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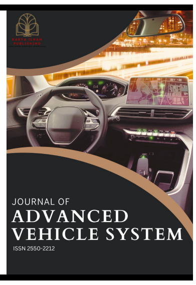

Virtual Matching and Optimization of Turbocharger Parameters for Marine Diesel Engines to Achieve Fuel and Emission Efficiency Targets

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ABSTRACT

The performance and environmental impact of marine diesel engines are strongly influenced by turbocharger configuration and condition. As shipping industries face increasing pressure to meet fuel efficiency and IMO Tier III emission standards, simulation-based optimization offers a cost-effective solution for improving performance while reducing environmental impact. This study investigates how variations and degradations in turbocharger parameters affect the performance of a MAN B&W 6S60MC-C two-stroke marine diesel engine using the TRANSAS Full Mission Engine Room Simulator. The main objective is to evaluate how fault-aware turbocharger matching strategies can sustain engine efficiency and emission compliance under degraded conditions. Results show that optimized configurations enhance combustion stability, reduce fuel consumption, and improve emission performance, while degradation levels of 15–20% significantly impair power and increase pollutant output. The findings demonstrate the importance of adaptive and fault-aware turbocharger optimization strategies for ensuring operational reliability, regulatory compliance, and sustainable marine propulsion.

1. Introduction

Marine diesel engines remain the backbone of international shipping but face rising challenges related to environmental regulation and operational efficiency. Turbochargers are essential for improving combustion efficiency and reducing emissions; however, their performance deteriorates over time due to fouling, blockage, or mechanical wear. Optimizing turbocharger parameters under these real-world conditions is therefore crucial to maintain efficiency and emission compliance. To meet increasingly stringent emission regulations (IMO Tier III, etc.), researchers have been exploring

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virtual matching and optimization of turbocharger parameters under realistic engine-fault or performance-decay conditions.

Recent studies have pushed forward in several directions. Shen *et al.,* [1] conducted a detailed parametric investigation on dual-fuel marine two-stroke engines, defining three types of turbocharger decay (turbine efficiency, nozzle ring area, shaft mechanical efficiency) and quantifying their impacts on performance and emissions in both diesel and gas modes. Experimental reconditioning of turbochargers has also been shown to be effective: Nyongesa *et al.,* [2] demonstrated that scheduled overhaul in marine auxiliary engines can recover lost performance, reduce fuel consumption, and lower CO, NO_x, CO_2 emissions. Health assessment and diagnostics are also growing fields: Li *et al.,* [3] proposed methods based on combining zero-dimensional engine models with machine learning to evaluate the deterioration of turbochargers before severe faults occur. Another recent work by Tadros & Boulougouris *et al.,* [4] focused on calibration of NO_x emission models for high-speed marine engines, enabling more faithful prediction under load variation.

Beyond decay and diagnostics, improvements in turbocharger matching and control schemes are also being explored. Meng *et al.,* [5] propose a dual turbocharger with synergistic control (speed–pitch) for low-speed marine diesel engines, showing improvements in transient response (especially reducing black smoke) as well as fuel consumption. Works like "Matching and Optimization to Minimize Fuel Consumption and NO_x Emission for a Marine Diesel Engine with Turbo-Assisted Exhaust Gas Recirculation" Zhang *et al.,* [6] use multi-objective optimization (e.g. NSGA II) on turbocharger plus EGR systems to find matching laws that balance BSFC and NO_x trade-offs. There are also studies focusing on seasonal and ambient effects (air/water temperatures) showing how environmental variation affects turbocharger performance and emissions. For example, Ceylan *et al.,* [7] simulate a two-stroke MAN-B&W engine in different seasonal conditions and observe measurable shifts in emissions when ambient temperature or seawater temperature changes.

Despite this progress, several gaps remain. Many optimization studies assume "ideal" baseline turbocharger performance, and fewer works systematically integrate performance decay (blockages, fouling, mechanical losses) into turbo-matching strategies under varying operating loads. Also, studies that combine both steady-state and transient conditions, with emissions and fuel consumption simultaneously, remain limited.

Previous simulation-based optimization studies have successfully improved engine performance under ideal conditions, but few have incorporated the effects of component degradation or fault conditions. This study addresses that gap by using the TRANSAS Full Mission Engine Room Simulator to simulate realistic fault scenarios and assess their impact on key performance indicators such as brake-specific fuel consumption (BSFC), scavenge air pressure, and gaseous emissions. The research aims to establish guidelines for turbocharger matching that balance performance and emissions even under deteriorating conditions. Therefore, this study aims to fill in some of those gaps by using a virtual simulation (TRANSAS / engine-room simulator) to introduce realistic turbocharger performance degradations (air cleaner blockage, nozzle blockages, cooler side blockages etc.), at various severity levels, and to examine how those affect engine power output, brake specific fuel consumption (BSFC) and emission of NO_x, CO, etc. By doing so, we intend to derive matching and optimization guidelines for turbocharger configuration that balance fuel economy and emissions even under degraded turbocharger health. Our research contributes both fault-aware matching strategies and insights for engine operators who cannot always maintain "perfect" turbocharger condition but must still meet performance and environmental targets.

