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Costs Associated with Voluntary Speed Reduction Requests In Central California Marine Sanctuaries To Protect Endangered Whales

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1. INTRODUCTION

Global economic growth and resultant rise in demand are drivers of international shipping trade. Ocean going cargo vessels have increased in number, while becoming larger with increased service speeds. This has increased the potential for cargo vessels to lethally strike whales (Laist et al. 2001). These more numerous and faster vessels also place whales at greater risk and can reduce the recovery of at-risk whale populations. (Monnahan et al. 2014, Knowlton et al. 2001).

On the U.S. Pacific west coast, ship-strike deaths - as confirmed by the necropsies of stranded dead whales – resulted in the death of 23 large whales while fishery-related entanglements caused 15 deaths from 2012 to 2016. (Carretta et al. 2018). Most collisions between large ships and whales go unnoticed as the majority of large whales sink after death (Rockwood et al., 2017).[1] Models estimate that 83 endangered blue, fin, and humpback whales are killed along the U.S. west coast between May and September of each year, suggesting that total annual ship strike mortality often exceeds blue and humpback Potential Biological Removal (PBR) management thresholds, which serve as an annual limit for combined sources of human-induced mortality to these federally protected species (Rockwood et al., 2017).[2]

In selected transit lanes within three central California national marine sanctuaries (Cordell Bank, Greater Farallones and Monterey Bay), a Vessel Speed Reduction (VSR) program was implemented to lessen mammal morbidity and

[1] Collisions between large vessels and whales may not be reported because vessel crew are not aware of the collision especially with smaller species of whales. Carcasses may sink and even if they float, they may be consumed by scavengers or too decomposed to reach shore or otherwise be discovered.

[2] In 2021 the PBR for humpback whales along the California, Oregon and Washington coasts was 29.4 whales per year while the PBR for blue whales in the Eastern North Pacific was calculated to be 4.1 whales per year. Refer to NOAA Fisheries, Marine Mammal Stick Assessment Reports by Specifies/Stock. Revised March 14 and 15, 2022, respectively.

mortality from fatal ship strikes. In the VSR program vessel speeds are requested to be voluntarily reduced to ten knots during a selected portion of the year.

This analysis investigates changes and the relative impact on vessel operating costs borne by vessel owners and operators of bulk, container, roll-on roll-off (ro-ro) and tank carriers. Individual estimates of vessel capital costs, overhead, inventory carrying costs, main propulsion and auxiliary fuel use are made. Altered societal costs resulting from changes in fuel use (main propulsion and auxiliary power) were also assessed across nine major pollutant groups including carbon monoxide, carbon dioxide, nitrogen oxide, sulphur oxide, methane, ammonia, particulate matter (2.5 and 10 microns) and reactive organic gases.

2. NATIONAL MARINE SANCTUARIES

U.S. national marine sanctuaries are areas within the United States waters where special protections are afforded to the marine environment. Fifteen national marine sanctuaries are managed by the Office of National Marine Sanctuaries (ONMS) under the National Ocean Service (NOS) within the National Oceanic and Atmospheric Administration (NOAA).[3]

2.1. Cordell Bank National Marine Sanctuary

Located off the coast of California, Cordell Bank National Marine Sanctuary (CBNMS) was established in 1989 to protect and preserve the marine ecosystem surrounding the Cordell Bank.[4] The CBNMS covers approximately 25 square nautical miles – roughly 3.4 nautical miles wide and 7.2 nautical miles long and rises to within 115 feet of the ocean surface and is characterized as a rocky habitat (i.e., rock reef, boulders, cobbles, etc.) surrounded by soft sediments (i.e., sand

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[3] As of 2018 there were 13 national marine sanctuaries. Mallows Bay National Maine Sanctuary located on the Maryland side of the Potomac River in Charles County MD was added on September 3, 2019 and the Wisconsin Shipwreck NMS designated on June 22, 2021.

[4] National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Office of National Marine Sanctuaries (ONMS). Refer to: https://cordellbank.noaa.gov/

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and mud) on the continental shelf floor.[5] Later expanded to 971 square nautical miles to include additional waters and submerged land in 2015, the CBNMS is bordered on the north, east and south by the Greater Farallones with a southern-most boundary 42 miles west-northwest of San Francisco.[6] (Refer to Figure 1) The entire CBNMS is about presently 1,286 square nautical miles in area.

2.2. Greater Farallones National Marine Sanctuary

This sanctuary supports blue, gray, and humpback whales in addition to harbor seals, elephant seals, Steller sea lions, and dolphins. Large white shark populations are also resident in this area.

Overall, some 36 marine mammal species live within its boundaries.[7] It was initially designated as the Gulf of Farallones National Marine Sanctuary on January 16, 1981. On June 9, 2015, it was expanded to its present size of 2,488 square nautical miles and renamed Greater Farallones National Marine Sanctuary (GFNMS) running offshore by about 30 miles from Port Arena to below Point Reyes, CA. It is located within the California Current ecosystem, one of four major boundary currents in the world.

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[5] NOAA, NOS, ONMS. https://cordellbank.noaa.gov/about/bank.html and "Earth is Blue", page 34.

[6] National Marine Sanctuaries, 2019. Earth is Blue, Magazine of the National Marine Sanctuaries, Page 34.

[7] https://marinesanctuary.org/sanctuary/greater-farallones

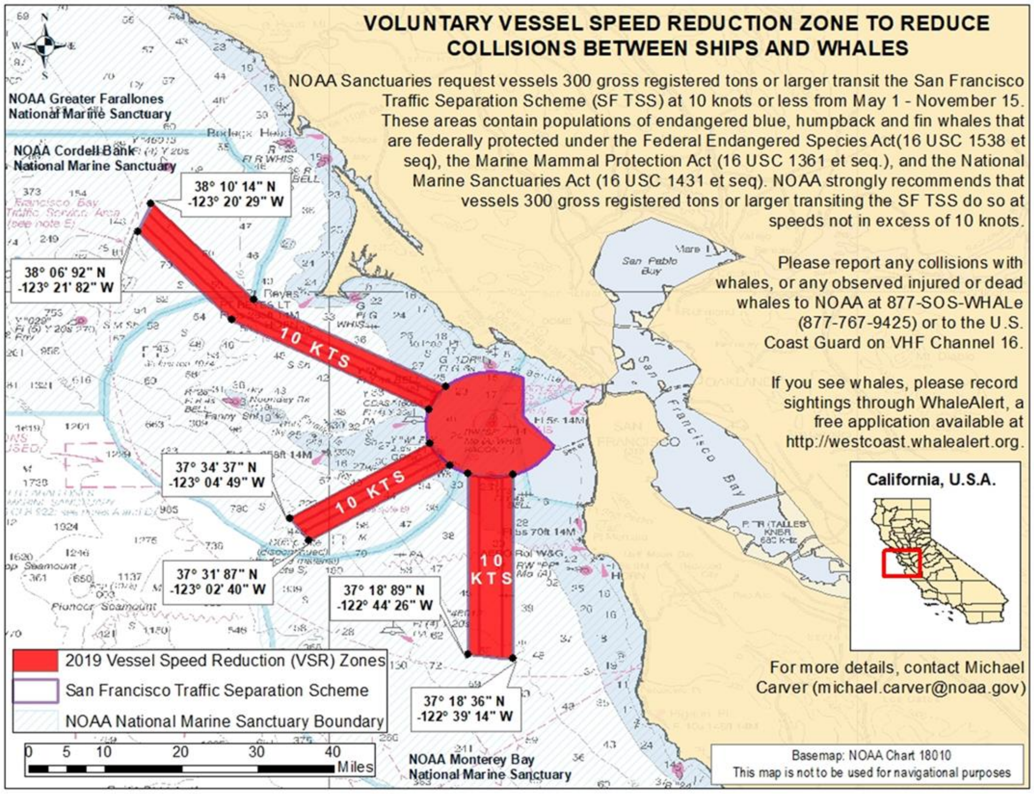

Figure 1Voluntary Vessel Speed Reduction Zone to Reduce Collisions Between Ships and Whales

2.3. Monterey Bay National Marine Sanctuary

Located off the central coast of California, Monterey Bay National Marine Sanctuary (MBNMS) supports many types of mammals (e.g., a number of species of whales including Baird's, Hubb's and Blainville's beaked, blue, Bryde's, California gray, fin, Lesser beaked, Minke, North Pacific right, pygmy sperm, Short-finned pilot, Sperm and Stejneger's beaked whales, etc.) Overall, this total sanctuary encompasses an area of 4,602 square nautical miles. These three sanctuary regions are collectively adjacent to the San Francisco Port District and are encompass major west coast north-south and east-west shipping lanes.

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3. DATA SOURCES

3.1. USA Trade® Online

USA Trade® Online managed by the Census Bureau of the Department of Commerce was utilized as the primary source of inventory carrying cost calculations of average cargo value for all types of vessels. Two classes of vessels were investigated. Subtracting fully cellular container data that is provided separately from all vessel data provided an estimate for all other types of vessels (e.g., dry bulk, tank, general, and Ro-Ro). While individual ship types are not specifically identified, more granular analysis of commodities which are typically unique to certain ships (e.g., finished automobiles and trucks in ro-ro vessels) might be teased from the data to a limited degree. While it could be advantageous to identify cargo costs by individual type of vessel, sufficient data (e.g., cargo weight and cargo value) may not be publicly available for all desired combinations of size and vessel type. Data from 2003 to 2018 suggests the overall average weight of an imported Twenty-Foot Equivalent (TEU) container across the entire U.S. was 7.3 metric tons, while exported TEUs averaged 9.7 metric tons, reflecting the difference in commodities imported (e.g., apparel) versus commodities exported (e.g., machinery and a variety of by-products for recycling).[8] The weighted average for imports and exports was 8.2 metric tons.

