

PERFORMANCE VERIFICATION METHODOLOGIES FOR VESSELS WITH WIND ASSISTED PROPULSION

ANEMOI

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Summary

The paper compares three established methods for verifying the performance of wind assistance installations:

1. **ANEMOI in-service ON/OFF verification and model-calibration methodology**
2. **ITTC guidelines for sea trials and supporting performance prediction (ITTC 7.5-04-01-02 & ITTC 7.5-02-03-01.9)**
3. **DNV practice for in-service ON/OFF testing (DNV-RP-0686)**

While all three methodologies rely on ON/OFF comparison logic, they differ in objective, scope, treatment of environmental variability, and how uncertainty and extrapolation are handled.

Overall, the comparative analysis shows that the three methodologies are complementary rather than competing. ITTC guidelines provide a structured and controlled verification baseline, DNV practice provides a statistically rigorous framework for long-term in-service assessment, and ANEMOI verification methodology demonstrates how in-service measurements can be combined with modelling to deliver actionable fuel-saving predictions. The findings suggest that future standardisation efforts would benefit from selectively combining these strengths.

The paper aims at informing, and provoking, debate to guide the evolution of methods for verifying the performance of wind assistance installations.

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Nomenclature

AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
DNV	Det Norske Veritas
DOF	Degrees Of Freedom
FSAM	Fuel Saving Assessment Methodology
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite System
ISO	International Organisation for Standardisation
ITTC	International Towing Tank Conference
KT	Propeller Thrust Coefficient
KQ	Propeller Torque Coefficient
LiDAR	Light Detection and Ranging
MEPC	Marine Environment Protection Committee
P	Power
PPP	Performance Prediction Program
PTI	Power Take In
RPM	Revolutions Per Minute
SOG	Speed Over Ground
STW	Speed Through Water
TWA	True Wind Angle
TWS	True Wind Speed
V	Vessel Speed
WAPS	Wind-Assisted Propulsion System

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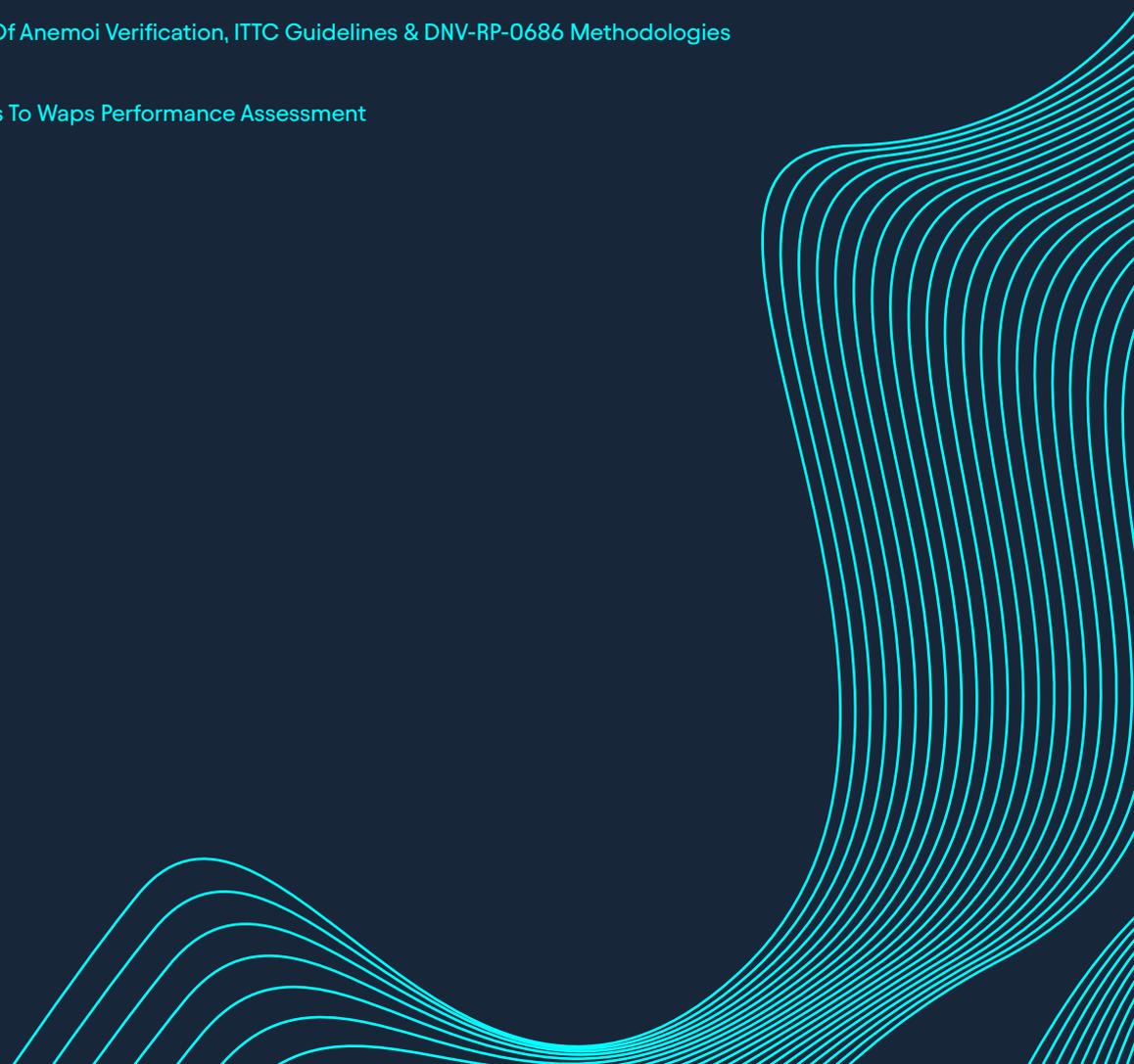
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1. Introduction

Maritime transport is a critical enabler of global trade, carrying over 80% of goods traded worldwide [1], but it is also a significant and growing source of emissions, with shipping's share of global anthropogenic greenhouse gas (GHG) emissions increasing from 2.76% in 2012 to 2.89% in 2018 [2].

In response, increasingly stringent decarbonisation targets and regulatory frameworks are stimulating interest and accelerating the adoption of wind-assisted propulsion as a practical and compelling fuel-saving measure for energy efficiency. A growing number of wind assisted propulsion systems (WAPS) are now available on the market, including rotor sails, wing sails, and suction sails, which generate aerodynamic thrust that reduce net propulsion power demand and/or to supplement propulsion power at a given power setting [3].

As installations of WAPS increase, there is a growing requirement for performance verification methodologies that are technically credible, operationally practical, and comparable across vessels, routes and operating profiles. Unlike conventional speed-power trials, WAPS performance is strongly dependent on apparent wind conditions (speed and angle), and verification approaches must address wind measurement difficulties, coupling between aerodynamic and hydrodynamic response, and the challenge of isolating small performance benefits from environmental variability.



1.1. Purpose of paper

This paper evaluates three representative methodologies of performance verification of wind assistance installations:

- **ANEMOI, Performance Verification of Wind-Assisted Ship Propulsion Systems by ON/OFF Testing [4], verified by Lloyd's Register, hereinafter; 'ANEMOI verification'**
- **ITTC, Recommended Procedures and Guidelines 7.5-04-01-02 - Sea trials for assessing the power saving from wind assisted propulsion [5] together with ITTC, Recommended Procedures and Guidelines 7.5-02-03-01.9 - Predicting the Power Saving of Wind Powered Ships [6] hereinafter; 'ITTC guidelines'**
- **DNV, Recommended Practice DNV-RP-0686 - Performance of wind assisted propulsion systems [7] hereinafter; 'DNV practice'**

The purpose of this paper is to compare and clarify differences, identify gaps and limitations, of each methodology and provide recommendations to support a possible need for a future industry-wide standardisation of performance verification of wind assistance installations. Alternative approaches not addressed in this paper are briefly discussed in Appendix 2.

