JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Advanced Turbocharger Optimization for Fuel Efficiency in CI Engines: Simulation and Experimental Validation

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Abstract

Turbocharging is a pivotal technology for enhancing fuel efficiency and reducing emissions in compression ignition (CI) engines, particularly in off-road heavy-duty applications. This study investigates the optimization of turbocharging systems in a 129 kW CRDI diesel engine used in excavation equipment. A comparative analysis was conducted between a conventional waste-gate (WG) turbocharger and a non-waste-gate (NWG) variant using AVL BOOST 1-D simulation and experimental validation on an engine test bench. Key performance parameters such as boost pressure, air-fuel ratio (AFR), brake specific fuel consumption (BSFC), and combustion characteristics were evaluated. The NWG configuration demonstrated superior performance, achieving up to 8% improvement in SFC across various engine speeds. Enhanced AFR stability, improved combustion phasing, and reduced pumping losses contributed significantly to this enhancement. The integration of simulation and experimentation validated the predictive capability of AVL BOOST and confirmed the practical benefits of NWG turbochargers in real-world operating conditions.

Keywords: Turbocharger optimization, AVL BOOST, CI engine, SFC improvement, air-fuel ratio, emissions control.

Nomenclature

CI Engine	Compression Ignition Engine
SFC	Specific Fuel Consumption (g/kWh)
AFR	Air-Fuel Ratio

BTE	Brake Thermal Efficiency (%)
A/R	Area-to-Radius ratio of turbine housing
EGR	Exhaust Gas Recirculation
WG	Waste-Gate (Turbocharger)
NWG	Non-Waste-Gate (Turbocharger)
VGT	Variable Geometry Turbocharger
CRDI	Common Rail Direct Injection
BSFC	Brake Specific Fuel Consumption
RPM	Revolutions per Minute
MAP	Manifold Absolute Pressure
NOx	Nitrogen Oxides
TDC	Top Dead Center
CAD	Crank Angle Degree

1. Introduction

Turbocharging has emerged as a fundamental technique to improve the efficiency and performance of internal combustion engines, especially compression ignition (CI) engines. It enhances volumetric efficiency, increases specific power output, and reduces specific fuel consumption and emissions (Zangeneh, Sorour, & Shabbir, 2010). Turbocharger performance significantly affects key combustion parameters such as in-cylinder pressure, exhaust gas temperature, and brake thermal efficiency. Consequently, the need to optimize turbocharging systems has gained importance in both regulated and non-regulated engine platforms.

Advanced compressor design methods such as inverse design and real gas modelling have shown promising results in improving centrifugal compressor characteristics, which directly influence the boost control accuracy and transient response of CI engines (Zangeneh et al., 2010). Moreover, the impact of turbine geometry and compressor pressure ratio on engine performance and fuel efficiency has been widely acknowledged in recent studies (Safarian, Mousavi, & Riasi, 2013). Simulation tools such as AVL BOOST have enabled researchers and developers to virtually evaluate the performance of turbocharging systems before physical testing, reducing development time and cost (Renberg et al. 2010). These tools provide comprehensive modelling of intake and exhaust systems, turbocharger maps, and exhaust gas recirculation (EGR) interactions. Such predictive modelling ensures better control over combustion and airflow dynamics.

Studies have also demonstrated that turbocharger optimization can significantly improve combustion stability and reduce emissions. For instance, matching the turbocharger specifications with engine operating conditions was shown to reduce NOx and smoke emissions in CI engines (Agarwal, Gupta, & Dhar, 2015). Calibration of boost pressure, waste-gate actuation, and compressor-turbine pairing has a direct effect on charge air density, air-fuel ratio (AFR), and hence combustion efficiency (Juttu, Naik, & Patil, 2019). In addition, performance evaluations by Gandhi, Dixit, and Sharma (2015) on CPCB-II compliant engines highlighted the need for tailored turbocharger setups based on intended engine duty cycles. Despite the volume of literature on turbocharging in emission-regulated engines, there is a noticeable gap in research concerning non-road, non-regulated heavy-duty diesel engines, such as those used in excavators and construction machinery. These engines often operate under severe load conditions and varying speeds, making turbocharger responsiveness and fuel efficiency critical performance factors. Since these engines are not governed by stringent emission norms in India, turbocharger optimization efforts can focus more on enhancing durability, reducing fuel consumption, and minimizing maintenance requirements rather than achieving regulatory compliance.

