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Assessing the Sustainability of the Most Prominent Type of Marine Diesel Engines under the Implementation of the EEXI and CII Regulations

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Abstract: The wide spread of the Diesel engine has been instrumental in the development of modern shipping. Marine Diesel engines dominate today as an option for the propulsion of commercial ships. While replacing Diesel engines with alternative propulsion engines is difficult to achieve, companies, in light of the new EEXI regulations, are turning to improvements, such as operating at lower rotational speeds, higher maximum combustion pressures, and more efficient overcrowding systems. The purpose of this research paper is (i) to present the basic operating principles of marine Diesel engines, (ii) to study the main differences between electronically controlled Diesel engines and their mechanically controlled counterparts, and (iii) to evaluate their performance under newly introduced IMO's EEXI regulations. Thus, after comparing Wärtsilä RTA and WinGD WX, the paper concluded that WinGD WX, being electronically controlled, will perform more effectively under new EEXI regulations, as it offers (i) reduced fuel consumption in low-load mode, (ii) zero-smoke emission at all operating speeds, (iii) very stable operation at low speed, (iv) more straightforward engine setup leading to less maintenance, (v) more extended periods between maintenance, mainly due to better load distribution between cylinders and more perfect combustion. From a regulatory perspective, the new limitations installed by the newly implemented EEXI and CII regulations will cause fewer implications in electronically controlled engines, while from an economic standpoint, the electronically controlled engines decrease OPEX and require fewer personnel, due to their efficiency at low loads and overall flexibility.

Keywords: marine diesel engines; Wärtsilä RTA; WinGD WX; EEXI; CII



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1. Introduction

The production of a project using thermal internal combustion engines is based on the heat supply from the combustion of suitable fuels at high pressure to the working “medium”, part of which can be recovered as a mechanical project. At the same time, the rest is exported into the environment [1]. The German engineer Rudolf Diesel significantly increased the reliability of internal fuel engines [2]. In 1892, he patented the first of a series of patents for the well-known engine bearing his name, which continued to grow in a realistic form in the following years with the support of companies, such as Friedrich Krupp AG, Maschinenfabrik Augsburg, and Gebrüder Sulzer [3].

The WinGD company comes from the Sulzer Corporation, founded in 1893 when the Sulzer brothers agreed with Rudolf Diesel to buy and implement his idea for a new technology engine. On 10 June 1898, the construction of the first Diesel engine began in Winterthur, Switzerland, where the company's headquarters are still located today [4].

In 1905, the Sulzer company manufactured the first two-stroke Diesel marine engine. Five years later, in 1910, a diesel naval engine was installed for the first time on a merchant ship, namely, two Sulzer 4SNo.6a engines with a total capacity of 1118 kW were installed on the Italian ship “Romanga”.

The wide spread of the Diesel engine played a decisive role in the development of modern shipping. The first large ship equipped with Diesel engines was the 678 ton *Romagna* (1910), with propulsion through two four-cylinder Sulzer engines of 180 kW each [5]. The first company to install this engine on a seagoing ship in 1912 was Burmeister and Wain on *Selandia*, which travelled 20,000 nautical miles from Copenhagen to China. Since then, and by 1920, 16 ships with Diesel propulsion had been built from the same shipyard. In 1914, there were less than 300 ships that used Diesel engines for their propulsion, while a decade later, this number amounted to 2000, ending in 1940, where 8000 ships operated using marine Diesel engines [6]. With the passage of time and the development of technology, marine engines acquired a smaller size, and increased power and performance, thus radically changing the architecture of ships. Combined with the increase in fuel prices, it became an unprofitable operation of other forms of propulsion (e.g., steam turbines, gas turbines, etc.) [7].

The adoption of overcrowding gave a large rise to the construction of smaller engines with greater control. Overcrowding began to be applied in the 1920s to four-stroke engines for the more effective cylinders leaching but with mechanical compressors. The first marine Diesel engine using turbo proof was built in 1927 by MAN [1].

While in the 1920s, the Sulzer company dominated the market of ship and rail oil engines worldwide, in the 1930s, fuel injection without air was established in all types of engines. The next step is developing the overcrowding technology that leads to engines with increased power, less weight, and less space requirement. The first two-stroke Diesel engine with overcrowding was the Sulzer 6TAD48 in 1946 [4].

A significant development in naval engines was the use of heavy oil since the mid-1950s, and suitable lubricants were used to neutralize the acidic derivatives of the combustion of heavy oil and make it possible to reduce engine wear (cylinder oils). Moreover, in the 1950s, the technology of overcrowding is now widely used in all marine Diesel engines. Sulzer launches the most successful engine range of type R (RSAD, RD, RND, RL, etc.) [7].

In 1972, Sulzer launched the first marine engine to use natural gas as fuel. This is the Sulzer 7RNMD90 located on the Norwegian ship *Venator*. In 1983, Sulzer launched the series of sluggish two-stroke marine engines, Diesel RTA, with pistons of 380 to 840 mm [8].

In 1990, the Sulzer company established its subsidiary, New Sulzer Diesel Ltd., responsible for manufacturing Diesel engines. In April 1997, New Sulzer Diesel Ltd. merged with Wärtsilä Diesel and created the Wärtsilä NSD Corporation, later Wärtsilä Corporation [9].

Since 1981, research has begun to create electronically controlled marine Diesel engines. The result is the creation of the first in 1998 and then the development of the RT-flex engine series. The first engine of the RT-flex series came into operation in September 2001 and quickly enjoyed great commercial success [10].

In 2015, Wärtsilä Switzerland Ltd., the part of Wärtsilä responsible for the manufacture of two-stroke Diesel marine engines, merged with China State Shipbuilding Corporation (CSSC, Beijing, China) and created Winterthur Gas & Diesel Ltd. (WinGD, Winterthur, Switzerland). In WinGD, Wärtsilä initially holds a 30% stake, which will eventually transfer in 2016, resulting in WinGD being 100% owned by China State Shipbuilding Corporation (CSSC) [11].

Since the beginning of 2010, the creation of dual-fuel engines has been investigated as a possible solution for ships to comply with the IMO regulations on pollutant emissions. In 2011, the X series of electronically controlled marine engines was introduced, offering better performance in terms of fuel economy and emission reduction. In 2013, dual-fuel engines under the name X-DF were officially released. At the end of 2019, 300 orders had already been made for dual-fuel marine engines [12].

WinGD currently holds a 36% stake in the global market for marine Diesel engines, 60% in dual-fuel marine engines, and 100% in engines that fuel liquefied gas (LNG).

The rapid development of naval engines in recent years has turned the interest to manufacturing slow-moving machines of large diameter pistons, a higher degree of compression, and a high degree of efficiency [8].

Specifically, Diesel naval engines are responsible for the emission of 20 million tons of nitrogen oxides (NO_x), 10 million tons of sulphur oxides (SO_x), and 1 million tons of other pollutants. In 27 countries of Europe, while pollutant emissions from cars seem to decrease, ships' emissions continuously increase. It is characteristic that from 2000 to 2020, ships' NO_x and SO_x emissions increased by about 40% [13]. As a consequence of the above, the designers of marine Diesel engines, in recent years, have had to deal with the strictest emission limits of harmful pollutants. These limits were imposed by national, local, and international authorities to reduce air pollution and its impact on human health and climate change. It is worth noting that now all manufactured machines should be fully harmonized with the IMO—MARPOL Annex VI regulations, which sets all those conditions concerning air pollution. Specifically, the IMO document MEPC 58/23/Add.1 details all the requirements for how a machine should undergo the stage of testing and testing in order to be certified that it is entirely in line with this regulation, and then the corresponding certificate (Engine International Air Pollution) can be issued: Prevention Certificate—EIAPP. Finally, and according to the regulation, each ship must also carry the related « NO_x Technical File» where all those elements of the engine that harmonize with the regulation, as well as all the parameters and data measured during the process of testing the engine, are detailed. The above is certified by a representative of the classification society during the test procedure (there is also a corresponding document signed and stamped by the classification society). Furthermore, very recently, the new IMO's EEXI regulations were enacted, forcing all marine engines to perform at lower operational loads and thus directly affecting their overall performance [14].

