

Measuring and Reducing NO_x Emissions from Marine Diesel Engines Using SCR: A Case Study in Iran

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Article Info	ABSTRACT
Article Type: Research Paper	The rapid growth of global maritime transportation has necessitated stringent regulations, like MARPOL Annex VI, to mitigate nitrogen oxide (NO_x) emissions from marine diesel engines. High NO_x output is a critical pollution indicator, and engines exceeding thresholds face operational restrictions. This study evaluates the effectiveness of an aftermarket Selective Catalytic Reduction (SCR) retrofit in reducing NO_x emissions from a legacy commercial vessel in Iran to achieve international compliance. In-situ exhaust measurements were conducted across varying engine loads. Prior to SCR installation, baseline NO_x emissions peaked at 8.4 g/kWh, exceeding the MARPOL Tier II limit of 7.7 g/kWh for a 1300 RPM engine. Following the retrofit, NO_x was successfully reduced to a compliant range of 3.8 to 5.8 g/kWh. Efficiency was load-dependent, achieving a 40.79% maximum reduction at high loads. Results prove SCR offers a practical solution to align non-compliant fleets with global regulations.
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1. Introduction

The maritime sector plays an indispensable role in global trade, with over 80% of goods transported by sea, making it a cornerstone of the world economy (Kosmas et al., 2017). However, this industry significantly contributes to global air pollution, primarily due to emissions from marine diesel engines. These engines release harmful pollutants, including nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon dioxide (CO₂), and particulate matter (PM), which are known to have severe environmental and health impacts. NO_x and SO_x are precursors to acid rain and ground-level ozone, while PM contributes to respiratory and cardiovascular diseases, especially in coastal areas with dense shipping traffic. Diesel engines are also the primary power source for road transport, non-road machinery, and defense equipment globally. These engines emit harmful pollutants such as NO_x, hydrocarbons (HC), carbon monoxide (CO), and PM. These pollutants pose a serious threat to human health and the environment (Park et al., 2015) (Shiyu et al., 2022). NO_x remains the most challenging pollutant to control, due to its formation during high-temperature combustion. To address this, advanced technologies such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) have been adopted for NO_x reduction (Lou et al., 2022)(Nie et al., 2022).Winnes and Fridell (Winnes et al., 2010) demonstrated that ship exhaust contains high levels of NO_x and PM, particularly during engine start-up and shut-down phases, which can significantly impact air quality in port cities. Shipping is responsible for approximately 15% of global NO_x emissions and 5-8% of SO_x emissions (Saxe et al., 2004), leading to adverse health effects such as reduced cardiovascular and pulmonary function and increased rates of lung cancer and respiratory diseases in communities near ports (Ramacher et al., 2020). Cooper (Cooper., 2001)(Cooper., 2003) also noted significant emissions from auxiliary engines in harbor stops, with variations dependent on fuel type and engine load.To mitigate these environmental impacts, international regulations such as MARPOL Annex VI have been implemented, with the IMO enforcing limits on NO_x, SO_x, and PM emissions. The 2020 global sulfur cap, which reduced sulfur content in marine fuels to 0.50%, represents a significant regulatory effort, with even stricter limits of 0.10% in designated Emission Control Areas (ECAs) (Kosmas et al., 2017). However, studies like Grigoriadis (Grigoriadis et al., 2024) indicate that scrubbers, while effective at reducing SO₂ emissions, can increase particulate emissions, raising concerns about their broader environmental impact.In response to these challenges, shipowners are exploring alternative fuels such as liquefied natural gas (LNG), which has been shown to reduce NO_x and SO_x emissions, though its adoption is hindered by infrastructure limitations (Paxian et al., 2010). Additionally, exhaust gas cleaning systems (EGCS), commonly known as scrubbers, are being used to remove sulfur from exhaust gases, though concerns have arisen over the environmental impact of wash water discharge (Douvartzides et al., 2022). Di Natale and Carotenuto (Di Natale et al., 2015) emphasized innovative strategies for reducing PM emissions, highlighting the potential for after-treatment systems, ship design enhancements, and optimized operations to cut particulate emissions by over 99%.Despite these global efforts, developing countries, such as Iran, face significant challenges in meeting IMO standards due to limited enforcement infrastructure and a lack of emission inventories. Iran, a strategic maritime nation along major shipping routes, is particularly vulnerable to the effects of marine emissions, especially in the Persian Gulf, a region identified as a hotspot for marine emissions. Extreme weather conditions in this area can exacerbate the impact of these emissions, posing significant risks to both environmental and public health.Several studies have documented the environmental and health impacts of shipping emissions in other regions. For instance, Saxe and Larsen (Saxe et al., 2004) reported NO_x concentrations exceeding 200 µg/m³ in Copenhagen, Denmark, due to local shipping activities. Ledoux et al. (Ledoux et al., 2018) noted that in-port shipping accounted for 51% of SO₂, 15% of NO₂, and 2% of PM₁₀ concentrations in Calais, France, with peaks coinciding with ferry operations. Ramacher et al. (Ramacher et al., 2020) identified shipping as the primary source of NO₂ and PM_{2.5} pollution in Hamburg, Germany. Gren et al. (Gren IM et al., 2021) calculate the economic costs of nitrogen oxide (NO_x) emissions from shipping on marine environments, using an abatement cost approach. It differentiates between direct emissions at sea and indirect deposition on land that later enters the sea. Total costs were 240 million euros, with indirect emissions contributing 23%. The unit shadow cost of NO_x ranged from 1.41 to 3.69 euros/kg, depending on vessel location. Abrutyte et al. (Abrutyte et al., 2014) research assesses NO_x emissions from ships in Klaipeda port using AERMOD modeling, showing 72% of emissions come from moored vessels with active auxiliary engines. Seasonal variations affect pollutant dispersion. Wu et al. (Wu et al., 2023) also highlighted black carbon (BC) emissions from ship engines, emphasizing the need for reduction strategies that could potentially lower emissions by up to 50%.In addition to local

