ENVIRONMENTAL IMPACTS OF OCEAN SHIPPING IN A FREIGHT CONTEXT
A Summary of Current Assessments, Future Trends, and Approaches to Mitigation

James J. Corbett
University of Delaware

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Table of Contents

TABLE OF CONTENTS ............................................................................................................................................1
LIST OF TABLES.......................................................................................................................................................1
LIST OF FIGURES......................................................................................................................................................1
EXECUTIVE SUMMARY .........................................................................................................................................2
1. GOODS MOVEMENT ...........................................................................................................................................3
   1.1 INTERNATIONAL FREIGHT CONTEXT.....................................................................................................................3
   1.2 CATEGORIZING ENVIRONMENTAL IMPACTS OF OCEAN SHIPPING..............................................................4
   1.3 FREIGHT EMISSIONS AND ENERGY OVERVIEW ............................................................................................4
2. WORLD FLEET ENERGY USE AND EMISSIONS ESTIMATES .........................................................................5
   2.1 FLEET PROFILE.....................................................................................................................................................5
   2.2 DESIGNATING AND ESTIMATING INTERNATIONAL MARINE FUEL USAGE ..............................................................7
   2.3 CURRENT ACTIVITY-BASED EMISSIONS ESTIMATES............................................................................................11
3. GEOGRAPHIC ALLOCATION OF SHIP ACTIVITY, ENERGY, EMISSIONS...................................................13
   3.1 COMPARING TOP-DOWN AND BOTTOM-UP APPROACHES ....................................................................................13
   3.2 IMPROVING LARGE-SCALE SPATIAL MODELS......................................................................................................15
4. ENVIRONMENTAL TRENDS...........................................................................................................................16
   4.1 FREIGHT ENERGY AND EMISSIONS TRENDS.........................................................................................................16
   4.2 FORECASTING PRINCIPLES..................................................................................................................................18
5. OPTIONS FOR IMPROVING SUSTAINABILITY OF FREIGHT ........................................................................19
   5.1 ENVIRONMENTAL CONTROL TECHNOLOGY ........................................................................................................19
   5.2 ALTERNATIVE MARINE FUELS............................................................................................................................20
   5.3 OPERATIONAL CHANGES....................................................................................................................................21
REFERENCES ..........................................................................................................................................................22

List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OVERVIEW OF TYPES OF OCEAN SHIPPING POLLUTION</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>PROFILE OF WORLD COMMERCIAL FLEET, NUMBER OF MAIN ENGINES, AND MAIN ENGINE POWER</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>INTERNATIONAL MARINE FUEL SALES BY NATION 1990-1999</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>CRITERIA FOR DEFINING INTERNATIONAL OR DOMESTIC NAVIGATION</td>
<td>10</td>
</tr>
</tbody>
</table>

List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ILLUSTRATION OF OCEAN SHIPPING AS (A) A SUBSTITUTE AND (B) AS A COMPLEMENT FOR OTHER FREIGHT MODES.</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>DIFFERENCES BETWEEN ACTIVITY-BASED ESTIMATES OF ENERGY USE AND INTERNATIONAL MARINE SALES STATISTICS, SHOWING THE EFFECT OF INPUT PARAMETERS ON ACTIVITY-BASED ESTIMATES.</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>ESTIMATED WORLD FLEET FUEL CONSUMPTION (CIVILIAN, MILITARY, AND AUXILIARY) AND INTERNATIONAL MARINE BUNKER FUEL STATISTICS IN MILLION TON OF OIL EQUIVALENTS (Mt).</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>SUMMARY OF SHIP EMISSIONS POINT ESTIMATES.</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>ILLUSTRATION OF OCEANOING SHIP TRAFFIC, BASED ON ICOADS PROXY.</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>ILLUSTRATION OF STEEM RESULTS FOR NORTH AMERICA.</td>
<td>16</td>
</tr>
</tbody>
</table>
ENVIRONMENTAL IMPACTS OF OCEAN SHIPPING IN A FREIGHT CONTEXT
A Summary of Current Assessments, Future Trends, and Approaches to Mitigation

James J. Corbett

Executive summary

The marine transportation system has been defined as the network of specialized vessels, the ports they visit, and transportation infrastructure from factories to terminals to distribution centers to markets [MARAD, 1999]. Within such a definition, it is nearly impossible to consider ocean shipping separate from the goods movement context. On a worldwide basis, nearly 50,000 oceangoing vessels move cargo more than 33 billion ton-km annually. In the European Union, marine transportation moves more than 70% (by volume) of all cargo traded with the rest of the world; in the United States, more than 95% of imports and exports are carried by ships. This work is accomplished by ships using 2 to 4% of the world’s fossil fuels [Corbett, 2004a].

These inbound and outbound freight flows through national ports are connected to truck and train movement of goods through a transportation network. In fact, ocean shipping can be considered to be a “trip-generator” for intermodal cargoes in global trade, blending with domestic freight movements on nations’ roads and rails. This intermodal context is important when considering impacts of ocean shipping, particularly where modal tradeoffs in energy intensity and emissions are asymmetric.

The Organisation for Economic Cooperation and Development (OECD) continues to consider environmental impacts of freight transport, including waterborne transportation. Within the OECD framework, the International Energy Agency (IEA) provides statistics related to marine energy demand. The United Nations, through the International Maritime Organization (IMO), has direct responsibility for measures to improve the safety and security of international shipping and to prevent marine pollution from ships.

This report summarizes ocean shipping’s role in the causes of and solutions to environmental impacts of goods movement. Some of the work discussed in this document reflects a focus by the author on freight issues within a North American context; this may be considered to complement similar efforts in Europe, where studies on goods movement have been ongoing and are producing similar insights. While these impacts affect land, water, and air – and the health of humans and ecosystems – this report devotes most discussion to energy and air emissions.

The report is organized to discuss the role of ocean shipping within the context of goods transportation in Section 1. Sections 2 and 3 provide an overview of the magnitude and distribution of ship activity, specifically with regard to energy and emissions. These sections discuss the various data and approaches to evaluating impacts with an emphasis on modeling advances and common insights. Section 4 considers environmental trends for oceangoing freight, mostly dominated by growth in global trade. Section 5 outlines three primary approaches to mitigating oceangoing impacts. These fundamentally apply to all freight transport, and the report concludes by returning to the multimodal freight context, where oceangoing ships can provide some advantages (particularly energy and CO₂) and/or where water transportation may be improved to support efforts to make freight transport more sustainable.
1. Goods movement

1.1 International freight context

International maritime shipping is a critical element in the global freight transportation system that includes ocean and coastal routes, inland waterways, railways and roads. In some cases, the freight transportation network connects locations by multiple modal routes, functioning as modal substitutes (see Figure 1a). A primary example is containerized cargoes, also called intermodal or unitized cargoes, where the shipper or logistics provider has some degree of choice how to move freight between locations. However, international maritime transportation is more commonly a complement to other modes of transportation (see Figure 1b). This is particularly true for liquid and dry bulk cargoes, such as oil and grain. Here, international shipping connects roads, railways, and inland waterways through ocean and coastal routes.