Currently, engine manufacturers aim to reduce fuel consumption further and limit emissions of harmful gases. There is also an increased research interest in improving the degree of performance, increasing reliability with a corresponding reduction in maintenance needs and operating costs and finally, the expansion of electronic control of the engine's operation to achieve optimal and trouble-free operation while abiding by new EEXI regulations [15].

To this end, the paper initially presents the basic operating principles of marine Diesel engines. Then, it focuses on assessing the main differences between electronically controlled Diesel engines and their mechanically controlled counterparts. Finally, the main differences between those two engine types are utilized to evaluate their performance under newly introduced IMO's EEXI regulations [16].

2. Current Trends in Marine Diesel Engines

The following chapter presents the current trends in research around the evolution of marine Diesel engines. In particular, studies are presented on optimizing performance, reducing pollutant emissions, and more effective electronic control.

2.1. Performance Optimization Studies

The issue of optimizing performance and reducing pollutant emissions through systems applied to electronically controlled marine Diesel engines has been of great concern to researchers in recent years [17].

Scappin et al. [18] presented a model for predicting the oxide emissions (NO_x) and the performance of an electronically controlled marine Diesel engine. The results given by the model were verified by testing a MAN B&W 4T50 ME-X engine. The model was shown to have good reliability and the ability to be used to predict the effect of various factors on the performance and pollutant emissions of an electrically controlled Diesel marine engine. Milanese et al. [19] studied the creation of a sensor that can measure real-time elements and precisely adjust the supply of the required amount of lubricant. In this way, we can achieve significant savings in the consumption of lubricants. Jiang et al. [20] developed a model CFD simulation to investigate the effect of various fuel injection techniques combined with a gas recirculation system (EGR) on nitrogen oxide (NO_x) emission and fuel consumption in a marine Diesel engine [21]. They found that while initially fuel injection techniques

that lead to a reduction in pollutant emissions also lead to reduced efficiency, there are additional technologies that, with an appropriate combination, can simultaneously reduce pollutants and increase efficiency. Nguyen et al. [22] argue that it is extremely difficult to increase efficiency and reduce emissions in a marine Diesel engine through mechanical reconstructions. While the technology in the mechanical part of the engine seems already at the top level, the future lies in developing techniques of optimal control of each cylinder separately and the fuel pouring technology. Finally, they propose a simulation model that can be used to study the operation of cylinders under different fuel injection techniques [22].

2.2. Studies of Emission Abatement Technologies

Particular emphasis is given to research on technologies applied to marine Diesel engines that can reduce pollutant emissions. Most studies refer to technologies applied to electronically controlled marine Diesel engines.

Sun et al. [23] examine and evaluate computationally through a simulation model different techniques for limiting nitrogen oxide emissions (NO_x) in marine Diesel engines. They conclude that gas recirculation systems have better efficiency prospects than the Miller cycle application. Ni, Wang, and Li [24] find that according to studies, Diesel marine engines are responsible for more than 50% of the total emission of nitrogen oxides (NO_x) in coastal areas and ports. In this context, they review the regulations in force for reducing pollution and investigate various techniques for reducing pollutants coming from marine Diesel engines. Among other things, they examine exhaust gas recirculation techniques, the common rail system (CRS) fuel injection system and conclude that the combination of these can effectively reduce pollutant emissions from marine engines. Deng et al. [25], in another review of the regulations to reduce pollutants from marine Diesel engines, examine and evaluate different technologies to reduce emissions. P. Wang et al. [26] experimentally studied the effect of the Miller cycle on the operation, performance, and reduction in pollutant emissions in a marine Diesel engine.

2.3. Basic Principles of Operation

A simple slow-moving Diesel engine generally satisfies commercial ships' propulsion requirements. These machines can burn fuel of significantly worse quality than a mezzospeed engine since they have more time and space [8].

Presently, all engines have specific characteristics in common. All the modern machines used to propel commercial ships are two-stroke and overcrowded. Overcrowding, in addition to increasing power, also significantly improves fuel consumption [27].

With the term marine Diesel engine, we can, in this day and age, describe a reciprocating engine, which, although it has collected the amounts of heat by compressing air in the cylinders, ignites itself through fuel injection.

The ideal efficiency of this system ranges from 55–60%, from which about 40–45% of the heat is lost during extraction. Of course, all this is true with the following assumptions [8]:

- Compression and release times are adiabatic;
- Friction is considered negligible;
- There are no losses due to cooling and heat transfer to the environment.

As it is known, the theoretical Diesel cycle does not coincide with the real one due to the losses. It is noted that the indicative diagram of the pressure angle of the crank results from diagram P-V. It is essential as it serves the engineers while adjusting the fuel injection timing [28].

2.3.1. The Two-Stroke Operation Cycle

Two-stroke engines usually have air intake ports, which are revealed during the descent of the piston. The extraction is generally carried out by an exhaust valve at the top using the method of straight leaching or otherwise scanning (uniflow scavenging) [29].

Starting at the upper dead point (UDP), combustion has already begun, and the exhaust valve opens 110–120 degrees after the ANS to promote a quick release before

opening the intake port about 20–30 degrees later. In this way, the minimum mixing of exhaust gases and intake air is achieved, which is carried out due to the inertia of the exhaust gases, which move almost at the speed of sound and are removed from the intake air of the next cycle [30]. To maximize the compression time of the cycle, the exhaust valve must be closed before the intake port appears, but this can also be controlled through the machine's geometry and especially the piston (e.g., opposite piston engine). The intake ports will be closed at the same crank squadrons as those opened after the upper dead point (UDP) due to three geometries (i.e., 130–150 degrees before the ANS) and the exhaust valve itself. The fuel injection process begins at about 10–20 degrees before the upper dead point (UDP), and depending on the speed and the combustion, reaches 30–50 degrees [8,27].

Regarding construction, this type of engine has fewer cylinders, and thus fewer moving parts, which means there is less chance of creating a mechanical failure problem. Moreover, installation and maintenance work is facilitated by space in the engine room and machinery space. Therefore, the maintenance cost is often proven to be significantly decreased, as is the noise level [8].

a. Engine trunk

The trunk of the machine includes the frame, the base, the body of the cylinders, and the legators that connect these parts.

b. The basis of the engine

The engine base (bedplate) supports the engine and ensures the alignment of the axle. The base needs a robust, rigid, but also light construction, which is achieved by welding lamellae to form cringed beams connected by a series of transverse beams. The transverse beams also carry the lower half of the bearings of the machine's base. Bearings must withstand the loads carried by the engine's piston across pusher crank shaver kinematic mechanism, which are of varying intensity during a cycle of the engine and increase as the maximum and average engine pressure increases. The base is fixed to the engine room floor with special seats, and at the bottom of it is closed, forming the olive basin [31].

Finally, the drivers of the tensioners that connect the different parts of the engine are also integrated into the base. The tensioners (braces) penetrate the engine from the base to the body of the cylinders surrounding the liners and keep all sections crushed.

c. The cylinder skeleton and body

The frame is the central part of the engine, with the most significant volume, on which all the machine's other parts and essential components are attached. The body of the cylinders is placed in the upper part of the frame while the lower part rests on the machine's base. The machine's frame (A-frame) connects the assembly of cylinders with the base. It consists of a series of transverse frames (columns or columns) shaped "A" that are externally connected by the longitudinal axis with plates to create a cist structure. The access maintenance holes and the safety valves for crankcase explosions are placed in the longitudinal plates.

