TECHNIUM

Technium Vol. 31, pp.158-172 (2026)
ISSN: 2668-778X
www.techniumscience.com

Engine operating regimes: A propulsion performance study for low-speed two-stroke marine engines

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Abstract

Understanding the operating regimes of marine engines is essential for evaluating propulsion performance, operational safety, and efficiency in navigation. Although manufacturer load diagrams define the admissible operating envelope, real operating conditions frequently deviate from design assumptions due to resistance growth, environmental influences, and transient manoeuvring events. This study proposes a regime-based analytical framework for assessing propulsion performance in relation to the manufacturer-defined load diagram. The analysis is conducted through a case study of a 31,000 DWT multi-purpose container vessel equipped with a Wärtsilä 6RT-flex58T-D low-speed two-stroke marine diesel engine. Certified sea trial reports and endurance test records provide the primary dataset. Measured propulsion parameters are mapped onto the manufacturer load diagram to evaluate operating-point migration and associated performance implications. The results demonstrate that regime-induced migration of the operating point affects mechanical margin, air-supply availability, and thermal loading. Heavy-running conditions increase torque demand and move the operating point toward low-speed torque constraints, while transient regimes reveal limitations associated with turbocharger inertia and dynamic air–fuel imbalance. The proposed framework integrates manufacturer operating constraints with empirical sea-trial evidence to provide a structured approach for analysing marine engine performance under realistic operational conditions and supporting improved assessment of propulsion efficiency and operational margins.

Keywords: Marine engines; Ships propulsion performance; Engine operating regimes, Sea trial

1. Introduction

The operating regime of a marine diesel engine is fundamentally defined by the aggregate of its operating conditions and can be described through three primary magnitudes: crankshaft rotational speed, engine load, and the thermal state of the engine [1],[2]. From a theoretical perspective, regimes are classified according to the time-domain stability of these parameters. A permanent (steady-state) regime is characterised by near-constant values of speed and load, with thermal and mechanical stresses maintained within narrow limits by the engine manufacturer requirements and control systems. In contrast, a transient regime is characterised by significant time variations in angular velocity and torque, as encountered during starting, stopping, acceleration, deceleration, manoeuvring, or highly variable load profiles. Under transient conditions, the engine must also overcome inertial effects in the rotating parts system, together with turbocharger rotational inertia and scavenge receiver filling dynamics [3]. In addition, gas-exchange and turbocharging processes do not respond instantaneously to rapid fuel supply and load changes, which makes the thermal behaviour and operating margins more sensitive than under steady operation.

Within this theoretical framework, steady-state regimes are further distinguished by permissible duration and intensity. The continuous operation regime corresponds to the engine's capability to develop its maximum rated effective power and torque indefinitely without compromising reliability, durability, or safe thermal load. The intermittent or overload engine running regime allows operation above the continuous rating for short, explicitly limited time intervals, after which the engine must return to a permissible continuous region to avoid cumulative thermal overload and mechanical wear [4]. These concepts align with the manufacturer's operational definitions [5], where continuous service ranges are unrestricted, while overload regions are time-limited (commonly specified as a maximum duration per operating cycle, such as one hour within a twelve-hour period). This separation is important for performance assessment because it distinguishes operating points that are acceptable for sustained service from points that are permissible only as short-term excursions.

To examine how different operating regimes influence propulsion performance, the study adopts a structured analytical approach based on the manufacturer engine load diagram and certified sea-trial data. The following sections first present the case study vessel and propulsion system in order to define the technical context of the analysis. The engine load diagram and the corresponding operating envelope are then introduced as the reference framework for interpreting admissible operating points. Subsequently, the regime-based assessment methodology and the experimental sea-trial datasets are described. Finally, the methodology is applied to representative operating regimes in order to evaluate their influence on mechanical margin, thermodynamic stability, and propulsion efficiency under realistic service conditions.

2. Case study vessel and propulsion system

The study is based on a 31,000 DWT multi-purpose container vessel, fitted with a single-screw propulsion arrangement and a fixed pitch propeller (right-hand rotation). The propulsion plant is based on a conventional low-speed diesel main engine directly coupled to the shaft line, which represents a typical merchant-ship propulsion configuration and provides an appropriate engineering case for evaluating how operating regimes influence mechanical performance and operating margins under realistic service constraints.

