Bren School of Environmental Science & Management
University of California, Santa Barbara

REDUCING THE RISK OF VESSEL STRIKES TO ENDANGERED WHALES IN THE SANTA BARBARA CHANNEL:

An Economic Analysis and Risk Assessment of Potential Management Scenarios

A Group Project submitted in partial satisfaction of the requirements for the degree of
Master of Environmental Science and Management

by

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An Economic Analysis and Risk Assessment of Potential Management Scenarios

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. It is a three quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Christopher Costello, Faculty Advisor

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ABSTRACT

Endangered blue, fin, and humpback whales migrate through the Santa Barbara Channel region, an area that also receives some of the highest densities of commercial maritime shipping traffic in the world. This co-occurrence of ships and whales likely carries a risk of lethal vessel strikes to whales, as demonstrated by several confirmed deaths due to ship strikes in the region. The purpose of this project is to provide a framework for the Channel Islands National Marine Sanctuary (CINMS) and the National Marine Fisheries Service (NMFS) to evaluate the economic impacts and risk implications of different management scenarios for reducing the risk of lethal vessel strikes to whales by re-routing or slowing ships in the Channel region. We developed two models, one that estimates the change in relative risk of a lethal strike based on predicted whale distributions and a second that calculates the change in total cost to the shipping industry. We applied these models to four management scenarios. We conclude that a mandatory speed reduction has potential to be the most cost effective management option, but that further research is needed to refine our risk analysis. Ultimately, the project provides a basic methodology for analyzing the cost effectiveness of potential management scenarios for reducing the risk of vessel strikes to whales in any region where strikes occur.

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LIST OF ACRONYMS

AIS	Automatic Identification System
ATBA	Area To Be Avoided
BN	Base Number
CARB	California Air Resources Board
CINMS	Channel Islands National Marine Sanctuary
COLREGS	Convention on the International Regulations for Preventing Collisions at Sea
CRM	Coastal Relief Model
DMA	Dynamic Management Area
DWT	Deadweight Tonnage
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FOC	Flag of Convenience
IFO	Intermediate Fuel Oil
ILO	International Labor Organization
IMO	International Maritime Organization
ITF	International Transport Workers' Federation
LALB	Port Complex of Los Angeles-Long Beach
MCR	Maximum Continuous Rated power
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MMPA	Marine Mammal Protection Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OGV	Ocean-Going Vessel
PARS	Port Access Route Study
PWSA	Ports and Waterways Safety Act of 1972
SAC	Sanctuary Advisory Council
SAMSAP	Sanctuary Aerial Monitoring and Spatial Analysis Program
SECA	Sulfur Emission Control Area
SMA	Seasonal Management Area
SOLAS	International Convention for Safety of Life at Sea
SPUE	Sightings per unit effort
TSS	Traffic Separation Scheme
USCG	U.S. Coast Guard
UME	Unusual Mortality Event
VSRP	Voluntary Speed Reduction Program
VTS	Vessel Traffic Service
WAZ	Whale Advisory Zone

1. EXECUTIVE SUMMARY

Background

Renowned for its biological productivity, ecological diversity, and unique combination of oceanic features, the Santa Barbara Channel represents one of the most dynamic and species rich oceanographic regions in the world. As such, the area serves as an especially important feeding ground for migrating and resident populations of endangered blue, fin, and humpback whales. In addition to its ecological importance, the Channel region is a major shipping thoroughfare by which thousands of ships annually transit to and from the Port of Los Angeles/Long Beach. To safely direct ships entering and exiting the region, the International Maritime Organization (IMO) has designated an official Traffic Separation Scheme (TSS) that routes northbound and southbound vessels between the northernmost Channel Islands and the California mainland. These lanes overlap with whale aggregation sites, potentially placing endangered whales in the direct path of thousands of large vessels.

The co-occurrence of whales and ships, especially in confined areas such as the Santa Barbara Channel, increases the likelihood that a whale and ship will interact, which in the most severe cases leads to lethal injury. This scenario became tragically evident during the fall of 2007 when ship strikes were directly implicated in the deaths of four adult blue whales and one fetus in the Channel region. Prior to fall 2007, the maximum number of documented blue whale fatalities in a given year was three, a number that was inclusive of the entire California coast. The fall 2007 event thus represented an unusually high number of mortalities for a single year, and was especially atypical given that all the deaths were confined to the Santa Barbara Channel region.

In response to this event, NOAA’s National Marine Fisheries Service (NMFS) and Channel Islands National Marine Sanctuary (CINMS) are working in collaboration to evaluate possible long-term management scenarios, including mandatory speed reductions and changes to the existing TSS, for their ability to reduce the risk of a lethal strike. Integral to this evaluation is an analysis of the change in risk of a lethal strike resulting from management scenarios, as well as an assessment of the economic impacts to the shipping industry. Political constraints and feasibility will also factor into any evaluation of the effectiveness of management scenarios in reducing the risk of vessel strikes to whales.

Purpose

Recognizing the importance of implementing management scenarios that are both ecologically and economically acceptable, this project provides a framework by which NMFS and CINMS can evaluate both the risk implications and economic impacts of different management scenarios. Specifically we considered four potential management options:

- MANAGEMENT OPTION 1: Year-round mandatory speed reduction to 10 knots in the Channel;
- MANAGEMENT OPTION 2: Seasonal mandatory speed reduction to 10 knots in the Channel from April to September;
- MANAGEMENT OPTION 3: A narrowing of the TSS inside the Channel;
- MANAGEMENT OPTION 4: A shift in the TSS to the south of the Northern Channel Islands.

To evaluate and compare these management options, we developed two models, one that estimates the change in relative risk of a lethal strike based on predicted whale distributions and vessel traffic patterns, and a second that calculates the change in total cost to the shipping industry. By combining the results of these two models, we were able to determine which of the four management options resulted in the greatest reduction in relative risk per dollar cost to the industry.

Risk Analysis

To estimate the risk of lethal vessel strikes to whales in the Santa Barbara Channel, we developed a simple, two-dimensional surface model that combined estimates of whale distribution and vessel traffic patterns. We used vessel traffic data transmitted by ships via the Automatic Identification System to characterize ship traffic in the region for one year. By modeling a change in the speed and/or spatial distribution of vessels, in accordance with the associated management option, we were able to evaluate and compare the change in relative risk of lethal strikes resulting from each management option. Our risk analysis does not attempt to assess the absolute risk of lethal ship strikes to whales, nor does it estimate the number of lethal strikes likely occurring. Rather, we have specifically examined the change in both the relative risk of an encounter and the relative risk of a lethal whale strike resulting from each of the four management options.

We assumed that the relative risk of a lethal strike is a function of both the relative probability of a whale and the relative probability of a ship occupying a given area. Using standardized aerial observation data provided by CINMS, we developed two models to predict the relative distribution of whales in the Channel region. The first model (the Average Distribution Model) applied the average sightings per unit effort value uniformly throughout the study area, while the second (the Linear Predictive Model) predicted whale distribution based on the relationship between observed whale distributions and the static environmental variables of bathymetric depth, slope, and distance to shore. Both models were used separately to calculate the relative probability of a whale in a given area. These relative probabilities were then combined with the relative probability of a ship occupying the same areas under each management scenario to yield the relative probability of an encounter occurring between a whale and a ship in a given area. This value, however, provided no information on whether an encounter would be lethal, which is instead a function of ship speed – increased ship speed increases the probability of a lethal encounter. The relative risk of a lethal encounter was subsequently calculated by combining the relative probability of an encounter with the relative probability that an encounter would be lethal.

Relative risk was calculated, for both models, on a quarterly basis for each management option, and then summed over all four quarters to provide an annual relative risk. We then calculated the percent change in the annual relative risk for each management option compared to the annual relative risk for baseline conditions ("status quo"). The resulting value provided the percent by which each management option changed the relative risk of a lethal whale strike, as compared to the relative risk of the status quo.

Economic Analysis

To determine the economic implications associated with each management option, we designed a model that estimated the annual change in total cost to the shipping industry for each management scenario, using a random subset of transits through the region from July 2008 through June 2009. First, our model estimated the change in voyage costs, including changes in fuel and lubricant costs due to increased distance traveled or changes in speed. As a result of current and forthcoming air quality regulations, our model assumed that ships traveling within the Santa Barbara region will use more expensive, low-sulfur fuel. Where our model predicted that ships would speed up outside the region to make up for lost time due to increased distance traveled or a mandatory reduction in speed, we assumed they would do so using less expensive, regular fuel. Second, our model estimated the change in operating costs, including changes in crew costs and additional repair and maintenance cost. As with fuel costs, we made certain simplifying assumptions regarding whether crew overtime charges and additional repair costs would be incurred.

Our model also incorporated an additional hourly factor ("*alpha*") to account for certain unpredictable costs that, based on discussions with industry experts, were unlikely to be captured within the voyage or operating cost components of our model. Among other things, this hourly factor may include additional costs of delay or hourly operating costs potentially affected by increased time at sea. *Alpha* was parameterized using data on ship routes before and after air quality regulations were implemented in July 2009. A final component of our model accounts for the Navy's occasional requests that ships transiting the nearby Point Mugu Sea Range slow down or alter course due to ongoing operations within the area. As a result, we included the cost of an unexpected delay resulting from Navy operations for ships transiting on the south side of the Northern Channel Islands. This cost, which applies only to Management Option 4 (a shift of the TSS to the south), was calculated by multiplying the probability of a Navy request that a ship alter course or speed by the expected costs resulting from a missed or delayed port call.

Using these cost components, our economic model estimates the change in cost due to each management scenario by comparing the cost of a transit due to a change in management with the "normal" cost of a transit through the region. The change in costs was calculated annually for Management Options 1, 3 and 4 and from April to September for Management Option 2. To determine the "status quo" against which the change in cost was evaluated, we assumed that the route and speed of each vessel traveling through the region between July 2008 and June 2009 reflected "status quo" behavior and, thus, constituted the preferred operational profile of each ship. The resulting cost of each management scenario provided a basis for comparing the economic implications of potential management options with the estimated reduction in the risk of a lethal vessel strike to a whale.

Results and Conclusions

Of the four management scenarios, only year-round and seasonal mandatory speed reductions reduced the relative risk of a lethal strike. Conversely, both narrowing the TSS and shifting the TSS to the south may actually increase the relative risk of lethal strike. This is due largely to the fact that modeled shipping lanes would coincide with areas of greater predicted whale densities. On the other hand, mandatory speed reductions may directly reduce the lethality of a strike (as speed reduction has been shown to decrease the probability of a fatal encounter), without altering the spatial distribution of ships.

While mandatory speed reductions resulted in the greatest reduction in relative risk, narrowing the TSS was the only management option that resulted in a cost savings to the shipping industry. Savings are largely attributed to the fact that narrowing the TSS reduces the overall transit by 0.07 nautical miles. Mandatory speed reductions and shifting the TSS to the south, in contrast, resulted in costs to the shipping industry, as these options involve extra time spent at sea, changes in fuel and lubricant consumption, and potentially unexpected delays. In particular, shifting the TSS to the south resulted in the largest annual cost, estimated at nearly ten times the cost incurred by mandatory speed reductions.

Combining the results of the risk and economic models indicates that mandatory speed reductions are, according to these models, the most cost effective management options. While mandatory speed reductions do increase shipping industry costs, these costs are comparatively much lower than the cost of rerouting ships to the south. Furthermore, although narrowing the TSS results in cost savings, it simultaneously *increases* the probability of a lethal strike. It is also important to consider the ease with which each management option can be implemented when evaluating cost-effectiveness. These options would require the collaboration of numerous stakeholders, not to mention time, money, and possibly approval by domestic and international governing bodies.

Ultimately, however, the goal of this project is not to make policy recommendations, but rather to provide a framework for assessing the effects of different management options on the relative risk of a lethal strike and the cost to the shipping industry. In addition to risk and economic factors, a myriad of other considerations may affect the propriety of adopting a particular regulatory scheme to reduce the risk of vessel strikes to whales in the Channel. As a result, future analyses of different management scenarios should also consider other relevant factors, including policy, enforcement, or other issues that may complicate implementation. Moreover, the analyses we have presented here are based on the best available information. As such, new or better information should be integrated accordingly.

2. INTRODUCTION

Seasonal migrations of endangered blue (*Balaenoptera musculus*), fin (*Balaenoptera physalus*) and humpback (*Megaptera novaeangliae*) whales concentrate in the Santa Barbara Channel (Channel) region. These migrations overlap with the internationally designated shipping Traffic Separation Scheme (TSS) in the Channel, which experiences some of the highest densities of commercial maritime traffic in the world. This co-occurrence of ships and whales likely increases the risk of an interaction, including vessel strikes that are lethal to whales. With thousands of large vessels traveling through the Channel annually and maritime commerce expected to double over the next 15 years (Silber, Bettridge, & Cottingham, 2009), the existing threat of ship strikes to whales in the region is expected to increase.

Pursuant to the National Marine Sanctuary Act, the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA) designated the Channel Islands National Marine Sanctuary (CINMS) for the protection of the natural and cultural resources of the Northern Channel Islands. Within NOAA, the National Marine Fisheries Service (NMFS) is responsible for implementing the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA). During the fall of 2007, four blue whales were discovered in the Santa Barbara Channel region; in each case, the cause of death was determined to be a ship strike. Because the average total number of blue whales killed annually off the entire California coast is three, NMFS declared the 2007 incident to be an Unusual Mortality Event (UME), as defined under the MMPA (Berman-Kowalewski *et al.*, 2010).

As a result, CINMS and NMFS are evaluating possible management scenarios to reduce the risk of vessel strikes to whales in the Channel region. Integral to this evaluation is an assessment of the economic impact of possible management scenarios on the shipping industry. Effective strategies should strive to protect large cetaceans in the Channel, while also facilitating safe, efficient, and economical ship traffic. In response to the 2007 UME, the CINMS Sanctuary Advisory Council (SAC) recommended that NOAA evaluate various management options that focus on reducing the threat of ship strikes to endangered whales in the Channel (Abramson, Polefka, Hastings, & Bor, 2009). Largely derived from existing management measures to reduce whale strikes along the eastern seaboard and elsewhere in the U.S., these measures include:

- Mandatory and incentive-based options for vessel speed reduction;
- Voluntary seasonal and temporary speed reductions implemented through designation of Seasonal and Dynamic Management Areas (SMAs and DMAs);
- Designation of voluntary Areas To Be Avoided (ATBAs);
- Shifts in the current Traffic Separation Scheme; and
- Some combination of these options, as well as other innovative approaches.

3. PROJECT OBJECTIVES AND SIGNIFICANCE

The goal of this project is to create a framework for evaluating the economic impacts and risk implications of different management scenarios for use by agencies and others considering management options that reroute or slow vessels to reduce the risk of ship strikes to whales. Specifically, the objectives of this project are to:

- Assess relevant maritime policies and laws regulating the shipping industry, Channel traffic, and ports;
- Analyze vessel speed and traffic patterns in the Channel in conjunction with spatial and temporal whale sighting data;
- Create a predictive model of whale distribution to compensate for limited whale sighting data;
- Design a model to evaluate the relative probability of lethal vessel strikes to blue, fin, and humpback whales in the Channel region, and quantify the potential reductions in risk associated with a representative subset of four management options, including:
    - MANAGEMENT OPTION 1: A mandatory year-round speed reduction in the Channel;
    - MANAGEMENT OPTION 2: A mandatory seasonal speed reduction in the Channel, implemented through an SMA;
    - MANAGEMENT OPTION 3: Narrowing the existing TSS within the Channel; and
    - MANAGEMENT OPTION 4: Shifting the existing TSS to the south of the Northern Channel Islands;

- Develop a model to determine the change in cost to the shipping industry due to various management measures and apply it to the representative subset of options;
- Consider the feasibility of the various management options; and
- Use the results of the risk and cost models to evaluate management options.

Until now, no systematic attempt to quantify the effects of various management options aimed at reducing vessel strikes to whales in the Channel has been conducted. The information and data collected and analyzed for this project will provide CINMS and NMFS with a better understanding of the ecological impacts to whales and the economic impacts to the shipping industry of the four management options outlined above. Although the goal of the project is not to make policy recommendations, it is our hope that the results presented in this project will ultimately aid CINMS and NMFS in achieving their goal of reducing the risk of ship strikes to endangered whales in the Channel. It is expected that the methods and models developed for this study may be expanded in the future to guide the development of additional management approaches or modification of existing management options in the Channel Islands area, in other areas along the West Coast, and elsewhere where vessel collisions with whales occur.

4. BACKGROUND INFORMATION

Ship strikes to whales are of particular concern in the Santa Barbara Channel because three species that are known to occupy the area – blue, fin and humpback whales – are listed as endangered under the ESA and depleted under the MMPA. Gray whales were formerly listed as endangered under the ESA, but were delisted in 1994 (NOAA, 2009a; USFWS & NOAA, 1994). Especially for the three large whales – blue, fin, and humpback – ship strikes may represent a substantial source of mortalities and may hinder species recovery (Abramson *et al.*, 2009).

Blue, fin, and humpback whales migrating through the Southern California Bight aggregate in the Santa Barbara Channel because it supports dense krill populations near the northwestern Channel Islands (Fiedler *et al.*, 1998). At times, the movements of these great whales intersect with the designated TSS within the Channel, thereby increasing the probability of a collision between a whale and a vessel (Sanctuary Advisory Council, 2008).

This situation became tragically evident during the fall of 2007 when vessel strikes were directly implicated in the deaths of four blue whales (and one fetus) that stranded in the Channel Islands area. Prior to fall 2007, the maximum number of blue whale strandings along the entire California coast had been three, including the fall 1988 and 2002 "pulses" (Berman-Kowalewski *et al.*, 2010). These strikes spanned hundreds of miles (from Marin to San Diego Counties), and were also separated by several months (Sanctuary Advisory Council, 2008). In contrast, the four strikes that occurred during fall 2007 not only were confined to a small stretch of the West Coast (the Southern California Bight), but also occurred over a comparatively short timeframe (September to November 2007) (Berman-Kowalewski *et al.*, 2010). Due to these unusual circumstances, NMFS designated the incident as a UME, defined by the MMPA as "a stranding that is unexpected; involves a significant die-off of any marine mammal population; and demands immediate response" (MMPA, 1972; NMFS, 2011).

The situation is further compounded by the fact that whale strikes are difficult to detect. Of the whales that are recovered, it may be difficult to attribute the cause of injury or death to a ship strike. While studies have attempted to estimate the probability of a vessel striking a large whale, it is likely that the annual number of whales struck and killed by ships is larger than the number of those actually detected (Kraus *et al.*, 2005; Vanderlaan *et al.*, 2009). This underestimation is attributed largely to the fact that each whale killed as a result of a strike may not necessarily be discovered or positively identified as being struck (Kraus *et al.*, 2005). The detection of whale strikes is further discussed in Section 4.3.

The Santa Barbara Channel is a major shipping thoroughfare, with over 7,000 marine vessel trips transiting the Channel in 2005 (SBAPCD, 2009). Two major ports serve ships traveling through the Southern California Bight, each lying within 70 miles of CINMS: (1) Port Hueneme; and (2) the Port Complex of Los Angeles-Long Beach (LALB) (CINMS, 2009). LALB is the second busiest port in North America (CINMS, 2009). Since 1990, container trade at LALB has grown by 150% (CINMS, 2009), and despite recent declines during the economic recession, trade has already begun to increase (POLA, 2011). One of the principal great circle routes between Asia and Southern California ends just offshore of the northern border of Santa Barbara County (Dressler, Murphy, & Fournier, 2007). At this point, vessel traffic turns south and navigates along the California coast and through the Channel, which is the shortest and most economic course (CARB, 2009a; Dressler *et al.*, 2007). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, LALB and Port Hueneme traveled through the Channel (CINMS, 2009).

TSSs are employed worldwide to reduce the risk of human casualties and environmental damage associated with vessel collisions and vessel strandings. Along these same lines, the Santa Barbara Channel's TSS separates traffic traveling in opposite directions, while also ensuring that vessels stay clear of offshore oil platforms (Cockcroft, 1986). The existing TSS through the Channel is currently the only TSS approved by the United States Coast Guard (USCG) and the International Maritime Organization (IMO) for vessels traveling to LALB (see Figure 1) (Strong, 2009). To further reduce vessel strandings, the IMO has also designated Areas To Be Avoided (ATBAs). ATBAs are especially common in protected wildlife refuges and areas particularly hazardous to vessels (*e.g.*, shallow reefs) (Cockcroft, 1986). An ATBA surrounds CINMS to reduce the risk of environmental damage within the Sanctuary (IMO, 1991).

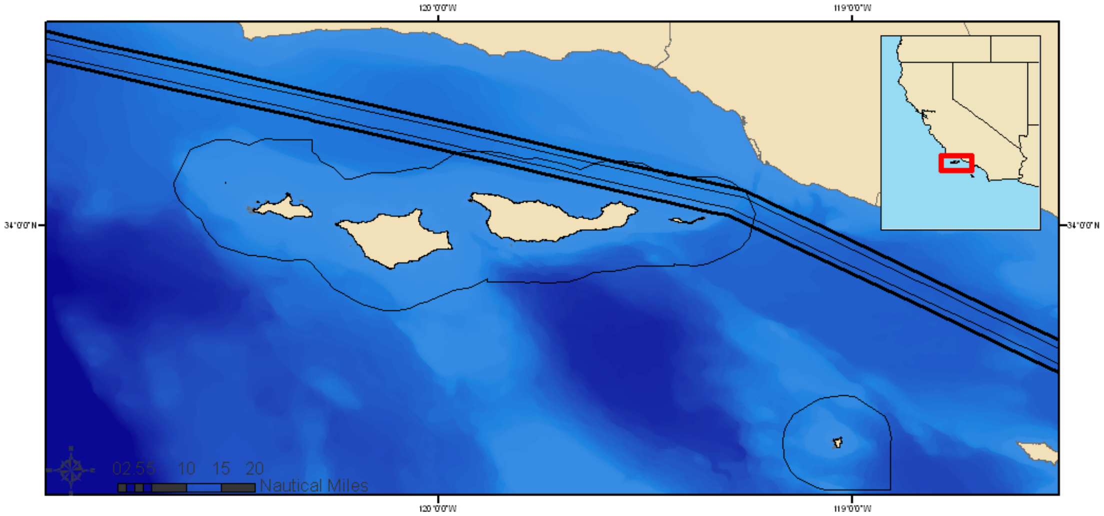


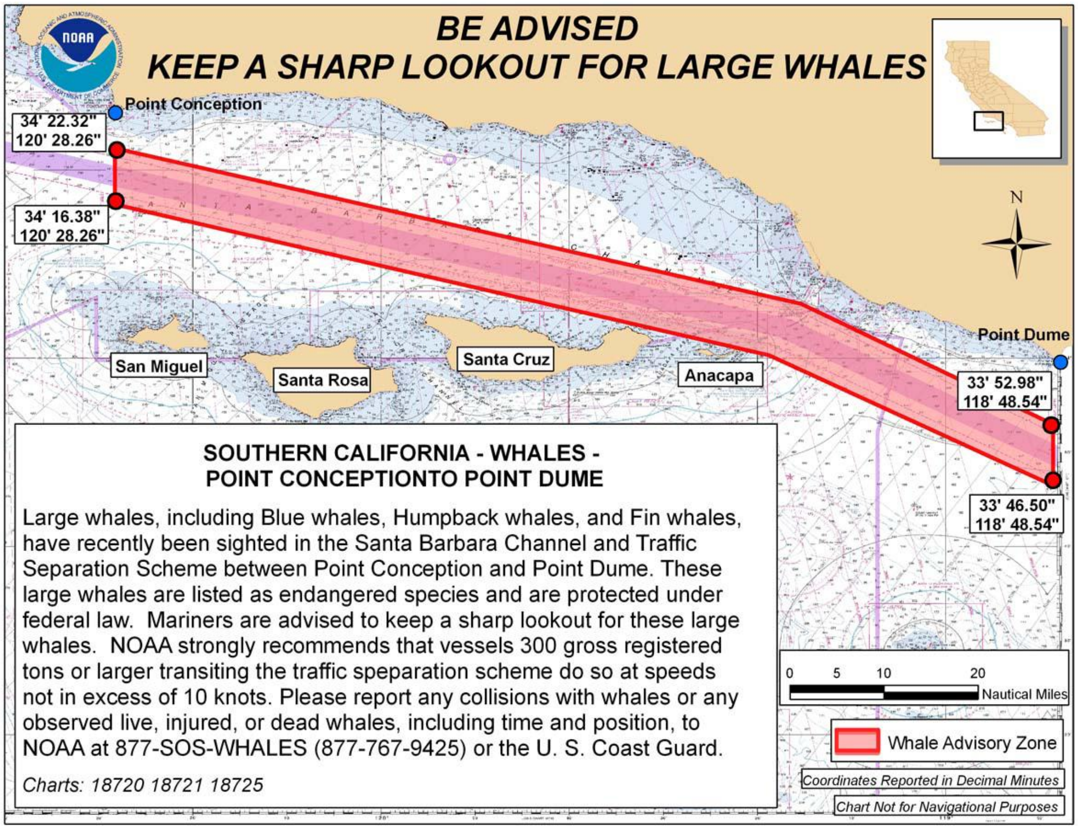
Figure 1: Map of the Santa Barbara Channel region, including the Channel Islands National Marine Sanctuary boundary and the designated Traffic Separation Scheme through the Channel.

In addition to the designated TSS and ATBA, other factors also influence vessel routing in the Channel. Recently, on July 24, 2008, the California Air Resources Board (CARB) adopted the Ocean-Going Vessel (OGV) Fuel Rule, a new regulation aimed at reducing emissions from ocean-going vessels (CARB, 2009a). The OGV Fuel Rule requires all large commercial vessels to use low-sulfur marine distillate fuel within 24 nautical miles of the California coast (CARB, 2009a). The first phase, which went into effect on July 1, 2009, requires vessel operators to use marine gas oil at or below 1.5% sulfur and marine diesel oil with a sulfur limit of 0.5% or less (CARB, 2009b). Phase 2 will go into effect on January 1, 2012, and requires a sulfur limit of 0.1% or less (CARB, 2009b).

