



Analysis of Exhaust Emission Reduction with Marine Fuel Additives

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ABSTRACT

The shipping industry and shipowners are facing challenges in reducing exhaust gas emissions while maintaining efficient fuel and energy consumption. In the maritime decarbonization process, the focus is on alternative marine fuels that have the potential to achieve sustainable and green shipping. However, their implementation process is not easy due to high cost, handling and storage complications, and availability issues. This research analyses additives in marine diesel fuels and their impact on the emission reduction process. The analysis focuses on a comparison between traditional additives and SulNOx marine additive, a fuel conditioner product that is relatively new to the maritime sector. The key benefits of SulNOx are emission reductions, an improved combustion process (more efficient combustion), lower fuel consumption, improved lubricity and reduced carbon deposits on cylinder liner and piston rings. A more efficient combustion process is achieved with the secondary atomization method due to the presence of glycol ether in the additive, which also reduces soot formation in the cylinder, resulting in reduced particulate matter emissions. In terms of economic aspects and energy efficiency, SulNOx's fuel savings could improve the Carbon Intensity Indicator (CII) of a ship and could reduce EU ETS costs. The average fuel savings and CO₂ reduction in metric tons per year are presented with a simple calculator, where users can gain insight into how much savings they may achieve when using SulNOx.

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1. Introduction.

Marine diesel engines remain the predominant propulsion technology in shipping owing to their high efficiency, robustness, and suitability for long-distance transport. Nevertheless, their combustion process generates carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), unburned hydrocarbons (HC), including methane (CH₄), and particulate matter (PM), all of which adversely affect environmental quality and human health (Grigoriadis et al., 2026). In response to these impacts, a range of policy measures has been introduced to reduce emissions from the maritime sector (Roy & Chakraborty, 2025). The International Maritime Organization (IMO) has established both global and regional limits on fuel sulphur content, including the 0.1% sulphur limit

in Sulphur Emission Control Areas (SECAs). Nitrogen oxide emissions are primarily regulated through engine certification standards, with additional requirements applying in designated Nitrogen Emission Control Areas (NECAs). The IMO's revised long-term greenhouse gas strategy, adopted in 2023, sets the ambition of achieving net-zero emissions from international shipping by around 2050, with indicative checkpoints for 2030 and 2040 relative to 2008 levels. In parallel, regional instruments such as the European Union Emissions Trading System and the FuelEU Maritime regulation are increasing the regulatory pressure on shipping companies, cargo owners, and financial institutions to monitor and reduce emissions (Xu & Liu, 2026). The tightening of regulatory requirements is expected to accelerate the adoption of cleaner maritime technologies and fuels in the coming years (Aakko-Saksa et al., 2023). Accordingly, fuel transition has emerged as one of the principal pathways toward maritime decarbonization. Alternative marine fuels, including methanol, ammonia, hydrogen, liquefied natural gas, and biofuels, are increasingly investigated as

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potential long-term options for reducing both air pollutant and greenhouse gas emissions. However, their widespread implementation remains constrained by high costs, limited bunkering and storage infrastructure, and technical and safety-related challenges (Foretich et al., 2021). Consequently, exhaust aftertreatment and combustion optimization continue to be important strategies for emissions mitigation in existing marine engines. Among these approaches, fuel additives have attracted growing attention because they may improve combustion efficiency, reduce fuel consumption, and lower exhaust emissions (Mahi et al., 2025).

2. Methodology.

The present study examines the effects of marine fuel additives, with particular emphasis on their potential to reduce emissions, improve fuel efficiency, and enhance engine performance. This work also introduces the ongoing project “Smart Emissions,” which aims to reduce exhaust gas emissions and optimize the energy efficiency of passenger ships. Within the framework of this project, the SulNOx additive is being evaluated on two diesel engines and on a Ro-Pax vessel to assess its applicability in marine environments. Concurrently, a systematic review of relevant scientific literature is being conducted to establish a robust comparative framework for interpreting the results obtained with SulNOx.

