Numerical model of variable valve timing distribution for a supercharged diesel engine

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ABSTRACT

Recently, there's been a strong drive to improve performance of diesel engines while reducing their greenhouse gases emissions. Techniques like exhaust gas recirculation, turbocharging, and variable valve timing have become widespread. The last technique fine-tunes valve operation based on engine speed, which optimize efficiency and power output while saving fuel. This study zeroes in on a specific 4-cylinder, 4-stroke diesel engine of 1.56-liter, GT-Power software is employed to examine a supercharged version and implementing diverse valve lift techniques. The findings are revealing a substantial 30% increase in power output. At 1000 rpm, power rises from 15.1 kW for the standard engine to 19.72 kW for the modified version. For higher engine speeds, the improvements become even more pronounced, reaching a 66% boost compared to the standard configuration. Furthermore, the newly configured engine showcases an impressive 13% decrease in fuel-specific consumption at elevated engine speeds, contributing to enhanced technical performance and fuel efficiency. The numerical model developed in this study holds the potential to aid in the design of novel diesel engines equipped with variable valve timing systems. To lend further support to these findings, experimental validation is recommended.

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1. INTRODUCTION

The fast development of the industry and transport sectors urges energetic and ecological transition to preserve the environment and rationalize exploiting natural and fossil energy resources [1], [2]. Due to their high fuel efficiency, industrial and urban transportation is widely assured by diesel engines (DEs) [3]. However, any inefficient functioning of these engines significantly contributes to greenhouse gas (GHG) emissions. This implies an urgent need for an energetic and ecological transition in the industry and transport sectors to preserve the environment and optimize the use of natural and fossil energy resources. It emphasizes the significance of DEs in industrial and urban transportation due to their high fuel efficiency but highlights that the inefficient functioning of these engines leads to GHG emissions. Therefore, the environmental protection agency (EPA) set these emissions for the new fabricated engines under 0.013 g/kWh particulate matter (PM) [4]. That is why many scientists have worked to improve performances to lower GHG emissions, and the subject has been thoroughly investigated in the last two decades [5]–[8]. As solutions, the focus was on turbocharging [9], [10], exhaust gas recirculation (EGR) [11], [12], and variable valve timing (VVT) [13], [14]. VVT is one of the tested methods to improve an engine's performance after treatment and the exhaust gas (EG) temperature [15]. Exhaust temperature increases, and the nitrogen oxides (NOx) emissions decrease with the optimization of the intake valve closure timing [16]. Gehrke *et al.* [17] reported temperature was increase up to 60 °C of on a single-cylinder engine after altering intake valve closures.

Intake valves (IVs) and exhaust valves (EVs) have always been considered a source of losses that must be carefully designed and controlled [18]. Therefore, DEs manufacturers didn't only focus on high-pressure fuel injection as a conventional solution for performance improvements but also on the development of VVT technologies [19], [20]. Adjusting the angle and time of valve opening impacts the pressure inside the cylinders and the power produced [21], [22]. VVT efficiently minimizes the turbocharged engine's size, improves thermal and volumetric efficiency, and reduces emissions [23]–[26]. One of the techniques of VVT to better convert the combustion heat into work is the delay of the opening of the intake valve towards top dead center (TDC). The previous studies [27], [28] recommend this control system to favor the axial stratification of the fuel even at low blend concentrations. The introduction of VVT in DEs allows removing some of the external engine emissions control devices and ensures thermal management of the exhaust gases and after-treatment system [29]. It also adjusts the engine's operating point to improve economic and ecological performances and maintains its high efficiency, especially at low and medium speeds [1]. This significant influence on engine performances [30] makes VVT a key parameter for DEs and natural gas engines [31].

According to Shiao and Dat [32], improving DEs performances can be assured by optimizing and controlling the intake mixture. Thus, controlling the valve timing can improve the engine's efficiency by reducing pumping losses. In addition, this process can reduce exhaust emissions of GHG, such as hydrocarbons (HC) and NOx [33]. Furthermore Zibani *et al.* [34], a VVT allows variation of valve events with rotation speed and increases engine performances by altering the camshaft timing using either pneumatic, hydraulic, or electromechanical devices, conclude in their work. The process will be as follows. At high speeds, the early opening of the IV, before the top dead point, allows a good charging of the combustion chamber, and its late closure allows the continuation of charging the chamber with high-speed air. At low speeds, the late closing of the IV pushes back a portion of the combustion mixture in the intake manifold, reducing usable power. However, the early opening of the EV reduces cylinder pressure, and its late closing allows a fresh air intake to cross the valve area and clean it [35]–[37]. In the work of Yuan *et al.* [38], the effective cylinder volume increased up to 14% due to the early closure of the IV. This directly influences the engine's volumetric efficiency and the indicated mean effective pressure.