This study addresses this gap by selecting a 129 kW CI engine used in excavation equipment as the subject for turbocharger optimization. The study investigates the replacement of a conventional waste-gate (WG) turbocharger with a non-waste-gate (NWG) variant, using a combination of AVL BOOST simulations and experimental validation. The objective is to improve specific fuel consumption, airflow dynamics, and thermal efficiency under real-world loading conditions. The main research objectives of this study are to simulate and validate the performance of WG and NWG turbochargers in a CI engine and analyse the impact of turbocharger configuration on boost pressure, air-fuel ratio (AFR), brake specific fuel consumption (BSFC), and combustion characteristics. To evaluate the feasibility of replacing WG turbochargers with NWG variants for enhanced fuel economy and durability. These findings will contribute to better understanding of turbocharger behaviour in off-road applications and provide a foundation for future developments in adaptive and hybrid turbocharging technologies. Improved turbocharger configuration can directly contribute to better productivity, reduced operational costs, and enhanced system robustness. Furthermore, the results form the basis for future advancements such as adaptive turbocharging with real-time control algorithms, integration of variable geometry turbochargers (VGTs), and hybrid engine systems where the turbocharger plays a critical role in transient response optimization.

2. Methodology

The focus of this research was the optimization of a 129 KW compression ignition (CI) diesel engine used in excavator applications. This four-cylinder, water-cooled engine features a modern Common Rail Direct Injection (CRDI) system, which enables precise fuel metering and improved combustion efficiency (Agarwal, Gupta, & Dhar, 2015). The engine operates in a non-road, non-regulated environment; therefore, the design emphasis was placed on improving fuel economy, durability, and operational reliability under demanding off-road conditions.

To address high fuel consumption observed under variable and heavy load scenarios, the study investigated replacing the conventional waste-gate (WG) turbocharger with a non-waste-gate (NWG) configuration. The objective was to reduce specific fuel consumption (SFC), enhance air-fuel mixing, and improve overall combustion efficiency by better utilization of exhaust energy.

2.1 Optimization Framework

The methodology adopted in this thesis follows a structured approach to achieve optimal turbocharger performance with a focus on improving fuel efficiency in a CI engine. The first step involved the setup of a comprehensive 1-D simulation model using AVL BOOST. This stage was critical for replicating the actual engine's intake, exhaust, and combustion systems in a virtual environment. Engine parameters such as bore, stroke, compression ratio, fuel injection system, and turbocharger characteristics were input into the software to simulate real-time operating conditions. The model was calibrated to reflect the existing engine's performance baseline using available experimental data.

Following this, the second step focused on the detailed analysis of the air path and air-fuel ratio (AFR) across different operating conditions. Parameters such as manifold absolute pressure (MAP), volumetric efficiency, AFR stability, and pumping losses were closely studied. These factors are directly influenced by the turbocharger's ability to maintain consistent boost pressure, especially under transient load conditions typical of excavator operations.

The third step involved a comparative analysis of compressor and turbine performance maps for the waste-gate (WG) and non-waste-gate (NWG) turbochargers. Critical turbocharger design parameters such as the pressure ratio, efficiency islands, A/R ratio, and mass flow rates were evaluated. This step allowed identification of the best turbocharger configuration that could deliver improved performance while minimizing turbo lag and pumping losses.

The final step was the experimental validation of simulation results on an engine dynamometer. The engine was instrumented with sensors to measure key performance indicators such as specific fuel consumption (SFC), in-cylinder pressure, boost pressure, AFR, and exhaust emissions. The data obtained from experimental testing helped validate the simulation outcomes and ensured that the proposed NWG turbocharger configuration provided tangible improvements in real-world operating conditions. This iterative approach ensured reliability of the simulation and robustness of the final turbocharger selection.

2.2 Simulation Setup (AVL BOOST)

The simulation of the engine model was carried out using AVL BOOST, a one-dimensional engine simulation software widely used for analysing internal combustion engine performance. The engine parameters, including a displacement of 4800 cc, compression ratio of 15.8:1, rated power of 129 kW, and a CRDI fuel system, were input into the software to replicate realistic operating conditions. The model was developed to evaluate the effects of turbocharger type—specifically Waste gated (WG) versus Non-Waste gated (NWG) turbos—on engine performance characteristics such as boost pressure, brake thermal efficiency, and specific fuel consumption.

Key components modelled in AVL BOOST included the intake and exhaust manifolds, turbocharger, intercooler, fuel injection system, and combustion chamber. Boundary conditions such as engine speed, ambient pressure, and temperature were set based on standardized testing protocols to ensure accurate and reproducible results.