In the study by Zadrąg et al. (2026), biodegradable additives are being tested on a Sulzer 6AL20/24 engine using conventional diesel fuel blended with two alcohol–water mixtures (ethyl and butyl alcohol with demineralized water). The results indicate a reduction in NOx emissions of 7.5%, with no significant change in CO2 emissions. The effects of environmentally friendly additives on exhaust gas composition and fuel consumption are analysed by Krakowski and Witkowski (2024). When a 2% silver-based additive is introduced into marine diesel oil (MDO), NOx emissions decrease by 4%, CO by 28%, and CO2 by 4.6%, while fuel consumption is reduced by approximately 3%.

A similar study conducted by Zablotzky and Sagin (2016) investigates a four-stroke diesel engine (6N21L Yanmar) operating on RME25 marine fuel with additives. The findings show reductions in NOx emissions ranging from 1.4% to 4.3%, fuel consumption by 3.5%, and SOx emissions by 15.6% to 22.9%. Additionally, Ryu et al. (2016) examine the use of oil-soluble calcium-based and iron-based additives in a large two-stroke marine engine fueled by heavy fuel oil (HFO).

The chemical manufacturing company Infineum conducted an extensive testing program (Infineum, 2023) using both high-sulphur fuel oil (HSFO) and very-low-sulphur fuel oil (VLSFO) in a Caterpillar MaK 6M20 four-stroke engine. The study measured fuel consumption and monitored emissions, including CO, CO2, NOx, SO2 and HC. The engine tests demonstrated average fuel savings of approximately 1% when using VLSFO, while NOx emissions with HSFO were reduced by 8.2%. Additional benefits included reduced smoke emissions, lower hydrocarbon output, and reduced fuel sludge deposits on the cylinder

liner, piston rings and injector nozzles. To validate the laboratory findings, sea trials were conducted on a 33,000-deadweight ton chemical tanker. The field tests confirmed a 0.8% reduction in fuel consumption, a 4% reduction in NOx emissions, and a 12% reduction in SOx emissions.

Fuelre4m and Voyage Marine (SplashTech 2026) conducted a full-scale operational trial to assess the impact of a combustion-enhancing fuel additive on marine engine performance. Testing on a commercial vessel fitted with twin Caterpillar 3512C engines demonstrated measurable improvements in fuel efficiency and propulsion performance following the addition of Re4mx Diesel treatment. The trial reported an 8.7% reduction in fuel consumption and a 5% increase in bollard pull under real-world operating conditions. Furthermore, combustion-related parameters indicated improved engine efficiency and reduced carbon monoxide emissions. These findings suggest that fuel-treatment additives may contribute to operational decarbonization efforts by enhancing combustion efficiency and lowering fuel demand in existing vessels without requiring engine retrofits.

Table 1: Comparison of different additives used in marine diesel engines.

Additive	Fuel Reduction (%)	NO _x Reduction (%)	PM Reduction (%)	SO _x Reduction (%)	Engine Type	Reference
Butyl alcohol + Ethyl alcohol + Demineralized Water	Not quantified (minor indirect)	Up to 7.5%	Not specified	Not specified	Sulzer 6AL20/24 marine diesel	Zadrąg et al. (2025)
Silver solution (2%)	~3%	Up to 4%	Not specified	Not specified	Delfin marine diesel (MDO)	Krakowski & Witkowski (2024).
Oxygen-bearing additive with light metal salts	3.5–5.8% (SFOC)	1.4–4.3%	Reduced	15.6–22.9%	Yanmar 6N21L (HFO)	Zablotzky & Sagin (2016)
CeO ₂ nanoparticles (90 ppm) + Water (2–6%)	Indirect (BSFC)	Reduced	Reduced	Not specified	Medium-speed marine diesel	E. J. Zhang, et al. (2018).
Ca-based organometallic	0.7–2.2%	Reduced	Reduced	Not specified	Large 2-stroke MAN B&W (HFO)	Ryu et al. (2016).
Infineum B Series (B402)	1–3% (SFOC)	1–4%	Black smoke ~14%	Up to 12–16%	Marine 2/4-stroke	Infineum Insight (2025)

Source: Authors.

