# DIGITAL PERFORMANCE MONITORING AS A MANAGERIAL GOVERNANCE INFRASTRUCTURE: EVIDENCE FROM BULK CARRIER OPERATIONS

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## Abstract

This study examines whether digital performance monitoring operates as a governance infrastructure in bulk carrier operations. While prior research highlights the predictive advantages of high-resolution onboard data, its managerial implications remain underexplored. Drawing on six months of minute-level operational data from a Kamsarmax bulk carrier, the study develops intensity-based fuel and emissions indicators and constructs conditional performance baselines to identify deviations under comparable operating conditions. The findings show that digital monitoring enhances transparency, benchmarking consistency, and structured detection of operational inefficiencies. Compared with traditional noon-reporting, continuous monitoring improves data completeness and reduces informational latency, allowing performance visibility to be embedded within active sailing periods rather than confined to voyage-end review. The results demonstrate that digital performance monitoring is not merely a modelling enhancement but a structural mechanism that reshapes control architecture, strengthens managerial accountability, and supports continuous performance governance in bulk shipping.

## Keywords

Digitalization, telemetry, performance monitoring, governance, shipping management

## 1 Introduction

Performance management in bulk shipping has traditionally relied on retrospective reporting systems. Noon reports, voyage summaries, and periodic fuel reviews provide structured but delayed visibility of vessel performance. While these mechanisms support regulatory compliance and benchmarking, they offer limited capacity for continuous oversight or structured real-time governance. As sustainable shipping management research indicates, effective performance measurement is a critical success factor for aligning operational behavior with environmental and strategic objectives (Chua et al., 2023).

The increasing deployment of high-frequency onboard telemetry fundamentally alters this operational landscape. Modern vessels continuously record propulsion parameters, fuel consumption, speed profiles, and environmental exposure at minute-level resolution. Research on ship fuel consumption modelling and telemetry integration demonstrates that high-resolution operational data enhances measurement accuracy and reduces structural estimation bias (Fan et al., 2022; Zhou et al., 2023; Nguyen et al., 2025). However, these studies primarily focus on predictive performance rather than managerial governance implications.

From an organizational information processing perspective, digital systems improve performance outcomes when they enhance information quality, processing capability, and coordination (Koh et al., 2026). Similarly, digital resource and capability research suggests that technology becomes performance-enhancing only when embedded within structured organizational processes (Li et al., 2026). In logistics and supply chain contexts, artificial intelligence and advanced analytics have been shown to strengthen strategic performance measures, particularly through improved information sharing and decision synchronization (Garg et al., 2025). Yet empirical evidence linking ship-level telemetry to managerial control architectures in bulk shipping remains limited.

High-frequency monitoring generates large volumes of operational data. However, data availability alone does not guarantee governance improvement. Decision-support research highlights the importance of structured knowledge extraction for transforming raw data into actionable signals (Tian et al., 2025). Moreover, digital governance studies warn that increased digitalization may introduce new accountability and control challenges if monitoring systems are not integrated within coherent governance frameworks (Wang, 2025). Thus, the managerial question is not whether telemetry improves modelling precision, but whether it enhances transparency, inefficiency detection, and operational control.

Existing ship performance research has largely emphasized optimization algorithms, predictive modelling, and machine learning accuracy (Fan et al., 2022; Nguyen et al., 2025). Comparatively fewer studies investigate how high-frequency monitoring reshapes managerial decision structures, reduces informational latency, or enables continuous governance. Maritime disruption management research underscores that resilience depends on timely information flows and adaptive control systems (Li et al., 2024). Yet the operational governance implications of telemetry remain underexplored.

This study addresses this gap by examining digital high-frequency vessel monitoring as a managerial decision-support mechanism in bulk shipping. Using operational evidence from a Kamsarmax bulk carrier operating under real commercial conditions, the paper investigates whether telemetry:

1. Enhances the transparency and measurability of intensity-based fuel and emissions performance
2. Improves managerial ability to detect and quantify operational inefficiencies
3. Enables a transition from retrospective voyage-end evaluation to continuous operational governance

By grounding empirical operational analysis within a digital governance and information processing framework, this study demonstrates how telemetry systems function not merely as data acquisition tools but as control architectures that reshape performance management in shipping organizations.

