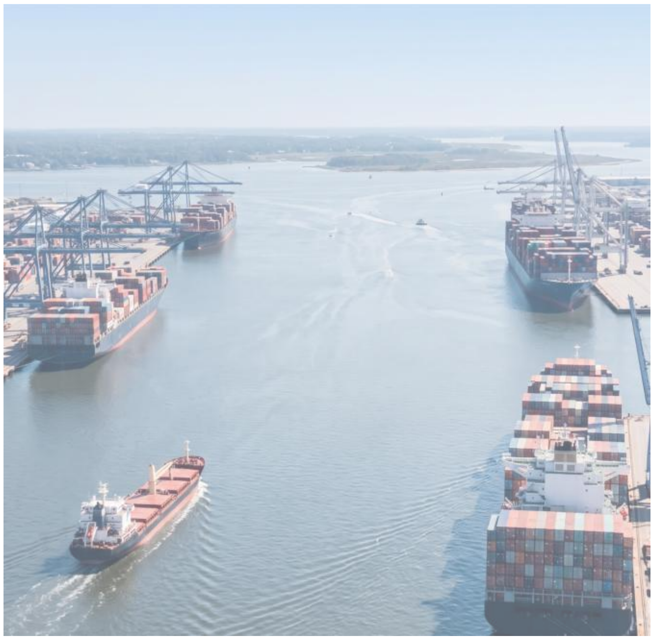

Evaluation of a Low-Sulfur Marine Fuel Requirement in Virginia

Economics, Environmental, and Public Health Assessment

ABSTRACT

This report evaluates the economic, operational, environmental, and policy implications of a proposed Virginia requirement for certain ocean-going vessels to temporarily use 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters. Using representative vessel characteristics, engineering assumptions, fuel-price data, and shipping economics, the analysis finds that incremental compliance costs are generally modest relative to voyage and fleet operating earnings. The requirement would primarily affect vessels currently using high-sulfur fuels with exhaust gas cleaning systems, while vessels already using compliant or alternative fuels would generally incur no additional costs. The report also considers fuel-switching feasibility, environmental and public-health benefits, implementation issues, and relevant legal and regulatory frameworks. Overall, the analysis concludes that the proposed requirement would impose measurable but limited (< 1%) economic costs while reducing localized sulfur and particulate emissions and eliminating scrubber washwater discharges within Virginia waters.

About This Report

Virginia's coastal waters support one of the nation's busiest maritime transportation systems while also encompassing some of its most valuable natural resources. As policymakers consider strategies to further reduce emissions from commercial shipping, it is important that proposed regulations be evaluated using transparent, evidence-based analysis that considers both economic impacts and environmental objectives.

This report examines the potential economic implications of a proposed Virginia requirement that would stipulate certain ocean-going commercial vessels to operate on 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters. Under the proposed requirement High Sulfur Fuel Oil (HSFO) and other residual fuel oils would not be permitted for use within Virginia waters, regardless if a vessel is equipped with an exhaust gas cleaning system (scrubber). Vessels currently relying on scrubbers while burning residual fuels would therefore be required to switch to LSMGO or other low-sulfur non-residual fuels before entering Virginia waters and remain on compliant fuel until they depart state jurisdiction.

Limitations

The findings presented in this report are based on representative operating conditions and publicly available market information. Actual compliance costs will vary depending on vessel type, fuel prices, voyage routing, freight markets, anchorage duration, weather, and other operational factors. Accordingly, the results should be interpreted as reasonable estimates of the order of magnitude of potential impacts rather than precise predictions for any individual vessel or shipping company.

Use of Artificial Intelligence

Portions of this report were developed with the assistance of generative artificial intelligence to support drafting, organization, editing, and technical synthesis. An alternative generative tool was used to validate report contents in conjunction with review by Protect Virginia. Generative AI is a powerful tool for synthesizing information but can sometimes produce erroneous results. Please contact Protect Virginia for any questions, corrections, or feedback.

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Date: August 2026

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Contents

Executive Summary

Virginia is considering legislation that would require certain ocean-going commercial vessels to operate on 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while navigating, anchoring, or conducting port operations within Virginia waters. Unlike proposals that prohibit exhaust gas cleaning systems (scrubbers), the proposed requirement regulates fuel use within Virginia jurisdiction rather than scrubber technology. Vessels equipped with approved scrubber systems could continue operating on High Sulfur Fuel Oil (HSFO) outside Virginia waters but would be required to temporarily switch to compliant fuel while operating within the Commonwealth.

The purpose of this report is to provide an objective assessment of the proposal's potential economic implications using transparent engineering assumptions, publicly available shipping data, representative vessel operating characteristics, and established economic evaluation methods. The analysis estimates the incremental cost of temporary fuel switching, compares those costs with representative voyage and fleet operating earnings, and places the results within the broader context of environmental protection, public health, implementation feasibility, and existing maritime regulations.

The report finds that the proposed requirement would affect only a portion of the commercial fleet. Vessels already operating on Low Sulfur Marine Gas Oil (LSMGO), liquefied natural gas (LNG), methanol, or other compliant fuels would generally incur no additional operating costs. The principal economic impact would be on vessels that currently rely on High Sulfur Fuel Oil (HSFO) in conjunction with approved exhaust gas cleaning systems while operating outside Virginia waters.

Using representative engineering assumptions and publicly available marine fuel prices, the analysis estimates that incremental compliance costs for most cargo vessels range from approximately $2,000 to $10,000 per voyage, depending on vessel type, fuel consumption, time spent in Virginia waters, anchorage duration, and prevailing fuel-price differentials. Cruise ships experience higher absolute fuel costs because of substantial hotel loads while in port; however, these costs represent a relatively small percentage of representative voyage operating earnings because of the significantly larger revenue base associated with cruise operations.

When expressed relative to representative operating earnings, the estimated economic impacts are modest. Voyage-level compliance costs generally represent less than one percent of operating earnings for large container vessels and approximately one to three percent for lower-margin bulk carriers. At the fleet level, annual compliance costs are estimated to represent approximately 0.61 to 0.91 percent of representative regional operating earnings, indicating that the proposed requirement, by itself, is unlikely to materially affect the competitiveness of Virginia ports or the long-term economic viability of commercial shipping operations.

Beyond compliance costs, the report examines the broader environmental context of the proposed requirement. Temporary use of compliant fuel within Virginia waters would reduce localized sulfur oxide and fine particulate emissions while eliminating scrubber washwater discharges during in-state operations. The report reviews established methodologies used in the United States and Europe to evaluate external damage costs associated with air pollution and discusses emerging scientific literature regarding potential ecological effects of scrubber washwater, including localized acidification, contaminant exposure, and potential impacts on aquatic food webs. While standardized methods exist for monetizing many air-emission damages, comparable methodologies for quantifying aquatic impacts remain under development.

The report also evaluates operational feasibility, implementation considerations, existing domestic and international regulatory frameworks, and legal and administrative issues associated with implementing a temporary fuel-use requirement. The analysis concludes that fuel switching is an established operational practice for vessels entering and leaving Emission Control Areas and that the proposed requirement would build upon existing compliance procedures rather than require new vessel technologies or significant vessel modifications.

Key Findings

- The proposed requirement regulates fuel use rather than scrubber technology.
- Only a portion of commercial vessels are expected to incur additional compliance costs.
- Fuel switching is an established operational practice already used when entering and leaving Emission Control Areas.
- Incremental compliance costs are measurable but modest relative to representative voyage and fleet operating earnings. At the fleet level, annual compliance costs are estimated to represent approximately 0.61 to 0.91 percent of representative regional operating earnings.
- The proposal will provide localized health and environmental benefits by reducing particulate and sulfur oxide emissions and eliminating scrubber washwater discharges while vessels operate within Virginia waters.
- Policy decisions require balancing private compliance costs against broader environmental and public health benefits.

Overall Conclusion

The analysis indicates that requiring temporary use of 0.10 percent sulfur LSMGO within Virginia waters would impose measurable but modest costs on the subset of vessels currently relying on HSFO with scrubber compliance. **Based on representative engineering assumptions and publicly available economic data, these costs are small relative to representative voyage and fleet operating earnings and are, by themselves, unlikely to materially affect the competitiveness of Virginia ports.** The fuel requirement reduces harmful air emissions and water pollution, mitigating risks to human health and marine life. The report provides policymakers with a transparent framework for considering engineering feasibility, operational practicality, economic impacts, environmental externalities, implementation considerations, and legal context when evaluating the proposed fuel-switch requirement.

Chapter 1: Introduction

1.1 Purpose of the Report

Virginia is considering legislation that would require certain large ocean-going commercial vessels (e.g. container ships, tankers, cruise ships) operating on High Sulfur Fuel Oil (HSFO) and other residual fuels to temporarily switch to sulfur low sulfur fuel (< 0.1%, e.g. Marine Gas Oil (LSMGO)) while operating within Virginia waters.

Unlike proposals that prohibit or restrict the use of exhaust gas cleaning systems (scrubbers), the requirement evaluated in this report does **not** ban scrubbers. Vessels equipped with approved scrubber systems could continue using them outside Virginia waters. The proposal instead requires vessels that currently rely on scrubbers while burning HSFO to temporarily operate on compliant low-sulfur fuel during transit, anchorage, and port operations within Virginia jurisdiction.

The purpose of this report is to evaluate the potential **economic impact** of that temporary fuel-switch requirement using publicly available engineering data, shipping market information, and representative operating assumptions.

Specifically, the report seeks to answer four questions:

- **Which vessels would be affected by the proposed requirement?**
- **How much additional operating cost would result from temporarily using LSMGO?**
- **How significant would those costs be relative to representative voyage and fleet operating earnings?**
- **How should those costs be considered alongside the environmental objectives of the proposed requirement?**

The analysis is intended to provide policymakers with an objective and transparent assessment of the proposed requirement's potential economic implications.

1.2 Background

Commercial shipping is a cornerstone of Virginia's economy.

The Commonwealth is home to one of the largest and most strategically significant port systems on the Atlantic coast. The Port of Virginia handles millions of tons of cargo annually and supports international trade across containerized freight, bulk commodities, petroleum products, automobiles, military cargo, and breakbulk shipments.

The port complex serves a diverse network of international trade routes linking Virginia with:

- East Asia
- Northern Europe
- the Mediterranean
- South America
- the Middle East
- Africa.

These maritime activities support thousands of jobs throughout Virginia while contributing substantially to state and regional economic activity.

At the same time, commercial vessels operate within the environmentally sensitive waters of the Chesapeake Bay and Hampton Roads, where policymakers continue to balance economic development with environmental protection and public health objectives.

1.3 Evolution of Marine Fuel Regulations

Historically, most commercial vessels burned residual High Sulfur Fuel Oil (HSFO) because of its relatively low cost and widespread availability.

Concerns regarding sulfur oxide emissions, particulate matter, and associated public health impacts led the International Maritime Organization (IMO) to progressively strengthen global marine fuel standards under MARPOL Annex VI.

Today, commercial vessels generally comply with sulfur regulations through one of three approaches:

1. Burning compliant low-sulfur fuels such as Very Low Sulfur Fuel Oil (VLSFO) or Low Sulfur Marine Gas Oil (LSMGO);
2. Burning HSFO while operating an approved Exhaust Gas Cleaning System (EGCS), commonly referred to as a scrubber; or
3. Using alternative fuels such as liquefied natural gas (LNG), methanol, or other emerging low-emission fuels.

The proposed Virginia requirement affects only the second category of vessels—those that currently rely on HSFO with scrubber compliance.

1.4 Policy Context

The proposed Virginia requirement reflects an important distinction in maritime environmental policy.

The proposed requirement **does not prohibit scrubber technology**.

Instead, it requires affected vessels to temporarily operate on **0.10 percent sulfur LSMGO** while within Virginia waters, thereby eliminating scrubber washwater discharge during that portion of the voyage while also reducing localized sulfur and fine particulate matter (PM2.5) emissions.

Because the requirement applies only during operations within Virginia jurisdiction, vessels may resume their preferred international compliance strategy after departing state waters.

This distinction is important because it substantially limits both the operational and economic scope of the proposal.

1.5 Scope of the Analysis

The report evaluates only the incremental operating costs associated with temporarily switching from HSFO to LSMGO while operating within Virginia waters.

The analysis focuses on representative commercial vessel classes serving Virginia ports, including:

- ultra-large container vessels
- container ships
- bulk carriers
- petroleum tankers
- roll-on/roll-off vessels
- cruise ships.

The report does **not** evaluate the following:

- changes in international shipping patterns
- vessel construction costs
- scrubber installation costs
- greenhouse gas emissions
- broader decarbonization strategies.

Likewise, vessels already operating on compliant low-sulfur fuels or alternative fuels are assumed to experience **no incremental compliance cost** under the proposed requirement.

1.6 Analytical Approach

The economic assessment combines marine engineering principles with representative shipping economics.

The methodology consists of these primary steps:

- Estimate representative fuel consumption while operating within Virginia waters.
- Calculate the incremental fuel cost associated with temporarily switching from HSFO to LSMGO.
- Compare those costs with representative voyage operating earnings.
- Estimate annual fleet-level impacts using representative vessel mixes and port-call assumptions.

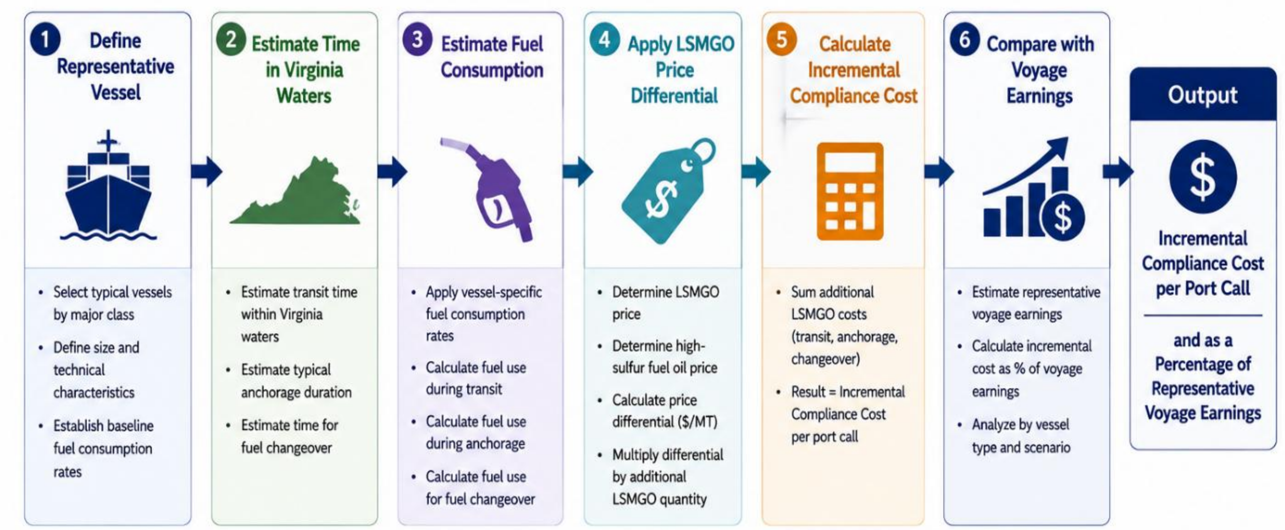

Figure 1-1: Economic Assessment Methodology Details.

Because detailed operating data for individual shipping companies are proprietary, the report relies on transparent engineering assumptions and publicly available industry information. All assumptions, calculations, and references are documented in the appendices.

1.7 Key Findings Preview

Although detailed results are presented in later chapters, several overarching observations emerge from the analysis.

- First, the proposed requirement affects only a portion of commercial vessels. Ships already operating on LSMGO, LNG, methanol, or other compliant fuels would not incur additional fuel-switching costs.
- Second, the proposal does not require vessel modifications or prohibit the use of scrubber systems outside Virginia waters.
- Third, fuel switching is already a routine operational practice for vessels entering and leaving Emission Control Areas worldwide.

- Finally, the analysis indicates that the **incremental fuel costs associated with temporary use of LSMGO generally represent a small percentage of representative voyage and fleet operating earnings**, even though absolute costs vary according to vessel type, transit distance, fuel prices, and anchorage duration.

These findings provide the framework for the detailed analyses presented in the chapters that follow.

1.8 Organization of the Report

The report is organized into ten chapters.

- **Chapter 1** introduces the purpose, scope, objectives, and analytical framework of the study.
- **Chapter 2** reviews the international and domestic regulatory framework governing marine fuel sulfur standards, compliance pathways, and the proposed Virginia fuel-switch requirement.
- **Chapter 3** describes marine fuel technologies, exhaust gas cleaning systems (scrubbers), and the engineering principles and operational procedures associated with fuel switching.
- **Chapter 4** presents the engineering assumptions, analytical framework, and economic methodology used to estimate representative compliance costs.
- **Chapter 5** estimates fleet-level economic impacts and evaluates the sensitivity of results to key engineering and market assumptions.
- **Chapter 6** examines the economic implications of the proposed requirement for cruise ship operations, which differ from cargo vessels because of higher hotel loads and operating profiles.
- **Chapter 7** examines environmental externalities associated with marine fuel use, including air emissions, scrubber washwater, public health considerations, and external damage cost methodologies used in the United States and Europe.
- **Chapter 8** discusses operational implementation, compliance verification, enforcement considerations, and potential effects on port operations.
- **Chapter 9** reviews the legal and administrative framework governing state authority, federal preemption, interstate commerce considerations, and implementation options.
- **Chapter 10** summarizes the principal findings, discusses policy implications, identifies study limitations, and presents the overall conclusions of the assessment.

Supporting assumptions, engineering data, calculation examples, and technical references are provided in the appendices.

1.9 Report Objective

Environmental policy frequently requires balancing private compliance costs against broader public benefits.

The objective of this report is not to recommend a particular legislative outcome, but rather to provide policymakers with a technically grounded assessment of the economic implications of a marine fuel-switch requirement while traveling through Virginia waters.

By presenting impacts in both absolute dollar terms and as percentages of representative voyage and fleet operating earnings, the report places incremental compliance costs within the broader context of commercial shipping economics.

This approach enables policymakers to evaluate whether the estimated costs are proportionate to the environmental objectives of the proposed legislation and provides a transparent analytical foundation for future legislative and regulatory discussions.

Chapter 2: Marine Fuel Sulfur Regulations and Compliance Pathways

2.1 Introduction

Commercial shipping is one of the most internationally regulated industries in the world. Ocean-going vessels routinely operate across multiple national jurisdictions during a single voyage, making internationally recognized environmental standards essential for maintaining both efficient maritime commerce and environmental protection.

The principal international framework governing air emissions from ships is the International Convention for the Prevention of Pollution from Ships (MARPOL), administered by the International Maritime Organization (IMO). MARPOL Annex VI establishes worldwide limits on sulfur oxide (SO_x), nitrogen oxide (NO_x), and particulate emissions from commercial vessels while allowing shipowners flexibility in selecting the most appropriate compliance method.

The proposed Virginia requirement evaluated in this report builds upon this existing regulatory framework. Rather than altering international sulfur standards, it would require a subset of vessels currently burning High Sulfur Fuel Oil (HSFO) with approved Exhaust Gas Cleaning Systems (EGCS) to temporarily use 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters.

Understanding the existing international regulatory structure is essential for evaluating the potential economic effects of such a requirement.