"Performance verification" is used in a broad sense, covering controlled verification (e.g., sea trials), statistically defensible in-service assessment, and where applicable the calibration/validation of a prediction method for voyage- or route-level savings. This paper assumes wind assistance installation is fully available (i.e., no downtime affecting delivered savings); the impact of system availability is outside the scope of this paper.



2. Challenges With Performance Verification

Changes in vessel performance with a wind assistance installation cannot be interpreted as a simple “added thrust” problem without a clearly defined analytical framework where:

- **Wind-assisted propulsion alters the coupled force and moment balance of a vessel, and**
- **Aerodynamic thrust and side force influence propeller loading, propulsive efficiency, leeway, rudder demand, and hydrodynamic resistance.**

The key challenges with performance verification are presented in Figure 1.

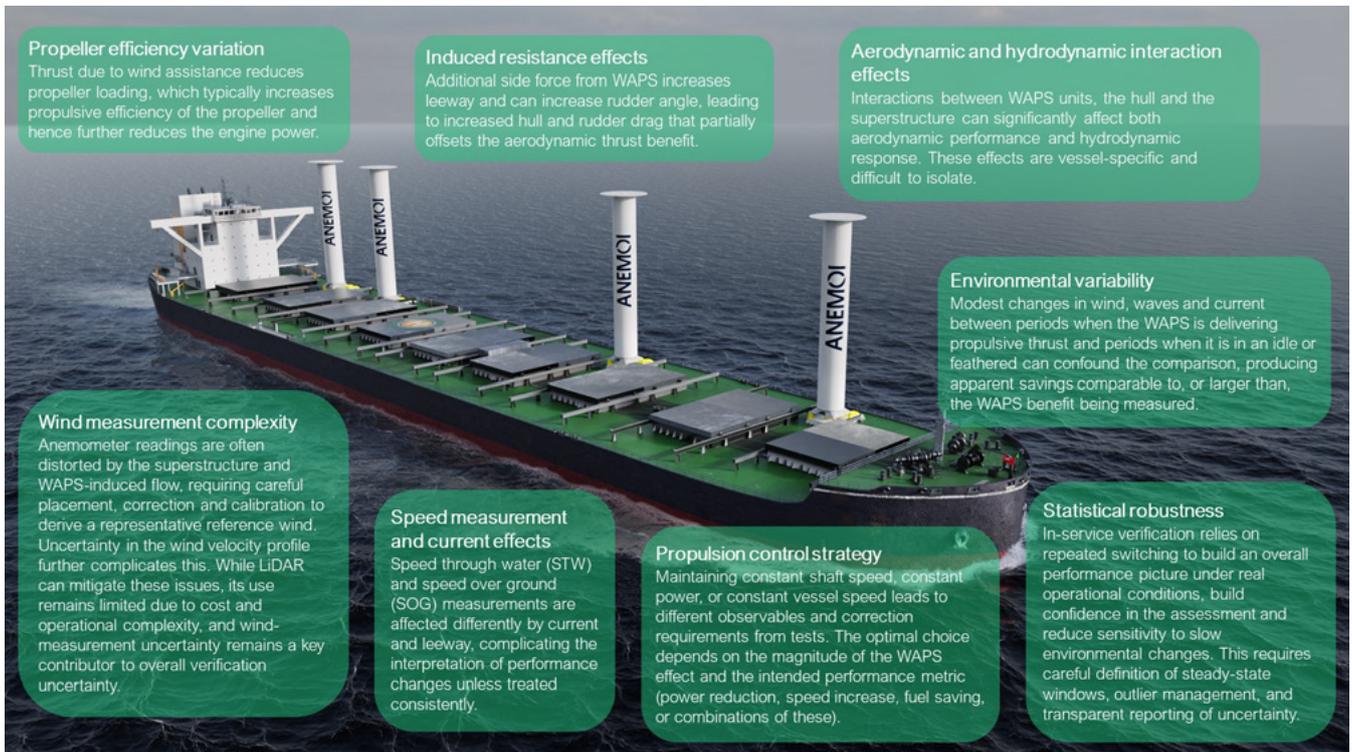


Figure 1: Key challenges with performance verification of vessels with wind assistance installations.

3. Overview Of Test Methodologies For Performance Verification

Figure 2 illustrates a generic performance verification workflow applicable to all three methodologies of performance verification evaluated. All three methodologies seek to quantify the performance impact of WAPS by comparing vessel behaviour with the system active (ON) and inactive (OFF), under broadly comparable environmental and operational conditions. However, they differ significantly in how tests are executed, how environmental variability is treated, how uncertainty is quantified, and whether measured results are extrapolated beyond the test conditions.



Figure 2: Flowchart showing the performance verification workflow.

The differences between methodologies are discussed in more detail in Section 4, along with recommendations that draw together the most effective elements to inform a potential debate on consolidated methodologies.

3.1. ANEMOI verification methodology

The ANEMOI verification methodology is designed for in-service performance verification using repeated ON/OFF tests during normal vessel operation, with the explicit objective of both measuring performance changes and developing and validating a vessel-specific Performance Prediction Program (PPP) [4].

Data quality assurance is central to the approach. ON/OFF comparisons are structured as paired baseline (OFF) and test (ON) windows, with the OFF condition represented by the time-weighted average of two baselines taken before and after the test window. Figure 3 illustrates an example OFF-ON-OFF test sequence in which measured power and speed exhibit a slow underlying drift, showing how a single "OFF" snapshot can misrepresent the true baseline during the ON window. Using two baselines (before and after) enables a time-weighted interpolation of the expected OFF condition at the test time, materially reducing scatter of results and inaccuracy due to slow environmental changes.