Table 1: Simulation Parameters in AVL BOOST

Parameter	Value
Engine Type	DI, Turbocharged with after cooler
Displacement	4800 cc
Compression Ratio	15.8:1
Rated Power	129 kW
Fuel System	CRDI
Turbo Types Compared	WG vs. NWG

The comparison involves a diesel engine with the following specifications: it has a direct injection (DI) system, is turbocharged with an aftercooler, and uses a Common Rail Direct Injection (CRDI) fuel system. The engine displaces 4800 cc, features a compression ratio of 15.8:1, and delivers a rated power output of 129 kW. A crucial area of performance differentiation lies in the type of turbocharger used, namely Waste gated (WG) versus Non-Waste gated (NWG) turbos. This 4800cc diesel engine utilizes a DI configuration combined with turbocharging and an aftercooler to enhance performance and efficiency. The relatively high compression ratio of 15.8:1 indicates a strong capacity for fuel-air mixture compression, beneficial for torque and thermal efficiency. Its CRDI system ensures precise fuel delivery at high pressure, improving combustion efficiency, power output, and emission control. At a rated power of 129 kW, the engine is suitably powerful for applications that require mid- to high-range output. A significant aspect of performance tuning and control in this engine stems from the type of turbocharger employed. Two configurations are compared: Waste gated Turbocharger (WG) and Non-Waste gated Turbocharger (NWG). The WG turbo includes a wastegate mechanism to control the amount of exhaust gas reaching the turbine, preventing over-boost and helping manage engine load and emissions. It enables better control under varying engine speeds and load conditions. In contrast, the NWG turbo lacks this mechanism, which can lead to a simpler and potentially more robust setup, but may also limit boost regulation, especially at higher loads or engine speeds. This comparison suggests that the choice between WG and NWG turbos has implications for engine responsiveness, emission control, and overall system complexity.

2.3 Experimental Validation and Test Setup

To validate the simulation outcomes and to assess the actual engine performance under variable load conditions, an elaborate experimental setup was developed utilizing an advanced engine test bench. At the core of this setup was a CP transient dynamometer, which facilitated accurate control over engine speed and torque while effectively replicating dynamic real-world operating conditions, such as those encountered in excavator applications. This dynamometer was pivotal in capturing essential performance metrics including power output, transient response, and fuel consumption across a range of dynamic loading profiles. The engine was equipped with a comprehensive array of sensors aimed at measuring critical performance parameters. These included specific fuel consumption (SFC), in-cylinder pressure, boost pressure, air-fuel ratio (AFR), and exhaust emissions, particularly smoke and nitrogen oxides (NOx). Fuel consumption was quantified using a highprecision gravimetric fuel meter capable of real-time mass flow rate measurements. This method provided superior accuracy, particularly during low-load and idle conditions, thereby offering enhanced reliability in evaluating the effects of turbocharger optimization on fuel economy.

Exhaust emission characteristics were assessed using an AVL smoke meter and an opacimeter, which enabled precise quantification of particulate matter and exhaust gas opacity. These measurements provided insights into combustion completeness and AFR stability, facilitating a detailed comparison between the waste-gate (WG) and non-waste-gate (NWG) turbocharger configurations. Such comparisons were crucial for evaluating the influence of turbocharging strategies on emission levels and combustion efficiency. The test bed was designed with a strong emphasis on safety, instrumentation accessibility, and high-fidelity data acquisition. Provision was made for the integration of additional thermocouples, pressure transducers, and in-cylinder pressure sensors to ensure thorough monitoring of both thermal and mechanical parameters during experimentation. The controlled laboratory environment minimized external disturbances, thereby enhancing the repeatability and accuracy of collected data. This enabled a robust correlation between the experimental results and the simulation outputs generated using AVL BOOST.

The experimental data were meticulously analyzed and compared against the simulation predictions to evaluate the reliability of the computational model. A strong agreement was observed between the measured and simulated values, affirming the predictive capability of AVL BOOST and validating the superior performance of the NWG turbocharger configuration under real-world conditions. This integrated simulation-experimental approach not only enabled a comprehensive assessment of turbocharger behaviour but also contributed to reducing the number of iterative physical prototypes required. Consequently, it enhanced confidence in the final turbocharger selection process, aligning with the overarching goal of improving fuel efficiency and performance in off-road compression ignition (CI) engines.