![Figure 1. Illustration of ocean shipping as (A) a substitute and (B) as a complement for other freight modes. First published in the IMO Study of Greenhouse Gases from Ships [Skjølsvik et al., 2000].](image)

Mode choice (especially for containerized cargo movement) involves balancing tradeoffs to facilitate trade among global corporations and nations. In the current global economy, competing factors have been time, cost, and reliability of delivery. Low cost modes may be less preferred than faster modes if the cargo is very time sensitive; however, slower, lower cost modes often carry much more cargo and, with proper planning, these modes can reliably deliver larger quantities to meet just-in-time inventory needs. Analogous to a relay race, all modes are needed to deliver containerized cargo from the starting line to the finish line.

One of the reasons that marine transportation moves so many ton-kilometers of cargo is cost efficiency. Marine transportation of bulk shipments average between $0.025-$0.035 (2.5 and 3.5 cents) per ton-km, according to U.S. national transportation statistics. These costs are generally less than but similar to rail, and typically much less than trucking. Except for high-value containerized goods that are shipped intermodally, the cost per ton-kilometer for trucking can be more than an order of magnitude greater than the cost of marine transportation. The significant

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1 Air freight is important as well, but not addressed in this report. Air freight moves much less global freight (by volume), and at significant energy per unit shipped. Some air freight is also co-loaded onto scheduled passenger liner service, whereas nearly all ocean, truck, and rail freight moves on dedicated freight vehicles.
growth in containerized shipping suggests that these cost-comparisons be updated for intermodal (containerized) cargoes.

1.2 Categorizing environmental impacts of ocean shipping

Environmental impacts from ocean shipping are several, and they can be summarized in different contexts. For this overview, environmental impacts of ocean shipping will be categorized as either episodic or routine. These designations help to explain why some aspects of ocean shipping, such as stack emissions, are so challenging to address. Example environmental impacts under this taxonomy are listed in Table 1. Some pollution related to ocean shipping is not directly from the ships, but from efforts to serve the ocean shipping sector through port infrastructure maintenance and fleet modernization.

Episodic pollution discharges are among those best understood by the commercial industry and policy makers, as evidenced by the international conventions and national regulations addressing them. The dominant mitigation approach is to prohibit pollution episodes from occurring (as in ocean dumping), to design systems that are safer (as in double-hulls to prevent oil spills or traffic separation schemes to avoid collisions), to confine activities that produce untreated discharges to safer times or locations (e.g., environmental windows for dredging), to require onboard treatment before discharge (e.g., oily water separators), and/or to provide segregated holding and transfer to reception facilities at port (as in sewage handling).

Routine pollution releases are different than episodic discharges because they represent activities necessary for the safe operation of the vessel, whether at sea or in port. Regulation of routine releases has lagged policy action to address episodic discharges, partly because these impacts were not as well understood in the past, and partly because operational behavior must change and/or new technology is required.

Table 1. Overview of types of ocean shipping pollution

<table>
<thead>
<tr>
<th>Episodic environmental events</th>
<th>Routine environmental events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel-based</td>
<td></td>
</tr>
<tr>
<td>Oil spills</td>
<td>Engine air emissions</td>
</tr>
<tr>
<td>Ocean dumping</td>
<td>Invasive species introductions</td>
</tr>
<tr>
<td>Sewage discharges</td>
<td>(ballast water/hull fouling)</td>
</tr>
<tr>
<td>Oily wastewater</td>
<td>Hull coating toxics releases</td>
</tr>
<tr>
<td>Vessel collisions</td>
<td>Underwater noise</td>
</tr>
<tr>
<td>Ship-strikes with marine life</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Port-based</td>
</tr>
<tr>
<td>Dredging</td>
<td>Stormwater runoff</td>
</tr>
<tr>
<td>Port expansion</td>
<td>Vessel wake erosion</td>
</tr>
<tr>
<td>Ship construction, breaking</td>
<td>Cargo-handling air emissions</td>
</tr>
</tbody>
</table>

1.3 Freight emissions and energy overview

Emissions associated with transporting freight can be significant [Energy Information Administration, 1998; OECD and Hecht, 1997; Skjølsvik et al., 2000]. According to the U.S. EPA, heavy duty truck, rail, and water transport together account for more than 25% of U.S. CO₂
emissions, about 50% of NOx emissions, and nearly 40% of PM emissions from all mobile
sources [Environmental Protection Agency, 2005a; Environmental Protection Agency, 2005b]. In
Europe, these modes generate more than 30% of the transportation sector’s CO2 emissions [Bates et al., 2001].

Adjusting the modal share of freight transport can significantly address regional mobility,
congestion, and environmental problems [Donnelly and Mazierès, 1999; European Commission,
1999; Maritime Administration, 2003; Skjølsvik et al., 2000; 2004; Yonge, 2004]. The
European Commission recently emphasized the role of short sea shipping in maintaining an
efficient transport system in Europe now and in the future [European Commission, 2001], and
the U.S. Department of Transportation’s Maritime Administration is exploring the development
of a robust short sea shipping system to aid in the reduction of growing freight congestion on
U.S. rail and highway systems [Maritime Administration, 2003].

Shipping is not only among the least costly modes of transportation, but also the most energy
efficient (with some exceptions generally proportional with high vessel speed and low service
capacity). Because fuel costs can represent between 20% and 60% of shipping costs, operators
have strong economic motivation to operate ships efficiently and to employ propulsion
technologies that reduce fuel consumption per cargo ton-km. For example, the use of high-
temperature, high-pressure (HTHP) engines that can combust low-cost residual fuels (a
byproduct of petroleum refining) stems directly from the desire to reduce fuel expenditures.

However, a consequence of marine engine technologies is increased air pollution. These HTHP
engines oxidize nitrogen effectively (thereby increasing NOx emissions), and emit many of the
impurities of residual fuel (including sulfur, toxics, and heavy metals) out the ship stack. Among
freight modes, waterborne transportation has been shown to cause significant air pollution
locally in port communities, add to long-range pollution transport in coastal regions of heavy
trade, and contribute to climate change on a global scale [Capaldo et al., 1999; Corbett and Fischbeck,
1997; Corbett et al., 1999; Corbett and Koehler, 2003; Corbett and Koehler, 2004; Endresen et al.,
2003a; Kasibhatla et al., 2000; Lawrence and Crutzen, 1999; Skjølsvik et al.,
2000]. Oceangoing shipping is also the least regulated freight mode, at least for air pollution.

