Politecnico di Torino
Doctoral Program in Energy Engineering
34^{th} cycle
Torino, 2022

Engine Technologies for Reduction of Fuel Consumption and Pollutant Emissions in Light-Duty Diesel Engines

Summary

To the Reviewers Attention:

Different strategies for reduction of fuel consumption and pollutant emissions in light-duty diesel engines have been explored in this research work. The aim is to provide consistent solutions that could be helpful in constraining the pollutant emissions on the existing combustion engines, without changing the infrastructure. Despite the trend in the electrification is rapidly growing, the internal combustion engines are not completely going to disappear from the market as the majority of off-road vehicles (and part of heavy-duty ones) will probably be still endowed with diesel-fueled engine, while light-duty electrified vehicles will also be equipped with this type of engines, within the various types of hybrid electric vehicles.

The different tested solutions include a model-based technique for the control of the load and NOx emissions, HVO fuel tested as "drop-in" fuel, i.e., simply replacing the feeding of a diesel engine, unconventional diesel combustion, specifically Premixed Charge Compression Ignition (PCCI) combustion, firstly tested with an engine fuelled with diesel, exploring the potentialities of multi-injection patterns with respect to single-injection strategies and conventional diesel combustion, and, finally, using Hydrotreated Vegetable Oil (HVO) fuel in a single early-injection configuration.

In the first part of the research work a model-based control for Brake Mean Effective Pressure (BMEP) and engine-out Nitrogen Oxides (NOx) emissions in a Euro VI 3.0L diesel engine for light-duty applications has been developed and assessed. This activity has been carried out in collaboration with Fiat Powertrain (FPT) Industrial. The control is based on the inversion of a predictive combustion model, which is able to estimate the in-cylinder pressure trace, the HRR trend and the relative combustion metrics by applying a single zone thermodynamic model. Different inputs are required, including the injection pattern from which NOx emissions can be estimated. It defines the cycle-by-cycle corrections for the timing of the main injection and for the injected fuel mass quantity with the aim of guaranteeing the desired levels of NOx emissions and torque (specifically BMEP), respectively. The functionalities of the controller, developed in the Matlab/Simulink environment, were firstly tested in the Model-in-the-Loop setup, by coupling it with a fast-running engine model, created with GT-Power software. The results from the load ramps tested at different engine rotational speeds proved the effectiveness of the model in reaching the desired targets of BMEP and NOx emissions. The real-time capability in performing the corrections was also demonstrated. Further experimental tests were performed on the real engine, by means of a proper rapid-prototyping setup. The main novelty is represented by the use of a lambda sensor installed in the intake manifold for the estimation of the performance of the controller in predicting NOx emissions with a real measurement of the oxygen concentration. This was possible by connecting the lambda sensor to a specific ETAS module (ES636), connected in a daisy-chain configuration with the one of the controller. The experimental tests were firstly carried out to calibrate the oxygen sensor and then to validate the functionalities of the controller over different load ramps. The results showed a good accuracy, with maximum average values of Root Mean Square Error (RMSE) equal to 90 ppm for the NOx emissions and 0.4 bar for the BMEP. In addition, an investigation about the influence of the engine thermal state on the NOx prediction has also been carried out by testing a load ramp at low engine rotational speed with increased stabilization time over the different steps

of the ramp and higher initial temperature for the coolant water. The influence of the higher temperature was verified, almost halving the NOx RMSE. This controller has also been combined with a closed-loop cycle-by-cycle architecture, composed of a Proportional-Integrative (PI) regulator and a lag compensator with the aim to improve the performance of the previously tested controller, smoothing undershoots and peaks occurred during the transitions. The simulations showed an increased overall performance of the system, guaranteeing a more stable behavior thanks to a further reduction of the error in the NOx prediction. The real-time capability of the controller was also verified, resulting in a promising solution for future tests on the real engine.

The second part of the activity has been focused on the study of alternatives in terms of combustion process (PCCI) and fuel (HVO). A study of the potentialities of multi-injection PCCI combustion strategies (i.e. double and triple) in reducing fuel consumption and pollutant emissions has been carried out. The experimental tests were performed on a modified version of the previously cited diesel engine, specifically designed to work in PCCI mode. They included different operating conditions. For the double pattern, injected fuel mass was split into two shots, equally dividing the quantity (q_{1st}/q_{2nd}=50/50%) or injecting the majority of the fuel by means of the first injection (q_{1st}/q_{2nd}=75/25%). Dwell time sweeps were performed by firstly varying the timing of the first injection, keeping constant the second one while the opposite was performed in a second moment. Triple injection patterns were instead tested by means of EGR sweeps. All these solutions were compared to the baseline case that featured a triple-injection Conventional Diesel Combustion (CDC) and to the single injection PCCI combustion. Two steady-state points were acquired (low to medium load), showing a good potential in reducing HC/CO emissions, compared to the single-injection strategy but still far from the conventional diesel combustion levels. The engine-out soot and NOx emissions were still under CDC levels, with minor penalties compared to the early single injection PCCI. Moreover, besides being still not able in reaching CDC values, multi-injection patterns allowed a reduction of the combustion noise and fuel consumption, especially at lower loads.