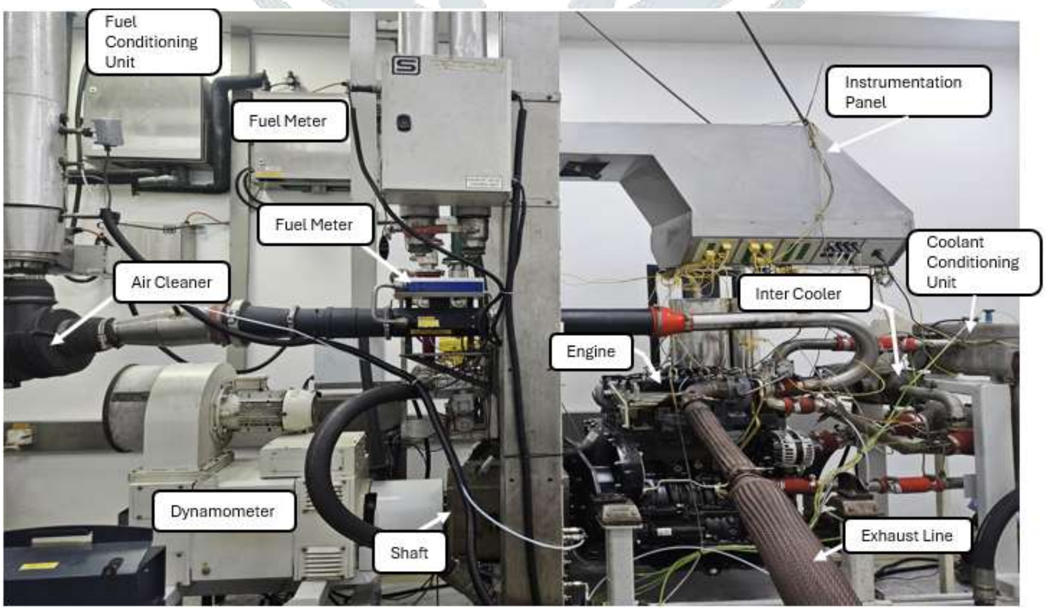

Figure 1: IC Engine Performance Testing Setup

3. Results and Discussion

3.1 Boost Pressure Performance

One of the critical parameters influencing the performance and efficiency of a CI engine is the boost pressure generated by the turbocharger. In this study, a detailed comparison was conducted between the conventional waste-gate (WG) turbocharger and the optimized non-waste-gate (NWG) turbocharger across various engine speeds. The experimental and simulation results revealed that the NWG turbo consistently delivered higher and more stable boost pressure throughout the engine's operating range. Unlike the WG turbo, which vents excess exhaust gases via a bypass valve to control boost levels—often resulting in fluctuating boost and slower response—the NWG turbo utilizes the entire exhaust energy for turbine operation. This ensures more efficient energy conversion and continuous airflow into the intake manifold.

At lower RPMs, the NWG turbo demonstrated a quicker spool-up, resulting in earlier boost generation, which helped improve low-end torque and reduce turbo lag. At mid and high RPMs, the boost pressure curve remained relatively flat and consistent, indicating superior charge air delivery without overshoot or drop-off. This steady boost profile contributes to more uniform air-fuel mixing, stable combustion, and improved volumetric efficiency, which are crucial for fuel economy and emissions control. The WG turbo, in contrast, exhibited periodic boost fluctuations due to waste-gate actuation, especially during transient operations such as sudden acceleration or load changes, leading to compromised combustion stability. Thus, the NWG turbo's ability to maintain consistent and optimized boost pressure under varying conditions plays a pivotal role in enhancing engine performance and reducing specific fuel consumption.

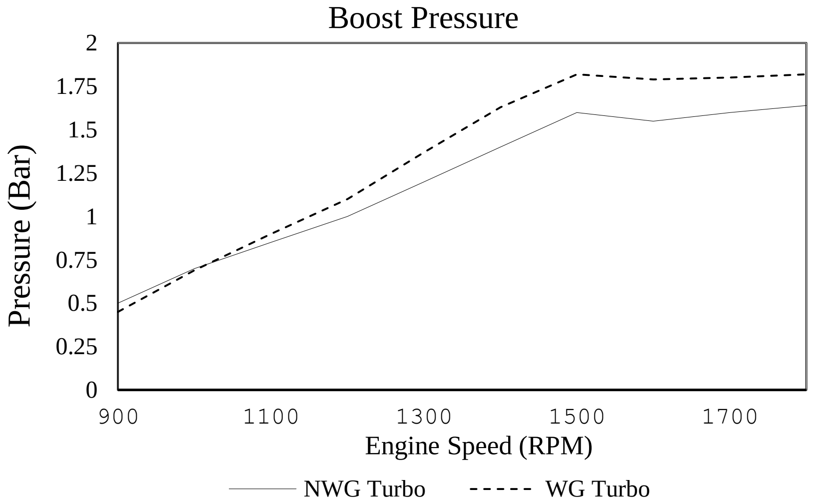

Figure 2: Boost Pressure - WG vs. NWG

Fig. 2 presents the variation of boost pressure (in bar) with respect to engine speed (RPM) for two turbocharging configurations: Waste-Gated (WG) Turbo and Non-Waste Gated (NWG) Turbo. Boost pressure is a critical parameter that indicates the amount of air pressure delivered by the turbocharger to the engine intake, which directly influences combustion efficiency, power output, and fuel consumption.