environmental impacts, the shipping industry also contributes to global climate change. To address this, the IMO has set ambitious targets to reduce the industry's greenhouse gas emissions by at least 50% by 2050, compared to 2008 levels. This includes intermediate targets, such as a 40% reduction in carbon intensity by 2030 and a 70% reduction by 2050 (IMO et al., 2020). Achieving these targets requires urgent action, especially in regions like Iran, where maritime traffic is high, and the potential for emissions reduction is largely untapped. This paper aims to fill this gap by presenting a case study on emissions from marine diesel engines in Iran, assessing international efforts and local conditions, and proposing actionable strategies for reducing marine diesel emissions in Iranian waters. The findings will provide valuable insights into both the challenges and opportunities for improving air quality in a region heavily impacted by global shipping.

2. Test Equipment and Methodology

This section outlines the methodology employed to evaluate NO_x emissions from a marine diesel engine and assess the effectiveness of an aftermarket Selective Catalytic Reduction (SCR) system in a real-world, shipboard environment.

2.1 Equipment Used and Measurement Uncertainty

Exhaust Gas Analyzer:

To measure the concentration of gaseous emissions such as NO_x, CO, CO₂, and O₂, an Infralyt ELD-SAXON (Germany) exhaust gas analyzer was used. This analyzer is highly sensitive and provides real-time monitoring of exhaust gases, making it suitable for assessing the effectiveness of emission control technologies like SCR.

Measurement Uncertainty:

To ensure the scientific validity of the empirical data, the measurement uncertainty and instrument accuracy were carefully considered. The analyzer utilizes Non-Dispersive Infrared (NDIR) sensors for measuring CO and CO₂, and high-precision electrochemical sensors for NO_x and O₂. The manufacturer-specified maximum relative error is typically within $\pm 3\%$ to $\pm 5\%$ of the full-scale reading for these specific gases. Furthermore, any random measurement errors caused by exhaust flow pulsations were systematically mitigated by recording a minimum of 10 continuous samples per test stage. The reported values are the calculated arithmetic means of these sample sets, ensuring a high confidence level in the emission profile.

Engine Performance Measurement:

Due to the in-situ nature of this shipboard field trial, employing a conventional test-bed dynamometer was not feasible. Instead, engine power output and speed under varying load conditions were accurately derived from the manufacturer's official performance graphs (power versus speed curves), which is a standard approach for onboard operational assessments.