The body of the cylinder blocks is the structural element of the machine that encloses the cylinders and is connected to the upper part of the frame. In large machines, the body of the cylinders surrounds and supports the liners, which form the cylinders [32].

d. Tunics

The sleeve is the cylindrical cross-sectional part of the machine, in which the piston regresses. Liners are placed inside the body of the rollers. The strain on the tunics is complex and periodically changing, with the strongest being the "encaustic" tendencies due to internal pressures.

The tunic is supported and held by the surrounding structure of the cylinder body. It does not need flexibility; therefore, foliar graphite that offers better self-lubrication properties is preferred. The construction of the tunic is carried out by rotary casting in order to maintain the homogeneity of the alloy.

In straight-washed engines, the intake ports at the bottom of the line of the liner have a device that twists the incoming air. This twist favors scanning, and since it increases as the piston compresses air due to maintaining momentum, it favors the dispersion and mixing of fuel [33].

e. Cylinder head—Exhaust gas valve

The head (cap–cap) of the cylinders is attached to the upper part of the liners forming together with the liners and the upper part of the piston, the space where the combustion takes place. In high-power engines, a separate head corresponds to each machine cylinder. The head includes the combustion chambers, the air intake and exhaust culverts, the openings for the installation of injectors, and a series of bases and positions of other elements and instruments of the machine [29].

Due to the long stroke of the piston with regard to its diameter (about 4/1), straight leaching is used where the exhaust valve in the cylinder cap becomes necessary. The exhaust valve obtains the maximum temperature of all parts of the combustion chamber as hot exhaust gases surround it during extraction. Due to the high temperatures and the constant contact with hot and highly corrosive exhaust gases, the valve material is usually a steel alloy with elements of lead, cadmium, and nickel, which give excellent strength properties but have a very high cost [32].

f. Piston

With its reciprocating motion within the cylinder, the piston converts the pressure from the exhaust gas release into mechanical work. Significant is the cooling of the piston achieved by the hasty impedance of coolant near the walls of the combustion area. The cooling of the piston is carried out with water or oil. The pistons have a complex interior design of cavities and holes to achieve good cooling internally by water or oil. Significantly higher heat flow rates are achieved with cooling water instead of oil [34].

g. Piston springs (piston rings)

The springs of the piston ensure the necessary sealing of the combustion area, to achieve the maximum possible compression of the air, to avoid the escape of exhaust gases to the bottom of the piston, and not to allow for the inflow of lubrication oil into the combustion area. Generally, the sealing springs are the machine components subject to the harshest operating conditions. During combustion, the springs face very high temperatures and cool unevenly as they pass through the lying ports, resulting in high voltages [35].

h. Connection rod

The thruster converts the reciprocating motion of the piston into a rotational motion on the crankshaft. It is connected either directly to the piston through the piston pin, or to the wagon, in the weighing, through the corresponding knob. It consists of the head, stem, and leg.

i. Actros—Weighing

The kneading actros assembly is part of the engine's kinematic mechanism and transfers the reciprocating motion of the piston to the canal [32].

j. Crankshaft

In large engines, the crankshaft is one of the engine's heaviest and most expensive components (accounting for 20% of the total weight and 10–12% of the cost). The crankshaft is made of forged steel parts of low content in other metals. Each part comprises two arms (guitars or cheeks) connected by the lower crank throw [36].

If the engine has a camshaft, the drive is received from the wheel at the end of the crankshaft or in the middle for engines with more than seven cylinders. The drive is transmitted by chains (chains) or by gears and counterweights. Timing can also be carried out electronically, from a crank position signal to cooperation with common rail systems and hydraulic exhaust valves [29].

k. Camshaft (camshaft)

The camshaft transmits the drive for opening and closing the intake and exhaust valves, while at the same time, it transmits the drive to auxiliary mechanisms (fuel pumps, starting air valves, powering take-up). The transmission of the movement to the camshaft from the crankshaft is carried out using gears or a chain, and the gear ratio of the movement is 1:1 for two-stroke engines. In slow-moving machines, a standard camshaft is usually mounted on the sides of the engine [37].

2.3.2. Electronically Controlled Diesel Naval Engines

J. Wang et al. [38] observed that electronically controlled Diesel marine engines, in addition to the advantages they offer, are complex systems, and the diagnosis of faults in them can prove challenging. On this basis, they propose a reliable diagnostic system that takes measurements in real time and, in cooperation with the electronic control unit (ECU), can help in the timely and accurate detection of engine failures. Rolle and Wiesmann [39] presented intelligent combustion monitoring (ICM) and intelligent combustion control (ICC). The above are control systems of cylinders and a marine Diesel engine as a whole, aiming at its more efficient and safer operation. Boullosa et al. [40] observed that the existing control systems used in marine Diesel engines depend to a large extent on the value of each measurement separately and need to take into account combinations of them or the overall condition of the engine. To improve the above issue, they proposed a control system that combines the measured values of different engine components and considers the operating condition of the ship [40].

As it is mentioned above, the introduction of electronically controlled marine Diesel engines, which in recent years has dominated, is an event of historical importance that deserves a place next to the invention of the first engine by Rudolf Diesel, the placement of the first naval engine in 1912, and the adoption of overcrowding in two-stroke marine engines in 1954 [2]. MAN Diesel and Sulzer (later Wärtsilä and now WinGD) have been researching for years in their experimental engines the operation without a camshaft utilizing electronic control in fuel injection and activation of exhaust gas valves. The aim is to create intelligent machines, i.e., that constantly monitor their operating conditions by adjusting the parameters to achieve better performance in fuel economy and reduced emissions. The plan's ultimate goal for creating intelligent machines is to create engines that, through sensors, will constantly collect data that will compare with the standard values. In the case of deviations, the appropriate actions for the reset will be applied immediately [41].

Studies of the above companies have shown that to improve the flexibility in the operation of the engine, it is necessary to check the timing of the fuel injection and activation of the exhaust valves during the operation of the engine. Trying to achieve this using camshaft systems would lead to complex mechanical systems of dubious reliability. The creation of engines that would not be controlled via a camshaft was now a one-way street [37].

Figure 1 shows man's plan for intelligent engines in diagrams. At the top of the figure, we can see the various engine operation programs that can be selected even from the navigating bridge [42]. Characteristically, we distinguish operating programs that focus on fuel economy, controlling pollutant emissions or protecting the engine. In the center of the diagram is the brain of the whole program, which is the electronic control of the motor. Through it, the engine's operating condition is constantly monitored, and the operation of critical parameters of the engine is checked, such as fuel injection pumps, exhaust valves, and the cylinder lubrication system, among others [43].

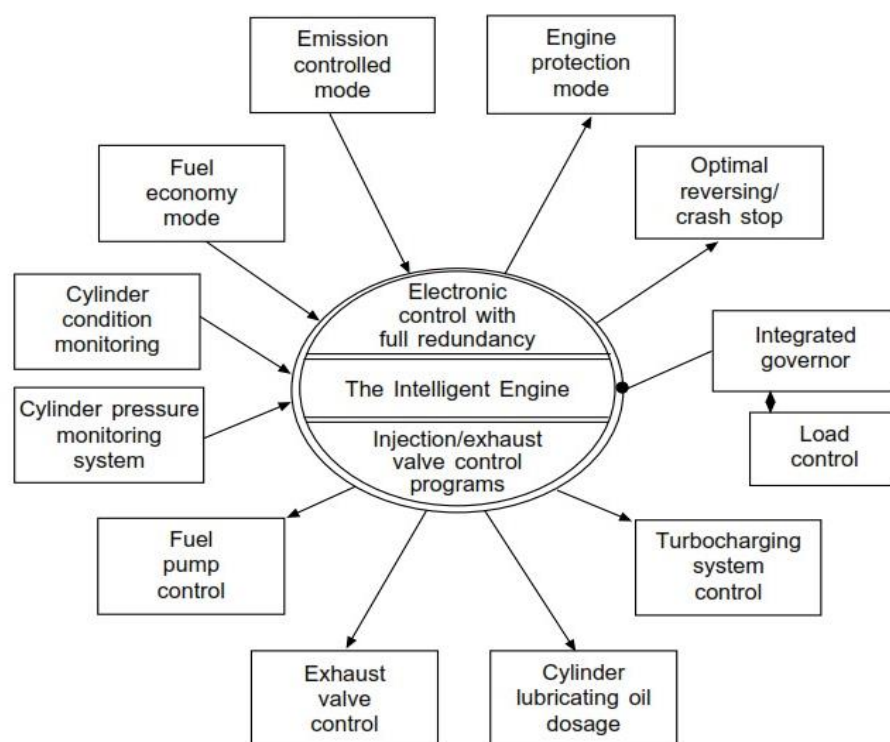


Figure 1. Chart analysis of intelligent machines [42].