The remainder of the paper is structured as follows. Section 2 reviews the literature on digital transformation, organizational information processing, and maritime decision-support systems. Section 3 defines the scope of the study and presents the research hypotheses. Section 4 outlines the methodological approach and dataset. Section 5 presents empirical findings. Section 6 discusses managerial implications and concludes.

# 2 Literature

## 2.1 Digital Monitoring and Organizational Information Processing

Digital transformation in maritime transport has been widely examined from technological, strategic, and organizational perspectives. Chua et al. (2023) argue that performance measurement constitutes a critical success factor in sustainable shipping management, emphasizing the importance of structured indicators in aligning operational behavior with strategic objectives. However, their analysis remains primarily conceptual and does not examine how high-frequency operational systems alter measurement architecture at the vessel level.

From a digital capability perspective, Li et al. (2026) demonstrate that digital resources contribute to improved performance only when embedded within organizational routines and capability-building processes. Similarly, Koh et al. (2026), drawing on organizational information processing theory, suggest that digital systems enhance resilience by improving information quality, timeliness, and processing capacity. These studies imply that the managerial value of digitalization lies not in technology itself, but in its integration within governance structures.

In parallel, technical ship performance studies have shown that high-frequency onboard telemetry improves predictive accuracy. Fan et al. (2022) review fuel consumption modelling approaches and conclude that incorporating real operational data enhances estimation reliability. Zhou et al. (2023) further demonstrate that combining onboard propulsion measurements with environmental variables improves model robustness. Nguyen et al. (2025) extend this approach by integrating Internet of Things (IoT)-enabled telemetry with explainable machine learning frameworks.

While these studies confirm the technical superiority of high-resolution data, they primarily evaluate prediction performance rather than governance implications. They assume that better data improves modelling outcomes but do not explicitly assess whether increased data frequency enhances transparency, measurability, or managerial oversight.

Thus, although digital capability research highlights the importance of information processing (Koh et al., 2026), and telemetry research confirms improved measurement precision (Fan et al., 2022; Zhou et al., 2023), limited empirical work bridges these two streams by examining telemetry as a performance visibility infrastructure within shipping governance.

This gap motivates the examination of high-frequency telemetry as an enabler of transparency and measurability in intensity-based performance metrics.

### 2.2 Intensity-Based Key Performance Indicators (KPIs) and Governance Architecture

Intensity-based metrics such as fuel consumption per nautical mile and $CO_2$ emissions per nautical mile have become central in regulatory and sustainability discussions. Schinas and Stefanakos (2014) analyze compliance under MARPOL Annex VI and highlight the growing regulatory emphasis on measurable emissions performance. Solakivi et al. (2022) and Altarriba et al. (2025) further argue that cost competitiveness and lifecycle emissions assessments reinforce the strategic relevance of fuel efficiency.

Chua et al. (2023) position performance measurement as a core mechanism in sustainable shipping management, identifying its role in linking operational practice to strategic outcomes. However, their review does not differentiate between aggregated reporting systems and high-frequency monitoring architectures.

In the operational optimization literature, Hu et al. (2022) and Sang et al. (2023) examine speed and fuel optimization strategies using predictive frameworks. These studies assume that accurate measurement precedes optimization but do not interrogate the governance dimension of measurement itself.

Consequently, while regulatory research establishes the importance of measurable intensity indicators, and optimization research assumes accurate operational measurement, limited attention has been paid to how telemetry strengthens the transparency and stability of intensity-based benchmarking under real commercial conditions.

This suggests a gap between recognising intensity metrics as governance instruments and understanding how high-frequency digital monitoring reshapes their measurability and comparability.

### 2.3 Telemetry, Interpretability, and Inefficiency Detection

A second critical issue concerns how digital monitoring supports managerial intervention. In logistics and supply chain research, Garg et al. (2025) show that artificial intelligence strengthens strategic performance measures through enhanced information sharing and decision synchronization. However, they find that performance impact depends on structured integration rather than technology adoption alone.

Within maritime navigation, Tian et al. (2025) demonstrate that knowledge extraction from operational data improves decision support in safety-critical scenarios. Similarly, Fan et al. (2025) introduce advanced decision-support methodologies that integrate structured signals to enhance operator performance. These studies confirm that transforming raw data into interpretable signals is essential for effective intervention.