- Ship Type: Multi-Purpose Vessel, equipped for containers and heavy cargo.
- Length Overall (LOA): 199.90 m
- Breadth: 28.20 m
- Design Draft: 9.50 m
- Gross Tonnage: 25,483
- Deadweight: 30,814 mt
- Container Capacity: 2,117 TEU
- Main Engine: Wärtsilä 6RT-flex58T-D Tier II
- Maximum Continuous Rating: 13,560 kW @ 105 rpm
- Continuous Service Rating: 8,136 kW @ 88.6 rpm (approx. 60% MCR)
- Propeller: 4-bladed, fixed pitch, Diameter 6,610 mm, Mean Pitch 5,596 mm
- Service Speed: 15.5 knots (at 10.5m draft, CSR with 15% Sea Margin)

The main engine is a Wärtsilä 6RT-flex58T-D (IMO Tier II), a single-acting, two-stroke, low-speed crosshead marine diesel engine with 6 cylinders, exhaust-gas turbocharging, and uniflow scavenging. The RT-flex concept replaces the conventional camshaft with a Wärtsilä common-rail system, providing fully electronic control of fuel injection and exhaust valve actuation, managed by the WECS-9520 control system. This allows for precise control of engine operation across the load range and is particularly relevant when interpreting transient regimes where fuelling can change rapidly relative to the scavenging air response.

For load-diagram mapping and definition of the reference operating envelope, the Maximum Continuous Rating (MCR) is adopted as the primary rated point, equal to 13,560 kW at 105.0 rpm. This MCR point provides the baseline reference for positioning measured operating points relative to the manufacturer-defined limits and permissible operating regions. The ship's design/service operating point is given as a Continuous Service Rating (CSR) of 8,136 kW at 88.6 rpm (approximately 60% of MCR). The permissible operating range is bounded by manufacturer-defined limit lines on the load diagram, including restricted zones relevant to heavy running and transient operation. An overload capability up to 110% power is permitted under a time limitation (maximum 1 hour per 12 hours) to prevent excessive mechanical and thermal load.

The propeller characteristics are defined by a diameter of 6.610 m, four blades, an expanded blade area of 19.40 m^2, and a mean pitch of 5.596 m (approximately $0.847 \cdot D$). These particulars are sufficient for characterising the nominal propeller demand behaviour and for supporting load diagram interpretation, including the establishment of a reference propeller characteristic used as the baseline for regime mapping and comparative performance assessment.

The marine engine load diagram provides a practical engineering representation of operating regimes by defining the permissible combinations of engine power and speed for a given rating and installation.

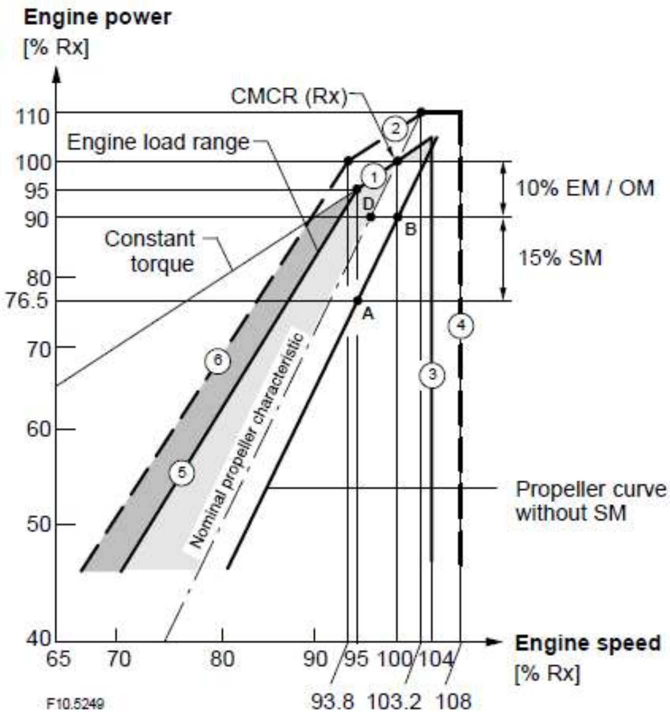

Figure 1 Engine load diagram

The engine load diagram delineates operating regions bounded by manufacturer-specified thermodynamic and mechanical constraints, including mean effective pressure related limits, admissible torque boundaries, maximum speed limits and any time-limited overload provisions. Within this framework, the propeller characteristic represents the demand side: a light-running curve approximates baseline operation for a clean hull in calm weather, whereas heavier-running characteristics represent increased resistance due to hull and propeller fouling, adverse sea states, shallow water effects or increased displacement.