To achieve the goal of reliability, it is necessary to have a system that can actively protect the engine from overload, lack of maintenance or other failures. The above system evaluates the engine's condition by monitoring and maintaining specific critical parameters within the desired limits. It is an online system that automatically samples the engine's operating data, including pressure measurements within the cylinders. The control system shall retain the data for the different engine modes. Moreover, it can effectively protect the engine from overload due to bad weather, polluted hull, and other everyday situations that lead to a sudden increase in load, always making the necessary adjustments and corrections [44].

The fuel injection system operates without the traditional camshaft using high-pressure hydraulic oil from a pump powered by the engine and an electronically controlled servo mechanical system that controls the operation of the injection pump pistol. Unlike pumps controlled via a camshaft, this pump has a variable path and channels only the required fuel for that load. Various standard functions can be created in order that the system works in a specific way for specific requirements. Changes in functions can be achieved immediately, thus ensuring great flexibility. Finally, the system can adjust a different amount and timing of injection in each cylinder, thus achieving greater balance in the load and pressure of the cylinders [40].

The operation of the exhaust valve system is similar to that of the fuel injection system, namely, it uses the supply of high-pressure hydraulic oil. However, the need to control this system is limited only to the valve opening and closing timing; therefore, it is significantly simpler. The lubrication of the cylinders is controlled by a system that constantly evaluates the amount of lubricant required depending on the machine's load. These systems are also used in conventional marine Diesel engines [41].

Operating standards can be selected from a control system mounted on the ship's navigating bridge. These operating standards are what concerns fuel saving or reducing pollutant emissions. Finally, the alarm mode will be activated automatically, taking advantage of the engine data when the values collected differ significantly from the normal ones. The above idea is now a reality with the largest manufacturers of Diesel marine

engines circulating models of electronically controlled engines, such as the ME series of MAN Diesel, the RT-flex series of Wärtsilä, and the X series of WinGD [12,42].

In contrast to two-stroke engines, the essential parts of electronically controlled engines are the following:

a. Common rail system

The standard rail system is a fuel injection system for Diesel engines in which the fuel first gains increased pressure through pumps, and then accumulates in the common collector. Finally, the injection of the accumulated high-pressure fuel from the typical collector is carried out in each cylinder separately at the appropriate time using electronically controlled control valves [45].

The idea of the common collector was adopted since it offers the advantage of separate operation of pumps and fuel injection. This also allows for a separate approach to the mechanical and hydraulic part of the design to supply fuel at a suitable pressure ready for injection. Moreover, this system allows for an independent control of the injection valves. In ordinary Diesel marine engines, three fuel injection valves in the lid of each cylinder can be operated separately [8].

The common rail system is the basis on which the operation of the electronically controlled nautical Diesel engine circulated by Wärtsilä and WinGD is based. Combining the standard collector system and electronic control offers improved operation at low speeds, engine acceleration, balance between cylinders, engine load control, and longer maintenance intervals. Moreover, it ensures perfect combustion at all speeds and operating loads, offering the advantages of lower fuel consumption, more environmentally friendly operation in terms of smokeless and lower NO_x emissions, and overall a cleaner engine with fewer combustion residues. The built-in fault control and diagnosis systems improve the engine monitoring process and increase its reliability [8,12].

The standard collector system is designed for operation with the traditional heavy oil used in shipping, and thus has everything from the already acquired technology. The first systems without a camshaft developed by Sulzer for electronically controlled engines used independent hydraulic fuel injection pumps. However, the transition from the above systems to the standard rail system was made due to the limited technological development possibilities offered by the system of independent pumps. Electronic control alone proved to be inadequate, and the creation of a different injection system was deemed necessary [46].

Electronically controlled naval engines are based on traditional slow-speed two-stroke marine engines. Compared to traditional mechanically controlled engines, a key difference is the absence of the camshaft, fuel injection pumps, exhaust valve actuation pumps, reversal servo engines, and all relevant control mechanical parts. On the contrary, they are equipped with a standard rail system for fuel injection and activation of exhaust valves and the functions are fully controlled electronically [8,35].

Four primary data characterize the operation of the common collector system of electronically controlled marine Diesel engines: the longitudinal fuel collector sideways of the cylinders, the supply unit on the side of the engine, a filter unit for the oil of the servo engine and finally, the integrated electronic control system including the angle sensor of the crankshaft [36].

b. Supply unit

Large amounts of the fuel and oil of the hydraulic systems are fed into the standard collector system by a supply unit driven through gears from the engine's crankshaft. The supply unit is mounted at the front of the engine, on the same side as the fuel collector, and at an average height.

Fuel supply pumps are powered through a camshaft with three-lobed cams. However, this camshaft should be distinct from the camshaft of traditional mechanically controlled naval engines. It is significantly smaller and with a significantly smaller diameter [47].

The fuel supply volume and the pressure on the collector are adjusted according to the engine's needs through a suction control system at the fuel injection pumps. This method

ensures that no more fuel will be squeezed than is required. The fuel pumps channel the compressed fuel to a nearby collector, then from two independent tubes of the driver to the standard fuel collector. A similar device with a first collector and two tubes is also used to oil hydraulic systems [48].

c. Oil of hydraulic systems—Control oil

The oil from hydraulic systems activates and controls the exhaust valve. Its supply is carried out through axial pistons of hydraulic pumps integrated into the supply unit. The operating pressure is controlled (indicative pressure of 200 bar), resulting in energy savings in the pumps. The number of pumps depends on the size of the engine and the number of cylinders and varies between 3 and 6.

The oil of hydraulic systems is a classic lubricating machine oil. It is pumped from the engine lubrication system after passing through a filter, and then separated into hydraulic system oil and control oil.

The control oil is supplied at a constant pressure of 200 bar from two electrically controlled oil pumps and is used as a working medium on all valves of the injection control unit (ICU) [49].

d. Fuel collector unit

The fuel collector unit is located just below the level defined by the cylinder caps and extends along the entire engine. The fuel control unit includes all the tubes and the corresponding equipment for the fuel, the oil of the hydraulic systems, any returns, and the control oil.

e. Injection Control Unit (ICU)

The fuel is injected from the common collector to the injection valves through separate units for each cylinder. This system precisely adjusts the fuel injection timing, the amount injected, and the injection patterns.

Each cylinder has three fuel injection valves, the same as those in the traditional Sicilian mechanically controlled Diesel naval engines. Each fuel injection valve located in the cylinder cap is controlled independently of the injection control unit of the specific cylinder in order that it can operate autonomously from the rest [50].

f. Exhaust valve control

The exhaust valves work with the help of a hydraulic thrust rod, which opens with the hydraulic pressure of the oil and closes with an air spring as in traditional mechanically controlled machines with camshafts. However, the activation energy comes from the hydraulic system in electronically controlled engines. There is a similar activation mechanism for each cylinder [37].