Since the initiation of Phase 1, approximately 50% of vessel operators previously using the Santa Barbara Channel TSS have abandoned it in favor of an alternate approach known as the "Western approach," which passes through the Navy's Point Mugu Sea Range (CARB, 2010; Law, 2009). Vessels are likely using this approach to avoid using the more expensive, low-sulfur fuel, and reduce the total cost of transiting the region (CARB, 2009a). The Sea Range covers approximately 36,000 square nautical miles and is used throughout the year for military research, development, testing and evaluation operations (Department of Navy, 2010). When the range is active, commercial vessels have historically delayed their travel or taken a longer route to go around the active area (CARB, 2009a).

On March 26, 2010, the IMO designated North American coastal waters (up to 200 nautical miles from the coast) as areas where international emission standards will apply to ships (EPA, 2010). The Environmental Protection Agency (EPA) expects drastic emissions reductions; by 2012 fuel cannot exceed 1% sulfur and by 2015 it is not to exceed 0.1% (EPA, 2010). It is uncertain what effect this new law will have on west coast vessel routes. Although the CARB restrictions are currently more stringent in California, the standards for CARB and IMO will be the same after 2015. Though it is difficult to predict what impact these restrictions may have with respect to vessel traffic, the majority of ship traffic may return to the traditional, shorter route through the Channel.

There are existing speed reduction programs in the region to reduce emissions and improve vessel safety; they include mandatory speed reductions and voluntary speed reductions with incentives provided to vessel operators. Current LALB harbor safety regulations prohibit vessels from exceeding 12 knots within the Precautionary Zone (HSC, 2008). As depicted in Appendix 1, the Precautionary Zone is a convergence zone for the two major shipping lanes in the LALB area, which extends approximately seven nautical miles from the federal breakwater (HSC, 2008). In 2001, LALB instituted a voluntary speed reduction program (VSRP) that lowers emissions by reducing the energy output of a vessel's main propulsion engine (CARB, 2009a). LALB also offers the Green Flag program, which awards discounted dockage fees to vessel operators who consistently slow down to 12 knots within 40 nautical miles of Point Fermin (CARB, 2009a). In 2008, LALB also enacted an incentive program that pays the cost differential for using the more expensive, cleaner fuel within 20 or 40 nautical miles of the port (CARB, 2009a).



SOUTHERN CALIFORNIA - WHALES -
POINT CONCEPTIONTO POINT DUME

Large whales, including Blue whales, Humpback whales, and Fin whales, have recently been sighted in the Santa Barbara Channel and Traffic Separation Scheme between Point Conception and Point Dume. These large whales are listed as endangered species and are protected under federal law. Mariners are advised to keep a sharp lookout for these large whales. NOAA strongly recommends that vessels 300 gross registered tons or larger transiting the traffic speparation scheme do so at speeds not in excess of 10 knots. Please report any collisions with whales or any observed live, injured, or dead whales, including time and position, to NOAA at 877-SOS-WHALES (877-767-9425) or the U. S. Coast Guard.

Charts: 18720 18721 18725

Figure 2: Example USCG-issued notice advising mariners of the presence of endangered whales in the Santa Barbara Channel. The notice recommends a voluntary speed reduction to 10 knots.

NOAA has worked with the USCG to inform mariners of the presence of whales in the Channel to help reduce the risk of vessel strikes to whales. When whales are first observed, usually in the late spring, NOAA requests that the USCG issue a notice advising mariners of the presence of whales (M. DeAngelis, pers. communication, March 4, 2011). When aggregations of five or more whales are observed within or near the TSS within a short period of time, NOAA will update the notice to include a recommended voluntary speed reduction to 10 knots in the Channel (see Figure 2) (Abramson *et al.*, 2009; M. DeAngelis, pers. communication, March 4, 2011). The effectiveness of the current voluntary speed reduction is limited, and NOAA is considering other voluntary and mandatory management options designed to reduce the risk of ship strikes (Abramson *et al.*, 2009). A number of management options that would slow or reroute vessel traffic, including changes in the Santa Barbara Channel TSS, Seasonal Management Areas (SMAs), Dynamic Management Areas (DMAs), and Areas To Be Avoided (ATBAs), are being considered to decrease the risk of vessel collisions with whales (Abramson *et al.*, 2009).

The following sections discuss relevant research and information in the areas of (1) whale ecology and behavior; (2) potential costs to the shipping industry of different management measures that re-route or slow down ships in the Channel region; (3) the effectiveness of different management measures in decreasing the probability of a ship strike; and (4) international and domestic actions required to implement these different measures.

4.1 PHYSICAL CHARACTERISTICS AND BATHYMETRY OF THE SANTA BARBARA CHANNEL

The Southern California Bight is a highly complex and intricate oceanic system, encompassing distinct bathymetric features, numerous local current and wind patterns, and characteristic marine communities. In the northernmost section of the Bight, the Northern Channel Islands of San Miguel, Santa Rosa, Santa Cruz, and Anacapa form a distinct east-west island chain (Figure 1). The spatial arrangement of these islands greatly influences oceanic processes within the Channel (Hickey, 1992). The continental shelf in the Channel region is located relatively close to the shoreline, just southwest of San Miguel and Santa Rosa Islands (Hickey, 1992). The shelf continues south, running to the west of the remaining Channel Islands (Hickey, 1992).

The most significant current in the Bight is the California Current, a broad, cold-water current that delivers nutrient rich waters from northern upwelling centers to the Bight. The surface flowing Davidson Countercurrent is also influential, transporting warmer, nutrient depleted waters from southern latitudes into the Bight (Miller *et al.*, 1999). Consequently, the Santa Barbara Channel represents a distinct transition zone within the Bight, where cold-water upwelling from the California Current meets deep-water undercurrents and warm, poleward flowing equatorial water carried by the Davidson Countercurrent (Gaines & Airame, 2009; Miller *et al.*, 1999). Within the Bight, numerous small-scale and seasonal eddies also trap nutrients and stimulate mixing between the warm and cool waters (Lynn & Simpson, 1987).

Point Conception is a major upwelling center along the California coast, forming the northern boundary of the Southern California Bight. Upwelling near Point Conception occurs most strongly during the spring and summer months, greatly enhancing local primary productivity (Gaines & Airame, 2009). Just south of this immense upwelling zone lie the San Miguel and Santa Rosa Islands, which receive strong inputs from these nutrient rich waters (Gaines & Airame, 2009). By contrast, the eastern Channel Islands, Anacapa and Santa Cruz, are characterized by nutrient depleted, warmer waters originating near Baja (Gaines & Airame, 2009).

4.2 WHALE ECOLOGY

WHALE ABUNDANCE BASED ON PREY DISTRIBUTION

In order to evaluate the management measures being considered by NOAA (NMFS and CINMS) and others, it is important to understand the life history and distributional characteristics of blue, fin and humpback whales and their use of the Bight, specifically the Channel area. Local topography and regional upwelling zones largely determine the distribution of whales within the Channel because high prey densities are often associated with areas of high primary productivity in the Channel and, consequently, influence whale abundance and distribution (Fiedler *et al.*, 1998). Primarily lunge-feeders, blue, fin, and humpback whales feed largely on euphasiids (krill), but also occasionally feed on small schooling fish species (Goldbogen, Calambokidis, Shadwick, Oleson, & McDonald, 2006; Stewart, Clapham, Powell, & Reeves, 2002). The two main euphasiid prey species are *Euphausia pacifica* and *Thysanoessa spinifera*, both of which congregate in areas downstream from upwelling centers and in close proximity to regions of steep topographic relief (Croll *et al.*, 1998). Within the Bight, *E. pacifica* and *T. spinifera* are strongly associated with continental shelf waters, and are particularly abundant near Point Conception, San Miguel, and Santa Rosa Islands (Fiedler *et al.*, 1998).

T. spinifera is a shallow water species and is not typically found at depths greater than 100 feet (Fiedler *et al.*, 1998). Within the Channel, this cold-water species is largely confined to the northwestern Channel Islands and exhibits a discrete recruitment season from May to July, coinciding with the period of strongest upwelling (Fiedler *et al.*, 1998). *E. pacifica*, in contrast, is a more predominant, wide ranging species occupying a greater range of depths (Fiedler *et al.*, 1998). Though *E. pacifica* populations undergo continuous recruitment, peak recruitment periods also coincide with periods of strong upwelling (Fiedler *et al.*, 1998). Near the Channel

Islands, peak adult euphasiid densities occur in late summer and early fall, lagging 3-4 months behind peak spring upwelling and primary production periods (Croll *et al.*, 2005).

While fin and humpback whales do not display preferential euphausiid feeding, studies by Fielder *et al.* (1998) indicate that blue whales preferentially feed on *T. spinifera*. This preference suggests that large numbers of feeding blue whales may congregate in shallower regions near the continental shelf, and can be particularly abundant just north of San Miguel Island where concentrations of *T. spinifera* are high (Fiedler *et al.*, 1998). Despite their preference for *T. spinifera*, blue whales are also known to congregate north of Santa Rosa Island where high *E. pacifica* concentrations are found (Fiedler *et al.*, 1998).

Seasonal and decadal variation in whale abundance and distribution has been observed in response to changes in sea surface temperatures, as well as the distribution and abundance of prey species (Benson, Croll, Marinovic, Chavez, & Harvey, 2002). Decreased upwelling in El Niño years results in predictably lower densities of krill in historically productive areas such as Point Conception and San Miguel and Santa Rosa Islands (Benson *et al.*, 2002). As a result, whale concentrations in these typically productive areas are predictably lower during El Niño years (Benson *et al.*, 2002).

WHALE DISTRIBUTION

Humpback Whales

The distribution of humpback whales is characterized by defined seasonal migrations. The principal stock seen in California waters spends the summer months feeding off the coasts of California, Oregon and Washington (Calambokidis *et al.*, 2000). During the winter, this stock migrates south to mating and calving grounds near Mexico and Costa Rica (Calambokidis *et al.*, 2000, 2001)

Migrating populations are typically found further offshore during the winter months, but concentrate in shallower, coastal waters during the summer. Winter humpback sightings are largely confined to central and northern California, while summer populations are more often seen in and around the Channel (Forney & Barlow, 1998). Although the concentration of humpback whales is highest in the summer, they are found in the Channel throughout the year. Humpback whales within the Channel tend to concentrate in offshore waters near the continental shelf and Channel Islands (Forney & Barlow, 1998).

Blue and Fin Whales

The seasonal movements of blue and fin whales are less defined in comparison to humpback migrations (Stewart *et al.*, 2002). Both species lack definitive migrations between distinct summer feeding grounds and winter mating grounds and are found year-round within the Bight. Fin whales are most heavily concentrated in the Channel during the summer and winter months (Forney & Barlow, 1998), while blue whale movements are largely dictated by the presence or absence of prey species (Fiedler *et al.*, 1998). Consequently, large concentrations of blue whales off the California coast and in the Channel correlate strongly with peak summer euphasiid densities (Fiedler *et al.*, 1998). Prior to the 1970s, blue whales were rarely observed off the central California coast, an area where they are now regularly observed (Calambokidis, 2009). Scientists attribute this distributional change largely to shifts in the location of prey species (Calambokidis, 2009). Within the Channel, blue and fin whales are typically concentrated in offshore waters, particularly near the edge of the continental shelf and around the Channel Islands (Calambokidis & Barlow, 2004; Forney & Barlow, 1998).

4.3 SHIP STRIKES

FACTORS INFLUENCING THE INCIDENCE, PROBABILITY AND DETECTION OF SHIP STRIKES

The proportion of confirmed strikes to the actual number of whales struck by ships is unknown; several factors cause uncertainty in the number of whale deaths caused by ship strikes. Whale deaths are attributed to ship strikes when whale carcasses (1) show signs of massive blunt impact trauma, including fractures of heavy bones such as the jaw, vertebrae or skull, (2) have evident propeller wounds, indicated by deep slashes or cuts into blubber on the dorsal aspect, or (3) are found on the bow of a ship (Laist, Knowlton, Mead, Collet, & Podesta, 2001). Identification of these characteristics may also lead to an overestimation of the number of strikes, as some whales may be struck post-mortem (Laist *et al.*, 2001). Disease, entanglement, and other factors also may increase the likelihood of whales being struck by causing them to spend more time at the surface (Laist *et al.*, 2001). However, it is highly likely that many strike-related deaths go unrecognized or unreported, and the number of whale fatalities ascribed to strikes is probably lower than the actual number of vessel-induced deaths (Douglas *et al.*, 2008; Jensen & Silber, 2004; Laist *et al.*, 2001). Several factors influence the incidence and probability of ship strikes and reduce the rate of strike detection, as described below.

Coincidence of Shipping Lanes with Areas of Upwelling

One factor leading to ship strikes in the Channel and along the West Coast may be that shipping lanes coincide with areas of upwelling. Because high densities of *T. spinifera* and *E. pacifica* are associated with upwelling centers, the abundance and distribution of whales in these areas are also high (Croll *et al.*, 1998; Fiedler *et al.*, 1998). According to Laist *et al.* (2001), the majority of ship strikes occur in areas near or at the edge of the continental shelf, which, in the case of the Santa Barbara Channel, also coincides with areas of upwelling, high prey density and the location of shipping lanes.

Effect of Oceanographic Variation on Migration Patterns

Whale migrations may also lead to seasonal increases in ship strikes, both along the coast of California and within the Channel. Defined migration patterns associated with humpback whales and, to some extent, blue whales, lead to seasonal increases in the abundance of whales in certain areas (Forney & Barlow, 1998). Seasonal and decadal variations in climate can also lead to changes in sea surface temperatures, affecting the locations of upwelling centers and the distribution of prey (Benson *et al.*, 2002). Shifts in the distribution of prey, and consequently the distribution of feeding whales, could lead to an increase or decrease in ship strikes in a given year, depending on whether prey distributions coincide with the location of ship traffic.

Foraging Behavior and Dive Physiology

Ship strikes to blue, fin and humpback whales likely increase as a result of the foraging behavior and dive physiology of lunge-feeders. Blue, fin, and humpback whales (Balaenopteridae) utilize a distinct dive physiology, consistently diving to depths below 200 meters and executing a series of lunges below dense patches of krill, in which large amounts of prey are ingested and filtered (Goldbogen *et al.*, 2006). When returning to the surface, the whales actively fluke for the majority of their ascent until approximately the final 30 meters, at which point they glide the remainder of the distance to the surface (Goldbogen *et al.*, 2006). Due to this repeated lunging, dives are energetically costly and consequently of relatively short duration. The high associated energy demand limits Balaenopterid dives relative to other whale species, and requires them to spend a significant portion of time recovering at the surface (Goldbogen *et al.*, 2006), thereby affecting the risk of a strike.

Blue and fin whales may be particularly susceptible to ship strikes because their comparatively large size compromises their agility and maneuverability (Goldbogen *et al.*, 2006). Their dive physiology also makes them less able to change direction and avoid vessels during their ascent to the surface (Goldbogen *et al.*, 2006). The behavior of whales in the vicinity of vessels is not completely understood; however, anecdotal evidence suggests that foraging whales are less responsive to approaching vessels (Laist *et al.*, 2001). There is also evidence to suggest that vessel noise confuses whales, making them unaware of approaching vessels. Underwater noise reflections, sounds from multiple vessels, and hull blockage of engine and propeller noises have all been identified as potential causes of confusion among whales (Laist *et al.*, 2001).

Factors Affecting Estimates of Ship Strikes to Whales

More ship strikes may occur than are confirmed due to the negative buoyancy of whales. All whales in the Balaenopteridae family, including blue, fin and humpback whales, are negatively buoyant. Their negative buoyancy stems primarily from their comparatively smaller percentage of blubber than other whale species (Nowacek *et al.*, 2001) and influences the likelihood that a strike will be detected. As a result of their negative buoyancy, whales killed by ship strikes are more likely to sink to the bottom of the ocean, especially when in deep water, than to wash up on shore or float at the surface (Allison *et al.*, 1991). It is unlikely that whales killed in deep waters will resurface because the hydrostatic pressure associated with increasing depth limits the production of decompositional gases (Allison *et al.*, 1991). Furthermore, because the edge of the continental shelf is relatively close to the west coast of the U.S., deeper waters occur closer to shore, increasing the proportion of ship-struck whales that may sink and are never recovered (Douglas *et al.*, 2008).

Whales killed in shallower, coastal waters may be carried out to sea by currents and tides and never recovered (Allison *et al.*, 1991). Whales struck by ship propellers are also unlikely to wash ashore or float, as propeller wounds open the body cavity, speeding up decomposition and the release of gases (Douglas *et al.*, 2008).

Of the whales that do wash up on shore, more are likely to be killed from ship strikes than reported because of a lack of confirmation from necropsy (Douglas *et al.*, 2008). In many cases, carcasses are too decomposed to determine the cause of death. In addition, some whales may be killed instantly as a result of blunt force trauma with little to no hemorrhaging, making the cause of death difficult to determine unless a full necropsy is conducted (Douglas *et al.*, 2008). Still other carcasses may not be examined closely enough during necropsy to find evidence of a ship strike that is not initially obvious (Douglas *et al.*, 2008). When conducting necropsies on North Atlantic right whales, the number of confirmed ship strike deaths increased beginning in the 1990s when scientists began flensing carcasses to the bone (Allison *et al.*, 1991). This technique revealed more substantial evidence of ship strikes than previous necropsy methods (Allison *et al.*, 1991). As a result, the number of right whale deaths attributed to ship strikes increased from 29% between 1970 and 1990, to 47% from 1990 to 1998 (Allison *et al.*, 1991).

Disproportionate Representation of Some Species and Age Groups

Despite their speed and size, fin whales appear more susceptible to ship strikes than other species (Laist *et al.*, 2001). Although blue whales are of similar size and shape, there are fewer records of ship strikes to this species along the West Coast (Douglas *et al.*, 2008). Still, of the species discussed here, blue and fin whales are more likely to be brought to coastal waters on the bow of a ship and discovered. Their tendency to be caught and remain on the bows of ships can be attributed to their larger surface area and characteristic shape in comparison to humpback whales (Douglas *et al.*, 2008). Fin whales and, to a similar extent, blue whales, have longer, streamlined bodies that can drape more evenly over the bow of a ship (Douglas *et al.*, 2008). Humpback whales, on the other hand, have a less evenly distributed body mass, such that, if ever caught on the bow of a ship, they will be more likely to become dislodged before reaching coastal waters (Douglas *et al.*, 2008). These factors make it appear that fin and blue whales are struck more often, though it is likely that only their rate of detection is higher (Douglas *et al.*, 2008).

Across all three whale species, evidence collected from recovered whale carcasses suggests that larger proportions of calves and juveniles are struck by ships than adults (Douglas *et al.*, 2008). For fin whales, records with complete information of ship-struck whales from the entire northern hemisphere indicate that every single whale was immature when struck (Laist *et al.*, 2001). Such evidence suggests that some aspect of the ecology or behavior of juvenile fin whales makes them particularly susceptible to ship strikes. This evidence may also account for the overall higher frequency of fin whale strikes in comparison to other species. Douglas *et al.* (2008) hypothesize that juvenile whales are struck more often because they may be more naive about ships than adults and may spend more time at the surface in the presence of ships. Larger whales may survive strikes long enough to dislodge themselves from the bows of ships (Douglas *et al.*, 2008). Laist *et al.* (2001) also hypothesize that larger proportions of juveniles of all species are struck because they spend more time at the surface and in shallow coastal waters, and are therefore not only more susceptible to ship strikes, but are more likely to be recovered based on their location.

EFFECTS OF VESSEL SIZE AND SPEED ON SHIP STRIKES

Although anecdotal records are the only information currently available for evaluating vessel operating factors related to ship strikes to whales, the incidence of strikes is positively correlated with the number, size, and speed of ships (Laist *et al.*, 2001; Vanderlaan & Taggart, 2007). Records show that, prior to 1950, ship strikes to whales were relatively infrequent (Laist *et al.*, 2001). However, since the 1970s, records indicate that ship strikes have been responsible for a considerable number of whale deaths (Laist *et al.*, 2001). This time period is also associated with a dramatic increase in the number of registered ships and maximum operating speeds among large, ocean-going vessels (Laist *et al.*, 2001).

The work of Laist *et al.* (2001) forms the foundation of the database of all known ship strikes to large whales worldwide. Historical records from 1885 to 2000 indicate that, while all types and sizes of vessels may hit whales, the most severe and lethal injuries involve ships that are over 80 meters long (Laist *et al.*, 2001). The substantial size of propeller injuries and massive blunt trauma observed on stranded ship struck whales further supports the finding that large ships are responsible for most lethal strikes (Laist *et al.*, 2001). In most cases, the whales were not seen by the vessels, or were seen too late to be avoided (Laist *et al.*, 2001).

Similarly, the likelihood of a vessel hitting and severely injuring or killing a whale is related to ship speed (Laist *et al.*, 2001; Vanderlaan & Taggart, 2007). In the majority of collision records where information on both vessel speed and the condition of the struck whale is available, ships were moving at 14 knots or faster when the whale was lethally or critically injured (Laist *et al.*, 2001). Vanderlaan and Taggart (2007) calculate the probability of lethality based on records of vessels striking several species of large whales worldwide. Vanderlaan *et al.* (Vanderlaan, Taggart, Serdynska, Kenney, & Brown, 2008) used the following equation – derived from Vanderlaan and Taggart's (2007) equation – to describe the probability of a lethal injury to a large whale given an encounter in area *i*, where *x* represents vessel speed:

Eq. 1

$$\boldsymbol{P(Lethal|Encounter)_i = \frac{1}{1 + exp^{-(-4.89+0.41\bar{x}_i)}}}$$

Where:
$\boldsymbol{\bar{x}_i}$ is average ship speed in area *i*

In their 2007 study, Vanderlaan and Taggart suggest that the chances of lethal injury decline from approximately 80% at a speed of 15 knots to 20% at a speed of 8.6 knots (Vanderlaan & Taggart, 2007). Furthermore, the probability of lethality declines to 50% at a speed of 11.8 knots (Vanderlaan & Taggart, 2007).

4.4 AUTOMATIC IDENTIFICATION SYSTEM

The Automatic Identification System (AIS) is a maritime navigation safety communications system that transmits vessel information to other ships and shore-based receiving stations (USCG, 2011a). USCG and IMO require that all vessels 300 gross tons or greater carry and use an AIS system to maintain security and safety of maritime activities (USCG, 2011a, 2011b). Employed throughout the world, AIS represents not only an important navigation tool for collision avoidance, but also plays an increasingly integral part in tracking and monitoring vessel movements. Every few seconds, a ship's onboard AIS transmitter broadcasts a VHF radio signal containing real-time vessel transit information, including the vessel's position, speed, and direction. Static data, such as the vessel type, its dimensions, and its destination, are transmitted every six minutes (USCG, 2011a). The radio signal can be picked up by receivers on other ships, by Vessel Traffic Service (VTS) centers, or by any other receiving station with the proper equipment to record this information.

Currently Scripps Institution of Oceanography manages a data stream from three AIS stations in the Santa Barbara Channel (M. McKenna, pers. communication, June 10, 2010). Ship tracks generated from the AIS data are shown in Figure 3. The first station is located at the Santa Barbara Harbor, which collected data from November 2006 to September 2009. A second station is located at Coal Oil Point, which was relocated from UCSB's Marine Science Institute in September 2008 and continues to collect data (M. McKenna, pers. communication, June 10, 2010). While installation of the Coil Oil Point station greatly improved the collection of AIS data within the Channel, consistent coverage to the south of the Channel Islands was still lacking. As a result, a third station was installed on Santa Cruz Island in March 2010. That station currently provides the most reliable coverage on the south side of the islands (M. McKenna, pers. communication, June 10, 2010).

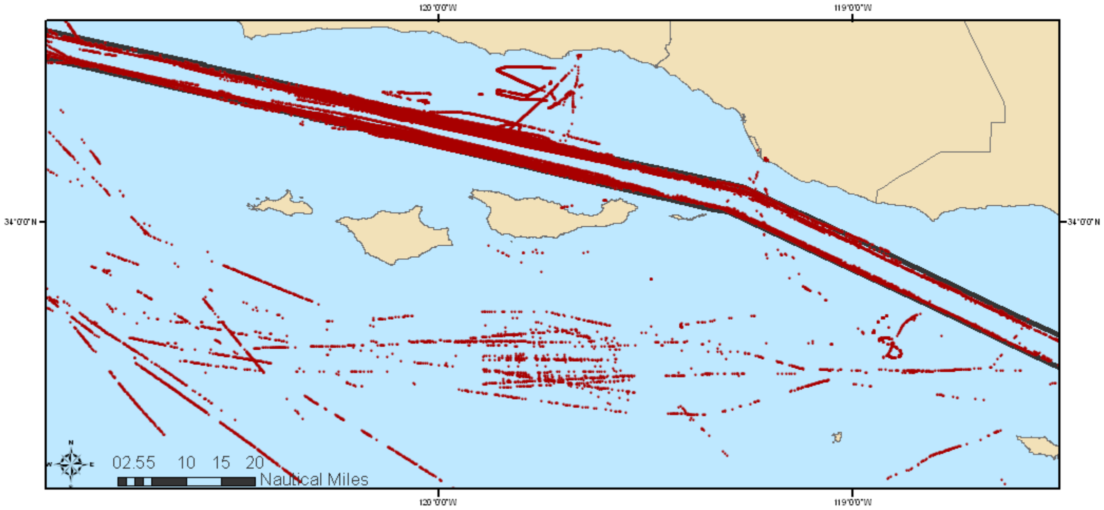


Figure 3: Vessel locations received by shore-based AIS transmitter at Coal Oil Point for June 2009. *AIS data provided by Megan McKenna, Scripps Institution of Oceanography.*

4.5 SHIPPING INDUSTRY

As previously noted, NOAA (specifically CINMS and NMFS) and other agencies are considering a number of management options to reduce the risk of ship strikes to whales in the Channel. Among those management scenarios are options that would slow or reroute vessel traffic, including SMAs, DMAs, and ATBAs (Abramson *et al.*, 2009). Shifts in the existing TSS are also being considered as a possible mechanism for reducing interactions between whales and ships. As described below in Section 4.6, the USCG is considering changes to the TSS in the Channel in response to an increased number of ships avoiding the Channel in favor of the “Western approach” (see Figure 4) (USCG, 2010a).