Normal operation is intended to remain on or near the nominal propeller curve where air supply margins and combustion conditions are favourable. However, as the operating point shifts away from this characteristic, particularly towards lower speed at a given power demand (higher torque region), air supply becomes less favourable and the engine approaches admissible torque limits and smoke-limited operation, with a tendency towards higher thermal and mechanical load. Such off-design operation is typically associated with reduced margins to limit lines and a deterioration of fuel conversion efficiency, which may be reflected in increased specific fuel consumption and higher emissions intensity. Transient and manoeuvring regimes impose additional constraints beyond those visible in steady-state maps, since dynamic processes can produce thermal overload and other limiting conditions even when the instantaneous power trajectory remains within the static envelope. Consequently, assessing real operating regimes requires a combined interpretation of the static load diagram and measured ship data, with a clear distinction between steady and transient behaviour in order to quantify operating margin and efficiency under realistic operational constraints.

To allow for consistent interpretation of all measured and projected operating points, the manufacturer's engine load diagram is used as an operating-envelope definition that links propeller demand, service margins and the engine's operational limits. For a fixed-pitch propeller installation, the propeller imposes a rigid coupling between rotational speed and absorbed power. Under conventional assumptions, the propeller law provides an adequate approximation of this demand behaviour, such that power varies with the cube of propeller speed:

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \qquad 1$$

The curve defined by this relationship is referred to as the propeller characteristic. When the engine and air system are in proper condition (i.e., satisfactory turbocharger performance, acceptable intake/exhaust pressure losses and correct injection settings), the Mean Effective Pressure (MEP) developed in service at a given load indication can be related to the equivalent MEP level at the same relative position on the test-bed load diagram. Consequently, the load diagram provides a transferable reference for interpreting in-service points, provided that the installation condition and air-path integrity remain within specified bounds.

On the load diagram, the propeller characteristic passing through the CMCR (Contract Maximum Continuous Rating) point (100% power at 100% rated speed) is taken as the nominal propeller characteristic, and test-bed load for fixed-pitch propeller engines is typically arranged to follow this curve. In contrast, sea trials are conducted with a new, clean hull and smooth propeller under favourable conditions, and the measured operating points therefore tend to lie below the nominal propeller characteristic (light-running behaviour). This distinction is important because the sea-trial curve represents a best-case demand condition rather than the long-term service condition.

In normal service, additional torque is generally required to maintain a given propeller speed compared with the sea-trial condition. This "sea margin" reflects increased hull and propeller resistance and altered inflow conditions, arising for example from marine growth affecting wake flow, changes in vessel draught due to load, propeller roughness or damage, adverse sea and weather, and shallow-water operation. As propeller torque demand increases, the engine MEP (and thus injected fuel quantity) must rise accordingly, and the corresponding operating point migrates leftwards relative to the sea-trial propeller curve when mapped onto the load diagram (higher torque at lower speed for comparable power demand).

Although hull cleaning and repainting reduce resistance, the vessel cannot typically be restored fully to the as-new sea-trial condition. Because thermal load correlates strongly with MEP, the position of the operating point relative to the propeller characteristic becomes a practical indicator of operating severity. If the operating point lies too far above the propeller curve, air supply and overall operating conditions may become inadequate. For best operating conditions in service, the engine operating point should therefore remain on or below the nominal propeller characteristic within the permissible service range.

3. Engine load diagram and operating envelope

Within this framework, the Continuous Service Rating (CSR) represents the service-condition operating point for contractual speed. Conceptually, Point A corresponds to the contractual speed in calm seas with a new, clean hull and propeller, whereas the same ship at the same speed in service conditions (aged hull and average weather) requires a higher power/speed combination represented by Point D. Point D is therefore identified as the CSR point and is used as a realistic basis for sustained service operation.

In merchant-ship practice, owners commonly specify the contractual loaded service speed at approximately 85% to 90% of CMCR. The remaining 10% to 15% power is retained as margin that can be used to recover schedule delays or to manage the interval between dry-dockings. This reserve is typically treated as an operational margin deducted from CMCR, and the 100% power reference line can be related back to the CSR point by dividing the power at Point D by 0.85 to 0.90. In the load-diagram interpretation, the margin terminology is used consistently as: EM (engine margin), OM (operational margin) and SM (sea margin).

Once the engine is optimised at CMCR (Rx), the admissible working range is bounded by manufacturer-defined border lines, which provide the operational constraints used for regime mapping:

- Line 1 (constant MEP / constant torque through CMCR): extends from 100% speed and power down to 95% power and speed and represents a constant torque (constant MEP) boundary through CMCR.
- Line 2 (overload limit): a constant MEP line extending from 100% power at 93.8% speed to 110% power at 103.2% speed, where the latter corresponds to the intersection of the nominal propeller characteristic with 110% power.
- Line 3 (continuous speed limit): the 104% speed limit for continuous operation; for reduced-speed ratings (NCMCR ≤ 0.98 NMCR) this limit may be extended to 106%, subject to torsional vibration constraints.
- Line 4 (overspeed limit): operation between 104% (or 106%) and 108% speed is only permissible during sea trials, if required to demonstrate ship speed at CMCR power in the presence of authorised representatives, and subject to torsional vibration constraints.
- Line 5 (admissible torque limit / low-speed constraint): extends from 95% power and speed to 45% power and 70% speed and is described by a power law of the form:

$$\frac{P_2}{P_1} = (\frac{n_2}{n_1})^{2.45} \qquad 2$$

As Line 5 is approached, the engine increasingly suffers from lack of scavenge air and its consequences. The region bounded by Lines 1, 3 and 5 therefore defines the principal area within which the engine should be operated. The area bounded by the nominal propeller characteristic, 100% power and Line 3 is recommended for continuous operation, while the region between the nominal propeller characteristic and Line 5 provides operational flexibility for acceleration, shallow-water effects and normal service variability.

- Line 6 (maximum torque limit in transient conditions): defined by the same power-law form through 100% power at 93.8% speed and represents a maximum torque boundary for transient operation.

The area above Line 1 represents overload and is permissible only with an explicit time limitation (typically maximum one hour during sea trials in the presence of authorised representatives). The band between Lines 5 and 6 (often indicated as a restricted/shaded area together with the constant torque line) is reserved for transient conditions such as fast acceleration and is treated as a “service range with operational time limit”.

Together, these definitions provide the manufacturer-consistent basis for interpreting operating-point migration and regime boundaries on the load diagram. In the present study, this envelope supports (i) a defensible distinction between continuous service operation, time-limited overload, and transient-only regions, and (ii) a consistent reference frame for mapping SR1/SR2 measured points and for interpreting projected heavy-running and manoeuvring behaviour relative to admissible torque and air-supply constraints.

4. Regime-based assessment

In the present regime-based assessment, marine engine performance is not treated solely as cycle efficiency at a nominal rating point. For a low-speed, 2-stroke propulsion engine operating behind a fixed-pitch propeller, performance is understood as the coupled ability of the engine and its scavenge air system to meet propeller demand while remaining within admissible mechanical and thermal limits. Engine performance is therefore interpreted through three interrelated dimensions, each directly linked to the position of the operating point on the engine load diagram.

First, performance comprises propulsive capability, defined as the ability to deliver the required torque at a given rotational speed without encroaching upon permissible mechanical load boundaries. In practical terms, this is reflected by the available torque reserve between the measured operating point and the relevant limiting curves, including constant torque boundaries and time-limited overload regions. Adequate initial margin allows the propulsion plant to accommodate resistance growth arising from hull fouling, environmental conditions or shallow-water effects without forcing operation into mechanically critical zones.

Second, performance includes thermodynamic stability, governed by the effectiveness of the turbocharging and scavenge system in maintaining sufficient charge-air pressure and air excess ratio across the operating range. A stable air supply supports controlled combustion temperatures and acceptable exhaust-side thermal load. As the operating point migrates towards low-speed, high-torque regions, air delivery can become limiting and turbine inlet temperatures may rise, reducing thermal margin and increasing component stress.

Third, performance encompasses fuel conversion efficiency, expressed through the variation of specific fuel oil consumption (SFOC) as the operating point moves across the load and performance map. Minimum SFOC is achieved only within a defined region of the engine operating field. Deviations from this region, whether driven by heavy running, overload or transient manoeuvring, lead to measurable efficiency penalties for the same delivered propulsive output.

On this basis, the analysis quantifies the migration of the operating point under different operational regimes, namely the baseline light-running sea-trial condition (SR1), the stabilised endurance condition (SR2), the projected heavy-running condition (R2) and the transient manoeuvring regime (TR1), and interprets this migration in terms of mechanical margin, thermodynamic stability and fuel conversion performance.

5. Experimental data and sea trial measurements

The quantitative analysis is based on the vessel’s Sea Trial Report, which provides a baseline of propulsion performance for a new, clean-hull condition. The trial programme was conducted in the East China Sea over 30 July to 4 August and includes steady propulsion performance measurements, main engine load and endurance holds, and manoeuvring trials. Steady operating points were recorded at discrete load steps of 45%, 60%, 75%, 90% and 100% MCR during the contract speed trial programme. The core variables used in the subsequent analysis are propeller shaft speed and shaft power, together with ship speed recorded by DGPS. Additional engine-state parameters are available from the main engine load and endurance test records, including scavenge receiver pressure and temperature, exhaust gas temperatures at several locations, turbocharger speed, cooling-water system data, and cylinder firing and compression pressure measurements. Trial condition information is also reported, including water depth and environmental descriptions (wind and sea state) per test block, allowing the measured points to be contextualised.