2. Literature Review

2.1 Overview of Turbocharger Matching and Optimization in Marine Engines

Researchers have consistently shown that turbocharger matching—that is, selecting appropriate turbocharger size, compressor/turbine efficiency and matching ratio—is crucial for both fuel economy and emissions control of marine diesel engines. For instance, Mizythras, Boulougouris & Theotokatos *et al.,* [8] proposed an objective-oriented methodology for matching single or parallel turbochargers to marine engines, reducing brake specific fuel consumption (BSFC) by up to ~5% while expanding the operational envelope.

Salazar *et al.,* [9] analysed large four-stroke marine diesel engines equipped with electrically divided turbochargers, focusing on optimization of variables such as compressor size, start of injection, valve timing etc. impacts fuel consumption. They found significant improvements, especially under low load.

Dual turbocharger systems and synergistic control have also been explored; C. Meng *et al.,* [5] showed that a dual turbo configuration with careful control can reduce black smoke emissions, accelerate intake pressure build-up, and reduce fuel consumption in transient operations.

2.2 Turbocharger Performance Decay, Faults, and Their Effects

A growing strand in recent literature addresses how turbocharger performance decays (due to fouling, blockage, nozzle ring erosion, etc.) impact engine performance and emissions. Shen *et al.,* [1] conducted parametric investigation on a marine large two-stroke dual-fuel engine, defining various types of decay (turbine efficiency, nozzle area, mechanical efficiency) and showing that these affect BSFC, engine speed, boost pressure, CO_2 and NO_x emissions.

Also, Chen *et al.,* [10] studied fault diagnosis in marine diesel engines and noted turbocharger decay among key contributing factors. Their work with data-driven models helps to track and mitigate these decays. Further work (e.g. "Turbocharger breakdown investigation") looks at physical degradation, nozzle ring erosion & morphological damage of nozzle rings under high load and how that impacts flow and performance.

2.3 Modelling and Diagnostic Techniques

On the modelling side, many recent works build or validate engine-turbocharger simulation models which incorporate performance decay or transient behavior. Examples:

i. The GT-Power model used by Shen *et al.,* [1] for marine large two-stroke dual-fuel engines, integrating the three decay types.
ii. The "Integrated turbocharger matching program" Mousavi *et al.,* [11] with zero-dimensional engine + compressor/turbine map database to explore various combinations.
iii. Data-driven fault diagnosis and health assessment: e.g. Li *et al.,* [3] developed a health assessment method combining a zero-dimensional model with machine learning to detect turbocharger deterioration before major faults.

There's also literature on hybrid air charging or electrically divided turbochargers. Salazar *et al.,* [9] explored the effect of optimization variables in hybrid architectures.

2.4 Multi-Objective Trade-Offs: Emission vs Fuel Efficiency vs Load/Transient Behavior

One recurring theme is the trade-off between minimizing fuel consumption and reducing emissions (especially NO_x, CO, CO_2) under different load and transient conditions. For example, Matching and optimization to minimize fuel consumption and NO_x emission for a marine diesel engine with turbo-assisted exhaust gas recirculation Zhang *et al.,* [6] uses multi-objective optimization (NSGA-II etc.) to find balance.

Another is the effect of ambient and operating conditions: air temperature, load profile, slow steaming, etc. Such externalities often change how turbocharger decay or matching plays out in practice. For example, the "Large Marine Engine Technology Evaluation Final Report" Chen *et al.,* [10] by EPA shows much operation in emission control areas occurs at low engine loads (< 25–50%), where performance and emissions can deviate significantly from certification test cycles.

2.5 Gaps in Current Literature

From what I see, these are gaps that still need filling:

i. Fault severity quantification: while some works define types of decay (nozzle ring, turbine efficiency etc.), relatively few simulate specific faults such as air cleaner blockage, cooler blockage, cracked nozzle, or worn piston rings with quantified severity levels (10%, 15%, 20%) as in your simulator data.
ii. Realistic marine main engine two-stroke simulation under faulted turbocharger matching: Many works use dual fuel or four-stroke, or model decay, but fewer use marine main two-stroke with these detailed fault types and transient operating conditions.
iii. Integration of emission, fuel consumption, and engine power together under faulted conditions: Some focus on one or two outputs (fuel or emission), but not always include cylinder power, BSFC, scavenging pressure together under multiple severity levels of turbocharger decay.
iv. Optimal matching under degrading performance: How to adjust turbocharger matching or control strategies when turbocharger health degrades – e.g. can you change matching ratios, vary turbo size, or use variable geometry turbine (VGT) to compensate under degraded conditions.

2.6 Relevance to Current Study

Your research, which uses a simulator (TRANSAS) to introduce realistic faults (air cleaner blockage, nozzle blockages, etc.) at multiple severity levels + monitors power output, BSFC, emissions, is well-positioned to fill several of these gaps. By combining multiple fault types, quantifying severity, and measuring multiple output variables, it will add to the body of knowledge in:

i. fault-aware turbocharger matching optimization
ii. understanding how engine performance and emissions degrade, which helps maintenance, diagnostics, and control
iii. perhaps in giving guidelines for matching or control strategies under degraded turbocharger health.