In ship fuel modelling research, Öztürk and Başar (2022) argue that regression-based approaches retain managerial value because they provide interpretable marginal effects. In contrast, Wang et al. (2023) highlight the trade-off between predictive accuracy and interpretability, noting that complex machine learning models may reduce transparency and accountability.

While predictive modelling research emphasizes accuracy, and decision-support research stresses structured signals, limited empirical evidence examines how regression residuals or deviation metrics function as inefficiency indicators within bulk carrier governance. Moreover, maritime disruption management literature suggests that resilience depends on timely information flows and adaptive responses (Li et al., 2024), yet the shift from retrospective evaluation to continuous governance enabled by telemetry remains insufficiently examined.

Thus, although prior studies establish that digital systems improve prediction (Fan et al., 2022), enhance optimization (Hu et al., 2022), and support decision-making (Tian et al., 2025), there is a clear gap in understanding how high-frequency telemetry restructures managerial control architecture by:

- Strengthening transparency of intensity-based KPIs
- Enabling structured inefficiency detection
- Reducing informational latency in governance processes

Addressing this gap requires empirical operational evidence linking telemetry-enabled analytics to managerial decision-support mechanisms under real commercial bulk carrier conditions.

## 3 Scope of the Study

Prior research confirms the technical advantages of high-frequency monitoring (Fan et al., 2022; Zhou et al., 2023; Nguyen et al., 2025). Yet the managerial implications of this transformation remain insufficiently examined in bulk carrier operations. In particular, it remains unclear whether high-frequency monitoring strengthens the transparency of intensity-based performance metrics used in governance frameworks (Chua et al., 2023), improves structured detection of operational inefficiencies, and alters the temporal architecture of performance control in line with organizational information processing perspectives (Koh et al., 2026).

Intensity-based metrics such as fuel consumption and $CO_2$ emissions per nautical mile are increasingly embedded in compliance and benchmarking systems (Schinas and Stefanakos, 2014). Yet most applications rely on aggregated voyage-level summaries. The question remains whether high-frequency monitoring strengthens the transparency, comparability, and statistical stability of such transport-normalized indicators under real commercial conditions. If telemetry improves granularity and consistency, it should enhance the measurability of these governance-relevant KPIs.

In parallel, decision-support research highlights that operational value arises when data are transformed into interpretable signals that enable intervention (Tian et al., 2025). Regression-based modelling retains importance in this context because it provides explainable marginal effects and quantifiable deviations (Öztürk and Başar, 2022). By contrast, accuracy-oriented black-box models may weaken accountability when decision logic is opaque (Wang et al., 2023). Whether telemetry-enabled analytics produce structured inefficiency signals suitable for daily managerial oversight in bulk carrier operations remains empirically underexplored.

Moreover, organizational information processing research suggests that digital systems improve control capability when they reduce informational delay and ambiguity (Koh et al., 2026). Maritime disruption management literature similarly emphasizes the importance of timely information flows in strengthening adaptive response (Li et al., 2024). Despite these insights, empirical evidence is limited on whether high-frequency vessel monitoring changes the temporal structure of performance management, enabling a shift from retrospective voyage-end review to continuous operational governance.

The analysis operationalizes this perspective by examining measurable effects on KPI stability, deviation detection, and temporal control structure. Accordingly, the following hypotheses are examined.

**H1:** High-frequency vessel telemetry enhances the transparency and measurability of intensity-based fuel and emissions performance in bulk carrier operations.

This proposition evaluates whether increased data granularity strengthens the stability and visibility of transport-normalized indicators used for benchmarking and compliance-oriented performance management (Schinas and Stefanakos, 2014; Chua et al., 2023).

**H2:** Telemetry-enabled analytics improve managerial ability to detect and quantify operational inefficiencies under real commercial conditions.

This proposition assesses whether interpretable performance models generate structured deviation signals that support oversight and intervention (Öztürk and Başar, 2022; Tian et al., 2025; Wang et al., 2023).

**H3:** High-frequency digital monitoring enables a transition from retrospective performance evaluation to continuous operational performance governance.

This proposition examines whether reduced informational latency and increased signal frequency alter the temporal architecture of managerial control (Li et al., 2024; Koh et al., 2026).