In Table 1, additives reported in the cited scientific articles and reports that have been tested on marine diesel engines are compared. Most results indicate a slight reduction in specific fuel oil consumption (SFOC). The NOx reduction is highest (7.3%) when using butyl and ethyl alcohol, while other studies report reductions of up to 4%. The reductions in PM and SOx emissions are, in most cases, not quantified but rather described qualitatively as overall decreases. These reductions are typically more pronounced in engines operating on HFO due to the higher sulphur content of the fuel.

3. SulNOx fuel additive.

The SulNOx marine fuel additive is being used in upcoming research tests conducted as part of the Smart Emissions project. Prior to initial testing, it is necessary to review and verify its potential in terms of exhaust emission reduction, fuel savings, and enhancement of overall ship energy efficiency. The additive is manufactured by the chemical company Nouryon and is a biodegradable and 100% organic compound that can be used

with HFO, MDO, VLSFO, and certain biofuels, but it is not compatible with alternative fuels.

The SulNOx Group claims that its additive promotes secondary atomization, meaning that, after fuel injection, the treated fuel forms smaller droplets compared to untreated fuel. Secondary atomization refers to the further breakup of fuel droplets after their initial formation during injection, resulting in finer droplets that enhance fuel–air mixing and combustion efficiency. The company attributes this effect to glycol ethers (SulNOx Eco Fuel, 2025), which improve fuel dispersion, whereby water present in the fuel vaporizes in the combustion chamber prior to ignition, leading to micro-explosions that fragment larger fuel droplets. These larger droplets are typically associated with soot formation, and their reduction results in a more complete combustion process.

Table 2 presents a comparison between SulNOx and common additives used in various applications. When compared with conventional additives, it offers additional benefits such as improved lubricity properties (Veritas Petroleum Services, 2023), reduced soot formation, and lower PM emissions. Furthermore, one of its advantages is cleaner engine components, including cylinder liners, fuel injectors, piston rings, and filters. Consequently, it may reduce maintenance requirements for engine crews as well as overall maintenance costs.

In terms of emission reduction, the average reductions are estimated at 26% for CO₂, 14% for NO_x, 96% for PM, and 65% for SO_x. However, it is not specified to which marine fuel type or diesel engine configuration these values apply. Another advantage of SulNOx is the low required dosage (1:2000, i.e., 1 ml per 2 L of fuel). These advantages, along with product availability, are the reasons for its selection in the project; however, several uncertainties remain and will be investigated during the experimental phase, such as the time required to observe measurable effects and compatibility with fuel systems and fuel injectors.

Table 2: Comparison between traditional additives and SulNOx additive in the marine sector.

Category	Common Additives	Sulnox Eco
Working principle	Often relies on cetane boosters or waste fossil fuel components.	Atomizes fuel into smaller particles for cleaner combustion (secondary atomization).
Composition	Often petroleum-derived or metal-based.	100% organic, biodegradable, no fossil waste or metals.
Emissions Reduction	May enhance combustion but does little to reduce soot, particulates, or other harmful emissions.	Over 96% fewer particulates, 26% less CO ₂ , 14% less NO _x , and 64% less SO _x .
Lubricity effect	Many do not improve lubricity, some increase wear.	Adds an average 17% lubricity, reduces wear and cleans the engine.
Application	Often fuel-specific, some require hardware.	Works with diesel or petrol engines, no retrofits needed.

Source: Authors.

