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Şcoala Doctorală de Studii Inginereşti

Research on retrofitting a compression-ignition engine to improve performance and reduce pollutant emissions

Teză de doctorat – Rezumat

pentru obținerea titlului științific de doctor la
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în domeniul de doctorat inginerie mecanică

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This doctoral thesis addresses the challenge of reducing the greenhouse gas emissions and atmospheric pollutants from transport, this being one of the major priorities of international and European climate policy. The Paris Agreement establishes the objective of limiting the increase in global average temperature to well below 2 °C and, ideally, to 1.5 °C above pre-industrial levels, while the European Union has translated this strategic direction into the European Climate Law and the Fit for 55 legislative package, which aims to reduce net greenhouse gas emissions by at least 55% by 2030 and to achieve climate neutrality by 2050. Within this framework, the transport sector occupies a central position, as it accounts for approximately one quarter of the European Union's total greenhouse gas emissions, with road transport generating the dominant share of these emissions. In addition, although electrification, green hydrogen, and synthetic fuels are considered strategic directions for the future of European mobility, technical and economic realities show that a significant share of commercial fleets and existing diesel vehicles will remain in operation for many years to come, particularly in Central and Eastern Europe.

This discrepancy between the European Union's ambitious climate objectives and the actual pace of fleet renewal justifies the need for transitional solutions that can be applied immediately to vehicles already in service. From this perspective, the retrofitting of existing diesel engines becomes a relevant option both technically and economically, as it can reduce emissions and improve performance without the costs and environmental impact associated with prematurely replacing an entire fleet. Recent literature and life cycle assessment analyses cited in the thesis show that, if the energy mix used for auxiliary solutions is favorable, modernizing existing vehicles can reduce total life-cycle emissions by 30–50% compared with the direct replacement scenario involving new vehicles, by avoiding the embedded emissions associated with manufacturing and by reducing operational emissions. Consequently, the thesis is aligned with a research direction consistent with current European trends: it does not challenge the transition toward very low- or zero-emission mobility but rather proposes an intermediate pathway for the progressive decarbonization of already existing commercial diesel vehicles.

Building on this context, the doctoral thesis investigates, from an integrated perspective, the possibilities for sustainable retrofitting of a Euro 3 commercial diesel engine used in road transport, under conditions where emission reduction must be achieved without complete fleet replacement and without excessive increases in cost or technical complexity. The research stems from the observation

that a significant share of the diesel fleet in operation is subject to retrofitting interventions oriented almost exclusively toward increasing power and torque, without a rigorous assessment of their effects on emissions, fuel consumption, and durability. In contrast to this partial approach, the thesis proposes and validates the concept of sustainable retrofitting, defined as the controlled modernization of an existing propulsion system through the combination of mutually compatible solutions capable of reducing environmental impact, maintaining or improving performance, and remaining feasible for real-world applications.

The foundation of the thesis is the principle that emission reduction in diesel engines cannot be achieved effectively through isolated measures applied to a single subsystem; rather, it requires a systemic approach in which fuel, injection strategy, boosting, electronic control, and real-time monitoring are treated as interdependent elements of the same propulsion system. On this basis, the research proposes an experimental architecture combining diesel–hydrogen dual fueling in the form of HHO, water–methanol injection, mechanical upgrades of the injection and turbocharging systems, and the integration of an IoT-based torque measurement and operating monitoring system. Thus, the thesis is not a sequence of isolated studies, but a unified research program developed in successive stages, aimed at assessing both the individual effects of each solution and the cumulative effects and interactions among them.

The overall objective of the thesis is the development and validation of an integrated retrofit package for a Euro 3 commercial diesel engine, such that relevant reductions in NOx, CO, HC, and particulate emissions may be achieved, while maintaining or even improving the energetic and mechanical performance of the propulsion system. The targets formulated in the thesis aim at reductions of 20–30% for the principal pollutants relative to the reference configuration, the maintenance or reduction of specific CO_2 emissions, moderate efficiency gains, and the limitation of additional retrofit costs to approximately 20% of the vehicle's initial value. To achieve this objective, six specific objectives are defined: evaluation of diesel–hydrogen/HHO dual fueling, investigation of water–methanol injection, analysis of retrofit modifications to the injection system and ECU, conceptual assessment of hybrid electrical turbochargering, development of an IoT-based monitoring system, and finally, the synergistic integration of all solutions into a fully retrofitted configuration.