Together, these hypotheses position high-frequency telemetry not merely as a technological enhancement but as a structural transformation of performance visibility, inefficiency detection, and managerial control in bulk shipping operations.

# 4 Methodology

## 4.1 Operational Context and Data Architecture

The empirical analysis is based on high-frequency onboard telemetry collected from a Kamsarmax bulk carrier operating under real commercial conditions during a six-month period. The vessel is equipped with integrated propulsion and navigation monitoring systems recording engine load, fuel flow, speed over ground, and environmental parameters at one-minute resolution.

Unlike traditional noon reporting systems, which provide aggregated daily or voyage-end summaries (Fan et al., 2022), the telemetry system produces continuous streams of operational data. For analytical consistency and managerial interpretability, minute-level observations were filtered for steady sailing conditions and aggregated into structured daily performance records, consistent with structured decision-support approaches in operational analytics (Öztürk and Başar, 2022).

The analysis therefore focuses on how high-frequency monitoring reshapes performance visibility and managerial control capability within bulk carrier operations.

**4.2 Data Preprocessing and KPI Construction**

High-frequency telemetry datasets require structured preprocessing to ensure that performance indicators reflect operational reality rather than sensor noise or measurement artifacts. Research on real ship datasets highlights that analytical reliability depends critically on filtering discipline and data integrity control (Cai et al., 2024). In governance terms, unreliable preprocessing may distort performance signals and undermine managerial accountability.

The preprocessing workflow followed established principles in telemetry-based operational analytics (Gupta et al., 2022; Nguyen et al., 2025). The objective was to isolate steady propulsion conditions and eliminate observations that could introduce bias into intensity-based performance metrics.

The procedure consisted of:

1. Removal of sensor groups not associated with propulsion performance
2. Elimination of null values and non-numeric entries
3. Exclusion of non-sailing periods using vessel stopped indicators and propulsion power thresholds
4. Filtering of unrealistic operational values based on engineering plausibility criteria
5. Aggregation of minute-level telemetry into structured daily performance records
6. Construction of intensity-based key performance indicators

Operational filtering criteria included confirmation of engine running condition, speed over ground above minimum sailing threshold, positive propulsion power, and removal of extreme outliers inconsistent with propulsion physics. Preventing unrealistic preprocessing practices and potential data leakage aligns with methodological recommendations in predictive modelling research (Pang and Dong, 2026).

Fuel consumption per nautical mile and $CO_2$ emissions per nautical mile were constructed by normalizing fuel flow rates by distance sailed, consistent with transport-normalized intensity modelling approaches (Zhou et al., 2023; Hu et al., 2022). Specific fuel oil consumption was retained as recorded by the onboard telemetry system.

Following structured filtering, the propulsion-related dataset consisted of 129,416 valid minute-level observations representing steady sailing conditions. To enable managerial interpretability and governance-relevant benchmarking, these observations were aggregated into daily averages, resulting in 115 structured daily performance records. Descriptive statistics reported in Section 5 reflect the high-frequency dataset prior to aggregation, while regression-based governance analysis relies on the aggregated daily structure.

### 4.3 Performance Baseline Estimation and Inefficiency Detection

To convert high-frequency operational data into structured performance signals, a conditional performance baseline was estimated linking propulsion and environmental conditions to intensity-based key performance indicators, consistent with regression-based decision-support approaches in shipping performance analytics (Öztürk and Başar, 2022).

The analytical framework specifies expected fuel and emissions intensity given main engine load percentage, speed over ground, and environmental exposure. The resulting fitted values represent operationally expected intensity performance under observed sailing conditions, in line with conditional benchmarking practices used in operational fuel consumption studies (Zhou et al., 2023; Fan et al., 2022).

Deviations between observed and expected performance are captured through residual values, which are interpreted as structured indicators of relative underperformance or outperformance. Interpretable deviation signals are central to explainable decision-support systems, particularly where transparency and accountability are required (Wang et al., 2023; Tian et al., 2025). Positive deviations indicate higher-than-expected intensity under comparable operational conditions, while negative deviations indicate relative efficiency gains.