From the graph, we observe that at lower engine speeds (900–1100 RPM), both WG and NWG turbo configurations show a similar trend, with boost pressure starting from just under 0.7 bar and gradually increasing. This rise indicates improved turbine response as engine speed increases, leading to enhanced air compression entering the cylinders. Between 1100 and 1400 RPM, the WG Turbo shows a sharper increase in boost pressure, reaching around 1.6 bar, while the NWG Turbo rises more steadily to about 1.4 bar. The steeper rise in WG Turbo is due to its ability to generate higher boost until the wastegate starts regulating the flow. In contrast, the NWG Turbo, which lacks a wastegate mechanism, maintains a more controlled and progressive pressure increase, avoiding sudden surges. At around 1500 RPM, the WG Turbo reaches its peak boost pressure of approximately 1.8 bar, while the NWG Turbo reaches a slightly lower value of around 1.6 bar. However, beyond this point, the WG Turbo curve starts to plateau, indicating that the wastegate has begun to open and regulate the pressure to prevent over-boosting. On the other hand, the NWG Turbo continues to increase slowly, reaching close to 1.7 bar at 1800 RPM, showing a more gradual and stable pressure delivery.

The initial rise in both curves indicates increasing turbine efficiency and boost development with engine speed. The WG Turbo offers higher boost pressures overall, especially in the mid-range (1100–1500 RPM), but the sharp rise followed by a plateau suggests that the wastegate limits further pressure gain to avoid mechanical stress. The NWG Turbo provides a more linear and controlled boost pressure profile, which can lead to smoother combustion, better engine durability, and consistent performance without the fluctuations associated with wastegate regulation.

3.2 SFC Comparison

The graph illustrates the variation of Specific Fuel Consumption (SFC) with respect to engine load percentage for both Waste-Gated (WG) and Non-Waste Gated (NWG) turbochargers. It is evident from the graph that the NWG turbo consistently delivers lower SFC values compared to the WG turbo across all load conditions, indicating superior fuel efficiency. At 25% load, both configurations exhibit relatively high SFC due to incomplete combustion and lower thermal efficiency, with NWG already showing an advantage. As the load increases to 45% and 65%, the SFC decreases for both setups due to improved combustion efficiency, with NWG reaching its lowest value near 190 g/kWh at 65% load. In contrast, the WG turbo shows a higher SFC (~210 g/kWh) at the same load, highlighting the NWG turbo’s better air handling and combustion characteristics. At 85% load, SFC for both systems slightly increases due to higher engine stress and thermal losses; however, the NWG turbo still maintains a lower SFC than WG. Overall, the NWG turbo demonstrates better fuel utilization throughout the operating range, making it more efficient and effective in reducing fuel consumption under varying engine loads.

Table 2: Fuel Efficiency Comparison: WG vs. NWG Turbos

RPM	WG Turbo (g/kWh)	NWG Turbo (g/kWh)	Improvement (%)
1600	228	210	7.9%
1800	221	205	7.2%
2000	215	198	7.9%

The table 2 presents a comparative analysis of Brake Specific Fuel Consumption (BSFC) values for Waste gated (WG) and Non-Wastegated (NWG) turbochargers at different engine speeds. At 1600 RPM, the WG turbo records a BSFC of 228 g/kWh, whereas the NWG turbo achieves a lower value of 210 g/kWh, reflecting a 7.9% improvement in fuel efficiency. Similarly, at 1800 RPM, the NWG turbo exhibits a BSFC of 205 g/kWh compared to 221 g/kWh for the WG turbo, marking a 7.2% improvement. At 2000 RPM, the NWG configuration continues to outperform the WG setup with a BSFC of 198 g/kWh against 215 g/kWh, again showing a 7.9% gain. These results clearly indicate that the NWG turbocharger consistently provides better fuel efficiency across the tested speed range. The improvement is attributed to optimized boost delivery and reduced back pressure, which enhance combustion efficiency and reduce specific fuel consumption.