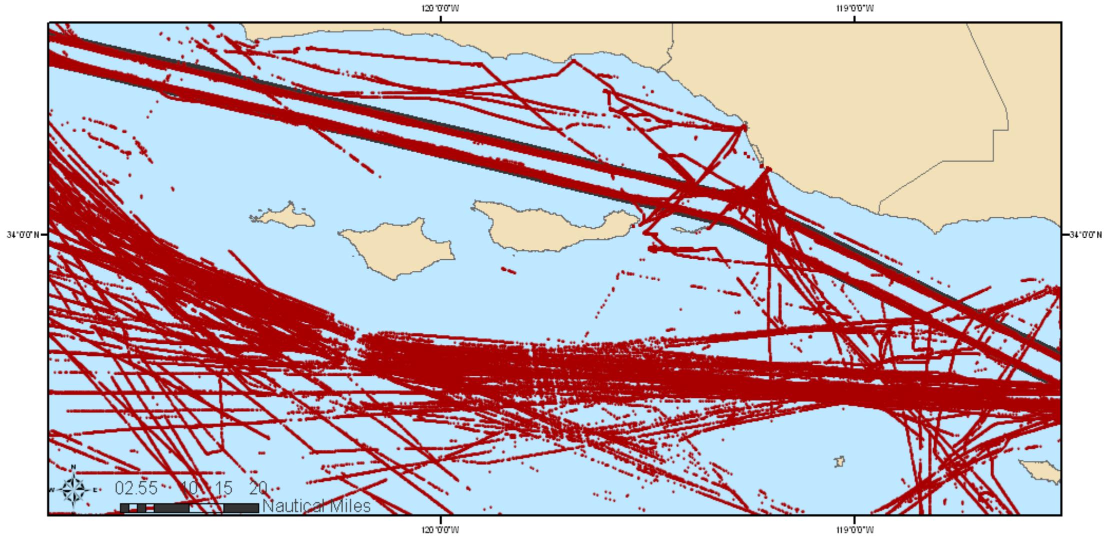


Figure 4: Vessel locations received by shore-based AIS transmitter at Coal Oil Point for September 2009 showing increased traffic south of the Northern Channel Islands after implementation of CARB's low-sulfur fuel rule in July 2009. *AIS data provided by Megan McKenna, Scripps Institution of Oceanography.*

A primary goal of this project is to evaluate the economic impact of the changes that may occur to the shipping industry should the management measures evaluated be implemented. Should implementation occur, ships would be required to either slow down or change their traditional route through the region. Consequently, costs would be incurred from a longer route or additional time at sea required to transit the region at a slower speed.

INDUSTRY COST STRUCTURE

Although the cost structure of the shipping industry is complex, costs can be divided into four primary categories: operating, voyage, capital, and cargo-handling costs (Figure 5) (Stopford, 1988). Operating costs are the daily expenses associated with ship operations, such as the cost of the crew, supplies, repairs and maintenance, insurance, and administrative expenses (Stopford, 2009). Voyage costs are the variable costs associated with any given trip, including fuel costs, canal dues, and port fees (Stopford, 1988). Port fees generally consist of dues for towage, pilotage, traffic control systems, reporting, mooring and unmooring, berth, and tonnage (Notteboom & Vernimmen, 2009). Cargo-handling costs include the costs of loading and unloading cargo from ships (Stopford, 2009). Capital costs are very high in the shipping industry, as much as 42% of the total costs incurred by a ship, and the industry relies on a steady cashflow to finance these investments (Stopford, 2009).

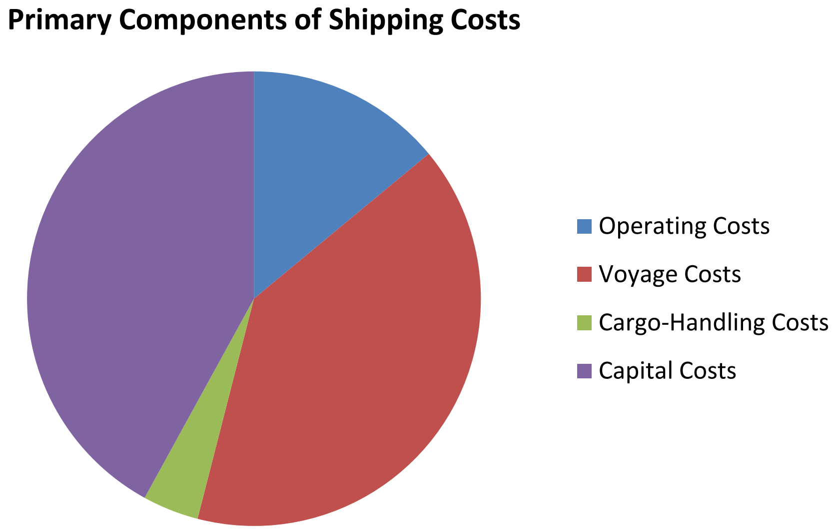


Figure 5: The approximate contribution of the main cost categories to a ship's total cost (Stopford, 2009).

We have quantified certain costs for vessels traveling through the Channel region to evaluate the effects of our selected management measures on the shipping industry. Management measures being considered will primarily affect a ship's voyage costs by increasing the distance traveled or reducing the speed of travel, thereby affecting the ship's fuel and lubricant consumption and the time required to transit the region. Fuel costs constitute the largest component of a ship's voyage cost, and the cost of fuel is dependent on the fuel price, vessel speed and size, main and auxiliary engine types, and hull shape and condition (Stopford, 2009). To quantify the effects of the evaluated management measures, we characterized the vessel traffic traveling through the region and evaluated the effect of management on voyage costs and operating costs for vessels transiting the region.

Slow Steaming and Cost Savings from Speed Reduction

Speed reduction has recently been promoted as a method for reducing the cost of fuel on a vessel's voyage. With high fuel prices and an economic recession affecting profitability in the shipping industry, a number of shipping companies have turned to slow steaming or even super slow steaming to save fuel (Bankes-Hughes, 2010; COSCO Group, 2009; Maersk, 2009; ZIM, 2009). In 2007, Maersk shipping line began operating over 100 of its vessels at 10% of their engine load to reduce fuel consumption and greenhouse gas emissions (Maersk, 2009). Maersk led a study to verify that its ships could operate safely at this super slow steaming speed, saving as much as $1 million a year for one ship due to a 10-30% reduction in fuel consumption (Maersk, 2009).

The fuel savings associated with speed reduction are coupled with other costs associated with a change in shipping operations. To maintain service levels, for example, cargo liner companies have added ships to their fleet to allow for slower transits (Bankes-Hughes, 2010), which may result in additional capital and operating costs. Slow steaming may also result in additional engine wear, and engine manufacturers sell retrofit kits to reduce mechanical issues associated with slow steaming (Bankes-Hughes, 2010).

Economic Model Design

We designed an economic model to predict the financial impacts of management options on cargo ships, tankers and cruise ships traveling through the Channel. The model examines the additional costs and/or fuel savings associated with speed reductions and/or alternate routes. This model was influenced by several other models within the literature that analyze vessel traffic regulation changes and the effects of changes in ship speed on operating costs.

A 2002 study by Kite-Powell and Hoagland calculated costs to the shipping industry associated with the management measures being considered by NMFS for East Coast vessel traffic (Kite-Powell & Hoagland, 2002). Kite-Powell and Hoagland (2002) calculated the costs of expected and unanticipated additional transit time for potential management measures, in which ships were slowed to 10 knots over 25 nautical miles for 60 days and, for some ships, over 20 nautical miles for 20-30 days as part of a dynamic management measure, depending on the port of call. Vessels were categorized based on vessel type, size, and cargo type. Each vessel category was assigned a normal operating speed, daily operating cost, and port entry constraints to facilitate inclusion of these factors in the analysis of costs incurred as a result of unanticipated delays due to dynamic management (Kite-Powell & Hoagland, 2002). Kite-Powell and Hoagland (2002) used a conservative approach to avoid underestimating the effects of the management options considered. The economic analysis predicted an average cost per affected port call of $2,350 resulting from delays. The total cost for any vessel was less than 0.5% of the annual operating cost (Kite-Powell & Hoagland, 2002).

In order to understand the effects of fuel costs on cargo liners, Notteboom and Vernimmen (2009) introduced a cost model that included operating and capital costs. They also provided fuel consumption estimates based on vessel speed for four different container ship sizes, indicating a positive relationship between vessel speed and fuel consumption (Notteboom & Vernimmen, 2009). Corbett, Wang, and Winebrake (2009) created a model to estimate the optimum speed for vessels to maximize annual profit. The function derived from the model indicates that optimum speed is dependent on fixed daily costs, fuel consumption, fuel prices, and the design speed of the vessel (Corbett, H. Wang, & Winebrake, 2009).

The value of time and the cost of bunker fuel are important considerations for analyzing management options. A 2008 analysis of the effect of changes in oil prices on transportation systems included a time element based on contingent valuation surveys of shippers deciding which transportation modes and routes to utilize (TEMS, 2008). The total of the fuel cost and the time cost for any given speed revealed different optimal operating speeds for different oil prices (TEMS, 2008). Ronen (1982) incorporated penalties for late arrival or bonuses for early arrival into a three-part cost model designed to predict optimal vessel speed. Another factor considered in existing models is the value of the cargo being carried, and whether there are costs accrued by cargo owners from the extra transit time (Ronen, 1982).

With guidance from these existing models and industry input, we created a new model to evaluate the effects on the shipping industry of management measures aimed at reducing the risk of whale strikes in the Channel region. Specifically, for the purposes of this project, we used the model to evaluate the effects of implementing proposed management measures described in Section 5.1 on ships traveling through the region. It is likely, however, that the model will prove useful in assessing the effects of similar measures on shipping costs and the risk of vessel strikes to whales along the West Coast as well as elsewhere in the U.S. and worldwide.

4.6 POLITICAL CONSTRAINTS

INTERNATIONAL AND DOMESTIC ACTIONS REQUIRED TO IMPLEMENT CHANGES TO VESSEL ROUTING SCHEMES

Long-term management measures to reduce ship strikes to whales in the Channel region may require changes to vessel routing schemes in the Channel. The

United States Coast Guard (USCG) is the principal domestic agency charged with adopting vessel routing schemes in the U.S. Any resulting domestic changes that affect international navigation must in turn be approved by the International Maritime Organization (IMO) to ensure they are reflected on worldwide navigation charts. Accordingly, implementing any management strategies that would involve changes to vessel routes will require coordination with and approval of the USCG and, to the extent international navigation is affected, the IMO.

USCG Authority

Pursuant to the Ports and Waterways Safety Act of 1972 (PWSA, 2009), the USCG "is the sole body charged with the duty of promulgating traffic separation schemes" necessary to ensure safe access for vessels traveling to and from ports in the United States (*Defenders of Wildlife vs. Gutierrez*, 2008). Among other things, PWSA authorizes USCG to designate fairways and Traffic Separation Schemes (TSSs) to improve vessel routing and safety (PWSA, 2009). Prior to establishing or modifying a fairway or TSS, the PWSA requires the USCG to conduct a study of issues affecting port access, including potential traffic densities and safety concerns (PWSA, 2009). PWSA requires the USCG to "take into account all relevant factors concerning…protection of the marine environment…including but not limited to…environmental factors" (PWSA, 2009). The USCG must coordinate with other relevant entities, including federal, state and international agencies, as well as interested stakeholders, such as maritime and environmental organizations, to reconcile, if possible, the need for safe port access with other reasonable uses of the nation's waterways (PWSA, 2009). Once the USCG designates a fairway or TSS, vessel navigation has the paramount right of use over all other uses in that area (PWSA, 2009).

Port Access Route Study: In the Approaches to Los Angeles-Long Beach and in the Santa Barbara Channel

On April 7, 2010, the USCG initiated a Port Access Route Study (PARS) aimed at increasing the safety and efficiency of the vessel traffic routing scheme in the approaches to LALB and in the Channel (USCG, 2010a). Specifically, the USCG sought public comment on modification of the existing vessel traffic routing scheme in the Channel and in the approaches to LALB based on recently observed departures of vessel traffic from the designated TSS within the Channel (USCG, 2010a). The USCG initiated the PARS in response to increased vessel traffic bypassing the

Channel TSS and opting instead to use the Western approach (USCG, 2010a), depicted in the green box in Figure 6.

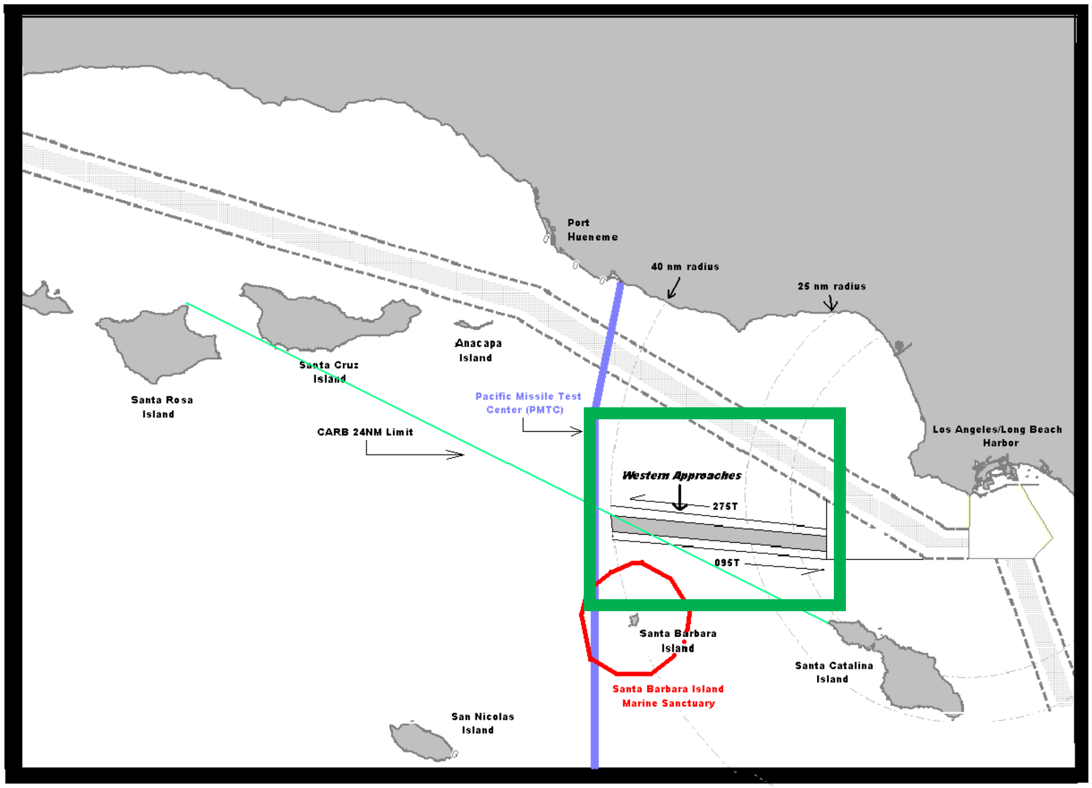


Figure 6: Voluntary traffic lanes for ships using the Western approach to LALB (shown in green). Reproduced from (LALB Harbor Safety Committee, 2009).

The Western approach does not currently contain designated fairways or an approved TSS (USCG, 2010a). Although endorsed by the LALB Harbor Safety Committee, the Western approach traffic lanes are strictly voluntary and are approved neither by the IMO nor by any U.S. federal authority (Strong, 2009). Accordingly, IMO regulations designed to prevent collisions (COLREGS) in designated TSSs do not apply to the Western approach's voluntary traffic lanes (Strong, 2009).

As a result of increased traffic and safety concerns, the PARS sought comment on whether designation of a vessel routing scheme, such as a TSS, within the Western approach would reduce congestion, increase vessel traffic predictability, and/or improve maritime safety in the area (USCG, 2010a). In particular, the PARS notice asked whether USCG should: (1) maintain current vessel routing measures; (2) modify the existing traffic separation schemes; or (3) adopt one or more alternative vessel routing solutions, including area(s) to be avoided (USCG, 2010a). The PARS notice further requested comment on existing navigational hazards in the study area, pressures on existing routing schemes (*e.g.*, increasing traffic density), measures to improve traffic management efficiency, and potential costs and benefits of the possible vessel routing solutions outlined above (USCG, 2010a).

A variety of parties commented on the PARS notice, including several that raised the issue of vessel strikes to whales. Specifically, the Department of the Navy's Naval Air Warfare Center Weapons Division strongly opposed the creation of a new traffic separation scheme within the Point Mugu Sea Range (Figure 7) because of the potential to (1) severely disrupt military training and testing exercises; (2) compromise national security; (3) increase the risk of vessel-to-vessel collisions involving Very Large Crude Carriers; and (4) negatively affect large whales (Department of Navy, 2010). The CINMS Advisory Council urged the USCG to ensure that any changes to the traffic separation scheme not only ensure vessel safety, but also consider the needs of large whales and other marine life within and near the Sanctuary (SAC, 2010). NMFS stated that the region is an important area for many species, including large whales, protected under the Endangered Species Act and the Marine Mammal Protection Act (NMFS, 2010a). NMFS submitted whale observation data for fin, blue, and humpback whales within the study region, and offered to assist the USCG by reviewing and providing feedback on the forthcoming study prior to its public release (NMFS, 2010a, 2010b). CINMS also encouraged the USCG to consider the effect of different routing schemes, speed reductions and other actions that could potentially reduce the risk of vessel strikes to endangered whales (CINMS, 2010b).

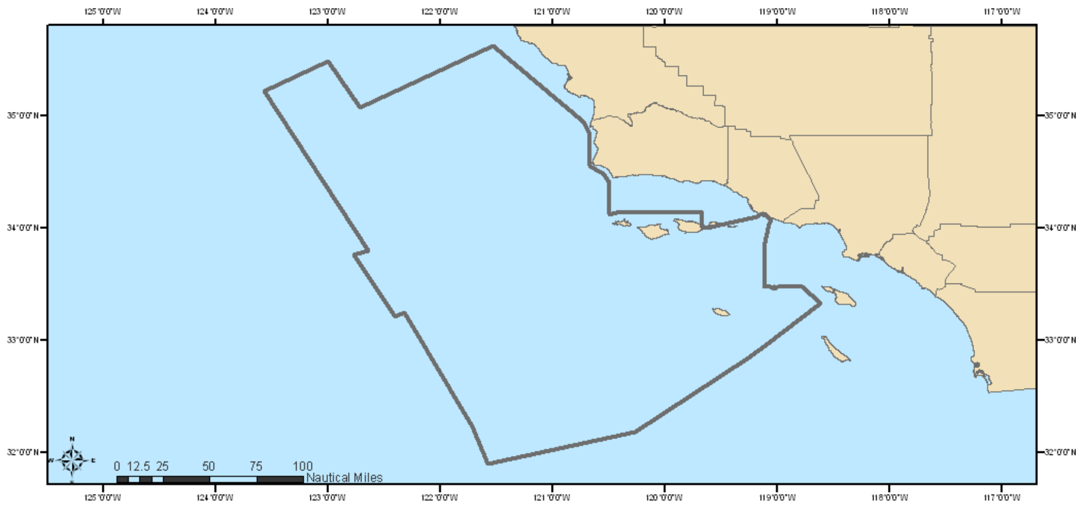


Figure 7: Boundary of the Point Mugu Sea Range in the Santa Barbara Channel region (shown in black).

The Environmental Defense Center, the Center for Biological Diversity, Friends of the Earth, Natural Resources Defense Council, and Pacific Environment similarly urged the USCG to consider as part of its analysis the effect of changes in vessel traffic schemes and other actions, such as a speed reduction, on the risk of ship strikes to whales in the region (Center for Biological Diversity, Friends of the Earth, Natural Resources Defense Council, & Pacific Environment, 2010; Environmental Defense Center, 2010). Cascadia Research Collective's whale research biologist John Calambokidis, who has studied large whales off the California coast for 25 years, observed that the unusual mortality event in fall 2007 appears to be the result of an overlap between the existing TSS and prime blue whale habitat (Calambokidis, 2010). Calambokidis thus urged the USCG to examine areas within the study region where high concentrations of whales overlap with existing or proposed shipping lanes (Calambokidis, 2010). Among other things, Calambokidis recommended that the USCG consider shifting the existing traffic lanes away from areas of high whale densities or, where such a shift is infeasible due to existing hazards such as oil platforms, to consider reducing the width of the current TSS configuration by narrowing the lanes and separation zone to better avoid areas of high whale densities (Calambokidis, 2010).

In October 2010, the California Air Resources Board (CARB) filed comments indicating it is considering amending its regulations to extend the existing low-sulfur fuel requirement to 24 nautical miles beyond the Channel Islands (consistent with

NOAA's Contiguous Zone, as depicted in Appendix 2). The goal of the proposed amendments is to recapture reductions in air emissions caused by the shift of traffic south of the Northern Channel Islands and to reduce the number of vessels transiting the Point Mugu Sea Range (CARB, 2010). The CARB amendments may become effective as soon as late 2011 (CARB, 2010).

The PARS is scheduled to take six to twelve months to complete (USCG, 2010a) and is still underway at the time of finalizing this report. The USCG anticipates that it will publish the results of its Notice of Study in the Federal Register in June 2011 (USCG, 2010b).

East Coast PARS

Deaths from ship strikes have been identified as a primary factor impeding population recovery of critically endangered North Atlantic right whales (*Eubalaena glacialis*) (NMFS, 2008). In 2004 and 2007, the USCG accordingly completed two PARS on the East Coast to evaluate NMFS management options to reduce ship strikes to right whales (USCG, 2005a). The results of the PARS on the East Coast led to implementation of voluntary and mandatory commercial regulations seeking to reduce ship strikes to right whales in specific areas along the eastern seaboard (Abramson *et al.*, 2009; NMFS, 2008). These modifications, discussed below, provide examples of policies that could be applied in the Santa Barbara Channel region (Abramson *et al.*, 2009; NMFS, 2008).

Eleven management strategies, including four of potential relevance to ship strikes in the Channel, were adopted as a result of the East Coast PARS. First, the Boston, Massachusetts TSS was initially shifted and the shipping lanes later narrowed to reduce overlap with high densities of right whales, thereby reducing the probability of ship and whale interactions (Abramson *et al.*, 2009; NMFS, 2008). Although ships are not required to travel within the TSS, failure to do so forgoes certain legal protections and may result in liability if a collision or other incident occurs. Second, terminal licensing restrictions were imposed that require tankers traveling to two deepwater liquefied natural gas terminals in Massachusetts Bay to slow to 10 knots or less when notified with real time acoustic buoy detection of right whales in the TSS (McGillivary, Schwehr, & Fall, 2009).

Third, Seasonal Management Areas (SMAs) and Dynamic Management Areas (DMAs) were adopted that require commercial ships to slow to 10 knots or less in specific areas along the eastern seaboard during certain periods of the year when right whale concentrations are high (Abramson *et al.*, 2009; NMFS, 2008). Although compliance is voluntary within the DMAs, speed reductions within the SMAs are mandatory (Abramson *et al.*, 2009; NMFS, 2008). Fourth, a voluntary Area To Be Avoided (ATBA) was implemented in the Great South Channel Area adjacent to the Boston TSS; this area is a feeding ground for right whales, and it is expected that compliance with the ATBA could reduce the risk of right whale ship strikes by 63% (Abramson *et al.*, 2009; NOAA, 2009b). NOAA is responsible for monitoring compliance with the voluntary measures and, if necessary, implementing mandatory measures if compliance is low (NMFS, 2008). In a related proceeding, Canada also sought to reduce ship strikes by shifting the TSS in the Bay of Fundy to areas with lower right whale densities (Roberts, 2005).

The Role of the International Maritime Organization

Created in 1948, the IMO is a specialized agency of the United Nations governed by member states. The primary purpose of the IMO is to develop and maintain an international regulatory framework for shipping safety, environmental concerns, legal issues, security, and efficiency through recommendations and conventions, the latter being defined as binding legal instruments (IMO, n.d.). Subsequently, a state that ratifies a convention must incorporate the requirements of the convention into its national law (IMO, n.d.).

There are two primary IMO routing conventions: (1) the International Convention for Safety of Life at Sea (SOLAS) and (2) the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) (IMO, n.d.). SOLAS Chapter V designates the IMO as the sole organization that can establish and adopt ship routing measures at the international level. Rule 10 of COLREGS defines the actions that can be taken by ships in or near TSSs (Roberts, 2005). Before 1997, only TSSs were classified as mandatory routing measures (Roberts, 2005). In 1997, however, the IMO expanded its category of mandatory routing measures to include other measures, such as ATBAs or other designations aimed at protecting marine resources (Roberts, 2005).

Although not required by domestic or international law, NOAA and the USCG historically have collaborated with the IMO to formally sanction ship traffic routing systems modified as a result of a Port Access Route Study (USCG, 2005b). The benefit of IMO approval is that it ensures that any USCG-modified routing measures will be incorporated into worldwide navigation charts and that any modified geographical coordinates will be distributed to the IMO's 166 member states (USCG, 2005b). Most of the routing measures recommended by the East Coast PARS did not affect international navigation and thus were not submitted to the IMO for approval (USCG, 2005b). The modification to the Boston TSS, however, was an amendment to an existing IMO-approved TSS; as a result, the U.S. sought formal IMO approval of the modified TSS to ensure its revised coordinates would be reflected on worldwide navigation charts (USCG, 2005b). Because IMO-sanctioned routing measures are more likely to be recognized and adhered to by national and international shipping interests (Roberts, 2005), it is likely the USCG would seek IMO approval of any future management actions that alter the configuration of the existing TSS within the Channel, move the TSS, or otherwise re-route vessel traffic within the study area.

5. METHODOLOGY

5.1 SELECTION OF MANAGEMENT OPTIONS

In response to the 2007 blue whale UME, the CINMS Advisory Council recommended that NOAA consider a variety of management measures for reducing vessel strikes to whales in the Santa Barbara Channel region (Abramson *et al.*, 2009). While we have developed economic and risk models that can be applied to different management scenarios that re-route or slow down vessels to reduce the risk of ship strikes to whales, in this project, we have evaluated a subset of four specific management options. These were chosen with guidance from CINMS and NMFS as illustrative options, and may not necessarily be the best possible options for reducing the risk of vessel strikes to whales in the region. The selected management options include (1) a mandatory year-round speed reduction; (2) a mandatory seasonal speed reduction; (3) narrowing the existing TSS within the Channel; and (4) shifting the TSS to the south of the Northern Channel Islands. Each of these options is described below.

MANAGEMENT OPTIONS 1 & 2: MANDATORY YEAR-ROUND AND SEASONAL SPEED REDUCTIONS

Studies evaluating the relationship between the incidence of ship strikes to whales and ship speed indicate that serious injury or death to whales decreases drastically at lower speeds (Laist *et al.*, 2001; Vanderlaan & Taggart, 2007). Guided by these studies, the SAC recommended that NOAA consider mandatory vessel speed reductions as one of several methods to reduce the incidence of ship strikes to large whales in the Channel (Abramson *et al.*, 2009). We have analyzed two alternative speed reduction scenarios: (1) a year-round mandatory speed reduction, and (2) a mandatory seasonal speed reduction, which could be implemented as part of a Seasonal Management Area (SMA).