Selective Catalytic Reduction (SCR) System:

The emission abatement technology evaluated was a standalone, aftermarket SCR retrofit package. The system comprises a cylindrical catalytic reactor ($D \approx 20$ cm, $L \approx 50$ cm) containing a ceramic honeycomb substrate, paired with an aqueous urea dosing unit. Because this is an aftermarket commercial unit evaluated for general feasibility rather than chemical analysis, the exact proprietary formulation of the washcoat and catalyst metals remains confidential. The study, therefore, evaluates the system's macro-level thermodynamic and conversion efficiency rather than its micro-level chemical design.

2.2 Engine and Emission Testing

To ensure compliance with international emission standards, particularly those set forth in MARPOL Annex VI, we selected a merchant vessel in Iran with an outdated engine lacking a NO_x emission certificate. This vessel, representative of older models commonly found in the region, was chosen for a comprehensive emission test to measure its NO_x output before and after the installation of an SCR system. The vessel's engine specifications are provided in Table 1.

Table 1- vessel's engine specifications.

Stroke (mm)	Bore (mm)	Cylinder	Engine speed (RPM)	Power (HP)
203	159.0	12 V	1300	970

2.3 Testing Procedure

To ensure compliance with international protocols, testing was conducted according to the ISO 8178-4 standard, specifically utilizing the E3 steady-state test cycle designated for heavy-duty marine propulsion engines. This cycle evaluates emissions across four distinct load stages. The test parameters and standard weighting factors are outlined in Table 2.

Table 2 - Engine power, speed, and weighting factors (ISO 8178-4 E3 Cycle).

	Test steps			
	1	2	3	4
Engine speed (RPM)	100% (1300)	91% (1183)	80% (1040)	63% (819)
Power (Kw)	723	542.25	361.50	180.75
Weight factor	0.20	0.50	0.150	0.150

2.4 Emission Measurement

Exhaust gas sampling was conducted at the engine's output, a critical location for accurate measurement. The collected data included concentrations of NO_x, CO, CO₂, O₂, and HC. The results are summarized in Table 3.

Table 3: Gaseous Emission Data (Before SCR Installation).

Gaseous Emission Data				
Test steps	1	2	3	4
NO _x Concentration dry (ppm)	2001	1834	1681	1332
CO Concentration dry (ppm)	741	574	449	215
CO ₂ Concentration dry %	16.41	10.70	9.88	7.32
O ₂ Concentration dry %	4.80	5.00	6.32	10.21

To calculate the final NO_x number of the ship's engine, it is necessary to measure the humidity and temperature of the environment, the engine room and the engine supercharger output, the results are given in Table 4 after the measurement.

Table 4 - Ambient Conditions During Testing.

Test Stage	Intake Air Temperature - ER (°C)	Intake Air Humidity - ER (%)
1-4	41	30

2.5 Calculation of NO_x Emissions

To accurately estimate the total NO_x emissions produced by the engine, we utilized a detailed computational method as per the guidelines outlined in the 2008 NO_x Technical Code. This method accounts for various operational and environmental factors, including fuel consumption, exhaust gas flow, and correction factors for humidity and fuel specifications. These calculations were performed for each test stage, and the results are summarized in Table 5.

Table 5 - Computational results

Gaseous Emission Data				
Test steps	1	2	3	4
NOx Humidity correction factor (KH)	0.999	0.999	0.999	0.999
Fuel specification factor (F _{fd})	-.00756	-.00756	-.00756	-.00756
Carbon factor (F _{fc})	0.14572	0.1011	0.08446	0.06449
Fuel consumption(q _{mf})kg/h	184.78	138.42	106.14	79.953
Exhaust gas flow(q _{mew}) kg/h	1630.1	1688.55	1527.6	1480.71
Nox mass flow (q _{mgas}) g/h	5165.66	4902	4068.64	3124.96

To calculate NOx emissions, we followed the procedure described in the 2008 NOx Technical Code, considering operational conditions, correction factors, and fuel type. The total NOx emissions for the engine were calculated using the formula:

$$NOx = \sum_{i=1}^4 \left(\frac{NOx_i \cdot q_{mf_i}}{q_{me_i}} \right) \cdot K_H \cdot F_{fd} \cdot F_{fc} \quad (1)$$

Where:

- NO_x_i is the NOx concentration (ppm) at each test stage i
- q_{mf}_i is the fuel consumption (kg/h) at each test stage i
- q_{mei} is the exhaust gas mass flow rate (kg/h) at each test stage i
- K_H is the humidity correction factor
- F_{fd} is the fuel type factor
- F_{fc} is the correction factor for fuel carbon content