3. Methodology

3.1 Simulation Environment

The TRANSAS Full-Mission Engine Room Simulator was used for this study. It allows for detailed modelling of real-world marine engine operations and includes an integrated marine diesel engine model with turbocharging systems. Engine and Turbocharger Model

The simulation included:

i. A four-stroke, medium-speed marine diesel engine model.
ii. Adjustable turbocharger configurations including turbine/compressor size, efficiency, and pressure ratios.
iii. Matching ratio (the correlation between compressor and turbine flow rates).

Test Scenarios:

Different turbocharger configurations were simulated under various conditions:

i. Engine loads: 25%, 50%, 75%, and 100%
ii. Ambient air temperature and pressure variations
iii. Constant fuel quality and engine displacement

Each scenario measured:

i. Brake-Specific Fuel Consumption (BSFC)
ii. NO_x Emissions
iii. Turbocharger Speed and Boost Pressure

3.2 Parameter Setup on Simulator

The simulation experiments were conducted using the TRANSAS Full Mission Engine Room Simulator (ERS 5000), replicating the MAN B&W 6S60MC-C two-stroke marine diesel engine installed in tanker vessels. The baseline operating condition was set at an engine load of approximately 81% MCR, with constant ambient conditions of 22 °C air temperature, 60% humidity, and 750 mmHg atmospheric pressure.

Key performance indicators, including cylinder power output, scavenging air pressure, brake-specific fuel consumption (SFC), and exhaust gas emissions (NOx, CO, SOx, CO_2), were monitored throughout the simulations. The parameters were systematically varied to introduce different levels of turbocharger performance decay and associated engine faults.

Fault scenarios were applied incrementally at 10%, 15%, and 20% severity levels across components such as air cleaner blockage, cooler air side blockage, cooler tube blockage, turbine fouling, piston ring wear, nozzle blockage, poor air spring, and damaged exhaust valve. Each fault condition directly influenced the turbocharger efficiency and, consequently, the air-fuel ratio supplied to the cylinders.

Cylinder indicator diagrams were recorded to compare combustion pressure development between cylinders, while emission data and SFC were extracted for each test run. These parameters provided a quantitative basis for evaluating the relationship between turbocharger efficiency, fault severity, and overall engine performance.

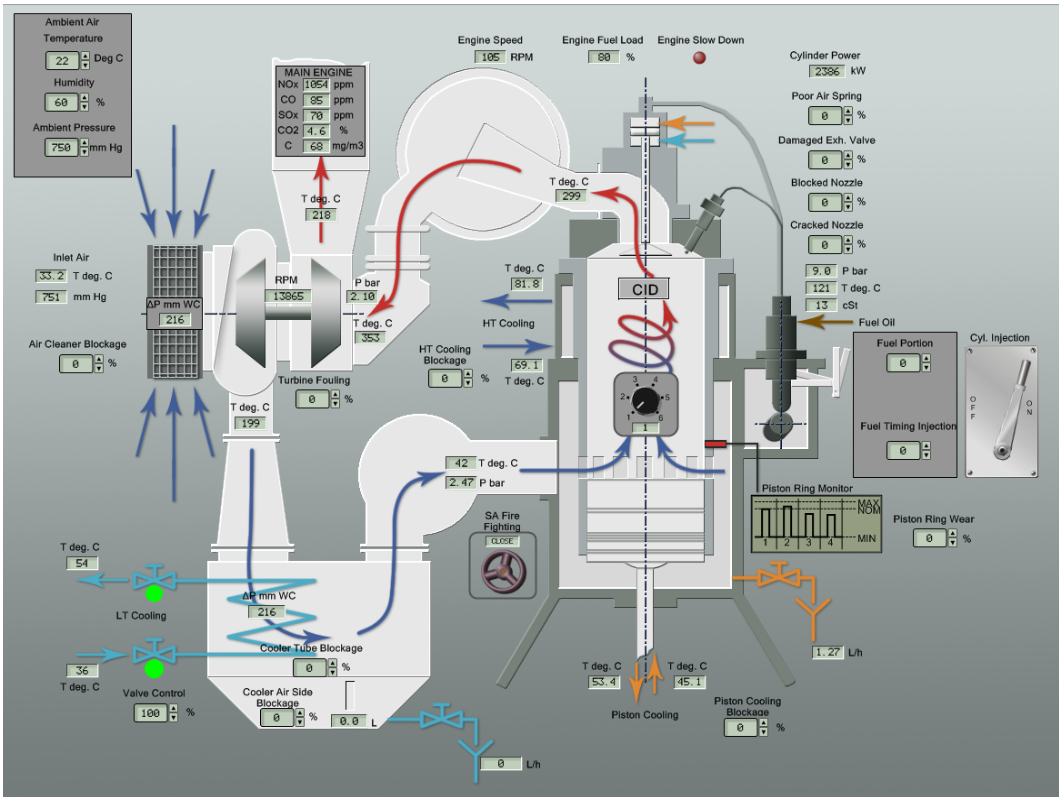

Fig. 1. Default setting of turbocharger

This study was started with the default operating condition of a marine two-stroke engine simulator such as in Figure 1. The engine runs at 105 RPM with 80% fuel load, and all fault parameters such as air cleaner blockage, cooler blockage, and component wear are set to 0%. The turbocharger operates normally.