This deviation-based approach enables:

- Identification of days characterized by systematic performance gaps
- Quantification of inefficiency magnitude
- Differentiation between controllable operational variation and environmental effects

Unlike retrospective fuel summaries, which reflect absolute consumption levels (Fan et al., 2022), the baseline framework produces conditional diagnostics that account for propulsion demand and external exposure. By isolating deviations from expected performance, the system generates interpretable signals that may trigger managerial review or operational adjustment, consistent with structured performance governance principles (Koh et al., 2026).

**4.4 Governance Temporal Structure and Informational Latency**

Traditional vessel performance management relies predominantly on periodic reporting cycles. Noon reports and voyage summaries provide aggregated indicators that are reviewed retrospectively, often after operational conditions have already evolved. Such structures support compliance and record-keeping, but they inherently embed informational delay within the performance governance process (Fan et al., 2022).

High-frequency telemetry alters this temporal structure. By generating continuous operational signals, the system enables performance indicators to be constructed and evaluated within the operational cycle rather than after its completion. This shift reduces informational latency, defined here as the time gap between operational behavior and managerial visibility.

To assess this temporal dimension, the analysis considers:

- The frequency of performance signal generation
- The continuity of monitoring across operational days
- The capacity to identify deviations during, rather than after, performance cycles
- The stability of daily structured indicators derived from minute-level inputs

By aggregating high-frequency telemetry into daily structured performance records, the monitoring architecture retains managerial interpretability while preserving informational granularity. This configuration allows deviations from expected performance to be identified within short operational intervals, enabling corrective attention without waiting for voyage-end summaries.

Organizational information processing theory suggests that reduced informational delay enhances coordination and control capability (Koh et al., 2026). Similarly, maritime disruption management research highlights the importance of timely information flows for adaptive response and resilience (Li et al., 2024). Within this framework, high-frequency vessel monitoring functions as a governance infrastructure that supports continuous oversight rather than episodic review.

The temporal restructuring of performance visibility therefore represents not merely technological enhancement, but a modification of managerial control architecture in bulk shipping operations.

# 5 Results

## 5.1 Performance Visibility and Intensity-Based KPI Stability

The descriptive statistics of the filtered telemetry dataset (Table 1 and Table 2) indicate consistent and measurable intensity-based performance behavior over the six-month observation period. Fuel consumption per nautical mile averaged 0.0802 mt/nm with moderate dispersion, while $CO_2$ emissions per nautical mile averaged 10.533 t/nm. Specific fuel oil consumption averaged 156 g/kWh.

**Table 48.** Descriptive Statistics of Operational KPIs.

| KPI | Mean | Std. Dev. | Min | Max | N |
|---|---|---|---|---|---|
| **Fuel per Nautical Mile (mt/nm)** | **0.0802** | **0.0164** | **0.0413** | **0.1856** | **129416** |
| **$CO_2$ per Nautical Mile (t/nm)** | **10.533** | **2.151** | **5.427** | **24.794** | **129416** |
| **Specific Fuel Oil Consumption (g/kWh)** | **156.0** | **8.3** | **120.3** | **188.1** | **129416** |

Source: Authors

**Table 2.** Descriptive Statistics of Operational Drivers.

| KPI | Mean | Std. Dev. | Min | Max | N |
|---|---|---|---|---|---|
| **Speed Over Ground (knots)** | **10.9** | **1.5** | **5.3** | **15.6** | **129416** |
| **Main Engine Load Percentage (%)** | **56.1** | **10.9** | **40.0** | **79.8** | **129416** |
| **True Wind Speed (knots)** | **15.43** | **7.15** | **0.00** | **39.98** | **129416** |

Source: Authors

Operational driver statistics further confirm that the dataset reflects commercially realistic sailing conditions. Speed over ground averages 10.9 knots with a standard deviation of 1.5 knots, ranging between 5.3 and 15.6 knots. Main engine load averages 56.1 percent (SD = 10.9), with observed values between 40 and 79.8 percent of maximum continuous rating. True wind speed averages 15.43 knots (SD = 7.15), ranging from calm conditions to approximately 40 knots.

The dispersion patterns indicate meaningful operational and environmental variability without extreme structural instability. In particular, engine load and speed remain within typical bulk carrier operating envelopes, while wind variability introduces measurable but bounded environmental exposure. The large number of filtered high-frequency observations (N = 129,416) strengthens statistical stability prior to daily aggregation.