3.2. Maritime Administration

The United States Department of Transportation's Maritime Administration (MARAD) annually reports statistics on imported and exported cargo. While not including any commodity specification when identified by port district, data on the tonnage and cargo value (in nominal U.S. dollars) is provided in its *U.S.*

[8] The twenty-foot equivalent unit (often TEU or teu) is an inexact unit of cargo capacity often used to describe the capacity of container ships and container terminals. It is based on the volume of a 20-foot-long (6.1 m) intermodal container, a standard-sized metal box that can be easily transferred between different modes of transportation, such as ships, trains and trucks. (Rowlett 2000) There is a lack of standardization in regard to height, ranging between 4 feet 3 inches (1.30 m) and 9 feet 6 inches (2.90 m), with the most common height being 8 feet 6 inches (2.59 m). Refer to: http://en.wikipedia.org/wiki/Twenty-foot_equivalent_unit.

Waterborne Foreign Trade by U.S. Customs Districts for the years 2003 to 2017.[9] In addition, U.S. Customs Ports which identify ports of entry throughout the country provide data on international containerized cargo in their U.S. Waterborne Foreign Container Trade.[10] Vessel tonnage based on the number of TEUs it is carrying was estimated from the MARAD databases for both import and export traffic. This facilitates estimation of average container weight from which it is possible to estimate average cargo value per TEU.

3.3. National Navigation Operation and Maintenance Performance Evaluation and Assessment System (NNOMPEAS)

NNOMPEAS is a United States Army Corps of Engineers (USACE) tool for estimating marine transportation costs and performing economic analyses on USACE waterway projects. It is the standard source for all marine transportation cost data and is employed as the basis for considering the benefits of proposed USACE projects**.** NNOMPEAS is constructed from a large number of variables (e.g., vessel length, breadth, draft, engine horsepower, crew, distance traveled, cost of fuel, engine fuel efficiency, the diameter of the propeller, etc.), all of which affect the costs of operating the vessel. It does not include profit margin, market pricing decisions, competitive pricing strategies, etc. Actual vessel operating and transportation costs are highly sensitive and not shared by marine transportation companies for competitive reasons.[11] Alternatively, the best data available are outputs from the detailed NNOMPEAS model. This gives the USACE a more stable platform upon which to make comparisons across multiple years without having to consider the competitive elements of cost and volatility of rates.

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[9] Data is provided from the Census Bureau's Foreign Trade Division.

[10] Data is provided from the Port Import Export Reporting Service (PIERS) provided by the Journal of Commerce /UBM Global Trade. Data is collected from vessel manifests and bills of lading. The data covers loaded containers only.

[11] As they are market driven by a wide-variety of influences, vessel rates are not uniformly representative of vessel operating costs and tend to be significantly more volatile.

In addition to vessel cost, the NNOMPEAS system has an emissions application for provision of volume estimates of nine emission types which are based on variables such as fuel type used, engine type and size, vessel speed, etc.[12] Finally, lightweight and deadweight figures for each vessel, along with the estimated weight of stores (fuel, water, crew, food, etc.), permit the calculation of cargo-carrying capacity.

4.1. Automatic Identification System (AIS)

In 2000, the International Maritime Organization (IMO) adopted a new requirement (as part of a revised new Chapter V) for all ships to carry AIS capable of providing information about the ship to other ships and to coastal authorities automatically.[13] The regulation which became effective December 31, 2004[14] requires AIS to be fitted aboard all ships of 300 gross tons and greater engaged on international voyages, cargo ships of 500 gross tons and greater not engaged on international voyages (domestic trips), and all passenger ships regardless of size. AIS data from Marine Cadastre was processed with an ArcGIS software application to estimate individual vessel transit segments to estimate overall vessel trip average transit speeds.[15]

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[12] The Environmental Protection Agency (EPA) has accepted the process and end estimations of pollutant emissions in the NNOMPEAS model.

[13] Refer to International Maritime Organization (IMO) website on AIS transponders. http://www.imo.org/OurWork/Safety/Navigation/Pages/AIS.aspx

[14] The regulation applies to ships built on or after 1 July 2002 and to ships engaged on international voyages constructed before 1 July 2002, according to the following timetable: (1) passenger ships, not later than 1 July 2003; (2) tankers, not later than the first survey for safety equipment on or after 1 July 2003; and (3) ships, other than passenger ships and tankers, of 50,000 gross tonnage and upwards, not later than July 1, 2004.

[15] Marine Cadastre is a joint initiative between the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) and the Department of the Interior's Bureau of Ocean Energy Management (BOEM). It is a system that enables boundaries of maritime rights and interests to be recorded, spatially managed and physically defined in relation to the boundaries of other neighboring or underlying rights and interests .

4. MAMMAL PROTECTION ACT

Due to heightened concerns regarding some species of marine mammals being in danger of depletion or extinction due to human activities (e.g., excess hunting, vessel strikes, overfishing, etc.), the Marine Mammal Protection Act (MMPA) was enacted in 1972. The MMPA provided for prohibitions, required permits, and criminal and civil penalties to shield marine mammals. This act prevents the harassment, capture, injury, and killing of all species of whales, dolphins, seals, sea lions, walruses, manatees, dugongs, sea otters, and polar bears.

4.2. Studies on the Impact of Vessel Speed and Routing

For over 25 years, a relationship between vessel speed, growing vessel size and mammal mortality has been observed. Laist et al. (2001) in a long term study stated that fatal vessel-whale strikes began in the 19th century and later increased as the number and speed of vessels increased and recommended that measures to reduce vessel speed may be beneficial. Russell et al. (2001), Vanderlaan et al.(2006), Wiley et al. (2011), Conn et al. (2013), and Van de Hoop et al. (2014) determined that vessel speed reductions can significantly reduce the probability of a whale being struck by a ship. Reductions in speed were also reported to reduce the severity of whale injuries by Laist et al. (2001), Wang et al. (2007), Wiley et al. (2011), Van der Hoop et al. (2012) and Conn et al. (2013). Douglas et al. (2008) cite that dramatic differences in occurrences of ship-stuck whales occurred across species, with fin whales exhibiting the highest number of vessel strikes in the state of Washington.

Wang et al. (2007) observed that for vessels greater than 500 metric tons, speed was more important than vessel size alone in determining a lethal injury to a whale. Vanderlaan et al. (2007) estimated the probabilities of whale mortality for different vessel speeds. They found that the greatest rate of change in lethal injuries occurred between vessel speeds of 8.6 and 15 knots.[16]

[16] A regression model demonstrates that at vessel speed above 15 knots the probability of a lethal injury asymptotically approached 1. Speeds of less than 8.6 knots are shown to result in nonlethal injuries define as minor or no apparent injury.

Another solution has been to reroute vessel transits around areas of high whale density. Many researchers (e.g., Russell, et al. (2001), Nichols et al. (2005), Redfern et al. (2013), Conn et al. (2013), Dransfield, et al. (2014)) have commented on this through recommendations of alternative routes or suggesting that certain routes be followed. Additional recommendations cited geographic areas to be avoided included Abramson et al. (2009), Betz et al. (2011). These spatial solutions also can include the establishment of areas to be avoided, which are often seasonal in nature (Van der Hoop et al. (2012)).[17] In noting the wide-scale of the problem of vessel strikes on whales, Flynn (2019) stated:

"Ship strikes of whales are a growing concern around the world and especially along the U.S. West Coast, home to some of busiest ports in the world and where ship strikes on a number of species including blue, fin, and humpback whales have been documented"

Many researchers have documented that the problem of vessel strikes is quite pervasive. Monnahan et al. (2014) postulated that the problem ran from the Channel Islands National Marine Sanctuary (CINMS) to the northern portions of the U.S. West Coast.

4.3. Types of Vessel Speed Reduction Requests

Requests for reductions in vessel operating speeds to protect endangered whales have been trialed and established on both voluntary and mandatory bases.[18] Lagueux et al. (2011), Nathan Associates (2012), Silber et al. (2012, 2012a, 2012b), Mullen et al. (2013), Van der Hoop et al. (2012) and Conn et al. (2013) have reported on mandatory speed reduction measures that have been implemented along the East Coast of the U.S. to protect the North Atlantic Right Whale. Following the first year of the rule's implementation, NOAA's Office of General Counsel began issuing Notices of Violation and Assessment of civil

[17] These are also referred to as Seasonal Management Areas (SMAs).

[18] Some of the requests have also included altering the routes taken by vessels.

penalties (NOVAs), to some of the more egregious violators (Silber et al. 2012). Thus far, fines have ranged from $5,750 to $92,000 (Silber et al. (2014))

Incentive-based VSR efforts implemented by ports have shown success at achieving and maintaining high levels of cooperation from large vessel operators. The Ports of Los Angeles and Long Beach have employed incentives to reward vessels for slowing down to 12 knots when they were within 40 nautical miles. In addition, the Port of Long Beach also rewards ships that have newer and cleaner engines through financial incentives (e.g., lower dockage fees) and public recognition through their "Green Flag Program".[19]

Starting in 2007 for the Channel Island Sanctuary area of southern California and in 2012 for the central California sanctuaries study area, NOAA implemented VSR requests for all vessels ≥ 300 gross registered tons (GRT) transiting within specified zones to reduce speeds to 10 knots or less during peak whale abundance. In the San Francisco Bay region, the seasonal VSR request is in effect from May 1st through November 15th. VSR requests are communicated through the U.S. Coast Guard's published and broadcast local notice to mariners, NOAA weather radio, and through letters signed by NOAA regional administrators and the USCG Rear Admiral, which are sent to all companies with vessels that frequent the area. Voluntary cooperation levels – as measured by the percent of total distance traveled at 10 knots or less - in the San Francisco Bay region with NOAA VSR requests has improved in recent years, from 45% in 2017 to 64% percent in 2020 across all vessels 300 GRT or larger. Refer to Table 1.