The effects of early and late IV closure on EG temperature at low DE operating speeds showed that both early and late closure of the IV caused a rise in that temperature. This VVT technique increases thermal management efficiency but decreases fuel consumption due to low pumping losses [14]. Wenzhi *et al.* [39] registered a 12% increase in engine power when the DE was running at 2590 rpm. They conclude that IVs and EVs can be fitted at the optimal time for their opening and closure to produce more power for the same fuel consumption and improve the engine's efficiency. In their theoretical and experimental study of the influence of strategic IV modes on engine fuel consumption, Teodosio *et al.* [40] concluded that early or late IV closure caused an increase in fuel consumption. However, early IV closure is more efficient at low speeds than late closure, and at high speeds, an improved braking-specific fuel consumption (BSFC) is achieved. Mahrous *et al.* [41] simulated a 4-valve engine, analyzed its performance for different IV timings, and concluded that the operating range of non-typical IV strategies is wider than the typical ones. Jia *et al.* [42] simulated a premixed charge compression ignition (PCCI) engine and analyzed the influence of injection and the IV closure timing on the engine's performance and GHG emissions. They proved that injection timing directly affects emissions, and they can use this effect to reduce them.

Antonelli *et al.* [43] examined the effect of IVs and EVs closure timing on the performance of two different engines. They concluded that the degree and timing of these valve openings significantly affect the engine's isentropic efficiency. Hunicz and Mikulski [44] conducted an experimental analysis of heat transfer impacts in homogeneous charge compression ignition (HCCI) engines. They indicated that it is possible to apply passive valve overlap on this engine to help the gas flow variance between the intake port and the cylinder and improve combustion phases. Mahrous *et al.* [41] studied the effects of the valve overlap (VO) angle on engine performances on the same engine type. They arrived to fix the IV closure and EV opening times and modify the IV opening and EV closing times [45]. The VO angle was reported to influence the air-fuel mixture significantly, and the perfect air-fuel mixture was obtained at high VO angles. Reported by Xu *et al.* [46] on a reactivity-controlled compression ignition (RCCI) engines, using VVT in optimal strategies shows an excellent improvement potential for GHG emissions and fuel consumption efficiency.

In several previous studies, the controllability of IVs and EVs has been reported as high, and the valve transition is quick. That's why valves design examination and its parameters were the subjects of these studies. The aim of controlling the opening and closure of the valve is to reduce fuel consumption and GHG emissions under different engine speeds [47]–[51]. Especially at low speeds, reducing pumping losses and optimizing fuel consumption are strongly advised [52], [53]. Badami and Mura [54] tested three control strategies: i) variable speed with fixed cutting, ii) variable cutting with fixed speed, and iii) fixed speed with fixed cutting. They found that the variable valve-cutting strategy is more efficient. Another interesting work is the one done by Schernus *et al.* [55], who examined a single-cylinder gasoline engine. They first determined the required pressure to open the valve using MATLAB software. Then, they improved the intake and exhaust manifolds' geometry to reduce back pressure. Finally, they quantified the required forces to open these valves when varying their opening time [55], [56]. Gibson and Kolmanowski [57] controlled the valves independently to improve the efficiency of the camless engine by increasing torque and minimizing fuel consumption. They delayed the IV closure at a specified time, which increased its recovery time. However, this achievement can change the air-fuel combustion fraction [57], [58].

In their recent study, Demir *et al.* [59] investigated the effect of VVT on the volumetric efficiency of a DE. The volumetric efficiency has been observed to increase with rpm, and results showed that adjusting the opening of the IV is not as efficient as closing it early. During VO, the EV opens late, increasing pressure inside the cylinder. It has also been observed that VVT doesn't affect the swirl ratio, and volumetric efficiency improves by increasing the VO, while reverse airflow negatively affects the volumetric efficiency. Khudhur *et al.* [60] studied the effects of VO on performances and GHG emissions of full-load operation engines by varying the closure timing of IVs and EVs. Their results showed that decreasing the VO period improved the engine's performance and significantly reduced GHG emissions. According to Thomasson *et al.* [29], VO allows more efficient combustion and reduces waste through scavenging, improving performance by reducing pumping losses. They also noticed that early exhaust increases exhaust temperature at low loads. The Bapiri and Sorusbay [61] study focused on VVT effects on the performance of the different types of engines by testing naturally aspirated engines (NAEs) and turbocharged DEs. These last ones exhibited a more significant performance response to VVT than the first ones.

The simulations of the engine's VVT system done by Fontana and Galloni [62] showed that pumping losses and BSFC could be reduced using the VVT system even at transient loads. Further experimental work by Wronski *et al.* [18] on piston expanders with VVT indicated that optimal VVT helps reduce injection and exhaust losses. It also significantly affects the system's performance and efficiency. Finally, the updated work by Kim *et al.* [63] confirmed the previously announced conclusions on NAEs. However, comparing the obtained results in NAEs to gasoline engines showed that natural gas engine IV timing was different than conventional gasoline engines at low speeds.