Importantly, intensity indicators exhibit stable variation patterns without structural breaks across the daily aggregation window. Unlike voyage-level summaries that compress performance into single aggregate indicators, the telemetry-derived dataset enables repeated and comparable daily benchmarking under steady sailing conditions (Figure 1).

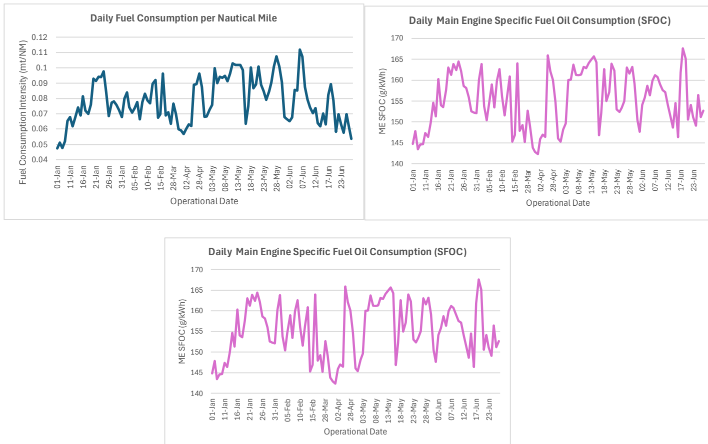


**Figure 78.** Daily evolution of operational performance indicators over the six-month observation period.

Source: Authors

The correlation structure further enhances transparency (Table 3). The high correlation between fuel and $CO_2$ intensity (r = 0.9999) confirms internal structural consistency of KPI construction. Main engine load shows strong positive association with fuel intensity (r = 0.747), while speed over ground exhibits a moderate negative relationship with fuel per nautical mile (r = -0.142). True wind speed shows moderate but weaker correlation (r ≈ 0.366 with fuel intensity), indicating environmental influence without dominance.

**Table 3.** Correlation Matrix

| | Fuel per Nautical Mile (mt/nm) | CO2 per Nautical Mile (t/nm) | ME SFOC (g/kWh) | Main Engine Load Percentage | Speed-Over-Ground | True Wind Speed |
|---|---|---|---|---|---|---|
| Fuel per Nautical Mile (mt/nm) | 1 | | | | | |
| CO2 per Nautical Mile (t/nm) | 0.999926241 | 1 | | | | |
| ME SFOC (g/kWh) | 0.845334503 | 0.846941227 | 1 | | | |
| Main Engine Load Percentage | 0.746799722 | 0.747348301 | 0.755514705 | 1 | | |
| Speed-Over-Ground | -0.142152758 | -0.140544879 | 0.140991273 | 0.531169708 | 1 | |
| True Wind Speed | 0.366354277 | 0.365707558 | 0.221452681 | 0.163880289 | -0.225423 | 1 |

Source: Authors

These patterns demonstrate that intensity-based KPIs derived from high-frequency telemetry remain statistically stable, internally coherent, and conditionally interpretable across operational days. The increased granularity strengthens performance visibility by allowing consistent benchmarking under comparable sailing conditions.

Collectively, the evidence supports the proposition that high-frequency telemetry enhances transparency and measurability of transport-normalized fuel and emissions indicators in bulk carrier operations, consistent with H1.

### 5.2 Conditional Baseline and Structured Inefficiency Signals

To assess whether telemetry-enabled analytics support structured inefficiency detection, a conditional performance baseline was estimated linking engine load, vessel speed, and environmental exposure to intensity-based KPIs.

**Table 4.** Regression Results for Operational Intensity Models (N = 115)

| Variables | Fuel per NM | $CO_2$ per NM | ME SFOC |
|---|---|---|---|
| **Intercept** | **0.07148***** | **9.36465***** | **139.83874***** |
| | **(-0.00245)** | **(-0.32716)** | **(-3.29764)** |
| **Main Engine Load (%)** | **0.001694***** | **0.22261***** | **0.64091***** |
| | **(-0.000034)** | **(-0.00459)** | **(-0.04628)** |
| **Speed Over Ground** | **−0.007919***** | **−1.03838***** | **−1.77865***** |
| | **(-0.000249)** | **(-0.03325)** | **(-0.33511)** |
| **True Wind Speed** | **0.000027** | **0.00353** | **−0.02051** |
| | **(-0.000049)** | **(-0.00652)** | **(-0.06575)** |
| **$R^2$** | **0.9623** | **0.9611** | **0.6655** |
| **Adj. $R^2$** | **0.9612** | **0.9601** | **0.6565** |
| **F-statistic** | **943.55***** | **914.35***** | **73.61***** |