3.1. Experimental sea trials.

Before a new fuel additive can be tested under real operating conditions, it must comply with applicable ISO standards and the requirements of classification societies. Lloyd's Register evaluated the SulNOx fuel additive across multiple marine fuel blends, assessing compliance with ISO 8217, an international standard that specifies the requirements for marine fuels used

in diesel engines and boilers prior to onboard treatment, both with and without the additive. The testing demonstrated that dosing various DM and RM fuel blends with SulNOx Eco did not affect any of the fuel parameters specified in ISO 8217, confirming full compliance with industry standards (Lloyd's Register, 2022).

Table 3: Average fuel savings for different ship types (SulNOx annual report 2025).

Ship type	Sub-type	Average fuel reduction
Tanker	Small product tanker	7%
	Suezmax	5%
	Aframax	5%
	Bunkering barge	4%
	VLCC	3%
	Average	5%
Bulk Carrier	Ultramax	6%
	Supramax	5%
	Handysize	5%
	Capesize	3%
	Average	5%
Containership	ULCV	5%
	Feeder	5%
	Average	4%
RO-RO ship	Vehicles carrier	3%
	Average	3%
Offshore support	Crew boat	9%
	Supply ship	6%
	Average	8%
Passenger ship	Cruise ship	5%
	Superyacht	5%
	Average	5%

Source: Authors.

Table 3 presents a recent industry case study in which SulNOx was used during sea trials on various vessel types (SulNOx Annual Report, 2025). Eastern Pacific Shipping (EPS), one of the world's largest privately owned shipping companies, adopted the SulNOx fuel additive across at least 30 vessels following an eight-month evaluation period. The trials were conducted on a range of vessel types, including container ships, tankers, bulk carriers, offshore vessels, Ro-Ro vessels, and passenger ships. According to the report, the trials demonstrated consistent benefits, including fuel savings, reduced engine wear, and lower maintenance requirements resulting from cleaner engine operation. The same report states that Crystal Cruises entered into a collaboration with the SulNOx Group in February 2025 and reported average fuel savings of 3.4% over a ten-month period. While the report does not provide quantitative emission reduction data for individual pollutants, participating shipowners reported visible improvements in exhaust emissions, particularly reduced black smoke, which is generally indicative of more efficient combustion.

4. Results and discussion.

The results of this study demonstrate the potential of fuel additives to reduce fuel consumption in marine diesel engines.

Based on the sea trials conducted, the use of the SulNOx additive resulted in an average fuel consumption reduction of approximately 5%. Although promising, these findings should be further validated through testing with different diesel fuel grades and over longer operational periods.

The other additives reviewed in this paper achieved average fuel savings of approximately 3%. While this reduction may appear modest, it can translate into significant cost savings when applied to large marine engines with high daily fuel consumption, particularly in periods of elevated fuel prices.

Improved fuel efficiency also contributes to enhanced environmental performance by reducing CO₂ emissions. This can positively affect a vessel's Carbon Intensity Indicator (CII), a framework introduced by the IMO to assess and rate the operational carbon efficiency of ships. Under the CII framework, vessels receive an annual rating ranging from A to E based on their carbon intensity performance. The objective of this measure is to encourage shipowners to improve fuel efficiency and reduce CO₂ emissions per unit of transport work.

Potential fuel savings may also influence compliance costs under the European Union Emissions Trading System (EU ETS), a market-based mechanism designed to reduce greenhouse gas emissions by assigning a financial cost to carbon emissions. The EU ETS cost can be estimated using the following equation(1):

$$\text{EU ETS} = \frac{F_c \cdot EF_{CO_2} \cdot \text{year rate}}{\text{Trading within or to Europe}} \cdot \text{ice class} \cdot CO_2 \text{ price.} \quad (1)$$

where;

F_c – fuel consumption

EF_{CO_2} – emission factor of CO₂

year rate – phased introduction (2024=40%, 2025=70%, 2026=100%)

trade – within EU=100%, from/to EU=50%

In the EU ETS calculation, an ice-class adjustment of 5% is applied regardless of whether the vessel operated in ice conditions during the reporting period. The CO₂ price is based on the European Union Allowance (EUA), which represents the market price for emitting one tonne of CO₂-equivalent. EUA prices fluctuate daily in response to market conditions and energy demand. For the purposes of this study, the average EUA price for June 2026, €77.37 per tonne of CO₂-equivalent, was used (Trading Economics, 2026).