Table 1: Percent of Vessels GE 300 GRT Travelling At Or Below Requested Slow Speeds

REGION	2017	2018	2019	2020
San Francisco Bay Region NOAA Voluntary Slow Speed Request	45%	45%	58%	64%

Request [19] Shipping News. 2019. "Ships Slow Down For Cleaner Air-Port of Long Beach's green Flag Program Rewards Ocean Carriers", MI News Network, June 28.

Southern California Region NOAA Voluntary Slow Speed	18%	23%	50%	54%

Source: https://nmsfarallones.blob.core.windows.net/farallones-prod/media/docs/20190815-blue-whales-and-blue-skies.pdf

In 2014 in Southern California, in response to low adherence recorded by NOAA with voluntary VSR requests, an incentive-based VSR program – known as the Protecting Blue Whales and Blue Skies Program - was initiated between NOAA's Channel Islands National Marine Sanctuary, county air district agencies, and NGO partners and was expanded to include study areas in the San Francisco Bay region in 2017.[20] This program offers enrolled companies financial incentives (e.g., reductions in dockage fees) as well as positive press for high adherence with the slow speed requests which runs from May 15th to November 15th each year. Companies were also offered the option of turning down incentive payments and several did so in favor of receiving additional public recognition for their high level of cooperation.

5. BASIS OF STUDY

5.1. Previous Research Approaches

A wide variety of economic analysis approaches have been employed to assess the financial impacts of changes in vessel transit times. This has manifested itself in assessing monetary impacts to vessel owner and shipper profitability (Kite-Powell et al. (2002), Reeves et al. (2007), Chang et al. (2012)) and changes in port infrastructure and management (Le-Griffin et al. (2006)) due to increased vessel transit times have been addressed. Methods include value and costs associated with whale watching input-output analysis, non-market willingness to pay (Giraud et al. (2002), Farr et al. (2014), and Onofri (2015)) and travel cost methods (Hoagland et al. (2000)) have been employed. Refer to Table 2.

[20] Refer to: https://www.ourair.org/air-pollution-marine-shipping/

Table 2: Examples of Economic Impacts From Previous Studies

AUTHOR(S)	OBJECTIVE	RESULT FOCUS	RESULTS ADJUSTED TO $ 2019
Nathan et al. (2012)	Assess the economic impact of the 2008 North Atlantic Right Whale rule	Direct impact to shippers Indirect impact to shippers Impact on commercial fishing	$29.8 Million $19.7 Million $1.1 Million
Corbett et al. (2009)	Is vessel speed reduction a cost-effective CO_2 mitigation option?	Fuel tax of $150 per ton would decrease CO2 emitted by 20%-30% Speed reduction mandate targeted to reduce CO2 emissions by 20% cost	$211 per ton $42 - $281 per ton
Kite-Powell et al. (2002)	Cost to shippers along the US East Coast of reducing ship speed to 10 knots when traveling in/out of ports over a distance of 25 nm during an annual season lasting 60 days	Average cost (related delay costs) per ship call Average cost per affected ship call Average cost of management measure per port Total annual cost to US East Coast shipping industry	$704 $3,309 $2.9 million $14.1 million
Betz et al. (2011)	Four management scenarios analyzed with respect to impacts on shippers	Year-round mandatory speed reduction to 10 knots Seasonal mandatory speed reduction to 10 knots Narrow the TSS in the channel Shift the TSS to the south of the channel Total annual cost incurred by all the	$3.0 million $1.3 million $67,709 $23.6 million

		ships in the model Total annual industry costs	$3.6 billion $36.0 billion
Silber et al. (2012)	Evaluate the effectiveness of the 2008 North Atlantic Right Whale Ship Strike Reduction Rule	Maximum total (direct and indirect) economic impacts Using 2009 bunker fuel prices Using 2012 bunker fuel prices	 $65.5 million and $98.6 million $61.5 million and $92.7 million
Gonyo et al. (2019)	Evaluate impact of speed reductions and/or routing changes on the Channel Islands National Marine Sanctuary	Changes in total vessel costs (before and after) Baseline Costs No changes in routes (10 knot) limit No change in routes (12 knot limit) Altered routing (10 knot) Altered routing (12 knot) Reroute only	 $73.0 million $71.5 million $71.9 million $74.0 million $74.5 million $70.5 million

6. STUDIES ON VESSEL EMISSIONS

Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x), Particulate Matter ($PM_{2.5}$ and PM_{10}) and Carbon Dioxide (CO_2) are combustion products that are emitted into the environment in the form of engine exhaust. SO_2 emissions are mainly due to the presence of sulphur in the fuel burned. NO_2 is produced from the reaction of nitrogen and oxygen gasses in the air during combustion, especially at high temperatures. PM of varying dimensions come from finely divided solids or liquids that includes dust, fly ash, smoke, soot, fumes, mists and condensing vapors.[21] All may be suspended in the air for extended periods of time. Lack et al. (2012) reports that black carbon (BC) is a component of fine particulate matter ($PM_{2.5}$) and unlike other pollutants tends to decline with increases in engine speed.[22] CO_2 occurs from many natural sources including combustion of organic matter, volcanic outgassing and mainly from burning of fossil fuels for power generation and transportation. It has been of increasing concern owing to its contribution to increased climate temperature.

There is a lot of work on this topic. Pope et al. (2002) remarked that these emissions have been linked to a wide variety of morbidity issues (e.g., chronic and acute cardiopulmonary diseases) as well as premature mortality – especially among those with compromised health conditions. Wang et al. (2007a) estimated that in 2002 North American shipping consumed about 47 million metric tons of heavy fuel oil and emitted 2.4 million metric tons of SO_2.

Buhaug et al. (2009) estimated that containerships were among the largest maritime emitters of CO_2. He stated that while there were only about 4,100 containerships operating throughout the world (about four percent of the entire registered fleet) they consumed over 70 million metric tons of bunker fuel and emitted over 230 million metric tons of CO_2. Olmer et al. (2017) reported that three ship types accounted for 55% of the total shipping CO_2 emissions: container ships (23%), bulk all other carriers (19%), and oil tankers (13%).[23]

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[21] Overall, PM comes in a variety of sizes (e.g., 10 micrometers) with 2.5 micrometers in diameter posing the greatest risk to health.

[22] (PM2.5) is particulate matter is made up of tiny pieces of solids (soot) with a diameter of 2.5 micrometers or less. When inhaled they can get deep into respiratory systems and cause serious health problems.

[23] There are about 55,000 merchant ships that trade internationally. These include 15,106 general cargo ships, 12,258 bulk cargo carriers, 7,350 crude oil tankers, 7,027 ro-ro passenger ships, 5,664 chemical tankers, 5,307 container ships, and 2,031 liquefied natural gas tankers as of January 26, 2022. Refer to: https://www.thomasnet.com/insights/container-shipping-by-the-numbers

6.1. Societal Benefits from Reductions in Emissions

The Clean Air Act requires the Environmental Protection Agency (EPA) to establish ambient air quality standards for nitrogen oxides, ozone, particulate matter, carbon monoxide, sulphur dioxide and lead which are considered to be harmful to public health and the environment.[24] One method to control pollution is a market-based approach which provides economic incentives for reducing emissions. Under such a program, a central entity sells or allocates a limited number of permits that allows release of a specific volume of pollutant over a set time period. California's cap and trade program was among the first and is among the largest across the world.[25] Under their program, polluters can be made to pay for each ton of CO_2 they emit which provides them with incentives to lessen emissions on their own. Under such a system, reported cap and trade costs of emissions do not necessarily reflect total societal costs as valuations reflect market forces which may be impacted by external events (e.g., periods of economic downturn). As such, emission costs in this study are based on scientific estimations of societal costs across a number of sectors rather than cap and trade market results.

Wang et. al (1994) estimated emission values for several pollutants per ton across 17 major metropolitan areas.[26] Adjusted to $2019 values in metric tons, he reported damage-based costs for the San Francisco area for ROG and PM_{10} was $3,415 and $11,265, respectively.[27]

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[24] Refer to: https://www.epa.gov/naaqs/nitrogen-dioxide-no2-primary-air-quality-standards

[25] California passed the Global Warming Solutions Act (AB 32) in 2006. It was signed into law on September 27, 2006.

[26] Table S.1, Damage based emission values, Page 5

[27] ROGs (Reactive Organic Gases) are the result of fuel combustion and through the evaporation of organic solvents (excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate). PM10 is particulate matter is made up of tiny pieces of solids (soot) with a diameter of 10 micrometers or less. When inhaled they can get deep into respiratory systems and cause serious health problems.