Variable valve timing (VVT) systems exert precise control over the opening and closing of intake valves (IVs) and exhaust valves (EVs) in correspondence with engine speed. This dynamic regulation aims to heighten volumetric efficiency, attain optimal torque characteristics, and curtail fuel consumption. This article aims to construct a comprehensive model of the intake process in a diesel engine (DE) that incorporates the capacity to adjust valve lifting heights and openings. This strategic manipulation endeavors to diminish fuel consumption while concurrently enhancing engine performance.

This undertaking encompasses designing and creating a numerical model for a DE using GT-Power software. The model scrutinizes the effects of distinct VVT techniques on the DE's power output and specific fuel consumption. Additionally, diverse VVT techniques on DEs are assessed by varying lifting heights and valve openings to deepen the project's significance and identify the ideal operational conditions.

We believe that VVT can streamline the dimensions of turbocharged engines, eliminate the need for external engine emissions control apparatus, and optimize the engine's operating parameters for superior economic and ecological performance. Among the pioneering dimensions of our proposed approach are: i) the innovative application of VVT to diesel engines, ii) yielding heightened fuel efficiency and lowered emissions, iii) exploration of unconventional intake valve strategies to broaden the engine's operational envelope, iv) leveraging VVT to amplify the efficiency and performance of varied engine types, including premixed charge compression ignition (PCCI) and reactivity controlled compression ignition (RCCI) engines, v) investigation into the influence of VVT on piston expanders to augment system efficiency, and vi) crucially, the thorough evaluation of VVT techniques by varying lifting heights and valve openings to fine-tune engine operation.

2. METHOD

2.1. Engine properties

The simulated engine is a 4-stroke DE with four cylinders and a total volume of 1.56 liters. This specification lays the foundation for the subsequent analyzes and experiments performed. Table 1 summarizes the geometric characteristics used in this study.

2.2. Numerical model with GT-Power

Our research commences with an in-depth investigation and modeling of a supercharged diesel engine, laying the groundwork for our subsequent analyses. The pivotal step involves utilizing GT-Power software to model the engine intricately, integrating our chosen valve lift techniques. As a robust 1-D simulation tool, GT-Power accurately simulates the dynamic behaviors of various engine components by tracking pressure, temperature, and mass flow within distinct parts of the system. Renowned for its stability and ability to conduct steady-state and transient simulations, GT-Power is tailor-made for motor and power control analysis. It is a versatile platform for simulating a wide array of combustion engines.

Table 1. Engine's geometric characteristics

Parameter	Value	Parameter	Value
Cylinder volume	1560 cm^3	IV early opening (IVEO)	6.5°
Bore x stroke	75×88.3 mm	IV late opening (IVLO)	33°
Number of cylinders	4	EV early closure (EVEC)	6.5°
Compression ratio	18.1	EV late closure (EVLC)	35°
Max Power	81 kW at 5500 tr/min	Max lift	8.2 mm
Max torque	220 N.m at 2500 tr/min		

The distinguishing feature of GT-Power lies in its precision in emulating real-world engines. Each engine component, including cylinders, crankcases, pipes, and turbochargers, requires meticulous parameter identification to facilitate a faithful simulation. Our selection of GT-Power as the core simulation tool in this study stems from a multitude of advantages, including:
- Conformance to industry standards, rendering it a staple among major engine manufacturers.
- Inclusion of wave dynamics through a robust solution of the Navier-Stokes equations, capturing the intricate flow phenomena.
- Versatility in accommodating engines of varying sizes, spanning from compact utility engines to large-scale marine applications.
- Adaptability to accommodate advanced and unconventional concepts, making it an ideal tool for innovative investigations.
- Integration of cutting-edge combustion and after-treatment models, enhancing the fidelity of simulation results.
- Comprehensive turbocharger modelling capabilities that encompass an array of configurations, encompassing sheathed, supercharged, two-stage, compound-turbo, and twin-entry turbines.

By harnessing the capabilities of GT-Power, we delve into a comprehensive exploration of our research objectives, delivering insights to reshape engine design, and performance optimization.

2.2.1. Simulation of the DE with a turbocharger

Engine modeling begins with the environment block in which the ambient conditions of the intake air are configured: the value of temperature, pressure, and humidity. This block is linked to the compressor, whose characteristics are configured through an external file that contains the cartographic data. The compressed air will be cooled by a heat exchanger modeled by a grid of pipes. The cooled air flows to the IVs, the lift of which is regulated according to the angle of rotation of the crankshaft. The cylinder block relates to the fuel injectors, whose settings contain all the data that can affect engine operation, such as geometry, pressure, fuel temperature, and injection start angle. Finally, the EVs manage the release of exhaust gases, whose settings are similar to the IVs. These gases drive the turbine, whose characteristics are introduced similarly to the compressor. The GT-Power model of the DE with a turbocharger is illustrated in Figure 1 (see Appendix).