The calculations of fuel consumption, fuel costs, and EU ETS costs are presented in Table 4, which compares two scenarios. The first scenario assumes operation without the SulNOx additive, while the second assumes a 5% reduction in fuel consumption resulting from the use of SulNOx. The analysis is based on a Handysize bulk carrier (35,000–55,000 DWT) operating within EU waters, with an average fuel consumption of 30 tonnes of VLSFO per day (Gunes, 2023). A VLSFO price of USD 895 per tonne was applied, representing the average price reported in the latest bunker price list for the Port of Rotterdam (Ship & Bunker, 2026).

The total CO₂ emissions are calculated as:

$$E_{CO_2} = F_c \cdot EF_{CO_2} \quad (\text{tons}). \quad (2)$$

where the CO₂ emission factor of 3.206 is used based on the IMO carbon conversion factor

Table 4: Comparison of two scenarios for one voyage of Handy-size bulk carrier.

Ship information	Without SulNOx	With SulNOx
Voyage (days)	90	90
Fuel consumption (t/day)	30	28.5
Fuel consumption (t/voyage)	2700	2565
Fuel costs (\$)	2416500	2295675
CO ₂ emissions (t)	8656.2	8223.39
EU ETS costs (€)	669730.19	636243.68
Savings		
CO ₂ emissions (t)	/	432.82
Fuel costs (\$)	/	120825
EU ETS (€)	/	33486.51

Source: Authors.

A 5% reduction in VLSFO consumption, from 2,700 to 2,565 tonnes, would result in fuel savings of 135 tonnes and a reduction of approximately 432 tonnes of CO₂ emissions, based on the IMO carbon conversion factor of 3.206 t-CO₂ per tonne of fuel consumed. For a 90-day voyage, this reduction would translate into fuel cost savings of approximately USD 120,825.

These results highlight the potential benefits of using marine fuel additives, as fuel savings may contribute to both lower CO₂ emissions and reduced operating costs. However, the findings presented here are based on theoretical calculations and assumptions representing a best-case scenario. Future work will focus on measuring fuel consumption and emissions under real operating conditions, where the additive is used with marine diesel fuel over an extended period, to validate the results obtained in this study.

5. Conclusion.

The potential of marine fuel additives as a means of reducing exhaust gas emissions has gained increasing attention in recent years. This study examined the application of various fuel additives within the shipping industry and identified several potential benefits, including fuel savings, reduced exhaust emissions, improved engine efficiency, and lower maintenance requirements. Certain additives, such as SulNOx, may also enhance fuel lubricity and improve the combustion process in marine engines. The improved combustion process will result in more cleaner cylinder liner, piston rings and injectors, due to reduced formation of soot by unburnt fuel residuals. In terms of maintenance operations, fuel additives could reduce maintenance costs and unplanned maintenance actions on the main and auxiliary engines.

Although the reported reductions in fuel consumption are relatively modest, typically ranging from 3% to 5%, even small improvements can result in substantial fuel savings given the high fuel consumption of large slow-speed marine engines. In addition to reducing operating costs, lower fuel consumption can contribute to improved energy efficiency and a better CII rating.

By offering a practical means of reducing fuel consumption and emissions, marine fuel additives could support the maritime sector's transition from conventional fossil fuels to alternative energy sources. Their relatively low implementation costs, broad availability, and compatibility with a wide range of vessel types and fuel grades make them a potentially valuable transitional solution for achieving near-term decarbonization objectives.

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