Research on the Implementation Path of Maritime Carbon Monitoring Systems

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Abstract. With global shipping accelerating its transition toward low-carbon development, establishing a scientific and operable carbon monitoring system has become essential. Existing mechanisms such as the EU MRV and IMO DCS are shaping a shift from voluntary cooperation to rule-based competition. For China, a major shipping nation, simply adopting international frameworks cannot accommodate its diverse fleet, complex operations, and uneven digitalization. This study reviews key monitoring technologies — including BDN-based methods, tank level measurement, flowmeters, and direct CO_2 monitoring—and assesses their applicability within China. It further proposes an implementation pathway featuring multi-source data integration, digital governance, metrological traceability, differentiated monitoring strategies, and linkage with national carbon markets. The findings provide a framework to support accurate carbon accounting, regulatory compliance, and the sector's green transition.

Keywords: Carbon Emission; Carbon Border Adjustment Mechanism; Measurement System; Metrological Traceability.

1. Introduction

Against the backdrop of the global maritime sector's accelerated transition toward green and low-carbon development, establishing a scientific, unified, and implementable carbon emission monitoring system has become the shared choice of major shipping nations. The EU's MRV scheme, as a representative regional regulatory model, continues to expand its influence, while the IMO is steadily advancing the standardization of the DCS framework. As a result, international governance of maritime carbon emissions is shifting from "voluntary cooperation" to "rule-based competition.". For China—both a major shipping nation and a major trading power—it is essential not only to participate actively in global governance, but also to build a carbon monitoring framework that aligns with its own shipping structure, port-shipping industry model, and regulatory needs, thereby supporting future international discourse power and the industry's green transition. In particular, given the diversity of vessel types, complexity of operating models, long and intricate port–hinterland logistics chains, and uneven levels of digitalization across Chinese shipping enterprises, simply adopting existing international systems cannot meet domestic realities. China therefore needs a more adaptable and forward-looking institutional system for data collection, metrological traceability, monitoring methodologies, and accounting procedures, so as to provide a reliable foundation for subsequent carbon accounting, carbon trading mechanisms, and low-carbon shipping policies. dvancing the sustainable development of international carbon markets and global climate governance [1].

2. Introduction to Maritime Carbon Monitoring Technologies

2.1 Tracking of Bunker Delivery Notes (BDNs) and Periodic Fuel Tank Inventory Method

The Bunker Delivery Note (BDN) serves as a critical document during ship fuel bunkering operations. According to the requirements of MARPOL, vessels of 400 gross tonnage or above are required to retain the BDN for each fuel delivery onboard for a period of three years. Additionally, a

representative fuel sample of each delivery must be preserved onboard for 12 months or until the corresponding fuel batch is fully consumed, whichever is later.

Surveys indicate that most ships currently collect their annual fuel consumption data using the "BDN accumulation method." Thus, the BDN provides an essential basis for identifying the type of marine fuel used and calculating the corresponding fuel consumption. The formula for calculating fuel consumption over a given time period is as follows:

$$\begin{aligned}\text{Fuel Consumption} &= \text{Opening Inventory} + \text{BDN Quantity} - \text{Closing Inventory} \\ &\quad - \text{Fuel Discharged During Period}\end{aligned}$$

The primary sources of carbon emissions from ships include main engines, auxiliary engines, boilers, gas turbines, and inert gas generators. Each emission source utilizes different types of fuels with distinct carbon emission factors.

When applying the BDN tracking and periodic fuel tank inventory method to calculate greenhouse gas emissions, only the total fuel consumption of the emission sources can be roughly estimated. It is not possible to analyze fuel consumption for each emission source individually. This monitoring approach relies heavily on data provided by external suppliers, and its reliability depends on the completeness of external information sources. Consequently, the method is susceptible to human-induced biases, such as inaccurate data entries due to non-standard formats or missing parameters in BDN documentation, potentially causing breaks in the fuel transaction record chain [2].

Moreover, the credit risk exposure of this method warrants attention. When suppliers engage in false reporting of fuel quantities or characteristics, ship operators—lacking independent verification mechanisms—often fall into a passive regulatory position. Furthermore, this method records only static fuel delivery data, making it difficult to establish a dynamic correlation model with real operational parameters. Under conditions involving multiple consecutive voyages or complex sea states, variables such as main engine load fluctuations or route adjustments can significantly affect fuel efficiency, yet such variations cannot be effectively traced through original delivery data.