The simulation is carried out on the model created to determine the characteristics of our engine when operating in different regimes. For these tests, the initial conditions were set at the level of the engine intake system as follows: i) Engine speed: 1000 rpm, 2000 rpm, 2500 rpm, 3800 rpm, 5500 rpm, and 7000 rpm; ii) Intake air temperature: 300 K; and iii) Inlet air pressure: 1 bar.

2.2.2. Simulation of the proposed DE model with VVT

The model in Figure 2 (see Appendix) is for a supercharged DE with a variable valve control system, allowing valve control according to the engine's speed. This system is designed to dynamically adjust valve operation based on engine speed, an important feature for improving performance under different operating conditions. The intake cams, as well as the exhaust, each have a specific profile to control the valves to increase engine efficiency and overall power.

3. RESULTS AND DISCUSSION

3.1. Valve lift laws

The first step is determining the valve lift laws according to the engine's characteristics, i.e., a variable valve lifting mechanism and a standard camshaft. The motion laws of the intake valve were determined with zero thermal clearance of the valve train. Figure 3 shows the four configurations of the motion laws of the intake and exhaust valves used in the simulations. The grey curve represents the classical configuration mechanism. As seen in Figure 3, the valve lift distribution laws chosen for the simulations show the following features:

- Obvious deviation of the maximum opening law curves from the ones with the classical mechanism (grey curve).
- Asymmetry of all the four laws: the valve lifting is at a reduced gradient compared to their closing.
- The variation of the valve lift height affects the opening and closing moments and the angular duration of opening. Valve acceleration and mechanism reliability limit the lift and close ramps. Therefore, it is necessary to extend the duration to increase the lift height.

Figure 4 illustrates the variations of IV's early opening (EO) and late closure (LC) lift angles as a function of its lift height for the four scenarios. We observe that for the maximum opening law, the IV opens with an advance of 5 °CA to the top dead center (TDC), while the minimum opening law opens at an advance of 10 °CA relative to TDC. The positive effect of using the minimum law is to cancel the recycling of burnt gases by closing the IV earlier, which can be exploited especially at idle at low speed. Hence, the advantage of using the minimum law at low idle speed is to reduce the intensity of the reverse flows from the cylinder toward the intake manifold. However, the end of intake means, at the same time, the beginning of the compression process. Therefore, the effective compression ratio will differ for the valve lift scenarios. Figure 5 illustrates the variations of EV's early opening (EO) and late closure (LC) lift angles as a function of its lift height for the four scenarios.

Valves cross as a function of their lift heights is presented on the valve overlap (VO) variation graph in Figure 6. If we analyze Figure 6, we observe that the overlap is positive (simultaneous opening of intake and exhaust valves), even when using the minimum law (33 °CA). This causes some burnt gas recycling through the EV.

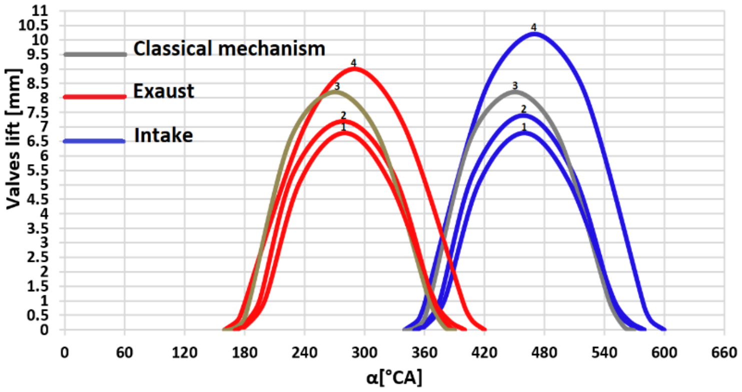

Figure 3. Distribution laws of the simulated motor

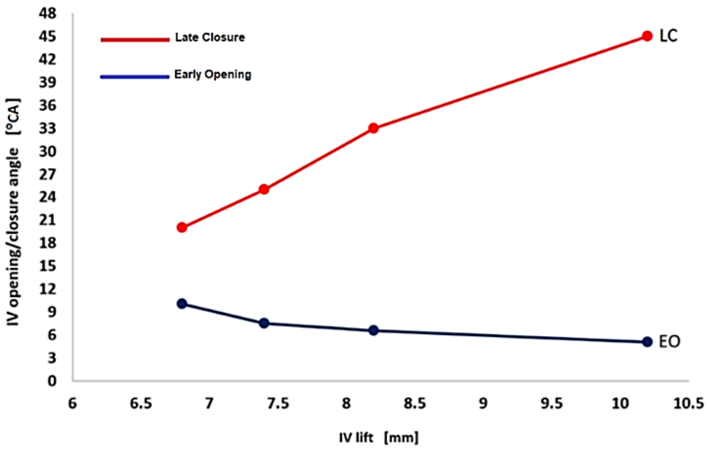

Figure 4. Variation of IV early opening and late closure for the four configurations