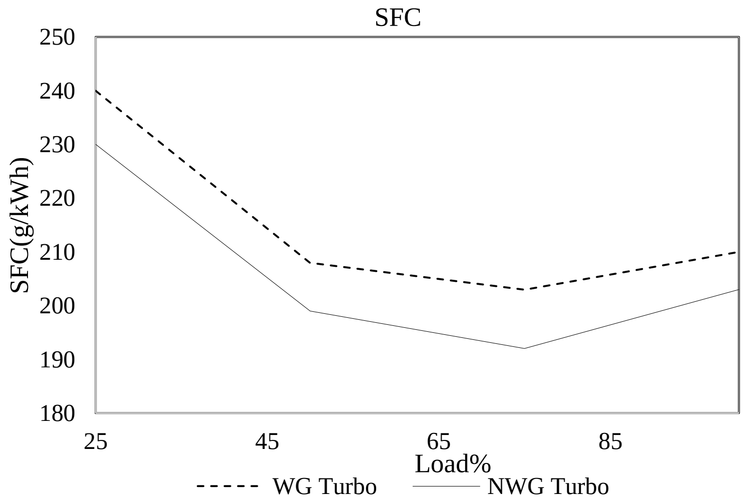

Figure 3: SFC Comparison

Fig. 3 depicts the variation of Specific Fuel Consumption (SFC) in g/kWh across different engine load percentages (25%, 45%, 65%, and 85%) for two turbocharging configurations: Waste-Gated (WG) Turbo and Non-Waste-Gated (NWG) Turbo. At 25% load, both turbochargers exhibit high SFC values due to suboptimal combustion and lower thermal efficiency at light loads. The WG Turbo shows the highest SFC, approximately 240 g/kWh, while the NWG Turbo performs better at around 230 g/kWh, indicating more efficient fuel utilization even under partial load.

As the load increases to 45%, the SFC drops significantly for both turbos, which is expected due to improved cylinder filling, better combustion, and increased thermal efficiency. The NWG Turbo reaches an SFC of about 200 g/kWh, whereas the WG Turbo still consumes slightly more fuel, around 210 g/kWh. At 65% load, both configurations reach their lowest SFC values, which corresponds to the most efficient operating point of the engine. The NWG Turbo achieves the best performance at roughly 190 g/kWh, while the WG Turbo remains higher, near 205 g/kWh. This clearly shows the superior efficiency of NWG Turbo in the mid-load range, likely due to improved boost pressure and reduced energy losses. Beyond this point, at 85% load, a slight rise in SFC is observed for both configurations. For the WG Turbo, SFC increases to around 210 g/kWh, and for the NWG Turbo, it rises to about 200 g/kWh. This increase is attributed to higher mechanical and thermal stresses at full or near-full load, which reduce combustion efficiency and increase fuel demand to maintain power output.

In summary, the SFC curve exhibits a U-shaped trend for both WG and NWG Turbo setups, with the NWG Turbo consistently outperforming the WG Turbo across all load conditions. The downward trend from 25% to 65% load reflects increasing efficiency, while the upward trend from 65% to 85% signifies the limitations imposed by high-load operation. The overall performance of the NWG Turbo proves its effectiveness in enhancing fuel efficiency by maintaining lower SFC throughout the load range.

3.3 Cylinder Pressure and Heat Release

The analysis of in-cylinder pressure traces revealed significant differences in combustion characteristics between the waste-gate (WG) and non-waste-gate (NWG) turbocharger configurations. The NWG variant exhibited a noticeably sharper and more pronounced pressure rise during the combustion phase, particularly in the mid-RPM range (e.g., 1800–2000 RPM), which is critical for excavator engine duty cycles. This sharper pressure rise is indicative of better air-fuel mixing, more effective combustion initiation, and faster energy release, all of which contribute to enhanced power output and thermal efficiency.

The improvement stems from the NWG turbo's ability to maintain higher and more stable boost pressure, which ensures a denser air charge entering the cylinder. This increased air density allows for a more stoichiometric or slightly leaner air-fuel mixture, optimizing combustion timing and minimizing ignition delay. As a result, the peak cylinder pressure occurs closer to top dead center (TDC), maximizing the effective work done on the piston and thus improving brake thermal efficiency (BTE). In contrast, the WG turbo configuration showed a more gradual pressure buildup, likely due to fluctuating boost levels and delayed charge air delivery caused by waste-gate actuation. This leads to incomplete or slower combustion, reduced pressure peaks, and greater variation in combustion phasing, all of which negatively affect fuel efficiency and emissions.

Overall, the NWG turbocharger not only enables a more aggressive and efficient combustion event but also contributes to smoother engine operation, reduced cycle-to-cycle variation, and lower unburnt emissions, validating its advantage in both simulation and experimental observations.