Currently NOAA recommends under certain circumstances that vessels voluntarily reduce their speed when traveling through the 88 nautical mile length of the Channel between Point Conception and Point Dume known as the Whale Advisory Zone (WAZ) (CINMS, 2010a). Specifically, through USCG-issued Local Notices to Mariners (see Figure 2), NOAA recommends that vessels greater than 300 gross registered tons traveling through the WAZ maintain a speed at or below 10 knots when aggregations of five or more whales are observed in or near the TSS. Compliance with this voluntary measure, however, has been low (McKenna, Katz, Condit, & Walbridge, 2011; Silber & Bettridge, 2010).

In contrast, the mandatory year-round and seasonal speed reductions modeled in this report would require ships to slow from their regular operating speeds to a maximum of 10 knots in the WAZ (Figure 8). We have assumed the year-long speed reduction would, as expected, be in place throughout the year. To model the seasonal speed reduction, we assumed the restriction would be in place from April through September. Although whale abundance is variable from year to year, this time frame was selected because it aligns with quarters 2 and 3 from our analysis, and because the time frame roughly corresponds to the period of time when large aggregations of whales are most commonly present in the Channel region (*i.e.*, from June through September) (Abramson *et al.*, 2009; Benson *et al.*, 2002; Calambokidis *et al.*, 2000; Fiedler *et al.*, 1998; Forney & Barlow, 1998). NOAA's recommended speed reductions through the WAZ have generally occurred during this time period, but have sometimes remained in effect through October, November, or even December (S. Hastings, pers. communication, Feb. 22, 2011; M. DeAngelis, pers. communication, March 4, 2011). By modeling a half-year and a year-round speed reduction, we provide a practical range of risk reduction and cost estimates. The estimates for a seasonal mandatory speed reduction implemented for longer than a half year would likely fall between the estimates for the half-year and the year-round values.

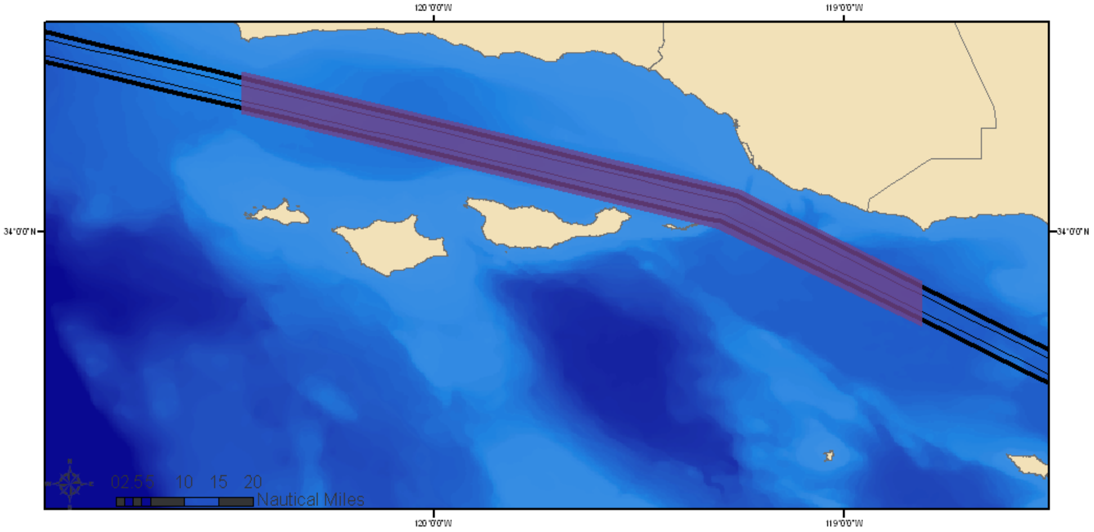


Figure 8: Whale Advisory Zone (WAZ) (shown in purple) along an 88 nautical mile extent of the TSS through the Santa Barbara Channel.

Feasibility and Other Policy Considerations

It is important to consider the feasibility of enacting a speed reduction and the likelihood that ships will comply with any new mandatory speed restrictions. As previously mentioned, in December 2008, NMFS established mandatory seasonal management areas (SMAs) along the eastern seaboard to reduce the threat of vessel strikes to North Atlantic right whales (NMFS, 2008). In particular, vessels 65 feet or greater in overall length are required to slow to no more than 10 knots within multiple SMAs along the East Coast, including four 20 nautical mile zones within the Mid-Atlantic region and one 50 nautical mile zone within the northeast region (NMFS, 2008).

An analysis of vessel speeds through the East Coast region during the year after these management strategies went into effect, however, shows that compliance with mandatory vessel speed restrictions was relatively low, with vessels exceeding 10 knots during 68% of transits (Silber & Bettridge, 2010). Possible reasons for this include insufficient enforcement (indeed, as noted below, mariners were accorded a one year “grace period” to comply), a lack of public knowledge about the rule, or a deliberate disregard for the regulation (Silber & Bettridge, 2010). Evidence also suggests that some commercial vessel engines are not designed to operate for extended periods of time at such low speeds, and industry representatives have expressed concern that doing so will potentially reduce engine performance, increase engine wear, and result in additional costs (Bankes-Hughes, 2010).

Within the Channel Islands region, responses to CARB's OGV Fuel Rule, in which ship traffic moved beyond the 24 nautical mile zone apparently to avoid using higher cost, low-sulfur fuel (CARB, 2009a), suggest that ships may move farther offshore to avoid localized regulations that increase costs. If a mandatory speed reduction within the existing TSS increases costs for certain vessels, it thus may provide an incentive for those ships to avoid transiting the Channel and instead choose other routes. Overall, these factors potentially provide negative incentives to comply with a 10 knot speed reduction and are important considerations in assessing the feasibility of this management option.

A variety of measures exist that could improve the success of a mandatory speed reduction by increasing the level of compliance. First, while rigorous efforts were made on the East Coast to spread awareness of the new regulation, improved communication to mariners, and especially foreign vessels, could increase compliance (Silber & Bettridge, 2010). The year-round and seasonal speed reductions considered in this analysis, as opposed to a dynamic speed reduction in which vessels are only asked to slow down when whales are observed in the Channel, may also encourage greater compliance by making it easier for shipping companies to plan their routes accordingly. Penalties could also be administered to vessels that fail to adhere to speed requirements. On the East Coast, for example, NOAA began issuing formal citations after a one-year "grace period" during which it engaged in outreach efforts to alert mariners to the new speed restriction along the eastern seaboard (M. DeAngelis, pers. communication, Feb. 22, 2011). Penalties for violations of the 10 knot speed restriction range from \$2,500-\$5,500 for the first violation, \$5,000-\$8,000 for the second violation, and \$7,500 up to the current statutory maximum of \$11,000 under the MMPA (or even higher under the ESA) for the third violation (NOAA, 2008, 2010).

The use of incentives, as well as improved monitoring and enforcement, may also promote adherence to speed restrictions. Previously discussed emissions reduction programs at the LALB, which include the voluntary vessel speed reduction program (VSRP) and the Green Flag incentive program, have been successful at encouraging ships to slow down to 12 knots within 20 or 40 nautical miles of the ports (Abramson *et al.*, 2009). This relative success may be due to the fact that the VSRP was officially recognized by shipping industry representatives who signed a Memorandum of Understanding, while the Green Flag program offered incentives in the form of reduced dockage fees, assignment of vessel unloading crews prior to port arrival (to encourage a slower approach to the port), and visible awards for vessels that complied with the VSRP (Abramson *et al.*, 2009). More recently, the ports have also begun improving compliance with the VSRP through tariff reduction incentives and requiring adherence to the program as a condition for renewing lease agreements (Abramson *et al.*, 2009). These initiatives have proven largely successful at reducing ship speeds in the vicinity of the ports (Abramson *et al.*, 2009). Finally, by providing constant supervision of vessel behavior, comprehensive vessel monitoring around the ports likely plays an important role in promoting compliance (Abramson *et al.*, 2009).

It is possible that some combination of penalties (in the case of mandatory requirements) and incentives (in the case of voluntary measures) could be replicated or extended to the Channel region and applied to promote speed reductions and enhance compliance with whale strike management actions (Abramson *et al.*, 2009). To the extent voluntary measures are adopted, establishing incentive programs would require interagency collaboration, funds for program administration, and potentially monetary rewards (Abramson *et al.*, 2009). Nonetheless, as vessel operators become accustomed to speed reductions over time, it is possible that such incentive-based programs could be gradually replaced with phased-in mandatory requirements, including escalating penalties for non-compliance (Abramson *et al.*, 2009). Thorough monitoring and enforcement will also be essential to ensuring adherence to mandatory speed restrictions, and would need to be further developed in the Channel (Abramson *et al.*, 2009).

MANAGEMENT OPTION 3: NARROW THE TRAFFIC SEPARATION SCHEME WITHIN THE CHANNEL

The SAC also suggested that NOAA consider exploring whether a shift in the TSS may reduce the risk of ship strikes to whales in the Channel region (Abramson *et al.*, 2009). We thus explored modifying the existing vessel lanes within the Channel in accordance with IMO regulations, including the IMO's recommendation that traffic lanes not overlap with drilling rigs, exploration platforms, or other offshore structures (IMO, 2003) Among other things, we considered the proximity of the existing TSS to Anacapa Island as well as the locations of the 20 oil and gas platforms present within the Channel region (Santa Barbara Channelkeeper, 2006). Given these considerations, we concluded that it would be difficult to make significant adjustments to the current traffic lanes without conducting a comprehensive analysis of the potential risks posed by these existing physical constraints, a task that was beyond the scope of our project.

Accordingly, rather than rerouting the TSS within the Channel, we modeled a more modest change that involves narrowing the separation between the existing traffic lanes. Specifically, we narrowed the Traffic Separation Zone between the northbound and southbound lanes from its current width of 2 nautical miles to a new width of 1.35 nautical miles (Figure 9). We selected this new width of 1.35 nautical miles based in part on our analysis of the relative probability of a whale being present (see Section 5.2 below), which revealed several areas adjacent to the southbound traffic lane with comparatively higher numbers of whale observations, and in part upon our desire to minimize any decrease in the width of the Traffic Separation Zone. By concentrating ships into a smaller area, while also moving them away from the Channel Islands where whales have been observed, such a change could potentially reduce the risk of a ship striking a whale. While there are many possible alternative configurations for the TSS through the Channel, we modeled this narrowed scenario to demonstrate one possible outcome of this type of management option.

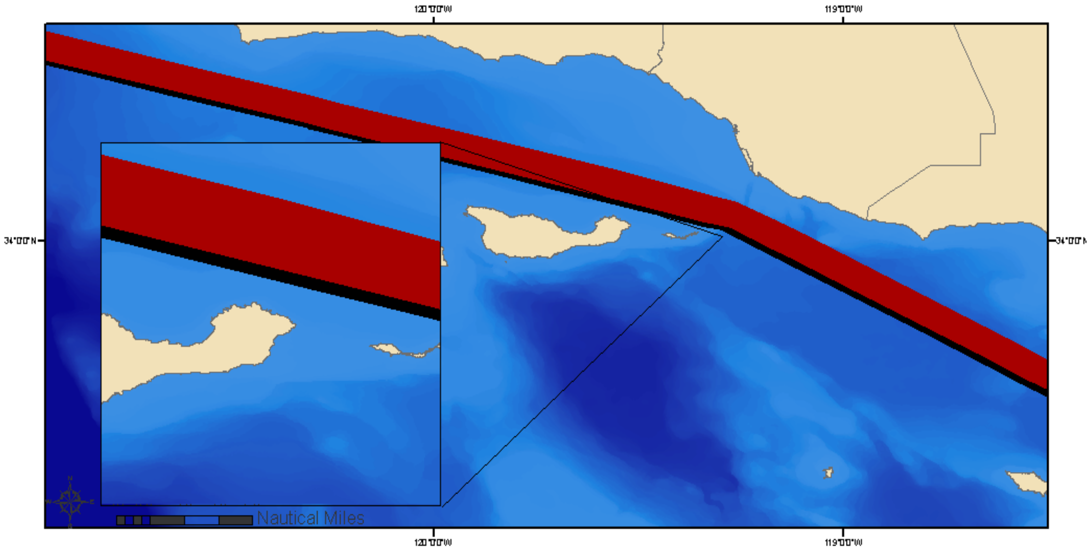


Figure 9: Narrowing the TSS was modeled by decreasing the separation zone in the existing TSS (shown in black) from 2 nautical miles to 1.35 nautical miles. The narrowed TSS is shown in red.

Feasibility and Other Policy Considerations

When assessing possible variations for moving the TSS within the Channel, we initially considered rotating and narrowing the TSS to potentially avoid comparatively higher numbers of whale observations adjacent to the existing TSS and elsewhere in the Channel. Consideration of this option arose in part from similar changes adopted as a result of the East Coast Port Access Route Study (USCG, 2005a). In that case, the USCG rotated and narrowed the eastbound and westbound lanes of the Boston TSS from 2 to 1.5 nautical miles in width, while leaving the separation zone unchanged at one nautical mile wide (IMO, 2006; Silber & Bettridge, 2010). In its request for IMO approval of the re-configured TSS, the U.S. opined that the proposed changes would diminish overlap between the traffic lanes and areas with substantially higher densities of right whales, without adversely affecting transiting ships or maritime safety in light of recent advances in navigational capabilities (IMO, 2006; Silber & Bettridge, 2010). The U.S. further stated that the proposed width of the Boston TSS was consistent with the width of other global TSS lanes previously approved by the IMO (IMO, 2006; Silber & Bettridge, 2010).

We ultimately did not pursue this scenario, however, as it appeared to require two or more changes to the traffic scheme in the Channel, including (1) narrowing the width of the TSS; (2) straightening the "turn" near Anacapa Island in a manner that would bring the northbound lane closer to one or more offshore oil and gas platforms, and/or (3) the introduction of a second "turn" within the Channel, likely within the region north of Santa Cruz Island. As a result, we concluded that, for the limited purposes of this project, narrowing the Traffic Separation Zone was the most feasible option for altering the existing vessel traffic lanes within the Channel.

As previously mentioned, USCG is currently involved in a PARS to assess the feasibility of modifications to the existing vessel routing scheme within the Channel (USCG, 2010a). Any management option that alters the configuration of the existing TSS within the Channel would require adoption by USCG; IMO approval would likely also be necessary (USCG, 2005b). Although vessels are not required to travel within IMO-approved traffic lanes, mariners who do so benefit from legal protections not otherwise afforded when taking an alternate route (Abramson *et al.*, 2009).

MANAGEMENT OPTION 4: SHIFT THE TRAFFIC SEPARATION SCHEME TO THE SOUTH OF THE NORTHERN CHANNEL ISLANDS

The fourth management option we evaluated involves rerouting ships to the south side of the Northern Channel Islands. Since July 2009, when CARB began to require ships within the Channel to use more expensive, low-sulfur fuel, AIS data show an increasing number of ships transiting through this region, instead of using the designated TSS within the Channel. As previously discussed, approximately 50% of vessel traffic that previously traveled within the TSS has moved south of the

Northern Channel Islands; indeed, for some months, over 70% of cargo ships and tankers traveling through the region utilized this "Southern Region" (Senyk, 2010).

Shifting the TSS to the south of the Northern Channel Islands would increase the distance of a transit through the region, compared to a transit through the existing TSS. To determine the increased distance, we established a hypothetical alternative TSS (the "Southern TSS") outside the Channel. Using AIS data, we traced the routes of all large vessels using the Southern Region in September 2010 to determine a realistic placement for alternative traffic lanes (Figure 10). We connected the hypothetical traffic lanes to the "Western approach" – the unofficial western traffic lanes designated in 2009 for vessels entering or exiting the Port Complex of Los Angeles and Long Beach (Law, 2009). We identified two common points where the existing TSS and the Southern TSS diverged (one on the western end and one on the eastern end) and measured the distance in nautical miles from one point to another using each route. The distance measured inside the Channel was 112.7 nautical miles, and the distance using the Southern TSS was 126.5 nautical miles. We accordingly used the increased distance of 13.8 nautical miles to estimate the change in shipping industry costs as a result of this management scenario.

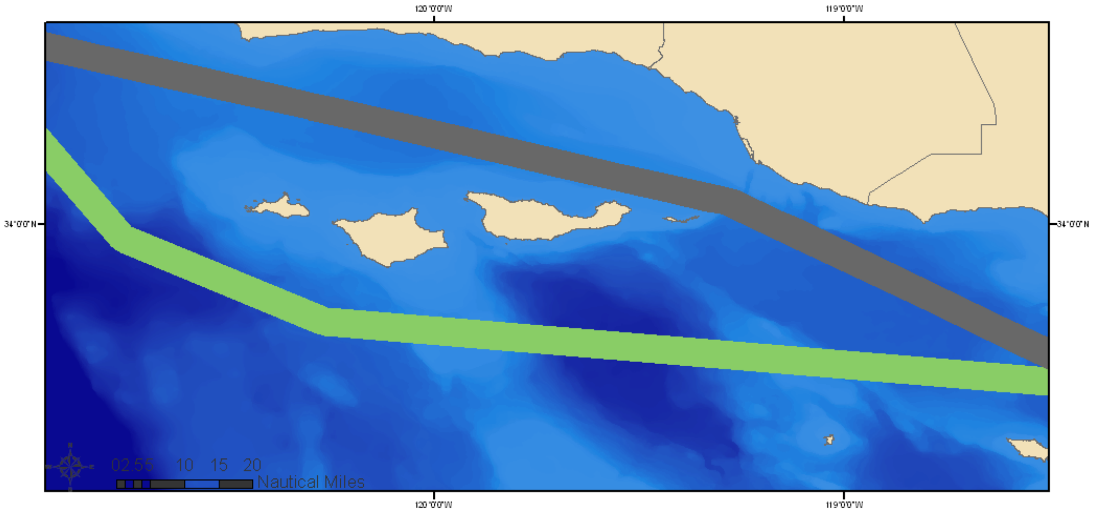


Figure 10: A hypothetical "Southern TSS" was drawn (in green) based on vessel routes after implementation of CARB's low-sulfur fuel regulation. The existing TSS is shown in gray.

Feasibility and Other Policy Considerations

Despite the current usage of the Southern Region, it is nonetheless important to consider the feasibility of implementing this management option and the issue of compliance. As with narrowing the existing TSS, the USCG is currently assessing the viability of moving the TSS to the south of the Northern Channel Islands (USCG, 2010a), and ultimately has sole discretion to determine whether this management option is feasible from a safety and efficiency standpoint. IMO approval also would likely be required.

Another important consideration in assessing the feasibility of this management option is its rerouting of vessels through the Navy's Point Mugu Sea Range. If this alternate route were to affect military operations in the Sea Range, the Navy may incur substantial costs. Indeed, the Navy has opposed rerouting ships to the south because doing so could, among other things, delay or otherwise interfere with testing, training and evaluating operations, and result in significant costs to the Department of Defense (with a single cancelled operation potentially costing millions of dollars) as well as decreased readiness of overseas troop deployments (Department of Navy, 2010).

If the TSS were officially relocated to south of the Northern Channel Islands, it is unknown whether ships would require incentives or penalties to comply with this route. While ships are presumably traveling through this region because it is currently the most cost effective option, impending air regulations will likely eliminate the benefit to mariners associated with this alternate route. Consequently, in the future, ships may have more incentive to travel through the Channel. Although, as noted, ships are not required to travel within the TSS, traveling an alternate route foregoes certain legal protections and may result in greater liability in the event of a collision (Abramson *et al.*, 2009). This risk of liability may not, however, provide adequate incentive for ships to follow established lanes, as evidenced by the current increase in traffic in the Southern Region as a result of the low-sulfur fuel regulation.

5.2 ANALYSIS OF THE CHANGE IN RELATIVE RISK FOR EACH OF THE FOUR MANAGEMENT OPTIONS

GENERAL METHODOLOGY

To estimate the risk of lethal strikes to whales in the Santa Barbara Channel, we developed a simple, two-dimensional surface model that uses estimates of whale distribution and ship traffic patterns to evaluate the change in relative risk of lethal strikes resulting from the each of the four management options. Our risk analysis does not attempt to assess the absolute risk of lethal ship strikes to whales, nor does it estimate the number of lethal strikes likely occurring. Rather, we have specifically examined the change in relative risk of a lethal strike to a whale resulting from each of the four management options. Our model allows us to evaluate and compare the effectiveness of the four management options in reducing both the relative risk of encounters between whales and ships, as well as the relative risk of lethal strikes to whales.

Spatial Resolution of the Study Region

Our study area encompasses the Santa Barbara Channel region and is bounded by latitudes 35˚30'N and 33˚21'N and longitudes 120˚57'W and 118˚30'W. Given the large spatial scale encompassed by the study area, it was necessary to break down the region into a series of units that were able to better capture the probability of an encounter occurring between a whale and a ship. Past studies have demonstrated the importance of evaluating the risk of whale strikes on a scale that is both small enough to characterize variability in ship traffic, yet large enough to include a sufficient number of whale and ship observations (Fonnesbeck *et al.*, 2008). Currently, little is known about the response behavior of whales in close proximity to ships (Fonnesbeck, Garrison, Ward-Gieger, & Baumstark, 2008; Nichols & Kite-Powell, 2005). We therefore chose to estimate the relative risk of lethal strikes to whales on a coarse scale and transformed the study region into a grid consisting of 5 km x 5 km cells. The grid encompassed a total of 1,175 cells and was generated using the 'Fishnet' tool within the Data Management toolbox in ArcGIS (9.3).

Spatial Ship Data

Automatic Identification System (AIS) data were received in the form of daily log files from Scripps Institution of Oceanography's Whale Acoustics Lab. The log files were parsed and imported into a centrally located PostgreSQL server at CINMS. We queried the PostgreSQL database to evaluate the number and speed of ships within the study area for a one-year period from July 1, 2008 to June 30, 2009. We selected this time period as a representative year for two reasons. First, the AIS data available to us for this time frame were of higher quality than prior years, due to the installation of a receiver at Coal Oil Point in September 2008. Second, the selected timeframe provided the most recent and complete set of year-long transit data prior to implementation of CARB's low-sulfur fuel regulation. The implementation of the low-sulfur fuel regulation on July 1, 2009 changed the pattern of ship behavior substantially as the cost and feasibility of using low-sulfur fuel within the Channel caused many operators to transit on the south side of the Northern Channel Islands

(CARB, 2011). Thus, we assume that the year before the regulation came into effect represents traditional vessel traffic.

In order to generate a dataset of the representative intra-annual traffic patterns of vessels within the study region during one year, we queried the AIS database for monthly subsets of all transits within the geographic extent of our grid. AIS data were obtained for all cargo ships, tankers, cruise ships, and “other” vessels transiting the region during this time period. We excluded vessels such as tugs, dredge vessels, towboats, fishing vessels, pleasure craft, research vessels, law enforcement and military vessels, and small passenger vessels. Each of these vessel types has been excluded for one or several of the following reasons:

- Due to the vessel size, speed, or location of operation, it is not likely to be affected by management scenarios;
- Due to the nature of the vessel’s operation, it may be exempt from regulations relating to our modeled management scenarios; and/or
- The economic impacts to the type of vessel are expected to be minimal.

The category of “other” vessels was included in our analysis, as many ships within this category are mislabeled cargo ships and tankers that would likely be affected by the management scenarios. In excluding vessels such as tugs, dredge vessels, towboats, etc. the overall number of ships included in the analysis was reduced. Because limiting the subset of vessel types had already led to an underestimation in the number of ships within the study region (and therefore of the probability of an encounter between a whale and a ship), we assumed that inclusion of the “other” vessel category would not incorrectly inflate estimates of the relative risk of a lethal strike to a whale.

MATLAB was then used to aggregate ship data (ID number and speed) for each month within each grid cell using the latitude and longitude coordinates associated with the AIS transmissions of each ship. The unique number of ships within each grid cell was then calculated for each aggregated monthly data set. This provides a highly conservative estimate of the unique number of ships within a grid cell during a monthly period, because it does not account for vessels entering a given cell multiple times during that month (*i.e.*, return trips, backtracking). We then calculated the average speed of the unique ships within each grid cell for each aggregated monthly data set. This estimate of the average speed of ships transiting a grid cell was calculated from AIS transmissions for each unique ship and therefore may not represent the average speed of each vessel over its entire transit through the

Channel. To generate quarterly aggregates of ship traffic patterns, the unique number of ships within a grid cell was summed across three-month periods (January to March, April to June, July to September, and October to December) and the average speed of all unique ships transiting through the cell were averaged across the three-month periods. We chose to divide the year into four quarters (beginning at the start of the calendar year) to capture both the intra-annual variability in ship traffic patterns and whale distribution patterns and to simplify our risk calculations.

Spatial variability was observed when comparing the number of ships transiting the TSS in the center of the Channel, to those ships transiting the TSS along both the eastern and western edges of the Channel. This variability is due in part to limitations associated with AIS receiving stations, which have limited reception along both the eastern and western extremes of the Channel. Reception is comparatively higher along the central portion of the TSS, resulting in the seemingly higher ship densities in this area. Using AIS data to generate quarterly ship counts thus likely results in an underestimation of the actual number of ships transiting the eastern and western regions of our study area. To correct for this data limitation, we averaged the number of ships in each grid cell for the entire length of the TSS during each quarter and subsequently applied this average equally to all cells within the TSS. While this simplified approach does not reflect the true number of ships transiting each cell within the TSS or the potential change in ship density across the TSS, it nevertheless more accurately assumes that a ship traveling within the centralized portion of the TSS also utilizes the eastern and/or western extremes of the TSS. Because our goal was to compare the change in relative risk of a lethal strike among management options – as opposed to quantifying the absolute risk of a lethal strike – assigning an average ship value to all cells within the TSS was not expected to alter the outcome of our analysis. The average ship value we applied to the cells within the TSS may be an under- or over-estimate of the actual number of ships transiting the TSS. However, the change in the estimated relative risk of a lethal strike resulting from management options would remain proportional across management options according to our modeling methodology.