From an experimental standpoint, the thesis uses as its research platform a four-cylinder inline diesel engine with a total displacement of 1896 cm^3, a compression ratio of 19.5:1, a Bosch VP37 rotary pump in the baseline configuration, a Garrett GT1749V variable-geometry turbocharger, and a side-mounted intercooler, installed in a Euro 3 homologated vehicle. The nominal series values are 66 kW maximum power at 3750 rpm and 210 Nm maximum torque at approximately 2100 rpm. The reference configuration is compared with multiple successive stages of retrofit modification in order to identify separately the effect of each intervention and, subsequently, of their combinations. Power and torque measurements were carried out on a MAHA LPS 3000 dynamometer, while exhaust gas emissions and opacity were determined with a Capelec 3200 analyzer and certified equipment, under controlled temperature and atmospheric pressure conditions.

The experimental methodology is organized in stages, from the reference configuration to the final integrated configuration. Stage E1 provides the baseline for comparison, E2 addresses diesel–HHO dual fueling, E3 analyzes water–methanol injection, E4 focuses on injection and ECU parameter optimization,

E5 addresses hybrid electric turbochargers at a conceptual level, E6 introduces IoT monitoring, and E7 validates the integrated operation of the solutions within a fully retrofitted scenario. All measurements were carried out with control of the variables, repeated test series at the relevant operating points, and an approach designed to ensure direct comparability across configurations.

The results obtained for objective O1 show that HHO supplementation in the diesel intake favorably affects primary emissions and combustion quality. In the tests performed at approximately 820 rpm and 2000 rpm, CO concentration decreases from 0.061% to 0.020% at idle and from 0.084% to 0.026% at 2000 rpm, while HC is reduced from 45 ppm to 14 ppm at idle and from 37 ppm to 15 ppm at 2000 rpm. At the same time, the CO_2 fraction in exhaust gases decreases from 3.91% to 2.56% at idle and from 4.22% to 2.58% at 2000 rpm, while O_2 concentration increases from 14.30% to 17.02%, respectively from 14.10% to 16.89%. These results indicate more complete combustion, a reduced fraction of fossil carbon burned, and an improved oxidizing character of the mixture, confirming that diesel–HHO dual fueling can constitute an effective solution for reducing CO and HC emissions, while also providing a basis for further optimization.

For objective O2, water–methanol injection is analyzed as an internal combustion cooling technique and as a means of controlling NOx formation. The literature integrated into the thesis and the original results show that appropriate water or water–methanol ratios can reduce exhaust gas temperature by approximately 100–200 °C and NOx emissions by 30–60%, especially at high load and in the speed range representative of road operation. In the logic of the thesis, the role of water–methanol injection is twofold: on the one hand, it functions as an independent NOx reduction solution in the baseline configuration; on the other hand, it is used as a compensatory method for undesirable thermal effects generated by dual fueling and by performance-oriented ECU recalibration and mechanical upgrades. In this way, WMI becomes a balancing element between efficiency objectives and emission objectives.

Objective O3, devoted to modifications of the injection system and ECU, occupies a central place in the thesis because it directly links mechanical interventions, electronic control, and engine response. The implemented upgrades include replacing the injector nozzles with 0.270 mm units, upgrading the Bosch VP37 pump to a 12 mm plunger, installing a Garrett GT1749VB turbocharger, replacing the side-mounted intercooler with a front-mounted unit, and adapting the intake pathway through larger-diameter metal piping and manifold modifications. In parallel, the Bosch EDC15 ECU was recalibrated by modifying fuel maps, injection timing, torque and smoke limiters, EGR, and boost pressure control. The results show that this coherent combination of modifications enables maximum power to rise from 66 kW to more than 110 kW and maximum torque from 210 Nm to approximately 300 Nm, confirming the ability of a well-designed retrofit package to substantially increase engine performance without compromising combustion control.