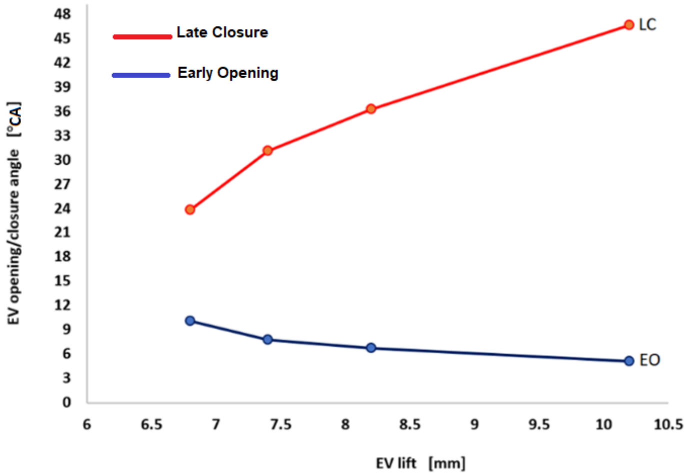

Figure 5. Variation of EV early opening and late closure for the four configurations

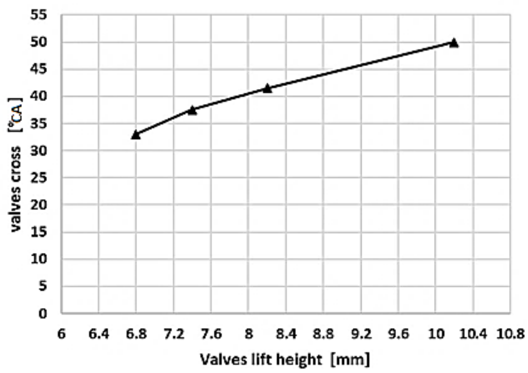

Figure 6. Valve overlap (VO) variation for the four configurations

The GT-Power simulation will allow us to determine how the parameters of each valve opening configuration will affect the power output, fuel consumption, and GHG emissions at different regimes. Table 2 synthesizes the valve opening characteristics for the four different configurations considered. Table 2 resumes crank angles of early opening and late closure for intake and exhaust valves relative to normal distribution laws or CAs shared in Figure 3, where graphs show that opening gaps for EV and IV are 180°-360° and 360°-540° respectively.

Table 2. Valve opening and lift distribution settings

	IV EO/LC	EV EO/LC	Lift [mm]	Opening duration IV/EV	Cross duration
1st configuration	10°/20°	9.8°/23°	6.8	210°/212.8°	33°
2nd configuration	7.5°/25°	7.5°/30°	7.4	212.5°/217.5°	37.5°
3rd configuration (standard engine)	6.5°/33°	6.5°/35°	8.2	219.5°/221.5°	41.5°
4th configuration	5°/45°	5°/45°	10.2	230°/230°	50°

3.2. Simulation results for the different valve opening and lift configurations

To determine the effects of the different valve timing settings, we simulate the engine with GT-Power and determine the power output and specific fuel consumption variation with the rpm. Secondly, we propose an optimized engine configuration with two scenarios of valve opening and lift configurations for low and high regimes. Finally, the optimized configuration will be analyzed in detail and compared with the original engine configuration to identify the effect of this new technique on engine performance.

3.2.1. Engine power variation

In Figure 7 and Table 3, we illustrate the variations of the engine power with speed for the four configurations. The power outputs in the four configurations are comparable at low operating speeds.

However, at 1000 rpm, the second configuration reaches 19.72 kW, a 30% increase over the standard engine at 15.18 kW. This is due to a reduction in the quantity of residual gases.

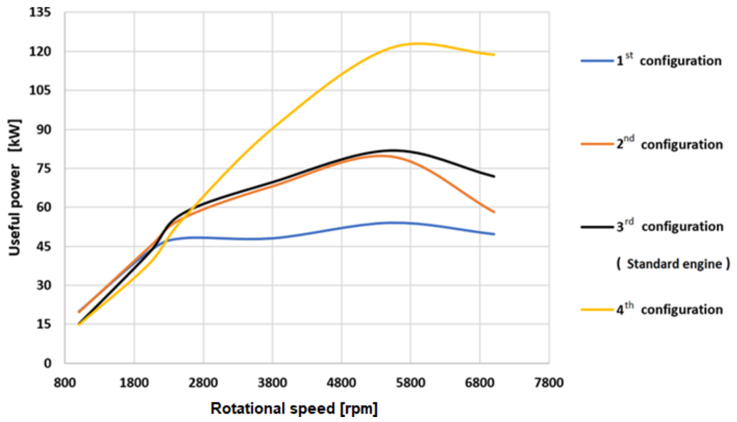

Figure 7. Power output as a function of engine operating speed

Table 3. Variation of useful engine power during operation [kW]

rpm	1st configuration	2nd configuration	3rd configuration (standard engine)	4th configuration
1000	19.893	19.729	15.184	14.765
2000	42.791	44.191	42.096	37.773
2500	48.170	55.713	57.594	55.322
3800	48.149	68.045	69.637	90.329
5500	54.139	79.480	81.784	121.236
7000	49.757	58.158	71.836	118.749

The increase in the rotational speed leads to an unrestricted intake flow and favorable conditions for dynamic overload. Therefore, the fourth configuration becomes more and more efficient than the others, thanks to the increased intake valve opening duration. It explains the significant difference in power at 7000 rpm, with a 66% increase (at 118.75 kW) compared to the initial value of 71.8 kW.