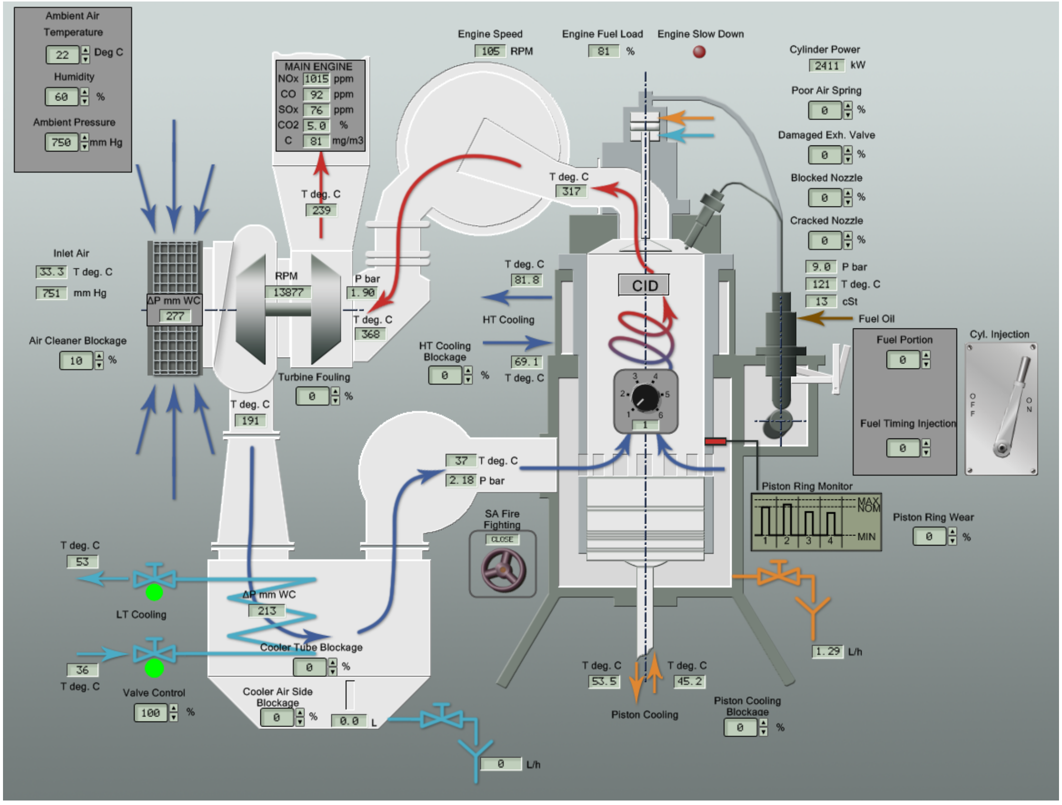

Fig. 2. Turbocharger setting with 10 % fault

This research was continued with 10 % fault of the turbocharger as presented in Figure 2. The engine runs at 105 RPM with 80% fuel load, and all fault parameters such as air cleaner blockage, cooler blockage, and component wear are set to 10%. The turbocharger operates normally.