2.2 Evolution of Marine Sulfur Regulations

For decades, commercial vessels primarily operated on residual heavy fuel oils because they were relatively inexpensive and provided high energy density. These fuels often contained sulfur concentrations exceeding **3 percent by mass**, substantially higher than fuels used in most land-based transportation.

Combustion of sulfur-containing fuels produces sulfur dioxide (SO_2), which contributes to

- formation of fine particulate matter ($PM_{2.5}$)
- acid deposition
- reduced visibility
- adverse respiratory and cardiovascular health effects.

Recognizing these impacts, the IMO progressively strengthened sulfur-emission standards through amendments to MARPOL Annex VI.

The most significant recent change occurred on January 1, 2020, when the global sulfur limit for marine fuels was reduced from 3.50 percent to 0.50 percent by mass outside designated Emission Control Areas (ECAs).

This regulation, commonly referred to as the **IMO 2020 Sulfur Cap**, represented one of the largest global reductions in transportation-related sulfur emissions.

2.3 Emission Control Areas (ECAs)

Certain coastal regions have adopted more stringent sulfur standards because of higher population density and increased exposure to shipping-related air pollution.

These regions are designated by the IMO as **Emission Control Areas (ECAs)**.

Within an ECA, vessels must generally operate using fuel containing **no more than 0.10 percent sulfur** unless they are using an approved equivalent compliance system.

Current ECAs include

- North American ECA
- United States Caribbean ECA
- Baltic Sea ECA
- North Sea ECA
- Mediterranean Sea ECA (effective in 2025)

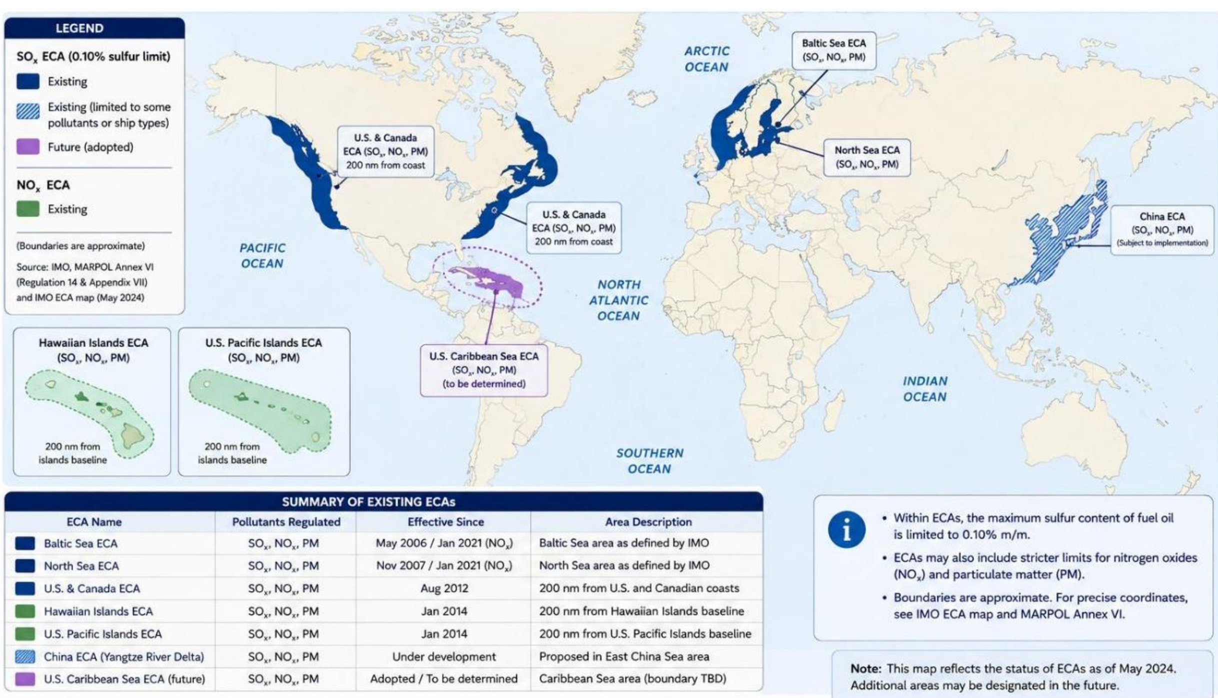

Figure 2-1. Emission Control Areas (ECAs) reducing SOx, NOx, and PM2.5 emissions.

The North American ECA already requires vessels approaching the United States to transition to compliant fuel well before reaching coastal waters.

Consequently, international carriers are already familiar with routine fuel-switching procedures.

In addition to IMO established ECAs, countries, states and other localities have further regulated ship emissions and scrubber discharge.

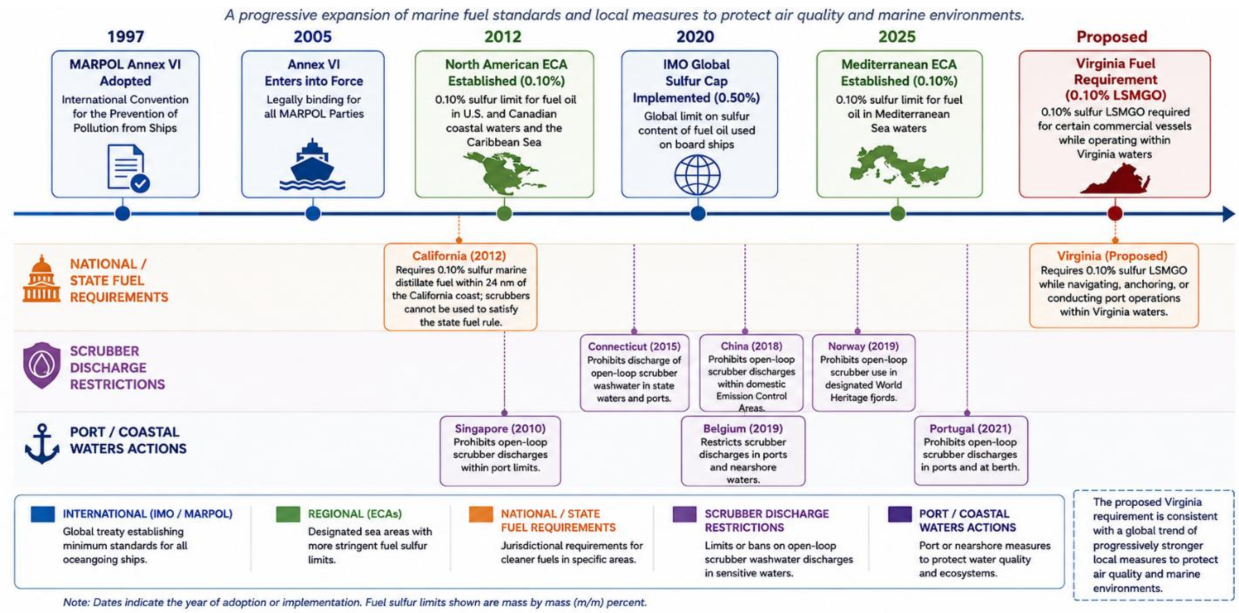

Figure 2.2. Timeline of pollution regulations.

2.4 Compliance Options Under MARPOL

MARPOL Annex VI allows vessel operators to comply through multiple pathways.

Option 1 — Low-Sulfur Marine Fuels

Many commercial vessels comply by burning fuels that already satisfy sulfur limits, including

- Low Sulfur Marine Gas Oil (LSMGO)
- Very Low Sulfur Fuel Oil (VLSFO)
- Ultra-Low Sulfur Marine Diesel
- other compliant marine distillates

Vessels already using LSMGO or other compliant marine distillates would generally **not incur additional fuel costs** under the proposed Virginia requirement. Other residual fuels and fuels with greater than 0.1% sulfur would incur some additional cost increase, but less that of those burning HSFO.

Option 2 — Alternative Marine Fuels

An increasing number of vessels now operate using alternative fuels, including

- Liquefied Natural Gas (LNG)
- Methanol
- Liquefied Petroleum Gas (LPG)
- Biofuels
- Emerging zero-carbon fuels

These vessels also fall outside the primary scope of the proposed Virginia requirement.

Option 3 — Exhaust Gas Cleaning Systems (Scrubbers)

A third compliance pathway allows vessels to continue burning HSFO while removing sulfur compounds from engine exhaust using an approved Exhaust Gas Cleaning System (EGCS).

Scrubbers reduce sulfur emissions sufficiently to satisfy IMO emission standards while allowing operators to continue using lower-cost residual fuel.

Because scrubber installation requires substantial capital investment, they are more likely found on

- large container ships
- bulk carriers
- crude oil tankers
- cruise ships.

These vessels typically consume large fuel volumes, allowing operators to recover installation costs through fuel savings.

2.5 Types of Scrubber Systems

Commercial scrubbers generally fall into three categories.

Open-Loop Systems

Open-loop scrubbers use seawater to absorb sulfur compounds from engine exhaust.

The resulting washwater is treated on board before discharging back into surrounding waters.

These systems generally have the lowest operating cost but continuously discharge treated washwater while operating.

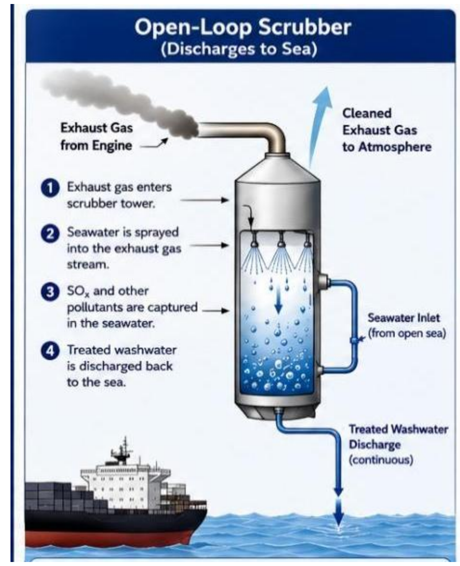

Figure 2-3 OL Scrubber

Exhaust Gas Cleaning Systems (Scrubbers)

Scrubbers remove sulfur compounds from engine exhaust before those gases are released into the atmosphere.

The process involves:

1. engine exhaust leaving the main engine;
2. contact between exhaust gases and water within the scrubber tower;
3. absorption of sulfur compounds into the treatment water;
4. release of cleaned exhaust gases through the ship's funnel.

Depending on system design, treatment water may either be discharged overboard or retained on board for later disposal.

The scrubber removes sulfur from the exhaust stream but does **not** change the sulfur content of the fuel itself. Additionally, it is effective at removing sulfur oxides but is less effective at removing other harmful emissions (e.g. fine particulate matter – PM2.5)

Closed-Loop Systems

Closed-loop systems recirculate treatment water and retain washwater on board for later disposal at approved reception facilities.

These systems minimize overboard discharge but require additional equipment and waste handling.

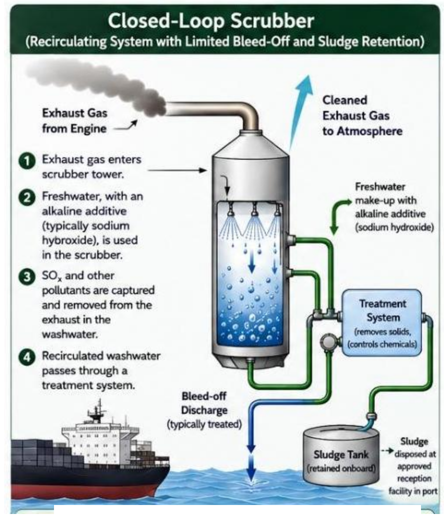

Figure 2-4 CL Scrubber

Hybrid Systems

Hybrid scrubbers combine both operating modes.

Operators may use open-loop operation offshore while switching to closed-loop mode where local regulations restrict washwater discharge.

2.6 The Virginia Proposal

The proposal evaluated in this report differs from some local scrubber regulations adopted elsewhere because **it does not prohibit scrubber ownership or operation**.

Instead, it would require vessels currently burning HSFO using scrubber compliance to temporarily operate on 0.10 percent sulfur LSMGO while operating within Virginia waters.

Outside Virginia jurisdiction, vessels could resume their preferred fuel and compliance strategy in accordance with international regulations.

Accordingly, this proposal should be understood as a **temporary fuel-use requirement rather than a technology prohibition**.

2.7 Applicability of the Proposed Requirement

One of the most important characteristics of the proposed requirement is that **not all commercial vessels are affected**.

Vessels already operating on

- LSMGO
- LNG
- methanol
- or other compliant fuels

would generally experience **no incremental fuel-switching cost** because they already use compliant fuel.

The proposal primarily affects vessels that currently rely upon

- HSFO and
- approved scrubber systems.

Industry data indicate that scrubber-equipped vessels represent **a minority of the global fleet by vessel count**, although they account for a significantly larger share of total cargo-carrying capacity because scrubbers are concentrated on larger oceangoing vessels.

As a result, the proposed requirement affects only a portion of commercial shipping activity serving Virginia ports.

2.8 Why This Matters Economically

The distinction between affected and unaffected vessels is fundamental to the economic analysis presented in later chapters.

Because most vessels already operate using compliant fuels, **the proposed requirement does not create new operating costs for the entire commercial fleet**.

Instead, incremental fuel costs are concentrated among vessels currently realizing fuel-cost savings through continued HSFO use with scrubber compliance.

Consequently, the economic impact of the proposal should be evaluated in terms of

- the number of affected vessels
- the duration of operations within Virginia waters
- prevailing bunker fuel price differentials and
- representative operating earnings.

2.9 Chapter Summary

International sulfur regulations have significantly reduced shipping-related air emissions while allowing vessel operators flexibility in selecting among several approved compliance methods.

The proposed Virginia requirement does not alter these international standards or prohibit scrubber technology. Rather, it would require a subset of vessels currently operating on HSFO with scrubber compliance to temporarily use 0.10 percent sulfur LSMGO while operating within Virginia waters.

Because many commercial vessels already use compliant fuels, the proposal affects only a portion of commercial shipping activity. This distinction forms the basis for the economic impact assessment presented in the following chapters.

Chapter 3: Marine Fuel Technologies and Vessel Fuel-Switching Operations

3.1 Introduction

The economic impact of the proposed Virginia fuel-switch requirement depends on how commercial vessels are powered, the fuels they currently use, and the engineering procedures required to transition between fuel types.

While the proposal has been described as a change in fuel use, implementing such a requirement involves well-established operational procedures that are already routinely performed by vessels entering and leaving Emission Control Areas (ECAs) around the world.

This chapter reviews the principal marine fuels used in commercial shipping, explains how scrubber-equipped vessels operate, and describes the engineering considerations associated with temporarily switching from High Sulfur Fuel Oil (HSFO) to 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters.

3.2 Marine Fuel Types

Commercial vessels today operate using several different fuel types depending on vessel design, operating profile, fuel availability, and regulatory requirements.

High Sulfur Fuel Oil (HSFO)

HSFO is a residual petroleum fuel produced during the refining of crude oil. Because it is less refined than marine distillate fuels, it has traditionally been one of the lowest-cost fuels available to commercial shipping.

Typical characteristics include

- sulfur content up to 3.50 percent (outside regulated areas)
- high viscosity
- high density
- requires onboard heating before injection into marine diesel engines.

HSFO remains economically attractive because it is generally less expensive than low-sulfur marine fuels.

Very Low Sulfur Fuel Oil (VLSFO)

Following implementation of the IMO 2020 sulfur cap, many operators transitioned to Very Low Sulfur Fuel Oil (VLSFO).

Typical characteristics include

- sulfur content not exceeding 0.50 percent
- lower sulfur emissions than HSFO
- lower viscosity than traditional residual fuels
- compatible with most existing marine diesel engines.

Today, VLSFO has become the commonly used compliance fuel for many international shipping companies.

Low Sulfur Marine Gas Oil (LSMGO)

LSMGO is a refined marine distillate fuel that complies with the 0.10 percent sulfur standard required in Emission Control Areas.

Compared with HSFO, LSMGO

- contains significantly less sulfur
- has much lower viscosity
- does not require extensive heating before use
- burns more cleanly with lower sulfur oxide emissions.

Throughout this report, the term LSMGO refers specifically to marine gas oil meeting the 0.10 percent sulfur specification.

Alternative Marine Fuels

A growing number of vessels now operate using alternative fuels, including the following:

- Liquefied Natural Gas (LNG)
- methanol
- liquefied petroleum gas (LPG)
- biofuels and
- emerging low-carbon fuels.

These vessels generally fall outside the scope of the proposed Virginia fuel-switch requirement because they already comply with applicable sulfur emission standards.

Fuel	Sulfur Limit	Fuel Type	Requires Scrubber	Complies with Proposed Virginia Requirement
HSFO	Up to 3.50%	Residual	Yes	✕
VLSFO	≤0.50%	Low-sulfur residual/blended fuel	No	✕
LSMGO	≤0.10%	Distillate	No	✓
LNG	Near zero	Alternative fuel	No	✓
Methanol	Near zero sulfur	Alternative fuel	No	✓

3.3 Why Some Vessels Continue to Burn HSFO

Despite increasingly stringent sulfur regulations, many large commercial vessels continue to burn HSFO because they have installed approved Exhaust Gas Cleaning Systems (EGCS) called scrubbers.

The economic rationale is straightforward.

Although scrubbers require substantial initial capital investment, they allow operators to purchase lower-cost HSFO instead of more expensive low-sulfur fuels.

For vessels consuming large quantities of fuel over many years, the fuel savings may offset the cost of installing and operating scrubber systems.

Consequently, scrubbers are commonly installed on

- ultra-large container vessels
- Capesize bulk carriers
- crude oil tankers
- cruise ships.

3.4 Fuel-Switching Operations

Commercial vessels routinely switch between different marine fuels during international voyages.

Typical reasons include:

- entering Emission Control Areas
- leaving Emission Control Areas
- fuel availability
- engine maintenance
- operational requirements.

Fuel switching is therefore an established engineering practice rather than an unusual operating procedure.

3.5 Engineering Considerations

Although fuel switching is routine, it must be conducted carefully because HSFO and LSMGO have different physical properties.

Fuel Temperature

HSFO is highly viscous and must be heated before entering the engine fuel system.

LSMGO has much lower viscosity and generally requires little or no heating.

Rapid temperature changes can damage fuel pumps and injection equipment.

Fuel Viscosity

Marine engines are designed to operate within specified fuel viscosity ranges.

Changing too rapidly from heated HSFO to cooler distillate fuel can reduce lubrication within fuel pumps.

Consequently, manufacturers recommend gradual fuel transitions.

Fuel Compatibility

Residual fuels and distillate fuels may differ chemically.

Operators therefore monitor

- fuel temperature
- viscosity
- density
- fuel stability
- engine operating conditions

during the changeover process.

The following table compares the properties of various fuels:

Property	**HSFO**	**VLSFO**	**LSMGO**
Sulfur	High	Medium	Low
Viscosity	High	Medium	Low
Density	High	Medium	Low
Requires Heating	✓	Often	✗
Cold Flow	Poor	Moderate	Good

3.6 Typical Fuel Changeover Procedure

Although procedures vary among vessel classes and engine manufacturers, a typical transition involves:

1. confirming adequate compliant fuel on board;
2. calculating the required changeover location;
3. gradually reducing fuel temperature;
4. introducing compliant fuel into the fuel system;
5. monitoring engine performance;
6. confirming completion before entering the regulated area.