Table 3. Estimations of Societal Emission Damage

SELECTED EMISSIONS (EMISSION ABBREVIATION)	DAMAGES PER METRIC TON ADJUSTED TO ($2019 DOLLARS) [28]	GLOBAL MEAN SURFACE TEMPERATURE IMPACT[29]	PATHWAY TO COMPOSITION – HEALTH IMPACTS
Carbon Monoxide (CO)	$769	Warming	Surface Ozone
Carbon Dioxide (CO_2)	$102	Warming	None
Nitrogen Oxide (NO_x)	$81,740	Cooling	Surface $PM_{2.5}$ and ozone
Sulphur Dioxide (SO_2)	$51,240	Cooling	Surface $PM_{2.5}$
Methane (CH_4)	$5,612	Warming	Surface Ozone
Ammonia (NH_3)	$30,500	Cooling	Surface $PM_{2.5}$
Black Carbon (BC)	$329,400	Warming	Surface $PM_{2.5}$

Source: Shindell, Table 1 and Table 2

Shindell (2015) estimated monetary damages across a number of pollutants. Estimated damages across several pollutants are delineated in Table 3. The Interagency Working Group on Social Cost of Carbon (2010) estimated the cost of CO2 at $113 per ton.30 This equates to $125 per metric ton ($2019). Muller et al. (2006, 2011) reported results from the Air Pollution Emissions Experiments and Policy Analysis (APEEP) model. They reported the cost per metric ton of PM2.5 was $49,522 ($2019) in San Francisco. It is designed to estimate the marginal epidemiological, value of human health effects and concentration

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[28] Refer to: Shindell (2015) Table 2, Median Total (3% discount rate), page 319.

[29] From Shindell. (2015) Table 1 "The global mean surface temperature impact is also a proxy for the many additional climate impacts that occur alongside global mean temperature change, including changes in sea-level, rainfall, heatwaves, etc." page 315.

[30] Page 31.

damages of emissions in almost 10,000 districts in the contiguous U.S. Nebel et al. (1958) reported that the impact of engine speed on the concentration of oxides from nitrogen is complicated but as engine speed increases, higher levels of NOx emissions result.[31]

7. MARINE FUEL USE AND COST

Between 1985 and 2000 when oil prices either fell or were fairly constant, vessel energy efficiency was not a major concern. This is reflected in Corbett et al. (2009) noting characteristic speeds of newer containerships (increased to) between 20 and 23.7 knots.[32]

Although marine shipping based on mechanical specifications may be capable of relatively high speeds, vessels are often operated at "economic" speeds that are less than the speeds they could sustain based on their design.[33] This difference is driven by the desire of the ship owner to optimize the best overall financial result over the economic life of the vessel. The USACE has noted that economic speeds traditionally can be 14 to 18 percent less than service speed. This practice has increased in recent years with the increase in the cost of marine fuels which are the dominate portion of total vessel operating costs.[34] As Liang (2014) states:

> *"Slow steaming is no longer a new concept to shipping. The practice of deliberately slowing down the speed of a ship is in fact a common operating feature of today's shipping market as a way to lower costs by reducing fuel consumption."*

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[31] This is due in part to increased aggressiveness of compression and higher combustion temperatures.

[32] Representing the 25th and 75th percentiles, Table 1, Page 595.

[33] Referred to as slow steaming.

[34] Source: Kevin Knight and Ian Mathis, USACE, Institute for Water Resources, Appendix H: Guide to Deep-Draft Vessel Operating Costs, Page H-28, 2010.

7.1. Changes in Vessel Emission Regulations

The Californian Air Resource Board (CARB) since July 1, 2009 has required use of marine diesel oils (MDO) or marine gasoils (MGO)[35] in Californian waters.[36] Reported by the Energy, Finance and Future Weekly, heavy fuel oil (HFO), also referred to as "Bunker C" while relatively inexpensive and used extensively, was responsible for 15 percent of global Sulphur dioxide (SO_2) emissions.[37] Paris (2019) later opined that 13 percent of world-wide sulphur-dioxide emissions came from shipping**.** Due to the level of pollutants, especially SO_x and related emissions, the International Maritime Organization (IMO) issued new ship emission regulations (IMO 2020) that requires vessels use lower-Sulphur bunkering fuel effective January 1, 2020.[38] Under the IMO 2020 standard, in addition to the 0.5 percent Very Low Sulphur Fuel Oil (VLSFO), shippers can employ Low Sulphur Marine Gas Oil (LSMGO) with a Sulphur content of 0.1 percent to replace the currently used High Sulphur Fuel Oil (HSFO) that contains up to 3.5 percent Sulphur content.[39] Refer to Table 4

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[35] Marine gasoil describes marine fuels that consist exclusively of distillates. Similar to diesel fuel MGO has a higher density. It does not have to be heated or centrifuged as does Heavy Fuel Oil (HFO).

[36] The following regulations are in force when operating within the 24 nautical mile regulatory zone off the California Coastline: From 1 July 2009, Marine gas oil (MGO) at or below 1.5% Sulphur content, or Marine diesel oil (MDO) at or below 0.5% Sulphur content. From 1 January 2012, Marine gas oil (MGO) or Marine diesel oil (MDO) at or below 0.1% Sulphur content.

[37] Source: https://lookbackatchina.wordpress.com/2014/07/09/the-end-of-the-era-of-heavy-fuel-oil-in-maritime-shipping/; July 9, 2014 by Haifeng; downloaded May 14, 2015.

[38] Emission control areas include: (1) The Baltic Sea Area; (2) the North Sea Area; (3) the United States; (4) Canada; and the United States Caribbean Sea area.

[39] The term HVO (Heavy Viscosity Oil) is often used interchangeably with HFO (Heavy Fuel Oil). This is as opposed to IFO (Intermediate Fuel Oil) and the more refined distillates of MDO (Marine Diesel Oil) and MGO (Marine Gas Oil). HVO or HFO is what is often referred to as residual oil, bunker C oil or bunker number 6 (and sometimes bunker number 5) fuel oils. IFO is usually a blending of HVO and MDO (traditionally about 10 percent MDO give or take though this specification may have changed as IFO is not as commonly used anymore for shipping). The ranges in viscosity for these four basic classes of fuel are based on

Table 4 Dominant Marine Fuel Types

FUEL TYPE	DESCRIPTION	SULPHUR CONTENT
VLSFO	IMO 2020 grade bunkers	Maximum 0.5% sulphur
LSMGO	Compliant with 2015 Emission Control Areas (ECA) regulations[40]	Maximum 0.1% sulphur
HFO	Heavy Fuel Oil[41]	Cap of $3.5% sulphur Most common 2.5% sulphur[42]
MGO	Marine Gasoil	Maximum 1.5% sulphur

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ranges for centistoke-equivalent with the heaviest fuels approaching or exceeding 380 Ct. and with IFO being in the range of between 180 Ct. and 380 Ct. with the vast majority being closer to 180 Ct.. Most of these fuels now have low-sulphur designations or variants as well and usually will employ the "LS" in labeling to indicate as such (i.e., LSHVO, LSHFO, LS+380, LS-C, etc.)

[40] Emission Control Areas (ECAs) also referred to as Sulphur Emission Control Areas (SECAs), are areas of the sea where stricter controls were established to minimize airborne emissions from ships as defined by Annex VI of the 1997 Maritime Pollution (MARPOL) Protocol. Regulations on these emissions (SOx; NOx; Ozone Depletion (ODs); and, (4) Volatile Organic Compounds (VOCs) began in May 2005. Beginning in July 2010, a more stringent version of Annex VI was enforced in the ECAs with significantly lowered emission limits. As of 2011 there were four existing ECAs: the Baltic Sea, the North Sea, the North American ECA, including most of US and Canadian coast[5] and the US Caribbean ECA.

[41] Source: U.S. Energy Information Administration (EIA, August 2019, 2020)

[42] https://www.exxonmobil.com/en/marine/technicalresource/news-resources/imo-sulphur-cap-and-mgo-hfo#:~:text=The%20current%20global%20sulphur%20cap,today%20%2D%20is%20around%202.7%25.

7.2. Industry Impact

Paris (2019) reported that the new fuel guidelines are estimated to impact the approximate 60,000 vessels in international trade. At the time of this statement, industry executives estimated that they would have to pay a 25 to 40 percent premium on fuel.[43] With heavy or residual fuels then costing about $440 per metric ton, this would place future costs between $550 and $616 per metric ton. Their estimates appear high since as of July 2020 prices of low-sulphur fuels was about $317 to $369 per metric ton. (Refer to Table 5). Blackmon (2020) reported that the majority of shippers had chosen to use lower-sulphur fuel. Macleod (2019) stated that scrubbers cost his firm between two and four million dollars per vessel with an expected payback of 18 months or less.[44] In this analysis, the USACE recommended average fuel costs from 2017 to 2019 be employed to represent a more accurate and acceptable assessment of long-term fuel cost. MGO average costs were $648 per ton while HFO costs were $351 per ton. Main or primary system bunkerage costs were based on a weighted average of two-thirds HFO and one-third (MGO) was employed ($449 per ton).

Auxiliary power to support aboard operational and environmental loads including interior climate control, lighting etc. can sometimes be powered at least in part through power take-off (PTO) unit from main propulsion engines or from one or more standalone auxiliary engines. In this study it was assumed that the fleet employed stand alone and main propulsion PTO sources of auxiliary power in equal proportions employing scrubbers where appropriate. The cost of fuel for auxiliary power was set as the average of HFO and MGO prices (assessed at $500 per ton).

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[43] This would have an impact on fuel for both main propulsion and auxiliary power engines,

[44] Robert Macleod, CEO, Frontline Management A/S, a Norway-based tanker firm in The Wall Street Journal's *"Maritime Emissions Rule Triggers Split in Shipping Costs*", December 20, 2019. Story by Costas Paris. Scrubber retrofitting costs to facilitate use of higher sulphur fuel oil would be offset through the use of lower cost fuels.