2. World fleet energy use and emissions estimates

2.1 Fleet profile

Most energy in marine transportation is used by cargo or passenger transport vessels – ships that
move cargo or passengers from one place to another in trade. A profile of the internationally
registered fleet of ships greater than 100 gross tons is shown in Table 2 [Lloyds Maritime
Information System (LMIS), 2002]. Transport vessels account for almost 60% of the ships and
nearly 80% of the energy demand of the internationally registered fleet (not including military
ships). Considered along with military ships, cargo ships account for 40% of the world fleet of
vessels and 66% of world fleet fuel use. Cargo ships are analogous to on-road trucking because

\[\text{2 Also see U.S. Maritime Administration, } \text{http://www.marad.dot.gov/Programs/shortseashipping.html.}\]

\[\text{3 Much of this discussion is adapted or excerpted from the author’s work published in the Encyclopedia of Energy}\]

they generally navigate well-defined (if unmarked) trade routes similar to a highway network. Other vessels are primarily engaged in extraction of resources (e.g., fishing, oil or other minerals), or primarily engaged as support vessels (vessel-assist tugs, supply vessels). Fishing vessels are the largest category of non-transport vessels and account for more than one-quarter of the total fleet. Fishing vessels and other non-transport ships are more analogous to non-road vehicles, in that they do not generally operate along the waterway network of trade routes. Rather, they sail to fishing regions and operate within that region, often at low power, to extract the ocean resources. As a result, fishing vessels require much less energy.

The registered fleet has approximately 84,000 four-stroke engines with total installed power of 109,000MW and some 27,000 two-stroke engines with total installed power of 164,000MW. Engines with “unknown” cycle types and “turbines” together make up only about 2.5% of total installed power for main engines. This suggests that 27,000 two-stroke marine prime movers account for almost 60% of the commercial fleet’s total energy output and fuel consumption, and more than half of the energy demanded by the world oceangoing fleet (including military ships). A majority of these engines are large-bore, low-speed diesel engines with above 10MW rated output. Two-stroke engines are the main consumers of bunker fuel and are the major sources of oceangoing ship emissions, followed by four-stroke engines.

<table>
<thead>
<tr>
<th>Ship type</th>
<th>Number of ships</th>
<th>Percent of fleet</th>
<th>Number of main engines</th>
<th>Percent of main engines</th>
<th>Installed power (MW)</th>
<th>Percent of total power</th>
<th>Percent of energy demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo Fleet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Container vessels</td>
<td>2662</td>
<td>2%</td>
<td>2755</td>
<td>2%</td>
<td>43,764</td>
<td>10%</td>
<td>13%</td>
</tr>
<tr>
<td>General cargo vessels</td>
<td>23,739</td>
<td>22%</td>
<td>31,331</td>
<td>21%</td>
<td>72,314</td>
<td>16%</td>
<td>22%</td>
</tr>
<tr>
<td>Tankers</td>
<td>9098</td>
<td>8%</td>
<td>10,258</td>
<td>7%</td>
<td>48,386</td>
<td>11%</td>
<td>15%</td>
</tr>
<tr>
<td>Bulk/combo carriers</td>
<td>8353</td>
<td>8%</td>
<td>8781</td>
<td>6%</td>
<td>51,251</td>
<td>11%</td>
<td>16%</td>
</tr>
<tr>
<td>Non-Cargo Fleet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger</td>
<td>8370</td>
<td>8%</td>
<td>15,646</td>
<td>10%</td>
<td>19,523</td>
<td>4%</td>
<td>6%</td>
</tr>
<tr>
<td>Fishing vessels</td>
<td>23,371</td>
<td>22%</td>
<td>24,009</td>
<td>16%</td>
<td>18,474</td>
<td>4%</td>
<td>6%</td>
</tr>
<tr>
<td>Tugboats</td>
<td>9348</td>
<td>9%</td>
<td>16,000</td>
<td>11%</td>
<td>16,116</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>Other (research, supply)</td>
<td>3719</td>
<td>3%</td>
<td>7500</td>
<td>5%</td>
<td>10,265</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>Registered Fleet Total</td>
<td>88,660</td>
<td>82%</td>
<td>116,280</td>
<td>77%</td>
<td>280,093</td>
<td>62%</td>
<td>86%</td>
</tr>
<tr>
<td>Military Vessels²</td>
<td>19,646</td>
<td>18%</td>
<td>34,633</td>
<td>23%</td>
<td>172,478</td>
<td>38%</td>
<td>14%</td>
</tr>
<tr>
<td>World Fleet Total</td>
<td>108,306</td>
<td>100%</td>
<td>150,913</td>
<td>100%</td>
<td>452,571</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

1 Percent of energy demand is not directly proportional to installed power because military vessels typically use much less than their installed power except during battle. Average military deployment rate is 50% underway time per year [Navy, 1996]; studies indicate that when underway Naval vessels operate below 50% power for 90% of the time [NAVSEA, 1994]. Therefore, energy demand was adjusted in this Table to reflect these facts.
2 The data upon which military vessel power was based specified the number of engines aboard Naval ships.
3 This table was previously presented in other publications [Corbett, 2004a; Corbett and Koehler, 2003].
Fuel types used in marine transportation are different from most transportation fuels. Marine fuels, or bunkers, used in today’s fleet, can be generally classified into two categories: residual fuels and other fuels. Residual fuels, also known as heavy fuel oil (HFO), are a blend of various oils obtained from the highly viscous residue of distillation or cracking after the lighter (and more valuable) hydrocarbon fractions have been removed. Since the 1973 fuel crisis, refineries adopted secondary refining technologies (known as thermal cracking) to extract the maximum quantity of refined products (distillates) from crude oil. As a consequence, the concentration of contaminants such as sulfur, ash, asphaltenes, and metals has increased in residual fuels.

To reduce operating expenses, marine engines have been designed to burn the least costly of petroleum products. Residual fuels are preferred if ship engines can accommodate its poorer quality, unless there are other reasons (such as environmental compliance) to use more expensive fuels. Of the two-stroke, low-speed engines, 95% use heavy fuel oil and 5% are powered by marine distillate oil (MDO). Fuel consumed by 70% of the four-stroke, medium-speed engines is heavy fuel oil (HFO), with the remainder burning either MDO or marine gas oil. Four-stroke, high-speed engines all operate on MDO or marine gas oil (MGO). The remaining engine types are small, high-speed diesel engines all operating on MDO or MGO, steam turbines powered by boilers fueled by HFO, or gas turbines powered by MGO.

### 2.2 Designating and estimating international marine fuel usage

The nations selling the most fuel to commercial ships are typically nations with strong interests in the cargoes or services those ships provide. Some 140-150 million metric tons of fuel are recorded as sold for international marine fuel consumption in recent years. OECD nations account for roughly half of these fuel sales and provide one illustration of historical consumption trends in the overall fleet [Energy Information Administration, 2001; International Energy Agency, 1977-1997]. Table 3 presents a summary of the top nations selling international marine fuels during the 1990s, according to the World Energy Database [Energy Information Administration, 2001]. The United States provides most of the world’s marine fuels by far, and together the top twenty nations selling international marine fuels (shown in Table 3) account for more than 80% of total marine fuel sales.