Most operators begin fuel switching before reaching the regulatory boundary to ensure fully compliant fuel reaches the engines upon entry.

Accordingly, this report assumes an average one-hour fuel changeover buffer when estimating incremental fuel consumption for all vessels, except cruise ships. It is assumed cruise ships have a three-hour fuel changeover due to increased complexity.

3.7 Operational Time Within Virginia Waters

The quantity of compliant fuel required depends primarily upon

- transit distance
- vessel speed
- anchorage duration
- auxiliary engine use.

Typical Hampton Roads transits involve only several hours of main engine operation within Virginia waters.

Longer Chesapeake Bay transits to Baltimore require additional operating time within state waters and therefore consume larger quantities of compliant fuel.

Because fuel consumption is proportional to operating time, longer in-state transits generally experience higher incremental fuel costs.

3.8 Vessels Affected by the Proposal

The proposed Virginia requirement would primarily affect vessels meeting all the following conditions:

- operating on HSFO or other residual fuels with sulfur content greater than 0.1%
- operating within Virginia waters.

It would generally **not affect** vessels already operating on

- LSMGO
- LNG
- methanol
- other compliant fuels.

Consequently, the economic impact is concentrated among a subset of larger commercial vessels rather than the whole commercial fleet.

3.9 Operational Implications

Importantly, the proposed requirement would not require:

- engine modifications
- installation of additional pollution-control equipment
- removal of existing scrubber systems
- changes to international voyage planning.

Instead, affected operators would temporarily use compliant fuel during the portion of each voyage occurring within Virginia waters before resuming their preferred fuel outside the regulated area.

Because similar fuel-switching procedures are already routinely performed when entering Emission Control Areas worldwide, the proposal represents an extension of an existing operational practice rather than the introduction of a new engineering concept.

3.10 Chapter Summary

Commercial vessels currently comply with sulfur-emission regulations using several approved pathways, including low-sulfur fuels, alternative fuels, and scrubber systems operating with HSFO.

The proposed Virginia requirement affects only the subset of vessels currently relying on HSFO with scrubber compliance. Those vessels would temporarily operate on 0.10 percent sulfur LSMGO while within Virginia waters.

Although fuel switching requires careful management of temperature and viscosity, it is a well-established engineering procedure routinely performed by commercial vessels entering and leaving Emission Control Areas around the world.

Understanding these operational requirements provides the technical foundation for estimating the incremental fuel consumption and compliance costs evaluated in the following chapters.

Chapter 4: Economic Methodology and Analytical Assumptions

4.1 Introduction

The primary objective of this report is to estimate the incremental operating cost associated with requiring certain commercial vessels to temporarily switch from High Sulfur Fuel Oil (HSFO) to 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters.

Because individual shipping companies do not publicly disclose voyage-specific fuel consumption, operating costs, fuel procurement contracts, or profitability, the analysis presented in this report uses a transparent engineering-economic methodology based on representative operating conditions and publicly available industry information.

Rather than attempting to estimate the precise financial impact for any individual vessel, the methodology estimates the **order of magnitude** of compliance costs across representative vessel classes operating at Virginia ports. For this analysis, it is assumed that LSMGO is approximately 50% to 65% more expensive than HSFO.

4.2 Analytical Framework

The economic analysis follows four sequential steps:

1. Estimate the quantity of additional LSMGO required while operating within Virginia waters.
2. Calculate the incremental fuel cost resulting from the difference between HSFO and LSMGO prices.
3. Compare that incremental fuel cost with representative voyage operating earnings.
4. Evaluate fleet-level impacts using representative vessel mixes and annual port calls.

This methodology provides a consistent framework for comparing the relative impact of the proposed requirement across multiple vessel types and operating scenarios.

4.3 Incremental Fuel Cost

The incremental compliance cost is determined by two principal factors:

- the quantity of fuel consumed while operating within Virginia waters and

- the price difference between HSFO and LSMGO.

The incremental fuel cost is estimated as:

ΔC = **V x** (**PLSMGO – PHSFO**)

where:

- **ΔC** = incremental fuel cost
- **V** = quantity of fuel switched to LSMGO (metric tons)
- **PLSMGO** = market price of LSMGO
- **PHSFO** = market price of HSFO

Only the fuel consumed while operating within Virginia waters is included in the calculation.

4.4 Fuel Consumption Estimate

The total quantity of compliant fuel required depends upon

- transit distance
- vessel speed
- main engine fuel consumption
- auxiliary engine fuel consumption
- anchorage duration
- fuel changeover requirements.

For analytical purposes:

V = (**TTransit** x **FMain**) + (**TAnchor** x **FAux)** + (**TBuffer x FMain**)

where:

- **TTransit** = transit time
- **TAnchor** = anchorage duration
- **TBuffer** = fuel changeover period
- **FMain** = main engine fuel consumption
- **FAux** = auxiliary engine fuel consumption

The methodology assumes that fuel switching begins prior to entering Virginia waters to ensure compliant fuel reaches the engine before the vessel crosses the regulatory boundary.

4.5 Representative Operating Assumptions

Representative operating assumptions were developed using published engineering information and vessel operating characteristics.

Transit Speed

Representative operating speed:

10–14 knots

reflecting typical Chesapeake Bay transit conditions.

Fuel Changeover

Representative fuel transition period:

1 hour

This assumption reflects typical engine manufacturer guidance for gradually changing fuel temperature and viscosity during transition between HSFO and marine distillate fuels (including LSMGO).

Main Engine Fuel Consumption

Representative values:

Vessel Class	Fuel Consumption (MT/hour)
Ultra-Large Container Vessel	2.5–3.5
Large Container Vessel	2.0–3.0
Panamax Bulk Carrier	1.0–1.5
Capesize Bulk Carrier	1.4–1.8
Aframax Tanker	1.2–1.6
Suezmax Tanker	1.4–1.8
Roll-on/Roll-off Vessel	1.5–2.5
Large Cruise Ship	2.5–4.0

Auxiliary Engine Consumption

Representative values:

Representative auxiliary fuel consumption includes electrical generation for navigation systems, cargo equipment, crew/passenger accommodations, lighting, refrigeration, ventilation, communications, and other onboard services.

Vessel Class	Fuel Consumption (MT/hour)
Container Ships	0.5–0.8
Bulk Carriers	0.2–0.4
Tankers	0.2–0.4
Roll-on/Roll-off Vessels	0.3–0.5
Cruise Ships	1.5–3.0

4.6 Fuel Price Assumptions

Marine bunker prices fluctuate continuously.

Fuel Price Variability

The largest source of variability is the difference between HSFO and LSMGO prices.

Using the last three complete calendar years, the annual average G20 marine gas oil (MGO/LSMGO proxy) and HSFO prices show both fuels declining overall, with the average price differential roughly at $293/MT in 2025. Ship & Bunker reports 2023 averages of $897/MT for MGO and $512/MT for HSFO, 2024 averages of $812/MT and $515/MT, and 2025 averages of $754/MT and $461/MT.

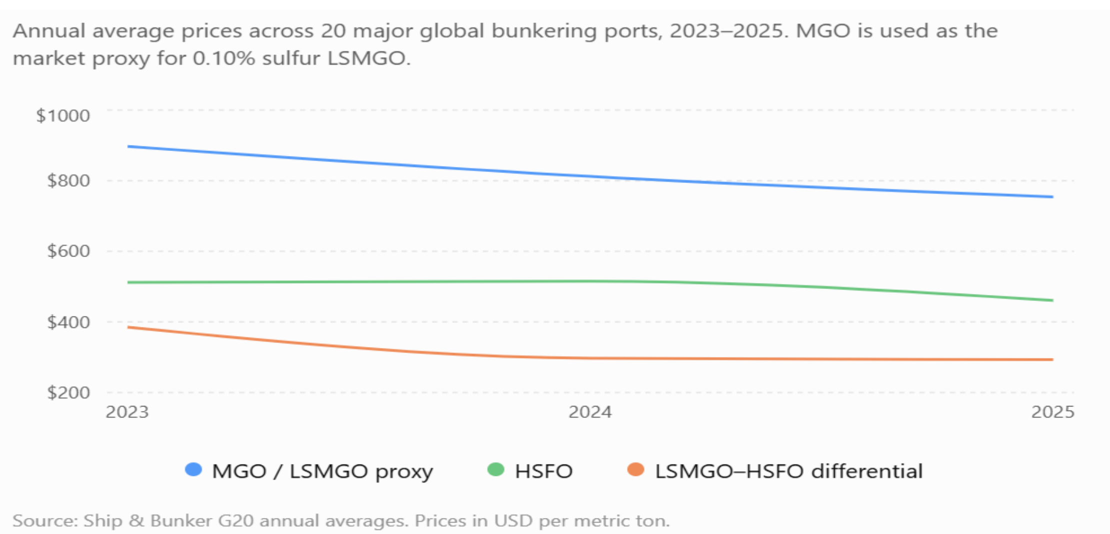

Figure 4-1 Three-year variability in LSMGO and HSFO prices

Accordingly, this report uses representative market ranges rather than a single fuel price.

Scenario	HSFO ($/MT)	LSMGO($/MT)	Price Spread ($)	% Increase
Low	500	750	250	50%
High	575	950	375	65%

These values are consistent with representative bunker market conditions reported by maritime fuel market services.

4.7 Voyage Earnings

Voyage earnings vary by ship classification and other factors including

- vessel capacity
- utilization
- representative freight revenue
- operating margin
- Time Charter Equivalent (TCE) earnings (standardized **daily earnings rate);**
- voyage duration
- representative operating expenses

Summary of Earnings by Vessel Type

The representative Earnings Before Interest and Taxes (EBIT) values are intended to characterize voyage-level operating earnings rather than the financial performance of any specific shipping company. Representative EBITs were derived from publicly available financial disclosures.

Vessel Class	Earnings Before Interest and Taxes
Ultra-Large Container	$2,100,000
Large Container	$1,000,000
RoRo / PCTC	$550,000
Tanker	$345,000
Bulk Carrier	$220,000
Chesapeake Bay Transit	$529,000*

*Weighted average of Large Container, Tanker, Bulk Carrier, and RoRo EBITs

4.8 Measuring Economic Impact

The report expresses economic impact using both

- incremental fuel cost (dollars) and
- percentage reduction in representative voyage operating earnings.

The percentage impact is calculated as:

Percent Impact = (ΔC/(Estimated Voyage EBIT) x 100

Earnings Before Interest and Taxes (EBIT) is corporation's revenue minus operating expenses. It was selected because it measures operating profitability before financing and tax effects. It reflects the earnings generated by vessel operations and is therefore more appropriate for comparing operating cost changes rather than revenue alone. EBIT values are sector-representative estimates based on public financial disclosures and industry data, not the actual earnings of individual vessels.

Presenting results in percentage terms allows comparison among vessels of different sizes and operating profiles.

Fleet impacts on commercial vessels

Vessel / Scenario	Low Compliance Cost ($)	High Compliance Cost ($)	Low Impact (%)	High Impact (%)
Large Container Vessel	$4,398	$6,597	0.44%	0.66%
Ultra-Large Container Vessel (14,000 TEU)	$6,838	$10,256	0.33%	0.49%
Bulk Carrier	$2,271	$3,406	1.03%	1.55%
Tanker	$2,819	$4,228	0.82%	1.23%
Ro/Ro	$3,158	$4,738	0.57%	0.86%

The compliance cost impact is relatively small compared to profits.

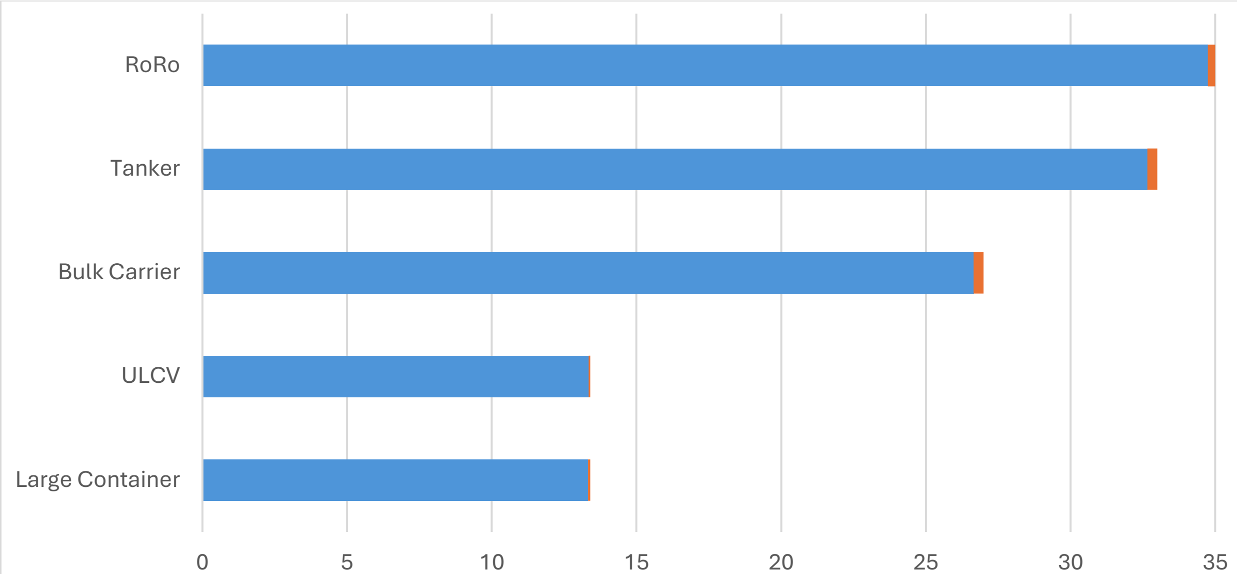

Figure 4-2. Estimated Profit Margin by Vessel (Compliance Reduction Midpoint in Orange)

4.9 Sensitivity Analysis

Sensitivity analysis was performed by varying input parameters by 20% to determine the relative impact on compliance cost. Relative contributions are shown in Figure 4-3, with fuel price differential being the leading contributor.

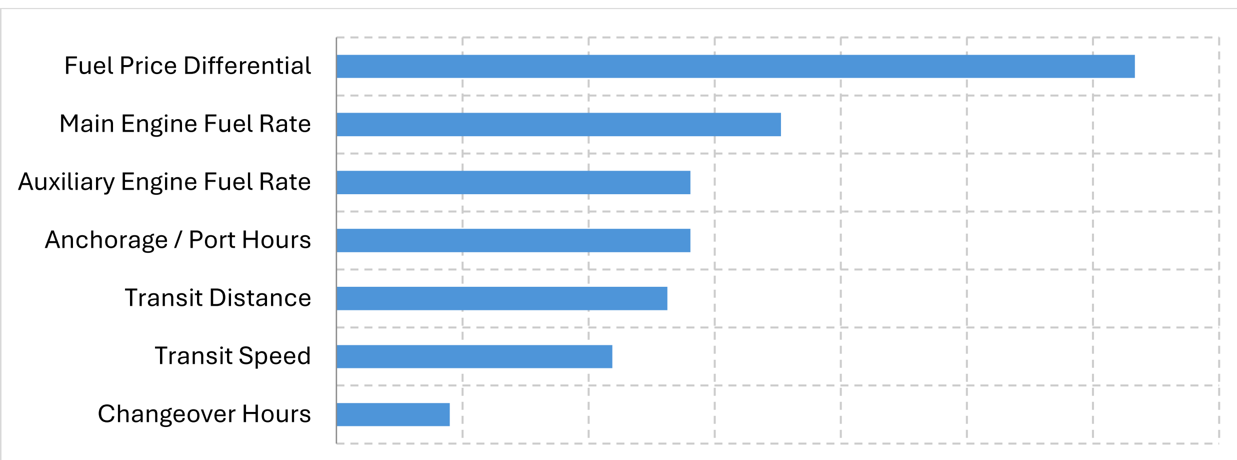

Figure 4-3. Sensitivity ranking shows relative cost drivers.

4.10 Analytical Limitations

Several limitations should be recognized.

First, actual fuel consumption varies according to

- weather
- draft
- engine loading
- vessel maintenance
- operating speed.

Second, fuel prices fluctuate daily.

Third, voyage profitability varies significantly among vessel classes and freight markets.

Finally, carriers frequently purchase fuel using long-term contracts or hedging arrangements rather than spot-market prices.

Accordingly, the analysis is intended to estimate the likely range of compliance costs rather than predict the exact operating cost for any individual vessel.

4.11 Chapter Summary

The voyage-level analysis indicates that requiring temporary use of 0.10 percent sulfur LSMGO within Virginia waters would increase operating costs for affected vessels by approximately **$2,000 to $10,000 per voyage**, depending on vessel type, transit distance, anchorage duration, and bunker fuel prices.

Expressed relative to representative voyage operating earnings, these costs are generally estimated to range from 0.33% to 1.55% for most commercial vessel classes.

This report employs a transparent engineering-economic methodology to estimate the incremental operating cost associated with requiring temporary use of LSMGO while vessels operate within Virginia waters.

The methodology combines representative fuel consumption, HSFO price differentials, voyage operating characteristics, and publicly available shipping market information to estimate both voyage-level and fleet-level impacts.

Because shipping economics vary across vessel classes and market conditions, subsequent chapters present results as representative ranges and percentage impacts rather than single deterministic values.

The next chapter expands this analysis to estimate the cumulative annual impact on representative shipping companies serving Virginia ports and evaluates those costs within the broader context of regional shipping economics.

Chapter 5: Fleet-Level Economic Impact Assessment

5.1 Introduction

The voyage-level analysis presented earlier in this report estimates the incremental compliance cost associated with individual vessel transits through Virginia waters. While those estimates are useful for understanding the operational impact on a single voyage, policymakers are also interested in the broader economic question:

> **What would the proposed fuel-switch requirement cost a representative shipping company serving Virginia ports?**

This chapter expands the analysis from individual vessel calls to the fleet level by estimating the cumulative annual compliance costs for a representative international carrier. The analysis also evaluates those costs relative to modeled regional operating earnings to determine whether the proposed requirement would materially affect commercial shipping operations.

Because shipping companies do not publicly disclose route-specific operating costs or profitability by individual port, the estimates presented in this chapter are based on representative operating assumptions intended to illustrate the likely order of magnitude of annual compliance costs.

5.2 Fleet-Level Analytical Framework

Fleet-level costs are estimated by combining

- representative annual Virginia port calls
- representative vessel mix
- Impact modeling by vessel class (Chapter 4).

The annual compliance cost is calculated as:

$$Fleet\ Imact_{low} = \sum Vessel\ Precentage_i\ X\ Vessel\ Impact_{low}$$

$$Fleet\ Imact_{high} = \sum Vessel\ Precentage_i\ X\ Vessel\ Impact_{high}$$

This approach provides a transparent estimate of annual operating costs impacts that are attributable to the proposed Virginia fuel-switch requirement.

5.3 Representative Fleet Profile

For analytical purposes, the report models a representative international carrier serving Virginia ports through multiple trade lanes.

The illustrative fleet profile assumes approximately **200 annual Virginia port calls**, distributed across representative vessel types and services.

Service	Annual Calls	Vessel Percentage
East Asia / Pacific Container Services	80	40%
Northern Europe / Mediterranean	40	20%
Middle East / South Asia	30	15%
Central & South America	30	15%
Chesapeake Bay / Baltimore Services	20	10%
Total	**200**	**100%**

These assumptions are intended to represent a typical operating profile for a major international carrier and are not intended to describe any specific shipping company.