In the actuation mechanism, the oil of the hydraulic system acts on the underside of a piston, on the “all-o” side of which is the engine’s oil. The hydraulic control of the oil flow of the servo machines leads to the precise timing of the opening and closing of the exhaust valve.

The exhaust valve has two electronic sensors that give feedback to the engine control system in order that the system knows the valve’s position at all times. The electronic control system of the exhaust gas valve offers complete flexibility in the timing of its opening and closing [51].

All the functions of the electronically controlled nautical Diesel engine are controlled and monitored by the electronic control system. Wärtsilä and WinGD use the Wärtsilä engine control system (WECS). The above is a modular electronic control system consisting of several separate microprocessor modules for each cylinder.

Figure 2 illustrates diagrammatically the operation of an electronically controlled Diesel engine that uses the standard rail technology, the parts of which were analyzed above. The fuel accumulated in the common collector at high pressure (1000 bar) through the injection control units reaches the fuel injection valves. Moreover, the control oils

and hydraulic systems are at a pressure of 200 bar and are used, among other things, to control the activation of the exhaust valve. Finally, everything is connected to the central control system of the electronically controlled naval engine responsible for continuously monitoring the operating condition and the setting of the operational parameters [52].

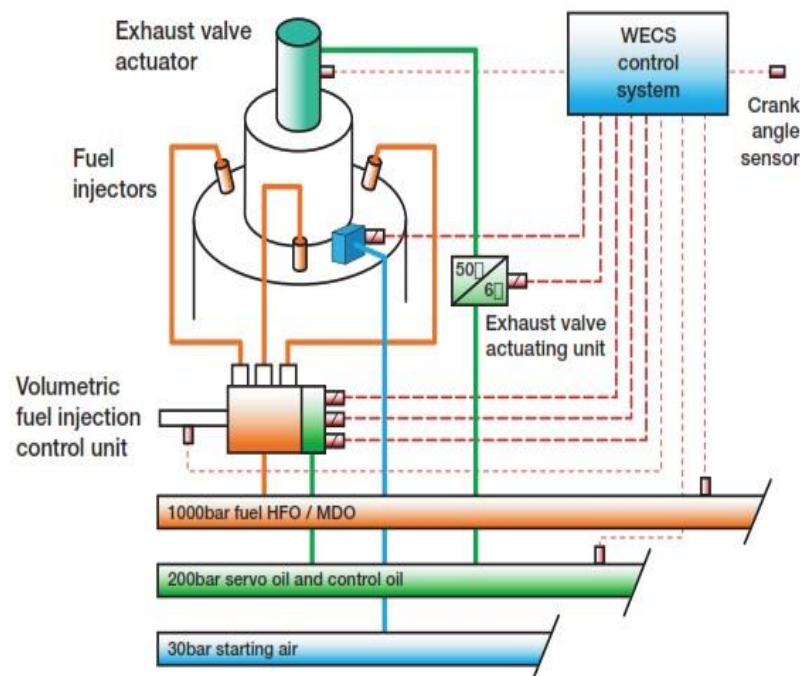


Figure 2. Diagrammatic representation of the operation of the standard collector system [52].

Modifications to the timing of the fuel injection and the operation of the exhaust valve require studying elements such as the pressure inside the cylinder and engine performance elements. The intelligent combustion monitoring (ICM) system combines pressure sensors inside the cylinders with measurements of the crankshaft's position using a dynamic mathematical model to monitor engine operation. The above can offer significant benefits, such as increased reliability, reduced operating costs, minimization of the risk of mechanical or thermal overload of the cylinders, and balanced operation of the engine [53].

Another electronic control system used in electronically controlled marine Diesel engines is the smart combustion control (SCC) system. This system bases its operation on the continuous and accurate recording of the pressure inside the cylinders to improve the engine's performance over the entire range of operating loads and not adjust to a single operating point. The data it collects are compared with standard data from the engine tests resulting in a long-term improvement in the engine performance [54].

The research and development department of WinGD has announced that it is already planning a new electronic control system (WinGD Integrated Control Electronics—WiCE) that will be installed in total in the electronically controlled marine Diesel engines manufactured by the company. Key elements of this system will be its modular structure consisting, among others, of a central control unit, a unit for monitoring the operation of the cylinders, and other smaller subsystems. The main objective will be to monitor the engine's operation in real time and improve the control of operational parameters [55].

3. Material and Methods

As already stated, the primary purpose of this research paper is to study the operation and evolution of marine Diesel engines. This study is expected to significantly contribute to the shipping industry as the in-depth knowledge of the technology and the way marine engines operate significantly affects all departments of a shipping company. The analysis carried out in this research paper concerns both the operation and the tech-

nological developments and innovations that can help fully inform the people who staff the technical department, the crew department and, more broadly, the staff of a shipping company [56–58]. Specifically, the objectives of this research project are:

- (i) The presentation of the basic operating principles of Diesel marine engines.
- (ii) The main differences in the structure and operation of electronically controlled Diesel engines from the corresponding mechanically controlled ones.
- (iii) The evaluation of the performance of each engine type under the installation and enforcement of the new EEXI legislation.

For this, the comparative analysis of two distinct technologies of naval Diesel engines (Wärtsilä's RTA series is for mechanically controlled engines while WinGD X is electronically controlled) is conducted based on content analysis of information provided by Wärtsilä RTA and WinGD X company sites [59,60].

Additionally, comparative analysis is developed to effectively demonstrate the advantages and disadvantages of each engine type and provide practical outcomes upon the election of an engine type based on a vessel's operational requirements under the enforcement of the new EEXI regulations [61–63]. This comparison concerns the following areas, which are considered of vital importance during an election of a ship engine:

- Performance;
- Fuel economy;
- Pollutant emissions;
- The operation and maintenance.

4. Comparison of Mechanically and Electronically Controlled Naval Engines: Wärtsilä RTA and WinGD X Series

This chapter presents a comparison of mechanically and electronically controlled marine Diesel engines. In particular, the comparison concerns the series of mobiles of the Wärtsilä RTA series and the WinGD X series. The former is traditional mechanically controlled Diesel naval engines widely used on ships, while the latter is modern electronically controlled Diesel naval engines. It is worth noting that it was chosen to compare engines with a common starting point manufactured by the same company. In contrast, those of the Wärtsilä company were preferred due to the interest in the common collector system they use [64].

4.1. Wärtsilä RTA

Wärtsilä's two-stroke Diesel RTA series of slow-moving marine engines was launched in late 1981 and was an intersection with the company's previous engines. The main difference was the engine's different leaching systems and valves' presence [8].

The original RTA series was released with six models with corresponding piston sizes of 380 mm, 480 mm, 580 mm, 680 mm, 760 mm, and 840 mm. More models formed the RTA-8 series and were supplemented in 1984 with the RTA-2 series, which included two more models with pistons of 520 mm and 620 mm. The RTA-2 series, in turn, was expanded in 1986 with an engine with a piston of 720 mm. Finally, in 1988, the RTA84C engine with a piston of 840 mm was released, specially designed to offer high power and high speeds that meet the propulsion needs of large container ships. In the same year, various design improvements were introduced for the RTA-2, and in 1992, it was completely upgraded to RTA-2U with an increase of up to 9% in engine power [65,66].

The RTA engine range experienced a significant new expansion in 1991 with the introduction of the RTA84T "Tanker" model, designed to meet the propulsion requirements of VLCC-type and large cargo ships. The first engine of this type was put into service in 1994. The RTA48T, RTA58T, and RTA68T models that followed were smaller, allowing ship designers to create smaller engine rooms. In contrast, their reduced size and weight contributed to easier monitoring and maintenance. In 1994, the RTA96C engine was launched as a solution to the market's needs for propulsion of large and fast container ships [67].