#### Table 3. International marine fuel sales by nation 1990-1999 [Energy Information Administration, 2001]

<table>
<thead>
<tr>
<th>Percent of Total Sales</th>
<th>Nations Selling Residual Bunkers</th>
<th>Nations Selling Other Bunkers</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;15%</td>
<td>United States (18%)</td>
<td>United States (22%)</td>
</tr>
<tr>
<td>6-15%</td>
<td>Singapore (9%), Russia (9%), Netherlands (8%), United Arab Emirates (8%)</td>
<td>Saudi Arabia (12%)</td>
</tr>
<tr>
<td>2-5%</td>
<td>Japan, Saudi Arabia, Belgium, South Korea, Spain, South Africa, Greece</td>
<td>Hong Kong, Singapore, Netherlands, South Korea, United Kingdom, Spain, Russia</td>
</tr>
<tr>
<td>~1%</td>
<td>France, Taiwan, China, Italy, Egypt, Netherlands Antilles, Hong Kong, United Kingdom, Germany</td>
<td>Thailand, Greece, India, Belgium, Italy, Brazil, Indonesia, Denmark, Egypt, Venezuela, Germany</td>
</tr>
<tr>
<td>&lt;1%</td>
<td>47 other countries</td>
<td>92 other countries</td>
</tr>
</tbody>
</table>

1. This table or similar was previously presented in other publications [Corbett, 2004a; Corbett et al., 1999].
The term “international marine fuel” introduces a classification problem for environmental assessments. The basic issue is whether statistics describe total energy consumption by shipping or not. Understanding what portion of ocean shipping energy is described by international marine sale statistics requires a historical review of energy cooperation and reporting among nations. This section reviews relevant background based on published history of the International Energy Agency (IEA) and current studies of past marine fuel demand.

The IEA was established in 1974 within the OECD framework, in part, to promote “co-operation with oil producing and other oil consuming countries with a view to developing a stable international energy trade as well as the rational management and use of world energy resources in the interest of all countries” [Scott, 1994]. The IEA Agreement on an International Energy Program (IEP) was designated to be the “focal point for the industrial countries’ energy co-operation on such issues as: security of supply, long-term policy, information “transparency”, energy and the environment, research and development and international energy relations” [Scott, 1994].

This required the development of energy statistics, particularly for oil supplies that were disrupted during the 1973 oil crisis. Motivated by energy security (including an oil sharing system), these statistics were to be the basis for emergency allocations among signing nations. According to the IEA agreement [Scott, 1994], fuels were to be included within a nation’s “oil stocks” if, among other conditions, they were a) in barges; b) in intercoastal tankers; c) in oil tankers in port; or d) in inland ship bunkers. Fuels were to be excluded from domestic stocks if, among other conditions, they were a) in seagoing ships’ bunkers; or b) in tankers at sea.

International marine fuels statistics were not intended to represent the total energy used by ships engaged in global commerce. Rather, these data were used to differentiate those fuels within a nation’s domestic stock from those not eligible for emergency allocation calculations within the oil emergency sharing system. Specifically, the IEP agreement tasked the “Standing Group on Emergency Questions” to consider common rules for the treatment of marine bunkers in an emergency, and of including marine bunkers in the consumption against which stocks are measured” [Scott, 1994]. Later, the IEA clarified that a nation’s marine fuel stocks “may not be counted if they are held as international marine bunkers, since such bunkers are treated as exports under a 1976 Governing Board decision incorporated into the Emergency Management Manual (EMM)” [Scott, 1994].

Since then, IEA definitions have been reworded to be more consistent with reporting guidance under IPCC [Houghton et al., 1997; International Energy Agency, 1987]. Currently, the IEA defines “international marine bunkers (fuel) [to] cover those quantities delivered to sea-going ships of all flags, including warships. Consumption by ships engaged in transport in inland and coastal waters is not included.” The IEA defines national navigation to be “internal and coastal navigation (including small craft and coastal vessels not purchasing their bunker requirements under international marine bunker contracts). Fuel used for ocean, coastal and inland fishing should be included in agriculture.”

This definition leads to significant error in terms of estimating total energy used by the fleet when historical sales data is misinterpreted as complete energy consumption by oceangoing
ships. For example, in 1997 and 1999 published work, Corbett and Fischbeck clearly assumed that international marine fuel sales represented consumption \cite{corbett1997,fischbeck1999}. Later work produced activity-based methodologies and guidance that identified best practices for calculating updated global estimates \cite{houghton1997,icf2005,thomas2002,unfccc2004}. In 2003 and 2004, Corbett and Koehler replaced these sales-based assumptions with activity-based estimates of ship energy requirements that exposed the bias of sales statistics and suggested the error could range between 25% for cargo ships and a factor of two for the world fleet \cite{corbett2003,corbett2004}. Recent estimates based on ship activity and installed engine power also conclude that the world fleet of ships (including cargo, noncargo, and military vessels) consumes some 280 million metric tons of fuel per year, with more than 200 million metric tons required for cargo ships alone.

Figure 2 illustrates how different input parameters can produce different estimates of oceangoing fleet fuel consumption \cite{corbett2004}. Independent work largely confirms the validity of activity-based methodologies and supports the insight that world marine fleet energy demand is the sum of international fuel sales plus domestically assigned fuel sales \cite{endresen2005,endresen2004,endresen2003}. Some debate continues about the best estimates of global fuel usage within these bounds, but the major elements of activity-based inventories are widely accepted. Considering the range of current estimates using activity-based input parameters, oceangoing ships consume 2-4% of world fossil fuels.

![Figure 2](image_url)
Core Inventory of Air Emissions in Europe (CORINAIR), under the Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe (EMEP) funded by the European Environmental Agency \cite{Woodfield2003}, adapted better criteria for labeling traffic as international or domestic that conforms to pollution-inventory guidance requirements rather than IEA energy allocation criteria \cite{Thomas2002}.

Fuel used by ships is allocated for emissions inventory purposes according to a simple but more accurate check list with regard to the voyage characteristics, as shown in Table 4. This may still leave unresolved the problem of using energy statistics collected by OECD and IEA – especially with regard to the past. However, applications of the activity-based methodology to past fleet data provide important insights to overall assessment of oceangoing ship emissions trends.

Table 4. Criteria for defining international or domestic navigation \cite{Thomas2002}

<table>
<thead>
<tr>
<th>Journey Type</th>
<th>Domestic</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Originates and terminates in same country</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Departs from one country and arrives in another</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Departs in one country, makes a ‘technical’ stop in the same country without dropping or picking up any passengers or freight, then departs again to arrive in another country</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Departs in one country, stops in the same country and drops and picks up passengers or freight, then departs finally arriving in another country</td>
<td>Domestic Segment</td>
<td>International Segment</td>
</tr>
<tr>
<td>Departs in one country, stops in another country and drops and/or picks up more passengers or freight, then departs, finally arriving in the same country</td>
<td>Domestic Segment</td>
<td>International Segment</td>
</tr>
<tr>
<td>Departs in one country, stops in the same country and only picks up more passengers or freight and then departs finally arriving in another country</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Departs in one country with a destination in another country, and makes an intermediate stop in the destination country where no passengers or cargo are loaded</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Eyring et al \cite{Eyring2005} estimates fuel usage over a historical period from 1950 to 2000. This important work also confirms that fuel sales do not fully describe ship activity, and provides insight into bias in marine fuels statistics developed under the IEA allocation criteria. As illustrated in Figure 3, ship activity over the past half century increased marine fuel energy use more substantially than implied by international marine fuel sales statistics. Four important explanatory insights are suggested by this data.