A further breakdown by vessel type is needed to incorporate the mix of vessels along each route.

Trade Route	ULCV	Large / Feeder Container	Bulk Carrier	Tanker	RoRo	Total	Percent
East Asia & Pacific	60	20	0	0	0	**80**	**40.00%**
Northern Europe & Mediterranean	0	28	0	0	12	**40**	**20.00%**
Middle East & South Asia	0	0	14	16	0	**30**	**15.00%**
Central & South America	0	10	10	10	0	**30**	**15.00%**
Chesapeake Bay / Baltimore	0	5	5	5	5	**20**	**10.00%**
Total	**60**	**63**	**29**	**31**	**17**	**200**	**100.00%**

5.4 Fleet Impacts

Using representative voyage distribution of **200 annual Virginia calls** the Fleet Average can be modeled.

Trade Route	Annual Calls	Weighted Low Impact	Weighted High Impact
East Asia & Pacific	80	0.35%	0.53%
Northern Europe & Mediterranean	40	0.48%	0.72%
Middle East & South Asia	30	0.92%	1.38%
Central & South America	30	0.76%	1.14%
Chesapeake Bay / Baltimore*	20	1.15%	1.73%
Fleet Weighted Average	**200**	**0.61%**	**0.91%**

**Larger value the result of longer duration in Virginia waters*

These estimates indicate that the proposed requirement would generally represent **approximately 0.61% to 0.91% of modeled regional operating earnings** under representative market conditions.

5.5 Comparison with Normal Shipping Cost Variability

Commercial shipping operates within highly dynamic markets.

Carrier profitability routinely changes because of

- bunker fuel prices
- freight rates
- charter markets
- port congestion
- vessel utilization
- global trade volumes.

During the past decade, fluctuations in bunker fuel prices alone have often exceeded several hundred dollars per metric ton.

Consequently, the annual compliance costs estimated in this report fall within the range of operating-cost variability that international shipping companies routinely manage.

This comparison provides important context for evaluating the relative magnitude of the proposed requirement.

5.6 Sources of Uncertainty

Although representative fleet modeling provides useful insight, several factors could influence actual compliance costs.

These include

- changes in bunker fuel prices
- vessel deployment decisions
- annual call frequency
- terminal congestion
- anchorage delays
- freight market conditions.

Because these variables change over time, the report presents annual costs as representative ranges rather than fixed values.

5.7 Chapter Summary

The fleet-level analysis indicates that the proposed Virginia fuel-switch requirement would impose a measurable but modest increase in annual operating costs on carriers currently relying on HSFO with scrubber compliance.

For a representative carrier distribution to Virginia's ports, a reduction of **approximately 0.61% to 0.91% of modeled regional operating earnings** is estimated.

The 200-call distribution is a normalized representative sample designed to capture the relative mix of major trade routes and vessel classes serving Virginia waters. It is not intended to reproduce total annual port traffic; rather, it provides a transparent, scalable basis for weighing vessel-specific compliance costs across the principal commercial shipping segments evaluated in the study.

These findings suggest that the proposed requirement would create a limited economic impact relative to the scale of commercial shipping operations while allowing policymakers to evaluate those costs alongside the environmental and public health considerations examined in the following chapter.

Chapter 6: Economic Impact Assessment for Cruise Ships

6.1 Introduction

Although this report primarily evaluates the economic impact of a proposed fuel-switch requirement on commercial cargo vessels, Virginia also serves as a port of call for ocean-going cruise ships. Currently cruise ships represent less than 1% of ship traffic and were therefore excluded from the previous analysis. Also, cruise ships present a unique operating profile because they function as both transportation platforms and floating hospitality facilities.

Unlike cargo ships, cruise ships maintain substantial electrical demand while underway, at anchor, and alongside a berth. As a result, fuel consumption during a port call is influenced not only by propulsion requirements but also by the continuous operation of onboard systems such as air conditioning, lighting, restaurants, entertainment venues, water production, wastewater treatment, and hotel services.

Because these operating characteristics differ significantly from those of cargo vessels, the potential economic impact of requiring a temporary switch from High Sulfur Fuel Oil (HSFO) to 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) warrants separate evaluation.

6.2 Virginia Cruise Operations

Virginia’s cruise activity is centered primarily at the Half Moone Cruise and Celebration Center in Norfolk. While the number of annual cruise calls is substantially lower than commercial cargo vessel traffic, cruise ships are among the largest vessels operating in Virginia waters.

Representative cruise itineraries include

- Caribbean voyages
- Bermuda cruises
- Canada and New England itineraries
- repositioning voyages between seasonal home ports.

Typical port calls range from 8 to 14 hours, although turnaround operations involving passenger embarkation and provisioning may extend longer.

6.3 Representative Vessel Characteristics

Modern cruise ships vary considerably in size; however, the representative vessel used in this analysis reflects a contemporary large cruise ship serving U.S. East Coast ports.

Characteristic	Representative Value
Gross Tonnage	110,000–180,000 GT
Passenger Capacity	2,800–5,000
Crew	1,000–1,500
Length	290–340 meters
Transit Speed in Virginia Waters	10–12 knots
Typical Virginia Port Stay	10–14 hours

These values are representative of vessels currently operating in the North American cruise market and are intended for analytical purposes.

6.4 Fuel Consumption Profile

Cruise ships consume fuel differently than cargo vessels because of their substantial “hotel load”. Even when propulsion engines are operating at reduced power or are shut down alongside a berth, auxiliary generators continue supplying electricity to support passenger accommodations and hotel services.

Representative fuel consumption is summarized below.

Operating Condition	Fuel Consumption
Main propulsion engines	2.5–4.0 MT/hour
Auxiliary generators (hotel load)	1.5–3.0 MT/hour

Hotel loads are significantly greater than those of cargo vessels due to continuous passenger services, making auxiliary fuel consumption the dominant factor during extended port calls.

6.5 Methodology

The methodology used for cruise ships is identical to that applied throughout this report for cargo vessels.

Incremental compliance costs are calculated by:

1. Estimating the quantity of fuel consumed during:
    a. fuel changeover,
    b. transit within Virginia waters,
    c. anchorage or port operations.
2. Multiplying total fuel consumption by the representative price differential between HSFO and LSMGO.
3. Comparing the resulting incremental cost with representative voyage operating earnings.

Using a consistent methodology across vessel classes allows direct comparison of relative economic impacts.

6.6 Representative Compliance Cost

A representative

Passenger Capacity	3000
Main Engine / Propulsion Fuel Rate	3.25 MT/hr
Hotel / Auxiliary Generator Fuel Rate	2.25 MT/hr
Total Regulated Transit Distance per Port Call	70 nm
Transit Speed	11 knots
Berth / Hotel Hours	12 hr
Fuel Changeover Time	3hr

Depending on vessel size, hotel load, and fuel prices, representative compliance costs generally range from **$13,223 to $19,849 per port call**.

Although cruise ship compliance costs are higher than other vessel classes due to hoteling, the EBIT (est. $2,250,000) for cruise ships is also relatively high due to ticket sales and other amenities. **The compliance impact is 0.59% to 0.88% of earnings**, which is broadly consistent with other classes of vessel discussed in Chapter 4.

6.7 Economic Context

Although cruise ships incur higher absolute fuel costs than many cargo ships, they also generate substantially greater revenue per voyage.

Representative sources of cruise revenue include

- passenger ticket sales
- onboard dining

- beverage sales
- retail operations
- shore excursions
- casino operations
- specialty entertainment
- spa and hospitality services.

Accordingly, the incremental fuel cost associated with operating on LSMGO within Virginia waters represents a relatively small component of overall voyage economics.

6.8 Fleet Trends and Future Considerations

The cruise industry has invested significantly in cleaner propulsion technologies during the past decade.

Many newly constructed vessels now operate using

- Liquefied Natural Gas (LNG)
- shore power (where available)
- advanced wastewater treatment systems
- hybrid exhaust gas cleaning systems
- battery-assisted auxiliary systems.

In addition, many cruise ship operators already purchase compliant fuels for itineraries that include Emission Control Areas.

As fleet modernization continues, the proportion of cruise ships affected by a Virginia fuel-switch requirement is expected to decline.

6.9 Chapter Summary

The analysis indicates that cruise ships would incur higher absolute fuel-switch costs than most cargo vessels because of their substantial auxiliary power requirements during port calls. Under representative operating conditions, incremental compliance costs are estimated to range from $13,000 to $20,000 per Virginia port call.

Despite these higher absolute costs, cruise ships also generate substantially greater voyage revenue and operating earnings. As a result, the estimated economic impact generally represents **approximately 0.59% to 0.88% of representative voyage operating earnings**, making it one of the smallest percentage impacts among the vessel classes evaluated in this report.

Furthermore, many modern cruise ships already operate on compliant fuels or alternative propulsion systems in regulated waters. Consequently, the long-term economic effect of a Virginia fuel-switch requirement on the cruise industry is expected to diminish as fleet modernization continues.

Overall, the available evidence suggests that the LSMGO fuel-switch requirement would not materially affect the economic viability of cruise operations serving Virginia ports while providing the same localized environmental benefits associated with reduced sulfur emissions and the elimination of scrubber washwater discharge during operations within Virginia waters.

Chapter 7: Environmental Externalities and Public Policy Considerations

7.1 Introduction

The previous chapters estimated the private operating costs associated with requiring certain commercial vessels to temporarily switch from High Sulfur Fuel Oil (HSFO) to 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters.

Economic cost, however, is only one component of a public policy evaluation.

Environmental regulations are generally adopted because some costs associated with economic activity are not reflected in private market transactions. Economists refer to these as **externalities**—costs imposed on society rather than the producer or consumer.

This chapter reviews the environmental and public health considerations associated with marine fuel use and explains why governments often require pollution-control measures even when those measures increase private operating costs.

7.2 The Economic Concept of Externalities

Markets function efficiently when the full cost of producing a good or service is reflected in its market price.

However, when pollution affects individuals who are not party to the original economic transaction, a portion of the true cost is effectively transferred to the public.

Examples include:

- increased healthcare expenditures;
- environmental remediation;
- ecosystem degradation;
- reduced commercial fisheries;
- diminished recreational resources.

These costs are often referred to as **externalized costs** because they are borne by society rather than by the source generating the pollution.

Environmental regulation seeks to reduce these externalities by encouraging cleaner technologies or requiring pollution-control measures.

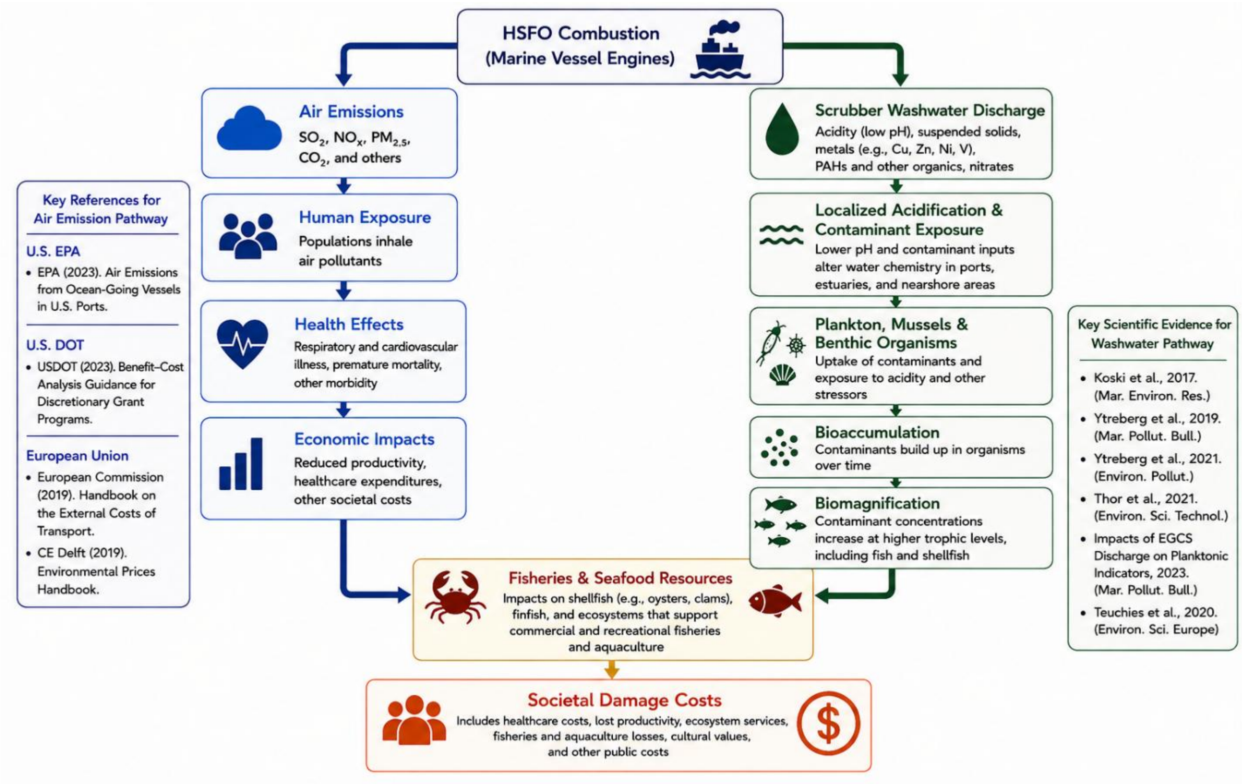

Figure 7-1 Conceptual Pathways of Air and Water Pollution

7.3 Marine Air Emissions

Commercial shipping is among the most fuel-efficient modes of freight transportation on a ton-mile basis. Nevertheless, the scale of global maritime commerce makes the sector a significant source of sulfur oxides (SO_x), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), black carbon, and greenhouse gas emissions. Vessels operating on residual fuels, including high-sulfur fuel oil (HSFO), emit pollutants that contribute to degraded air quality in coastal communities, ports, and shipping corridors.

Combustion of HSFO produces emissions that include

- sulfur dioxide (SO_2)
- sulfate aerosols formed through atmospheric oxidation of SO_2
- fine particulate matter ($PM_{2.5}$)
- black carbon
- nitrogen oxides (NO_x)

- trace metals and polycyclic aromatic hydrocarbons (PAHs) associated with residual fuel combustion.

These pollutants are associated with a broad range of adverse public health outcomes. Extensive epidemiological research has demonstrated that long-term exposure to $PM_{2.5}$ and sulfur-related air pollution increases the risk of premature mortality, ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), asthma exacerbations, respiratory infections, and reduced lung function. Exposure has also been linked to increased hospital admissions, emergency department visits, and higher rates of cardiovascular and respiratory disease, particularly among children, older adults, and individuals with pre-existing medical conditions.

Growing scientific evidence further suggests that chronic exposure to fine particulate matter may contribute to neurodegenerative diseases, including cognitive decline and Alzheimer's disease, through inflammatory and vascular mechanisms affecting the central nervous system. In addition, prenatal exposure to elevated concentrations of $PM_{2.5}$ has been associated with adverse birth outcomes, including preterm birth, low birth weight, impaired fetal development, and increased risk of infant respiratory disease. Certain constituents of residual-fuel emissions, including PAHs and some heavy metals, are also recognized or suspected carcinogens and may increase lifetime cancer risk with prolonged exposure.

Beyond the direct health effects, air pollution generated by marine shipping imposes substantial economic costs on society. These costs include increased healthcare expenditures, lost worker productivity, missed school and work days, disability, reduced quality of life, and premature mortality. Because many of these costs are borne by public healthcare systems, employers, families, and taxpayers, rather than by the emitting source, they represent a significant negative externality associated with marine fuel combustion.

The International Maritime Organization (IMO) adopted progressively more stringent sulfur limits under MARPOL Annex VI to reduce these public health impacts by lowering sulfur oxide emissions and the formation of secondary fine particulate matter. The proposed Virginia requirement would further reduce sulfur emissions from vessels operating within Virginia waters by requiring the use of compliant low-sulfur fuels rather than higher-sulfur residual fuels.

7.4 Scrubber Washwater

Approved Exhaust Gas Cleaning Systems (scrubbers) reduce atmospheric sulfur emissions by transferring sulfur compounds from engine exhaust to treatment water.

Open-loop scrubbers discharge this treated washwater back to the surrounding marine environment after onboard processing.

Published research has identified washwater constituents including

- sulfate compounds
- nickel
- vanadium
- zinc
- polycyclic aromatic hydrocarbons (PAHs)
- suspended solids.

The concentration of these constituents varies according to fuel characteristics, scrubber design, and engine operating conditions.

Scientific research continues to evaluate the long-term ecological implications of repeated washwater discharge, particularly within enclosed or environmentally sensitive waterways.

7.5 Chesapeake Bay as a Sensitive Receiving Environment

Virginia's coastal waters are part of the Chesapeake Bay, the largest estuary in the United States.

The Bay supports

- commercial seafood industries
- recreational fisheries
- tourism
- military installations
- maritime commerce
- nationally significant ecological resources.

Because vessel traffic is concentrated within relatively narrow navigation channels and port approaches, localized pollutant loading may differ substantially from offshore ocean conditions.

Virginia has invested billions of dollars in nutrient reduction, habitat restoration, stormwater management, wastewater treatment, and Chesapeake Bay restoration initiatives.

Consequently, policymakers have expressed interest in evaluating additional measures that may reduce pollutant loading from all significant sources, including commercial shipping.

7.6 Potential Benefits of Fuel Switching

Requiring temporary use of LSMGO while vessels operate within Virginia waters is expected to

- reduce sulfur oxide emissions associated with HSFO combustion
- reduce formation of fine particulate matter (PM2.5)
- eliminate scrubber washwater discharge during periods when vessels operate on compliant fuel
- reduce localized inputs of combustion-related contaminants into Virginia waters.

Because the proposed requirement applies only during operations within Virginia jurisdiction, these benefits would be localized rather than global.

The magnitude of these benefits depends upon

- the number of affected vessels
- duration of in-state operations
- fuel consumption
- existing compliance practices.

Anticipated Environmental and Public Health Benefits

Requiring vessels to temporarily operate on low-sulfur marine gas oil (LSMGO) while transiting, anchoring, or berthing within Virginia waters produces localized environmental and public health benefits by reducing both air emissions and waterborne pollutant discharges associated with the combustion of residual marine fuels.
Compared with vessels operating on high-sulfur fuel oil (HSFO) or other non-compliant residual fuels, the use of LSMGO would be expected to:

- substantially reduce sulfur dioxide (SO_2) emissions;
- reduce the atmospheric formation of sulfate aerosols and secondary fine particulate matter ($PM_{2.5}$);
- lower emissions of combustion-related particulate matter associated with residual fuel combustion;
- eliminate the need for scrubber operation during periods when compliant fuel is used, thereby eliminating scrubber washwater discharges within Virginia waters;
- reduce the introduction of acidity, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other combustion-derived contaminants into Virginia's marine environment; and
- improve air quality in and around ports, shipping channels, and nearby coastal communities.

Reductions in sulfur dioxide and fine particulate matter are expected to provide localized public health benefits by decreasing population exposure to pollutants associated with respiratory disease, cardiovascular disease, asthma exacerbations, hospital admissions, and premature mortality. Improved air quality may also reduce lost workdays, school absences, healthcare expenditures, and other societal costs associated with air pollution. While these benefits accrue directly to residents of Virginia's coastal communities, many of the associated healthcare costs are borne by public health systems, employers, insurers, and taxpayers. Consequently, reductions in emissions represent a reduction in external costs that are not reflected in the private cost of marine transportation.