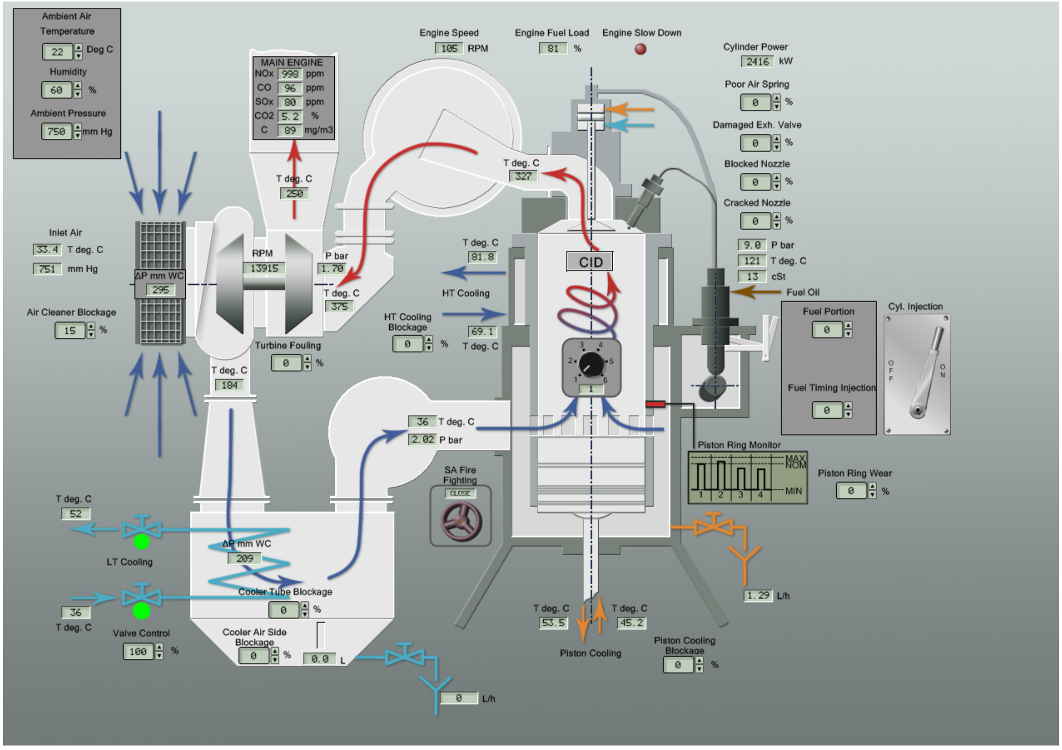

Fig. 3. Turbocharger setting with 15 % fault

In a simulated more critical situation, the turbocharger was set with 15 % fault as displayed in Figure 3. This diagram shows the default operating condition of a marine two-stroke engine simulator. The engine runs at 105 RPM with 80% fuel load, and all fault parameters such as air cleaner blockage, cooler blockage, and component wear are set to 15%. The turbocharger operates normally.

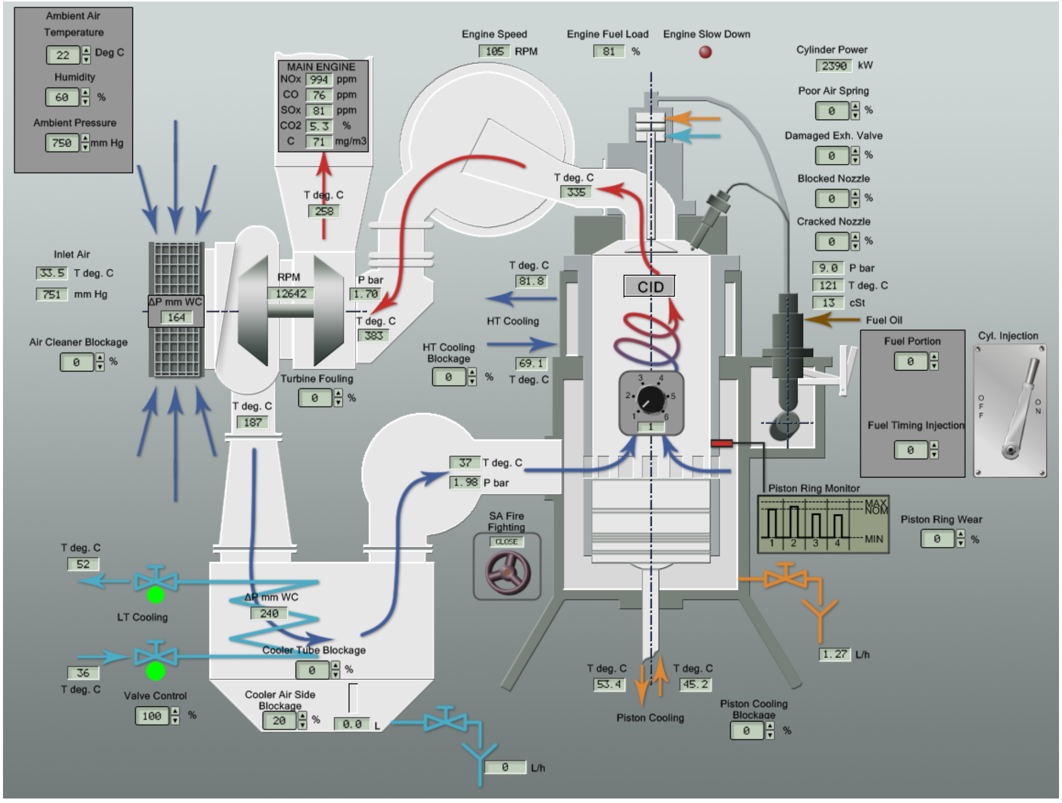

Fig. 4. Turbocharger setting with 20 % fault

In the most critical situation in this study was simulated the turbocharger with 20 % fault as portrayed in Figure 4. This diagram shows the default operating condition of a marine two-stroke engine simulator. The engine runs at 105 RPM with 80% fuel load, and all fault parameters such as air cleaner blockage, cooler blockage, and component wear are set to 20%. The turbocharger operates normally.

4. Result & Discussion

4.1 Brake-Specific Fuel Consumption (BSFC)

The simulation clearly demonstrated that turbocharger matching plays a decisive role in fuel economy. Compared with the baseline configuration, optimized settings reduced BSFC by nearly 5%, particularly in the medium to high load range (50–85%). This suggests that proper air supply and pressure balance help stabilize combustion and enhance thermal efficiency. Conversely, once turbocharger degradation was introduced, BSFC began to rise progressively, with the steepest increase observed at 20% severity. The rise in fuel consumption under higher degradation levels reflects the combined effects of reduced scavenging air and incomplete combustion, which forced the engine to burn more fuel for the same power output.