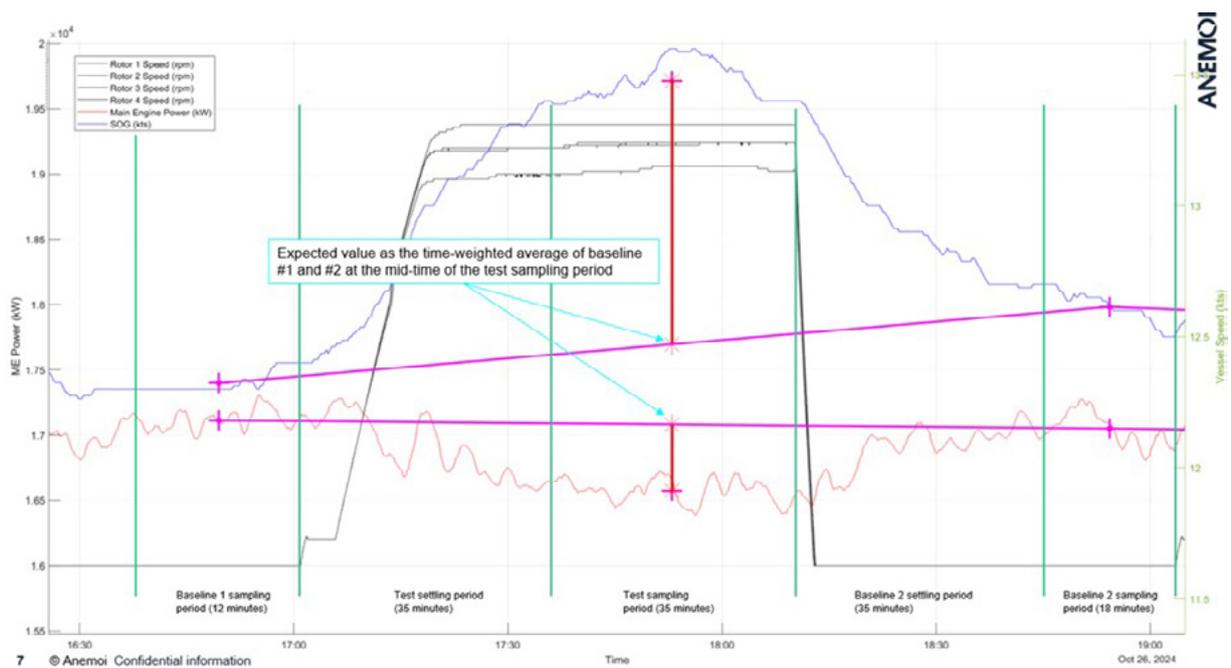


Figure 3: Example OFF-ON-OFF test sequence illustrating slow baseline drift and the use of pre- and post-OFF baselines to interpolate the expected OFF condition during the ON window [pink markers and connecting lines], with red vertical lines indicating the deviation of the ON condition from the interpolated OFF reference for vessel speed and main engine power.

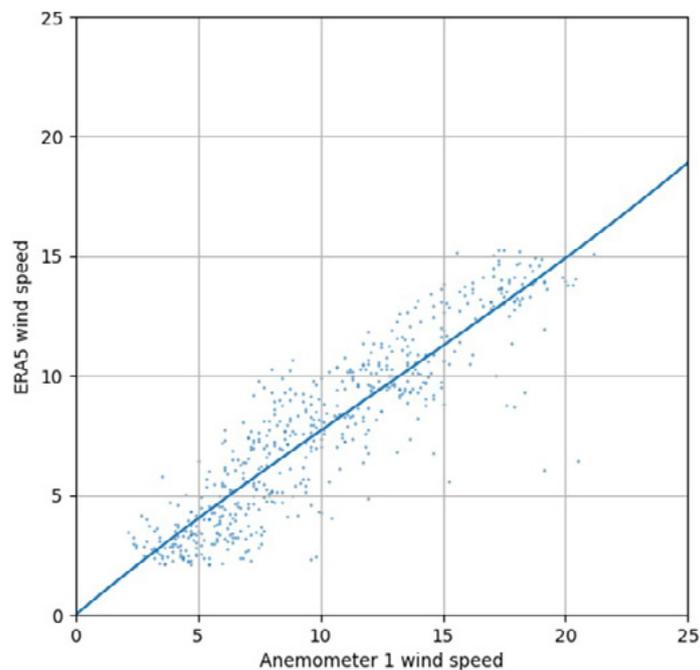


Figure 4: Example reference-wind calibration using ERA5 hindcast data: anemometer wind speed compared against ERA5 to derive the upstream wind correction applied in subsequent analysis.

Multiple anemometers are used, typically located forward and aft, with directional selection logic applied to identify the least disturbed sensor for a given apparent wind direction. A defined correction and calibration workflow is then applied to the on-board apparent wind measurements to derive a consistent upstream reference wind, including bias-correction of the measured wind time series against hindcast datasets (e.g., ERA5), Figure 4, and scaling to sail mid-height using a power-law vertical profile. This reference-wind calibration anchors the wind input used to derive non-dimensional forward force coefficients and allows the calibrated performance model to be applied in voyage simulation against standard hindcast data. Current effects are estimated and compensated so that comparisons are made on a speed-through-water basis (assuming the current is steady or varies approximately linearly over the test window).

The change in net forward force due to WAPS is inferred from measured changes in the propulsion operating point. Propeller open-water characteristics, Figure 5, together with measured shaft speed and torque, and thrust deduction are used to estimate effective thrust and net forward force. Where ON/OFF speeds differ, the methodology estimates the WAPS-OFF resistance at the WAPS-ON speed using a quadratic resistance-speed relationship ($R \propto V^2$), with an exponent of two generally appropriate at low Froude numbers, or using the resistance-speed relationship from model tests. Using the open-water curves captures the change in advance ratio and open-water propeller efficiency as the WAPS thrust unloads the propeller, improving the fidelity of the inferred force balance. As thrust is derived directly from measured shaft torque and speed (rather than from a local speed-power relationship), the method remains applicable even when the ON/OFF response produces a material change in vessel speed and is less sensitive to any change in the local speed-power slope between OFF and ON conditions caused by altered propeller loading. The measured change in net forward force between OFF and ON conditions is then compared with PPP predictions. Discrepancies are used to calibrate and adjust the PPP model, producing a performance-verified model of the vessel with WAPS.

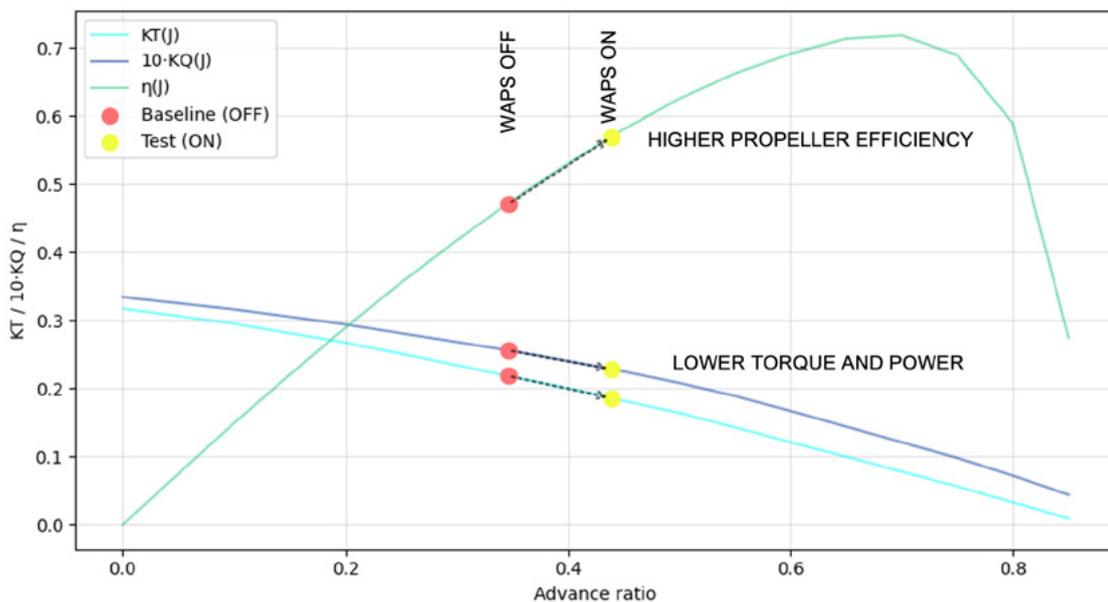


Figure 5: Typical propeller open-water characteristics [KT, KQ and efficiency] with representative ON/OFF operating points overlaid. The arrows indicate the shift in propeller operating point from baseline (rotors OFF) to test condition (rotors ON), illustrating the increase in advance ratio and associated decrease in torque coefficient and thrust coefficient and the significant increase in propeller efficiency.

Once calibrated, the PPP is used to extrapolate performance beyond the tested conditions and to generate route- and voyage-specific predictions of fuel and emissions savings. This enables gaps in the measured dataset (e.g. apparent wind angles between tested values) to be addressed through model-based extrapolation, while retaining traceability to full-scale verification data.