The proposed requirement would also reduce the discharge of scrubber washwater from vessels that would otherwise rely on exhaust gas cleaning systems while operating on residual fuels. Eliminating these discharges during operations within Virginia waters would reduce localized inputs of acidic washwater, suspended solids, trace metals, and persistent organic contaminants into the Chesapeake Bay and Virginia's tidal waters. Although the proposed requirement would not eliminate these discharges globally, it would reduce pollutant loading within one of the nation's most environmentally and economically important estuarine systems.

Because the proposed fuel-switch requirement applies only while vessels are operating within Virginia jurisdiction, the resulting environmental and public health benefits would be localized rather than global. This targeted approach focuses emission reductions and water-quality improvements where human populations, sensitive aquatic habitats, commercial fisheries, recreational resources, and port activities are most concentrated. The magnitude of these benefits depends on several factors, including:

- the number and types of vessels subject to the requirement;
- the proportion of the fleet currently operating on non-compliant fuels;
- the duration of vessel transit, anchorage, and berthing within Virginia waters;
- engine load and fuel consumption during in-state operations;
- existing fuel-use and scrubber operating practices;
- the prevailing fuel price differential influencing compliance behavior; and
- the spatial distribution of vessel traffic relative to nearby population centers and environmentally sensitive waters.

While this report primarily evaluates the commercial compliance costs associated with the proposed fuel-switch requirement, these costs should be considered alongside the corresponding reductions in public health and environmental externalities. A comprehensive benefit-cost assessment would incorporate the economic value of avoided air pollution, reduced healthcare expenditures, improved workforce productivity, and avoided impacts to Virginia's marine and coastal ecosystems. Such an assessment would provide a more complete measure of the net societal effects of the proposed regulation.

7.7 Comparison with Compliance Costs

Chapters 4 and 5 estimated that the proposed requirement would increase annual operating cost impacts for a representative fleet is approximately:

0.61% to 0.91% of modeled regional operating earnings.

The policy question therefore becomes one of proportionality.

Specifically:

> **Are the estimated compliance costs proportionate to the potential public environmental and health benefits associated with reducing HSFO use within Virginia waters?**

7.8 External Damage Cost Factors

Previous analyses presented quantify the direct compliance costs associated with requiring ocean-going vessels to temporarily operate on low-sulfur marine gas oil (LSMGO) while transiting Virginia waters. These costs represent private expenditures incurred by vessel operators through the purchase of higher-cost compliant fuel.

Environmental regulations, however, are typically evaluated using a broader economic framework that considers both compliance costs and the societal costs of pollution. These societal costs, commonly referred to as external damage costs or environmental externalities, represent impacts that are borne by the public rather than by the entity producing the emissions. External costs associated with commercial shipping include adverse human health effects, environmental degradation, reduced labor productivity, climate impacts, ecosystem impairment, and other consequences that are not reflected in the market price of marine transportation.

Although this report focuses primarily on estimating compliance costs, understanding the methodology used to estimate external damage costs provides important context for evaluating the broader economic implications of the proposed Virginia fuel-switch requirement.

7.9 Methodology

External damage costs are commonly estimated using a two-step process. First, pollutant emissions are estimated using established emissions inventory models such as the U.S.

EPA Shore Power Emissions Calculator. Second, pollutant-specific damage values are applied to estimate the societal costs associated with each pollutant.

General equation:

$D = \Sigma(E_i \times V_i)$

Where:
- D = Total external damage cost ($)
- E_i = Annual emissions of pollutant i (metric tons)
- V_i = Monetized damage value assigned to pollutant i ($/metric ton)

The total external damage cost is the sum of the damage associated with each emitted pollutant. Figure 7-1 illustrates this methodology.

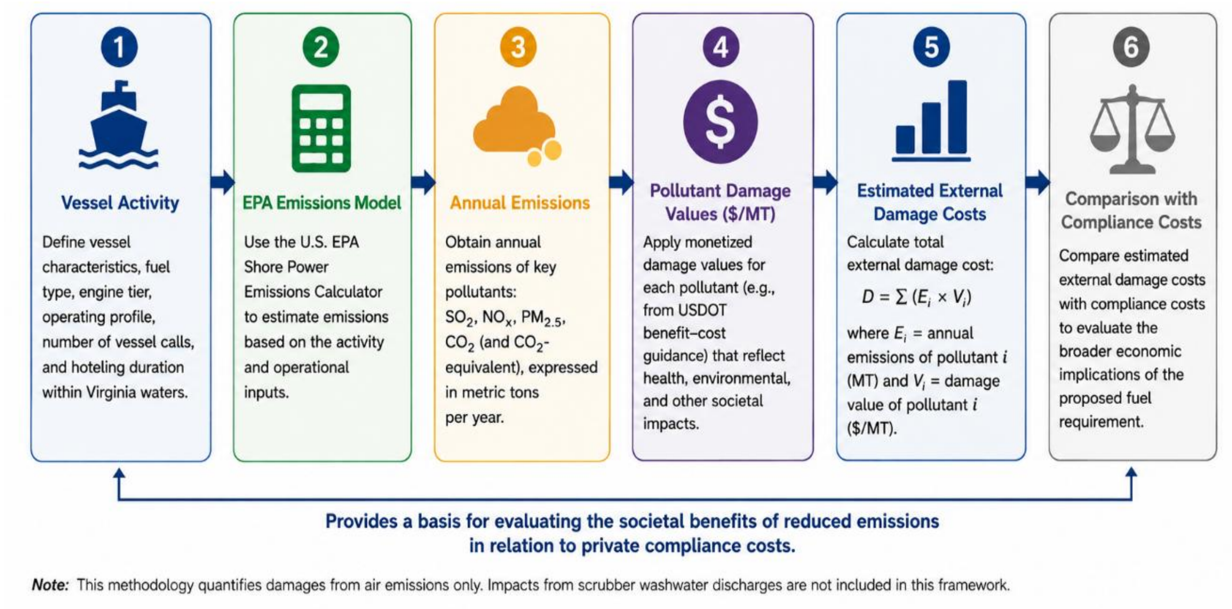

Figure 7-2 External Damage Cost Methodology

7.10 Illustrative External Damage Cost Calculation

To illustrate the external damage-cost methodology, a representative 3,000-passenger cruise ship was evaluated assuming 50 port calls per year, with an average of 8 hoteling hours per call. The vessel was modeled as a Tier II, approximately 100,000-GT cruise ship, and two fuel scenarios were evaluated: HFO at 3.50% sulfur and MGO at 0.10% sulfur.

Annual vessel emissions were estimated using the U.S. EPA Shore Power Emissions Calculator, which uses inputs including vessel type, engine tier, fuel type, number of vessel calls, hoteling duration, and electric-grid region. The calculator provides estimated annual emissions of SO_2, NO_x, $PM_{2.5}$, and CO_2.

The resulting emissions were converted to estimated societal damage costs using pollutant-specific values from the **2023 U.S. Department of Transportation benefit-cost guidance**. The general calculation is:

$$D = \Sigma(E_i \times V_i)$$

where D is total estimated external damage cost, E_i is annual emissions of pollutant i (metric tons), and V_i is the monetized damage value assigned to pollutant i ($ per metric ton).

For example, the damage associated with fine particulate matter is calculated as:

$$D\_PM2.5 = E\_PM2.5 \times V\_PM2.5$$

The same calculation is performed for each modeled pollutant, and the individual damage estimates are summed to determine the total estimated external cost.

Using this methodology, the representative cruise ship produced estimated annual health and environmental damage costs of approximately:

Fuel scenario	Estimated annual external damage cost
MGO — 0.10% sulfur	**$2.8 million**
HFO — 3.50% sulfur	**$12.2 million**

These results indicate that, for the operating scenario evaluated, the estimated external damage associated with HFO combustion was approximately **$9.4 million per year greater than MGO**. This estimate is only while docked, transit pollution is not assessed.

The modeled $PM_{2.5}$ results show a similar pattern. Estimated annual fine particulate emissions were 7.0 MT for HFO and 0.82 MT for MGO, corresponding to an approximately 88% reduction in $PM_{2.5}$ when comparing MGO with HFO.

A peer-reviewed published particulate-emission factors of approximately 2.5 g/kWh for HFO and 0.35 g/kWh for MGO, an approximately 86% reduction, provides an independent reasonableness check on the modeled particulate reduction.

7.11 International Application of External Damage Methodologies

The methodology described above is consistent with internationally recognized environmental economic practice. In the United States, EPA develops emissions inventory methodologies while the U.S. Department of Transportation (USDOT) applies pollutant damage values in transportation benefit-cost analyses. The European Commission and CE Delft employ the same general framework, although the monetary damage values differ because they are derived from European demographic, environmental, and economic data.

7.12 Air Emission Externalities

Combustion of heavy fuel oil produces sulfur dioxide (SO_2), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), and other combustion-related pollutants. These emissions contribute to respiratory and cardiovascular disease, premature mortality, increased healthcare expenditures, reduced productivity, reduced visibility, ecosystem degradation, and climate-related impacts.

Because sulfur dioxide forms sulfate aerosols and secondary $PM_{2.5}$, reductions in sulfur emissions produce benefits extending beyond direct reductions in SO_2 emissions. These societal benefits are generally borne by the public and are commonly evaluated using external damage methodologies.

Air Pollutant	Primary Health Effects	Broader Societal Impacts
Sulfur Dioxide (SO_2)	Airway irritation, asthma exacerbation, respiratory inflammation	Increased emergency room visits and hospital admissions
Fine Particulate Matter ($PM_{2.5}$)	Premature mortality, cardiovascular disease, stroke, chronic respiratory disease	Higher healthcare costs, reduced life expectancy, lost productivity
Sulfate Aerosols	Secondary $PM_{2.5}$ formation, reduced lung function	Increased regional air pollution and public health burden
Nitrogen Oxides (NO_x)	Respiratory irritation, ozone formation	Increased respiratory illness and environmental degradation
Black Carbon	Respiratory and cardiovascular effects	Climate forcing and localized health impacts
PAHs & Heavy Metals	Toxicity, carcinogenic potential, neurological effects	Long-term public health and environmental contamination
Prenatal Exposure to $PM_{2.5}$	Preterm birth, low birth weight, impaired fetal development	Increased neonatal healthcare costs and long-term developmental impacts
Long-Term $PM_{2.5}$ Exposure	Cognitive decline and increased risk of dementia and Alzheimer's disease	Increased long-term healthcare and caregiving costs

7.13 Scrubber Washwater Externalities

The methodology described above primarily evaluates atmospheric emissions and generally does not monetize pollutants discharged through exhaust gas cleaning systems (scrubbers). Consequently, conventional air-emission damage assessments may underestimate the total environmental implications of marine fuel selection.

Open-loop scrubbers discharge acidic washwater containing suspended solids, trace metals, polycyclic aromatic hydrocarbons (PAHs), nitrates, and other combustion-derived contaminants. Closed-loop systems substantially reduce routine overboard discharge through recirculation and treatment but continue to generate concentrated waste streams requiring controlled disposal.

Scientific studies have demonstrated that scrubber washwater can produce localized reductions in pH and introduce dissolved metals and organic contaminants into coastal waters. Localized acidification can affect calcifying organisms including oysters, clams, mussels, and plankton. Heavy metals and PAHs can be absorbed by plankton and benthic organisms, where they can bioaccumulate and biomagnify through marine food webs, ultimately reaching commercially important finfish and shellfish.

Unlike atmospheric emissions, there is currently no universally accepted methodology for assigning standardized monetary values to these aquatic impacts. Therefore, they are recognized qualitatively as additional environmental considerations rather than quantified within the compliance-cost analysis. Figure 7-1 illustrates the conceptual pathways linking air emissions, scrubber washwater, ecological effects, fisheries, and societal damage costs.

Water Pollutant	Primary Marine Life Effects	Broader Societal Impacts
General Scrubber Discharge / Washwater	Systemic biological breakdown in fish, including neurological impairment (erratic swimming, slowed predator avoidance) and endocrine disruption.	Threats to the seafood industry; public health risks from toxins traveling up the food web.
Polycyclic Aromatic Hydrocarbons (PAHs)	High mortality of microplankton and copepods; systemic biological breakdown in fish (neurological and endocrine disruption); mutagenic potency and dioxin-like effects; embryonic abnormalities, cardiotoxicity, and bone disruption; bioaccumulation in fatty tissues, liver, and bile; reduced egg production and	Public health risks from biomagnification of toxins in local food chains; threats to the seafood economy; human carcinogenic and mutagenic risks; contamination of coastal drinking water; risks to Indigenous and subsistence fishing communities; societal

	survival; shell dissolution in oysters and crabs.	damage costs due to marine ecotoxicity.
Acidic sulfates / Acidic washwater (Low pH)	Shell dissolution in calcifying organisms (oysters, crabs, and coral building organisms); high mortality of microplankton and zooplankton; lethal to larvae and embryos in hatcheries; reduced seawater buffer capacity; increased bioavailability and remobilization of metals; cardiotoxicity in fish larvae.	Contributions to ocean acidification and acid rain; threats to the seafood economy (e.g., losses in hatcheries); negative impacts on the sustainable development of aquaculture; reduction of CO_2 uptake capacity in the ocean.
Heavy metals (Vanadium, Nickel, Lead, Copper, Zinc, Mercury, Chromium)	Systemic biological breakdown in fish (neurological and endocrine disruption); high mortality of microplankton; shell dissolution in oysters and crabs; bioaccumulation in tissues and zooplankton; impaired gonadal development and reduced reproductive activity; larval development failure; tissue damage and severe respiratory distress; impaired molting and lethargy.	Public health risks from biomagnification of toxins in local food chains; threats to the seafood economy and seafood-dependent communities; gastrointestinal issues from exposure; risks of DNA damage and developmental abnormalities in humans; threats to global fish stocks.
Nitrates / Nitrites / Nitrogen oxides (NOx)	Eutrophication effects on phytoplankton; damage to marine ecosystems and wildlife; high mortality of microplankton.	Contribution to general deterioration of the environment and nitrogen pollution in coastal areas; exacerbation of eutrophication.

7.14 Relevance to Virginia

Virginia supports one of the largest commercial seafood industries on the Atlantic coast (a $1.27 billion industry and over 10,000 jobs). Commercial fisheries, shellfish aquaculture, seafood processing, recreational fisheries, and maritime tourism contribute substantially to the Commonwealth's economy. Protection of Chesapeake Bay water quality therefore has ecological, public health, and economic significance.

Although the direct economic effects of scrubber washwater on Chesapeake Bay fisheries have not yet been quantified using standardized valuation methodologies, potential impacts on water quality, shellfish resources, and marine food webs represent additional environmental considerations beyond those captured by conventional air-emission damage models.

7.15 Existing Regulatory Trends

The proposed Virginia fuel-switch requirement is consistent with a broader international trend toward progressively reducing the environmental and public health impacts of commercial shipping. Over the past three decades, maritime regulation has evolved from establishing global minimum standards for air emissions to implementing increasingly targeted regional, national, and local measures designed to protect sensitive coastal environments and densely populated port communities.

Key milestones in this evolution include

- the adoption of MARPOL Annex VI, establishing international standards for the prevention of air pollution from ships
- implementation of the IMO 2020 Global Sulfur Cap, limiting the sulfur content of marine fuels used outside Emission Control Areas (ECAs) to 0.50 percent
- establishment of Emission Control Areas (ECAs), including the North American ECA, requiring the use of fuels containing no more than 0.10 percent sulfur or equivalent emission-control technologies
- adoption of state, national, and port-specific restrictions on open-loop scrubber washwater discharges in jurisdictions including California, Connecticut, Singapore, China, Norway, Belgium, and numerous European ports
- increasing adoption of cleaner marine fuels, including low-sulfur marine gas oil (LSMGO), liquefied natural gas (LNG), methanol, and other lower-emission fuels and
- continued investment in alternative propulsion technologies, shore power, battery-assisted systems, and other strategies intended to reduce vessel emissions in ports and nearshore waters.

Collectively, these developments reflect a clear progression in maritime environmental policy. Initial regulations focused primarily on reducing air emissions from ships operating globally, while more recent measures increasingly address localized environmental impacts within ports, estuaries, and other environmentally sensitive waters. Many jurisdictions have concluded that additional protections are warranted where vessel emissions and discharges occur near population centers, critical habitats, and economically significant coastal resources.

The proposed Virginia requirement follows this established regulatory trajectory by addressing emissions and fuel use only while vessels operate within Virginia jurisdiction.

Rather than establishing a new international standard, the proposed requirement represents a geographically targeted measure intended to improve air quality and reduce pollutant inputs to Virginia's coastal waters while remaining consistent with the broader evolution of maritime environmental regulation.

Unlike the global requirements established under MARPOL Annex VI, the proposed Virginia requirement is designed to address localized environmental conditions within the Chesapeake Bay and Virginia's tidal waters. Like other state and regional initiatives, it reflects the principle that coastal jurisdictions may adopt additional measures to protect public health and sensitive marine ecosystems where localized environmental impacts justify more stringent operational requirements.

7.16 Principal Findings

The environmental and economic analyses presented in this report lead to the following principal findings:

- **Commercial shipping is a critical component of Virginia's economy**, but vessel operations generate air emissions and environmental externalities that are not fully reflected in the private cost of maritime transportation.
- **The proposed Virginia fuel-switch requirement would apply only to vessels operating on non-compliant fuels while within Virginia waters.** Vessels already using compliant fuels would not be affected.
- **The incremental compliance costs identified in Chapters 4 and 5 are measurable but modest** relative to representative voyage earnings and the overall economic value of maritime commerce.
- **Temporary use of compliant fuel would reduce sulfur dioxide (SO_2) emissions, decrease the formation of secondary fine particulate matter ($PM_{2.5}$), and eliminate scrubber washwater discharges** while affected vessels operate within Virginia waters.
- **These environmental improvements have the potential to reduce public health and environmental externalities**, including healthcare costs, lost productivity, and pollutant loading to the Chesapeake Bay and Virginia's tidal waters.
- **The proposed requirement is consistent with broader international and regional regulatory trends** toward reducing emissions and protecting sensitive coastal environments.

Ultimately, the proposed Virginia fuel-switch requirement represents a localized operational measure that seeks to balance modest private compliance costs against the potential public benefits of improved air quality, enhanced water quality, and reduced environmental and public health impacts.

7.17 Chapter Summary

The proposed Virginia fuel-switch requirement should be evaluated within the broader framework of environmental economics rather than solely as an isolated operating expense. While commercial shipping is a vital component of Virginia's economy, vessel operations generate air emissions and waterborne discharges whose public health and environmental costs are not fully reflected in private market transactions.

Requiring the temporary use of 0.10 percent sulfur LSMGO while operating within Virginia waters has the potential to produce measurable localized public health and environmental benefits. Transitioning away from residual fuel combustion reduces sulfur dioxide emissions and fine particulate matter ($PM_{2.5}$) formation in coastal port communities, while eliminating scrubber washwater discharges prevents localized inputs of acidity, heavy metals, and persistent organic contaminants into the Chesapeake Bay.

Evaluating these localized environmental improvements alongside the estimated private compliance costs provides policymakers with a transparent framework for assessing policy proportionality. Because the estimated compliance costs represent a relatively small percentage of representative regional operating earnings, the central policy question is whether these modest compliance costs are justified by the corresponding public benefits of reduced air pollution, enhanced water quality, and lower societal externalities. The following chapter examines the practical operational and feasibility considerations associated with implementing the proposed fuel-switch requirement.