The speed–power measurements are reported for a ballast condition with a forward draught of 4.69 m and an aft draught of 8.10 m. Water depth during the speed trial runs is reported in the range 62.2 to 70.0 m, which is sufficient to minimise shallow-water effects for the analysed points.

From the full sea trial programme, three test blocks are selected because they provide the most defensible datasets for regime-based assessment. The Ship Speed and Propeller Shaft Power Test is used to define the baseline steady operating characteristic under trial conditions, using the five discrete load points and the double-run reciprocal heading procedure to obtain mean values that reduce the influence of current and wind on the speed–power relationship. The Main Engine Load Test and Endurance Test is used to characterise thermally stabilised behaviour at sustained loads, including endurance holds of 120 minutes at 60% and 90% MCR and 240 minutes at 100% MCR, providing a reliable basis for interpreting temperatures, pressures, and turbocharging response at defined operating points. The manoeuvring programme, including crash stop and zig-zag or turning trials, is used to represent transient operation through time-series kinematic response data (speed, heading, rudder and position), supporting regime definition even where high-frequency engine load telemetry is not available.

The selected datasets are applied with explicit traceability to the certified sea trial documentation and the engine operating manual, using the manufacturer engine load diagram as the common reference frame for interpreting operating points and regime boundaries. SR1 establishes the baseline steady propulsion characteristic under light-running trial conditions using the five mean steady points (shaft speed, shaft power and DGPS speed), which are used to derive the reference propeller-demand relationship and map measured points onto the load-diagram plane relative to the relevant limit lines. SR2 represents thermally stabilised high-load operation using the stated endurance durations together with the corresponding recorded engine condition parameters such as scavenge pressure, turbocharger speed, exhaust gas temperatures and cylinder pressures, supplemented where available by trial fuel properties and corrected SFOC. TR1 represents transient operation using manoeuvring time, which allows for defensible classification of dynamic regime. However, as synchronised engine rpm, power and torque time series are not reported for manoeuvres, a continuous transient trajectory cannot be reconstructed quantitatively on the load diagram from the sea trial report alone. Accordingly, TR1 is treated through vessel-response records, while the load diagram is used to frame the discussion of transient operating restrictions and the expected migration of the operating point.

To move from the manufacturer-defined operating envelope to vessel-specific evidence, the quantitative analysis is anchored in the certified Sea Trial Report for the case vessel. Manufacturer guidelines and test-bed curves define an idealised reference condition (standard ambient assumptions, controlled charge-air/exhaust conditions, and prescribed propeller-law load on the test bed). In service, however, the instantaneous working point on the load diagram is determined by the coupled response of hull resistance, wake field, fixed-pitch propeller demand, and environmental conditions. The Sea Trial Report is therefore used as a validated baseline map of extractable propulsion performance against which heavy-running and transient regimes can be interpreted in a technically defensible manner.

SR1 - Light-running baseline

The steady speed–power programme is used to define the vessel’s light-running propulsion characteristic for a clean hull and favourable trial condition. The discrete operating points provide measured shaft power and shaft speed pairs that describe the effective propeller-demand curve under the trial state. This baseline is essential because the engine does not operate on a single theoretical propeller characteristic in service: resistance growth (fouling), weather and load condition change the required torque at a given propeller speed. By mapping the SR1 points onto the Wärtsilä load diagram and comparing them with the nominal propeller characteristic and relevant limit lines, SR1 quantifies the initial torque/speed reserve (light-running margin). In practical terms, this reserve is the buffer that allows future resistance increases to be absorbed without immediately pushing the engine towards thermally and aerodynamically unfavourable regions, including reduced scavenge-air margin at higher torque for a given speed. Establishing SR1 therefore prevents subsequent discussion of heavy running from becoming qualitative, because it fixes the starting point and the available margin in measured terms. For the SR1 regime, the dataset comprises engine speed, shaft power and DGPS ship speed at the discrete load points of 45%, 60%, 75%, 90% and 100% MCR, supplemented by the reported trial conditions, including water depth and relative wind speed and direction. Mean values from reciprocal runs are used to minimise environmental bias, and these points define the light-running baseline used for subsequent mapping and comparison.

Table 1 Speed and propeller shaft test.