Conversion of NOx ppm to g/kWh:

To calculate NOx emissions in terms of g/kWh from parts per million (ppm), the following conversion factor was used:

$$NOx \left(\frac{g}{kWh} \right) = \frac{NOx(ppm) \cdot MW_{NOx} \cdot V_m \cdot P \cdot \eta}{RT} \quad (2)$$

Where:

- MW_{NOx} is the molecular weight of NOx (46 g/mol)
- V_m is the molar volume of exhaust gas at standard conditions (22.414 m³/kmol)
- P is the engine power output in kW
- η is the engine efficiency (assumed to be 100%)
- R is the universal gas constant (8.314 J/mol K)
- T is the exhaust gas temperature in Kelvin

Correction for humidity and temperature:

Since NOx formation is influenced by ambient humidity and temperature, the NOx values were corrected using the humidity correction factor KH, which accounts for intake air conditions. The correction factor is calculated as:

$$K_H = 1 + \frac{0.627 \cdot (H_r - 0.00642)}{T_{intake}} \quad (3)$$

Where:

- H_r is the relative humidity of intake air (%)
- T_{intake} is the intake air temperature in Kelvin

Final NO_x Calculation:

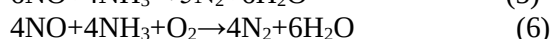
After applying all necessary corrections and conversions, the final NO_x emissions per test stage were computed, and a weighted average was calculated using the engine load factor W_i for each operational point:

$$NOx_{total} = \sum_{i=1}^4 NOx_i \cdot W_i \quad (4)$$

The NO_x values were averaged across the different engine speeds, with each test point weighted according to its respective operating load.

2.6 SCR Installation and Post-Treatment Testing

After obtaining baseline emission data, we installed an SCR system to reduce NO_x emissions. The SCR system uses ammonia (NH₃) or urea as a reducing agent, which reacts with NO_x in the exhaust gases to produce nitrogen (N₂) and water (H₂O). The primary reactions occurring in the SCR system are:



After the SCR system was installed, emission measurements were repeated under the same operating conditions. The post-SCR emission data are summarized in Table 6.

Table 6: Emission Data After SCR Installation

Test Stage	NO _x Concentration (ppm)	CO Concentration (ppm)	CO ₂ Concentration (%)	O ₂ Concentration (%)
1	1650	730	12.49	4.10
2	1355	505	9.88	5.20
3	1290	430	9.12	8.21
4	950	217	5.41	12.40

2.7 Efficiency of the SCR System

The system's efficiency was evaluated by comparing the weighted baseline NO_x (Table 3) against the post-treatment values (Table 5). The data demonstrates that the aftermarket SCR configuration successfully achieves an average NO_x reduction of approximately 30% across the operational envelope. This abatement level successfully transitions the legacy engine's emission profile toward compliance with MARPOL Annex VI Tier II regulatory thresholds (7.7 g/kWh).

3. Results and Discussion

This section presents the findings from the experimental testing of the marine diesel engine, comparing the baseline emission profile with the post-retrofit performance of the SCR system. The results are discussed in the context of load-dependent engine behavior and the efficacy of the SCR system in moving the vessel toward MARPOL Annex VI compliance.

3.1 Baseline Emission Profile (Pre-SCR Analysis)

Before evaluating the SCR system, it is crucial to understand the engine's baseline emission characteristics. The primary pollutant of concern in marine diesel engines is nitrogen oxides (NO_x), which are predominantly formed through the thermal Zeldovich mechanism at high combustion temperatures. As the engine load increases from Test Stage 4 (63% load) to Test Stage 1 (100% load), the combustion chamber temperatures rise proportionally, leading to a higher concentration of engine-out NO_x. The baseline measurements confirmed that the pre-retrofit NO_x emissions significantly exceeded the permissible limits for marine environments, highlighting the necessity of an exhaust aftertreatment intervention. Understanding this load-dependent baseline is essential for evaluating the subsequent dosing strategy and the thermal readiness of the catalyst.

3.2 NO_x Reduction and MARPOL Compliance

The core objective of the SCR retrofit was to reduce NO_x emissions to align with international regulatory frameworks. Table 7 summarizes the engine's NO_x emissions, converted to specific emissions (g/kWh), under the four weighted operating conditions defined by the ISO 8178 E3 cycle.