Spatial Whale Data

Whale observation data of blue, fin, and humpback whales were provided by CINMS, from archived data collected through its Sanctuary Aerial Monitoring and Spatial Analysis Program (SAMSAP). Initiated in 1997, SAMSAP utilizes standardized aerial monitoring to record the location of large cetaceans in and around the boundaries of CINMS. SAMSAP surveys were conducted on a bi-weekly to monthly basis, although longer gaps in the data occurred due to weather, aircraft maintenance and aircraft availability. To conduct aerial surveys, SAMSAP employs an airplane equipped with GPS, special data collection software, and onboard data collectors that record coordinates and other relevant information for each sighting. Observations are recorded by two trained observers on board either side of the plane during each flight, and observers scan an area extending about 2.5 nautical miles from the plane. The attributes of the SAMSAP data set include: a time series of the latitude and longitude coordinates of the plane; the heading, speed and altitude at which the plane was traveling; the Beaufort sea state; a weather index; a measure of glare on the water surface; a water color index; the increment angle at which the whale was sighted; the species name of the observed cetacean; the size of the group observed; whether or not a calf was present; and additional comments about the sighting. For our analysis, we used SAMSAP data archived between 1997 and February of 2010 (inclusive). Table 1 below shows the total number of survey flights conducted per year:

Table 1: Total number of SAMSAP survey flights conducted per year.

YEAR	NUMBER OF FLIGHTS
1997	13
1998	26
1999	6
2000	6
2001	8
2002	35
2003	22
2004	13
2005	26
2006	20
2007	10
2008	8
2009	16
2010	4
Total	**213**

Table 2 below shows the months of each year during which the SAMSAP conducted surveys (gray indicates a survey occurred):

Table 2: Months for which SAMSAP surveys were conducted.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1997							■	■	■	■	■	
1998	■	■	■	■	■	■			■	■	■	■
1999	■	■	■	■	■							
2000						■	■	■		■		
2001					■	■		■				
2002	■	■	■		■	■	■	■	■	■	■	■
2003	■	■		■	■		■	■		■	■	
2004	■			■		■	■	■				
2005	■	■	■	■	■	■	■		■	■	■	
2006	■	■	■	■	■	■	■	■	■			
2007						■	■	■	■	■	■	■
2008				■	■	■	■		■			
2009		■	■	■	■	■						■
2010	■	■	■									

Within the data set, there were a total of 101 observations of groups of blue whales (totaling 195 individual whales), 70 observations of groups of humpback whales (177 whales total), and 20 observations of groups of fin whales (29 whales total). Combining blue, humpback and fin whale observations across all years resulted in a total of 191 whale group observations (401 whales total). The average number of whales sighted per observation across all years was approximately 2 individuals, and the maximum group size observed was 15 individual whales (all humpbacks). Seasonal whale distribution within the Channel region, however, varied among species during the study period. For example, humpback whale abundance peaked between April and June (aggregated across all years), while blue whale abundance tended to peak between June and November. Fin whale abundance remained more evenly distributed throughout the year (see Appendix 3). In combining all whale observations, peak abundances were observed during April through July, and again during September through November. Analysis of whale observation data also revealed inter-annual variability. When compared across years, for example, the years 1998 and 2002 were characterized by anomalously large numbers of observations of blue and humpback whales (see Appendix 3). There was a total of 67 observations in 1998 and a total of 33 observations in 2002. The year of the Unusual Mortality Event (2007) was not distinguished by an unusually large number of observations.

We used the SAMSAP data to geo-locate the whale observation points within our grid cells based on the coordinates of the transect line, altitude and heading at which the plane was traveling, and the increment angle at which a sighting occurred (Figure 11). First the perpendicular distance of a whale observation point from the aerial transect line was calculated using simple geometry:

Eq. 2

$$\boldsymbol{d} = \mathbf{tan}(\boldsymbol{\theta}) \times \boldsymbol{a}$$

Where:
d is the perpendicular distance
θ is the increment angle
a is the altitude of the plane

Next, the perpendicular distance (d) and the heading at which the plane was traveling were used to define the distance to move the whale observation point to the east or west of the transect line, as well as the distance to move the whale observation point to the north or south of the transect line:

Eq. 3

$$\boldsymbol{d_{ew}} = \boldsymbol{d} \times \mathbf{sin}(\boldsymbol{\phi})$$

Where:
$\mathbf{d_{ew}}$ is the distance to move observation east or west of transect line
d is the perpendicular distance of observation from transect line
φ is the heading angle at which the plane is traveling

Eq. 4

$$\boldsymbol{d_{ns}} = \boldsymbol{d} \times \mathbf{cos}(\boldsymbol{\phi})$$

Where:
$\mathbf{d_{ns}}$ is the distance to move observation north or south of transect line
d is the perpendicular distance of observation from transect line
φ is the heading angle at which the plane is traveling

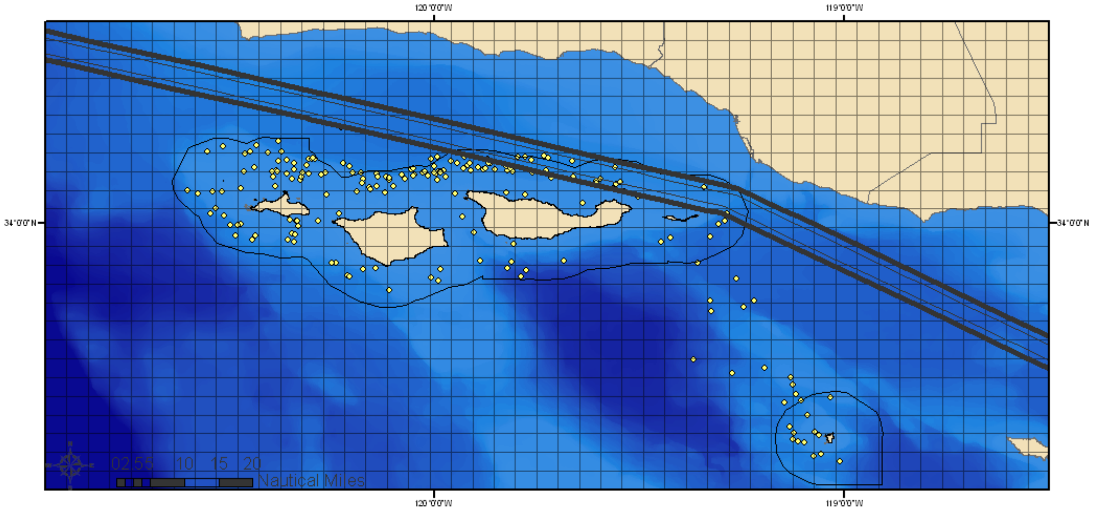


Figure 11: SAMSAP whale observation data geo-located (in yellow) within 5 km by 5 km grid cells defining the study region.

In order to account for the bias that can arise from estimating whale distributions based on uneven distribution of effort within grid cells, it was necessary to standardize all whale observations by the effort exerted during surveys (Kenney, Winn, & Macaulay, 1995; Nichols & Kite-Powell, 2005). Details on the duration and route of each separate aerial survey were compiled and used to measure the survey effort expended (time of flight path through cell, in fraction of a day) by month for each individual grid cell, hereafter referred to as the “effort” of each cell. Many grid cells in our study region were not surveyed and therefore were assigned an effort of zero (0). Standardization of sightings entailed dividing all observations in a grid cell by the amount of time (fraction of a day) spent surveying that cell. The resulting value was referred to as the “sightings per unit effort” (SPUE) value. Cells that were surveyed and contained no sightings were assigned a SPUE value of zero (0), and cells that were not surveyed were not given a SPUE value. SPUE values were calculated for each month and were averaged across all years from 1997 to 2010 (inclusive) to yield a monthly average SPUE value for each grid cell. The monthly average SPUE values were then summed across the three-month periods to generate quarterly SPUE values for each cell. We assume differences in quarterly SPUE values reflect the seasonal variability in whale observations. Average quarterly SPUE values for the entire study region (excluding cells with no effort) are provided in Table 3 below.

Table 3: Average SPUE values and standard deviations for the entire study region calculated for each quarter of the year based on SAMSAP data from 1997 to 2010. Quarter 1 is January through March, quarter 2 is April through June, quarter 3 is July through September, and quarter 4 is October through December.

QUARTER	AVERAGE SPUE	STANDARD DEVIATION
1	0.003	0.030
2	0.029	0.101
3	0.026	0.099
4	0.022	0.071

Evaluating Relative Probabilities of Ships and Whales in a Given Location

In order to evaluate and compare the change in risk of the different management options, it was necessary to define the relative probability of a ship being present within a grid cell, as well as the relative probability of a whale being present within a grid cell. Because the available ship traffic data and whale sighting data do not quantify the absolute distribution and number of whales and ships present in the study region, we were unable to calculate the actual probability of a whale or a ship being present in a given grid cell. We assume, however, that the relative probability of a whale being present in a grid cell where effort was expended and the relative probability of a ship being present in a given grid cell are directly proportional to the actual probabilities of such events.

Relative Probability of a Ship Occupying a Grid Cell

Quarterly ship density values were used to estimate the relative probability of a ship occupying a grid cell during each of the four quarters. Ship density values were made relative to one another by dividing the quarterly ship density value of each cell by the maximum ship density value observed in any cell for the entire study period, a method conducted separately for each of the four quarters. Therefore, across all quarters the relative probability of a ship occupying a grid cell ranges between zero (0) and one. The relative probability of a ship occupying a grid cell *i* for each quarter was calculated as:

Eq. 5

$$\boldsymbol{P_{rel}(Ship)_i = \frac{Ship_i}{max(Ship_i)}}$$

Where:
Ship$_i$ is the number of ships occupying grid cell *i*

Relative Probability of a Whale Occupying a Grid Cell

Quarterly SPUE values for each grid cell *i* were made relative to one another by dividing the quarterly average SPUE value of each cell by the maximum SPUE value observed in any cell for the entire study period, a method conducted separately for each of the four quarters. Therefore, across all quarters the relative probability of a whale occupying a grid cell ranges between zero (0) and 1. The relative probability of a whale occupying a grid cell *i* was calculated as:

Eq. 6

$$\boldsymbol{P_{rel}(Whale)_i = \frac{SPUE_i}{max(SPUE_i)}}$$

Where:
SPUE$_i$ is the sightings per unit effort value in grid cell *i*

<u>Predictive Model</u>

While SAMSAP whale observation data proved useful, our analysis remained severely constrained by the notable lack of whale observations, both within the Channel and especially to the south of the northernmost Channel Islands (Figure 11). Further confounding this issue was the fact that the SAMSAP monitoring program is largely confined to the Sanctuary's boundaries, and thus a majority of the grid cells within the defined study region were not surveyed. Lack of survey effort in the majority of grid cells not only limited our ability to calculate the relative probability of a whale occupying a cell not surveyed, but further rendered it impossible to compare the change in risk resulting from different management options. Due to these data constraints, it was necessary to create a predictive model to estimate the relative probability of a whale occupying any given grid cell in our study region.

Average Distribution Model

We first created a simple predictive model that applied the average number of observed relative whale probabilities, for a specified quarter, to all cells equally within the grid. This method was applied for each of the four quarters separately. This version of the model assumes that whales are evenly distributed throughout our study region. While this assumption may or may not hold, the model nevertheless provides a baseline by which management options can be easily evaluated and is a simple benchmark, particularly when spatial distribution data are sparse. Modeling changes in ship densities or speeds as a result of management options is a key factor in determining the change in relative risk of a lethal strike. Analyzing the effect of these changes under the assumption that whales are evenly distributed across the study region may serve as a useful proxy for estimating changes in relative risk.

Linear Predictive Model

To partially overcome the limitations of a uniform whale distribution model, we developed a more refined predictive model that uses additional variables to estimate the relative probability of a whale in a grid cell. Typically, cetacean densities are estimated using line-transect surveys aboard ships or airplanes (Becker *et al.*, 2010; Kenney *et al.*, 1995; Pittman, Costa, Kot, Wiley, & Kenney, 2006; R. Williams & O'Hara, 2009). Based on these density estimates, subsequent habitat modeling is then employed to project finer-scale whale distributions based on environmental predictors (Becker *et al.*, 2010). In this case, however, it was not possible to project whale densities based on survey data alone because SAMSAP data were not collected according to systematic, traditional line-transect surveying methods.

Generalized linear models (which are extensions of linear models) have been used to project whale densities and abundances based on environmental habitat data (Becker *et al.*, 2010). Whale sighting rates and densities can be modeled as a continuous function of specific environmental variables believed to influence whale behavior and feeding habits, including bathymetric features and surface currents (Becker *et al.*, 2010; Best & Halpin, 2009). Studies analyzing linkages between cetacean distribution and environmental variables have further concluded that static habitat features (*i.e.*, continental shelf edge) may in some cases offer more explanatory power of cetacean distribution patterns than dynamic features such as sea surface temperature and chlorophyll-a concentration, which can describe prey aggregation that may influence cetacean distribution (Best & Halpin, 2009; Pittman *et al.*, 2006). Moreover, some attempts to incorporate dynamic variables such as sea surface temperature and chlorophyll into predictive models have proven unsuccessful due to data limitations (Best & Halpin, 2009).

Given these conclusions and data limitations of our own, we developed a linear model to predict whale distribution as a function of the static environmental variables of bathymetric depth, slope, and distance to shore. These three variables have been used as predictors of whale distribution in the literature (Becker *et al.*, 2010; Best & Halpin, 2009; Fonnesbeck *et al.*, 2008; Pittman *et al.*, 2006; R. Williams & O'Hara, 2009). While these static environmental features have been demonstrated to influence whale distribution in coastal regions and for feeding aggregations, they may not capture the variability in whale migration behaviors or the variability in oceanographic temperature fronts that can affect feeding aggregations (Becker *et al.*, 2010). Despite these limitations, we chose to use the three static environmental predictor variables and thus our model likely does not capture all variability in whale distribution in the study region. The resulting predictive model we developed assumes a normal distribution and uses a linear function to estimate the quarterly relative probability of a whale in a cell as a function of the predictor variables defining each grid cell:.

Eq. 7

$$\boldsymbol{P_{rel}(Whale)_i = \beta_0 + \beta_1 D_i + \beta_2 M_i + \beta_3 S_i + \varepsilon_i}$$

Where:
$\mathbf{P_{rel}(Whale)_i}$ is the relative probability of a whale in cell *i* for each quarter
$\mathbf{D_i}$ is the distance to shore in nautical miles of the centroid point in cell *i*
$\mathbf{M_i}$ is the minimum depth of cell *i*
$\mathbf{S_i}$ is the average bathymetric slope of cell *i*
$\boldsymbol{\beta_0}$, $\boldsymbol{\beta_1}$, $\boldsymbol{\beta_2}$, and $\boldsymbol{\beta_3}$ are estimated regression coefficients
$\boldsymbol{\varepsilon_i}$ is the error

The predictor variables for each grid cell were calculated in ArcGIS (9.3) using a bathymetric layer (3 arc-second resolution) from the U.S. Coastal Relief Model (CRM) provided by NOAA’s National Geophysical Data Center. The minimum bathymetric depth (in meters) within each grid cell was calculated using the ‘Zonal Statistics’ tool in the Spatial Analyst toolbox. The percent rise of bathymetric slope was calculated from the CRM bathymetry data, and the average slope was then sampled using the Zonal Statistics tool. The distance to shore (in nautical miles) from the centroid point of each grid cell was calculated using the ‘Near’ tool in the Spatial Analyst toolbox.

The model was fit to the relative probability of a whale in a cell (generated from observed SPUE values (Eq. 6)) separately for each quarter. The number of cells for which we had SPUE values for each quarter was 333, 297, 274, and 224, respectively. We tested combinations of the predictor variables for each quarter and compared the model deviance, or the measure of the lack of fit between the model and the data, for each combination. The deviance for each model tested was indistinguishable (changes less than 0.1) for each quarter. Upon visual inspection, the predictions based on all three static environmental variables were the most consistent with the observed sightings (see Appendix 3). For each quarter, the selected model was then used to predict the relative probability of a whale in each cell over the entire study region (see Appendix 3). If predicted values fell below zero (0) – an unrealistic prediction of a negative probability of whale presence – they were retroactively assigned a value of zero (0). More details on model fit for each quarter are presented in Appendix 3.

ESTIMATING THE RELATIVE RISK OF A LETHAL STRIKE

Estimating the Relative Probability of an Encounter

The relative probability of an encounter between a whale and a ship occurring in grid cell *i* was determined by multiplying the relative probability of a whale occupying grid cell *i* (Eq. 6) by the relative probability of a vessel occupying grid cell *i* (Eq. 5). The relative probability of an encounter occurring between a vessel and a whale in grid cell *i* was calculated for each quarter as:

Eq. 8

$$\boldsymbol{P_{rel}(Encounter)_i = P_{rel}(Ship)_i \times P_{rel}(Whale)_i}$$

Where:
$\boldsymbol{P_{rel}(Ship)_i}$ is the relative probability of a ship occupying a grid cell *i*
$\boldsymbol{P_{rel}(Whale)_i}$ is the relative probability of a whale occupying a grid cell *i*

Estimating the Relative Risk of a Lethal Strike

Alone, the relative probability of an encounter between a whale and a ship in a given area does not estimate the lethality of strike, which is primarily a function of speed. First, we used the logistic regression model estimate provided by Vanderlaan *et al.* (2008) (Eq. 1), along with the average speed calculated in each cell, to estimate the probability of a lethal strike. Quarterly average speed for each grid cell was generated by averaging the mean speed traveled by all unique ships in each grid cell for each month. The probability of a lethal strike is calculated as:

Eq. 1

$$\boldsymbol{P(Lethal|Encounter)_i = \frac{1}{1 + exp^{-(-4.89+0.41\bar{x}_i)}}}$$

Where:
$\boldsymbol{\bar{x}_i}$ is average ship speed in cell *i*

We then quantified the relative risk of a lethal whale strike based on the event of the relative probability of an encounter between a ship and a whale (Eq. 8) and the consequence, which is the probability that the encounter is lethal (Eq. 1) (Vanderlaan *et al.*, 2009; Vanderlaan *et al.*, 2008). The relative probability of a lethal strike in grid cell *i* was calculated for each quarter as:

Eq. 9

$$\boldsymbol{RR_i = P_{rel}(Encounter)_i \times P(Lethal|Encounter)_i}$$

Where:
$\boldsymbol{P_{rel}(Encounter)_i}$ is the relative probability of an encounter between a whale and a ship in grid cell *i*
$\boldsymbol{P(Lethal|Encounter)_i}$ is the relative probability of a lethal strike given an encounter

Calculating Confidence Intervals

To quantify the error associated with our estimates of the change in relative risk of a lethal whale strike for each management option, we calculated 95% confidence intervals using bootstrap re-sampling methods. First, to calculate 95% confidence intervals for the estimates of the change in relative risk when using the Average Distribution Model, we calculated the sample mean and standard deviation of the relative probability of a whale in a grid cell (generated from observed SPUE values) across all grid cells for each quarter (see Table 3). Next we calculated the residuals of the Average Distribution Model values compared to the observed values and randomly generated an error term for each cell from a normal distribution of the residuals. We then added the randomly generated error term for each cell to the average relative whale probability value to generate a new average relative probability of a whale value for each cell for each quarter. This process was repeated

1,000 times for each quarter and each management option. For each cell of each iteration, the randomly sampled probability of a whale value was used to calculate the relative risk of a lethal strike. The final bootstrapped distributions of the change in relative risk of each management option compared to current management – or the status quo – were used to calculate the 95% confidence intervals.

To calculate 95% confidence intervals for the estimates of the change in relative risk of a lethal strike when using the Linear Predictive Model, we again used bootstrap re-sampling methods. First, we used the residuals of the fitted values generated by the Linear Predictive Model for each cell during each quarter and randomly generated an error term for each cell from a normal distribution of the residuals. We then added the error term for each grid cell to the predicted relative probability of a whale in each grid cell. These probability values for each quarter were then used to calculate the change in relative risk of a lethal whale strike for each management option. This process was repeated 1,000 times for each quarter. The resulting bootstrapped distributions of the change in relative risk for each management option compared to the status quo were used to calculate the 95% confidence intervals.

ANALYSIS OF MANAGEMENT SCENARIOS

Management options considered in our analysis influence the risk of a lethal whale strike by either (1) altering the probability of a ship occupying a given grid cell or given region of grid cells, or (2) altering the average speed of ships transiting a cell. We assume that the first scenario – altering the probability of a ship occupying a cell – directly affects the probability of an encounter between a ship and a whale, while the second scenario – reducing ship speed – directly affects the probability of a lethal strike given an encounter. To evaluate the change in risk according to each management option, it was necessary to modify either ship densities or the average ship speed of individual grid cells in our model.

To begin, we characterized baseline traffic conditions by calculating both the relative probability of a ship occupying a cell, and the average speed of all unique ships transiting a cell during each quarter based on AIS data for our representative year. These relative probabilities and average speeds were then used to compare changes in ship densities, both across quarters and among management options. Once these baseline values representing ship traffic had been established (the “status quo”), we calculated the baseline relative probability of an encounter and relative risk of a lethal strike to a whale using predicted whale distribution from both the Average

Distribution Model and Linear Predictive Model. Management options were then modeled by either relocating ship traffic or reducing ship speeds, and the change in risk for each management option was quantified by calculating the percent change from the status quo values.

Management Option 1: Year-Round Mandatory Speed Reduction

To model the effect of a year-round mandatory speed reduction to 10 knots in the Whale Advisory Zone (WAZ), we first identified the grid cells within the TSS that also fell within the WAZ. The average speed of ships traveling within each of these cells was assigned a new average speed of 10 knots for each quarter, except for those cells whose original average speed was less than 10 knots, in which case the original value was left unchanged. We then used values of the relative probability of a ship in a cell and results from both predictive models of whale distribution under the status quo scenario to calculate the change in relative risk of a lethal strike for this management option.

Management Option 2: Seasonal Mandatory Speed Reduction

To model the effect of a seasonal mandatory speed reduction to10 knots in the WAZ during the months of April through September, we used the same methodology described above for the year-round mandatory speed reduction, but limited the analysis to quarters 2 and 3. Therefore, we only assigned a new average speed of 10 knots for ships occupying cells within the TSS and WAZ during quarters 2 and 3. In order to calculate the change in relative risk for this management option, we compared the relative risk during the seasonal mandatory speed reduction to the baseline relative risk values for only quarters 2 and 3, rather than for the entire year.

Management Option 3: Narrow the Traffic Separation Scheme within the Channel

Narrowing the existing TSS by reducing the traffic separation zone from its current width of 2 nautical miles to 1.35 nautical miles would have the effect of reducing the number of grid cells in our model through which ships would transit. We thus modeled this management option assuming that the number of ships would increase in each grid cell located within the newly designated traffic lanes. We identified fourteen grid cells in the existing TSS that were not included as part of the narrowed TSS; this option reduced the number of cells transited within the TSS by 10.2%. For each of these grid cells, the probability of a vessel occupying that cell was assigned a value of zero (0) and the average speed of all ships was also assigned a value of zero (0). The probability of a ship occupying the narrowed TSS was determined by first summing the probability of a ship across all grid cells in the existing TSS. This value was then divided by the total number of grid cells comprising the narrowed TSS, a method that essentially redistributed the same amount of vessel traffic across a smaller area. We then calculated the change in relative risk of a lethal strike under this management option compared to the status quo scenario using results from both the Average Distribution Model and the Linear Predictive Model.

Management Option 4: Shift the Traffic Separation Scheme to the South of the Northern Channel Islands

Under this management option, we assumed that all ships in the existing TSS would relocate to the hypothetical TSS south of the Northern Channel Islands (the “Southern TSS”). All grid cells falling within and intersecting the existing TSS were thus assigned values of zero (0) for the relative probability of a ship occupying those grid cells and for the average ship speed. As with the narrowing scenario, fewer cells comprise the Southern TSS than the existing TSS due to the orientation of the Southern TSS. We therefore followed the same methodology as described for narrowing the lanes, in which the relative probability of a ship occupying a grid cell was first summed across all cells in the existing TSS, and then divided by the total number of cells in the Southern TSS. The resulting value was subsequently applied to each grid cell in the Southern TSS. Similar to modeling Management Option 3, the average speed of all unique ships traveling within the grid cells of the existing TSS was applied to the grid cells of the Southern TSS. We then combined the relative probabilities of ships and average speeds with the relative probabilities of whale distribution predicted by both the Average Distribution Model and the Linear Predictive Model to calculate the relative risk for this management option.

5.3 ANALYSIS OF THE CHANGE IN TOTAL COST FOR EACH OF THE FOUR MANAGEMENT OPTIONS

GENERAL METHODOLOGY

We designed a model to determine the change in cost to the shipping industry as a result of the management options for reducing the risk of vessel strikes to whales evaluated in this project. Our economic model does not attempt to estimate the total economic impact of the potential management scenarios. Rather, we were specifically interested in determining the costs of management scenarios to large commercial vessels accessing west coast ports. We determined the cost of each management scenario by calculating the change in total operating and voyage costs for a selected subset of ships transiting the region. As noted, the three types of vessels we have included in our analysis are cargo ships, tankers, and cruise ships. Other vessel types have been excluded for the reasons outlined in Section 5.2.

Characterizing Vessel Traffic

To apply our economic model to vessel traffic in the Channel, we first collected data from the Automatic Identification System (AIS) to generate a list of ship transits through the Santa Barbara Channel region for the one-year time period selected – July 1, 2008 to June 30, 2009 (refer to Section 5.2 for date range selection).

As noted in Section 4.4, the nature of AIS is that vessels equipped with this system transmit GPS coordinates every few seconds, which results in numerous records of each transit through the region. Thus, to distinguish individual transits for our economic analysis we organized our AIS output into daily records, so that we generated a single record for each transit through the region. In our initial total list of transits, this caused an individual overnight trip through the Channel to appear as though it were two separate transits. We corrected for this error by averaging the speeds reflected on consecutive days, and deleting the duplicate records. Following these corrections, our representative year of ship traffic included a total of 5,725 transits through the region.

Random Subset of Ships

Because our detailed economic analysis required collection of specific data on each ship from printed volumes of Lloyd’s Register of Shipping, it was infeasible to conduct a detailed analysis of each of the 5,725 transits. Instead, we analyzed in detail a random sample of 10% of the transits through the region for the selected time period (July 2008 through June 2009), which we believe was a large enough subset to characterize the types and sizes of ships transiting the region. After excluding ships that were not pertinent to our analysis, as discussed below, this resulted in a total of 488 transits made by 334 individual ships. For each of these ships, we obtained vessel-specific data from Lloyd’s Register of Shipping, including tonnage, speed, engine power and age, among other parameters, which we incorporated into our model. Lloyd’s is a publication and vessel data system that contains specific data for nearly every ocean-going vessel in the world fleet, and is considered to be a leading resource for obtaining ship characteristics (Starcrest Consulting Group, LLC, 2010).