Chapter 8: Implementation Considerations

8.1 Introduction

The preceding chapters evaluated the regulatory framework, engineering requirements, economic implications, and environmental considerations associated with requiring certain commercial vessels to temporarily operate on 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while within Virginia waters.

Assuming policymakers determine that such a requirement is appropriate, the next consideration is implementation.

This chapter examines the practical and operational issues associated with implementing a Virginia fuel-switch requirement, including vessel operations, compliance verification, fuel availability, enforcement considerations, and potential impacts on maritime commerce.

8.2 Operational Feasibility

From an engineering perspective, the proposed requirement does not introduce a new operational practice.

Commercial vessels operating internationally already perform fuel switching when entering and leaving Emission Control Areas (ECAs).

These procedures are incorporated into

- vessel operating manuals
- Safety Management Systems (SMS)
- engine manufacturer guidance
- crew training programs.

Consequently, the engineering procedures necessary to comply with a Virginia fuel-switch requirement are already familiar to vessel operators.

8.3 Fuel Availability

Successful implementation depends upon reliable availability of compliant marine fuel.

Virginia's commercial ports already supply multiple compliant fuels, including

- Low Sulfur Marine Gas Oil (LSMGO)
- Other marine distillate fuels or alternatives

Because vessels operating internationally routinely purchase compliant fuel before entering Emission Control Areas, the proposed requirement would not require creation of new fuel infrastructure.

Operators would instead adjust onboard fuel management practices to ensure sufficient LSMGO is available during operations within Virginia waters.

8.4 Fuel Changeover Procedures

Marine engine manufacturers provide detailed guidance for changing between residual fuels and marine distillates.

Typical procedures include

- gradual reduction of fuel temperature
- controlled viscosity transition
- monitoring fuel system pressures
- confirmation of stable engine operation.

Fuel switching is normally completed before entering regulated waters to ensure compliant fuel has displaced residual fuel throughout the engine fuel system.

The methodology used in this report assumes a representative one-hour transition period consistent with common industry practice.

8.5 Compliance Verification

Compliance could be verified using methods already employed under existing marine fuel regulations.

These include

- bunker delivery notes
- fuel sampling
- engine room logbooks
- fuel changeover records
- onboard inspections
- electronic voyage information.

Many of these records are already maintained under international regulations.

Accordingly, implementation would primarily involve verification of existing operational documentation rather than creation of entirely new reporting systems.

8.6 Enforcement Considerations

Responsibility for enforcement would depend upon the legal authority established by the Commonwealth.

Potential approaches could include

- inspections during normal port-state control examinations
- documentation review during port calls
- review of electronic record submission
- random compliance audits
- coordination with federal maritime agencies.

The objective would be to verify compliance while minimizing disruption to commercial operations.

8.7 Economic Implementation Considerations

Unlike regulations requiring installation of new equipment, the proposed fuel-switch requirement would generally not require

- capital investment
- engine replacement
- scrubber modification
- vessel redesign.

Compliance costs arise primarily from:

- purchasing compliant fuel
- fuel consumed during the transition period.

Consequently, implementation costs consist largely of operating expenses rather than long-term capital expenditures.

8.8 Effects on Port Operations

The proposed requirement is not expected to significantly alter routine port operations.

Commercial vessels would continue to:

- follow existing pilotage requirements
- use existing navigation channels

- berth at existing terminals
- conduct normal cargo operations.

No changes to terminal infrastructure or cargo-handling equipment would be required.

Accordingly, direct operational impacts on Virginia ports are expected to be minimal.

8.9 Competitive Considerations

A common concern regarding regional environmental regulations is whether they place one jurisdiction at a competitive disadvantage.

Several characteristics of the proposed fuel-switch requirement reduce that risk.

First, the requirement would apply uniformly to affected vessels operating within Virginia waters. This provides consistent fuels cost for all vessels.

Second, only fuel consumed during operations within Virginia jurisdiction is affected.

Third, compliance does not require permanent vessel modifications.

Finally, commercial shipping companies already comply with differing environmental requirements in numerous international jurisdictions.

The analysis presented in Chapters 5 and 6 indicates that estimated compliance costs are modest relative to representative voyage and regional operating earnings.

8.10 Potential Implementation Challenges

Although implementation is feasible, several practical considerations warrant attention.

These include

- fluctuations in fuel prices
- periods of extended anchorage
- seasonal port congestion
- evolving marine fuel markets
- coordination with existing federal regulations.

Periodic review of implementation experience would allow policymakers to evaluate whether modifications or refinements become appropriate over time.

8.11 Principal Findings

Several observations emerge regarding implementation.

- Fuel switching is already a routine operational practice throughout international shipping.
- Compliant marine fuels are already widely available.
- No vessel modifications are required.
- Existing operational records provide a basis for compliance verification.
- Estimated compliance costs consist primarily of incremental fuel expenses.
- Direct impacts on Virginia port operations are expected to be limited.

Overall, the proposed requirement appears technically and operationally feasible using existing marine engineering practices.

8.12 Chapter Summary

Implementation of a Virginia fuel-switch requirement would build upon operational procedures already used throughout the international shipping industry.

Because affected vessels already possess the engineering capability to transition between HSFO and compliant low-sulfur fuel, implementation would primarily involve operational fuel management rather than technological modification.

The economic analysis presented in earlier chapters indicates that the resulting compliance costs are generally modest relative to representative shipping operations. Consequently, implementation considerations appear to present fewer challenges than the broader policy questions regarding environmental objectives and regulatory authority.

The following chapter examines the legal and administrative considerations associated with implementation under existing federal and international maritime law.

Chapter 9: Legal and Administrative Considerations

9.1 Introduction

The preceding chapters evaluated the engineering, economic, operational, and environmental implications of a proposed Virginia requirement that certain commercial vessels temporarily operate on 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while within Virginia waters.

In addition to those technical and economic considerations, implementation of any state environmental requirement affecting commercial shipping must also be evaluated within the context of existing federal and international law.

This chapter summarizes the principal legal and administrative considerations that policymakers should evaluate when considering a state fuel-switch requirement. It is intended to identify the relevant legal framework rather than provide legal opinions regarding the validity of any specific legislation.

9.2 International Regulatory Framework

International commercial shipping is governed primarily through treaties administered by the International Maritime Organization (IMO).

The principal international regulation governing marine fuel sulfur content is MARPOL Annex VI, which establishes sulfur-emission standards while allowing several approved compliance pathways, including

- compliant low-sulfur fuels
- approved Exhaust Gas Cleaning Systems (EGCS)
- alternative marine fuels.

The proposed Virginia requirement would not alter these international standards.

Rather, it would establish operational fuel-switching requirements applicable only while vessels are operating within the Virginia jurisdiction.

9.3 Federal Regulatory Authority

Within the United States, several federal agencies regulate different aspects of commercial shipping.

These include:

- U.S. Environmental Protection Agency (EPA)

- U.S. Coast Guard (USCG)
- U.S. Army Corps of Engineers
- Customs and Border Protection (CBP)

The EPA administers federal air-emission regulations implementing portions of MARPOL Annex VI.

The Coast Guard is responsible for vessel inspection, navigation safety, and many aspects of maritime enforcement.

Accordingly, any state regulatory proposal should be evaluated for consistency with applicable federal statutes and regulations.

9.4 State Authority

States have traditionally exercised authority over numerous environmental matters within their territorial waters, including

- water quality
- wastewater discharges
- coastal resource protection
- public health
- environmental permitting.

Virginia also possesses responsibilities under the Chesapeake Bay restoration framework and other state environmental programs.

Whether a specific fuel-switch requirement falls within existing state authority would ultimately depend upon statutory language, legislative intent, and judicial interpretation.

That determination is beyond the scope of this report.

9.5 Federal Preemption

One legal issue commonly raised in maritime regulation is federal preemption.

Federal preemption arises when Congress has occupied a regulatory field or when state law conflicts with federal law.

Because commercial shipping is inherently interstate and international in nature, environmental requirements affecting vessel operations may require careful evaluation to determine whether they are compatible with:

- federal maritime statutes

- federal environmental laws
- international treaty obligations.

This report does not attempt to resolve those legal questions.

Rather, it recognizes that legal review would be an important component of any legislative proposal.

9.6 Interstate Commerce Considerations

The United States Constitution grants Congress authority to regulate interstate and foreign commerce.

State regulations affecting commercial shipping may therefore be evaluated under established constitutional principles governing interstate commerce.

Important considerations include whether a proposed requirement

- applies uniformly
- serves a legitimate public purpose
- imposes unreasonable burdens on interstate commerce
- conflicts with federal regulatory objectives.

These issues would require legal analysis during legislative development.

9.7 Existing State and International Examples

Several jurisdictions have adopted environmental requirements affecting vessel operations beyond minimum international standards.

Examples include

- California vessel fuel requirements prior to full implementation of IMO 2020;
- Connecticut exhaust scrubber ban
- restrictions on open-loop scrubber discharge adopted by numerous ports and coastal states
- regional environmental requirements implemented within Emission Control Areas.

These examples demonstrate that vessel operations are already subject to differing environmental requirements in various jurisdictions.

However, each regulatory program was developed within its own legal framework and should not be interpreted as direct precedent for Virginia.

9.8 Administrative Implementation

Should Virginia adopt a fuel-switch requirement, implementation would likely involve several administrative components.

These could include

- regulatory guidance
- compliance documentation
- inspection procedures
- reporting requirements
- coordination with federal agencies.

Whenever practical, implementation could build upon documentation already maintained by vessels under existing international regulations, thereby minimizing additional administrative burdens.

9.9 Policy Considerations

The policy question addressed throughout this report is distinct from the legal question.

Economically, the report concludes that the proposed requirement would impose relatively modest operating costs on the subset of vessels currently relying on HSFO with scrubber compliance.

Legally, policymakers must determine

- whether sufficient authority exists
- how implementation responsibilities would be assigned
- whether additional legislation or rulemaking would be required.

These determinations involve legal and administrative judgments beyond the scope of the economic analysis presented here.

9.10 Principal Findings

Several observations emerge from the legal review.

- International sulfur standards already recognize multiple compliance pathways.
- The proposed Virginia fuel-switch requirement would supplement rather than replace international requirements.
- Implementation would require careful evaluation of state and federal authority.

- Existing documentation maintained by commercial vessels may facilitate compliance verification.
- Legal review would be an essential component of legislative development.

9.11 Chapter Summary

The engineering and economic analyses presented in earlier chapters indicate that the proposed Virginia fuel-switch requirement is technically feasible and economically modest for affected vessels.

Implementation, however, also requires consideration of the broader legal framework governing international shipping.

Although this report does not provide legal opinions, it identifies the principal legal and administrative issues that should be considered during legislative development, including federal authority, interstate commerce, implementation responsibilities, and consistency with existing maritime regulations.

These considerations provide the final context for the overall policy assessment presented in Chapter 10.

Chapter 10: Conclusions and Policy Assessment

10.1 Introduction

This report evaluates the potential economic, operational, environmental, and policy implications of a proposed Virginia requirement under which certain commercial vessels that otherwise rely on High Sulfur Fuel Oil (HSFO) with approved Exhaust Gas Cleaning Systems (EGCS) would temporarily use 0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO) while operating within Virginia waters.

The assessment combines representative vessel operating profiles, marine-engineering assumptions, publicly available shipping-market and financial information, and scientific literature. The analysis is intended to provide a transparent framework for evaluating the magnitude of potential compliance costs and placing those costs in context. It is not intended to predict the operating cost or profitability of any individual vessel, carrier, or port call.

The results are preliminary and should be interpreted as representative analytical estimates. Actual outcomes would depend on fuel prices, vessel characteristics, routing, speed, anchorage duration, freight-market conditions, and the final design and implementation of any Virginia fuel-switch requirement.

10.2 Principal Findings

Finding 1 - The Requirement Would Affect Only a Subset of Vessel Traffic

The proposed Virginia fuel-switch requirement would principally affect vessels that use HSFO in combination with an EGCS as their normal sulfur-compliance strategy. Vessels already operating on LSMGO or another fuel that satisfies the applicable sulfur standard would generally not incur an incremental fuel-switch cost attributable to the proposal. Cruise ships are excluded from the representative 200-call cargo-fleet analysis because they account for a small share of Virginia vessel traffic and have materially different hotel-load characteristics; they are evaluated separately in Chapter 6.

Finding 2 - Compliance Is Primarily an Operating-Fuel Cost, Not a Capital Requirement

The modeled requirement does not assume engine replacement, scrubber removal, installation of new pollution-control equipment, or redesign of existing vessels. Affected vessels would continue to use their existing propulsion and EGCS arrangements outside the regulated operating period. The principal modeled economic effect is therefore the incremental cost of substituting compliant low-sulfur fuel for HSFO during the portion of the voyage subject to the requirement.

Finding 3 - Fuel Switching Uses Established Marine Operating Practices

Fuel changeover between residual and distillate fuels is an established marine-engineering practice. The report's implementation analysis indicates that affected vessels generally possess the systems and operational capability needed to perform such transitions. Implementation would therefore rely primarily on fuel management, recordkeeping, and verification rather than new vessel technology.

Finding 4 - The Final Fleet-Weighted Impact Is Approximately 0.61% to 0.91% of Representative EBIT

Chapter 5 expands the vessel-level calculations to a normalized representative cargo fleet of 200 Virginia port calls. The 200-call distribution is not an estimate of total Virginia vessel traffic. It is a scalable analytical sample designed to preserve the assumed mix of major trade routes and vessel classes and to provide a consistent basis for weighting vessel-specific compliance impacts.

Using the final route and vessel weighting adopted in the report, the modeled fleet-level compliance burden is approximately 0.61 percent to 0.91 percent of representative operating earnings (EBIT). This is the controlling fleet-level profitability range for the study and supersedes broader preliminary ranges used during earlier stages of the analysis.

Finding 5 - Cruise Ships Have Higher Compliance Cost but Low Earnings Impacts

Cruise ships maintain substantial auxiliary and hotel loads while in port and therefore differ materially from cargo vessels. Chapter 6 evaluates a representative large cruise ship separately and estimates compliance costs of approximately $13,000 to $20,000 per Virginia port call, with an impact of approximately 0.59 percent to 0.88 percent of representative voyage operating earnings. Cruise ships are not included in the 200-call cargo-fleet weighting.

Finding 6 - Voyage-Level Compliance Costs Are Measurable but Generally Modest

For the principal cargo-vessel classes evaluated in Chapter 4, representative incremental compliance costs are generally approximately $2,000 to $10,000 per affected call. Expressed relative to representative voyage EBIT, the modeled impacts generally range from approximately 0.33 percent to 1.55 percent for the principal commercial vessel classes. Longer Chesapeake Bay operating profiles produce higher impacts, with the representative extended-transit case estimated at approximately 1.15 percent to 1.73 percent of voyage EBIT.

These results demonstrate that absolute compliance cost and percentage profitability impact are not the same measure. Larger vessels may incur greater dollar fuel costs, while vessel classes with lower representative earnings can experience a larger percentage impact.

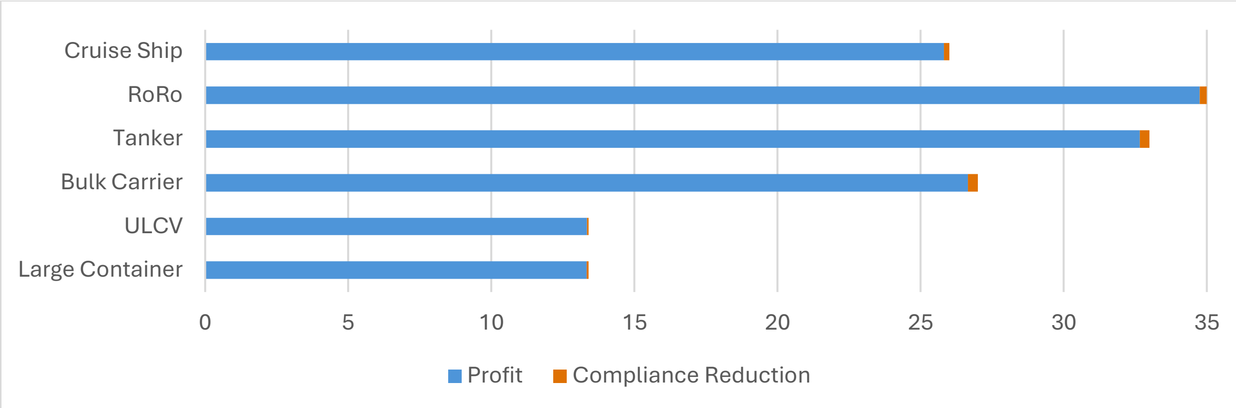

Figure 10-1Relative Profits vs. Compliance Cost Reduction by Vessel Class. The X-axis is the vessel profit margin (e.g. typical cruise ship profit margin is 26%).

Finding 7 - Environmental and Public-Health Considerations Extend Beyond Private Compliance Cost

The environmental review indicates that temporary operation on compliant distillate fuel would reduce sulfur dioxide emissions and sulfate particulate formation and would eliminate scrubber washwater discharge during the period in which an affected vessel operates on compliant fuel. These changes can provide localized air-quality, water-quality, ecological, and public-health benefits.

The report does not monetize those benefits. Their magnitude would require additional analysis comparing emissions and discharges from LSMGO operation with HSFO operation using a compliant scrubber under Virginia-specific exposure and environmental conditions. Accordingly, potential environmental and health benefits should be considered as policy-relevant benefits rather than as quantified offsets to the compliance-cost estimates in this study.

10.3 Overall Economic Assessment

The economic analysis indicates that the proposed Virginia fuel-switch requirement would impose a real but generally limited incremental operating cost on affected vessels. The principal reasons are that the requirement applies only during operations within Virginia waters, affects only vessels whose normal compliance strategy relies on HSFO or other residual fuels, and does not require the modeled fleet to undertake permanent capital modifications.

For the representative cargo fleet, the final modeled compliance burden of 0.61 percent to 0.91 percent of EBIT is small relative to representative operating earnings, although the effect is not uniform across vessel classes. Bulk carriers, tankers, and longer Chesapeake Bay transits can experience larger percentage effects than high-earning container services.

The analysis therefore supports evaluation of both the fleet-weighted result and vessel-class-specific impacts rather than relying on a single average alone.

The modeled cost should also be viewed in the context of the normal variability of shipping economics. Bunker prices, freight rates, charter markets, congestion, utilization, and global trade conditions can materially change vessel profitability. This context does not eliminate the compliance cost, but it helps establish its relative scale.

10.4 Policy Assessment

The central policy question is not whether the proposed fuel-switch requirement has a cost; the analysis demonstrates that it does. The relevant question is whether the magnitude and distribution of that cost are proportionate to the environmental and public-health objectives the policy is intended to advance.

Several considerations emerge from the analysis:

1. The affected fleet is narrower than total commercial vessel traffic because vessels already using compliant fuels generally would not incur an incremental fuel-switch cost.
2. The requirement is modeled as a temporary operating-fuel substitution rather than a permanent vessel-conversion requirement.
3. Fuel switching is technically feasible using established marine operating practices, although vessel-specific procedures and adequate changeover time remain important.
4. The final representative cargo-fleet profitability impact is approximately 0.61% to 0.91% of EBIT, with variation among vessel classes and routes.
5. Cruise ships are considered separately because their hotel loads and port operating profiles differ from cargo vessels. They are less than 1% of the commercial shipping.
6. Potential air-quality, water-quality, ecological, and health benefits are relevant to policy evaluation but are not monetized in this report.
7. Implementation should include clear geographic applicability, documentation requirements, enforcement procedures, and periodic review of operating experience.