3.2 ITTC 7.5-04-01-02 methodology

The ITTC guidelines define a standardised sea-trial procedure intended to verify the power savings delivered by a WAPS under controlled conditions [7.5-04-01-02] [5] and for predicting the power savings of wind-powered ships [7.5-02-03-01.9] [6]. Verification is achieved through paired runs with and without the WAPS active, typically conducted over a limited number of wind directions dependent on the test day wind conditions but can be extended to include a larger number of conditions conducted over a longer period during operation. The approach allows for an early confirmation of the WAPS performance under the observed conditions.

A baseline speed-power relationship without WAPS is used as a counterfactual baseline mapping to convert observed differences in speed or power between paired runs into a consistent “power difference due to WAPS” at the trial condition. This baseline may be derived from a conventional speed trial, model tests, or a speed-variation test conducted in conjunction with the wind-assisted sea trial.

The ITTC procedure prioritises control of test conditions and measurement quality over post-test correction. It does not define a formal correction methodology for local wind disturbance caused by superstructure or WAPS, instead recommending mitigation measures such as multiple anemometers, LiDAR measurements, or CFD-informed sensor placement. Similarly, current correction is deliberately limited; the preferred speed reference (speed over ground or speed through water) is selected based on local current variability and instrument reliability rather than applying analytical current corrections. Corrections are applied narrowly to maintain run-pair comparability, including air-resistance alignment when wind varies within a pair of runs and accounting for idling/non-retractable WAPS resistance in the OFF state.

Post-processing follows a structured sequence. The power difference attributable to WAPS is first derived at the sea-trial conditions and compared to the model predictions at the same conditions to validate the prediction method. The prediction method should be selected and implemented in accordance with ITTC 7.5-02-03-01.9 [6], which outlines approaches for predicting wind-assisted power savings across design stages and links standard indicators to procedures of increasing fidelity (and computational cost). However, it is primarily a framework and does not provide detailed procedures for performance predictions or model calibration. If agreement is satisfactory, the validated model may be used to extrapolate performance to broader wind conditions through a power-saving matrix and voyage simulation. The ITTC procedure explicitly recognises that uncertainty in both the sea-trial procedure and performance predictions is not yet well established and therefore advises against using sea trials alone to confirm contractual performance guarantees. Nonetheless, it strongly recommends standardised sea trials for each installation to provide early, comparable verification.



3.3 DNV-RP-0686 METHODOLOGY

The DNV Recommended Practice [DNV-RP-0686] is designed primarily for repeated in-service ON/OFF switching tests conducted during normal vessel operation [7]. Its objective is to quantify WAPS performance during the encountered environmental conditions with explicit treatment of statistical uncertainty and confidence intervals, rather than to validate or calibrate a predictive performance model. The DNV practice defines a framework structured around specific “use cases” ranging from confirmation of favourable-condition performance to long-term operational evaluation. Two alternative test procedures are specified, with the choice determined by the magnitude of the vessel speed change when switching the WAPS ON or OFF.

- **Procedure I**

[benefit by reduced power] applies when the ON/OFF speed difference is less than approximately one knot. In this case, performance benefit is quantified by comparing shaft power at near-constant vessel speed. Residual speed differences are corrected using a representative speed-power curve; the curve should be based on WAPS ON but may be based on WAPS OFF if the speed change is less than one knot and the relative $\Delta P-\Delta V$ behaviour is expected to be similar. The curve may be derived from sea trials, model tests, CFD, or supporting ON-ON and OFF-OFF tests conducted as part of the campaign. Shaft-speed control strategies are prescribed to limit speed deviations and improve comparability between ON and OFF periods.

- **Procedure II**

[benefit by increased speed] applies when the ON/OFF speed difference exceeds one knot. Performance is quantified using energy consumption per distance, with shaft speed set to representative operating points for conventional and WAPS operation, based on the baseline speed-power relationship.

Environmental conditions (wind, waves, current), draft and trim, and hull/propeller condition (fouling and roughening) are assumed to be effectively equal between ON and OFF periods. The analysis does not apply analytical corrections for variation in these factors, because such corrections can introduce additional uncertainty and potential bias (for example, when normalising results to a reference condition). This is to reduce the uncertainty associated with such corrections, including avoiding bias in the correction to a normalised condition. Instead, it relies on many tests, robust statistical filtering to validate steady-state conditions, and statistical aggregation to reduce the influence of uncontrolled variability. Uncertainty quantification is integral to the methodology, with confidence intervals derived using Student's t-distribution and minimum observation requirements linked to the intended use case and coverage of tested conditions.

DNV practice focuses on verification of in-service WAPS performance rather than supporting the development of predictive performance models. As a result, demonstrated performance benefits are limited to conditions that are represented in the switching dataset. Where favourable wind conditions occur infrequently during the test period, the assessed savings may be conservative compared to the WAPS's broader operational potential. Conversely, where favourable wind conditions occur often during testing, the assessed savings may be optimistic. Extended verification periods can mitigate this by increasing condition coverage, although increased time spent with the WAPS inactive or in idle mode may influence overall utilisation and hence savings during the verification phase.



3.4 Simplified comparison of ANEMOI, ITTC & DNV methodologies

A simplified and consolidated comparison of Anemoi verification, ITTC guidelines and DNV practice is shown in Table 1. A detailed comparison of the three methodologies is provided in Appendix 1.

Table 1. Simplified & consolidated comparison of the three methodologies.

Area	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686
Purpose and Scope			
Verification Objectives	Long-term in-service verification (+ model calibration)	Short-term sea trial verification	Long-term in-service evaluation (+ statistical confidence)
Intended Use	Calibrate fuel-saving PPP model (FSAM)	Verify WAPS power saving	Quantify WAPS performance (agreed use case)
Location	In-service trading routes	Dedicated trial area or normal-service voyage (boundary conditions controlled)	In-service routes (may include sea trials)
Core Methodology and Performance Definition			
Logic (ON/OFF)	ON/OFF comparison	ON/OFF comparison	ON/OFF comparison
Performance Metric	Net change in forward force	Power difference (ΔP)	Procedure I: power saving ($\Delta V < 1$ knot) Procedure II: energy per distance ($\Delta V > 1$ knot)
Speed Handling	Allows speed changes; infers thrust from shaft signals and propeller curves; corrects for resistance change with speed squared or model test resistance	Correct speed change using speed-power curve; minimise ΔV	Proc I speed correction using speed-power curve; Proc II uses energy/distance
Test Design and Operational Envelope			
Conditions	Quasi-steady conditions	Defined trial boundary conditions (wind/sea state/water depth)	Many tests across operational profile (filtered for stationarity)
Wind speed	AWS ≥ 10 knots	TWS ≥ 8 m/s (or sufficient for measurable effect)	Coverage agreed per use case
Wind angle	AWA from ahead to astern	Min. 5 wind angles ($>10^\circ$ apart)	Broad polar coverage
Wind Measurement	At least two anemometers	Ship anemometer + LiDAR recommended (measure and/or calibrate); CFD/multiple anemometers to minimise distortion	At least one anemometer; LiDAR preferred (particularly if multiple WAPS installed)
Control Logic	Constant RPM & heading	Steady course & min. rudder movement; constant power, shaft speed or vessel speed	Formalised control logic to minimise speed-correction uncertainty
Corrections and Uncertainty			
Wind Correction	Select least-disturbed anemometer; interference/height corrections; calibration using hindcast data	LiDAR/calibration emphasis; placement via CFD/multiple anemometers	Consistent wind measurement; LiDAR/anemometer quality focus
Variability Management	Accept in-service variability; corrections + OFF-ON-OFF (averaging of two OFF baselines)	Minimise variability via site + boundary-control; limited corrections	Assumes environment effectively equal; many tests + statistical filtering/aggregation
Uncertainty and Model Use	Diagnostic + PPP calibration; supports extrapolation	Uncertainty not yet established; not for contractual guarantees; validates external matrix/PPP	Formal uncertainty framework; report statistical bounds; prediction optional

4. Three Methodologies Compared: Findings & Recommendations

This section summarises and discusses the key findings from comparison of the three methodologies, focusing on their practical implications for performance verification and standardisation. The recommendations that follow draw together the most effective elements across the three approaches to inform a consolidated methodology.