1. The analysis by Eyring et al indicates that early marine fuel statistics reported by IEA accounted for most fleet activity.

2. IEA guidance differentiating domestic bunker sales from international sales produced clear divergence in later years.

3. Explanatory factors for this divergence could either be a) improved compliance with IEA guidance over time, and/or b) increased frequency of voyage segments that include at least two ports within a nation. The clarity of IEA bunker fuel designation criteria suggests compliance to be both simple and consistent among nations and over time. If so, a primary cause of divergence between total fuel use and international fuel sales would perhaps be increased multiple-port calls within a nation over time. This change in
voyage behavior is consistent with the rise of containerized shipping during the 1970-1980 decade where increasing divergence would be expected during rapid transition to multi-port containerized logistics (see triangle in Figure 3), followed by stabilized container service patterns and constant differences between fuel usage and statistics.

4. Divergence (among estimates and/or categorical designations) will continue to require explanation and/or reconciliation. This discrepancy may remain controversial because not all statistical sources for marine fuels define international marine fuels the same way [Olivier and Peters, 1999].

![Figure 3. Estimated world fleet fuel consumption (civilian, military, and auxiliary) and international marine bunker fuel statistics in million ton of oil equivalents (Mt), reproduced from [Eyring et al., 2005]. Wedge illustrates rapid divergence of total fuel use and international bunker sales during the rise of containerization.](image)

**2.3 Current activity-based emissions estimates**

Emissions inventories for oceangoing ship are calculated using activity-based methodologies referenced above. In general, the steps are relatively clear [Corbett and Koehler, 2003]:

**Step 1:** Identify the vessel(s) to be modeled, and engines in service  
**Step 2:** Estimate the engine service hours for the voyage or voyage segment  
**Step 3:** Determine the engine load profiles, including power and duty cycle  
**Step 4:** Apply emissions or fuel consumption rates for specific engine/fuel combinations  
**Step 5:** Estimate emissions or fuel consumption for the voyage or voyage segment  
**Steps 6+:** Assign emissions spatially and temporally both in and out of port regions

These efforts yield a total value for the fleet emissions included in the scale of the estimate (e.g., port-based, national, regional, global). Figure 4 presents a summary of recent activity-based estimates for NOx (as elemental nitrogen), SOx (as elemental sulfur), and particulate matter (PM$_{10}$). The inventory by Corbett and Fischbeck (1999) used international marine fuels and fuel-based emissions factors; Endresen et al (2003) also used fuel-based emissions factors, but included activity-based data such as operating hours, engine load, and specific fuel consumption.
Figure 4. Summary of ship emissions point estimates [Corbett et al., 1999; Corbett and Koehler, 2003; Endresen et al., 2003a; Eyring et al., 2005]. Box-plots represent the 5th and 95th percentile results from uncertainty analysis; whiskers extend to lower and upper bounds [Corbett and Koehler, 2003; Corbett and Koehler, 2004].
These ranges suggest that NOx and SOx pollution from oceangoing ships represent some 15-30% of global NOx emissions and 5-7% of global SOx emissions, while fuel usage ranges 2-4% of world fossil fuels. Spatial representation is required to fully understand environmental impacts at regional and local scales, especially for particulate matter (PM). Mapping these emissions requires additional steps, discussed in the next section.

3. Geographic allocation of ship activity, energy, emissions

3.1 Comparing top-down and bottom-up approaches

Principle existing approaches for producing spatially-resolved ship inventories generally can be categorized as either top-down or bottom-up. Top-down approaches assign global ship emissions inventories, which can be estimated statistically, to each location according to spatial proxies of emissions intensity. The first global spatial representation of ship emissions used a proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS), then a data set of voluntarily reported ocean and atmosphere observations with ship locations resolved at 1-degree by 1-degree [Corbett and Fischbeck, 1997; Corbett et al., 1999]. This work assumed that the reporting ship fleet was representative of the world fleet, spatial distribution of reporting frequencies represented the distribution of ship traffic intensity, and emissions were proportional to traffic intensity. Endresen, et al. improved the global spatial representation of ship emissions by using ship size (gross tonnage) weighted reporting frequencies from the Automated Mutual-assistance Vessel Rescue system (AMVER) data set [Endresen et al., 2003b]. Endresen et al. implicitly assumed that ship energy consumption and emissions are proportional to ship size [Endresen et al., 2003b], which is not true for some types of ships. Wang, et al. addressed potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, current version of COADS at 0.1-degree by 0.1-degree resolution) and AMVER data sets, the two “best” global ship traffic intensity proxies. An example of ICOADS data is shown in Figure 6. These two self-reported proxies draw different samples from the global fleet and produce traffic intensity representations that differ significantly across certain regions. For example, AMVER represents more traffic on tanker routes and ICOADS represents more traffic on container ship routes. Advancements that improved the accuracy of the top-down approach using ICOADS as spatial proxy [Wang et al., 2006a], include trimming over-reporting vessels, using multiple-year data, and weighting ship observations with ship installed power to mitigate sampling bias, augment sample data set, and to account for heterogeneity of ships regarding energy use and air emissions.

Bottom-up approaches were applied by Lloyd’s register and Entec UK Limited to produce regional ship emissions inventories for the EMEP area, the Baltic Sea, and the Mediterranean Sea [Commission of the European Communities and Entec UK Limited, 2002; Lloyd's Register, 1999; Lloyd's Register and International Maritime Organization, 1998]. In this type of approach, ship and route specific emissions are estimated based on historical ship movements, ship

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attributes, and ship emissions factors. Emissions are assigned to locations of the most probable navigation routes, which are simplified to straight lines between ports in those studies.

Streets, et al. estimated emissions from international shipping in Asian waters based on commodity flow associated with major sea routes [Streets et al., 1997; Streets et al., 2000]. The accuracy of this method, which can be categorized as a bottom-up approach using trade as a proxy for emissions, is limited by the assumed relationships between the volume of trade flow and emissions, which are more closely related to ship installed power, load profile, etc., and by the aggregation of individual voyage routes into major shipping lanes.

Both bottom-up and top-down approaches have strengths and weaknesses. A top-down approach is quicker, demands relatively fewer resources and may cost less than a bottom-up approach [Wang et al., 2006a]. Top-down inventories can be improved by updating the global inventories and/or the spatial/temporal proxy of the ship emissions intensity. Accuracy of top-down approaches is limited by the accuracy of global inventories and how well spatial proxies represent total fleet activity.