The thesis also critically discusses the effects of ECU recalibration when applied in isolation, without complementary control measures. The data show that performance-oriented recalibration alone may apparently reduce smoke signals or improve certain operating regimes, yet it may simultaneously increase CO_2 and lead to a less favorable overall emissions balance if not matched with adequate air supply, combustion cooling, and injection-system adaptation. This observation is important for the general conclusion of the thesis: performance and emission reduction must not be treated separately, but rather through an optimized system-level compromise.

For objective O4, the thesis provides a systematic review of the literature on hybrid-electric turbochargers. The synthesized studies indicate potential thermal efficiency gains of 3–10% and comparable reductions in specific fuel consumption, particularly in dynamic cycles, by reducing turbocharger's lag and improving the management of exhaust gas energy. Although this technology is not experimentally implemented in the final thesis configuration, its analysis serves a strategic purpose: it illustrates how the solutions validated on the experimental engine may be extended in the future toward more advanced propulsion architectures, consistent with European trends toward partial electrification and the functional hybridization of auxiliary systems.

Objective O5 develops the monitoring and validation component of the research through the creation of an IoT-based bidirectional torque measurement system, based on resistive strain gauges mounted on the shaft, a Wheatstone bridge, an HX711 module, and an ESP8266 microcontroller with wireless data transmission. Static calibration, conducted over the 5–50 Nm range and in both directions of rotation, revealed an almost linear relationship between signal and applied torque, with $R^2 \approx 0.999$, a mean absolute error of approximately 0.56 Nm, and accuracy better than 2.5 Nm across the entire analyzed range. These results demonstrate that the proposed IoT system can be used not only as a laboratory support tool, but also as a data infrastructure for real-time propulsion-system monitoring, enabling diagnosis, predictive analysis, and the subsequent development of a digital twin.

Objective O6 represents the synthesis and integrated validation stage of the thesis. In this phase, the solutions investigated separately are combined into a fully retrofitted configuration, and the engine is tested in before–after comparative scenarios under the same operating conditions. The integrated analysis shows that when water–methanol injection, ECU modifications, and mechanical upgrades are combined coherently, total emissions reductions of approximately 25–40% can be achieved relative to the reference configuration operating solely on diesel fuel. At the same time, these reductions are obtained without major penalties in mechanical performance, and in certain operating zones there are even improvements in overall efficiency and propulsion response. The importance of this stage lies in demonstrating that the proposed solutions are not only feasible individually but can also function synergistically within a unified sustainable retrofit architecture.

From a scientific and applied standpoint, the original contributions of the thesis are multiple. First, the thesis defines and experimentally validates an integrated concept of sustainable retrofitting for a Euro 3 commercial diesel engine, adapted to the technical and economic realities of existing fleets. Second, the research quantifies, on the same experimental platform and under comparable conditions, the effects of diesel–HHO dual fueling, water–methanol injection, and ECU and mechanical modifications on performance and emissions. Third, the thesis develops and validates a low-cost IoT torque measurement system capable of supporting advanced monitoring and future digital-twin applications. Finally, the work demonstrates that the coherent integration of these solutions can transform an existing commercial diesel engine into a configuration significantly closer to current efficiency and emission requirements, offering a realistic transitional pathway between the existing conventional fleet and Europe's climate objectives.

In conclusion, the thesis is situated within a highly relevant research direction for the European Union, in which the decarbonization of road transport is addressed not only through the rapid replacement of existing vehicles, but also through the intelligent modernization of those already in operation. The

results obtained confirm that diesel–HHO dual fueling, water–methanol injection, injection optimization, IoT monitoring, and the staged integration of these solutions can constitute a viable technological package for reducing emissions and improving the performance of commercial diesel engines. Through this contribution, the thesis provides both a solid experimental basis and a conceptual framework applicable to energy and technological transition strategies in European road transport.

Keywords: compression ignition engine, retrofitting, emission reduction, performance enhancement.