4.1 Scope and application

All three methodologies are founded on ON/OFF comparison logic, but they diverge in objective and scope. The ITTC procedure is explicitly framed as a verification tool, intended to confirm wind propulsion performance in controlled conditions and to validate pre-existing performance prediction matrices. However, it also includes a pathway to estimating the power saving for all weather conditions and supporting voyage simulation, provided that a power-saving matrix has been derived [e.g. in accordance with ITTC 7.5-02-03-01.9 [6]] and that the comparison between prediction and sea-trial results is satisfactory. In this sense, ITTC acts as a verification and a validation gate for an external prediction model, but it does not prescribe how that model (or matrix) should be formulated or calibrated; if agreement is not satisfactory, the prediction provider is expected to update the complete matrix, without a defined calibration procedure within the ITTC guidelines itself.

In contrast, both the ANEMOI and DNV approaches are oriented toward in-service application, recognising that representative coverage of operational and environmental conditions cannot realistically be achieved through short-duration trials alone. The ANEMOI methodology further extends beyond verification by explicitly using ON/OFF test results to calibrate a vessel-specific performance prediction model, enabling extrapolation to voyage- and period-level fuel savings.



RECOMMENDATION

Where verification is intended to reflect real-world operation, in-service testing under representative conditions is recommended to provide a realistic picture of WAPS performance. If a quick and controlled verification of performance is required, but limited to the conditions encountered during the trials, then the ITTC approach provides the steps needed to quantify the WAPS performance for the trial conditions and to validate the performance predictions at those conditions. Where results are expected to inform operational or commercial decisions beyond the tested conditions, verification should be paired with an accompanying performance prediction methodology that supports model development and calibration for prediction beyond the measured envelope. Given that detailed modelling procedures are difficult to standardise across organisations, such a methodology should require a clearly documented and auditable approach (including defined scope and assumptions, data quality/coverage expectations, calibration and change-control procedures, and stated limits on extrapolation) and include model evaluation and governance requirements including validation/acceptance metrics, uncertainty reporting and benchmarking against shared reference cases and/or curated datasets.

4.2 Performance metrics

The ANEMOI verification methodology adopts a force-based analysis, deriving the net change in forward force from measured propulsion response. ITTC guidelines express performance primarily as a power difference at the trial condition, optionally normalised to a reference speed consistent with conventional speed-power trial practice. The DNV practice quantifies benefit either as power saving or energy per distance (depending on the operational strategy of the vessel with WAPS) and reports results as statistically bounded estimates rather than deterministic point values. These differences reflect distinct priorities: diagnostic understanding and prediction (ANEMOI), controlled verification at installation (ITTC), and statistically robust in-service assessment (DNV).

A practical advantage of force-based metrics is reduced dependence on speed-power curve use when ON/OFF speeds differ, because thrust is inferred from shaft signals using propeller open-water characteristics, making the propeller unloading effect and associated change in operating point and efficiency explicit. For power- and energy-based metrics, the speed-power curve introduces two separable sensitivities that should be controlled in the verification protocol. First, when ON and OFF speeds differ and results are referenced to a common speed, the corrected power saving depends on the speed-power curve used and on the magnitude of the ON/OFF speed difference. Second (implication), where a WAPS-OFF speed-power curve is used to evaluate the baseline power at the ON speed, the baseline point generally corresponds to the OFF propulsion setting required to achieve the ON speed (often a different shaft rate and therefore a different propeller operating point than the paired constant-setting trial point). The reported power saving therefore combines (i) the measured change in shaft power at the trial setting with (ii) a curve-based estimate of the additional power required to reach the ON speed in OFF operation and should not be interpreted as a decomposition at a single propeller operating point. Power-based metrics may nevertheless be more readily understood by stakeholders who are more familiar with kW than kN.

RECOMMENDATION

Select performance metrics consistent with the intended use. Force-based metrics are preferred where diagnostic insight, model calibration, and reliable extrapolation are required. Where power- or energy-based metrics are used for reporting, the verification protocol should define (i) how ON/OFF speed differences are handled, (ii) how the speed-power curve is derived and applied (including whether it is based on ON or OFF operation), (iii) acceptable limits on ON/OFF speed difference to control sensitivity of corrected results to curve choice and local speed-power behaviour, and (iv) how changes in propulsive efficiency are accounted for due to WAPS unloading the propeller, both in the tests and in the PPP for voyage simulation.



4.3 Environmental variability

The ITTC methodology seeks to minimise variability through test-site selection and boundary-condition control, deliberately limiting analytical corrections. The DNV practice takes the opposite stance, treating environmental conditions as effectively equal between ON and OFF periods and relying on large numbers of tests, robust statistical filtering to validate steady-state conditions, and statistical aggregation to manage residual variability. The ANEMOI verification methodology occupies an intermediate position, accepting the variability of in-service conditions but applying correction and normalisation for wind distortion and current effects to improve comparability between test pairs, and using two OFF periods for each ON period [OFF-ON-OFF] to reduce noise from approximately linearly varying environmental effects.

These choices have direct implications for data requirements: ITTC guidelines depend on carefully planned trials (with uncertainty driven by wind conditions on the test day); DNV practice depends on large sample sizes; and ANEMOI depends on structured data processing and auxiliary information such as hindcast datasets.

RECOMMENDATION

For in-service verification under variable conditions, the authors' view is that applying correction and normalisation is preferable to relying on a very large number of tests or extensive filtering to manage environmental variability. This preserves more usable data and avoids unnecessary testing and data rejection which reduces WAPS uptime and realised savings. Where "controlled" conditions are assumed, verify this against recorded measurements and apply corrections where deviations are material. In particular: (i) baseline-drift correction [OFF-ON-OFF]: represent the OFF condition during each ON window by time-weighted interpolation between OFF periods either side of the ON period, rather than relying on a single OFF snapshot; (ii) wind-measurement correction: apply a consistent anemometer selection and correction workflow (least-disturbed sensor by direction, interference/height corrections, and, where available, calibration against an upstream reference such as LiDAR) so apparent wind inputs are comparable between ON and OFF and suitable for comparison to predictions based on hindcast wind data.



4.4 Uncertainty treatment

The ITTC procedure explicitly acknowledges that uncertainty is not yet well established and advises against contractual use of sea-trial results, positioning transparency and standardisation ahead of quantified confidence. The DNV practice places uncertainty quantification at the centre of the methodology, with formal confidence intervals and minimum data requirements linked to defined use cases. The ANEMOI verification methodology manages uncertainty implicitly through data filtering, paired test design, and model calibration quality, but does not prescribe a formal probabilistic uncertainty framework as a primary output. As a result, DNV practice is currently best aligned with regulatory or third-party verification contexts that require explicit confidence bounds, while ANEMOI verification is optimised for performance understanding and prediction.



RECOMMENDATION

Where verification outcomes are intended for third-party review, regulatory purposes, or contractual decisions, explicit and transparent uncertainty quantification is recommended (e.g., measurement and sampling uncertainty, and where applicable environmental correction/model uncertainty and statistical confidence).