4.2 Emission Characteristics

Optimized configurations also led to measurable improvements in emission performance. NO_x emissions were reduced by as much as 12% under balanced turbocharger settings, a result of lower combustion temperatures and more efficient air–fuel mixing. However, degradation scenarios changed this trend significantly. At 10% fault severity, a slight rise in NO_x was observed, likely due to overcompensation of the turbocharger attempting to maintain pressure. With increasing degradation to 15% and 20%, emission quality deteriorated further, with noticeable rises in unburned hydrocarbons, soot, and CO. These findings emphasize that even small efficiency losses in the turbocharger can quickly compromise compliance with emission standards.

4.3 Engine Power and Performance Balance

The impact of turbocharger condition on power output was complex. At 10% degradation, engine power slightly increased to 2411 kW, which may be attributed to short-term overloading of the turbocharger. However, as faults became more severe, power declined progressively—dropping to 2400 kW at 15% severity and further to 2390 kW at 20%. The non-linear relationship between severity and power loss indicates compounded effects from reduced airflow, disturbed combustion, and additional mechanical resistance.

When different fault types were compared, blocked nozzles and damaged exhaust valves showed the sharpest decline in performance, with power falling below 1800 kW at 20% severity. In contrast, faults such as piston ring wear and cooler tube blockage had relatively minor impacts, showing only marginal variations around the baseline. The poor air spring condition presented an unusual pattern, producing a slight increase in power, though likely at the cost of higher emissions. These variations highlight that not all faults contribute equally to performance decay, underscoring the importance of fault-specific monitoring and maintenance strategies.

4.4 Overall Insights

The results collectively demonstrate that turbocharger optimization is not only about maximizing efficiency at ideal conditions but also about ensuring resilience under real-world degradation. While optimized matching can significantly reduce BSFC and NO_x, performance under fault conditions varies widely depending on the type and severity of the fault. The study suggests that one-size-fits-all solutions are insufficient. Instead, adaptive and fault-aware strategies—such as incorporating variable geometry turbochargers (VGTs) and real-time monitoring—are necessary for sustaining both fuel efficiency and compliance with IMO Tier III regulations.

Table 1
Turbocharger decay versus engine performance

Turbocharger Decay	**Power Output (kW)**	**SFC (g/kWh)**	**Scavenge Air Pressure (bar)**
0 % (Baseline)	2386	180	2.47
10 %	2411	190	2.18
15 %	2400	198	2.02
20 %	2390	206	1.88

Table 2
Effect of turbocharger performance decay on engine performance

Turbocharger Efficiency Loss	Description of Condition	Cylinder Power Response	Expected Emission Behaviour
0 % (Baseline)	Normal, optimal performance	Reference value (2386 kW)	Normal emission levels
10 %	Minor fouling	Slight increase (2411 kW)	Potential rise in NOx due to overcompensation
15 %	Moderate fouling / wear	Drop in power (2400 kW)	Increased unburnt hydrocarbon, CO
20 %	Advanced	Further drop (2390 kW)	Higher soot, HC, and CO emissions

As turbocharger efficiency decreases, engine power and emissions are affected. At 0% loss, performance is normal. A 10% loss slightly increases power but raises NOx. At 15% and 20% loss, power drops and emissions worsen, showing more CO, unburnt fuel, and soot.

Table 3
Summary of engine performance based on main engine 2 stroke diesel MAN B&W 6S60MC-C Tanker LCC with various percentages of severity

Fault	10% Severity	15% Severity	20% Severity
Air Cleaner Blockage	2411 kW	2416 kW	2390 kW
Blocked Nozzle	2259 kW	1978 kW	1719 kW
Cooler Air Side Blockage	2414 kW	2398 kW	2390 kW
Cooler Tube Blockage	2389 kW	2386 kW	2398 kW
Cracked Nozzle	2402 kW	2386 kW	2402 kW
Damaged Exhaust Valve	2297kW	2047 kW	1779 kW
Piston Ring Wear	2387 kW	2394 kW	2402 kW
Poor Air Spring	2450 kW	2416 kW	2421 kW
Turbine Fouling	2416 kW	2399 kW	2412 kW
Default setting		**2386 kW**	