Load (% MCR)	Shaft Speed (rpm)	Mean Shaft Power (kW)	Mean Ship Speed (kn)	Water Depth (m)
45%	80.2	5408.0	14.97	62–67
60%	88.3	7198.5	16.50	65–67
75%	95.3	9088.0	17.62	65–67
90%	101.4	10826.5	18.53	67–68
100%	105.1	12046.0	19.04	69–70

SR2 - Thermally stabilised engine behaviour

The SR2 provides operating conditions in which the engine approaches a quasi-equilibrium thermal state at sustained load. These periods are the most suitable basis for interpreting charge-air delivery, turbocharger matching, combustion temperature level and exhaust-side thermal load at defined operating points. Parameters such as scavenge receiver pressure, turbocharger speed and exhaust gas temperatures form a "healthy signature" for compliant continuous operation on this specific installation. In load-diagram terms, SR2 corresponds to operation within the continuous service range, where the air path is expected to maintain adequate air–fuel ratio and component thermal limits remain satisfied. SR2 is therefore used as the reference condition against which off-design regimes are discussed: when heavy running or transient operation shifts the working point towards reduced scavenge margin or higher specific thermal load, SR2 provides the benchmark for what stable, acceptable operation looks like in this case. For the SR2 regime, the focus is placed on parameters that represent thermodynamic stability under sustained load.

Table 2 Endurance load schedule.

Load (% MCR)	Engine Speed (rpm)	Shaft Power (kW)	Hold Duration (min)
60%	88.5	7129	120
90%	101	11307	120
100%	105	12509	240

Table 3 Engine thermal and air parameters.

Parameter	60% MCR	90% MCR	100% MCR
Scavenge air pressure (bar)	1.75	3.10	3.07
Turbocharger speed (rpm)	10364	12734	12779
Exhaust gas temperature before turbine (°C)	359	435	465

R2 - Heavy-running behaviour

A recognised limitation of sea trials is that they are intentionally conducted in benign conditions with a new, clean hull and smooth propeller; severe weather and long-term resistance growth are not directly captured. To evaluate the influence of increased resistance, the sea-trial baseline is used as the input for a controlled projection. Specifically, a representative sea margin (expressed as increased delivered power/torque demand at a given propeller speed) is applied to the measured SR1 propeller-demand curve to generate an indicative service propeller characteristic. When mapped onto the engine load diagram, this transformation makes the expected migration of the operating point explicit: at a given propeller speed, higher resistance implies higher torque and mean effective pressure, shifting the working point leftwards and upwards relative to the light-running baseline. The engineering value of this step is that regime change becomes visible and testable against manufacturer constraints, allowing projected points to be assessed for proximity to low-speed/air-deficit boundaries and for increased thermal load implied by higher mean effective pressure at reduced speed.

TR1 - Representing transient operation through manoeuvring kinematics

The manoeuvring trials (e.g., crash stop and turning/zig-zag manoeuvers) provide time-history evidence for transient regimes in which the propulsion plant experiences rapid changes in propeller load and engine command. Where the trial report does not provide synchronised high-frequency engine torque/power telemetry during manoeuvres, the vessel response records (speed decay, heading evolution, rudder demand and time-to-stop) still capture the timescale and severity of the transient event. From a machinery perspective, these manoeuvres are important because the engine turbocharger system has inertia: during rapid load changes, air delivery does not instantaneously track fuelling, and short-duration operation with reduced excess air and elevated thermal stress may occur relative to steady-state expectations. TR1 is therefore used to evaluate transient operating restrictions and to clarify why transient behaviour cannot be interpreted as a sequence of quasi-steady load-diagram points without additional synchronised engine measurements. As synchronised engine torque and instantaneous fuelling or fuel index data are not provided for manoeuvres, transient engine trajectories cannot be reconstructed directly in the load-diagram plane from the Sea Trial Report alone. TR1 is therefore represented kinematically, while the load diagram is retained as the reference frame for interpreting transient operating restrictions and expected operating-point migration.