4.5 Prediction and extrapolation

The ITTC methodology treats prediction as a supporting element to the sea-trial, using ITTC 7.5-02-03-01.9 [6] to define the nominated prediction at the trial conditions and then to extend results to route or representative weather savings via a power saving matrix and voyage simulation once agreement is demonstrated. Sea-trial results are used to validate consistency with those predictions, and where agreement is not satisfactory, the prediction provider is expected to update the complete matrix (not only the tested conditions), while any updates to the prediction are treated as an external modelling step rather than being prescribed within the trial procedure. DNV practice treats modelling as optional and secondary, mainly for comparison or operational insight rather than as part of the verification deliverable. By contrast, the ANEMOI methodology links measurement and prediction in a closed loop, using ON/OFF tests to calibrate vessel-specific coefficients before applying the validated model to long-term route simulations, enabling extrapolation beyond the tested envelope but increasing reliance on model structure, corrections, and calibration quality.



RECOMMENDATION

Where performance verification outcomes are intended to inform long-term, voyage-specific, or commercial decisions, a model-based approach is recommended as it enables extrapolation beyond the tested conditions, thereby reducing the volume of testing required and maximising realised savings. The methodology should require a clearly documented and auditable, step-by-step prediction workflow that defines how sea-trial or in-service evidence are used to calibrate and validate prediction models, with explicit requirements for full-scale calibration, validation and acceptance criteria, and transparent reporting of model assumptions, scope, and limits of extrapolation.

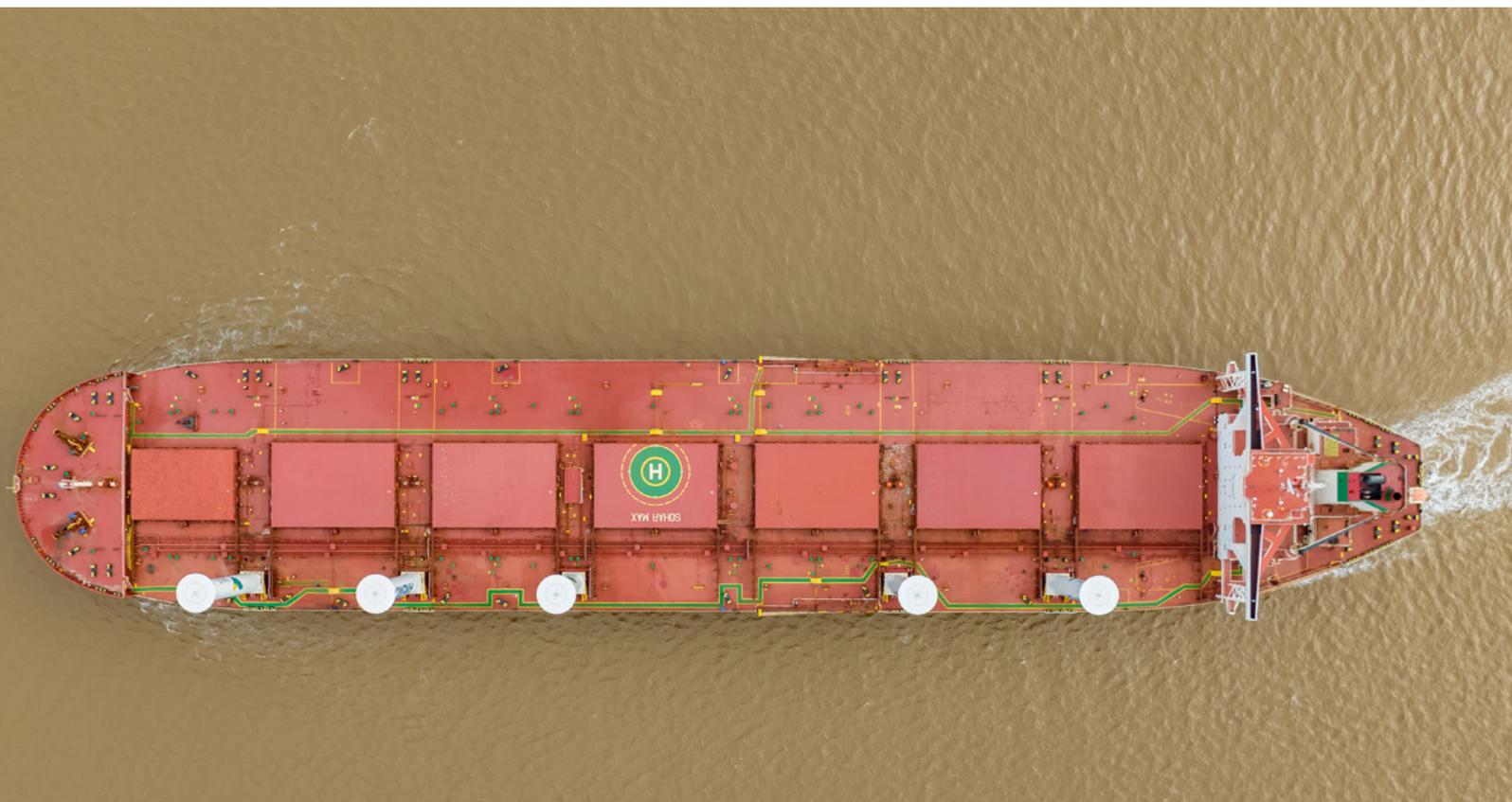
Conclusions

This paper has compared three established approaches for verifying the performance of WAPS: the ANEMOI in-service ON/OFF verification and model-calibration methodology [4], the ITTC guidelines for sea trials and supporting performance prediction [ITTC 7.5-04-01-02 and ITTC 7.5-02-03-01.9] [5, 6], and the DNV practice for in-service ON/OFF testing [DNV-RP-0686] [7]. While all three rely on ON/OFF comparison logic, they differ in objective, scope, treatment of environmental variability, and how uncertainty and extrapolation are handled.

The ITTC guidelines are aimed at controlled, short-term verification of performance predictions at the trial conditions, with separate guidance outlining standards-level expectations for building performance prediction models across different fidelity levels (without prescribing implementation details). The DNV practice provides a statistically robust framework for long-term in-service assessment. The ANEMOI methodology integrates medium-term in-service ON/OFF verification with an explicit vessel-specific calibration step, to support voyage- and route-level past and future fuel savings estimation.

Overall, the comparative analysis shows that the three methodologies are complementary rather than competing. ITTC guidelines provide a structured and controlled verification baseline, DNV practice provides a statistically rigorous framework for long-term in-service assessment, and ANEMOI verification methodology demonstrates how in-service measurements can be combined with modelling to deliver actionable fuel-saving predictions.

Future standardisation efforts would benefit from combining controlled verification principles, explicit uncertainty treatment, and validated performance prediction within a unified framework. Such convergence would improve comparability, strengthen confidence in reported savings, and support wider adoption of WAPS.



Authors Biography

Dr Josef Camilleri is the Performance Analysis Manager at Anemoi. In this role, he leads the development and validation of robust vessel performance analysis and verification methodologies, communicates results through technical outputs and customer engagement, supports sea trials, and contributes to the development of industry standards. His previous experience includes similar roles at V.Ships and Silverstream Technologies, and he holds a PhD in Maritime Technology from the University of Southampton.

Luke McEwen is the Technical Director at Anemoi. He leads the company's engineering team, responsible for the development of Rotor Sails and deployment systems for ships and the verification of their performance. Luke spent four years sailing around the world, races sailing dinghies competitively and holds a Master's degree in Engineering from the University of Cambridge.