The engines of the Wärtsilä RTA series continued to improve in terms of power, durability, and reliability by introducing new technologies and correcting disadvantages that emerged through the experience of its daily use on ships. In 1999, the phasing-out of an old model, such as the one with a 380 mm piston, began, which is no longer in great demand. Moreover, with this move, Wärtsilä aims to achieve that all engines in the RTA series meet the requirements set out in the IMO Annex VI NO_x for nitrogen oxide emissions (NO_x). The launch, in mid-1999, begins and the development of electronically controlled marine Diesel engines of the RT-flex series, which is a natural continuation of the RTA series with a transition to electronic control [8].

4.2. WinGD X Series

The WinGD X series' electronically controlled Diesel naval engines are a continuation of Wärtsilä's RT-flex series, which in turn are based on the traditional slow-speed two-stroke marine engines of Wärtsilä's RTA series. The research that resulted in the creation today of electronically controlled marine Diesel engines was launched in 1980 by the Sulzer company. In 2007, Wärtsilä announced the creation of the X engine generation based on the existing ones. The X series first electronically controlled Diesel series of diesel engines were released in 2012 and are the X35 and X45. The X40, X62, X72, and X62 models will be announced and added to the series in the same year. In particular, the X62 and X72 engines are designed to meet the requirements for the propulsion of a wide range of ships, such as Panamax and Capesize cargo ships, Aframax and Suezmax oil tankers, and Feeder container ships and Panamax. At the end of 2012, two more models, the X82 and the X92, will be added to the X series. To be precise, for the X92, the announcement of its release coincides with the tightening of the regulations on pollutant emissions, which this engine seems to cover perfectly [12].

The last addition to the X engine range was the X52, announced in 2013. This particular engine is described as the most compact option in its class. Further research has also led to improved versions (B) for the X62 and X72 models in 2014 [68].

Since 2015, when the X engine series has come under the umbrella of WinGD, no change has occurred. In June 2019, three new models were announced. These were the improved (D) version of the X82, the hybrid version, and the dual-fuel version of the X40 model.

In December 2019, WinGD announced four new models—short-drive engine variants for the already successful X52 and X62 models. The new models are released with the codes X52-S2.0 and X62-S2.0 and the corresponding dual-fuel engines [69].

Since its establishment, which results from a merger as analyzed above, WinGD has kept the same names in the engine lines as those used by Wärtsilä, including the X engine range. However, the number of old series that remains available is gradually decreasing, with the result that today only two models of engines from the RT-flex series are available. The rest of the models released by WinGD belong to the X series [55].

Figure 2 depicts all models of two-stroke marine Diesel engines released by WinGD. All engines are electronically controlled and belong to the X series except for two: the oldest series and RT-flex series [64,69].

4.3. Construction Differences

The WinGD X series' electronically controlled Diesel marine engines are a continuation of Wärtsilä's RT-flex series, which in turn are based on the traditional Wärtsilä series of Wärtsilä's traditional slow-speed two-stroke marine engines. A key difference compared to traditional mechanically controlled engines is the absence of the camshaft, fuel injection pumps, exhaust valve actuation pumps, reversal servo engines, and all relevant control mechanical parts. On the contrary, they are equipped with a standard rail system for fuel injection and activation of exhaust valves and the functions are fully controlled electronically.

Specifically, a mechanically controlled Wärtsilä RTA series Diesel engine and an electronically controlled RT-flex series of the same manufacturer are distinguished by the

absence of the camshaft and the corresponding drivetrain, conventional fuel pumps, and their replacement by the standard collector system and electronic control [8].

Table 1 presents the essential functions of an engine and how they are implemented both in the mechanical (RTA series) and in the electronically controlled engines (RT-flex and X series) [12,52].

Table 1. Comparison of design and functional parameters of mechanically and electronically controlled engines [55] edited by the author.

	RTA Series (Mechanically Controlled)	RT Series-Flex/X (Electronically Controlled)
Increase/maintain fuel pressure	One fuel pump in each cylinder/-	Fuel pumps in the fuel supply/collector unit
Fuel injection timing	Fuel cam on the camshaft	Electronic control
Exhaust valve activation	One actuation pump in each cylinder	Hydraulic activation system in the supply unit
Exhaust valve activation timing	Valve cam on the camshaft	Electronic control
Adjust the amount of fuel to be injected	Fuel regulator and fuel pump	Electronic control
Timing of air start	Start air dispenser	Electronic control
Inversion	Inversion of the cams	Electronic control

4.4. Performance Comparison

The electronically controlled Diesel naval engines of the WinGD X series are based on the reliable and tested for years mechanically controlled engines of the Wärtsilä RTA series. Their constructional and operational differences were analyzed both in the previous chapter and above. This chapter will study the main differences in performance and the advantages offered by electronically controlled engines over mechanically controlled ones.

The main differences and the most important advantages offered by the electronically controlled engines of the WinGD X series over the older mechanically controlled Wärtsilä RTA series can be summarized as follows [12,52]:

- Reduced fuel consumption in low-load mode;
- Ultra-low smoke emission at all operating speeds;
- Very stable operation at low speeds, even at 10% of the rated speed;
- Easier engine setup leading to less maintenance;
- Longer periods between maintenance mainly due to better load distribution between cylinders and perfect combustion.

Below we will analyze the main advantage by exploring how they arise and affect the operation of the engine and the ship as a whole [68].

4.4.1. Low Emissions

A key and apparent advantage of the engines of the WinGD X series compared to those of the Wärtsilä RTA series is the zero-smoke emission through the perfect combustion carried out with the help of the standard collector system presented above. Keeping the fuel at appropriately high pressure throughout the engine's operating range combined with precise fuel injection control and timing of the exhaust valve activation contribute to the emission of smoke pollutants below the limits of the visible even at very low speeds [17,20].

Another possibility offered by the electronically controlled diesel engines of the WinGD X series is the reduction in nitrogen oxide emissions (NO_x) without, at the same time, a significant increase in fuel consumption. In Diesel engines, achieving a simultaneous reduction in fuel consumption and nitrogen oxides (NO_x) emissions is generally difficult. The reduction in fuel consumption is achieved by such a timing that the combustion is completed when the combustion chamber is as tiny as possible (piston near the upper break-even point). However, in this case, the higher temperature will increase the emissions of nitrogen oxides.

For example, in a burning time of 10 ms with a temperature of 2400 K, the amount of nitrogen oxides produced is ten times more than at a temperature of 2200 K [70].

Different fuel injection standards can be created in electronically controlled marine Diesel engines. This is due to the fact that even each of the three injectors of each cylinder can be controlled separately [50].

The control of fuel injection can be a solution to the problem of simultaneously reducing fuel consumption and emissions of nitrogen oxides (NO_x). The sequential injection can lead to a decrease in the rate of heat emission during combustion, and thus to the reduction in nitrogen oxide (NO_x) emissions without, at the same time, increasing fuel consumption [17,71].

4.4.2. Steady Operation at Low Speeds

The WinGD X series' electronically controlled Diesel marine engines can operate more consistently at very low speeds compared to mechanically controlled ones such as those of the Wärtsilä RTA series. A typical example is their ability to operate consistently and smoke-free even at 10% of their service speed. The above property is beneficial when the ship is in canals [64].

Stable operation at low speeds is made possible by precise control of fuel injection. In particular, the ability to control each injection valve separately allows for turning off specific valves of each cylinder to inject the necessary amount of fuel at high pressure. Moreover, with this method, we have a better distribution of the thermal load between the cylinders as it does not stop the operation of the entire cylinder. Nevertheless, some of the three fuel injection valves operate in each cylinder. Finally, suppose the engine is running for some time at low speeds. In that case, electronic control ensures the alternation of the fuel injection valve in operation in order to ensure uniform stress on the combustion chamber and protection from damage [23,38].