2.2 Fuel Tank Level Monitoring Method

This method measures the fuel tank level height using detection devices such as level sensors or image recognition equipment. The measured height is converted to fuel volume using a tank calibration table, which is then converted to fuel mass through the fuel's density. The fuel consumption for a given voyage or time interval is calculated as follows:

$$\textit{Fuel Consumption (at sea)} = \textit{Departure Level} + \Delta\textit{Fuel Added} - \textit{Arrival Level} - \Delta\textit{Fuel Discharged}$$

$$\textit{Fuel Consumption (in port)} = \textit{Arrival Level} + \Delta\textit{Fuel Added} - \textit{Departure Level} - \Delta\textit{Fuel Discharged}$$

As the data foundation of this computational model, the accuracy of level monitoring technology directly affects the reliability of the monitoring data. Existing technologies mainly include float-type level gauges and pressure sensor-type level gauges.

Float-type gauges, based on the buoyancy principle, monitor level changes through a floating mechanism connected to a sensor. Their simplicity and ease of installation make them widely used on small- and medium-sized vessels. However, their accuracy is easily affected by tank deformation, liquid turbulence, and fuel density variations. In non-standard tank shapes or when using high-viscosity fuels, mechanical wear and sludge deposition on the float can lead to progressive measurement drift, requiring frequent cleaning and maintenance to maintain data reliability.

Pressure sensor-type gauges, in contrast, infer the fuel level by measuring static pressure at the tank bottom. This method is less sensitive to tank geometry and liquid surface fluctuations, offering better adaptability in large vessels with complex tank structures or mixed fuel storage scenarios. However, these contact-based sensors face risks such as probe blockage by sediment, pressure distortion due to moisture penetration, and temperature sensitivity, all of which increase system maintenance costs[3].

Under the IMO's tightened regulatory framework on carbon intensity indicators (CII), the systematic errors inherent in current level measurement technologies pose significant challenges for fuel consumption accounting and carbon emission evaluation. Studies indicate that accumulated measurement deviations from traditional devices during dynamic voyages can lead to over 5% error in carbon emission estimates, underscoring the importance of developing intelligent, high-precision monitoring technologies.

2.3 Flowmeter-Based Monitoring of Fuel Combustion Processes

The flowmeter monitoring method measures fuel flow at the inlet and outlet of the ship's fuel pipelines, recording in real time the fuel consumption of each emission source and each time interval. This allows for precise calculation of carbon emissions.

This method plays a critical role in international carbon verification frameworks (e.g., IMO DCS and EU MRV), enabling shipping companies to perform fine-grained energy management, assess equipment efficiency, and comply with MRV and verification requirements.

$$Fuel\ Consumption\ (at\ sea) = \sum(Flowmeters\ at\ emission\ sources\ during\ voyage)$$

$$\text{Fuel Consumption (in port)} = \sum(\text{Flowmeters at emission sources while in port})$$

Flowmeter-based methods are more precise and specific, allowing the determination of CO_2 emissions over time within a single voyage, making them suitable for ships traversing multiple national waters.

The key challenge for current flow measurement technologies lies in balancing environmental adaptability and economic feasibility. As global carbon metrology standards evolve, the amplification of measurement uncertainty in carbon accounting has become increasingly prominent. Future development of flowmeters should integrate multi-physics sensing and digital twin technologies to enhance precision and reliability, while advancing cost reduction, intelligent integration, and system scalability to enable wider deployment in carbon emission monitoring.

2.4 Direct CO_2 Monitoring Method

This method calculates total carbon emissions by directly measuring the CO_2 concentration and exhaust flow rate in real time. The fuel consumption during a voyage or specific time period can be estimated as follows:

$$Fuel\ Consumption\ (at\ sea) = Total\ Exhaust\ Volume \times CO_2\ Concentration/Carbon\ Emission\ Factor$$

$$Fuel\ Consumption\ (in\ port) = Total\ Exhaust\ Volume \times CO_2\ Concentration/Carbon\ Emission\ Factor$$

Spectroscopic-based gas monitoring technologies have become the mainstream approach for greenhouse gas (GHG) detection, offering high sensitivity, non-contact measurement, remote operation, and broad applicability. Commonly applied systems include:

Non-Dispersive Infrared (NDIR) Spectroscopy: utilizes the proportional relationship between gas absorption intensity and concentration; simple, low-cost, but with limited spectral resolution.