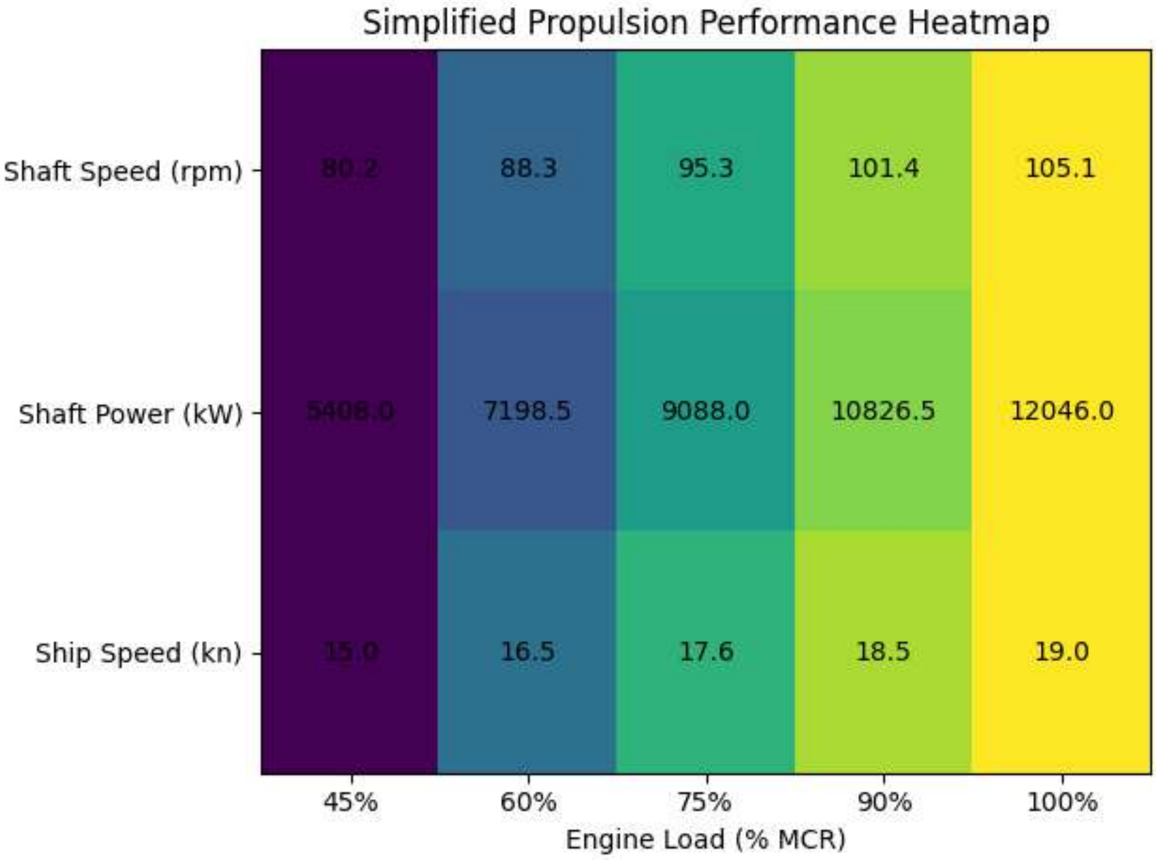

Figure 2. Simplified Propulsion Performance Heatmap in Matplotlib

This figure presents a heatmap representation of propulsion performance parameters derived from the sea trial dataset. The visualization is generated using Python with the Matplotlib library. The input dataset includes engine load (% MCR), shaft speed (rpm), mean shaft power (kW), and ship speed (knots).

For visualization purposes, the numerical values of shaft speed, shaft power, and ship speed were arranged into a matrix and normalized using a min–max normalization. This transformation scales each parameter between 0 and 1, allowing variables with different magnitudes and units to be visually compared within the same heatmap.

The heatmap was generated using the imshow() function from Matplotlib. The horizontal axis represents the engine load levels recorded during the sea trials (45–100% MCR), while the vertical axis represents the propulsion parameters. The color intensity indicates the relative magnitude of each parameter at the corresponding operating point.

This graphical representation highlights the progressive increase in shaft speed, shaft power, and vessel speed as the engine load approaches the maximum continuous rating, illustrating the expected propulsion performance trend during steady-state sea trial conditions.

6. Results and Discussion

To quantify the influence of operating regimes in a manner consistent with the manufacturer operating envelope, the analysis applies a comparative methodology referenced to the engine load diagram. Representative operating points derived from certified sea trial measurements and endurance records are mapped onto a common reference frame defined by the manufacturer load diagram, which specifies the admissible operating envelope and the principal limiting mechanisms, including the continuous operation range, time-limited overload, the constant-torque boundary, and low-speed restrictions associated with reduced air supply. Within this framework, regime effects are treated as systematic migration of the operating point in the power and speed plane, driven by changes in propeller demand during steady sailing and increased resistance, and by dynamic effects during manoeuvring.

For SR1, the initial reserve associated with light-running operation is expressed through the Light Running Margin (LRM), defined as the relative difference between the measured light-running propeller curve speed n_{light} and the nominal propeller characteristic speed n_{nominal} at the same absorbed power:

$$LRM = \frac{n_{light} - n_{nominal}}{n_{nominal}} \times 100\% \qquad 3$$

The heavy-running regime R2 is then represented by applying a service sea margin of 15% to the sea-trial baseline, producing projected operating points P_{R2}, n_{R2} on the load diagram that can be assessed for proximity to the manufacturer limit lines, particularly the admissible low-speed torque boundary:

$$P_{R2} = P_{SR1} \times (1 + SM_{15\%}) \qquad 4$$

where SM=0.15.