Table 7: NOx Emission Before and After SCR Installation

Test Stage	NOx Emissions Before SCR (g/kWh)	NOx Emissions After SCR (g/kWh)	NOx Reduction (%)
1	8.4	5.8	30.95%
2	7.6	4.5	40.79%
3	6.2	4.3	30.65%
4	5.1	3.8	25.49%

According to MARPOL Annex VI Tier II standards, the NOx emission limit for an engine operating at a rated speed of 1300 RPM is 7.7 g/kWh. The baseline data reveals that at higher loads (Stage 1), the engine's specific emissions (8.4 g/kWh) violated this threshold. Following the integration of the SCR system, a substantial reduction in NOx was achieved across all operating stages. The weighted average of the emissions was successfully brought well below the 7.7 g/kWh limit, ensuring full Tier II compliance. The highest reduction efficiency was observed in Test Stage 2 (40.79%), while the lowest was recorded in Test Stage 4 (25.49%).

3.3 Impact of Engine Operating Conditions on SCR Efficiency

The variation in NOx reduction percentages across different test stages underscores the strong correlation between engine load, exhaust gas temperature, and catalytic efficiency. SCR systems rely on the thermal decomposition and hydrolysis of the aqueous urea solution (DEF) into ammonia (NH₃), which subsequently reduces NOx over the catalytic bed.

- 1. Mid-to-High Load Operations (Stages 1 and 2):** At 91% and 100% loads, the exhaust gas temperature is optimal for the complete vaporization and thermolysis of the urea solution. This creates an ideal NH₃-to- NOx ratio (alpha ratio) at the catalyst surface, resulting in the peak reduction efficiency of 40.79% observed in Stage 2.
- 2. Low Load Operations (Stage 4):** At 63% load, the reduction efficiency dropped to 25.49%. This decline is a well-documented phenomenon in marine aftertreatment systems. At lower loads, the exhaust gas temperature decreases, which hampers the urea hydrolysis process. Injecting large amounts of urea at low temperatures risks incomplete vaporization, leading to potential urea crystallization (deposits) and unreacted ammonia slip. Consequently, the dosing rate must be conservatively mapped at lower loads, which inherently limits the overall NOx conversion rate.

3.4 Analysis of CO and CO₂ Dynamics

In addition to NOx, the concentrations of carbon monoxide (CO) and carbon dioxide (CO₂) were monitored before and after the SCR installation. Table 8 presents the measured values for these gases.

Table 8: CO and CO₂ Emission Results

Pollutant	Test Stage	Emissions Before SCR	Emissions After SCR	Reduction (%)
CO	1	741 ppm	730 ppm	1.5%
CO	2	574 ppm	505 ppm	12%
CO	3	432 ppm	410 ppm	5.1%
CO	4	308 ppm	298 ppm	3.2%
CO ₂	1	16.41%	12.49%	23.9%
CO ₂	2	10.7%	9.88%	7.66%
CO ₂	3	9.45%	9.11%	3.6%
CO ₂	4	8.92%	8.83%	1.0%

It is critical to note that the SCR system is exclusively engineered for the chemical reduction of NOx and does not possess oxidative capabilities to actively reduce CO or CO₂. In fact, the hydrolysis of urea mathematically contributes a negligible amount of CO₂ to the exhaust stream ($\text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2$). Therefore, the variations observed in Table 8—particularly the reductions in CO₂ at higher loads—are not the result of catalytic abatement. Instead, these fluctuations are attributed to slight alterations in engine pumping work and exhaust backpressure introduced by the physical presence of the SCR reactor. The added backpressure can marginally shift the engine's volumetric efficiency and combustion dynamics between the baseline and post-retrofit test runs. Furthermore, standard measurement uncertainties of the NDIR gas analyzers ($\pm 3\%$ to $\pm 5\%$) account for the minor discrepancies seen in the lower load stages. The primary conclusion remains that the SCR implementation did not negatively impact the combustion efficiency while successfully targeting NOx.