Non-Dispersive Ultraviolet (NDUV) Spectroscopy: similar to NDIR but suited for UV-absorbing gases such as ozone and nitrogen oxides.

Tunable Diode Laser Absorption Spectroscopy (TDLAS): employs narrow-linewidth tunable lasers for high-precision, high-speed detection; capable of both point and open-path monitoring of multiple gas species.

Ultraviolet Differential Optical Absorption Spectroscopy (UV-DOAS): measures differential absorption across UV wavelengths but is susceptible to interference from humidity and aerosols.

Fourier Transform Infrared (FTIR) Spectroscopy: captures broad infrared absorption spectra to identify multiple gas species simultaneously; ideal for laboratory and background monitoring but limited in field applications due to cost and complexity.

Although differing in technical principles, all these methods rely on molecular absorption of specific light wavelengths and measure changes in light intensity to infer gas concentration. Through

precise monitoring of atmospheric GHG concentration dynamics, researchers can provide high-quality data for climate models, assess emission reduction policy effectiveness, and support evidence-based climate strategies.

Amid the global restructuring of climate governance, GHG monitoring technology is transitioning from basic observation to high-precision quantification. This evolution is not merely a technical iteration but a strategic arena for international discourse power. Greenhouse gas monitoring instruments are indispensable tools of carbon metrology, and the development of high-precision, traceable measurement systems has become a strategic high ground in global carbon emission governance[4].

3. A Carbon Monitoring System Suitable for China's Shipping Sector

Given China's position as the world's largest trading nation and the most active maritime country, establishing a carbon monitoring system tailored to its shipping industry is a key prerequisite for achieving both national carbon neutrality goals and international compliance obligations under the IMO and EU regulatory frameworks. The design of such a system should align with China's technical foundation, data governance capacity, and the operational diversity of its shipping fleet.

3.1 Multi-tiered Architecture Integrating Data Sources

China's shipping carbon monitoring system should adopt a multi-tiered structure that integrates BDN-based accounting, onboard real-time monitoring, and port-level verification. Specifically, BDN and periodic fuel inventory data can serve as the basic verification layer, while flowmeter-based and CO_2 direct monitoring data constitute the dynamic operational layer. The combination of static and dynamic data sources ensures cross-validation and improves traceability across fuel supply, transport, and consumption chains[5].

3.2 Digitalized Data Governance and National Platform Construction

Building a unified "National Maritime Carbon Data Platform" is essential. This platform should leverage the existing digital infrastructure of the China MSA (Maritime Safety Administration) and the National Transportation Carbon Accounting System. Through standardized data formats, automatic uploading, and AI-assisted anomaly detection, it can enable real-time synchronization of monitoring data, enhance data reliability, and provide a data foundation for carbon market inclusion and ship performance evaluation.

3.3 Technical Standardization and Measurement Traceability

To ensure international recognition of monitoring results, China should strengthen its metrological traceability chain for marine carbon measurement. This includes developing reference materials for marine fuels, establishing calibration and verification specifications for flowmeters and gas analyzers, and constructing a national standard laboratory network for maritime emission testing. The traceability chain should extend from laboratory reference standards to shipboard instruments, ensuring measurement consistency with IMO DCS and EU MRV standards.

3.4 Adaptability to Fleet Diversity and Operational Scenarios

Given the wide variety of Chinese vessels—from large ocean-going carriers to coastal and inland ships—the monitoring framework should provide differentiated implementation paths. For example, large international liners can prioritize real-time flow and CO_2 monitoring, while small and medium vessels can adopt hybrid BDN–inventory methods combined with digital reporting tools. This tiered approach balances cost efficiency with accuracy and supports gradual upgrading across the industry.

3.5 Integration with Policy and Market Mechanisms

Finally, the carbon monitoring system should be linked with China's national carbon market, green port initiatives, and ship energy efficiency rating schemes. By establishing feedback loops between monitoring data, policy incentives, and operational behavior, the system can not only support compliance reporting but also drive technological innovation and low-carbon transformation within the maritime sector.

4. Summary

In summary, China's maritime carbon monitoring system should evolve toward a "multi-source, intelligent, traceable, and interoperable" framework. Such a system would not only strengthen domestic carbon governance capacity but also enhance China's influence in global maritime climate rule-making.

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