4.4.3. Fuel Consumption Reduction

The mechanically controlled Diesel marine engines of the Wärtsilä RTA series have always been highly competitive in the fuel consumption part across the entire spectrum of the operating load. Technologies such as variable injection timing (VIT) and variable shutdown of the exhaust gas valve (VEC) made the engines of this series relatively low in consumption, even at low operating loads [52].

The main objective in the process of developing electronically controlled Diesel marine engines was to maintain all the advantages offered by mechanical control in areas, such as power, speed, fuel consumption, emissions, etc. Specifically, in the fuel consumption part, the increased pressure at which the fuel is kept in the common collector's system ensures significant consumption savings even at low loads while maintaining at the same time maximizing the control of the combustion in the cylinder, and consequently the performance of the engine throughout the load range [72].

A significant advantage offered by electronically controlled WinGD X Series Diesel marine engines is the complete flexibility in both timing, quantity determination, and pressure during fuel injection and in the operation of the exhaust valve. This allows, through electronic control, for the adjustment of the engine to reduce fuel consumption [55].

4.5. Regulatory Implications

EEXI is an IMO mandatory goal-based standard for ship energy efficiency. Vessels in the scope of this regulation must submit (to the Flag Administration or Classification Society) a technical study with the respective EEXI calculations. In the case that the vessel's attained EEXI is higher than the required EEXI limit, which has been set for different ship sizes and types [73], the study should include the selected method to reach the required EEXI limit by implementing a technical solution to improve its energy efficiency performance.

Clarksons Research [74] estimates that only 30% of existing vessels (25,000+ dwt) conform with the EEXI's efficiency criteria, whereas 40% of tankers and 25% of bulk carriers are far from the required EEXI levels and will need drastic measures to comply.

Different technical options to improve the energy efficiency of existing ships can be considered under the goal-based approach of EEXI [75]. However, the EEXI equation is highly dependent on the parameter of the ship's speed, which means that these technical solutions have a marginal effect on improving the EEXI.

Due to the limited time given to existing ships to comply, the high retrofit cost associated with the installation of the considered energy efficiency technical solutions and their marginal effect to improve the EEXI, the most widely used option for the non-compliant ships appears to be the establishment of a semi-permanent (overridable in emergencies) limitation to the power of the main engine(s), thus imposing a speed limit to the vessel. This solution can take the form of either an engine power limitation (EPL) or a shaft power limitation (SHaPoLi) [76].

Implementing the EPL/SHaPoLi solution is different for mechanically and electronically controlled engines.

For mechanically controlled engines of existing ships, the simplest solution to comply with the EEXI regulation is to install a mechanical fuel index sealing system to limit the maximum engine power to the required level. In effect, the ship's main engine will not be able to operate above the limited power level except for emergencies. The actions needed for implementing the EPL in the case of mechanically controlled engines include changing the governor set to limit the fuel, and then adjusting a mechanical stopper with a sealing device.

For electronically controlled engines, the technical EPL solution consists of a password-protected software fuel limiter which electronically locks the fuel index or with a direct limitation of the power in the engine's control system in order that the ship's crew cannot release the EPL without permission.

The EPL is not supposed to alter the engine performance, and engine makers submit shop trial data to verify the adjustment of the engine in at least three loading conditions (typically 25%, 50%, and maximum power after EPL). Figure 3 shows the available power range for the case of SHaPoLi or electronic EPL and mechanical EPL [76].

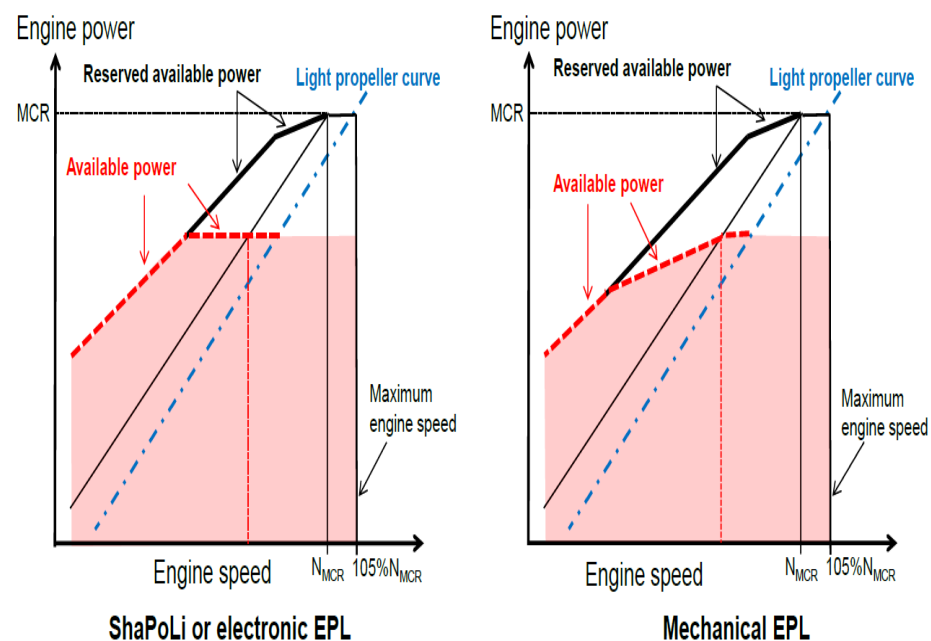


Figure 3. Engine and shaft power limitation options for existing ships to comply with the EEXI regulation [76].

The year 2023 is the first year of the full enforcement of the EEXI regulation, which marks the first time that an international regulation enforces a speed limit for ships. The global enforcement of this measure is considered straightforward since the control of the engine power is practically enforceable under the survey and certification schemes in the context of existing IMO regulations (i.e., MARPOL Annex VI); therefore, unlike the operational speed reduction, the speed limit will be easier to be monitored and verified.

There are also other regulations by IMO coming to effect in 2023 (e.g., the carbon intensity indicator—CII) that are expected to have further impacts on the ship's speed which may impose further operational adjustments of the speed. Overall, the actual effects that the new IMO regulations will have on the operation of marine engines remain to be seen. There are concerns that the imposed speed limit in practice will not be able to support the achievement of the IMO to set the target of reducing (by 40% in 2030) the overall greenhouse gas emissions from international shipping. According to an ICCT working paper [77], the EPL as a technical measure will not proportionately reduce the CO₂ emissions of shipping since most ships today are already operating at well below their maximum speeds, and thus well below their MCR.

As shown in Figure 4, the distribution of main engine loading factors varies in the three major ship types (containers, bulk carriers, and oil tankers) during 2019. Container ships had the lowest load factors, ranging between 10% and 30% MCR, while oil tankers and bulk carriers had more normal distributions around their annual averages of about 50% MCR [77]. Although the study does not report the mixture of mechanically and electronically controlled engines in the ship's sample, it is apparent that the operation at these low loads is less efficient for mechanically controlled engines.