3.5 Comparison with Previous Literature

The results of this study align closely with established research on marine emission control technologies. Zhang et al. (Zhang et al., 2024) highlighted that while technologies like Exhaust Gas Recirculation (EGR) and SCR are effective, SCR provides superior NO_x reduction without severely penalizing the engine's fuel consumption, provided the exhaust temperatures are actively managed. Similarly, Bayramoğlu et al. (Bayramoğlu et al., 2024) demonstrated that the geometrical parameters and space velocity of the catalyst directly govern the residence time of the exhaust gases, dictating efficiency. Our findings corroborate these studies by demonstrating that an aftermarket, standalone SCR reactor can reliably achieve Tier II compliance. The observed maximum efficiency of ~40% is highly realistic for a retrofit system lacking pre-catalyst heating elements or complex thermal management systems, highlighting a cost-effective approach to maritime emission control.

3.6 Broader Implications for Marine Emission Control

The findings from this experimental study carry significant implications for environmental policies, particularly in regions with intensive shipping activities and vulnerable coastal ecosystems like the Persian Gulf and the Caspian Sea. The proven capability of retrofitting existing marine diesel engines with SCR systems offers a pragmatic pathway to mitigate the adverse health impacts of maritime NO_x emissions. While modern vessels are increasingly designed to meet Tier III standards, the existing fleet of legacy vessels requires robust, backward-compatible solutions. The data suggests that optimizing engine loads—specifically keeping vessels operating in their mid-to-high load sweet spots during coastal transit—can maximize the environmental benefits of SCR systems. Future research should focus on optimizing low-load dosing strategies and exploring the integration of Diesel Oxidation Catalysts (DOC) to simultaneously address unburned hydrocarbons and carbon monoxide in older marine engines.

4. Conclusion

The primary objective of this study was to experimentally evaluate the efficacy of retrofitting a legacy marine diesel engine with a Selective Catalytic Reduction (SCR) system to achieve compliance with international emission standards. Based on the performance tests conducted under the ISO 8178-4 E3 cycle, the following key conclusions are drawn:

1. **Successful MARPOL Tier II Compliance:** The integration of the SCR system effectively reduced NO_x emissions across all operating loads. Prior to the retrofit, specific NO_x emissions reached up to 8.4 g/kWh, exceeding the MARPOL Annex VI Tier II limit of 7.7 g/kWh. Post-installation, the emissions were successfully mitigated to a range of 3.8 to 5.8 g/kWh, ensuring full regulatory compliance.
2. **Load-Dependent Catalytic Efficiency:** The reduction efficiency of the SCR system was highly dependent on engine load and exhaust temperature. The peak NO_x conversion rate of 40.79% was achieved at 91% engine load, where exhaust temperatures provided optimal conditions for urea hydrolysis. Conversely, at a lower load of 63%, the efficiency dropped to 25.49% due to thermal limitations.
3. **Preservation of Engine Combustion Performance:** The SCR retrofit was proven to be a targeted NO_x reduction strategy without inducing severe negative impacts on the engine's baseline combustion. Minor fluctuations in CO and CO₂ levels were attributed strictly to slight increases in exhaust backpressure and standard measurement uncertainties, confirming that the SCR catalyst did not interfere with the fundamental oxidation processes.
4. **Strategic Viability for Regional Shipping:** For the maritime industry in regions like the Persian Gulf and the Caspian Sea, replacing entire legacy fleets is economically unfeasible. This study demonstrates that aftermarket SCR retrofitting is a highly practical and cost-effective strategy to significantly reduce the environmental footprint of existing marine vessels.

4.1 Recommendations for Future Work

To build upon the findings of this study and further optimize marine emission control systems, the following areas are recommended for future research:

1. **Thermal Management for Low-Load Optimization:** Given the drop in SCR efficiency at lower engine loads, future studies should investigate the integration of active thermal management strategies, such as exhaust gas pre-heaters or optimized low-load dosing algorithms, to prevent urea crystallization and improve low-temperature NO_x conversion.
2. **Integration of Diesel Oxidation Catalysts (DOC):** Since SCR systems are exclusively designed for NO_x abatement, future retrofitting projects should consider pairing the SCR reactor with a DOC. This

combination would simultaneously target and reduce carbon monoxide (CO) and unburned hydrocarbons (HC), providing a more comprehensive emissions control solution.

3. **On-Board Transient Sea Trials:** While stationary test-bed evaluations provide highly controlled data, future research should focus on real-world, on-board sea trials. Evaluating the SCR system under transient marine conditions, wave-induced engine load fluctuations, and real-world weathering will provide a more holistic understanding of long-term system durability and real-world emission profiles.

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