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8. ANALYTICAL APPROACH

8.3. Study Area Traffic

Employing AIS data for all of calendar year 2019, almost 5.3 million AIS trip segments were reported within the study area.[45] When the trip segments were merged, a total of 10,780 "trips" were identified. These trips represent reporting of a vessel's position (by latitude and longitude) across adjacent points in time when the vessel was within the geographic boundaries of the study area. They may be short duration movements which merely cut across a small portion of the trapezoidal study area or reflect longer east-west or north-south movements.

In the study, over 1,200 unique cargo vessels were identified by IMO number.[46] Overall, container ships and tank vessels accounted for the majority of vessel traffic in the VSR areas during 2019. Refer to Figure 2. Rather than use self-reported AIS data where multiple IMO numbers can be seen to have been assigned to the same vessel, the USACE's NNOMPEAS data, based on vast inventories of individual vessel demographics from IHS / Lloyds Register-Fairplay, [47] Clarkson's Specialty Registers and the Waterborne Lines of the United States[48] was employed to verify, augment and enhance identification of individual vessel attributes.

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[45] Distances between individual vessel AIS reports represent a "trip segment". Concatenation of contiguous trip segments represents a "trip".

[46] The vessel types of only six vessels could not be identified.

[47] IHS Markit acquired the remaining 49.9 percent of Lloyds Register-Fairplay on June 18, 2009.

[48] The Waterborne Lines of the United States database, compiled by the Waterborne Commerce Statistics Center., is available internally to the USACE.

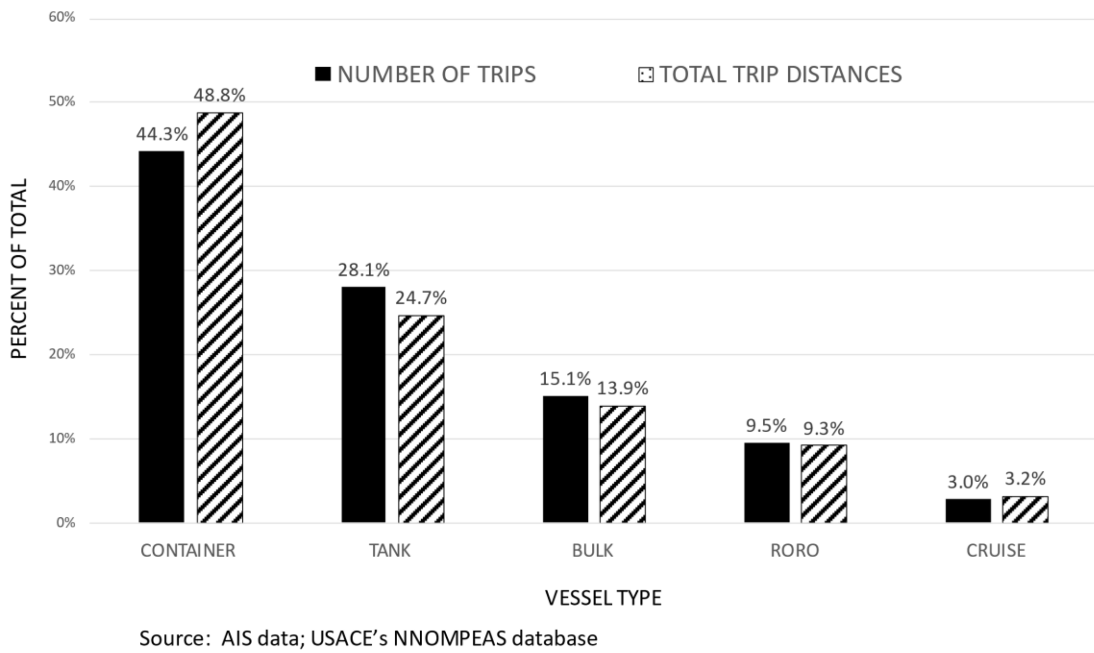

Figure 2 Containers Dominate Trips and Distance Through the Current VSRs

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9. COST DEVELOPMENT CONSIDERATIONS

9.1. Commodity Value

During vessel transit, vessel cargo owners face opportunity costs resulting from having assets tied up as inventory. This is referred to as Inventory Carrying Cost (ICC). If a vessel's trip time is extended through reduction in vessel speed, additional costs are borne by the cargo owner. In 2019 over $81.0 billion in cargo value was handled within the San Francisco Port District (SFPD). This represented transport of more than 59.2 million metric ton. Cargo or inventory value per ton in the SFPD was calculated on a weighted per metric ton basis based on the commodities typically carried by vessel type.49 Refer to Table 5. Regardless of the vessel size this approach enables individual vessel calculation of inventory carrying costs based on estimated cargo tonnage alone.

Table 5 Vessel Assignment By Commodity Group and Value

VESSEL TYPE	**HOW IDENTIFIED**	**IHS CODES INCLUDED**[50]	**AVERAGE VALUE PER METRIC TON ($2019)**[51]
Container (Many Commodities)	Traffic is specifically identified as "container" in USA Trade Online	Not Applicable.	$3,024
Ro-Ro (Finished Vehicles)	4 Digit HS Codes in "non container" vessels	IHC Codes 8701 to 8707	$16,579
Tank (Crude Oil and Refined Petroleum Products plus other bulk fluids,e.g., chemicals)	4 & 6 Digit HS Codes in "non container" vessels.	IHC Codes 2707 to 2942	$474
Bulk, General and All Other	6 Digit HS Codes	Remaining IHC codes not identified above moving in non-container ships	$333

Source: U.S. Department of Commerce, U.S. Census Bureau, USA Trade® Online

[49] Source: USA Trade Online

[50] Abbreviations as they appear in the code

[51] The overall cargo value of traffic during 2019 in the SPFD district averaged $1,368 per metric ton

9.2. Trip Distances and Transit Times

Based on reported latitude and longitude of individual transit segments in AIS, trips were developed for each unique vessel movement. Each trip had a distance and elapsed time calculated. Added transit times (e.g., the difference between reported transit speeds in the VSR and the recommended 10 knots in the VSR) were calculated and summed by vessel type.[52]

9.3. Cargo Capacity and Inventory Carrying Cost

As vessel size becomes larger a smaller proportion is often represented by non-cargo weight or components of DWT (e.g., stores, fresh water, fuel, crew, etc.).53 Based on USACE estimates, cargo carrying capacity was estimated to range between 80 and 95 percent of vessel DWT. Differences in transit speed were applied by transit distance to estimate augmented cargo (inventory) carrying costs due to the added time to traverse greater distances.54

9.4. Main Propulsion and Auxiliary Fuel

Traditionally, fuel use has represented a dominant portion of total vessel operational costs. Fuel utilization for main propulsion is highly variable and a function of transit speed and immersed draft while fuel employed to run auxiliary systems (i.e., electrical power) are relatively uniform with little if any changes

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[52] All vessels in the study data base had been reported in NNOMPEAS data base. Only 0.3 percent of the 7,300 vessel trips in the VSR were excluded due to unrealistic average transit speed which exceeded vessel deign maximum speed.

[53] Estimates of cargo carried was based on a percentage of reported deadweight tonnage (DWT) which is a measure of how much a vessel can carry by weight. It is not a measure of the vessel's weight itself (light displacement tonnage) but rather is the sum of the weights of cargo, fuel, fresh water, variable ballast water, provisions, passengers, crew and stores.

[54] Simply the cargo value (per ton) multiplied by the number of added hours in transit by the opportunity cost of capital as defined by the commercial paper rate (CPR). Commercial paper is often employed as an unsecured short-term loan by a corporation to finance inventories and receivables. In 2007, the CPR was about 5.5 percent. Source: Federal Reserve Bank of St. Louis. See: https://fred.stlouisfed.org/series/RIFSPPFAAD90NB. As of April 2018, the rate was over five percent. For the purposes of this analysis, a CPR of five percent was utilized.

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over the speed range of the vessel.[55] In the case of main propulsion, fuel use estimates were based on over 400 combinations of vessel speed and displacement depth for each vessel size and type. From these numerous point estimates, continuous fuel cost functions were developed for operations at sea for each vessel type and size combination. Employing an exponential specification, fuel use equations and coefficients of determination (R^2) were developed. R^2s for all fuel use estimations exceeded 0.99.