For the regime SR2, thermodynamic stability is evaluated through the behaviour of key process parameters during the hold period, including scavenge pressure p_{scav} and exhaust temperatures T_{exh} with deviations interpreted against the steady-state stability expectations stated in the engine documentation.

The quantitative workflow proceeds in next three steps:

(1) Baseline propulsion characteristic from sea trials (SR1).

The steady-state sea trial points establish the baseline propulsion characteristic under clean-hull, calm-water conditions. The baseline is expressed through the relationship between shaft power and shaft speed and is subsequently used as the reference propeller-demand curve for the vessel.

(2) Thermally stabilised reference condition from endurance records (SR2).

Endurance test records at sustained loads define a thermally stabilised reference condition. This reference is characterised using air-path and exhaust-side indicators, including scavenge pressure, turbocharger speed, and exhaust gas temperatures at defined measurement positions. For the 100% endurance condition, one representative measurement column is adopted for the reference SR2 operating point, while repeated entries are used as a consistency check.

(3) Evaluation of regime deviations relative to the baseline (R2 and TR1).

Deviations from baseline operation are evaluated relative to the SR1 reference curve. Increased resistance is represented through the service-margin projection applied to the baseline propeller curve, while transient regimes are assessed using manoeuvring time histories to characterise the timescale and severity of dynamic loading where direct synchronised torque and power telemetry is unavailable.

Engine performance is assessed through three coupled performance domains: mechanical margin, thermodynamic stability, and fuel conversion performance. The indicators are formulated so they can be evaluated from certified sea-trial measurements and endurance records while maintaining traceability to the load-diagram reference frame.

Mechanical margin and propulsive capability

The principal derived quantity is shaft torque, calculated consistently from measured shaft power and rotational speed as:

$$T = \frac{9550P}{n} \tag{5}$$

Where T is torque in N·m, P is shaft power in kW, and n is shaft speed in rpm. This torque representation enables direct comparison of steady operating points and projected resistance increases, since heavy running primarily manifests as increased torque demand at a given speed. To represent increased service resistance in a transparent manner, a service/sea margin projection is applied to the baseline steady points, expressed as:

$$P_{serv} = (1 + \delta)P_{trial} \tag{6}$$

with δ adopted as a representative sea margin (e.g., 0.15). At constant n, this implies a proportional increase in torque, $T_{serv} = (1 + \delta)T_{trial}$

The resulting differences in T and P provide a practical measure of mechanical loading sensitivity to regime change and support the interpretation of proximity to limiting boundaries on the load diagram.

For the thermodynamic stability domain, the endurance data are interpreted through air-path and exhaust-side indicators, using measured receiver/scavenge pressure p_{scav}, turbocharger speed n_{TC}, and exhaust gas temperatures at defined measurement positions. A compact exhaust-side indicator is the turbine temperature drop:

$$\Delta T_{turb} = T_{bt} - T_{at} \qquad 7$$

where T_{bt} and T_{at} are the exhaust gas temperatures before and after the turbine, respectively. Together with cylinder outlet temperature levels, these quantities provide an evidence-based representation of thermal loading and air-system adequacy at stabilised operating points.

7. Conclusions

For the fuel conversion domain, where trial documentation reports corrected specific fuel oil consumption, the regime influence is evaluated through the measured SFOC values and their variation with load. Where corrected SFOC is not explicitly reported for a given point, the analysis does not interpolate values and instead restricts quantitative efficiency comparisons to the reported operating points.

For transient operation, manoeuvring regimes are evaluated using vessel-response time histories, including speed–time decay during crash-stop manoeuvres and speed and heading evolution during turning and zig-zag tests. Although synchronised high-frequency measurements of engine torque and shaft power are not available for these manoeuvres, the vessel-response records provide valuable information on the intensity and characteristic timescale of transient propulsion loading. These kinematic responses are therefore used to interpret the dynamic behaviour of the propulsion system and to discuss the expected migration of the engine operating point relative to the steady-state load-diagram constraints. In addition, the general relationship between propulsion parameters and engine load derived from the sea-trial dataset is illustrated through a simplified heatmap representation (Figure 2), which provides a visual reference for the steady-state progression of shaft speed, delivered power and vessel speed across the tested load range.

The framework developed in this work converts operational concepts into a single coherent structure anchored in the manufacturer load diagram and verified by sea-trial data. By defining regime boundaries and associating them with operating zones, the study creates a basis for subsequent quantitative analysis of performance, safety margins, and efficiency loss under real operating conditions. This framework also supports consistent comparison between theoretical expectations and in-service behaviour, enabling downstream studies to evaluate specific regime-by-regime.

8. References

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Acknowledgments. Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor the granting authority can be held responsible for them. Project Number: 101139879.