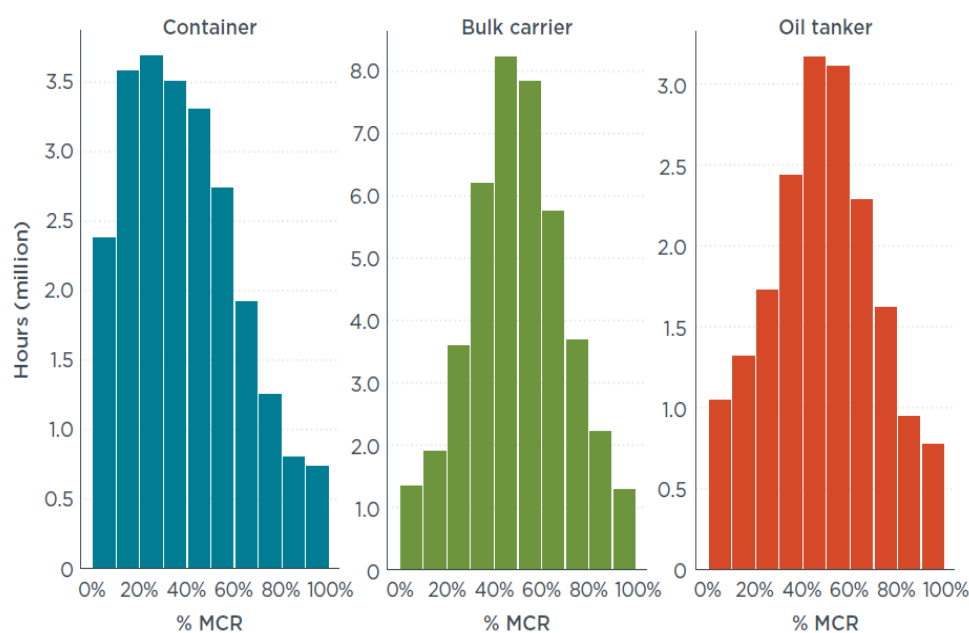


Figure 4. Main engine load factor distribution for containers, bulk carriers, and oil tankers in 2019 [77].

Overall, the new IMO regulatory requirements introduce limitations in the available power of installed marine engines of existing ships. Due to the increased flexibility of the electronically controlled engines, the setup to meet the EEXI requirement will be typically more straightforward, and the operation in low loads will be stable and with higher efficiency compared to mechanically controlled engines.

5. Discussion

The production of a project using thermal internal combustion engines is based on the impulsion of heat from the combustion of suitable fuels at high pressure to the working

medium, part of which can be recovered in the form of mechanical work. At the same time, the rest is expelled into the environment. The most widely used internal combustion engine is the Diesel engine. The Diesel engine's wide spread was instrumental in modern shipping's development.

A simple slow-moving Diesel engine generally satisfies commercial ships' propulsion requirements. These machines can burn fuel of much worse quality than a mezzo-speed engine since they have more time and space. All modern engines used to propel commercial ships are two-stroke and overcrowded [78]. The rapid development of naval engines turned the interest to manufacturing sluggish machines of large piston diameter, greater compression, and high efficiency. While replacing Diesel engines with alternative propulsion engines is difficult to achieve, companies are turning to improvements, such as operating at lower rotational speeds, higher maximum combustion pressures, and more efficient overcrowding systems. The introduction of electronically controlled Diesel marine engines, which in recent years has dominated, is an event of historical importance that deserves a place next to the invention of the first engine by Rudolf Diesel, the placement of the first naval engine on the Selandia ship in 1912 and the adoption of overcrowding in two-stroke naval engines in 1954 [1,79].

The said engines with electronically controlled injection and electronically controlled exhaust valve activation systems have made their appearance. They are beginning to dominate the market, thus leading to the era of "Smart Machines." These machines can adapt their operating parameters through electronic systems and aim at optimal performance [80].

A key difference compared to traditional mechanically controlled engines is the absence of the camshaft, fuel injection pumps, exhaust valve actuation pumps, reversal servo engines, and all relevant control mechanical parts. On the contrary, they are equipped with a common rail system for fuel injection and activation of exhaust valves and the functions are fully controlled electronically [81].

The common rail system is a fuel injection system for Diesel engines, in which the fuel first gains increased pressure through pumps, and then accumulates in the common collector. Finally, the injection of the accumulated high-pressure fuel from the typical collector is carried out in each cylinder separately at the appropriate time using electronically controlled control valves. The common rail system is the basis on which the operation of the electronically controlled naval Diesel engine circulated by Wärtsilä and WinGD is based [82]. The fuel accumulated in the common collector at high pressure (1000 bar) through the injection control units reaches the fuel injection valves. Moreover, the control oils and hydraulic systems are at a pressure of 200 bar and are used, among other things, to control the activation of the exhaust valve. All are connected to the central control system of the electronically controlled naval engine responsible for continuously monitoring the operating condition and adjusting the operational parameters.

Finally, it is worth noting that in recent years, and based on what has been mentioned above regarding the better performance of engines and the protection of the environment, dual fuel engines have appeared, where natural gas (LNG) is used as fuel. Initially, these engines were installed in ships transporting liquefied natural gas (mainly for construction reasons, where they consumed the exhausts of the cargo in order to keep the pressure of the cargo tanks at low levels). Nevertheless, due to the low price of LNG as fuel and the almost zero harmful pollutants in the atmosphere, they are installed in other types of ships with excellent results to date [83].

Comparison of Wärtsilä RTA and WinGD X under New IMO's EEXI Regulations

Wärtsilä's two-stroke diesel RTA series of slow-moving marine engines was launched in late 1981 and was an intersection with the company's previous engines. Moreover, the WinGD series X series' electronically controlled diesel marine engines are a continuation of Wärtsilä's RT-flex series, which in turn are based on the traditional Wärtsilä's traditional slow-speed two-stroke marine engines of the Wärtsilä RTA series [84].

Subject to the enforcement of the new EEXI regulations, the main differences and the most important advantages offered by the electronically controlled engines of the WinGD X series over the older mechanically controlled Wärtsilä RTA series can be summarized as follows:

- Reduced fuel consumption in low-load mode;
- Zero-smoke emission at all operating speeds;
- Very stable operation at low speeds, even at 10% of the rated speed;
- More straightforward engine setup leading to less maintenance;
- More extended periods between maintenance mainly due to better load distribution between cylinders and perfect combustion.

A vital and apparent advantage of the engines of the WinGD X series compared to those of the Wärtsilä RTA series is the zero-smoke emission through the perfect combustion carried out with the help of the standard collector system presented above. Keeping the fuel at an appropriate high pressure throughout the engine operating range combined with precise fuel injection control and timing of exhaust valve activation contribute to the emission of smoke pollutants below the visible limits even at very low speeds [85].

Diesel engines are generally complex to achieve a simultaneous reduction in fuel consumption and emissions of nitrogen oxides (NO_x). In electronically controlled marine Diesel engines, there is the possibility of creating different fuel injection standards at different loads. This is due to the fact that even each of the three cylinder injectors can be controlled separately. The control of fuel injection can be a solution to the problem of simultaneously reducing fuel consumption and emissions of nitrogen oxides (NO_x). The sequential injection can lead to a decrease in the rate of heat emission during combustion, and thus to the reduction in nitrogen oxide (NO_x) emissions without at the same time increasing fuel consumption; therefore, abiding with the new EEXI and CII legislation and EU MRV, as well as IMO CDS monitoring systems [86].

6. Conclusions

The electronically controlled Diesel marine engines of the WinGD X series can operate more consistently at very low speeds compared to mechanically controlled engines such as those of the Wärtsilä RTA series. Stable operation at low speeds is made possible through precise control of fuel injection, thus making the engine and then the ship much more agile in movements and maneuvers.

The mechanically controlled Diesel marine engines of the Wärtsilä RTA series have always been highly competitive in the fuel consumption part across the entire spectrum of the operating load. The same technology, followed by significant improvements, was bequeathed to the electronically controlled naval engines of the RT-flex and X series. Specifically, in fuel consumption, the increased pressure at which the fuel is kept in the common collector's system ensures significant consumption savings even at low loads. An essential advantage of electronically controlled WinGD X series Diesel marine engines is the complete flexibility in both timing, quantity determination, and pressure during fuel injection and operation of the exhaust valve. This allows, through electronic control, for the adjustment of the engine to reduce fuel consumption [87].

The regulatory review concludes that compulsory limitations in the propulsive power of many commercial ships, enforced by the new IMO legislative framework, will have fewer implications in electronically controlled engines due to their improved flexibility and overall ability to operate efficiently even at low loads. From an economic perspective, the electronically controlled engines are a more viable choice, due to decreased OPEX as a result of their efficient operation at low loads. Moreover, by requiring the installment of less operational processes, less personnel will be involved onboard and onshore.

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