A comparison between conventional diesel fuel and HVO has also been performed. The activity was carried out within a research project in collaboration with ENI. The experimental tests were performed to compare brake specific fuel consumption (bsfc), brake specific pollutant emissions (bsCO, bsHC, bsNOx and bsSoot) and combustion noise (CN) with conventional diesel B7 (fulfilling EN590 regulation) and HVO from a reference engine, the F1A provided by FPT Industrial. Preliminary experimental tests were acquired on 5 engine working points, representative of the behavior of the application of the engine to a light-duty commercial vehicle along a WLTC. The experimental results from the two fuels were compared, while maintaining the original baseline (diesel-oriented) calibration. Afterwards, different proportions of High-Pressure (HP) and Low-Pressure (LP) EGR were investigated at several lambda values. On 3 of these 5 points, Design of Experiments (DoE) test plans were performed. On the basis of the data obtained from DoE experimental campaign, final optimizations considering second order polynomial models were created and tested, with the constraints chosen in order to minimize the engine-out pollutant emissions (e.g. NOx or CO for low load and NOx or soot for high load). Last part of the activity concerned with tests at maximum torque for both fuels.

Finally, HVO has also been tested in a PCCI-like combustion mode. The experimental tests were carried out at the dynamic test bench of DENERG, Polito, using the FTP F1A Euro VI diesel engine, considering one single injection, aiming at reproducing, for high values of SOI (i.e., anticipated injection event) an early PCCI-like combustion process. One single engine working point was tested by performing sweep tests for the EGR and for the timing of the injection. The two EGR loops of the engine, high pressure (short route) and low pressure (long route), were both adopted in order to further explore the influence of the different types of EGR on the combustion process performed with two different fuels, diesel and HVO. The results from the experimental tests proved the simultaneous reduction of soot and NOx emissions. In particular, the PCCI combustion of HVO showed reductions in fuel consumption and pollutant emissions (especially of HC and CO) with respect to diesel oil, confirming the results obtained under conventional combustion mode. Moreover, the analysis of the Heat Release Rate (HRR) traces also revealed the tendency of the HVO, for its composition and higher reactivity, to produce a more relevant peak of the Low Temperature Heat Release (LTHR) phase and to reduce the Negative Temperature Coefficient (NTC) regime.

Outline

Chapter 1 - Introduction lays out the background and motivation of this research, placing it in the current scenario.

Chapter 2 - Experimental setup describes the dynamic test bench used for the experimental tests. Main focus is on the installed sensors and on the software systems of the control room, while the different adopted engines are described in the specific chapters.

Chapter 3 - Model-based control for BMEP and NOx emissions in a Euro VI 3.0L diesel engine describes the model-based technique for BMEP (torque) and NOx control by changing the injected fuel mass quantity and the timing of the main injection. Detailed analysis of the model is given in the first part, while in the second one, the results of its implementation in coupled simulations between Simulink and GT-Power and the ones of the experimental tests on the real engine are given.

Chapter 4 - Study of the potentialities of multi-injection PCCI combustion in constraining fuel consumption and pollutant emissions focus on the PCCI combustion and in particular on the multi-injection pattern for this type of unconventional combustion. The experimental results in terms of pollutant emissions plus fuel consumption are presented for double and triple injection strategies compared to the conventional diesel combustion and to the early PCCI combustion, characterized by a single injection pulse.

Chapter 5 - Experimental and numerical characterization of conventional combustion with standard and innovative fuels focus on the results coming from steady-state experimental tests, with the aim to compare the performance of the conventional diesel fuel with HVO, in terms of reducing pollutant emissions, noise and fuel consumption. This chapter is divided into 3 sections. In the first part an overview on the preliminary experimental tests is given, explaining the motivations that lead to the choice of the steady-state points to test. In the second part, the Design of Experiments test plan, obtained from the preliminary test data, is presented and explained. In this part, the results of some optimizations carried out on the basis of second order polynomial models built starting from the results of the Design of Experiments tests are also shown. Last part concerns with tests at maximum torque for both fuels.

Chapter 6 - Experimental and numerical characterization of PCCI combustion with HVO compares the experimental results performed with both conventional diesel fuel and HVO of an early PCCI-like combustion with the aim of evaluating the effectiveness of the PCCI combustion process with HVO fuel in reducing pollutant emissions and fuel consumption.

Chapter 7 - Conclusion and Outlook extracts the conclusions, followed by a brief discussion about future work.

Candidate,

Andrea Manelli

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Andrea Manelli

2022

*This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).