Vessel speeds are governed by both a lower and upper figure. The upper figure represents the maximum long-term speed the vessel can economically and physically maintain while the minimum speed is the lowest continuous speed that the vessel can be safely handled or operated with sufficiently stable engine operation. Mathis states:

"From a speed versus handling perspective, control in many ways is reduced with slower speeds, and independent hull control without external assistance is important in the offshore environment due to the typical lack (or reduced effectiveness) of tug assistance for offshore environments and the more significant wind and wave conditions that typically prevail in the offshore areas versus protected waters. Within protected waters and more confined reaches of the waterway, containerships may be able to operate at noted speeds within harbors (typically 8 to nearly 12 knots for many harbors) as engine operation is acceptably stable because the power to move the vessel in confined channels is greater than in comparatively open water due to bottom and bank suction or hydraulic displacement force (i.e., the power required to move the vessel at 12 to 14 knots at sea will move the vessel at considerably slower speeds within comparatively more confined channel prisms in protected reaches of the harbor and its supporting waterway system). Correspondingly, the issue again is stability of engine operations. Historically, at engine capacity below 46 to 58

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[55] Fuel cost as a portion of total costs is highly variable and is based on vessel size, vessel type and operating speed. In vessels operating at maximum design capacity (e.g., 25 knots), fuel costs for propulsion may represent 80 to 90 percent of total costs. In these cases, auxiliary fuel use would probably represent less than five percent of total costs. In cases where vessels were slow steaming (e.g., 10 knots), propulsion fuel costs would might be reduced to between 20 to 30 percent of total costs while auxiliary fuel costs might increase to 15 or more percent representing the added time it takes to perform the voyage.

percent of service speed (depending on vessel type, specifications or engine configuration, and other conditions) engine operation often becomes unstable and trying to run the prime mover at such levels of engine capacity often becomes impractical and can tremendously accelerate wear or possibly results in damage or increased maintenance, especially given the nature of how diesels operate and more directly, given that vessels typically or almost exclusively employ two-stroke slow-speed diesels for many of the medium to larger size vessels. There has been experimentation with practices of "bumping" where the engine is periodically run for a short time up to a certain speed and then shut down, allowing the vessel to coast followed by subsequent such cycles but this has been demonstrated to result in inordinate wear or stress on propulsion systems with increased maintenance and sometimes damage in addition to emissions issues. The perspective to keep in mind is that bulk and tanker vessels are more full-bodied and designed for slower speeds to so that operations at or about or near 50 percent of service speed provides for notably lesser speeds than for many or most fully cellular containerships."[56]

9.5. Societal Cost of Emissions

As emissions are a reflection of fuel utilization, they are calculated in a method similar to the methods employed to estimate fuel use. For each of the 400 or so point estimates for fuel use based on vessel type, speed and depth, resultant levels of emissions were calculated. From these
point estimates, continuous functions were developed in the same fashion as those employed to estimate fuel use.[57] Coefficients of determination (R^2) developed for emission estimations using exponential functions all equaled or exceeded 0.91. Based on estimated tons by pollutant emitted during each reported vessel trip,

[56] Source: USACE, Correspondence with Ian Mathis, March 22, 2016, October 6, 2020 and September 21, 2021.

[57] It should also be noted that NNOMPEAS model emission estimation volumes have been reviewed by the Environmental Protection Agency (EPA).

societal costs were estimated based on costs per ton provided by several sources (e.g., Shondell (2015), Muller et al. 2006, 2007)).

9.6. Vessel Capital and Overhead Costs

Vessel capital costs are relatively linear in nature relative to time. The higher the speed of the vessel, the lower total capital costs for the trip and vice versa. Hourly vessel capital cost was developed based on the estimated cost of the vessel (adjusted for salvage value) including the cost of scrubbers.[58] Overhead costs associated with depreciation, insurance, stores, crew compensation, etc. estimated by NNOMPEAS were also added to vessel type and size. Individual vessel costs were determined through addition of capital and overhead costs times the duration time of the vessel trip. These costs were later summed by vessel type.

10. VESSEL DESIGN AND MINIMUM SPEED LIMITATIONS

Due to their hull design and engine configuration, not all vessels can be safely operated at significantly slower speed. When evaluating speed restrictions for deep-draft cargo carriers, a critical underpinning for evaluations is understanding speed generally cannot be continuously reduced below minimal speed or power employment thresholds which are often a consequence of economy and efficiency of propulsion configuration and vessel design. Most moderate to large displacement hulls employ directly-coupled slow-speed diesel engines which simply require a given minimum engine speed and operating power level for stability of engine operation. Applied engineering relationships for prime mover design tend to result in a minimum speed typically equal to approximately one-half of the vessel's service speed rating with variability of minimum speed for a given vessel depending on an array of considerations related to actual operating conditions.

Such considerations include currents, waves, and wind in addition to variability of

[58] This included the cost of TEUs on container vessels.

hydraulic resistance corresponding to hull form, immersed draft and age or state of engine maintenance.

Given these general characteristics as described many relatively new fully cellular containerships constructed to support service speeds of 22 knots or more often have minimum speeds of approximately 11 to slightly more than 13 knots depending on variability of operating conditions while older containership hulls constructed around capabilities for speeds of 19 to 21 knots or less can often acceptably undertake minimum speeds of approximately 9 to 11 knots. Smaller containerized feeder vessels as well as most liquid and dry bulk carriers which tend to have service speed parameters significantly less than more current moderate to large line haul containerships can often support minimum speeds marginally under 10 to 11 knots based on service speed parameters of less than 20 knots with most of these designs having service speed ratings of 18 knots or less.

The safety deviation provision provided mariners with an exemption if conditions existed that restricted vessel maneuverability preventing safe navigation at speeds of 10 knots or less. Navigational safety is of paramount importance to NOAA. When the agency published the final rule implementing the 10-knot vessel speed restriction on the East Coast (73 FR 60173, October 10, 2008) the rule included a provision allowing vessels to deviate from the speed rule under certain conditions for reasons of safety.[59]

11. COSTS OF COMPLIANCE

Periods of vessel transit speeds during the VSR timeframe results in both linear and exponential impacts on vessel transportation costs. Costs associated with increased ICC, vessel and container capital, vessel overhead and auxiliary fuel costs and resultant emissions are linear in nature meaning that if the transit time on one trip is doubled, these costs for that trip would also double. At the same

[59] Specifically, the rule states that “a vessel may operate at a speed necessary to maintain safe maneuvering speed instead of the required ten knots only if justified because the vessel is in an area where oceanographic, hydrographic and/or meteorological conditions severely restrict the maneuverability of the vessel” (50 CFR § 224.105 (c)).

time, vessel speed reduction will decrease fuel use and resultant emissions for prime mover operations. Levels of both fuel use and consequential emissions follow exponential functions and decrease correspondingly due to lowering vessel speeds. As these cost estimates were made several years following implementation of the VSR zones, reductions in vessel speeds had already largely occurred. To estimate the full private and societal impact of speed reductions, vessel operational characteristics during pre-VSR times were estimated from vessel movements during times in the VSR area during non-speed reduction times as well as general operating demographics of vessels in the surrounding Cordell Bank, Greater Farallones and Northern area of the Monterey National Marine Sanctuaries.

11.1. Inventory Carrying Cost

Calculations for tank, ro-ro and bulk vessels were estimated by multiplication of available deadweight tonnage times cargo value times the commercial paper rate times the duration of the trip. Annual ICC in the VSR approached $5.9 million during 2019.[60] Refer to Table 6.

*T*able 6 Inventory Carrying Costs

VESSEL TYPE	ANNUAL ICC FOR ALL VESSELS ($ MILLIONS)	ICC INCREASE DURING VSR TO ATTAIN MAXIMUM 10 KNOT SPEED / 12 KNOTS FOR CONTAINER VESSELS ($ MILLIONS)	PERCENT CHANGE IN ICC DURING YEAR FROM TO ATTAIN 10 KNOTS	PERCENT CHANGE IN ICC DURING YEAR TO ATTAIN 12 KNOTS (CONTAINERS ONLY)
Bulk	$0.10	$0.01	10.0%	Not Applicable
Cont ainer	$3.71	$0.45 / $0.37	12.2%	10.0%

[60] As cruise vessels are not primary carriers of freight cargo, there were excluded from ICC calculations.

RO-RO	$1.02	$0.11	10.8%	Not Applicable
Tank	$1.05	$0.05	4.8%	Not Applicable
Total	$5.89	$0.62 / $0.54	10.5%	9.1%

Adherence to 10 knots for all vessels would result in an increase of about $0.6 million (about 10.5 percent) over the entire year. If container vessels were allowed a minimum speed of 12 knots, total annual ICC would increase by 9.1 percent.

11.2. Vessel Capital & Ongoing Operating Costs

Annual capital costs were developed by the USACE based on vessel type and DWT class or weight. First, annual vessel 2019 replacement less scrap costs for each vessel group were calculated based on the assumptions that the vessel was foreign flag (flag of convenience)[61], employed the use of high sulfur Heavy Viscosity Oil (HVO) fuel with scrubbers and typically have a 25-year economic service life.[62] Hourly vessel operating costs from insurance, maintenance, amortization and depreciation, stores, crew wages, insurance, etc. for each vessel

[61] The Institute of Shipping Economics and Logistics (2010) estimated that 86 percent of tonnage attributed to North American shipping companies was operated by foreign flag carriers. This number has undoubtedly increased as the DOT reported in 2010 the U.S. fleet represented 0.7 percent of the oceangoing self-propelled cargo carrying vessels of 1,000 or more tons declined to 0.4 percent in 2019. In addition, a 14.1 percent decline in the total DWT capacity of U.S. vessels occurred (4,584 to 3,939 thousand) tons during the 2010 to 2019 period.

[62] Costs were based on a five year average (2016-2020) with an average year of build was considered to be 2018. These costs include closed loop and hybrid scrubbers based on costs to retrofit existing vessels and cost of inclusion at the time of new construction. It was additionally assumed that 12 to 15 days of downtime due to annual maintenance would be allotted for establishing the length of an operational year for vessels.

type and size grouping were developed and multiplied by the time it took to traverse the area of analysis.[63]

To estimate the full capital cost of container vessels, capital costs including overhead for containers (TEUs) was also estimated. Based on the average estimated number of TEUs per container vessel grouping, annual capital cost for containers was calculated.[64] Beginning with the DWT of the vessel, a loading factor representing the portion of that weight attributed to cargo was calculated. From this gross cargo weight estimate, the number of TEUs carried by container vessels was calculated based on an average of two metric tons tare weight per TEU.[65] Total annual vessel and container capital costs exceeded $19 million. Restriction of vessel speeds to no more than 10 knots during the VSR period would add $3.3 million to annual costs (a total 17.0 percent increase) due to increased ICC, capital and overhead costs, and auxiliary fuel costs). If container vessels were allowed a minimum speed of 12 knots, capital costs would increase by 15.7 percent increase for all vessels. Refer to Table 7.