![Figure 5. Illustration of oceangoing ship traffic, based on ICOADS proxy.](image)

Although bottom-up approaches appear more accurate than top-down methods, large-scale bottom-up inventories also are uncertain because they must aggregate estimates for engine workload, ship speed, and most importantly, assign ships to routes. Accuracy of regional annual inventories in bottom-up approaches is limited by the large number of ship movements and potentially dynamic shipping routes when selected periods within a calendar year studied are extrapolated to represent annual totals [Commission of the European Communities and Entec UK
3.2 Improving large-scale spatial models

Recently, Wang et al introduced the Waterway Network Ship Traffic, Energy and Environment Model (STEEM) [Corbett et al., 2006b; Wang et al., 2006b]. STEEM was developed to quantify and geographically represent inter-port vessel traffic and emissions as contrasted with in-port activities which have been well-characterized in other studies [Starcrest Consulting Group, 2000; Starcrest Consulting Group LLC et al., 2004; Starcrest Consulting Group LLC et al., 2003; U.S. Environmental Protection Agency and ARCADIS Geraghty & Miller Inc., 1999a; U.S. Environmental Protection Agency and ARCADIS Geraghty & Miller Inc., 1999b]. STEEM applies advanced GIS technology and automatically assigns voyage port-pairs to actual shipping routes at a global scale. This model can be used to characterize ship traffic, estimate energy use and assess environmental impacts of shipping, etc.

STEEM adopts the strengths of both top-down and bottom-up approaches and attempts to overcome the weaknesses in each approach and improves ship emissions inventory both mathematically and theoretically. First, the model uses an empirical waterway network built from shipping routes revealed from observed historical ship locations. Spatial allocation is both more accurate than a bottom-up approach (which uses speculative routes) and a top-down approach (which uses biased spatial proxies). Second, as in a bottom-up approach, STEEM estimates energy use and emissions using complete historical ship movements, individual ship attributes, and the distances of routes. Calculations are expected to be more accurate than a top-down approach, which relies on the statistics of the world fleet and its operating profiles. Third, automation of repetitive processes makes this method capable of producing global energy and emissions inventories, which is a daunting task with existing bottom-up approaches. Fourth, since the network can be updated, modified, re-used, and shared among users, STEEM is perhaps more cost-effective than either top-down and bottom-up approaches.

STEEM has been applied to geographically characterize ship emissions for North America, including the United States, Canada, and Mexico. Some 170,000 separate voyages over the course of a year were routed from origin to destination using an empirically derived global shipping network. North American inventory results using STEEM is illustrated in Figure 6 can be reviewed at http://coast.cms.udel.edu/NorthAmericanSTEEM/. Application of STEEM to other environmental concerns, such as ship-strikes with marine mammals, is reported elsewhere and/or reserved for future work [Corbett et al., 2006a; Wang et al., 2005; Wang et al., 2007].

This work is being expanded to a multimodal model by connecting the road and rail networks to the waterway network to conduct optimal route analysis for various network attributes. The project is aimed at developing the methodology and tools for: (1) quantifying emissions from land-side and water-side freight transport alternatives; (2) evaluating tradeoffs among pollutants,

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5 Collaboration with James J. Corbett, University of Delaware, and James J. Winebrake, Rochester Institute of Technology, partially funded by the U.S. Department of Transportation (Research and Special Programs Administration) Contract #DTOS59-05-C-00420, Emissions Analysis of Freight Transport Comparing Land-Side and Water-Side Short-Sea Routes: Development and Demonstration of a Decision Modeling Tool.
costs, and travel time for moving freight between two points; and, (3) identifying optimal modal combinations within a network of travel paths that would lead to either minimum emissions, minimum energy use, minimum costs, or minimum travel time. This work should be ready for demonstration by mid-2007.

Figure 6. Illustration of STEEM results for North America.

4. Environmental trends

4.1 Freight energy and emissions trends

The estimation and allocation efforts discussed in Sections 2 and 3 describe a set of baseline conditions (and historic trends) from which forecasting can be considered. The multimodal and multicargo freight context must be considered when forecasting oceangoing environmental trends. This is because all freight modes respond to common drivers of change (e.g., economic growth, population demographics, energy prices), and cross-mode influences need to be included (e.g., metropolitan road congestion around one port diverting some cargoes to other ports). This applies whether one is considering air emissions or other environmental impacts. Three critical questions for forecasting freight activity and environmental impacts include:

1. **Baseline Conditions**: What are freight energy and activity patterns?
2. **Rates of Change**: What is forecast trend in energy needed?
3. **Patterns of Change**: Where is future freight activity be located?

While interrelated, these questions may be validated with some independence, considering uncertainty and requires bounding. Convergence is emerging on baseline estimates – at least in terms of major insights, through academic dialogue about uncertainty ranges in oceangoing energy and emissions. For example, most oceangoing shipping (~85%) occurs in the Northern Hemisphere and involves OECD nations. Trade routes are clearly visible, although some routes
are dominated by different commodity-specific ship types. These routes link to landbased modes with proportionality observed among major shipping lanes and major road and rail patterns.

Freight transportation, particularly international cargoes, are an important and increasing contributor to global and national economic growth, as well as state and regional economic growth in and around major cargo ports. The contribution of international trade is increasing as a proportion of U.S. gross domestic product (GDP) – i.e., freight transportation is growing faster than U.S. GDP [Bureau of Economic Analysis, 2006]. Economic activity related to imports and exports together contribute between 22% and 30% of U.S. GDP; moreover, the dominance of containerized cargoes in seaborne trade suggests that truck and containerized shipments may double by 2025 or sooner [TRB Executive Committee et al., 2006]. GDP in the U.S. is growing at ~3.7% compound annual growth rates (CAGR) since 1980, and the freight sector is growing at ~6.4% CAGR over the same period [Bureau of Economic Analysis, 2006]. This freight-sector growth rate in terms of dollar value is reflected in the observed ~6.3% to 7.2% annual growth rates of “high-value” containerized trade volumes, particularly from Asia [Vickerman, 2006].

The basic insight is that growth in GDP and trade volumes is compounded. Freight energy use is correlated to increases goods movement, unless substantial energy efficiency improvements are being made within a freight mode (e.g., U.S. rail) or across the logistics supply network. But even with efficiency improvements, compounding increases in trade volumes are likely to outstrip energy conservation efforts unless a technological or operational breakthrough in goods movement emerges.