More precisely, at low speeds, in the interval [1000-2100] rpm, the 2nd configuration gives better results. The 3rd configuration (standard engine) has the highest power for the engine speed range of [2100-2600] rpm. However, at higher speeds [2600-7000] rpm, the power output with the 4th configuration becomes significantly higher.

3.2.2. Fuel-specific consumption

Fuel combustion produces a large quantity of chemical substances emitted into the atmosphere. Therefore, fuel consumption significantly contributes to air pollution and greenhouse gas emissions. The fuel-specific consumption (FSC) results for the different configurations are presented in Figure 8 and Table 4.

Table 4. Variation in fuel-specific consumption [g/kWh]

rpm	1st configuration	2nd configuration	3rd configuration (standard engine)	4th configuration
1000	220.8	218	225.3	254
2000	247.36	244.33	245.21	266
2500	260	263	261	274
3800	324.5	310.35	301.7	299
5500	433	412.4	406.9	340.5
7000	594	589.2	577.6	497.3

Analysis of Figure 8 confirms that at low speed, the pumping losses are more significant in the fourth configuration because of the lack of homogeneity of the mixture. At 1000 rpm, the FSC of the second configuration decreases by 7.3 g/kWh, representing a 3% gain compared to the standard engine. With the speed increase, the energy recovered from the exhaust gases is higher and limits pumping losses while improving the consumption of the 4th configuration compared to the standard configuration by 66.4 g/kWh at 5500 rpm and 80.3 g/kWh at 7000 rpm. These quantities represent a 16% and 14% reduction compared to the original SFC at the same engine speeds.

At low speeds, in the interval [1000-2300] rpm, the 2nd configuration shows the lowest FSC results. The 1st configuration shows the best FSC for a limited speed range of [2300-2600] rpm. However, at average speeds [2600-3600] rpm, the 3rd configuration offers the best fuel consumption. Beyond that interval, the best SFC belongs to the 4th configuration.

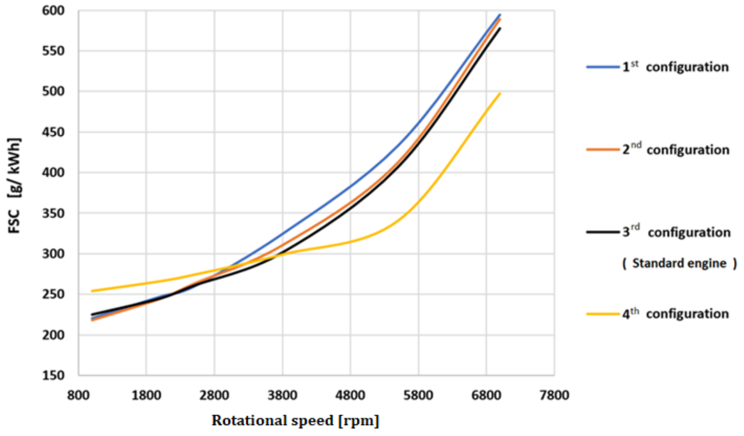

Figure 8. Fuel-specific consumption as a function of engine operating speed

3.3. Simulation results of the DE performances with optimized VVT

This section proposes an optimized VVT configuration that performs best at each engine speed. Therefore, we use the second configuration at low speeds and the fourth configuration at high speeds. These will be the ideal settings to improve engine performance. Finally, we compare the performance of the DE with optimized VVT with the standard engine equipped with a traditional turbocharger. The lift and valve opening time for the optimized VVT model displayed in Figure 2 (see Appendix) is presented in Table 5.

Table 5. Choice of lift and valve opening time

	IV EO/LC	EV EO/LC	Lift [mm]	Range In/Ex	Cross
Low rpm	7.5°/25°	7.5°/30°	7.4	212.5°/217.5°	37.5°
High rpm	5°/45°	5°/45°	10.2	230°/230°	50°

3.3.1. Engine power variation

Figure 9 and Table 6 illustrate the power output of the optimized VVT compared to the standard configuration. Again, we notice a significant power increase, especially at high speeds. The power in the new configuration is up to 30% higher at low speeds under 3800 rpm due to the mixture homogeneity improvement that leads to better combustion and reduces the quantity of residual gases. The power increases by up to 66% at higher speeds.