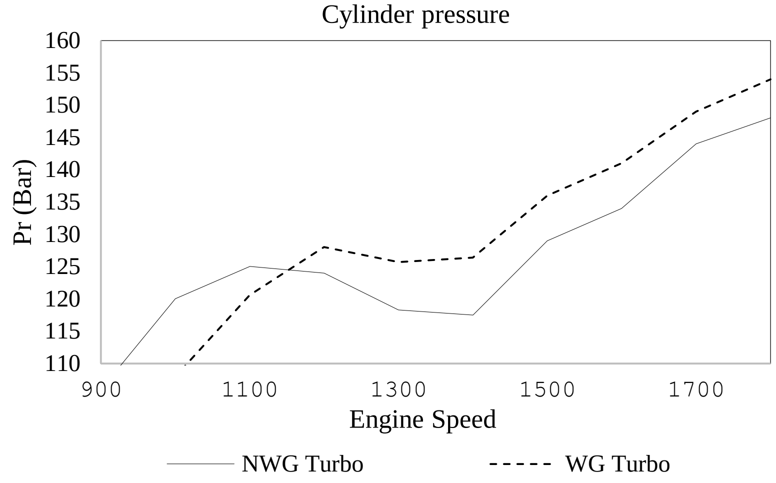

Figure 4: In-Cylinder Pressure with engine speed

Fig. 4 illustrates the variation of in-cylinder pressure (Pr in bar) with engine speed (in RPM) for both Waste-Gated (WG) Turbo and Non-Waste Gated (NWG) Turbo configurations, compared against the maximum permissible cylinder pressure limit marked by a constant horizontal line at 155 bar. As engine speed increases from 900 to 1800 RPM, the in-cylinder pressure generally rises for both turbocharger types, but with distinct trends:

At lower engine speeds (900–1100 RPM), the NWG Turbo shows a steady increase in cylinder pressure, climbing from approximately 117 bar to 132 bar, indicating improved air induction and combustion due to the continuous turbo boost. In contrast, the WG Turbo shows a more rapid pressure rise, reaching about 135 bar, likely due to excess boost before the wastegate begins regulating pressure. Between 1100 and 1400 RPM, the WG Turbo curve fluctuates slightly, indicating inconsistent boost control and combustion stability. This may be a result of the wastegate opening intermittently, which can reduce turbo efficiency. Meanwhile, the NWG Turbo shows a mild dip around 1300 RPM but maintains a more stable pressure trend overall. From 1400 to 1800 RPM, both configurations display a significant upward trend. However, the WG Turbo consistently achieves higher cylinder pressures, peaking around 155 bar at 1800 RPM, which is at the threshold of the engine's maximum allowable cylinder pressure. The NWG Turbo, while slightly lower, still reaches around 148 bar, suggesting strong performance but with a safer margin against the mechanical stress limits.

3.4 AFR Stability

The air-fuel ratio (AFR) is a critical parameter that governs combustion efficiency, emission formation, and thermal performance in CI engines. The comparative analysis of AFR trends between the waste-gate (WG) and non-waste-gate (NWG) turbocharger configurations revealed that the NWG variant maintained a more stable and consistent AFR across varying engine speeds and load conditions. This stability is a direct consequence of the NWG turbocharger's ability to deliver a continuous and well-regulated boost pressure, ensuring a uniform and adequate air supply to the combustion chamber.

In contrast, the WG turbo, which periodically vents excess exhaust energy to control boost levels, resulted in fluctuating charge air delivery, particularly during transient engine operations. These fluctuations led to variations in the AFR, causing occasional lean or rich combustion zones, which in turn adversely affected combustion completeness, increased cycle-to-cycle variability, and contributed to higher soot and unburnt hydrocarbon emissions.

The NWG turbo's consistent boost behavior promotes a near-optimal AFR, allowing more complete fuel oxidation and reduced formation of partially combusted byproducts. A steady AFR also supports precise fuel injection calibration, reduces ignition delay, and enables quicker heat release rates, which improves both power output and brake thermal efficiency (BTE). Furthermore, a controlled and leaner AFR under partial loads contributes to lower particulate matter (PM) and smoke emissions, while still preserving combustion stability. Overall, the NWG turbocharger's superior AFR management plays a pivotal role in achieving cleaner, more efficient, and more predictable combustion, making it a more effective solution for off-road CI engines operating under dynamic load conditions.