In the U.S. at least, growth factors embedded in mobile source energy and emissions models appear to capture this economic-driven growth in freight transportation. Some energy forecasts have linked freight activity (and associated energy consumption) to economic growth projections. For example, the EIA Energy Outlook “uses projections of dollars of industrial output to estimate growth in freight truck travel; industrial output is converted to an equivalent measure of volume output using freight adjustment coefficients” that assume constant average ton-miles per truck-year [Energy Information Administration, 2003]. Growth factors for trucking (single-unit and combination trucks) in the U.S. EPA’s mobile source models include a combination of a population (sales) and VMT growth factors, with adjustments for fuel economy and other operational factors [U.S. Environmental Protection Agency et al., 2004]. EPA compared rail freight ton-miles with railroad distillate fuel consumption data to indicate substantial improvements in rail freight energy intensity, adjusting emissions based on regulatory requirements [U.S. Environmental Protection Agency, 1998]. And, in its 2003 rulemaking, EPA assumed that freight growth was linked to increased tonnage volume [U.S. Environmental Protection Agency, 2003].

Historic and future growth rates for particular modes are consistent with the values discussed above. For example, EPA projects that truck population and vehicle miles traveled (VMT) will increase by 4.2% to 4.8% CAGR between 2002 and 2025 [U.S. Environmental Protection Agency et al., 2004]. For rail, EPA showed that growth rates in cargo ton-miles transported nearly doubled in recent periods, from ~2.4% CAGR between 1980 and 1995 to ~4.8% CAGR between 1990 and 1995 (illustrated in Figure 1-1 in U.S. EPA’s regulatory support document).
In fact, updating observed growth rates in cargo ton-miles moved by rail to include more recent years reveal a growth rate of ~3.6% CAGR from 1985 to 2004 [Davis, 2003; Dennis, 2005].

For the marine sector, EPA’s 2003 forecast methodology improved the similarity between economic and emissions forecasts, although emissions forecasts represent a compound average growth rate about 3.4% (range of 2.8% to 3.8%, depending on pollutant). While shipping growth rates accounted for the effect of increased tonnage in a newer fleet, they do not consider the effect of faster speeds – specifically the additional installed power to meet combined size and speed requirements. Correcting for these factors brings the forecasts for international marine activity into closer agreement with trucking growth rates (especially when rail cargo volume increases are considered), and better describes the role of imports growth on the intermodal freight system.

4.2 Forecasting principles
Forecasts can differ depending on their purposes and scales. Some forecasts look to reveal where timely investment and action at a local scale or by a single firm can produce the most benefit (e.g., profit). Validity of insights is determined by whether recommended actions produce expected outcomes for a given decision, not whether the forecast trend or future value is realized. Other forecasts are intended to be conservative or aggressive; that is, they intend to be biased to serve the decision makers’ value and tolerance for risk and surprise. This may describe large scale forecasts such as emissions or trade trends. A challenging class of forecasts may be considered “difference” forecasts, where alternative scenarios are described to illustrate how “a path taken” may differ from “a path not taken” rather than to determine which is most probable. These kinds of forecasts are common in policy domains, such as energy, environment, and economics (e.g., IPPC scenarios). Certainly, freight forecasting presents one challenging example, especially at the international or multinational scales, and especially when considering policy actions like a SOx Emissions Control Area (SECA) under IMO MARPOL Annex VI [International Maritime Organization, 1998].

Using a spatially-resolved, activity-based inventory of North American shipping activity derived from 172,000 port calls in 2002 to Canada, Mexico, and the United States, we adjust the base-year inventory to estimate emissions from commercial marine vessels for 2010 and 2020. We produce two forecasts: 1) an unconstrained scenario applying a common growth trend to forecast a business as usual (BAU) scenario without sulfur controls; and 2) a with-SECA scenario assuming IMO-compliant reductions in fuel sulfur to 1.5% by weight for all activity within the Exclusive Economic Zone (200 nautical miles) of North American nations. A report on this work will be completed in December.

Admittedly, the quality of forecasts of maritime shipping and trade is limited [Stopford, 1997], and thus forecasting of environmental impact from shipping is constrained by the quality of shipping and trade forecasts. Rather than attempt to define one forecast path among many conditional events determining future ship emissions, we employ a comparison of historic trends and forecast indicators related to maritime trade and energy to provide reasonable insight into a range of feasible forecasts. Individually, none of these forecasts can be considered more correct than another, as they represent different assumptions about the relationship between transportation energy, trade, and North American port activity. However, taken together, they
reveal a bounded range of trends with common insights useful in comparing sulfur controls with no action. We look for converging growth trends that are representative at several scales (port, region, coastal, and national) and informed by historic data.

Efforts to produce oceangoing ship emissions forecasts are ongoing in both the U.S. and Europe; results are not yet released and may not be definitive. These premises lead to a set of principles for describing how freight transport may change:

1. Define the forecast domain broadly through multiple perspectives on freight and economy.
2. Compare global, large regional forecasts with local efforts for converging insights, perhaps allowing for probabilistic assessment.
3. Include the rear-view mirror in forecasting (i.e., compare with persistence).
4. Consider first principles involving energy and environment: Some work-energy relationship must hold if fuel price matters to freight.
5. Make extrapolation adjustments as simple as possible, but no simpler: Assumptions inter-relating energy, economy, and technology should be checked for potential inconsistencies.
6. Look for surprise, avoid overconfidence: Recognize heterogeneity at all scales; use detailed scenarios to help broaden or delineate the forecast range, but do not rely on them as likely.

5. Options for improving sustainability of freight

5.1 Environmental control technology

Addressing technology’s role in mitigating environmental impacts of oceangoing freight requires that we review the full taxonomy of impacts illustrated in Table 1. This is beyond the scope of this report, which has focused on energy use and air emissions. Environmental control technologies have been studied by industry and researchers for each of the environmental impacts to which ships contribute. The marine sector is often able to implement technologies that diffuse from other areas and/or combine with innovation from within the industry to achieve improved environmental performances.

To varying degrees both innovation and diffusion of technology is at play in each environmental issue. For example, air emissions technologies are generally adapted or marinized from similar engines in other industries [Alexandersson et al., 1993; Cooper, 2001; Corbett and Fischbeck, 2001; Farrell et al., 2002; MAN and B&W, 1997; Quandt, 1996; Wartsila NSD, 1994; Wartsila NSD, 1998; Winebrake et al., 2005]. Emisions controls have been categorized as either pre-combustion, in-engine, or post-combustion controls [Corbett and Fischbeck, 2001]. Examples of each include, respectively, 1) water-fuel emulsions or intake air humidification, 2) injection timing or in-cylinder catalysts, and 3) selective catalytic reduction or sulfur scrubbers. Ballast water treatment technologies, benign hull coatings, and noise reduction technologies are not as readily transferable from related industries, requiring more direct development by industry vendors. Some are rather unique to maritime activity, such as underwater noise standards recommended in the International Convention for Exploration of the Seas [International Council for Exploration of the Sea (ICES), 1995].

The potential trade-off between increased energy demand for environmental technologies and their mitigation of specific impacts merits recognition. For oceangoing shipping, there may be
an increase in fuel use and carbon dioxide (CO₂) emissions when energy is directed to clean stack exhaust or treat and filter ballast water. This suggests that technology alone may not solve environmental issues, and that alternative energy sources or more sustainable freight logistics may play a role.