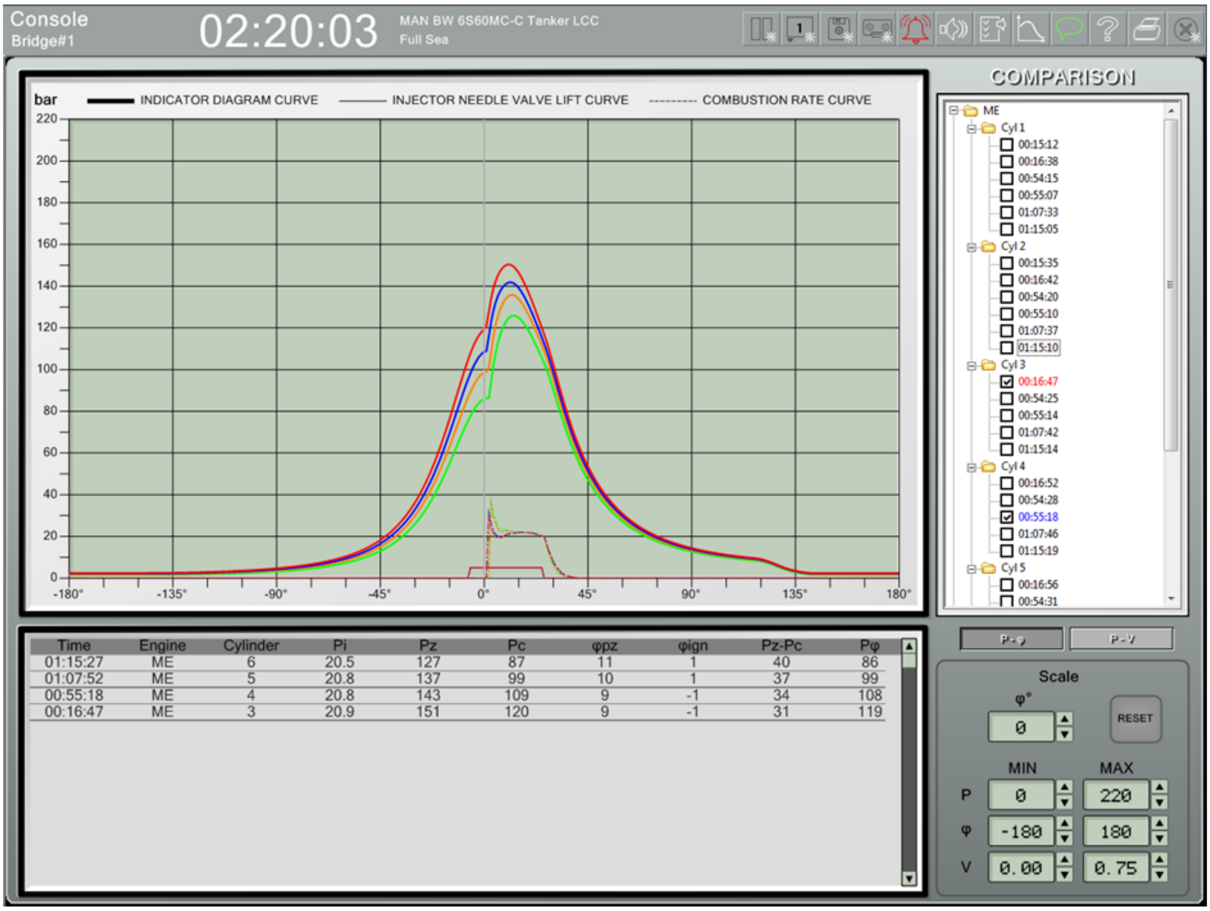

Fig. 5. Indicated power main engine 2 stroke diesel MAN B&W 6S60MC-C Tanker LCC for multi cylinder performance

The results indicate that optimized turbocharger configurations improve combustion stability and fuel efficiency, reducing BSFC and NOx emissions compared to the baseline. However, as degradation severity increases, both power output and emission performance deteriorate. At 20% degradation, significant increases in CO and unburnt hydrocarbons were observed, accompanied by a reduction in power output.

Among all simulated faults, blocked nozzles and damaged exhaust valves had the most severe effects, while piston ring wear and cooler tube blockage were less impactful. These findings highlight that not all degradation types contribute equally to performance loss, suggesting that maintenance priorities should target high-impact faults first.

From an industrial perspective, the results underscore the importance of integrating adaptive control mechanisms, such as variable geometry turbochargers (VGTs), to maintain air supply and efficiency under partial degradation. Academically, the findings provide reference data for enhancing fault-aware optimization models and simulation-based diagnostic systems.

5. Conclusion

This study confirmed that turbocharger matching and health condition have a direct and measurable influence on marine diesel engine performance, fuel economy, and emissions. By applying the TRANSAS engine room simulator, multiple degradation scenarios were introduced to assess their effects on power output, brake-specific fuel consumption, and pollutant formation. The results demonstrated that optimized turbocharger configurations can reduce BSFC by up to 5% and NO_x emissions by as much as 12% relative to baseline operation, indicating that simulation-based parameter matching can be a cost-effective strategy for achieving both fuel efficiency and emission compliance.

However, the findings also clearly show that turbocharger deterioration poses a significant risk to engine efficiency. Degradation levels above approximately 15% led to noticeable increases in BSFC and pollutant emissions, with blockage- and fouling-related faults producing the most severe impacts. In contrast, faults such as minor cooler fouling exhibited comparatively limited performance penalties. These outcomes highlight the need for prioritizing maintenance schedules and condition monitoring, as not all forms of turbocharger wear contribute equally to performance decline.

Overall, this research demonstrates that practical turbocharger optimization must move beyond idealized assumptions and instead incorporate fault-aware matching strategies. The significance of this work lies in showing how adaptive matching approaches can partially mitigate performance losses under non-ideal health conditions, enabling operators to maintain efficiency and meet IMO Tier III constraints even when turbocharger performance deviates from factory-new status.