Table 7 Vessel Capital Costs Including Overhead

VESSEL TYPE	ANNUAL CAPITAL COST FOR ALL MOVEMENTS (MILLIONS)	CAPITAL COST INCREASE DURING VSR TO ATTAIN MAXIMUM 10 KNOT SPEED (MILLIONS) / 12 KNOTS FOR CONTAINERS	PERCENT CHANGE DURING YEAR FROM TO ATTAIN 10 KNOTS	PERCENT CHANGE DURING YEAR TO ATTAIN 12 KNOTS (CONTAINERS ONLY)
Bulk	$0.87	$0.05	5.7%	Not Applicable

[63] Vessels built as early as 1971 were observed to have been involved in movements in the study area. As it is impractical to estimate separate capital costs for each vessel type and build year combination, the 2016 to 2020 timeframe was chosen as the basis for vessel costs. It is acknowledged that this decision will increase vessel capital costs over actual levels.

[64] Costs were based on a TEU with an average age of five years of age, 362 operational days per year, 24 hours per day and an overall 15 year expected life.

[65] Tare weight or dry weight is defined as the total weight TEU when the container is empty, meaning there is not any product in the container. Using an hourly cost of $0.039, TEU capital costs were estimated and added to container transport costs.

Container[66]	$7.52	$0.93 / $0.34	12.4%	4.5%
RO-RO	$0.99	$0.11	11.1%	Not Applicable
Tank	$5.56	$0.28	5.0%	Not Applicable
Cruise	$4.42	$1.93	43.7%	Not Applicable
Total	$19.36	$3.30 / $3.04	17.0%	15.7%

11.3. Fuel – Main Propulsion

Almost 1,100 metric tons of fuel would be saved each year if all vessels during the VSR period travelled at 10 knots. This would represent a reduction of almost $0.5 million (4.7 percent) in costs. Refer to Table 8. If container vessels were allowed to travel at a maximum of 12 knots, cumulative fuel use would decline over $0.3 million (3 percent).

Table 8 Main Propulsion Fuel Use (Metric Tons)

VESSEL TYPE	ANNUAL FUEL USE DURING YEAR	FUEL DECREASE DURING VSR TO ATTAIN MAXIMUM 10 KNOT SPEED / 12 KNOTS FOR CONTAINERS	PERCENT CHANGE IN FUEL DURING YEAR TO ATTAIN 10 KNOTS	PERCENT CHANGE IN FUEL DURING YEAR TO ATTAIN 12 KNOTS (CONTAINERS ONLY)
Bulk	1,042	-69	-6.6%	Not Applicable
Container	15,424	-745 / -355	-4.8%	-2.3%

[66] Including container costs.

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RO-RO	1,018	-50	-4.9%	Not Applicable
Tank	4,461	-152	-3.4%	Not Applicable
Cruise[67]	1,337	-68	-5.1%	Not Applicable
Total	23,282	-1,083 / -699	-4.7%	-3.0%

11.4. Fuel – Auxiliary Power

Unlike main power which changes exponentially with vessel speed, auxiliary power is largely constant regardless of vessel speed owing to the necessity of powering essential systems (e.g., bridge fitout and vessel controls, climate control, lighting, and support systems for containers, etc.) Given this relationship longer transit times simply increase the level of auxiliary power fuel use.

Lowering vessel speed would increase auxiliary fuel use as it is based on time rather than distance travelled. Almost 12 thousand metric tons of fuel are projected to be consumed during the year to power auxiliary devices. An additional two thousand metric tons in auxiliary fuel would be consumed at 10 knots for all vessels during the VSR resulting in a 16 percent cost increase. Refer to Table 10. If container vessels were allowed to travel at 12 knots, auxiliary fuel use would increase by over 1,700 metric tons and increase total annual costs by 14.6 percent.

[67] While cruise vessels are identified in the NNOMPEAS data base, estimates of their fuel use and emissions are not available. Based on the known GWT, DWT, length, width and depth of these vessels, proxy values were developed from containership standards.

Table 9 Auxiliary Fuel Use (Metric Tons)

VESSEL TYPE	AUXILIARY FUEL USED DURING YEAR	AUXILIARY FUEL USED DURING VSR AT CURRENT SPEEDS OVER 10 KNOTS	AUXILIARY FUEL USED IF ALL AT 10 KNOTS	CHANGE IN AUXILIARY FUEL USE 10 KNOTS / 12 KNOTS CONTAINERS ONLY	PERCENT CHANGE OVER YEAR 10 ALL VESSELS/ 12 KNOTS CONTAINERS ONLY
Bulk	399	157	180	23	5.7%
Container	7,646	3,361	4,312	951 / 790	12.4% / 10.3%
RO-RO	453	195	244	49	10.8%
Tank	1,558	506	587	80	5.1%
Cruise[68]	1,915	1,445	2,256	811	42.4%
Total	11,971	5,664	7,579	1,914 / 1,753	16.0% / 14.6%

11.5. Emissions – Main Propulsion

Speed reductions to 10 knots in the VSR area could reduce total emissions in excess of five thousand tons. If this occurred, societal costs from all emissions could be reduced about by $8.5 million If container vessels were allowed to transit at a maximum of 12 knots during VSR times, almost 4,200 metric tons of emissions could be eliminated with an associated savings of over $5.7 million. Refer to Table 10.

[68] Ibid.

Table 10. Main Fuel Propulsion Emissions and Societal Cost Savings

	TONS RELEASED DURING YEAR	TONS RELEASED DURING VSR WHEN SPEEDS ARE OVER 10 KNOTS	ESTIMATED TONNAGE RELEASE IF ALL AT 10 KNOTS	DECREASE IN EMISSION TONNAGE IF ALL MOVEMENTS AT 10 / 12 KNOTS CONTAINERS ONLY	REDUCED SOCIETAL COSTS ($ THOUSANDS) AT 10 KNOTS / 12 KNOTS CONTAINERS ONLY
Carbon Monoxide (CO)	210	92	83	(9) / (6)	($7) / ($4)
Carbon Dioxide (CO^2)	80,010	35,301	31,533	(3,768) / (2,742)	($384) / ($280)
Nitrogen Oxide (NO^x)	1,833	809	714	(95) / (64)	($7,758) / ($5,211)
Sulphur Oxide (SO^x)	3	1	1	(0) / (0)	($7) / ($5)
Methane (CH^4)	10	4	4	(1) / (0)	($3) / ($2)
Ammonia (NH^3)	0	0	0	(0) / (0)	($1) / ($0)
Particulate Matter ($PM^{2.5}$)	48	21	19	(2) / (1)	($120) / ($85)
Particulate Matter (PM^{10})	19	8	7	(1) / (0)	($44) / ($31)
Reactive Organic Gases (ROG)	109	48	44	(4) / (3)	($14) / ($10)
Total	82,242	36,284	31,405	(5,229) / (4,166)	(8,338) / ($5,713)

During the year, the dominant emission released were carbon dioxide, at over 97 percent of total emission tonnage. Nitrogen oxide represented just over two percent of emitted tonnages.[69] All other emissions collectively accounted for less than one percent of all emissions. Due to the greater impact of nitrogen oxides, they accounted for almost 92 percent of total economic savings from all emission reductions

11.6. Emissions – Auxiliary Power

Annual emissions in the VSR area exceeded 45 thousand tons, with the carbon dioxide representing the majority of emissions. Refer to Table 11. Similar to main propulsion nitrogen oxide represented little over two percent of the total weight of emissions; they accounted for 92 percent of total environmental costs. Slowing all vessels to 10 knots during VSR time would increase total emissions by over three thousand metric tons costing society over $5.6 million.

Table 11. Auxiliary Emissions and Societal Cost Savings

EMISSION	TONS RELEASED DURING YEAR	TONS RELEASED DURING VSR WHEN SPEEDS ARE OVER 10 KNOTS	ESTIMATED TONNAGE RELEASE IF ALL AT 10 KNOTS	INCREASES IN EMISSION TONNAGE IF ALL MOVEMENTS AT 10 / 12 KNOTS (CONTAINERS ONLY)	INCREASED SOCIETAL COSTS ($ THOUSANDS) AT 10 / 12 KNOTS (CONTAINERS ONLY)
Carbon Monoxide (CO)	108	48	56	8 / 6	$6 / $5

[69] "The amount of carbon dioxide (CO2) that is produced from burning a fuel weighs more than the amount of the fuel itself, because during complete combustion, each carbon atom in the fuel combines with two oxygen atoms in the air to make CO2. The addition of two oxygen atoms to each carbon atom forms CO2, which has an atomic weight of 44—roughly 3.6667 times the atomic weight of the carbon, which is 12." Source: U.S. Energy Information Agency, Frequently Asked Questions.

Carbon Dioxide (CO^2)	41,125	18,145	20,976	2,831 / 2,121	$289 / $216
Nitrogen Oxide (NO^x)	942	416	475	59 / 46	$4,830 /$3,760
Sulphur Oxide (SO^x)	1	1	1	0 / 0	$5 /$4
Methane (CH^4)	5	2	2	2 / 1	$2 / 1$
Ammonia (NH^3)	0	0	0	0 / 0	$0 / $0
Particulate Matter ($PM^{2.5}$)	25	11	13	2 / 1	$80 / $54
Particulate Matter (PM^{10})	27	4	5	1 / 1	$29 / $25
Reactive Organic Gases (ROG)	56	25	29	5 / 4	$15 / $11
Total	**42,289**	**18,652**	**21,557**	**2,908 / 2,180**	**$4,776 /$3,076**

If 12 knot speeds for containers only were allowed, added emissions of 1,524 metric tons would result burdening society with over $2.9 million in costs.