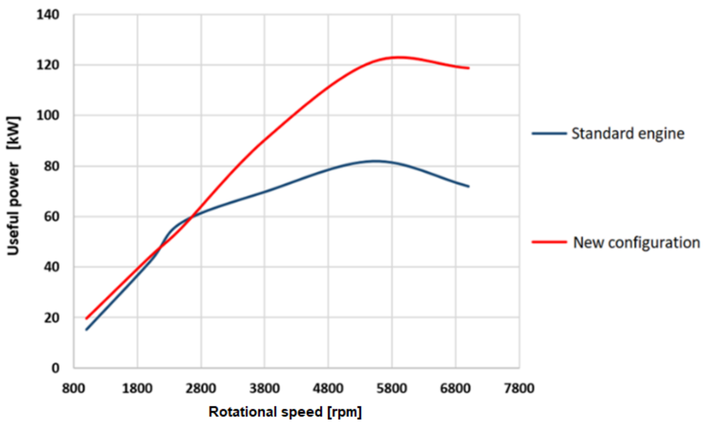

Figure 9. Useful power as a function of engine operating speed

3.3.2. Fuel-specific consumption

FSC results as a function of engine operating speed for the optimized configuration and the standard one is illustrated in Figure 10 and Table 7. The results in Figure 10 show a significant gain in FSC at high engine speeds for the optimized VVT configuration compared to the standard one. This gain is estimated at 3% at 1000 rpm, reaching a maximum of 16% at 5500 rpm and 14% at 7000 rpm.

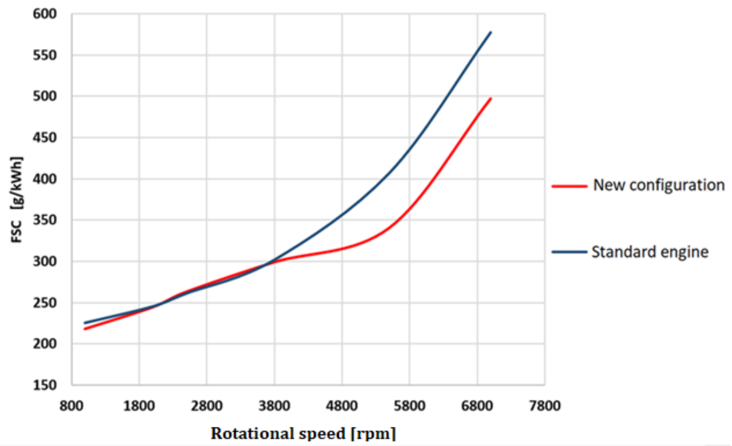

Figure 10. Fuel-specific consumption as a function of engine operating speed

Table 6. Engine power variation [kW]

rpm	New configuration	Standard engine
1000	19.729	15.184
2000	44.191	42.096
2500	55.713	57.594
3800	90.329	69.637
5500	121.236	81.784
7000	118.749	71.836

Table 7. Specific consumption variation [g/kWh]

rpm	New configuration	Standard engine
1000	218	225.3
2000	244.33	245.21
2500	263	261
3800	299	301.7
5500	340.5	406.9
7000	497.3	577.6

4. CONCLUSION

In this comprehensive investigation, we have successfully constructed a sophisticated GT-Power model to explore the intricate interplay of various valve opening and lift configurations within a turbocharged diesel engine. Our primary focus was to assess the impact of diverse variable valve timing (VVT) configurations on power output and fuel consumption. These outcomes were elucidated by conducting an in-depth analysis of how the VVT technique influences the thermodynamic cycle and the intricate pressure and temperature relationships inherent to the engine's operation. This allowed us to discern the advantages and limitations associated with each configuration. The complexity of modern diesel engines (DEs), regulated by electronic components and an array of sensors, necessitated the utilization of advanced modeling software to attain accurate results.

In a significant stride towards optimization, we proposed an intricately optimized VVT strategy incorporating two distinctive valve opening configurations tailored for low and high regimes. Compared with the conventional setup, the optimized VVT yielded substantial enhancements, boasting an impressive 66% surge in power output and a commendable 16% reduction in fuel-specific consumption (FSC) at high rpm. Moreover, this novel configuration showcased its prowess by augmenting technical performance and curbing fuel consumption even at low rpm, where the gains amounted to an appreciable 30% enhancement in power output and a commendable 3% reduction in FSC.

The outcomes achieved across the various phases of our study have demonstrated remarkable promise. More importantly, they have unveiled the pronounced influence of lift variation and valve opening timing on the engine's overall performance. The most noteworthy contributions include: i) A substantial reduction in fuel consumption during high rpm regimes; ii) A modest yet meaningful reduction in fuel consumption during low rpm regimes; and iii) A discernible increase in engine power output.

The insights garnered through our work hold the potential to guide the development of novel DE designs integrated with VVT systems, ultimately bolstering their performance while simultaneously enhancing fuel efficiency. To validate and substantiate our findings, experimental validation remains a crucial step moving forward.