Taken together, these findings provide a basis for evaluating proportionality without assuming that either the fuel compliance cost or the potential public benefit is negligible.

10.5 Key Uncertainties and Limitations

The analysis relies on representative assumptions because vessel-specific operating costs, voyage profitability, fuel contracts, and route-level financial information are generally proprietary. Important sources of uncertainty include

- the LSMGO-HSFO price differential
- actual vessel speed, engine loading, and fuel consumption

- the regulated transit distance attributed to each port call
- anchorage and berth duration
- the duration and fuel use associated with vessel-specific changeover procedures
- annual port-call frequency and the mix of vessel classes and trade routes
- freight rates, charter markets, utilization, and voyage profitability
- the availability and use of shore power for cruise ships and
- the final regulatory boundary, implementation schedule, exemptions, and enforcement approach.

The 200-call fleet is a normalized representative distribution, not a forecast of actual annual traffic. Similarly, representative EBIT and operating-margin assumptions are analytical benchmarks derived from public industry information and should not be interpreted as the actual earnings of a specific vessel or company. The results should therefore be used as ranges for policy analysis rather than point forecasts.

10.6 Final Assessment

Based on the engineering, operational, economic, environmental, and implementation analyses presented in this report, the proposed Virginia fuel-switch requirement is best characterized as a targeted operating requirement affecting a subset of commercial vessels during the limited portion of their voyages occurring within Virginia waters.

For the representative cargo fleet evaluated in the study, **the final modeled compliance burden is approximately 0.61 percent to 0.91 percent of representative earnings (EBIT)**. Voyage-level impacts vary by vessel class and operating profile, while the separately evaluated cruise-ship case is estimated at approximately 0.59 percent to 0.88 percent of representative voyage operating earnings. **These results indicate measurable costs, but costs that are generally modest relative to the representative earnings measures used in the study.**

The proposed requirement would also be expected to reduce sulfur-related and particulate air emissions and eliminate scrubber washwater discharge during the period in which affected vessels operate on compliant fuel. **Although this study does not fully monetize the environmental and health effects, the scientific literature establishes links between these pollutants and adverse public-health and marine-ecosystem effects.**

Ultimately, adoption of this requirement remains a policy decision that requires balancing these measurable private compliance costs against the potential public health benefits associated with reducing vessel emissions and the health of the Chesapeake Bay and other Virginia water by eliminating scrubber washwater discharge.

This report is intended to provide a transparent analytical framework to assist policymakers in making that determination.

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Appendix B: Engineering Assumptions and Methodology

B.1 Purpose

This appendix documents the engineering assumptions used throughout the economic analysis. Because commercial vessel operating characteristics vary considerably by vessel class, engine design, cargo loading, weather conditions, and voyage profile, the values presented herein are intended to represent **typical operating conditions** for vessels calling at Virginia ports. These assumptions provide a transparent and reproducible basis for estimating the incremental fuel consumption associated with a proposed Virginia requirement that ocean-going commercial vessels operate on **0.10 percent sulfur Low Sulfur Marine Gas Oil (LSMGO)** while within Virginia waters.

The methodology is based on standard marine engineering principles, published vessel performance data, manufacturer guidance, and publicly available industry references.

B.2 Operational Assumptions

The proposed requirement requires vessels operating on residual fuels outside Virginia waters to complete a fuel changeover before entering Virginia jurisdiction and to remain on LSMGO until departing state waters.

For analytical purposes, vessel operations are divided into four phases:

1. **Fuel Changeover** – Transition from residual fuel to LSMGO before entering Virginia waters.
2. **Inbound Transit** – Navigation from the Virginia Capes to the destination port.
3. **Anchorage and Port Operations** – Operation while awaiting berth or conducting cargo or passenger operations.
4. **Outbound Transit** – Navigation through Virginia waters before resuming the operator's preferred fuel outside state jurisdiction.

Only fuel consumed during these phases is included in the compliance cost calculations.

B.3 Representative Transit Distances

Representative transit distances in Virginia waters used in this report are summarized in the following table.

Route	Distance
Virginia Capes to Hampton Roads terminals	30–40 nautical miles
Virginia Capes to Newport News	35 nautical miles
Virginia waters enroute to Baltimore	Approximately 120 nautical miles
Total Chesapeake Bay transit to Baltimore	Approximately 170 nautical miles

Actual distances vary depending upon berth assignment, pilot boarding location, traffic management, weather, and navigation requirements.

B.4 Representative Operating Speeds

Commercial vessels typically reduce speed while operating within the Chesapeake Bay.

Vessel Class	Typical Speed
Container Ships	10–14 knots
Bulk Carriers	10–13 knots
Tankers	10–13 knots
Roll-on/Roll-off Vessels	10–14 knots
Cruise Ships	10–12 knots

These operating speeds are consistent with normal harbor transit and navigation practices.

B.5 Fuel Changeover Assumptions

Changing between residual fuels and marine distillates requires careful management of fuel temperature and viscosity to protect engines and fuel injection equipment.

For this analysis, the following assumptions are used:

Parameter	Assumed Value
Fuel changeover period	1 hour (3 for cruise ships)
Fuel used during changeover	LSMGO
Fuel switching method	Existing onboard changeover procedures

The analysis assumes that no vessel modifications are required because fuel changeover procedures are already standard practice for ships operating in Emission Control Areas (ECAs).

B.6 Representative Fuel Consumption

Main Propulsion Engines

Vessel Class	Fuel Consumption (MT/hour)	Value used in bound estimates
Ultra-Large Container Vessel	2.5–3.5	3
Large Container Vessel	2.0–3.0	2.5
Panamax Bulk Carrier	1.0–1.5	1.4
Capesize Bulk Carrier	1.4–1.8	
Aframax Tanker	1.2–1.6	1.5
Suezmax Tanker	1.4–1.8	
Roll-on/Roll-off Vessel	1.5–2.5	2
Large Cruise Ship	2.5–4.0	3.25

Auxiliary Engines

Representative auxiliary fuel consumption includes electrical generation for navigation systems, cargo equipment, crew accommodations, lighting, refrigeration, ventilation, communications, and other onboard services.

Vessel Class	Fuel Consumption (MT/hour)	Value used in bound estimates
Container Ships	0.5–0.8	.65
Bulk Carriers	0.2–0.4	.3
Tankers	0.2–0.4	.3
Roll-on/Roll-off Vessels	0.3–0.5	.4
Cruise Ships	1.5–3.0	2.25

B.7 Fuel Price Assumptions

Marine fuel prices fluctuate continuously with global petroleum markets. Rather than relying on a single price observation, this report evaluates a range of representative price differentials.

Scenario	HFSO*	LSMGO	Price Differential
Low	$500/MT	$750/MT	$250/MT
High	$575/MT	$950/MT	$375/MT

*Residual fuel represents the category of fuels that would not be permitted for use within Virginia waters under the proposed requirement.

B.8 Fuel Consumption Formula

The quantity of LSMGO required while operating within Virginia waters is calculated as:

Fuel Required = (Transit Time × Main Engine Fuel Consumption) + (Anchorage Time × Auxiliary Fuel Consumption) + (Fuel Changeover Time × Main Engine Fuel Consumption)

Where:

- **Transit Time** = Time spent navigating within Virginia waters.
- **Anchorage Time** = Time spent at anchor or alongside a berth while operating onboard systems.
- **Fuel Changeover Time** = One-hour transition period before entering Virginia waters.
- **Main Engine Fuel Consumption** = Representative propulsion fuel use (MT/hour).
- **Auxiliary Fuel Consumption** = Representative hotel and electrical load (MT/hour).

The incremental compliance cost is then calculated by multiplying the quantity of LSMGO consumed by the price differential between residual fuel and LSMGO.

B.9 Sources of Engineering Variability

Actual vessel fuel consumption varies according to several operational factors, including

- vessel size and hull design
- engine manufacturer and operating condition
- cargo loading and draft
- weather and sea state
- tidal currents
- vessel speed
- anchorage duration
- traffic congestion

- maneuvering requirements.

Consequently, the values presented in this report should be interpreted as representative engineering assumptions rather than precise operating characteristics for any individual vessel.

B.10 Engineering Basis for the Analysis

The assumptions presented in this appendix are consistent with published marine engineering guidance and industry practice. Fuel consumption estimates and fuel-switch procedures were informed by technical publications from engine manufacturers, classification societies, and international regulatory guidance, including

- International Maritime Organization (IMO), *MARPOL Annex VI*
- MAN Energy Solutions, marine engine operating manuals
- Wärtsilä, marine fuel and engine operation guidance
- DNV, *Alternative Fuels Insight* and technical publications
- U.S. Environmental Protection Agency (EPA), marine engine emissions guidance.

These references provide the engineering foundation for the representative operating assumptions used throughout this report.

Appendix C: Representative Vessel Characteristics and Operational Profiles

C.1 Purpose

The economic impact of the proposed Virginia marine fuel-switch requirement depends on the type of vessel, the amount of time it operates within Virginia waters, and the quantity of fuel consumed during transit and port operations. This appendix summarizes the representative vessel classes, operating profiles, and trade routes evaluated throughout this report.

The values presented are **engineering estimates** developed from publicly available vessel specifications, marine engineering references, and industry operating practices. They are intended to represent typical operating conditions and should not be interpreted as the operating characteristics of any specific vessel.

C.2 Vessel Classes Evaluated

The analysis focuses on the principal classes of ocean-going commercial vessels serving the Port of Virginia and transiting the Chesapeake Bay.

Ultra-Large Container Vessels (ULCV)

Typical Characteristics

Parameter	Representative Value
Capacity	14,000–24,000 TEU
Deadweight	150,000–220,000 DWT
Main Engine Fuel Consumption	2.5–3.5 MT/hour
Auxiliary Fuel Consumption	0.5–0.8 MT/hour

Typical Cargo

- Consumer goods
- Manufactured products
- Refrigerated cargo
- Retail merchandise

Representative Trade Routes

- East Asia
- Southeast Asia

- Panama Canal
- U.S. East Coast

Large Container Ships

Parameter	Representative Value
Capacity	8,000–14,000 TEU
Deadweight	90,000–150,000 DWT
Main Engine Fuel Consumption	2.0–3.0 MT/hour
Auxiliary Fuel Consumption	0.5–0.7 MT/hour

These vessels commonly serve transatlantic routes between Virginia and Europe as well as services to South America and the Caribbean.

Panamax Bulk Carriers

Parameter	Representative Value
Deadweight	65,000–80,000 DWT
Main Engine Fuel Consumption	1.0–1.5 MT/hour
Auxiliary Fuel Consumption	0.2–0.4 MT/hour

Typical Cargo

- Grain
- Coal
- Fertilizer
- Aggregates
- Agricultural products

Capesize Bulk Carriers

Parameter	Representative Value
Deadweight	150,000–200,000 DWT
Main Engine Fuel Consumption	1.4–1.8 MT/hour
Auxiliary Fuel Consumption	0.2–0.4 MT/hour

Typical Cargo

- Iron ore
- Metallurgical coal
- Steam coal

Petroleum Tankers

Aframax

Parameter	Representative Value
Deadweight	80,000–120,000 DWT
Main Engine Fuel Consumption	1.2–1.6 MT/hour
Auxiliary Fuel Consumption	0.2–0.4 MT/hour

Suezmax

Parameter	Representative Value
Deadweight	120,000–200,000 DWT
Main Engine Fuel Consumption	1.4–1.8 MT/hour
Auxiliary Fuel Consumption	0.2–0.4 MT/hour

Typical Cargo

- Crude oil
- Refined petroleum products
- Liquid chemicals

Roll-on/Roll-off (RoRo) Vessels

Parameter	Representative Value
Vehicle Capacity	5,000–8,000 vehicles
Main Engine Fuel Consumption	1.5–2.5 MT/hour
Auxiliary Fuel Consumption	0.3–0.5 MT/hour

Typical Cargo

- Passenger vehicles
- Heavy equipment
- Agricultural machinery

- Military vehicles

Cruise Ships

Cruise ships were evaluated separately because of their substantially higher auxiliary ("hotel") electrical demand.

Parameter	Representative Value
Gross Tonnage	110,000–180,000 GT
Passenger Capacity	2,800–5,000
Main Engine Fuel Consumption	2.5–4.0 MT/hour
Auxiliary Fuel Consumption	1.5–3.0 MT/hour

Main Engine Fuel Consumption Summary

Representative values:

Vessel Class	Fuel Consumption (MT/hour)	Value used in bound estimates
Ultra-Large Container Vessel	2.5–3.5	3
Large Container Vessel	2.0–3.0	2.5
Panamax Bulk Carrier	1.0–1.5	1.4
Capesize Bulk Carrier	1.4–1.8	
Aframax Tanker	1.2–1.6	1.5
Suezmax Tanker	1.4–1.8	
Roll-on/Roll-off Vessel	1.5–2.5	2
Large Cruise Ship	2.5–4.0	3.25

Auxiliary Engine Consumption Summary

Representative values:

Representative auxiliary fuel consumption includes electrical generation for navigation systems, cargo equipment, crew accommodations, lighting, refrigeration, ventilation, communications, and other onboard services.

Vessel Class	Fuel Consumption (MT/hour)	Value used in bound estimates
Container Ships	0.5–0.8	.65
Bulk Carriers	0.2–0.4	.3

Tankers	0.2–0.4	.3
Roll-on/Roll-off Vessels	0.3–0.5	.4
Cruise Ships	1.5–3.0	2.25

C.3 Representative Virginia Operating Profiles

Representative operating conditions used throughout the report are summarized below.

Activity	Typical Duration
Fuel Changeover	1 hour
Hampton Roads Transit	3–4 hours
Chesapeake Transit to Baltimore	10–12 hours
Anchorage (Typical)	12–24 hours
Extended Anchorage Scenario	48 hours

These values represent typical operating conditions used in the economic analysis.

C.4 Representative Trade Routes

Five representative trade lanes were selected because they account for a substantial share of international commercial traffic serving Virginia ports.

Trade Route	Typical Vessel Types
East Asia & Pacific	Ultra-Large Container Vessels
Northern Europe & Mediterranean	Container Ships, RoRo Vessels
Middle East & South Asia	Tankers, Bulk Carriers
Central & South America	Tankers, Bulk Carriers, Feeder Container Ships
Chesapeake Bay to Baltimore	Mixed Commercial Fleet

These representative trade routes provide the basis for evaluating voyage-specific compliance costs.

C.5 Representative Fleet Composition

For purposes of estimating annual fleet-level impacts, the report assumes the following illustrative distribution of annual port calls.

Trade Lane	Annual Calls	Fleet Weight
East Asia & Pacific	80	40%
Northern Europe & Mediterranean	40	20%
Middle East & South Asia	30	15%
Central & South America	30	15%
Chesapeake Bay Transit to Baltimore	20	10%
Total	**200**	**100%**

These values are analytical assumptions intended to model a representative international carrier serving Virginia ports and are not derived from the operations of any individual shipping company.

C.6 Typical Fuel Consumption by Operating Phase

Representative fuel consumption varies according to the operational phase of a voyage.

Operating Phase	Main Engines	Auxiliary Engines
Fuel Changeover	Operating	Operating
Transit	Operating	Operating
Anchorage	Minimal	Operating
Berthing	Shut Down or Idle	Operating

This operating profile explains why extended anchorage has a measurable effect on compliance costs, particularly for vessels with high auxiliary electrical demand.

C.7 Operational Factors Affecting Fuel Consumption

Several factors influence actual fuel consumption during operations in Virginia waters, including

- vessel size and displacement
- cargo loading and draft
- transit speed
- tidal currents
- weather and sea state
- traffic congestion

- anchorage duration
- maneuvering requirements
- hotel load (particularly for cruise ships).

Accordingly, the values presented throughout this report should be interpreted as representative engineering estimates rather than exact operating characteristics.

C.8 Key Findings

Several observations emerge from the representative vessel characteristics used in this analysis:

- Container vessels generally have the highest propulsion fuel consumption but also the highest representative operating earnings.
- Bulk carriers and tankers consume less fuel during transit but may experience a greater percentage impact on voyage profitability because of lower operating margins.
- Cruise ships have the highest auxiliary fuel consumption because of continuous hotel operations but generally experience the smallest percentage impact on profitability due to significantly higher voyage revenues.
- Extended anchorage increases compliance costs for all vessel classes because auxiliary engines continue operating throughout the waiting period.

These representative operational profiles form the engineering basis for the economic analyses presented in Chapters 5 and 6.

Appendix D: Shipping Industry Taxation and Financial Context

D.1 Purpose

This appendix provides background information on the taxation and financial structure of the international shipping industry. While taxation is **not** incorporated into the economic impact calculations presented in this report, understanding the industry's financial and tax framework provides useful context when evaluating the proportionality of the estimated compliance costs associated with Virginia's proposed marine fuel-switch requirement.

The purpose of this appendix is not to critique existing tax policy, but to explain why the effective tax treatment of international shipping often differs from that of domestic industries and how that context relates to the industry's ability to absorb incremental regulatory costs.

D.2 International Shipping Taxation

International shipping has historically been subject to specialized tax regimes intended to promote global commerce and prevent double taxation. Because vessels routinely operate across multiple national jurisdictions, many countries have adopted alternative methods of taxing international shipping income.

As a result, the effective tax burden on international shipping companies may differ substantially from that imposed on corporations whose activities occur entirely within one country.

Depending on vessel ownership, country of incorporation, and vessel registry, international shipping companies may be subject to

- Conventional corporate income taxation
- Alternative tonnage tax systems
- Reciprocal international tax exemptions or
- Bilateral tax treaties.

Accordingly, there is no single tax rate applicable to all shipping companies.

D.3 United States Corporate Income Tax

For comparison, most domestic corporations operating in the United States are subject to the federal corporate income tax on taxable net income.

Current federal law establishes a 21 percent corporate income tax rate, exclusive of any applicable state corporate taxes.

Taxable income is generally calculated using actual revenues less allowable business expenses, depreciation, and other statutory deductions.

This standard corporate tax framework differs from the specialized taxation available to qualifying international shipping operations.

D.4 U.S. Tonnage Tax Regime

The United States permits certain qualifying shipping companies operating U.S.-flag vessels in international trade to elect taxation under Internal Revenue Code Subchapter R (26 U.S.C. §§ 1351–1359).

Rather than taxing actual operating profits, the tonnage tax calculates taxable income using a statutory formula based primarily on

- vessel net tonnage and
- days in qualifying service.

Because taxable income is determined using notional earnings rather than actual profits, the resulting effective tax rate may be substantially lower than the standard corporate income tax during periods of elevated freight rates and high profitability.

Congress adopted this framework to encourage U.S.-flag vessel registration and enhance the competitiveness of the U.S. merchant marine.

D.5 Foreign Shipping Income Exemption

A significant proportion of commercial vessels calling at Virginia ports are registered under foreign flags.

Under Internal Revenue Code § 883, qualifying foreign corporations engaged in international shipping may be exempt from U.S. federal income tax on income derived from the international operation of ships, provided certain ownership and reciprocity requirements are satisfied.