We did not have access to the copyrighted software database, but rather searched for each ship in reference books located in the reserves at the Southern California Marine Exchange in San Pedro, the San Francisco Public Library, and the Miami-Dade Public Library. Data collected on each of these ships were used in our model to determine the effect of management on the shipping industry.

Relevant Ships

Selecting relevant ships for analysis required that we utilize the vessel type listed in the AIS data stream. We used the ship types reported in AIS to select cargo ships, tankers, and cruise ships and to eliminate those ships that were not pertinent to our analysis. Some of the ships were listed as “other” or “unspecified” in the AIS data, including 10 transits by 9 unique ships in our random sample. To determine whether these ships were relevant to our analysis, we looked up more detailed information about their ship types and sizes using the online database at www.equasis.org. Three of the 9 ships (3 of 10 transits) fit the criteria for inclusion in our analysis and were incorporated into our economic model. In comparing this subset to the entire year of transits, we considered 3 of every 10 other/unspecified vessel transits to be relevant to our analysis and to incur costs. We excluded two ships from our analysis because the data were not available in Lloyd’s Register of Shipping or because the Lloyd’s data were inconsistent with the AIS data.

ECONOMIC MODEL

Our economic model estimates the change in costs that would occur should our selected management options to reduce vessel strikes to whales be implemented. This model is designed to reflect the change in the cost of an individual transit through the region. Specifically, the change in total cost was determined for any given transit, and is primarily a function of the change in voyage costs and the change in operating costs. The change in total cost was summed for all relevant transits from our random sample and then scaled up to represent the total cost to the industry for all the transits in an entire year. The following sections outline the costs affected by management options, as reflected by the following equation (see Appendix 4 for detailed equations).

$$\boldsymbol{\Delta TC = \Delta VC + \Delta OC + \Delta NC + \alpha \Delta \mathrm{t}}$$

Where:
ΔTC is the change in total costs
ΔVC is the change in voyage costs
ΔOC is the change in operating costs
ΔNC is the change in costs from a delay caused by Navy operations
αΔt is an additional hourly change in cost from increased time at sea

The change in voyage cost (ΔVC) includes a change in fuel and lubricant costs. The change in operating costs (ΔOC) resulting from management measures includes crew costs and additional repair and maintenance costs incurred as a result of a speed reduction. We also modeled the cost of an unexpected delay resulting from Navy operations (ΔNC) for ships transiting on the south side of the Northern Channel Islands under Management Option 4. Finally, we include an additional factor (αΔt) that accounts for costs not explicitly defined in our model; these costs may include the cost of delay or additional hourly operating costs that may be affected by increased time at sea. The following sections also discuss components excluded from our model, including the cost of lubricant for auxiliary engines, the cost of general stores, and administrative and insurance expenses.

Change in Voyage Costs

The change in voyage costs includes the difference in the cost of fuel and lubricant due to altered consumption during any transit through the region.

This equation is represented as follows:

$$\Delta \boldsymbol{VC} = \boldsymbol{\Delta FC_{TOT}} + \boldsymbol{\Delta LC}$$

Where:
ΔVC is the change in voyage costs
ΔFC_{TOT} is the change in fuel costs from main and auxiliary engine operation
ΔLC is the change in lubricant costs

Fuel Costs

The main component of the change in voyage cost is the change in fuel cost as a result of management. Fuel costs are determined by both the price of fuel and the amount of fuel consumed.

Fuel Price

To comply with existing international regulations governing the sulfur content of marine fuels, commercial ocean-going vessels typically use one or more of the following fuel types:

- IFO 380 – an Intermediate Fuel Oil mix consisting of 98% residual oil and 2% distillate oil;
- IFO 180 – an Intermediate Fuel Oil mix consisting of 88% residual oil and 12% distillate oil;
- MDO – a Marine Diesel Oil mix consisting mainly of distillate oil; and
- MGO – a Marine Gas Oil consisting of pure distillate oil (ITMMA, 2010).

The sulfur content of each fuel generally declines with the percentage of residual oil, with intermediate fuel oils having the highest sulfur content and marine gas oils having the lowest sulfur content, as summarized below in Table 4 (ITMMA, 2010).

Table 4. Sulfur content of marine fuels.

INDUSTRIAL NAME	COMPOSITION	ISO SPECIFICATION SULFUR WEIGHT %	WORLD RANGE
Intermediate Fuel Oil 380 (IFO 380)	98% residual oil 2% distillate oil	5%*	2.67%
Intermediate Fuel Oil 180 (IFO 180)	88% residual oil 12% distillate oil	5%*	2.67%
Marine Diesel Oil (MDO)	Distillate oil with trace of residual oil	2%	0.65%
Marine Gas Oil (MGO)	100% distillate oil	1.5%	0.38%

* IMO regulation capping sulfur at 4.5% superseded ISO specification

Source: Reproduced from (ITMMA, 2010).

Because distillate oil requires additional processing beyond that required for residual oil, the higher the distillate content, the more expensive the fuel (ITMMA, 2010). As a result, lower distillate, higher sulfur fuels such as IFO 380 tend to be cheaper, while higher distillate, lower sulfur fuels such as MGO tend to be relatively more expensive (ITMMA, 2010).

During our representative year (July 2008 through June 2009), IMO regulations required ships to use fuel with a sulfur content of 4.5% or less outside of designated Sulfur Emission Control Areas (SECAs) (IMO, 2008). Since then, however, international air regulations have tightened within the study region, and they are expected to become progressively more stringent in the future. Specifically, by August 2012, the IMO will require ships traveling within designated SECAs to use fuel with a reduced sulfur content of 1.0% (compared to the prior cap of 1.5%) (IMO, 2008). In March 2010, the IMO further adopted the U.S. and Canada's proposal to designate an area extending 200 nautical miles along most of the North American coast as a SECA (Federal Maritime Commission, 2010). As a result, ships traveling within 200 nautical miles of the West Coast will have to adhere to the reduced IMO sulfur fuel requirements beginning in 2012 (Federal Maritime Commission, 2010; IMO, 2008).

As a result of current and forthcoming IMO rules, in conjunction with the low-sulfur fuel regulations adopted by CARB, our model assumes that, in the future, ships traveling within the study region, including within the existing TSS and the hypothetical alternative TSS (the "Southern TSS") discussed above, will use lower sulfur, marine diesel or gas oil (MDO/MGO) for fuel. As discussed below, we further assumed that any increases in speed to make up for time lost due to an anticipated delay would occur outside the designated North American SECA. Accordingly, our model conservatively assumes that ships will use IFO 380, the cheapest fuel that complies with IMO regulations governing non-emission control areas, when making up time during other portions of their voyage outside of the study region.

Ideally, our economic model would have used different MDO/MGO and IFO 380 fuel prices for each transit from our sample, based on the actual transit date. Although historical pricing data for marine fuels are commercially available for a fee (Bunkerworld, 2010), funding limitations precluded access to these commercial databases for this analysis. We thus relied upon publicly-available pricing data for MDO/MGO. Unfortunately, public data are only sporadically available for certain dates or months, and then only for certain ports or fuel types. As a result, we relied upon historical fuel prices reported by Poten & Partners, a global broker and commercial advisor for the shipping industry. As of October 2009, for LALB, Poten & Partners reports that the price of MGO/MDO was approximately $625 per metric ton (Poten & Partners, 2009). Although Poten & Partners did not report the corresponding price for IFO 380 in October 2009, other industry experts have observed that, over the long term (in one case, from 1990 to 2008), MGO costs roughly twice as much as IFO 380 (ITMMA, 2010; World Shipping Council, 2008). We thus estimated the cost for IFO 380 to be $312.50, half that of the reported price for MDO/MGO (Poten & Partners, 2009). As noted, the MDO/MGO fuel price of $625 per metric ton was used for all transits within the study region, while the IFO 380 fuel price of $312.50 was used only to estimate the cost of fuel when operators make up time during other portions of their voyage outside of the study region. We believe these assumptions likely overestimate the long-term average price differential between MGO and IFO 380, and thereby represent a conservative estimate of the overall change in voyage costs under each management scenario.

Fuel Consumption

Almost all commercial marine vessels are powered by diesel engines because they are efficient and durable (Corbett, 2004). These large, deep-sea marine vessels generally have main engines, which are the predominant propulsion engines, and auxiliary engines that are primarily used to generate electricity while at sea (CARB, 2005; Chevron, 2008). Most main engines are slow-speed, two-stroke engines, while auxiliary engines are medium-speed, four-stroke engines (CARB, 2005; Chevron, 2008).

We calculated fuel consumption for an individual transit as the sum of fuel used in the ship's main and auxiliary engines (Corbett *et al.*, 2009; Corbett, 2004). For each type of engine, fuel consumption is calculated as a function of (1) installed engine power, (2) a specific fuel consumption factor, (3) engine activity hours, and (4) an engine load factor (Corbett *et al.*, 2009; Corbett, 2004; Starcrest Consulting Group, LLC, 2010). This model is based on current best-practice methodology for calculating emissions from commercial marine vessels (Corbett, 2004).

i. Engine Power

Installed engine power, also known as the Maximum Continuous Rated Power (MCR), is specified by the manufacturer as the maximum power an engine can attain during average cargo and sea conditions (Starcrest Consulting Group, LLC, 2010). Generally, engine power varies by engine size and type (Starcrest Consulting Group, LLC, 2010). We retrieved main and auxiliary engine power information from Lloyd's Register of Shipping. When ships had more than one main or auxiliary engine, we summed the power of each engine to determine total main engine power and total auxiliary engine power for each ship. The IMO does not require vessel owners to report auxiliary engine power, and in many cases this information was not available in Lloyd's Register (Starcrest Consulting Group, LLC, 2010). Because engine power is an important component for determining fuel consumption in our cost model, we estimated total auxiliary engine power values when they were not reported. As the basis for our estimate, we ran a regression of total auxiliary engine power against total main engine power of ships for which auxiliary engine power was provided (Appendix 5). We used our regression output to estimate auxiliary engine power where it was not otherwise available.

ii. Specific Fuel Consumption Factor

The rate of fuel consumption, known as a vessel's specific fuel oil consumption, is reported in g/kWh and varies depending on the ship's mode of operation, the engine type being considered (main or auxiliary and slow- or medium-speed), and the type of fuel used (IFO 380 or MDO/MGO) (European Commission & ENTEC UK Limited, 2002). Typically, vessel operational profiles are categorized according to three different activities: at sea, in port, or maneuvering (European Commission & ENTEC UK Limited, 2002). For purposes of our project, we have assumed that management enacted to reduce vessel strikes to whales will only affect ships at sea. Because the vast majority of ships pertinent to our analysis have slow-speed diesel main engines and medium-speed diesel auxiliary engines, we have applied values applicable to these engines across our entire sample of ships. Further, as discussed previously, we assumed vessels operating outside of emission control areas would use a fuel with a higher sulfur content (IFO 380), while ships within these areas will use MDO/MGO. Such fleet-average assumptions are necessary due to the large amount of variability among commercial vessels. Combined, these factors determined the specific fuel consumption values we incorporated into our fuel cost equations. Using values reported by ENTEC and used by CARB and LALB to calculate emissions data, we have determined specific fuel consumption to be as follows (European Commission & ENTEC UK Limited, 2002):

Table 5: Specific fuel consumption for slow- and medium-speed diesel engines.

ENGINE TYPE	FUEL TYPE	SPECIFIC FUEL CONSUMPTION (G/KWH)
Main (slow-speed diesel)	IFO 380	195
	MDO/MGO	185
Auxiliary (medium-speed diesel)	IFO 380	227
	MDO/MGO	217

Source: Reproduced from (European Commission & ENTEC UK Limited, 2002)

iii. Engine Activity Hours

Engine activity is equivalent to operation time and calculated according to the following equation (Corbett, 2004; Starcrest Consulting Group, LLC, 2010):

$$\boldsymbol{Act = \frac{d}{s}}$$

Where:
Act is engine activity hours
d is distance
s is speed

For our economic model, we were only concerned with engine activity within our region of interest and, more specifically, how engine activity hours changed as a result of management. For each transit, we calculated engine activity by dividing the length of a specified route through our region of interest by the average speed at which the vessel was traveling. This speed was either derived directly from AIS data, or, in the case of a speed reduction, manipulated to mimic compliance with the modeled scenario.

iv. Engine Load Factor

The load factor on an engine is defined as the ratio between the engine's power output at any given operating speed and its MCR power (Starcrest Consulting Group, LLC, 2010). This relationship is estimated using the Propeller Law (Corbett, 2004), which is the approximate cubic relationship between a vessel's operational speed and its maximum design speed. Due to the nature of this relationship, vessels rarely operate at 100% of their MCR power because it increases fuel consumption and can be extremely expensive (Starcrest Consulting Group, LLC, 2010). As a result, most vessel operators will generally limit their power output so that the engine load does not exceed approximately 83% of MCR (Starcrest Consulting Group, LLC, 2010). Our calculation of engine load factor was based on the Propeller Law and is reflected in the following equation (Corbett *et al.*, 2009; Starcrest Consulting Group, LLC, 2010):

$$\boldsymbol{LF = \left(\frac{AS}{MS}\right)^{3}}$$

Where:
LF is the load factor
AS is the speed the vessel is actually traveling
MS is the vessel's maximum or design speed

We determined operational speeds from AIS data, and retrieved vessel design speeds from Lloyd's Register of Shipping. In a few instances where vessel design speeds were unavailable, we estimated these values by determining a statistical relationship between a vessel's design speed and its main engine power and gross tonnage (Appendix 5).

Lubricant Costs

As previously discussed, we have characterized main engines as slow-speed, two-stroke engines, and auxiliary engines as medium-speed, four-stroke engines. These different engines have different lubrication oil requirements, as well as different rates of lube-oil consumption, known as the feed rate (Woodyard, 2009).

Main Engines

In slow-speed engines, the amount of cylinder oil is adjusted based on operating conditions, and is proportional to engine power and engine load, which determine the amount of fuel entering the cylinders, and the sulfur content of the fuel being burned (Chevron, 2008; MAN B & W Diesel A/S, 2002a; MAN Diesel, 2009a; Woodyard, 2009). We followed the same methodology for determining engine power and engine load as discussed in the section on fuel consumption.

During vessel operation, an acid is formed from the interaction between fuel sulfur and water in the engine, which is neutralized by calcium salts contained in lubricant oil (Chevron, 2008; Svensson, 2006). As a result, the sulfur content of the fuel determines the level of alkalinity required in the lubrication oil, known as its base number (BN) (Chevron, 2008; Svensson, 2006). Efficient operation requires the correct balance to be established between the sulfur content of the fuel, base number of the oil, and oil feed rate (Chevron, 2008; Svensson, 2006; Woodyard, 2009). The lubrication feed rate should be enough to neutralize acid corrosion on cylinder liners, but not too much that excessive calcium carbonate deposits form (Woodyard, 2009). A BN70 lubricant oil has a high ability to neutralize acid, and is commonly used with fuels that contain greater than 1.5 - 2% sulfur (MAN B & W Diesel A/S, 2002a, 2002b; Svensson, 2006). While BN70 oil can be used with low-sulfur fuel at a reduced feed rate, a low BN oil such as BN40-50, is better suited for engines that are required to run on low-sulfur fuel for extended periods of time in order to ensure adequate lubrication and engine cleanliness (Chevron, 2008; Exxon Mobil, 2011; MAN B & W Diesel A/S, 2002a; Svensson, 2006; Woodyard, 2009). Low-sulfur fuels produce less acid and, thus, require less neutralization. In our model we have conservatively assumed that ships will switch to BN40 oil so as not to underestimate the costs incurred by the shipping industry.

Similar to the methodology adopted by the LALB Inventory of Air Emissions in 2009, and detailed earlier in the fuel cost calculations, for purposes of our project, we assumed that prior to the low-sulfur fuel regulation imposed by CARB, all main engines operated using a higher sulfur fuel (IFO 380), which has an average sulfur content of 2.7% (Starcrest Consulting Group, LLC, 2010; Svensson, 2006). Based on the principle that the optimal cylinder oil dosage is proportional to the amount of sulfur entering the cylinders, we calculated BN70 cylinder oil dosage based on the equation 0.26 g/kWh x S% (MAN B & W Diesel A/S, 2002a, 2002b; MAN Diesel, 2008). For sulfur-dependent lube control, we therefore assumed that the cylinder oil dosage will be 0.7 g/kWh on vessels operating with high sulfur fuel (MAN B & W Diesel A/S, 2002b; MAN Diesel, 2008). In contrast, for fuel sulfur content below 2.3%, manufacturers recommend that minimum dosages do not fall below 0.6 g/kWh (MAN B & W Diesel A/S, 2002b; MAN Diesel, 2008, 2009a). Therefore, we assumed vessels operating with low-sulfur fuel (MGO/MDO) would use BN40 lube oil at a feed rate of 0.6 g/kWh (MAN B & W Diesel A/S, 2002b; MAN Diesel, 2008, 2009a).

Similar to our equations used to estimate fuel consumption, based on these assumptions, we estimated lube oil consumption by multiplying the feed rate (0.7 g/kWh or 0.6 g/kWh, depending on whether the vessel is operating on high or low-sulfur fuel, respectively) by main engine power, and converted the results to tons per hour. We then multiplied this rate of consumption by the engine load factor and operation time within our region of interest (determined by dividing distance traveled by operating speed). Finally, in calculating the change in the cost of lubricants from various management options, we multiplied the lubricant oil consumption by lube oil price (Appendix 4). Based on current prices for marine lubricants, we determined the price of a typical BN70 lubricant oil to be $6.5625 per gallon, and a typical BN40 oil to be $8.3458 per gallon (Exxon Mobil, 2011). Using the specific gravity of each product, which is specified on their product information sheets, we calculated the cost of BN70 and BN40 oil to be $1,852.17 and $2,406.19 per metric ton, respectively (Exxon Mobil, 2010a, 2010b, 2011).

Auxiliary Engines

Unlike slow-speed engines where lubrication is a function of operating conditions, auxiliary engines require splash lubrication, whereby excess cylinder lubrication is applied (Chevron, 2008). In these medium-speed auxiliary engines, the condition of engine hardware such as piston rings and liners is also a major determinant of lube oil consumption (Chevron, 2008). Because these factors cannot be accurately represented in our model, changes in lube-oil consumption by auxiliary engines is not included as a factor affecting total changes to shipping costs in our economic analysis.

Finally, high-speed diesel engines are used for emergency equipment such as generators, fire pumps, air compressors and life boats (Chevron, 2008). These uses do not fall within the scope of our study, and were not considered in our economic cost analysis. Other lubricants used on deep-sea marine vessels include turbine oils, hydraulic oils, gear oils, compressor oils, heat transfer oil, and open gear lubricants, greases and rust preventatives, were also assumed to make insignificant contributions to changes in total costs (Chevron, 2008). We eliminated these factors from our analysis because lube oil costs have generally been shown to have little impact on overall operating costs (Koehler, 2000). Past economic analyses conducted by CARB, LALB and the EPA that involve fuel consumption estimates similarly do not account for individual lubrication oil consumption rates.

Change in Operating Costs

One possible effect from the evaluated management scenarios to reduce the risk of strikes is that vessels may be delayed in their voyage because there could be an increase in time at sea as a result of slowing down or taking a longer route. This may cause a shipping company to incur additional operating costs. In our model, these costs are calculated as a function of the change in the number of hours at sea that would result from each of the management scenarios. Based on our review of operating costs, described below, we expected that crew costs would be the primary operating cost affected, but some additional repair and maintenance costs could also be incurred. These parameters are reflected in the following equation:

$$\Delta \boldsymbol{OC} = (\boldsymbol{CC})\Delta \boldsymbol{t} + (\boldsymbol{RM})\Delta \boldsymbol{t_r}$$

Where:
ΔOC is the change in operating costs
Δt is the change in time at sea
Δt_r is the duration of the speed reduction
CC is the change in crew costs
RM is the change in repair and maintenance costs

Crew Costs

Crew numbers and wages are variable, depending on the age and type of ship, its flag state, and the national and international labor laws under which it operates (MARAD, 2006; Stopford, 2009). Ships can be listed under a national register, an international register, or in an open register ("flags of convenience") (Stopford, 2009). We modeled the change in crew costs for a ship that would result from the proposed management scenarios based on the ship's flag (specifically, the type of register), type, age, and size. We assumed that a relatively small increase in time at sea (averaging less than three hours per transit) will not require that ships have additional crew members on board, but rather that some of the existing crew will be paid overtime for working additional hours. Thus, the change in crew costs resulting from increased time at sea for this model did not require complete knowledge of crew wages. Rather, it was only necessary to know the conditions under which overtime will be paid to crew members, as well as the rates of overtime pay for the ranks affected.

Open and International Registers

Nearly half of the world's merchant fleet is registered under a flag of convenience ("FOC"), also called an open register (Stopford, 2009). A nation providing an open register allows a shipping company to operate under its flag in exchange for fees and taxes. The shipping company receives the legal and economic benefits of operating under a flag other than its owner's state (Stopford, 2009). The ability to recruit crews internationally is one of many economic incentives for registering under a flag of convenience, as crew costs can be substantially lower than for other national register flags (Stopford, 2009).

FOC ships often employ their workers through agreements with the International Transport Workers' Federation (ITF). ITF has established recommended minimum wages based on guidelines from the International Labor Organization (ILO) (ITF, 2008). ITF provides guidance for minimum wages for each rank, but the wages paid to seafarers are variable (ITF, 2008; Stopford, 2009).

For our economic model, we assumed that FOC and other international register ships will not pay overtime to workers as a result of management options in the Santa Barbara Channel because of the nature of the international maritime labor market. Generally, workers under ITF collective bargaining agreements are guaranteed overtime pay for a certain number of hours (often 104 hours per month) (ITF, 2010a, 2010b). Though ITF agreements only cover workers on approximately one-third of open register ships (Lillie, 2006), ITF wages and employment practices generally set the standard for the international maritime labor market (Lillie, 2004). Ships not covered by ITF agreements often voluntarily pay similar wages to maintain competitiveness in the international labor market (Lillie, 2006). Furthermore, it is typical for overtime to be paid as part of a consolidated wage (Lillie, 2006). We assumed that FOC and international register ships that are not compliant with ITF guidelines will not pay overtime to their workers due to the nature of these types of registers (ITF, 2010c; Lillie, 2006). Though there is potential for additional overtime pay to be required for delays caused by management options, we further assumed that the relatively short amount of additional time at sea per transit will rarely cause additional at-sea labor costs for these ships.

United States

Ships registered under the United States flag are modeled separately from other national register flags because of high wages and the U.S.'s unique labor laws. United States commercial maritime workers are part of the U.S. merchant marine (MARAD, 2009). U.S. merchant marine workers are represented by unions such as Seafarers International Union and American Maritime Officers (MARAD, 2009).

To estimate the amount of overtime that would be paid to the workers on a U.S.-flagged ship, we applied approximate crew numbers and average overtime pay rates (Appendix 5, Table 13) per crew member to each ship for the total number of hours of delay. It is possible that not all crew members would be on duty during the additional time at sea, as crew member hours are not accrued during periods of rest (Fair Labor Standards Act, 1961). However, in order to avoid underestimating costs, we assumed that all crew members eligible for overtime pay would be paid overtime for the additional time at sea. U.S. labor law exempts many maritime employees from overtime pay requirements (Fair Labor Standards Act, 1961). Exempt employees include seamen whose primary duty is to assist in the operation of a vessel (Fair Labor Standards Act, 1961). However, most non-officers and even some officers are paid overtime (Pelletier, 2007). In contrast with ITF agreements, which may not be utilized by U.S. unions (Lillie, 2006), we assumed that U.S. overtime pay is not pre-configured into a worker's salary. We thus assumed that each worker would be paid 1.5 times his hourly rate for the additional time at sea in accordance with U.S. law (Fair Labor Standards Act, 1961).

The number of crew members on a ship is primarily determined by the ship's size, age, and type (MARAD, 2006). To estimate the number of crew members on board, we used the U.S. Department of Transportation Maritime Administration's 2006 report on crewing practices for foreign-flagged vessels using U.S. ports (MARAD, 2006). We assumed that U.S. vessels would have similar numbers of crew members on board, though some variability is expected.

A typical large cargo ship will have a captain, three deck officers or mates, a chief engineer, three assistant engineers, and six or more non-officers (Pelletier, 2007). We assumed that each ship employed this configuration of mariners. Though radio officers have not been required since 2007 (Stopford, 2009), we also assumed that a radio officer was onboard each ship in order to avoid underestimating the crew costs.

Pelletier (2007) reports average pay rates for the various types of crew on board U.S. ships. We used the median value of salary ranges for deep-sea vessels reported by Pelletier (2007). We calculated the basic hourly rate by dividing the median annual salary into 52 weeks, with 40 regular working hours per week (Appendix 5, Table 13). We then calculated the hourly overtime rate by multiplying the basic rate by 1.5. Using the estimated number of crew, we calculated an hourly cost of overtime pay for each ship that was delayed as a result of the management options.

Other National Registers

National registers require that ships operate under the regulations of the flag state (Stopford, 2009). Though labor laws and union activity across national registers vary, standards for paying overtime are established by the ILO (ILO, 2006). The 2006 ILO Maritime Labor Convention provides standards for overtime as part of a consolidated wage or for separate compensation (ILO, 2006). It is difficult to determine whether the crew aboard a national flag ship will be paid a consolidated wage for overtime or whether overtime will be paid separately. To avoid underestimating costs, we assumed that overtime will be paid separately to a ship’s crew for delays in the Santa Barbara region resulting from the management options we modeled. We applied the same crew numbers as for U.S.-flagged ships, derived from the U.S. Department of Transportation Maritime Administration’s 2006 report (MARAD, 2006).

Crew wages are likely to vary significantly among national registers, and it would be very difficult to determine pay rates for each nation of registry. We therefore developed a simple model using representative pay rates from Stopford (2009). For national register ships, we calculated an estimated overtime rate at 1.25 times the estimated regular hourly rate (Appendix 5, Table 14). Based on these overtime rates and crew numbers, we calculated an approximate total hourly overtime pay rate for national flag ships transiting the region.