APPENDIX

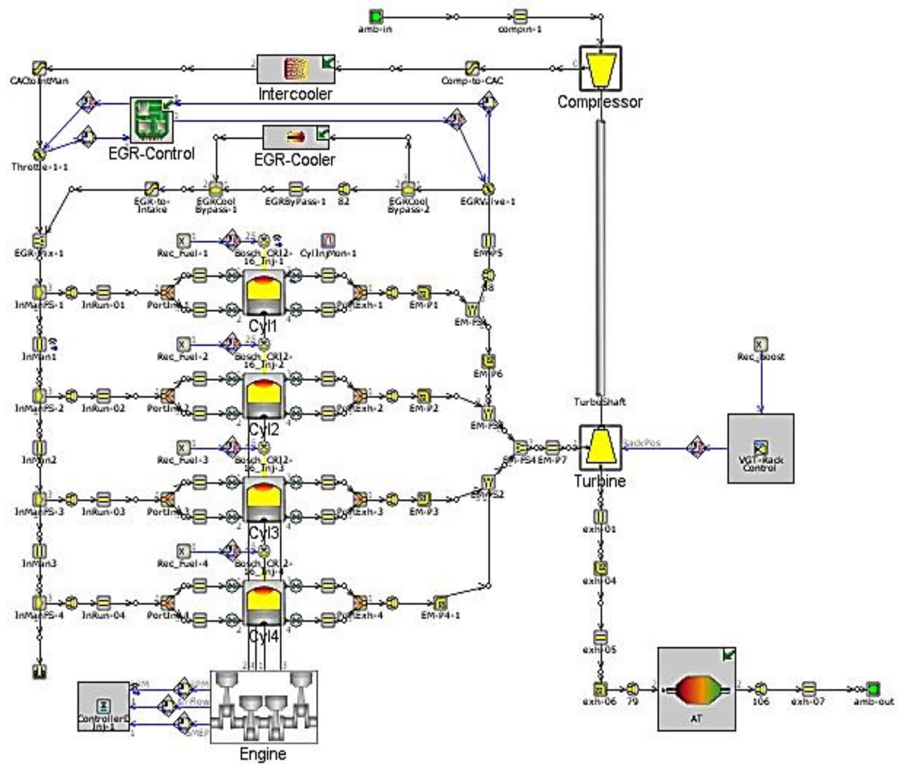

Figure 1. DE model with a turbocharger

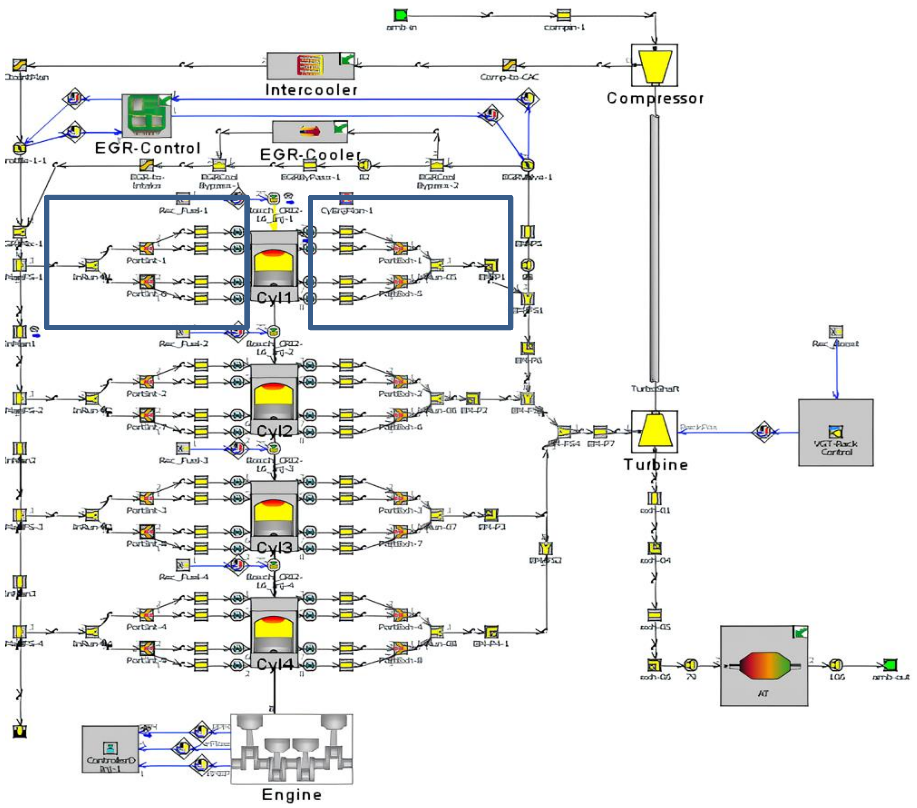

Figure 2. Model of the DE with new VVT configuration (modifications of intake and exhaust of each cylinder)

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