12. COMPLIANCE

While this study was centered on changes in operational and societal costs resulting from vessel transits, calculations of the number of vessels traveling at speeds greater than 10 knots during VSR periods were also calculated. Vessel trips under 10 knots ranged from 17 percent for cruise vessels to over 52 percent for container vessels in 2019. Refer to Table 14. When containers were allowed to travel 12 knots, their compliance increased to 69 percent, with an overall compliance rate of over 56 percent. The 10-knot figure is in line with previously reported cooperation figures for 2019 of between 50 and 58 percent for the Southern California Region NOAA Voluntary Slow Speed Request and San Francisco Bay Region NOAA Voluntary Slow Speed Request, respectively. Refer to Table 12.

Table 12. Compliance With VSR

VESSEL TYPE	PERCENT COMPLIANT (ALL VESSELS AT 10 KNOTS)	PERCENT COMPLIANT (CONTAINERS AT 12 KNOTS – ALL OTHERS AT 10 KNOTS)
Containers	52%	69%
Tank	47%	47%
Bulk	44%	44%
Ro-Ro	56%	56%
Cruise	17%	17%
Total	**49%**	**56%**

12.1. Speed Variability

While about fifty percent of vessels in the VSR defined area maintained less than 10 or fewer knots, it was also observed that overall speeds were reduced during VSR periods of time. Refer to Table 13. In addition, the variation in those speeds declined across all vessel types

Table 13. Average Vessel Speeds Within the VSR

VESSEL TYPE	AVERAGE SPEED OVER YEAR	STANDARD DEVIATION OVER YEAR	AVERAGE SPEED DURING VSR PERIOD	STANDARD DEVIATION DURING VSR PERIOD
Containers	12.4	2.93	11.3	2.76
Tank	10.5	1.53	10.2	1.30
Bulk	10.4	1.35	10.3	1.23
Ro-Ro	11.4	2.08	10.6	2.07
Cruise	12.4	2.65	11.5	2.23

13. CONCLUSIONS

13.1. Combined Private and Societal Sector Impact[70]

Combining both private and societal costs**,** calculations suggest complete compliance with the 10 knot speed limitations in designated VSR zones results in an annual increase of about $3.5 million. This represents an approximate 1.3 percent increase in total annual costs. If container vessels only were allowed a minimum 12 knot speed, total annual costs would increase by $2.1 million (about 0.8 percent). Refer to Table 14. Employing a 3.4 percent discount rate for a ten-year project, the present value of costs for complete compliance at ten knots

[70] The private sector is defined as vessel owners, operators, cargo owners, stores and fuel providers, credit providers, etc. while the societal sector is defined as the general population that can benefit from lower environmental emissions.

would be about $29.3 million. At 12 knots for container vessels only, the value of costs for all vessels would be $17.6 million.

Table 4. Summary of Private and Societal Costs (Millions $2019)

COST TYPE	ANNUAL COST	COST DURING VSR WHERE SPEED IS OVER 10 KNOTS	COST DURING VSR WHERE MAXIMUM SPEED IS 10 KNOTS	COST CHANGE DURING VSR FROM CURRENT SPEED TO 10 / 12 KNOTS[71]	PERCENT CHANGE OVER ANNUAL COST (ALL VESSELS AT 10 KNOTS)	PERCENT CHANGE OVER ANNUAL COST (CONTAINERS AT 12 KNOTS, ALL OTHERS AT 10 KNOTS)
Inventory Carrying	$6.6	$1.4	$1.8	$0.4 / $0.3	6.1%	4.5%
Vessel Capital and Overhead[72]	$17.0	$5.5	$6.5	$1.0 / $0.8	5.9%	4.7%
Main Propulsion Fuel Use	$9.5	$2.4	$2.1	$-0.3 / $-0.2	-3.2%	-2.1%
Main Propulsion Emissions	$146.0	$36.5	32.9	-$3.6 / -$1.9	-2.5%	-1.3%
Auxiliary Fuel Use	$5.9	$1.7	$2.0	$0.4 / $0.2	6.8%	3.4%
Auxiliary Fuel Emissions	$89.1	$39.3	$44.9	$5.6 / $2.9	6.3%	3.3%

[71] 12 knots for containers only

[72] Includes costs of vessel, overhead and Twenty Foot Equivalent (TEU) containers.

Total	$274.1	$86.8	$90.2	$3.5 / $2.1	1.3%	0.8%

13.2. Separate Private and Societal Sector Impacts

In the VSR zones, private costs of complete compliance with all vessels at 10 knots would be $1.5 million. This would represent an annual 3.8 percent increase. Refer to Table 15. If containers were allowed 12 knot minimum speeds, total private costs would advance by 2.8 percent ($1.1 million).

Table 15. Summary of Private and Societal Costs (Millions $2019)

COST TYPES	ANNUAL COST	COST DURING VSR WHERE SPEED IS OVER 10 KNOTS	COST DURING VSR WHERE MAXIMUM SPEED IS 10 KNOTS	COST CHANGE DURING VSR FROM CURRENT SPEED TO 10 / 12 KNOTS[73]	PERCENT CHANGE OVER ANNUAL COST (ALL VESSELS AT 10 KNOTS)	PERCENT CHANGE OVER ANNUAL COST (CONTAINERS AT 12 KNOTS, ALL OTHERS AT 10 KNOTS)
PRIVATE (Inventory Carrying, Vessel Capital and Overhead, Main Propulsion Fuel and Auxiliary Fuel Use)	$39.0	$11.0	$12.4	$1.5 / $1.1	3.8%	2.8%
SOCIETAL (Main propulsion and auxiliary Emissions)	$235.1	$75.8	$77.8	$2.0 / $1.0	0.9%	0.4%

[73] 12 knots for containers only

Total	**$274.1**	**$86.8**	**$90.2**	**$3.5 / $2.1**	**1.3%**	**0.8%**

Societal costs in the VSR zones would advance by $2.0 (with all vessels at 10 knots) and $1.0 million with container vessels only at 12 knots as added auxiliary emission costs would exceed remaining main propulsion emission cost reductions.[74] These would represent increases in societal costs of 0.9 and 0.4 percent, respectively. As vessels are operating on a flatter portion of the fuel utilization and emission curves which are modelled as exponential functions, additional reductions in speed results in lower additional reductions in fuel use and resultant emissions. At the same time, auxiliary fuel use and resultant emissions would increase on a linear basis based on the number of additional transit hours required to complete the trip at lower speed.

Societal costs in the expanded VSR zones would decline by $7.2 million (with all vessels at 10 knots) and decline by $6.7 million with container vessels only at 12 knots. These would represent deceases in societal costs of -1.3 and -1.2 percent, respectively. As vessels are operating on a steeper portion of the fuel utilization and emission curves which are modelled as exponential functions, reductions in vessel speed results in higher reductions in fuel use and resultant emissions. Overall, reductions in main propulsion emissions would more than offset increases in auxiliary emissions.

13.3. Final Perspectives

While previous studies (Gonyo et al. 2019) suggest private sector cost increases of about one percent from a similar VSR program in the Channel Islands National Marine Sanctuary, three issues should be acknowledged in putting the results from the current analysis in perspective. First, as this study is more inclusive in

[74] Implementation of the VSR several years ago no doubt resulted in reductions in total emissions and societal costs. While the original level of emissions is not precisely known it might be estimated through understanding that the number of vessel transits in the VSR were about 43 percent of those occurring in the expanded area. Based on an approximate $7.3 million value (Refer to Table 41) of reduced emissions in the expanded area, it is estimated that over $3.1 million in annual societal benefits may have already been enjoyed in the current VSR.

the identification and quantification of private costs it is not surprising that annual private cost increases of between 2.8 to 3.8 percent in the VSR zone. Second, with average vessel transit lengths of only 58 nautical miles in the VSR it should be recognized that average transit distances within the two study areas represent only a minor portion of typical overall vessel transit distances. Compared with voyage costs between San Francisco and Vancouver, BC (695 miles), Hawaii (2,500 miles), Shanghai (5,337 miles), Singapore (7,337 miles), or Melbourne, Australia (7,860 miles), added annual costs across the entire length of the voyage in the VSRs would represent only de minimis increases in total vessel and societal costs. For example, if the trip in the VSR area totaled 695 miles, the annual private sector impact would be little more than 0.3 percent (58/695 times 3.8 percent.) at 10 knot maximum speed for all vessels and just over 0.2 percent at 12 knot maximum speeds for container vessels. At longer overall transit distances, the impact would be even more de minimis as a 7,337-mile trip to Singapore would only represent little more than a 0.03 percent increase over private sector base level costs (3.8 percent times 58/7,337) with 10 knot maximum speed for all vessels and 0.02 percent at 12 knot maximum speeds for container vessels.

Third, given the contributory nature of pollutants on climate change, it is prudent to assess societal impacts resulting from vessel speed reductions. While the bulk of societal benefits from slower vessel transits have probably already been enjoyed in the VSR areas, \$6.7 to \$7.2 million in additional societal benefits might be enjoyed if reduced vessel speeds are expanded into other sanctuary areas.

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