Repair and Maintenance Costs

Routine repairs and maintenance include ongoing repairs that are made to a ship’s equipment (Stopford, 2009). We do not expect the frequency of routine maintenance to be affected by small increases in the distance traveled by a vessel. However, we modeled an increased hourly repair and maintenance cost for ships operating at low speeds due to a mandatory speed reduction. Though this management option would only affect speed for a short period of time for a given transit, we considered the available information on the costs of slowing down for longer periods of time ("super slow steaming") to quantify the cost of management options. Despite concerns about the impacts of super slow steaming on engine equipment, shipping companies, such as Maersk and CMA CGM, have demonstrated that ships can safely operate at as low as 10% of their maximum engine load (known as maximum continuous rating, or MCR) (Ludovic, 2010; Maersk, 2009).

Guidance is provided by engine manufacturers on maintenance and retrofits for ships operating between 10% and 40% MCR (MAN Diesel, 2009b; MAN Diesel & Turbo, 2010; Wärtsilä Corporation, 2010). Though engine retrofits are available for super slow steaming, manufacturers have indicated that the common two-stroke engines can safely operate down to 10% MCR without major modifications (MAN Diesel, 2009b). For operation between 10% and 40% MCR, engine manufacturer MAN Diesel recommends minor equipment modifications and increased monitoring from the engine operator (MAN Diesel, 2009b). To account for any increased maintenance costs as a result of a mandatory speed reduction, we assumed a 25% increase in the hourly maintenance cost for vessels whose engine load was reduced to between 10% and 40% MCR. To estimate hourly maintenance costs, we used example maintenance and spare parts costs for a Capesize bulk carrier provided by Stopford (2009) (Appendix 5, Table 14).

We modeled an additional cost for ships that would be required to operate below 10% MCR to comply with a speed reduction to 10 knots. It is difficult to anticipate the cost of operating a ship below 10% MCR because industry discussion of operation below 10% MCR is minimal. Manufacturers and shipping companies alike have primarily discussed reducing MCR to as low as 10% (Maersk, 2009; MAN Diesel, 2009b; Wärtsilä Corporation, 2010). Because engine manufacturers have not recommended operation below 10%, we assumed that a speed reduction requiring ships to operate below 10% will have additional costs in order to maintain normal engine functionality. We thus modeled this cost by including a 50% increase in hourly repair and maintenance costs for ships operating below 10% engine load as a result of a mandatory speed reduction to 10 knots.

This hourly additional repair and maintenance cost was multiplied by the duration of the speed reduction through the WAZ for all affected vessels. Vessels in our random sample that were already transiting at 40% MCR but were reduced to

10% MCR were only assigned a 25% increase. Only 2 vessels in our random sample were already transiting below 10% MCR; these vessels incurred no additional hourly repair and maintenance cost in our model.

Costs Not Affected by Management

There are a number of operating costs that we do not expect to be affected by management because they are routine costs that will not change with a few additional hours at sea. These include general stores, insurance and administrative costs.

Stores

General stores include the consumable domestic supplies used by the crew on-board (Stopford, 2009). We assumed that the consumption of domestic items will not be affected by a few additional hours at sea. Although lubricants are technically considered stores, we modeled lubricant consumption for main engines as part of the change in voyage costs (Appendix 4). As noted, lubricant consumption for auxiliary engines was not included in our model.

Insurance and Administrative Costs

The management options being considered will not result in substantial changes to a ship's operations. Therefore, we do not expect a ship's insurance or administrative costs to be affected, and they were not quantified in our model. Insurance includes physical loss or damage to the ship, as well as liability coverage. Administrative costs include registration fees and general costs required for running a shipping operation (Stopford, 2009). While there may be small changes to administrative activities to coordinate slow-downs or changes in routes, we do not expect these small changes to require more resources than currently utilized.

Cost of Delay from Navy Operations

The Navy occasionally asks ships transiting the Point Mugu Sea Range to slow down or alter course due to ongoing operations within the area (J. Ugoretz, pers. communication, Dec. 1, 2011). To quantify the potential cost of this delay, we determined the probability of the Navy asking a ship to alter course or speed by dividing the total number of Navy requests for one year by the total number of vessel transits through the Range. In particular, from July 2009 to June 2010, the Navy asked ships traveling on 126 unique transits through the Sea Range to slow down or alter course (J. Ugoretz, pers. communication, Dec. 1, 2011). Over the same time period, there were 3,332 transits through the region. This resulted in a probability of a Navy request of 0.037815.

We then multiplied the probability of a Navy request by expected costs resulting from an unanticipated missed or delayed port call. To calculate expected costs, we assumed that a ship delayed unexpectedly would pay overtime charges for cargo unloading as well as additional dockage charges. Based on discussions with industry experts, we assumed that it would take five longshoremen crews, on average, to unload a vessel's cargo (R. McKenna, pers. communication, Jan. 18, 2011). We then assumed that a vessel arriving late unexpectedly would have to pay overtime charges for each of those five crews, at a charge of $500 per crew, for a total overtime charge of $2500 per vessel (R. McKenna, pers. communication, Jan. 18, 2011). We next assumed that late-arriving vessels would pay an additional day's dockage charges, which is a tariffed rate incurred per 24-hour period (or any fraction thereof) (Port of Los Angeles, 2011). Because dockage charges vary by vessel length, we created three categories of length (under 195 meters, 195 to 285 meters, and over 285 meters), and assigned the associated dockage charge based on an average of each of the charges within the category. Specifically, ships shorter than 195 meters were assigned an average additional dockage charge of $1,544.50; ships between 195 and 285 meters were assigned an additional charge of $4,289.83; and ships longer than 285 meters were assigned an additional charge of $8,413.33. The average length of vessels within our sample was 247 meters.

We added the additional dockage charges to the crew overtime charges ($4,044.50 for ships under 195 meters; $6,789.83 for ships between 195 and 285 meters; $10,913.33 for ships over 285 meters), and multiplied those charges by the probability of a Navy request (0.037815) to estimate the potential cost of unexpected delays ($152.94 for ships under 195 meters; $256.76 for ships between 195 and 285 meters; and $412.69 for ships over 285 meters). These potential fees are outlined in Table 6 below:

Table 6: Expected cost of an unanticipated delay resulting from Navy operations.

SHIP LENGTH (FT)	ADDITIONAL DOCKAGE FEES ($)	CREW OVERTIME CHARGES ($)	PROBABILITY OF NAVY REQUEST	EXPECTED COST OF DELAY ($)
< 195	1544.50	2500.00	0.037815	152.94
195-285	4289.83	2500.00	0.037815	256.76
> 285	8413.33	2500.00	0.037815	412.69

Because Navy operations rarely affect traffic within the Channel, we applied this additional cost component for unexpected (as opposed to anticipated delays, such as when a mandatory speed reduction is in place) only when ships are re-routed from the Channel to the south of the islands, as discussed above under Management Option 4.

Accounting for Operator Behavior

Management options considered in this analysis may increase a ship's time at sea. However, anecdotal information and survey data (CARB, 2009c) suggest that operators may make up for time lost from an anticipated delay by increasing speed elsewhere on their voyage. The California Air Resources Board reports that most of the respondents to a 2007 survey of vessel and fleet operators said they would increase speed by one-half knot or greater to make up time (CARB, 2009c). While this behavior may benefit the operator by allowing him to maintain his schedule, the Propeller Law demonstrates that an increase in speed will result in additional fuel consumption and greater overall voyage costs.

To capture the additional cost of this behavior, we developed a second, alternative model that assumed all operators would speed up to make up any anticipated time lost due to management measures. Specifically, as reported by survey respondents (CARB, 2009c), we assumed each ship would increase its speed by one-half knot on another portion of its journey for whatever distance was necessary to make up the total amount of time lost. Due to a lack of ship-specific speed data in other regions, we assumed these vessels were originally traveling at the same speed recorded by AIS data in the Santa Barbara Channel region, and that ships could make up the time using high-sulfur fuel (IFO 380). We assumed that the increase in speed would occur outside the study area and thus would not affect the risk of a lethal strike in the region. Because narrowing the TSS did not increase time or distance at sea, this alternative model applied only to the year-round and seasonal mandatory speed reductions and the shift of the TSS to the south.

Model Calibration

As noted, CARB's low-sulfur fuel rule caused a significant portion of the region's vessel traffic to shift away from the Channel and into the Southern Region. We used this change in vessel behavior to test our model's ability to accurately calculate the effects of different management scenarios on shipping industry costs. In particular, we assumed that vessels would generally take the least-cost route, and that a robust model would predict most of the selected routes correctly.

Using AIS data, we identified which of the ships from our original random sample (July 1, 2008 to June 30, 2009) returned in the year after the CARB regulation went into effect (July 1, 2009 to June 30, 2010), and documented whether those vessels transited through the Channel or the Southern Region. We randomly sampled just over a third (37.5%) of the returning ships and used our model to predict which route was the least cost. We then compared our predictions to the ships' actual routes to assess how well our model predicted the selected routes. Overall, our model retroactively predicted the least-cost route taken in 66% of the transits. In an attempt to increase the predictive ability of our model, we incorporated an additional hourly factor, discussed below.

Alpha

Based on discussions with industry experts (T.L. Garrett, pers. communication, Nov. 2, 2010; R. McKenna, pers. communication, Jan. 18, 2011), we believe there are some economic costs not captured in our initial model. Specifically, certain industry costs are unpredictable due to the variability in costs between different types of ships and the proprietary nature of shipping cost information. In an attempt to incorporate these additional costs into our model, we introduced a parameter, *alpha*, into our model.

We considered a number of ways to model this additional cost and determined that *alpha* should be a constant multiplied by additional time at sea resulting from a change in management. The change in time is a common factor between each of our management options and in the decision for operators to voluntarily travel through the Southern Region after implementation of the CARB regulation. Our variable, *alpha*, when multiplied by the change in time (per hour), is primarily designed to reflect additional hourly operational costs. It may also reflect less tangible costs, such as the cost of a delayed arrival in port. Timeliness is a critical component of the shipping industry, and it is reasonable to expect that there will be additional costs of delay beyond the explicit factors included in the operating costs. Furthermore, inclusion of this additional cost as a function of time models a significant economic incentive for operators to make up time because the cost is eliminated if there is no net delay. Because it is typical for operators to speed up to make up time (CARB, 2009c), it is likely there are substantial costs of delay that out-weigh the fuel cost from speeding up.

To estimate *alpha*, we compared ship transits through the region both before and after implementation of the CARB low-sulfur regulation. For pre-CARB transits (July 1, 2008 to June 30, 2009), we used the reported price ($225) for IFO 380 as of December 12, 2008, at LALB, for all transits (Hellenic Shipping News Worldwide, 2008). For post-CARB transits (July 1, 2009 to June 30, 2010), we used the estimated fuel prices discussed above in Section 5.3. Specifically, we assumed that vessels transits through the Channel faced a higher fuel cost for MDO/MGO ($625), while vessel transits through the Southern Region incurred a lower fuel cost for IFO 380 ($312.50). As with model calibration, we then predicted the most cost-effective route for each transit, based on the underlying ship's operating profiles and vessel characteristics, and compared our predicted route to the actual route taken by the vessel for each transit.

Using MATLAB, we calculated that an *alpha* of $3465 per hour would maximize the number of times our model correctly predicted actual transit routes (see Appendix 4). By including an *alpha* of $3465 per hour in the model, we were able to accurately predict the actual route taken in 76% of the transits. As noted, when *alpha* was not included, we were able to retroactively predict only 66% of the transits correctly. Our estimate of *alpha*, moreover, appears to be a reasonable representation of unaccounted for costs, because hourly operating costs estimated in other studies are typically higher than our initial model predicts (Kite-Powell & Hoagland, 2002; Nathan Associates, Inc., 2008; USACE, 2000). Kite-Powell and Hoagland (2002), for example, modeled penalties ranging from $20,000 to $100,000 for delayed port calls – not including additional hourly operating costs incurred from the delay. The breadth of the Kite-Powell and Hoagland ranges, as well as other estimates within the literature, further support inclusion of *alpha* in our cost model. Because it improves the overall quality of our model and is consistent with other ranges for potentially unaccounted for costs, we incorporated an hourly *alpha* of $3465 into our economic analysis of management options to serve as a proxy for unpredictable or proprietary costs not otherwise captured within the voyage or operating cost components of our model.

Calculating Confidence Intervals

To quantify the degree of error associated with our cost estimates, we calculated 95% confidence intervals using a Monte Carlo sensitivity analysis. First, we identified parameters in our model that were uncertain or variable. These included fuel price, the cost of delay due to Navy operations, and *alpha*. Our sensitivity analysis included variability in each of these parameters based on what we believed to be reasonable ranges for each, as discussed below.

We varied the cost of regular fuel (IFO 380) by +/- 25 percent. We believe 25% is a reasonable amount of variability in fuel prices based on available data on the range of fuel prices for the time period we considered (Poten & Partners, 2009). For each iteration of our sensitivity analysis, we randomly selected a regular fuel price within this range. We also varied the cost of low-sulfur fuel (MDO/MGO) as a function of the cost of the regular fuel. We used the long-term cost differential of 93% between IFO 380 and MGO (ITMMA, 2010). We varied this relationship between the fuel prices by 25%, such that the cost of low-sulfur fuel ranged from 68% higher to 118% higher than IFO 380. For each iteration, a low-sulfur fuel price was generated from the randomly selected regular fuel price by multiplying it by a random number between 1.68 and 2.18 (to correspond with the ranges above). We believe this methodology provided reasonable ranges in both fuel prices: $234 to $391 per ton for IFO 380 and $475 to $800 per ton for low-sulfur fuel.

Our estimate of the cost of delay from Navy operations is uncertain. Though we are confident that our probability of delay is correct because it is based on annual Navy log data, there is uncertainty in the overall cost of an unanticipated delay. We believe 25% variability in this cost is reasonable, however, because other, unaccounted for port-related fees may be incurred if the Navy unexpectedly asks a ship transiting the Southern Region to slow down or alter course. Among other things, additional fees may be incurred if a vessel operator requires a pilot to standby for a late arrival ($367 per hour), or if a request for a pilot is cancelled less than one hour prior to the requested time ($367 flat fee) (Port of Los Angeles, 2011). A lengthy, unanticipated delay may further cause the operator to hire additional cargo unloading crews ($1,500-$2,000 per crew per hour, depending on time of day and whether overtime is incurred) (R. McKenna, pers. communication, Jan. 18, 2011), rent additional cranes for unloading containers ($672 per hour) (Port of Los Angeles, 2011), or incur other port-related fees to make up for lost time. As discussed below in Section 8.2, protracted delays that arise unexpectedly may in certain rare cases lead to a series of delayed or missed port calls during a ship's overall route, thereby resulting in substantial extraordinary costs not accounted for within our model.

We also varied *alpha* because there was a range of *alpha* values that resulted in the same number of correct predictions in our model calibration. We varied *alpha* across this range – from $3,465 to $3,535 per hour. By including variability in *alpha* in our Monte Carlo sensitivity analysis, we can account for some of the uncertainty in our *alpha* estimate and in our overall cost estimates.

After we established ranges for our parameters, we ran 20,000 iterations of our model, each using randomly selected values from the parameter ranges. We removed the upper and lower 2.5% to define our 95% confidence interval. These confidence intervals reflect our decision about what constitutes reasonable variation in our parameters, and are not calculated based on the underlying distribution of actual values. Thus, although they cannot be used to statistically differentiate among the management options, we nonetheless believe they can provide a basis for ranking different options based on potential variability in the costs incorporated into our model. These 95% confidence intervals are included in the discussion of our results.

ANALYSIS OF MANAGEMENT SCENARIOS

We designed our economic model to evaluate the effect of management scenarios on shipping industry costs. Specifically, management scenarios directly affect the distance traveled by ships and/or the speed at which they operate in the region. This model calculates the change in cost due to each management scenario by comparing the cost of a transit under management with the "normal" cost of a transit through the region. We assume the route and speed of each vessel traveling through the region between July 1, 2008 and June 30, 2009 to be status quo behavior and, thus, the preferred operational profile of each ship. Due to pending air regulations we assume that all ships traveling through the region will use low-sulfur fuel.

Management Option 1: Year-Round Mandatory Speed Reduction

A year-round mandatory speed reduction to 10 knots throughout the length of the 88 nautical mile WAZ will increase the time it takes most ships to complete a transit through the region. The amount of lost time depends on the vessel's original operating speed. For the purposes of this project, we assume that initial operating speeds are equivalent to those obtained from AIS data for each transit through the Channel. Because the initial average operating speed differs for each vessel traveling through the Channel, the amount of delay and, thus, the change in costs, will vary for each individual transit. Among our selected year of transits, the highest speed was 25.4 knots and the lowest was 8.9 knots. This wide range of speeds is likely due to differences in the vessels' design speeds and, as previously discussed, the fact that ships typically operate at some percentage of their maximum speed. The average speed across all transits through the Channel was 18.5 knots. In this scenario, we assumed that ships originally traveling through the Channel below the 10 knot speed restriction would maintain their original speed. Similarly, we assumed that ships initially traveling outside of the Channel would continue to do so and not be affected by this regulation.

In addition to time, this mandatory speed reduction will affect voyage costs in our model by altering fuel consumption. Lower speeds will reduce the engine load, which will cause a decline in fuel consumption. For any given ship, speed reductions generally lead to fuel savings while increases in speed result in higher fuel consumption (Notteboom & Vernimmen, 2009).

In addition to calculating the change in cost associated with slowing down within the management region, we also modeled the net change in cost if ships were to speed up outside the region.

Management Option 2: Seasonal Mandatory Speed Reduction

In our analysis, a seasonal mandatory speed reduction to 10 knots in the WAZ will only affect the shipping industry between the months of April and September, during which the SMA will increase the time it takes for a vessel to travel through the region. As previously described, the additional time required for a transit through the WAZ, and the resultant change in cost, will vary for each transit depending on the difference between the vessel's normal operating speed and the 10 knot restriction. Similar to the methodology applied to a year-round speed reduction, we assume that this seasonal regulation will also impact fuel consumption when it is in effect.

To model the change in cost to the shipping industry due to a seasonal mandatory speed reduction, we removed all transits that did not occur between the months of April and September from our representative year of transits. During this timeframe, 204 of the subset of 488 transits (168 of 334 individual ships) occurred. Among this smaller number of ships, the highest speed was 25.4 knots, the lowest was 9.9 knots, and the average speed was 18.7 knots. We used these vessel transits to calculate the change in cost associated with slowing down within the SMA, and also modeled the net change in cost should ships speed up outside the management region to make up for lost time.

Management Option 3: Narrow the Traffic Separation Scheme within the Channel

To model this option, we calculated the change in total costs associated with shortening the length of a southbound transit through the region by 0.07 nautical miles. While the impact of this management option will vary for each vessel transit through the region, overall it results in both a slight reduction in fuel consumption and a time savings for each transit. Because there is no time lost due to this regulation, we do not incorporate the possibility that ships will speed up elsewhere into our analysis of this management strategy. As with the speed reduction, we assumed that ships initially traveling outside of the Channel would continue to do so and not be affected by this regulation.

Management Option 4: Shift the Traffic Separation Scheme to the South of the Northern Channel Islands

Rerouting ships from the Santa Barbara Channel to the southern side of the Northern Channel Islands would result in an increased distance traveled for ships accessing California ports. As noted, to determine the increased distance, we established an alternative TSS (“Southern TSS”) outside the Channel, which increased the distance transited through the region by 13.8 nautical miles. The increased distance was used to estimate the change in shipping industry costs as a result of this management scenario. As previously discussed, we assumed ships relocated outside of the Channel will continue to travel at the same average operating speeds that they used in the Channel. Overall, this results in an increase in both transit time and fuel consumption. We also modeled the effect of this management option assuming that ships would speed up elsewhere to make up for lost time. Again, we assumed a shift in the TSS would not affect total costs for ships that previously traveled outside of the Channel.

6. RESULTS & DISCUSSION

6.1 RISK ANALYSIS

The relative risk of a lethal whale strike ("relative risk") was calculated on a quarterly basis for each management option, as well as for the current management (*i.e.*, "status quo"), according to both the Average Distribution Model and the Linear Predictive Model (see Section 5.2). For both models, the relative risk of each management option was summed over all four quarters to provide an annual relative risk. In order to assess the extent to which each management option would affect the relative risk compared to the status quo, it was necessary to calculate the percent change of the estimated annual relative risk from the relative risk of the annual status quo. The resulting value provided the percent by which each option changed the relative risk of a lethal whale strike, as compared to the relative risk of the status quo (Figure 12). The 95% confidence intervals surrounding the estimated changes in risk under the Average Distribution Model represent the variability in the observed SPUE, while the 95% confidence intervals surrounding the changes in risk under the Linear Predictive Model represent uncertainty in model predictions of the relative probability of a whale in a grid cell.

The overall greatest reduction in relative risk of a lethal whale strike results from the implementation of a year-round mandatory speed reduction to 10 knots. Similarly, a mandatory seasonal speed reduction to 10 knots also decreases relative risk. Model results are more variable, however, when considering either Management Options 3 (narrowing the TSS within the Channel) or Option 4 (shifting the TSS to the south). Depending on the whale distribution model employed, and taking into account 95% confidence intervals, both of these management options have the potential to either increase *or* decrease relative risk.

Our methodology evaluates the relative risk at a coarse spatial scale (5 km by 5 km grid cells) and a coarse temporal scale (quarterly periods). Our results are thus limited by the spatial and temporal scale at which relative risk was evaluated. These limitations are particularly apparent when evaluating Management Option 3 (narrowing the TSS) and Management Option 4 (shifting the TSS to the south), which, as noted, may result in either increases or decreases in relative risk.

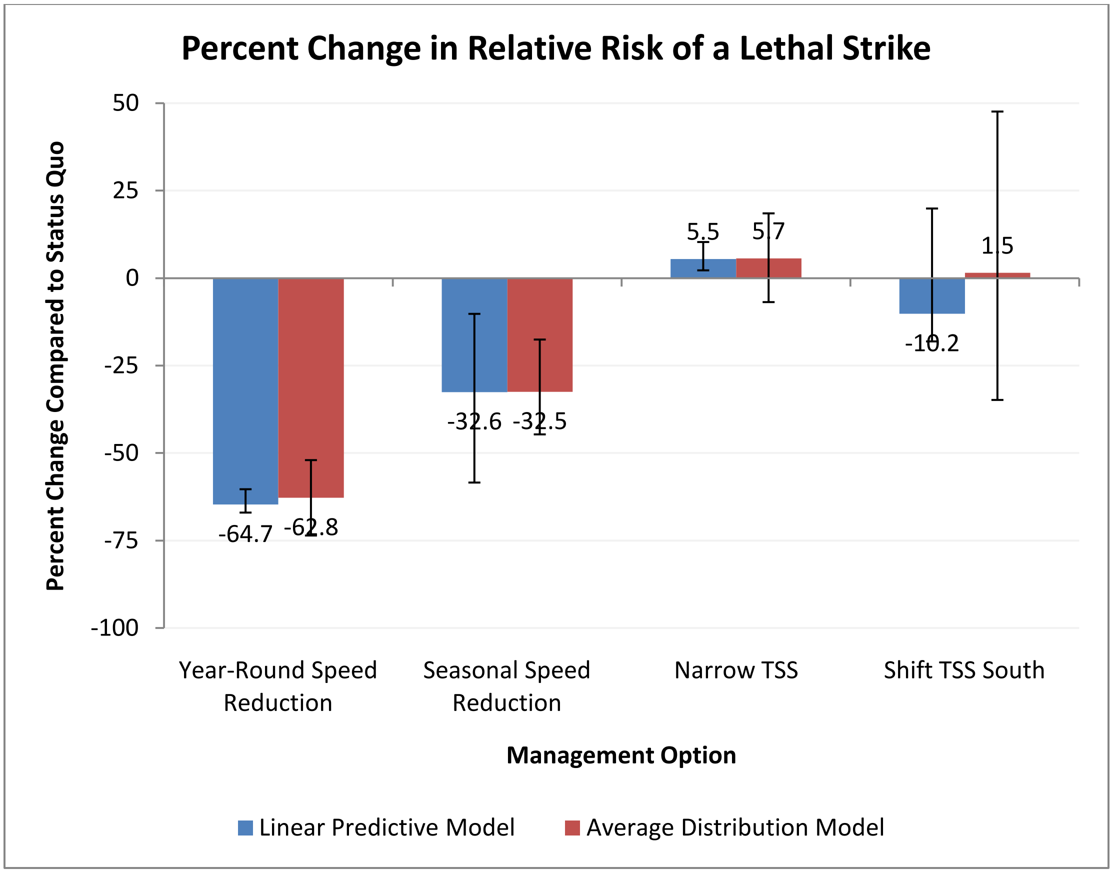


Figure 12: Compares the percentage by which each management option changes the relative risk of a lethal whale strike, in relation to the status quo. The blue bars show results using the Linear Predictive Model and the red bars show results using the Average Distribution Model. Error bars show 95% confidence intervals based on bootstrap re-sampling.

MANAGEMENT OPTION 1: YEAR-ROUND MANDATORY SPEED REDUCTION

When employing either whale distribution model, a mandatory speed reduction to a maximum of 10 knots results in the largest reduction in relative risk among the four management options. Applying the Linear Predictive Model, for example, results in a 64.7% reduction in the relative risk of a lethal whale strike (CI_{95} = -67.0%, -60.3%). Comparatively, applying the Average Distribution Model results in a 62.8% reduction in the relative risk of a lethal whale strike (CI_{95} = -73.5%, -52.0%).

Because relative risk is a function of both the spatial distribution and speed of ships, the comparatively large reduction in relative risk that results from a mandatory speed reduction is due in large part to the assumed relationship between speed and the lethality of a strike (Eq. 1). In contrast, narrowing or shifting the TSS changes only the spatial distribution of ships, not the ship speed, and thus affects only the probability of an encounter between a whale and a ship.

MANAGEMENT OPTION 2: SEASONAL MANDATORY SPEED REDUCTION

Of the four management options, a seasonal mandatory speed reduction (April through September) results in the second greatest reduction in relative risk. When applying the Linear Predictive Model, a seasonal mandatory speed reduction to 10 knots during April through September results in a 32.6% reduction in the relative risk of a lethal strike (CI_{95} = -58.4%, -10.3%). When applying the Average Distribution Model, the resulting reduction in the relative risk is 32.5% (CI_{95} = -47.3%, -20.3%).