Dr Santiago Suarez de la Fuente is the Ship Performance Group manager at Lloyd's Register Advisory. He is responsible for supporting clients in energy efficiency performance and verification, energy transition challenges and opportunities applying advanced modelling, data science, and state-of-the-art regulatory, industrial, and scientific resources. Santiago's previous roles focused on assessing potential energy transition solutions for the shipping industry under a large range of techno-economic scenarios to inform policymakers and key maritime stakeholders on their decision-making process. He holds a PhD in Marine Engineering from University College London.

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APPENDIX 1: Detailed Comparison Of ANEMOI Verification, ITTC Guidelines & DNV-RP-0686 Methodologies

Table 1. Objective and performance metric[s].

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Objective and intended use	Verify in-service WAPS performance and calibrate vessel and WAPS model using ON/OFF tests; use calibrated model (FSAM) for voyage fuel-saving prediction.	Short-term sea trial to verify power saving due to WAPS at limited conditions; used to validate a performance prediction matrix.	Framework for performance evaluation/verification of WAPS based on documentation and measured data; supports sea trial and in-service assessment with uncertainty estimation.	All use ON/OFF comparison logic; ITTC is short-term verification, ANEMOI and DNV are in-service/ long-term oriented.
Performance Metric	Net change in forward force [and non-dimensional coefficient]; net fuel saving from calibrated FSAM.	Power difference [ΔP] at sea-trial conditions; optional normalisation to reference condition; optional voyage average power saving.	Procedure I: power saving (speed change <1 knot). Procedure II: energy per distance (speed change >1 knot). Performance reported as confidence interval; fuel saving optional/not focus.	ANEMOI is force-based; ITTC is power-based; DNV is power or energy-per-distance depending on operating mode.

Table 2. Test conditions.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Test location and boundary conditions	Normal trading routes; accept variable environment but require quasi-steady conditions within each ON/OFF test.	Normal-service voyage between port calls or dedicated trial area, with defined boundary-condition requirements [deep water, avoid land effects, manage current influence, etc.].	Typically, in-service routes; may include sea trials; long-term evaluation may use planned/random ON/OFF tests over representative operational pattern.	ITTC minimises variability via site selection; ANEMOI and DNV manage variability via filtering and/or large sample sizes.
Wind conditions	Apparent wind speed ≥ 10 knots (5 m/s, ideally 8 m/s); cover apparent wind angle from ahead to astern, both sides; include some negative-thrust angles if feasible.	TWS should allow a measurable effect [≥ 0.3 knots speed change] or be at least 8 m/s; cover at least 5 wind angles spaced by more than 10° , covering thrust peak and zero-thrust regions; if performance is asymmetric, test five angles per side.	Coverage agreed per use case; performance results should be supported by broad polar coverage, including zero/negative benefit conditions in long-term evaluation.	ANEMOI and ITTC require sufficient wind to produce measurable signal; ANEMOI gives explicit AWS guidance; ITTC gives true-wind guidance; DNV emphasises coverage and stationarity rather than minima.
Propulsion/steering control	Keep main engine RPM and ship heading constant during ON/OFF; measure speed and power response.	Maintain steady course with minimal rudder change as per the test plan; propulsion can be controlled by constant power, shaft speed or vessel speed.	Minimise change in vessel speed between ON and OFF; within each period shaft RPM shall be constant (no tuning); Propeller shaft speed during ON and OFF periods can be: (1) kept constant if speed change <1 knot, (2) adjusted to keep total energy input (shaft power + WAPS operating power) constant, or (3) adjusted to maintain equal vessel speed. Maintain constant P/D for CPP; maintain steady vessel course throughout each set (rudder adjustments may be needed).	DNV formalises control logic to minimise speed-correction uncertainty; ANEMOI is agnostic to propulsion control strategy; ITTC allows multiple control modes but is less prescriptive on speed matching. All require steering control.

Table 3. Measurement framework.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Key measurements	Shaft power/torque/RPM; SOG and STW; AWS/AWA (selected anemometer); rotor RPM and PTI; weather data for air density; time synchronised.	GNSS track/COG/SOG; STW; shaft power/RPM; propeller pitch [CPP]; heading; AWS/AWA; WAPS PTI and setting; time [UTC]; waves/sea state as available.	AWS/AWA; vessel speed [SOG/STW and/or virtual speed]; shaft power/torque/RPM; WAPS power [rotor/suction/control] and operational mode event data; plus, optional quantities [humidity, fouling, pitch ratio, etc.]	All require wind, propulsion and speed measurements; DNV and ITTC explicitly require WAPS auxiliary power; ANEMOI includes it in net fuel saving.
Wind measurement definition	At least two anemometers (forward/aft); select most upwind anemometer by AWA range; LiDAR may remove need for correction.	Recommend LiDAR or pre-trial calibration/correction of anemometer; multiple anemometers and/or CFD to identify least disturbed location.	At least one anemometer required; wind LiDAR more accurate and recommended (especially if multiple WAPS are installed); anemometers should be unobstructed; lidar can calibrate anemometers/uncertainty.	All recognise anemometer disturbance as a key risk; ANEMOI is most prescriptive on correction workflow; ITTC and DNV strongly recommend LiDAR.

Table 4. Test procedure.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Test sequence	Baseline #1 [OFF] → Test [ON] → Baseline #2 [OFF]; repeated cycles (often 1 hr ON / 1 hr OFF).	Paired runs with WAPS ON/OFF at similar conditions; repeat across wind angles/conditions.	ON/OFF set: approach → measurement (10-15 min) → switch buffer → approach → measurement; can chain sets and reuse measurement periods to increase samples.	ANEMOI explicitly uses baseline-test-baseline to interpolate expected conditions; ITTC uses run pairs; DNV uses structured sets with defined buffers and approach time.
Approach / settling time	Settling time required for the net forward thrust from all tests to approach its asymptotic value. Depends on vessel type and loading condition.	Approach time required for the running averages of shaft rpm, shaft torque and vessel speed to reach stationary conditions; time between runs should be minimised.	Approach time required for shaft speed, torque, and vessel speed to reach stationary conditions; minimum approach time given as function of displacement; typically ~30 min for a large cargo ship	ANEMOI and DNV explicitly separate 'settling/approach' from measurement; ITTC assumes stability within the run and via approach between runs.
Measurement / sampling period	Sampling after settling until next mode change or max period; enforce minimum sampling duration for each Baseline/Test (typically 10-15 minutes).	Run duration ≥15 min for each run [ON or OFF].	Measurement period 10-15 min; not desirable <10 min; equal length for ON and OFF within a set; switch buffer 2-5 min.	ITTC prescribes longer minimum per run; DNV prescribes 10-15 min with gust-process rationale; ANEMOI uses longer cycles but samples only after settling.
Number of tests	No fixed minimum; run many tests across AWA/AWS and loading conditions to reduce scatter and support calibration. Evaluation may cover ~3 months	Minimum program can be done within one day with about five wind conditions.	Depends on use case; long-term evaluation may cover ≥1 year; polar diagram used to show coverage and test density.	ANEMOI and DNV rely on large sample sizes for statistical robustness; ITTC relies on controlled conditions and limited but distributed trials.

Table 5. Data validation.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Filtering / stationarity criteria	Reject tests if: (1) current dominates SOG, (2) wind angle varies, (3) engine rpm varies >2, (4) course varies >5°	Reject runs if the running averages of shaft speed, torque, and vessel speed are not stable.	Applies Chauvenet's criterion to remove outliers; reject ON/OFF tests if shaft speed, course over ground, heading, wind speed and angle, or water depth exceed defined stationary thresholds	ANEMOI and DNV provides explicit thresholds; ITTC define stability principles but leave thresholds more to practitioner judgement/criteria tables.