Instead of paying U.S. federal income tax on qualifying international shipping income, these operators typically incur costs such as

- port charges
- pilotage fees
- tug services

- terminal handling charges
- harbor maintenance fees
- customs and inspection fees.

The availability of the Section 883 exemption depends on statutory eligibility requirements and applicable international tax treaties.

D.6 Shipping Industry Profitability

The international shipping industry experienced unprecedented financial performance during the period following the COVID-19 pandemic.

Supply-chain disruptions, equipment shortages, elevated freight demand, and port congestion resulted in historically high freight rates between 2021 and 2022. During this period, major container shipping companies collectively reported hundreds of billions of dollars in net income.

Although freight markets have subsequently normalized, the industry generally remains in a stronger financial position than prior to the pandemic.

Profitability continues to vary significantly among

- container shipping
- dry bulk shipping
- tanker operations
- cruise operators and
- regional feeder services.

Consequently, the report evaluates compliance costs across multiple vessel classes rather than relying on a single profitability assumption.

D.7 Important Qualifications

Several important considerations should accompany this discussion.

- Effective tax rates differ among companies based on corporate structure and jurisdiction.
- Not all shipping companies qualify for the U.S. tonnage tax or Section 883 exemption.
- Freight markets are cyclical, and profitability varies significantly over time.
- The compliance costs estimated in this report are independent of tax treatment and were calculated without assuming any specific tax benefit.

Accordingly, this appendix is intended to provide financial context rather than estimate the tax liability of any individual operator.

D.8 Policy Context

Environmental regulations are frequently evaluated by comparing private compliance costs with broader public benefits.

The analysis presented in this report indicates that the incremental costs associated with requiring compliant fuel within Virginia waters represent a relatively small percentage of representative operating earnings for affected vessels.

When considered alongside the specialized tax treatment available to portions of the international shipping industry and the industry's demonstrated ability to adapt to previous fuel-quality regulations—including the IMO 2020 global sulfur cap and existing Emission Control Area (ECA) requirements—the estimated compliance costs appear proportionate to the scale of modern international shipping operations.

This observation does not imply that taxation justifies additional regulation. Rather, it provides financial context for evaluating whether the estimated compliance costs are likely to affect the long-term competitiveness of Virginia ports.

Appendix E: Representative Fleet Composition Methodology

E.1 Purpose

This appendix documents the methodology used to construct the representative fleet used in the fleet-level economic assessment. Because voyage-specific operating data, fuel procurement contracts, and financial information are proprietary, the report adopts a representative engineering-economic approach rather than attempting to model every individual vessel. The representative fleet provides a transparent, reproducible basis for estimating annual compliance costs and evaluating sensitivity to engineering and market assumptions.

E.2 Why a Representative Fleet

The report estimates compliance costs using representative operating conditions rather than actual vessel movements. This approach is consistent with the analytical framework described in Chapters 4–6, which relies on representative vessel characteristics, engineering assumptions, and publicly available market information. Using representative vessels allows consistent comparison across vessel classes while avoiding the need for confidential commercial data.

E.3 Why 200 Annual Calls

The representative fleet consists of 200 annual vessel calls. This number was selected as a normalized analytical sample rather than an estimate of actual annual Port of Virginia traffic. A 200-call fleet is sufficiently large to include the principal commercial vessel classes and major trade lanes while remaining easy to scale. Results may therefore be multiplied proportionally if future analyses use different annual call volumes or actual port statistics. The objective is internal consistency and comparability rather than forecasting traffic.

E.4 Representativeness

The fleet represents the dominant commercial cargo trades serving Virginia, including containerized freight, petroleum, dry bulk, and roll-on/roll-off cargoes. Vessel shares are assigned to representative international trade lanes that reflect the diversity of Virginia's maritime commerce. Each vessel class is assigned representative engineering characteristics, transit distances, speeds, anchorage times, fuel consumption rates, and voyage operating earnings.

E.5 Representative Trade-Lane Allocation

Trade Lane	Calls	Fleet Share	Representative Mix
East Asia / Pacific	80	40.0%	75% Ultra-Large Container, 25% Large Container
Northern Europe / Mediterranean	40	20.0%	70% Large Container, 30% RoRo
Middle East / South Asia	30	15.0%	53% Tanker, 47% Bulk
Central & South America	30	15.0%	33% Large Container, 33% Tanker, 33% Bulk
Chesapeake Bay / Baltimore	20	10.0%	25% Large Container, 25% Tanker, 25% Bulk, 25% RoRo
Total	200	100%	Representative analytical fleet

E.6 Representative Vessel Allocation

Vessel Class	Calls	Share	Representative EBIT
Ultra-Large Container	60	30.0%	$2.10 million
Large Container	63	31.5%	$1.00 million
Tanker	31	15.5%	$345,000
Bulk Carrier	29	14.5%	$220,000
RoRo	17	8.5%	$550,000
Total	200	100%	-

E.7 Discussion

The representative fleet maintains the trade-lane distribution used throughout the report while avoiding unsupported precision in assigning individual vessel types. Vessel class determines the engineering assumptions (fuel consumption, operating profile, and representative voyage operating earnings), whereas trade lane determines the representative annual call frequency and Virginia operating profile. This separation improves transparency and facilitates sensitivity analyses without changing the underlying engineering methodology.

E.8 Limitations

The representative fleet is an analytical construct designed to support comparative policy evaluation. It is not intended to reproduce actual Port of Virginia vessel-call statistics. Future analyses may substitute observed records or Port of Virginia traffic data for the representative fleet while retaining the same engineering equations and economic framework.

Appendix F: Representative Voyage EBIT, Operating Margins, and Compliance-Cost Effects

F.1 Purpose

This appendix documents and justifies the representative voyage EBIT values and operating margins used to place the modeled fuel-switching compliance costs in the context of normal vessel profitability. The main economic analysis measures compliance cost as a percentage of representative voyage EBIT. This appendix explains the basis for both the EBIT benchmarks and the sector operating-margin assumptions, includes the separately evaluated cruise-ship case, and translates the EBIT effect into a reduction in operating margin expressed in percentage points of voyage revenue.

F.2 Why Operating Margin Is an Appropriate Comparison

Operating margin is defined as EBIT divided by revenue. It measures the share of revenue that remains as operating profit after operating expenses and depreciation but before interest and income taxes. Because the report already uses EBIT as its measure of representative voyage operating earnings, EBIT operating margin is the accounting-consistent metric for comparing compliance costs with sector profitability. EBITDA margin is not used because it excludes depreciation and therefore is not directly comparable to the EBIT denominator used elsewhere in the report.

F.3 Analytical Framework

The analysis begins with the representative voyage EBIT and the low- and high-case compliance impacts already developed for each vessel class. The midpoint impact is defined as the arithmetic average of the low and high compliance-cost impacts. The effect on operating margin is then calculated by multiplying the representative operating margin by the midpoint compliance impact on EBIT. This converts the compliance burden from a percentage of EBIT into percentage points of revenue, allowing the compliance cost and operating margin to be compared on the same scale.

Operating Margin = EBIT / Revenue

Midpoint Impact on EBIT = (Low Impact + High Impact) / 2

Operating Margin Reduction (percentage points) = Representative Operating Margin × Midpoint Impact on EBIT

Post-Compliance Operating Margin = Representative Operating Margin − Operating Margin Reduction

F.4 Basis for Representative Operating Margins

The operating margins are analytical benchmarks derived from recent public financial disclosures of listed companies operating in comparable shipping and cruise segments.

They are not intended to represent a fixed long-run margin or the profitability of any specific voyage. Shipping and cruise markets are cyclical, so the adopted values should be interpreted as representative reference points for comparing the incremental compliance cost with normal operating profitability.

Container vessels - 13.4 percent

A 13.4 percent EBIT margin is used for both the Large Container Vessel and ULCV classes. Hapag-Lloyd reported 2024 Liner Shipping revenue of approximately USD 20.3 billion and segment EBIT of approximately USD 2.7 billion, implying an EBIT margin of about 13.4 percent. Applying one sector margin to both vessel sizes avoids implying that vessel size alone determines corporate operating margin; the different economics of the two model vessels are already reflected in their different representative voyage EBIT values. Hapag-Lloyd's 2025 results were materially weaker, which underscores the cyclicality of liner shipping and supports treating 13.4 percent as a representative benchmark rather than a permanent margin.

Bulk carriers - 27.0 percent

A 27.0 percent EBIT margin is used for the Bulk Carrier class. Star Bulk Carriers' 2024 public financial results provide a directly relevant dry-bulk benchmark. The selected margin is based on reported/pro forma operating income relative to voyage revenue and is consistent with the strong but cyclical dry-bulk market conditions represented by the report's earnings assumptions.

Tankers - 33.0 percent

A 33.0 percent EBIT margin is used for the Tanker class. Teekay Tankers' 2024 tanker-segment results provide a directly comparable public benchmark because the company reports tanker-specific operating results. The adopted value reflects segment operating income relative to segment revenue and is therefore more directly comparable to the representative tanker EBIT used in this report than a broader diversified-shipping margin would be.

RoRo / PCTC - 35.0 percent

A normalized 35.0 percent EBIT margin is used for the RoRo/PCTC class. Public results from Höegh Autoliners and Wallenius Wilhelmsen show unusually strong PCTC profitability in recent years. Rather than adopting the highest reported single-year margin, the analysis uses 35 percent as a normalized benchmark informed by both operators and by underlying operating performance after considering non-recurring items. This reduces dependence on one company or one peak market year.

Cruise ships - 26.0 percent

A normalized 26.0 percent EBIT margin is used for the representative large cruise ship. Royal Caribbean Group reported 2024 total revenue of approximately $16.5 billion; its reported EBITDA less depreciation and amortization implies an EBIT margin of roughly 27 percent. Carnival Corporation reported 2024 revenue of approximately $25.0 billion and operating income of approximately $3.6 billion, illustrating the meaningful variation among major cruise operators. A 26 percent benchmark is therefore used as a representative, relatively strong but not peak operating-margin assumption for a large contemporary cruise ship rather than as a forecast for any particular cruise line.

F.5 Basis for the representative voyage EBIT values

The representative EBIT values are normalized voyage-level operating-earnings benchmarks, not reported earnings for individual ships. Public companies generally disclose financial performance at the company or business-segment level rather than by vessel and voyage. The study therefore calibrates voyage EBIT to the relative revenue-generating capacity, market earnings, and operating economics of each vessel class, while using public segment margins as an independent reasonableness check. This approach is consistent with Chapter 4, which identifies vessel capacity, utilization, freight or passenger revenue, TCE or market earnings, voyage duration, and operating expenses as the principal drivers of voyage earnings.

Container vessels. The $1.0 million Large Container and $2.1 million ULCV EBIT assumptions preserve the expected earnings scale between a conventional large container vessel and a substantially higher-capacity ULCV. At the 13.4 percent container-sector margin, these EBIT values imply representative voyage revenues of approximately $7.5 million and $15.7 million, respectively. The resulting relationship is consistent with the report's use of vessel capacity and freight revenue as primary earnings drivers and avoids treating the two container classes as financially identical.

Bulk carriers. The $220,000 representative voyage EBIT is intentionally lower than the other cargo-vessel benchmarks, reflecting the lower revenue intensity and highly cyclical commodity-charter economics of dry-bulk shipping. At the 27.0 percent benchmark margin, the assumption implies approximately $0.81 million of representative voyage revenue. The value is used as a normalized policy-analysis benchmark rather than a claim about the earnings of a specific Panamax or Capesize voyage.

Tankers. The $345,000 representative voyage EBIT is positioned above the bulk-carrier benchmark but below the container and RoRo benchmarks, reflecting the tanker market's higher earnings potential while retaining substantial charter-rate cyclicality. At the 33.0 percent benchmark margin, it implies approximately $1.05 million of representative voyage revenue. Teekay Tankers' public tanker-segment results provide the principal sector profitability check.

RoRo / PCTC. The $550,000 representative voyage EBIT reflects the relatively strong revenue and profitability profile of vehicle carriers in the market period used for this study. At the normalized 35.0 percent margin, it implies approximately $1.57 million of representative voyage revenue. Public results from Höegh Autoliners and Wallenius

Wilhelmsen support treating PCTC profitability as stronger than the dry-bulk benchmark while also demonstrating why a normalized value is preferable to a peak-year result.

Cruise ships. The $2.25 million representative voyage EBIT used in Chapter 6 reflects the much larger revenue base of a large cruise ship, including passenger fares and onboard spending. At the 26.0 percent benchmark margin, it implies approximately $8.65 million of representative voyage revenue. This is consistent with the report's representative 3,000-passenger vessel and the multiple revenue streams identified in Chapter 6. The value is intended to represent a large-vessel voyage economics case, not the accounting profit of an individual sailing.

Taken together, the EBIT benchmarks are best understood as internally consistent scale assumptions anchored to public sector financial performance and the relative economics of the modeled vessel classes. Their purpose is to provide a common denominator for evaluating whether a several-thousand-dollar fuel-switching cost is economically material. They should not be interpreted as forecasts of a particular operator's voyage profit.

Vessel Class	Representative Voyage EBIT	Representative EBIT Margin	Public Benchmark
Large Container	$1,000,000	13.4%	Hapag-Lloyd 2024 Liner Shipping
ULCV	$2,100,000	13.4%	Hapag-Lloyd 2024 Liner Shipping
Bulk Carrier	$220,000	27.0%	Star Bulk 2024 dry bulk
Tanker	$345,000	33.0%	Teekay Tankers 2024 tanker segment
RoRo	$550,000	35.0%	Höegh / Wallenius Wilhelmsen PCTC
Cruise Ship	$2,250,000	26.0%	Royal Caribbean / Carnival 2024 cruise results

F.6 Midpoint Compliance-Cost Analysis

The following table applies the midpoint of the modeled low and high compliance-cost cases. The midpoint is used only as a central comparison case; the low and high bounds remain the appropriate sensitivity range elsewhere in the report.

Vessel	Low Impact (% EBIT)	High Impact (% EBIT)	Midpoint Impact (% EBIT)	Baseline Margin	Margin Reduction	Post-Compliance Margin
Large Container	0.44%	0.66%	0.550%	13.4%	0.074 pp	13.33%
ULCV	0.33%	0.49%	0.410%	13.4%	0.055 pp	13.35%
Bulk Carrier	1.03%	1.55%	1.290%	27.0%	0.348 pp	26.65%

Tanker	0.82%	1.23%	1.025%	33.0%	0.338 pp	32.66%
RoRo	0.57%	0.86%	0.715%	35.0%	0.250 pp	34.75%
Cruise Ship	0.59%	0.88%	0.735%	26.0%	0.191 pp	25.81%

Including the cruise-ship case, the midpoint analysis indicates that the modeled compliance cost reduces representative operating margins by approximately 0.055 to 0.348 percentage points. The largest reductions occur for bulk carriers and tankers, while the effects on the two container-vessel classes and the cruise-ship case are comparatively small. The cruise midpoint impact is 0.735 percent of representative voyage EBIT, equivalent to approximately 0.191 percentage point of the 26.0 percent benchmark operating margin. These values assume that the vessel operator absorbs the full incremental fuel cost and does not recover any portion through freight rates, fuel surcharges, charter terms, ticket pricing, or other commercial mechanisms.

F.7 Graphical Comparison

Figure F-1 compares each cargo-vessel class and the representative cruise ship's operating margin with the portion of that margin consumed by the midpoint compliance cost. Both measures are expressed on the same revenue-based scale: the operating margin is percent of revenue, while the compliance effect is the reduction in that margin in percentage points.

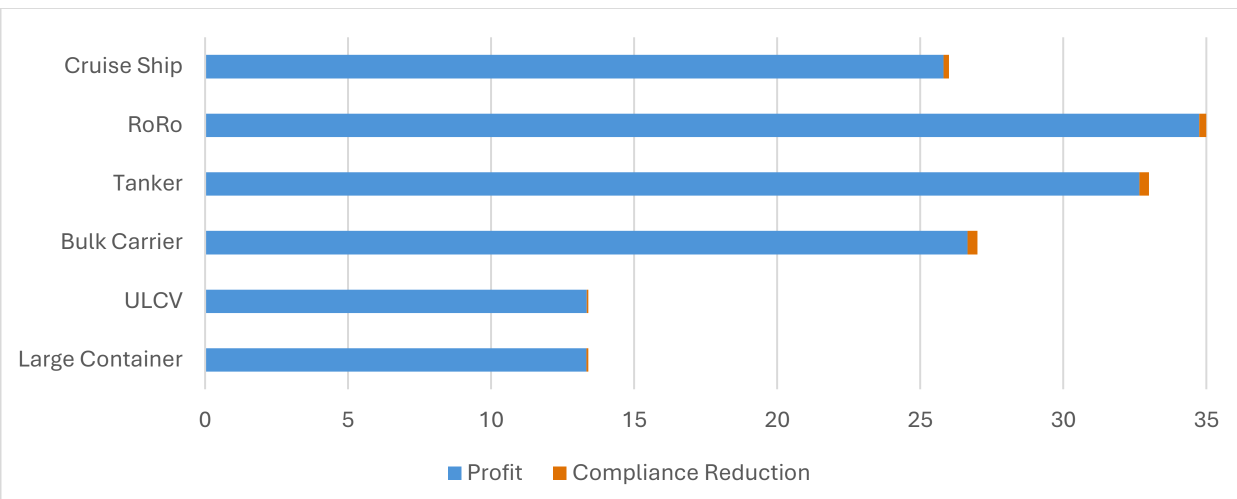

Figure F-1. Midpoint Compliance Cost Relative to Representative Operating Margin

F.8 Interpretation for the Economic Assessment

The operating-margin comparison provides context that is not apparent from compliance-cost dollars alone. Larger vessels generally incur larger absolute fuel-switching costs, but those costs remain small relative to representative voyage operating earnings. At the midpoint case, the modeled compliance cost consumes approximately 0.41 to 1.29 percent of representative voyage EBIT across the cargo classes and approximately 0.735

percent for the representative cruise ship. When translated into operating-margin terms, the reduction is approximately 0.055 to 0.348 percentage points across the full set of modeled vessel classes. Thus, even under the conservative assumption of no cost pass-through, the modeled effect is small relative to the representative sector operating margins used in the study.

The EBIT-impact percentage and operating-margin reduction should be presented together. The EBIT-impact measure shows the share of operating profit consumed by compliance cost, while the operating-margin measure shows how much the vessel sector's profitability ratio would change if the cost were fully absorbed. Together, the two measures provide a more complete indication of economic significance than either compliance-cost dollars or operating margin alone.

F.9 Limitations

The representative voyage EBIT values and operating margins are derived from company-level or segment-level public financial data, market information, and normalized voyage assumptions rather than vessel-specific voyage accounts. Actual profitability varies by freight or passenger market, charter structure, vessel age, utilization, cargo, route, itinerary, season, onboard revenue, and accounting policy. The selected values therefore should be used as analytical benchmarks rather than forecasts. Because shipping and cruise profitability are cyclical, future revisions of the report may update the EBIT or margin assumptions without changing the compliance-cost engineering model. Public benchmarks used for this appendix include Hapag-Lloyd 2024 Liner Shipping results, Star Bulk Carriers 2024 results, Teekay Tankers 2024 tanker results, Höegh Autoliners and Wallenius Wilhelmsen 2024 results, and 2024 results reported by Royal Caribbean Group and Carnival Corporation.