ANN strategy with the clarity of explicit closed form analytical representation of the polynomial regression techniques.

Gene Expression Programming (GEP) which has been developed as an off shoot of the versatile evolutionary based GA technique, has come to be recognized as an appropriate SIT to bridge this gap in contemporary meta-modelling paradigms [32–34]. As its

**Table 1**
Experimental engine specification.

| Specification | Resources |
|---|---|
| Make | Vidhata |
| No of cylinder | One(1) |
| Bore | 120 mm |
| Stroke | 139.7 mm |
| Displacement | 1580 cc |
| Cooling | Water |
| Compression ratio | 18:1 |
| *Valve timing* | |
| Exhaust valve opening | 35° before BDC |
| Exhaust valve closing | 4° after TDC |
| Inlet valve opening | 4° before TDC |
| Inlet valve closing | 35° after BDC |

**Table 2**
Specification of the fuel injector.

| Specification | Resources |
|---|---|
| Type | Common rail injection system |
| Make | Bosch |
| Injection pressure | 10–120 MPa |
| Number of holes | 5 (Symmetric) |
| Nozzle diameter | 0.15 mm |
| Injection angle | 120° |