Table 6. Data normalisation and corrections.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Derived quantities	Compute air density; correct AWS/AWA for interference and height; select relevant anemometer; compute mean of primary parameters per period; compute 'Expected' baseline conditions by time-weighted interpolation between Baseline #1 and #2.	Evaluate acquired data; compute mean and standard deviation of primary parameters per run; compile run-level dataset for post-processing steps.	Document data processing; compute virtual speed from propeller torque/RPM if used; check steady-state periods; evaluate data consistency (time-lag, KQ curve).	All rely on derived quantities; ANEMOI emphasises 'expected' interpolation to mitigate linearly varying conditions; DNV emphasises virtual speed and consistency checks.
Current and speed metric handling	Correct SOG for current using SOG-STW difference from Baselines; assumes approximately linear current variation over test.	No analytical current correction; select trial location/time to minimise currents; use GNSS-SOG when current is negligible/approximately constant; otherwise use STW where current varies and the speed log is verified reliable.	No current correction; assumes environmental conditions including current] are equal in ON and OFF segments; virtual speed is calculated from shaft signals to reduce speed uncertainty.	ITTC avoids current by test design; ANEMOI corrects within each test; DNV manages current sensitivity primarily via speed choice [STW/SOG] and virtual speed rather than explicit current correction.
Speed-power curve use (baseline mapping vs speed correction)	Estimate resistance change with speed (typically V^2 ; exponent adjustable); include propeller efficiency via open-water KT, KQ.	Use speed-power curve/direct power method per ITTC speed and power [P] trial guidance; convert measured [V, P] to ΔP at matched conditions; if speed-power curve is unavailable for the trial speed and loading, include additional speed variation tests.	For Procedure I: Convert ΔV to equivalent ΔP using a representative speed-power curve; the curve should be based on WAPS ON but may be based on WAPS OFF if the speed change is < 1 knot and the relative ΔP - ΔV behaviour is expected similar. Establish the curve from sea trials/model tests/CFD or supporting ON-ON / OFF-OFF tests using ≥ 3 shaft speeds within ± 1 knot of the target speed. Procedure II: No speed correction.	ANEMOI uses a generic resistance-speed law unless better data; ITTC uses the no-WAPS curve primarily as a baseline mapping for ΔP at trial/reference conditions; DNV Procedure I uses a curve primarily for speed correction ($\Delta V \rightarrow \Delta P$) and treats curve representativeness as a major bias source.
Aerodynamic corrections and OFF state drag	Wind corrected to upstream using hindcast data (e.g., ERA5); tests with large wind change excluded. Vessel aero drag (with/without WAPS) and WAPS OFF state drag included in modelling/prediction.	Correct superstructure air resistance when wind differs between run pair; subtract idle WAPS/foundation drag if not retracted/tilted.	No superstructure correction; assumes environmental conditions are equal in ON and OFF segments; aerodynamic resistance from WAPS in OFF period should be removed as per ISO 15016:2015; hindcast data may only be used for validation.	ITTC includes explicit aerodynamic correction terms; ANEMOI includes aerodynamics primarily in the calibrated model; DNV assumes constant environmental conditions and focuses on statistical robustness rather than explicit superstructure correction.
Wind height correction / reference height	Scale corrected wind to WAPS mid-height using $1/9$ power law.	Report results corrected to 10 m above water using $1/9$ power law; apply heel correction if heel $> 5^\circ$.	Wind should be representative at WAPS location; no single exponent mandated; when comparing to prediction, a gust factor for performance may be applied.	ANEMOI explicitly scales to WAPS mid-height; ITTC standardises reporting to 10 m; DNV prioritises representativeness and uncertainty rather than a fixed exponent.

Table 7. Performance analysis.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Performance calculation	Use propeller open-water chart: derive KQ/KT from shaft torque and RPM; compute propeller thrust and effective force; derive net change of forward thrust from ON/OFF including induced drag effects.	Compute ΔP between WAPS ON/OFF at sea-trial conditions as the sum of direct shaft-power reduction and equivalent power from speed increase.	Procedure I: compute instantaneous power saving (corrected for speed change). Procedure II: compute energy-per-meter saving. Both procedures: results aggregated and reported with confidence interval.	WAPS benefit is obtained from differences between ON and OFF periods and should include WAPS operating power; ANEMOI explicitly derives thrust and calibrates model coefficients; ITTC focuses on power difference verification at trial conditions and optional normalisation; DNV focuses on statistical performance estimation over many samples and formal presentation of uncertainty.
Model calibration and validation	Predict net change in force per test using FSAM; convert to force coefficient vs AWA; tune hull/rudder/WAPS coefficients to align predicted and measured curves; apply calibrated model to voyage fuel-saving prediction.	Compute ΔP between WAPS ON/OFF at sea-trial conditions as the sum of direct shaft-power reduction and equivalent power from speed increase.	Primary output is measurement-based performance with uncertainty rather than tuning of predictions by comparison with measurements.	ANEMOI includes an explicit tuning loop; ITTC requires model update if mismatch but does not prescribe tuning method; DNV is prediction-agnostic and centred on verified measured performance.
Long-term prediction and route savings	Net fuel-saving prediction uses baseline vessel performance plus WAPS forces, auxiliary power and four DOF effects; integrate across time steps in voyage simulation to obtain voyage net fuel saving.	If prediction matrix is available and validated, compute average saving potential for a route using the prediction procedure (ITTC 7.5-02-03-01.9 or MEPC.1/Circ.896); include measured WAPS power consumption in average power saving calculation.	Long-term framework emphasises continuous measurements and many ON/OFF tests to build confidence; results can be used to reflect impact on indices such as Carbon Intensity Index (CII) and support operational monitoring and reporting.	Long-term savings require extrapolation beyond the tested envelope using a prediction model. ITTC treats voyage simulation as optional post-step; ANEMOI provides an end-to-end fuel saving computation; DNV focuses on in-service performance evaluation with statistical confidence and verification.

Table 8. Uncertainty quantification.

Step	ANEMOI	ITTC 7.5-04-01-02	DNV-RP-0686	Comments
Uncertainty estimation and propagation	Not formally prescribed; mitigated via filtering, multiple tests and calibration fit quality (scatter vs AWA).	Uncertainty not well established; recommends not using sea trials for contractual guarantees; report mean/SD and traces for transparency.	Formal uncertainty evaluation (Sec 6) based on valid ON/OFF tests; confidence intervals (e.g., Student's t); recommend ON-ON/OFF-OFF tests to quantify baseline variability.	DNV is the only methodology with a defined statistical uncertainty framework; ANEMOI and ITTC acknowledge uncertainty but are less formal.

APPENDIX 2: Alternative Approaches To Waps Performance Assessment

Direct thrust measurement on the WAPS unit

Direct thrust measurements can provide valuable insight into the aerodynamic behaviour of the WAPS, and the forces generated by the device itself. However, this approach is not yet mature for robust full-scale savings verification and does not capture the coupled hydrodynamic response of the vessel, changes in propulsive efficiency, or operational adjustments such as rudder usage and speed control, which ultimately determine the realised fuel and emissions savings [8, 9].

ISO 19030-based analysis, comparing vessel performance before and after WAPS installation using long-term operational data.

While this approach benefits from large datasets, it requires extended monitoring periods to obtain statistically meaningful results. In its modification for WAPS, it requires higher frequency data to be able to capture the changes in wind conditions and performance. While the approach can capture hull fouling degradation through time, special care is needed to treat hull cleaning, propeller polishing and dry-docking events. In addition, the strict filtering and steady-state requirements of ISO 19030 result in significant data rejection under variable wind conditions, limiting its practicality for isolating WAPS effects [8].



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