Nevertheless, several limitations must be acknowledged. The analysis is based primarily on simulation rather than full-scale experimental validation, and transient load variations—which play a critical role in real operating profiles—were not included. Future work should therefore integrate real-engine verification, incorporate dynamic load transition behavior, and explore hybrid or variable-geometry turbocharging systems. In addition, combining adaptive turbocharger control with machine learning–based fault detection could support predictive maintenance and further enhance operational reliability and efficiency.

This study is limited by its reliance on simulation-based results and the focus on steady-state operating conditions, which may not fully represent real engine behaviors under variable sea and load conditions. Future work should include experimental validation on operating engines, extend the analysis to transient load changes, and examine advanced turbocharging technologies such as variable geometry or electrically assisted systems. Integrating predictive maintenance and data-driven fault detection models is also recommended to support real-time operational optimization.

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Declaration of generative AI and AI-assisted technologies in the writing process
During the preparation of this manuscript, the author(s) used OpenAI's ChatGPT to assist in improving the readability and language of the text. All content generated by ChatGPT was subject to thorough review, editing, and revision by the author(s) to ensure its accuracy, completeness, and alignment with the research objectives. The author(s) take full responsibility for the integrity and content of the published work.

References

[1] Shen, H., Yang, F., Jiang, D., Lu, D., Jia, B., Liu, Q., & Zhang, X. (2024). "Parametric Investigation on the Influence of Turbocharger Performance Decay on the Performance and Emission Characteristics of a Marine Large Two-Stroke Dual Fuel Engine." Journal of Marine Science and Engineering 12(8):1298. https://doi.org/10.3390/jmse12081298

[2] Nyongesa, A. J., Park, M. H., Lee, C. M., Choi, J. H., Pham, V. C., Hur, J. J., & Lee, W. J. 2024. "Experimental evaluation of the significance of scheduled turbocharger reconditioning on marine diesel engine efficiency and exhaust gas emissions." Ain Shams Engineering Journal 15 (8): Article 102845. DOI: 10.1016/j.asej.2024.102845

[3] Li, B., Liu, Y., Wang, J., Chen, H., and X. Zhao. 2025. "A Health Condition Assessment Method for Marine Diesel Engine Turbochargers Using a Zero-Dimensional Engine Model and Machine Learning." Measurement 251: 117283. https://doi.org/10.1016/j.measurement.2024.117283

[4] Tadros, M., & Boulougouris, E. (2025). Calibration Procedures for NO_x Emissions Model of a High-Speed Marine Diesel Engine Using Optimization Procedures. Journal of Marine Science and Engineering, 13(8), 1585.

[5] Meng, C., Chen, K., Chen, T., & Ju, J. (2025). Dual Turbocharger and Synergistic Control Optimization for Low-Speed Marine Diesel Engines: Mitigating Black Smoke and Enhancing Maneuverability. Energies, 18(11), 2910. https://doi.org/10.3390/en18112910

[6] Zhang, Y., Zhang, F., Leng, L., & Ren, Z. (2023). Matching and optimization to minimize fuel consumption and NO_x emission for a marine diesel engine with turbo-assisted exhaust gas recirculation. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 239(2-3).

[7] Ceylan, B. O. (2023). Investigation of Seasonal Effects on Two-Stroke Marine Diesel Engine Performance Parameters and Emissions. Journal of Marine Science & Application, 22, 795–808.

[8] Mizythras, Panagiotis, Evangelos Boulougouris, and Gerasimos Theotokatos. 2021. "A Novel Objective-Oriented Methodology for Marine Engine–Turbocharger Matching." International Journal of Engine Research 23 (12): 14680874211039705. https://doi.org/10.1177/14680874211039705

[9] Salazar, A. A., Salameh, G., Chesse, P., Bulot, N., & Thevenoux, Y. 2024. "Impact of Optimization Variables on Fuel Consumption in Large Four-Stroke Diesel Marine Engines with Electrically Divided Turbochargers." Machines 12 (12): 926. DOI link: https://doi.org/10.3390/2075-1702/12/12/926

[10] Chen, M., et al. (2024). Research on Fault Diagnosis Method for Marine Diesel Engines. Journal of Marine Science & Engineering, 12(12), 2348. Large Marine Engine Technology Evaluation Final Report. (2025). EPA Report.

[11] Mousavi, S., Nejat, A., Alaviyoun, S.S., and M. Nejat. 2021. "An Integrated Turbocharger Matching Program for Internal Combustion Engines." Journal of Applied Fluid Mechanics 14 (4): 1209-1222. https://doi.org/10.47176/jafm.14.04.32037

[12] Orhan, M., and M. Celik. 2024. "A Literature Review and Future Research Agenda on Fault Detection and Diagnosis Studies in Marine Machinery Systems." Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 238 (1). https://doi.org/10.1177/14750902221149291

[13] Zinage, Shrenik, Suyash Jadhav, Yifei Zhou, Ilias Bilionis, and Peter Meckl. 2022. "Data Driven Modeling of Turbocharger Turbine Using Koopman Operator." IFAC-PapersOnLine 55 (37): 175–180. https://doi.org/10.1016/j.ifacol.2022.11.180