Source: Authors

The conditional performance baseline demonstrates strong explanatory capacity for intensity-based KPIs. The framework explains 96.2 percent of the variation in fuel consumption per nautical mile ($R^2$ = 0.9623) and 96.1 percent of the variation in $CO_2$ emissions per nautical mile ($R^2$ = 0.9611). The explanatory performance for specific fuel oil consumption is lower but substantial ($R^2 = 0.6655$), indicating that propulsion and operational variables account for a meaningful share of thermodynamic efficiency variation.

Main engine load emerges as a statistically significant driver across all specifications ($p < 0.01$). A one-percentage-point increase in engine load is associated with an increase of 0.001694 mt/nm in fuel intensity and 0.22261 t/nm in $CO_2$ intensity. These magnitudes confirm that propulsion demand directly translates into transport-normalized performance outcomes.

Speed over ground exhibits a statistically significant negative association with fuel and emissions intensity ($\beta = -0.007919$ for fuel; $\beta = -1.03838$ for $CO_2$, $p < 0.01$), reflecting scale effects within the observed operational envelope. In contrast, true wind speed does not retain statistical significance once propulsion variables are controlled for, suggesting that environmental variability is largely mediated through operational adjustment rather than independently driving intensity deviations.

The high F-statistics for fuel (943.55) and $CO_2$ (914.35), both significant at the 1 percent level, indicate strong joint explanatory relevance of the selected operational variables.

Beyond coefficient interpretation, the key managerial contribution lies in the residual structure. Because expected intensity is conditionally estimated given propulsion and environmental exposure, residual values represent performance deviations under comparable operational conditions. Positive residuals therefore indicate higher-than-expected fuel or emissions intensity, while negative residuals indicate relative efficiency gains.

This conditional deviation framework enables:

- Identification of systematic underperformance days
- Quantification of inefficiency magnitude relative to expected baseline
- Clear differentiation between controllable operational effects and exogenous environmental exposure

The statistical robustness of the baseline strengthens the credibility of these deviation signals as governance-relevant indicators rather than random noise.

Taken together, the results demonstrate that telemetry-enabled analytics produce structured, interpretable inefficiency signals suitable for managerial oversight, providing empirical support for H2.

### 5.3 Informational Latency and Governance Continuity

The temporal structure of telemetry-based performance monitoring differs fundamentally from traditional reporting systems. Conventional noon reports provide a single daily entry, typically reviewed retrospectively within voyage-end evaluation cycles. In contrast, the examined telemetry system recorded operational variables at one-minute resolution, generating up to 1,440 observations per day. Over the six-month study period, this resulted in 129,416 propulsion-related records, subsequently structured into 115 daily conditional performance observations.

For contextual comparison, noon, arrival, and departure reports for the same vessel and time period were reviewed. These conventional records reveal structural limitations inherent in manual aggregation systems. Several reports contained missing fields, incomplete environmental entries, or internal inconsistencies attributable to manual input processes. In some instances, entire daily noon reports were unavailable. Even when complete, reporting resolution remained limited to a single aggregated entry per day.

The comparison demonstrates measurable differences in data completeness, temporal resolution, and structural consistency between manual reporting systems and telemetry-based monitoring. While noon reports provide static daily summaries, telemetry generates a continuous operational trace of propulsion behavior and environmental exposure. Even after daily aggregation for interpretability, telemetry-derived indicators are constructed from high-frequency inputs rather than isolated summary entries.

Empirically, the stability of fitted values and residual distributions indicates that performance deviations can be identified at the level of individual operational days rather than only after voyage completion. Structured deviation signals therefore emerge within active sailing periods.

From an organizational information processing perspective, reduced delay between operational behavior and managerial visibility strengthens control capability and adaptive response (Koh et al., 2026). Maritime disruption management research similarly emphasizes the importance of timely information flows for coordinated intervention (Li et al., 2024).