5.2 Alternative marine fuels

Alternative marine fuels (other than for performance improvement or cost reduction) were first studied following the 1970s reaction to the energy crisis. In the United States, a study by the National Research Council reviewed

> “the potential fuels that may be available to the marine industry from 1980 to 2000 and to define the economic, technical, environmental and social impacts of these alternative fuels on marine power plants. From the outset of this study the committee agreed that three basic questions face the maritime industry concerning alternative fuels: (1) What are the likely alternative fuels that may be used by the maritime industry? (2) What has to be done to use these fuels? (3) How will these fuels perform in various types of prime movers?” [National Research Council et al., 1980].

Little change occurred in the shipping industry with regard to alternative fuels since this report. Subsequent studies in the United States, Europe, and at the IMO researched these questions within the context of long-range pollution and climate change as well as energy security. The conclusions are remarkably similar, albeit with the benefit of more detailed analyses.

Potentially slow transitions to alternate fuels should not be ignored. The switch from coal to oil in the first part of last century spanned five decades. Essentially, the commercial sector was converting to oil-fired boilers powering marine turbines and introducing oil-fueled internal-combustion, compression-ignition engines – commonly known as the Diesel engine. Switching fuels was both a direct means of conservation and a technology enabler during the introduction internal combustion engines that ultimately replaced steam-turbines and boilers. Of course the reasons were economic: According to British Admiral Fisher’s remarks to Winston Churchill in 1911 (quoted in Yergin’s 1991 book, *The Prize* [Yergin, 1991], page 155), a cargo steamer could “save 78 percent in fuel and gain 30 percent in cargo space by the adoption of the internal combustion propulsion and practically get rid of stokers and engineers.”

Recently, Intertanko proposed that IMO consider a fleetwide switch to distillate fuel with a fuel-sulfur content no greater than 1% [Intertanko, 2006]. This may represent an emerging acknowledgment by industry that SECA designations (perhaps including the West Coast) will be supported on cost-benefit grounds in areas other than specified in IMO Annex VI. Intertanko’s proposal states that conversion to low-sulfur (1%) distillate fuel will achieve a “large reduction of SOx, and PM emissions … with no other investment than a higher price for the fuel” [Intertanko, 2006]. Recent research indicates that global fuel-switching without the option of aftertreatment technologies achieves environmental benefits at greater cost than if onboard technologies to remove SOx were allowed [Wang and Corbett, 2007]. Without fully evaluating the impacts of sulfur emissions from ships and the benefits of their reduction, it could be premature to conclude that a sulfur content of 1% is stringent enough for some of the most vulnerable regions, for which SECAs may be still merit consideration. In other words, uniform
fuel standards may not be most efficient, either in terms of cost to the fleet or in terms of environmental benefits.

Moreover, alternative fuels choices should not be made only on the basis of operating ship fuel consumption, but should also add impacts of extracting, refining, and delivering new fuels to replace marine heavy fuel oil (residual fuel). Assessing complete emissions from marine transportation (and to compare these emissions with landside alternatives), a *total fuel life-cycle* emissions analysis is needed. These analyses consider emissions and energy use along the entire fuel pathway—from extraction to use.

Recently completed research produced the Total Energy & Emissions Analysis for Marine Systems (TEAMS) model [Winebrake et al., 2006; Winebrake et al., 2007a; Winebrake et al., 2007b] . TEAMS captures “well-to-hull” emissions for a user-defined ship operating on a given shipping route. Emissions are calculated along the entire fuel pathway, including extraction, processing, distribution, and use in vessels. TEAMS is able to conduct this analysis for six fuel pathways: (1) petroleum to residual oil; (2) petroleum to conventional diesel; (3) petroleum to low-sulfur diesel; (4) natural gas to compressed natural gas; (5) natural gas to Fischer-Tropsch diesel; and, (6) soybeans to biodiesel. Results include total fuel life-cycle energy use and emissions of the following pollutants: greenhouse gases [carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄)], volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NOₓ), particulate matter (PM₁₀), and sulfur oxides (SOₓ). TEAMS calculates total energy consumption, fossil fuel consumption, and petroleum consumption associated with each of these six fuel pathways. TEAMS is available at [http://www.rit.edu/~teams/](http://www.rit.edu/~teams/).

In any case, the freight sector overall, and perhaps oceangoing shipping in particular, may offer some advantages in a shift to alternate transportation fuels. Some research has considered the choice of transportation mode, concluding that the freight sector presents fewer barriers (or at least lower cost thresholds) to the introduction of alternative fuels [Farrell et al., 2003]. With a focus on hydrogen, this work suggests that costs of alternative fuel transitions can be reduced by selecting a mode that uses a small number of relatively large vehicles that are operated by professional crews along a limited number of point-to-point routes or within a small geographic area. In addition, technological innovation in vehicle design will take place most quickly in modes where individual vehicles are produced to order and each receives significant engineering attention (not those manufactured in vast quantities on assembly lines). In ships, where transitions of the prime mover and fuel may be decoupled (at least partly), the potential rate of introduction alternative fuels may be quicker. Environmental benefits of introducing hydrogen fuel will occur in modes that have relatively less stringent pollution regulations. These insights, suggest that heavy-duty freight modes would be a less costly way to introduce hydrogen as a transportation fuel and a more effective way to advance hydrogen-related technologies so that they could subsequently be used more widely in light-duty vehicles.

### 5.3 Operational changes

As discussed earlier, while oceangoing ships are among the least regulated pollution sources (at least for air pollution), and while they employ high-temperature-high-pressure engines using low-quality fuels, most ships (especially slower liquid and dry bulk vessels) can move cargo very efficiently. As such, ocean freight can be part of the solution to more sustainable logistics in
inter/multimodal contexts. One clear opportunity is modernization and retrofit investment, but its success relies on industry’s perception of economic incentives [Kågeson and Associates, 1999; Theis et al., 2004].

More directly, environmental mitigation through behavior change is also an option. Examples are not limited to ballast water management requirements or navigation aids to reduce collisions and groundings. Recently mitigation measures to protect marine mammals and other marine life from ship-strikes has imposed mandatory reporting by ships and is proposing speed reductions and lane changes, at least intermittently [Firestone and Corbett, 2006; Firestone et al., 2006a; Firestone et al., 2006b; Firestone et al., 2006c; Wang et al., 2007]. Ship-strikes represent environmental impacts where industry operations become more sustainable without new technologies or vessel modifications. Additionally, air emissions reductions can be achieved through speed reductions as studied by IMO and as implemented through voluntary agreements with industry [Corbett, 2004b; Los Angeles Board of Harbor Commissioners et al., 2001; Skjølsvik et al., 2000].

Especially where these operational changes may affect global trade, these issues are not single mode concerns for oceangoing ships. As discussed in Section 1, the freight sector needs to be considered as an intermodal/multimodal network responding to common drivers differently than other mobile sources (autos) and coupled with larger sustainability issues such as land-use, resource extraction, labor and population. Within this context, both technological and operational measures can achieve more sustainable goods movement involving marine transportation.

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