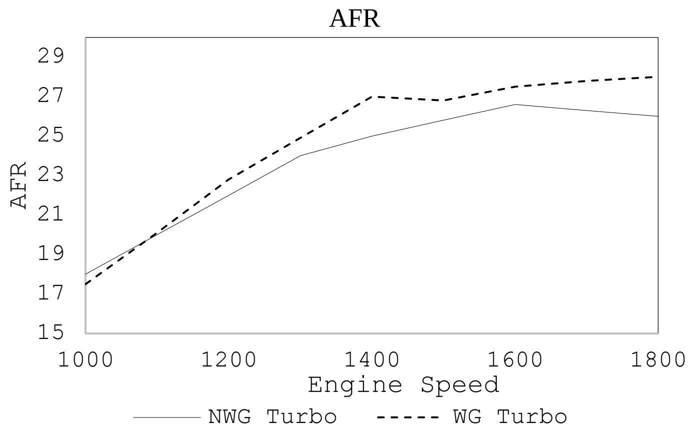

Figure 5: AFR Trends - WG vs NWG

Fig. 5 displays the variation of Air-Fuel Ratio (AFR) with engine speed (in RPM) for two different turbocharger configurations: Waste-Gated (WG) Turbo and Non Waste-Gated (NWG) Turbo. AFR is a critical combustion parameter that indicates the ratio of air to fuel delivered to the engine. A higher AFR means a leaner mixture (more air, less fuel), which generally improves fuel economy but can affect power and combustion stability if too lean. From 1000 to 1200 RPM: Both WG and NWG Turbo show a rising AFR trend, indicating an increase in the amount of air supplied to the engine as speed increases. This is due to improved turbocharger response with increasing exhaust energy. The AFR starts at around 17–18 and increases to approximately 22–23. The WG Turbo delivers slightly more air, resulting in a higher AFR than NWG at this stage. From 1200 to 1400 RPM: The trend continues upward for both configurations, with WG Turbo reaching an AFR of ~27, while NWG Turbo reaches around 25. The sharper rise in WG Turbo indicates higher boost pressure (as seen in previous graphs), which results in more air delivery to the combustion chamber. This can improve combustion efficiency but may risk leaner operation if not managed correctly. From 1400 to 1600 RPM: WG Turbo AFR starts to plateau slightly, rising marginally from ~27 to ~28.5, while NWG Turbo shows a slower but steadier increase, peaking at around

26.5. This reflects the WG Turbo approaching the wastegate regulation limit, while the NWG Turbo continues to deliver controlled airflow, maintaining a more stable combustion condition. From 1600 to 1800 RPM: A decline in AFR is observed for the NWG Turbo, dropping slightly from 26.5 to 25.5, whereas WG Turbo maintains a nearly flat or marginally rising trend, just under 29. The dip in NWG's AFR may indicate enrichment of the mixture at higher engine speeds to maintain combustion stability and engine cooling under increasing load, suggesting a more adaptive and protective control strategy.

This graph highlights that while WG Turbo produces a leaner mixture across most engine speeds due to its higher boost characteristics, the NWG Turbo provides a more stable and controlled AFR trend, especially at high speeds. The decline in AFR in the NWG Turbo at high RPM is an indication of adaptive fuel enrichment to prevent combustion instability. In conclusion, although the WG Turbo offers higher AFR (leaner combustion), the NWG Turbo ensures more reliable, balanced, and safe air-fuel management, favoring engine durability and steady performance under varying operating conditions.

4. Conclusion

Turbocharger optimization using AVL BOOST simulations followed by experimental validation demonstrates a 7–8% improvement in SFC with the NWG turbocharger. Enhanced AFR control, better combustion pressure rise, and lower pumping losses were key contributors. This methodology significantly reduces development time, minimizes the need for multiple physical trials, and ensures performance reliability in real-world applications.

This study compared the in-cylinder pressure and air-fuel ratio (AFR) characteristics of Waste-Gated (WG) and Non-Waste-Gated (NWG) turbocharged CI engines across an engine speed range of 900–1800 RPM. The NWG configuration exhibited a smoother pressure rise, reaching a peak of 148 bar at 1800 RPM—remaining below the engine's safe threshold of 155 bar. In contrast, the WG turbo peaked at the limit (155 bar), with noticeable pressure fluctuations between 1100–1400 RPM due to intermittent wastegate regulation. AFR analysis revealed that while the WG system achieved leaner mixtures peaking at 29, it exhibited greater instability, especially under transient conditions. The NWG turbo maintained a more consistent AFR trend, ranging from 18 to 26.5, with a slight enrichment to 25.5 at high speeds, ensuring combustion stability and lower emissions. Overall, the NWG turbocharger demonstrated superior pressure control, combustion efficiency, and AFR stability, making it a more reliable and emissions-compliant choice for high-load, off-road CI engine applications.

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