The lower reduction in risk resulting from a seasonal mandatory speed reduction, as compared to the reduction in risk under a year-round mandatory speed reduction, is due to the fact that ship speed changes only during quarters 2 and 3, rather than during the entire year. While our model only considers speed reductions for half of the year, sightings data suggest (see Appendix 3) that applying the speed reduction to quarter 4 would likely result in an additional reduction in risk (see Appendix 8). If the mandatory speed reduction to 10 knots is also applied to quarter 4, the reduction in the relative risk of a lethal strike may therefore be further increased.

MANAGEMENT OPTION 3: NARROW THE TRAFFIC SEPARATION SCHEME WITHIN THE CHANNEL

In contrast to speed reductions, narrowing the TSS shows the potential to increase the relative risk of a lethal strike. Applying the Linear Predictive Model, for example, increases the relative risk by 5.5% (CI_{95} = 2.2%, 10.3%). Similarly, when using the Average Distribution Model, the relative risk increases by 5.7% (CI_{95} = -7.2%, 18.1%).

The increased relative risk that results from either model is a result of an increase in the probability of an encounter between a whale and a ship within the narrowed TSS. To model Management Option 3, the narrowed TSS, the average number of ships occupying all grid cells in the original TSS was evenly distributed within the grid cells of the new, narrowed TSS. The narrowed TSS, however, covers fewer grid cells than the original TSS, thereby increasing ship density within each cell of the new, narrowed TSS. Increased ship density further increases the relative probability of an encounter, which in turn increases the relative risk of a lethal strike. When considering the 95% confidence interval of the Average Distribution Model, our results indicate that narrowing the TSS may either increase or decrease the relative risk of a lethal whale strike. Although these results indicate Management Option 3 may increase the relative risk of a lethal strike, shifting the TSS away from observed aggregations of whales near the Channel Islands may in fact decrease the risk of a lethal strike. It is likely that the coarse spatial and temporal resolution of this model, combined with limited whale distribution data, did not capture the true variability in either whale distribution or ship traffic patterns. Further analyses should consider these limitations when evaluating a shift or narrowing of the TSS.

MANAGEMENT OPTION 4: SHIFT THE TRAFFIC SEPARATION SCHEME TO THE SOUTH OF THE NORTHERN CHANNEL ISLANDS

Shifting the TSS to the south results in either an increase or decrease in relative risk of a whale strike, depending on the whale distribution model. When applying the Linear Predictive Model, shifting the TSS to the south reduces the relative risk by 10.2% (CI_{95} = -18.1%, 19.9%). The Average Distribution Model, on the other hand, increases the relative risk by 1.5% (CI_{95} = -44.6%, 37.8%).

To model a shift in the TSS to the south, the average number of ships occupying all grid cells in the original TSS was evenly distributed across all grid cells of the Southern TSS. Due to its orientation, the Southern TSS covers fewer grid cells than the original TSS, thereby increasing ship density within each grid cell of the Southern TSS. Increased ship density can further increase the relative probability of an encounter in a grid cell, which in turn increases the relative risk of a lethal strike.

The uncertainty that surrounds the percent change in relative risk resulting from Management Option 4 (represented by the 95% confidence intervals), is relatively large, compared to the uncertainty that surrounds the percent change in relative risk modeled for Management Options 1, 2, and 3. These wider confidence intervals can be attributed both to the uncertainty in predicted whale distribution in the area south of the Channel Islands, as well as to the fact that Management Option 4 affects more grid cells than Management Options 1, 2, and 3. Compared to the other management scenarios modeled, shifting the TSS to the south has the largest geographic range (*i.e.*, grid cells) over which the probability of an encounter may change. Consequently, uncertainty in whale distribution introduces greater uncertainty into our estimates of risk reduction under this scenario than for other scenarios.

The wide confidence intervals associated with the Linear Predictive Model, for example, are a function of uncertainty in the predicted distribution of whales to the south of the Channel Islands, whereas the wide confidence intervals associated with the Average Distribution Model are instead a function of variability in the observed relative probability of whales throughout the study region. Because the Linear Predictive Model and the Average Distribution Model predict different whale distributions, there is a discrepancy in the estimated change in relative risk between the two models. The Linear Predictive Model, for example, tends to predict a lower relative probability of whale presence in the region where the Southern TSS is located (see Appendix 3, Figure 22). In comparison, the Average Distribution Model assumes an even distribution of whales throughout the Channel region. Use of the Linear Predictive model thus results in a reduction in the relative probability of an encounter along the Southern TSS, compared to the Average Distribution Model.

6.2 ECONOMIC MODEL

For each management option, we summed the change in total cost of each transit in our representative sample. We then scaled up these results to estimate the aggregate change in total annual shipping costs for all ships transiting the region. In so doing, we assumed that the 572 transits included in our initial random sample are representative of the 5,725 transits through the region for the time period modeled (see Sections 5.2 and 5.3).

First, we present the change in total costs due to a change in management (also referred to as the "cost of management") under two alternate assumptions (Figure 13). Under the first alternative, we assume all operators do not speed up elsewhere on their voyage to make up time. Under the second, we assume all operators speed up one-half knot over a distance that allows them to make up all anticipated time lost. The average change in total costs, by ship type and size, for each management option under these two alternate assumptions is presented in Appendix 6.

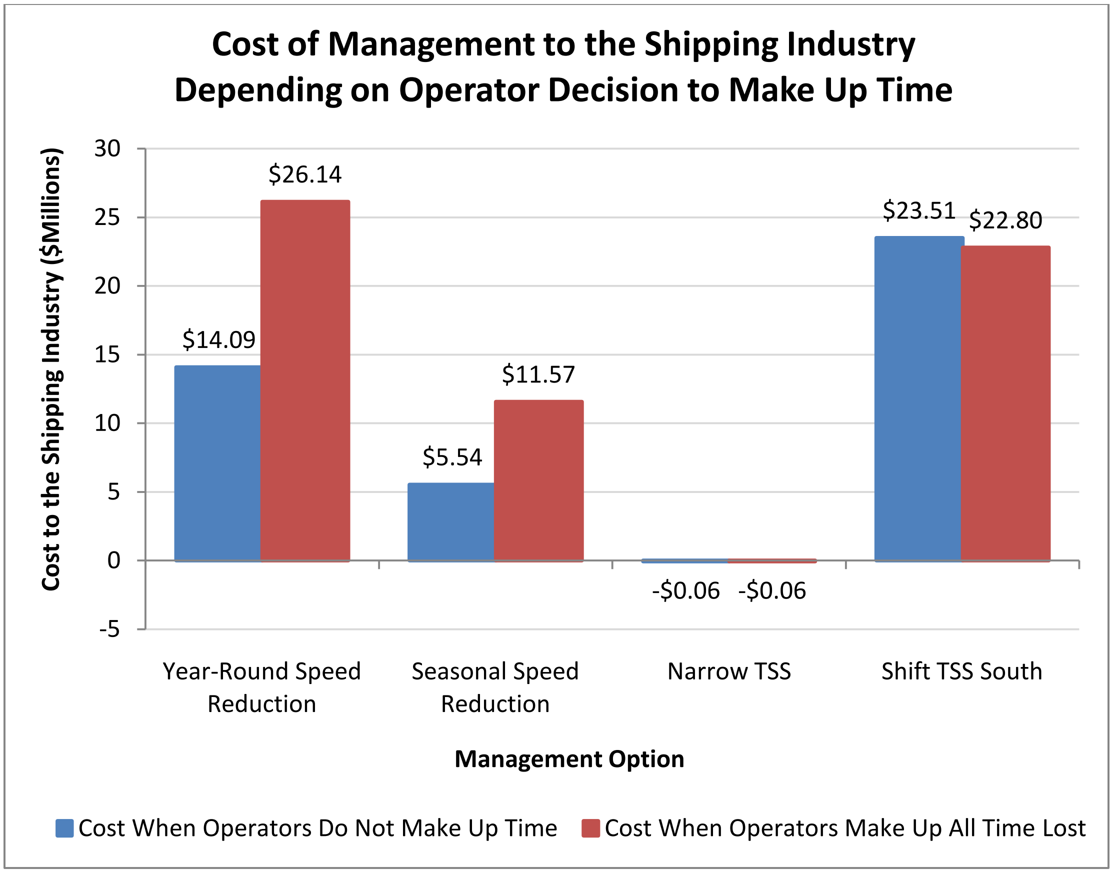


Figure 13: The cost of management to the shipping industry depends on whether operators choose to speed up to make up time lost as a result of management. For the Year-Round and Seasonal Speed Reductions and the Shift TSS South, speeding up by one-half knot to make up lost time influences the overall cost of management to the industry.

Second, rather than categorically assume all ships would follow a single course of action, we calculated the total change in cost assuming that operators would speed up elsewhere to make up for lost time only when doing so would result in lower costs. In addition to being more realistic from a cost-effectiveness perspective, this assumption allowed us to arrive at a single metric for comparing across management options. Specifically, we assumed the operator would not speed us elsewhere if doing so was more expensive. Conversely, we assumed the operator would speed up elsewhere if doing so was less expensive. Mathematically, we compared the costs for each transit, assuming that the operator (1) would make up time and (2) would not make up time, and then calculated the minimum cost for each vessel based on these two alternate assumptions (Figure 14). This analysis does not apply to Management Option 3 (narrowing the TSS), because there was no time lost as a result of the change in management. Although there may be constraints that determine whether an operator chooses to make up time elsewhere during the voyage, we believe it is reasonable to assume that each operator is likely to choose the most cost-effective mode of operation and that a typical cost of management will reflect this choice.

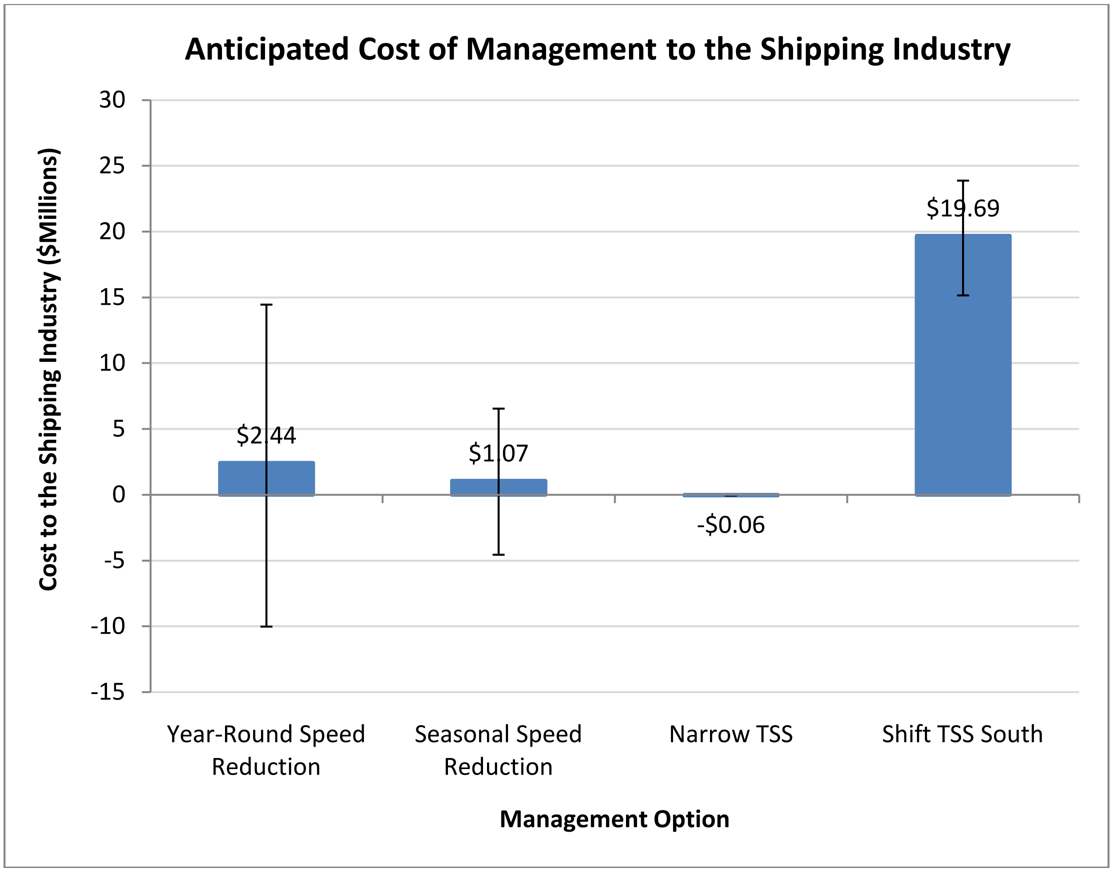


Figure 14: Anticipated cost of management to the shipping industry. We assumed operators choose optimally whether to make up lost time on other portions of their voyage based on least-cost. Error bars show 95% confidence intervals based on Monte Carlo sensitivity analysis.

The anticipated change in cost to the shipping industry when operators choose the most-cost effective mode of operation is lower than the predicted change in cost when all operators make up time or when none of the operators make up time. As shown in Appendix 6, the cost of management options varies across ship types and sizes. The decision to make up lost time may increase or decrease the cost of management for any given ship, depending on the type and size of the ship. The overall modeled cost of management when no operators make up time is relatively high because of the high cost of delay for some ships. Similarly, the overall modeled cost of management when all operators make up time is relatively high because of the increased cost of fuel from speeding up. The cost of management is substantially lower when operators choose optimally whether to make up time because each vessel transit in our model is assigned the lowest cost. Appendix 7 shows histograms of the cost of management scenarios for individual transits when operators do not make up time, when they make up time, and when they choose the least-cost mode of operation.

The costs reported here do not represent the total costs of vessels utilizing the region, but rather the change in costs incurred strictly as a result of management. To understand the potential impact of these additional costs on the industry, it is helpful to put the change in costs under each management option in the context of the overall annual cost of maintaining and financing ships (including operating, voyage, capital, and maintenance costs). For each ship in our sample, we estimated its total annual cost based on the U.S. Army Corps of Engineer's Deep Draft Vessel Operating Costs for the year 2000 (USACE, 2000) and daily operating costs reported by Kite-Powell and Hoagland (2002). Based on these sources, we estimate that the total annual cost incurred by the 334 ships in our model is approximately $3 billion. We used our estimate of the total expense required to operate the 334 ships in our random sample to approximate the total cost to operate all vessels that passed through the Channel during the selected time period. Because our random sample represents only about 10% of the vessels that traveled through the region, we multiplied these vessels' estimated total annual costs of $3 billion by 10 to arrive at a rough approximation of total annual industry costs of $30 billion. This total annual cost is independent of additional costs that would be incurred due to management enacted to reduce the risk of vessel strikes to whales. The annual change in cost for all ships passing through the Channel region is compared to the estimated total annual cost in Table 7.

Table 7: Comparison of the annual cost of management to overall annual cost of operating vessels. Cost of management is the total annual cost of management when operators take the least-cost route for all transits through the Channel region. Estimated overall cost for all vessels in the region is $30 billion.

MANAGEMENT OPTION	COST OF MANAGEMENT (ALL TRANSITS THROUGH THE REGION)	PERCENT OF OVERALL ANNUAL COST
Year-Round Speed Reduction	$2,436,109	0.00812%
Seasonal Speed Reduction	$1,070,877	0.00357%
Narrowing the TSS	-$56,453	0.00019%*
Shifting the TSS South	$19,687,252	0.0656%

*Narrowing the TSS results in 0.00019% savings from overall annual costs.

These results estimate the percentage of overall costs to the shipping industry represented by the change in cost as a result of one year of management. This estimate further relies on the assumption that only certain ships, including cargo ships, tankers, and cruise ships, will incur costs from management. If additional costs were incurred by vessels excluded from our model (see Section 5.3), these costs would need to be evaluated separately and considered in addition to the costs modeled here.

MANAGEMENT OPTION 1: YEAR-ROUND MANDATORY SPEED REDUCTION

Our model predicts that a year-round mandatory 10 knot speed restriction in the Whale Advisory Zone will result in an overall annual increase in cost to the shipping industry of $2.44 million.

The increased cost when operators do not make up time is largely a result of the increased time at sea from slowing down in the Channel. Approximately 46% of ships did not make up time and, on average, the speed reduction resulted in an increased time of approximately 4 hours and 45 minutes, with a maximum delay of 5 hours and 22 minutes. For these ships, the average increase in operating costs is approximately $17,232 for a single transit. However, the average savings on voyage costs as a result of reduced fuel and lubricant consumption is nearly $17,668 per transit. This amounts to an average total cost savings of $435 per vessel transit when operators do not make up time.

The remaining 54% of operators do make up time by speeding up elsewhere, which increases fuel consumption and results in an additional cost. The average voyage cost when operators speed up by one-half knot to make up time is approximately $1,363 per transit. While this behavior eliminates any cost saving from decreased fuel consumption, it also negates additional hourly costs, which would have amounted to $11,833, had the operator not sped up. As a result, removing additional operating costs outweighs the fuel savings from the speed reduction. Regardless of whether vessels speed up elsewhere or not, they are still subject to increased repair and maintenance costs if they operated below recommended speeds in the management region.

Among all vessels that will be impacted by this management option, the average total cost per transit is approximately $558.

The 95% confidence interval for the overall cost of a year-round Mandatory Speed Reduction is quite large, with a lower bound of -$10 million (a cost savings) and an upper bound of $14.4 million. This uncertainty is mainly due to the influence of fuel prices on the cost to the industry. The Monte Carlo sensitivity analysis allowed us to incorporate the variability in fuel price (among other factors) into the model, and the resulting variability in cost is substantial.

As noted, penalties for violations of the 10 knot speed restriction on the East Coast range from $2,500-$5,500 for the first violation, $5,000-$8,000 for the second violation, and $7,500 up to $11,000 for the third violation (NOAA, 2008, 2010). Using the lowest-cost methodology, we can use our model to predict which ships will find it cost effective to comply with the 10-knot speed reduction in the WAZ based on whether the change in total costs faced for the transit is less than the potential penalty. Of the 436 transits affected by Management Option 1 (year-long speed reduction), our model predicts that operators constituting 92% of the affected transits would find it cost effective to comply with the speed reduction if the fine were to range from $2,500 to $4,999 (equivalent to a first violation on the East Coast). Operators constituting the remaining 8% of transits would find it cost effective to comply if the fine were to range from $5,000 to $8,000 (equivalent to a second violation). Of the 187 transits affected by Management Option 2 (seasonal speed reduction), our model predicts that operators would find it cost effective to comply with the speed reduction for the same percentage of transits (92% and 100%) if the penalty were to range from $2,500 to $4,999 or $5,000 to $8,000, respectively.

MANAGEMENT OPTION 2: SEASONAL MANDATORY SPEED REDUCTION

A seasonal mandatory speed reduction, in which ships traveling through the WAZ are required to slow to a speed of 10 knots for six months, results in an increased annual cost to the shipping industry of approximately $1.07 million. As previously discussed, this calculation is made under the assumption that ships will operate in a manner that minimizes their costs.

Under a seasonal speed reduction, 52% of ships would incur either a lower change in total costs or a cost savings by speeding up outside of the management region to make up for time lost due to lower operating speeds. Among the ships that we assumed would speed up elsewhere, the cost incurred per ship of slowing down in the management region and not speeding up elsewhere was $6,285.61, whereas their average change in cost from management when they did make up for lost time was $1,606.27 per transit. As a result, we assumed these ships would speed up outside of the management region because doing so would minimize their costs.

We assumed the remaining 48% of ships would not make up for lost time by speeding up outside of the management region. The average cost per ship of slowing down in the Channel and not speeding up elsewhere was -$536 per transit, which represents a cost savings. In contrast, if they were to make up for lost time, they would accrue an average of $11,294 in additional costs per transit. There is a great deal of variability among both the ships that did and those that did not speed up outside of the management area. As a result, it is difficult to categorically predict how ships will behave based on their static characteristics. Overall, according to our model, those ships that would incur lower costs by speeding up were generally larger and faster, with an average deadweight tonnage (DWT) and design speed of approximately 70,000 and 24, respectively, compared to an average DWT and design speed of 46,000 and 20 among those that incurred a lower cost by not speeding up.

Among all vessels that will be impacted by this management option, the average total cost per transit is approximately $569.

The 95% confidence interval for the overall cost of a seasonal mandatory speed reduction to the shipping industry ranges from a lower bound of -$4.6 million (a cost savings) to an upper bound of $6.5 million. Similar to the year-round mandatory speed reduction, this uncertainty is primarily a result of great variability in the price of fuel.

MANAGEMENT OPTION 3: NARROW THE TRAFFIC SEPARATION SCHEME WITHIN THE CHANNEL

Narrowing the TSS within the Channel would have no cost to the shipping industry and is predicted to result in a slight annual cost savings of approximately $56,000. This savings is a result of the modest reduction in distance traveled by southbound traffic in the TSS. Because there is a small reduction in time at sea, our scenario involving operators making up time elsewhere is not relevant to this management option. Therefore, the estimated final cost savings is $56,000, or approximately $12 per transit. The 95% confidence interval around this value ranges from -$65,377 to -$47,784. We can therefore expect that this management option will have no cost and may, in fact, generate a small cost savings to the industry, even given the variability and uncertainty of parameters in our model.

MANAGEMENT OPTION 4: SHIFT THE TRAFFIC SEPARATION SCHEME TO THE SOUTH OF THE NORTHERN CHANNEL ISLANDS

Shifting the TSS to the south would result in a minimum overall increase in annual cost to the industry of $19.69 million.

When operators do not make up time, the change in total cost is a result of the cost of additional time at sea and an increased cost of fuel and lubricant for the distance added to the voyage. Overall, 46% of ships would have cost savings by not making up time. For these ships, the average delay resulting from this management option is 38 minutes, and the maximum delay is about 55 minutes. On average, operating costs are increased by about $2,315 per transit, and voyage costs are increased by approximately $3,535 per transit. Had these vessels made up for lost time, they would have incurred, on average, an increased voyage cost of approximately $7,413.

In contrast, the 54% of ships that make up lost time increase their average voyage costs from approximately $1,257 to about $2,860 per transit due to increased fuel and lubricant consumption. However, they decrease additional hourly operating costs from $3,115 to zero because there is no net increase in time at sea, which results in an overall reduction in costs by speeding up. As noted, our model assumes that all ships will use low-sulfur fuel in the future, based on the confluence of the CARB and IMO fuel regulations in 2015. However, ships traveling through the Southern Region prior to the heightened regulation would likely continue to use high-sulfur fuel, thereby accruing additional, short-term savings not reflected in our model.

Regardless of operator behavior, under this management scenario, there is also an added cost for all ships due to possible delays resulting from Navy operations in the Point Mugu Sea Range. Though not all ships will be affected by Navy operations, the average additional cost of a delay is $256 when distributed across all vessels.

Among all vessels that will be impacted by this management option, the average increase in total cost per transit is approximately $4,511.

The 95% confidence interval for shifting the TSS south is relatively small compared to the confidence interval of the mandatory speed reduction. The lower bound is $15.1 million, and the upper bound is $23.9 million.

7. CONCLUSIONS

Our analysis predicts that the greatest reduction in relative risk of a lethal whale strike likely occurs under the year-round and seasonal speed reduction scenarios (Management Options 1 and 2, respectively). As depicted in Table 8 below, the Linear Predictive Model and the Average Distribution Model predict that a year-round speed reduction (Management Option 1) will reduce the relative risk of a lethal whale strike by 64.7% and 62.8%, respectively, with an overall cost to the shipping industry of $2.44 million per year. This represents an increased cost of less than 0.1% of the overall annual cost of shipping in the region.

Table 8: Comparison of cost to the shipping industry and risk reduction under the Linear Model and the Average Distribution Model for the four management options evaluated.

MANAGEMENT OPTION	COST OF MANAGEMENT (MILLIONS)	PERCENT REDUCTION IN RISK LINEAR MODEL	PERCENT REDUCTION IN RISK AVERAGE MODEL
Year-Round Speed Reduction	$2.44	64.7	62.8
Seasonal Speed Reduction	$1.07	32.6	32.5
Narrowing the TSS	-$0.06	-5.5	-5.7
Shifting the TSS South	$19.69	10.2	-1.5

The Linear Predictive Model and the Average Distribution Model similarly predict that a seasonal speed reduction (Management Option 2) will reduce the relative risk of a lethal strike by 32.6% and 32.5%, respectively, with a cost of $1.07

million per year. While the year-long management option results in a larger reduction in risk than the seasonal speed reduction, the estimated cost of the seasonal speed restriction (Management Option 2) is less than half that of a year-long restriction (Management Option 1). Thus, our analysis suggests that adoption of a seasonal speed reduction would result in the greatest reduction in risk per dollar cost to the shipping industry. More specifically, a year-round speed restriction reduces the relative risk of a lethal strike by 25.7% per $1 million of cost to the shipping industry, while a seasonal speed restriction reduces the relative risk of a lethal strike by 30.4% per $1 million of cost.

In comparison, the Linear Predictive Model and the Average Distribution Model predict that narrowing the TSS (Management Option 3) would *increase* the relative risk of a lethal strike by 5.5% and 5.7%, respectively (see Table 8). This management option results in an estimated cost *savings* to the shipping industry of approximately $56,000 per year.

The Linear Predictive Model predicts that shifting the TSS to the south of the Northern Channel Islands (Management Option 4) decreases the relative risk of a lethal strike by 10.2%, while the Average Distribution Model predicts that Management Option 4 increases the relative risk of a lethal strike by 1.5%. The resulting estimated cost to the shipping industry is $19.69 million per year. In other words, our analysis predicts shifting the TSS to the south is the most expensive option considered and may *increase* the relative risk of a lethal strike.

Given the uncertainty in our results, it is unclear whether narrowing or shifting the TSS will reduce the risk of a lethal strike. However, our model results indicate that the year-round and seasonal speed reductions will likely reduce the risk of a lethal strike and are the most cost effective options considered (see Figure 15).

Ultimately, the goal of our project is not to make policy recommendations, but rather to provide a framework for assessing the effects of different management options on (1) the relative risk of a lethal strike and (2) the cost to the shipping industry. In addition to risk and economic factors, myriad other considerations may affect the propriety of adopting a particular regulatory scheme to reduce the risk of vessel strikes to whales in the Channel region. As a result, future analyses of different management scenarios should also consider other relevant factors, including policy, enforcement, or other issues that may complicate implementation. Moreover, the analyses we have presented here are based on the best available information. As new or better information becomes available in the future, the results reported here, as well as the assumptions underlying those results, may change.

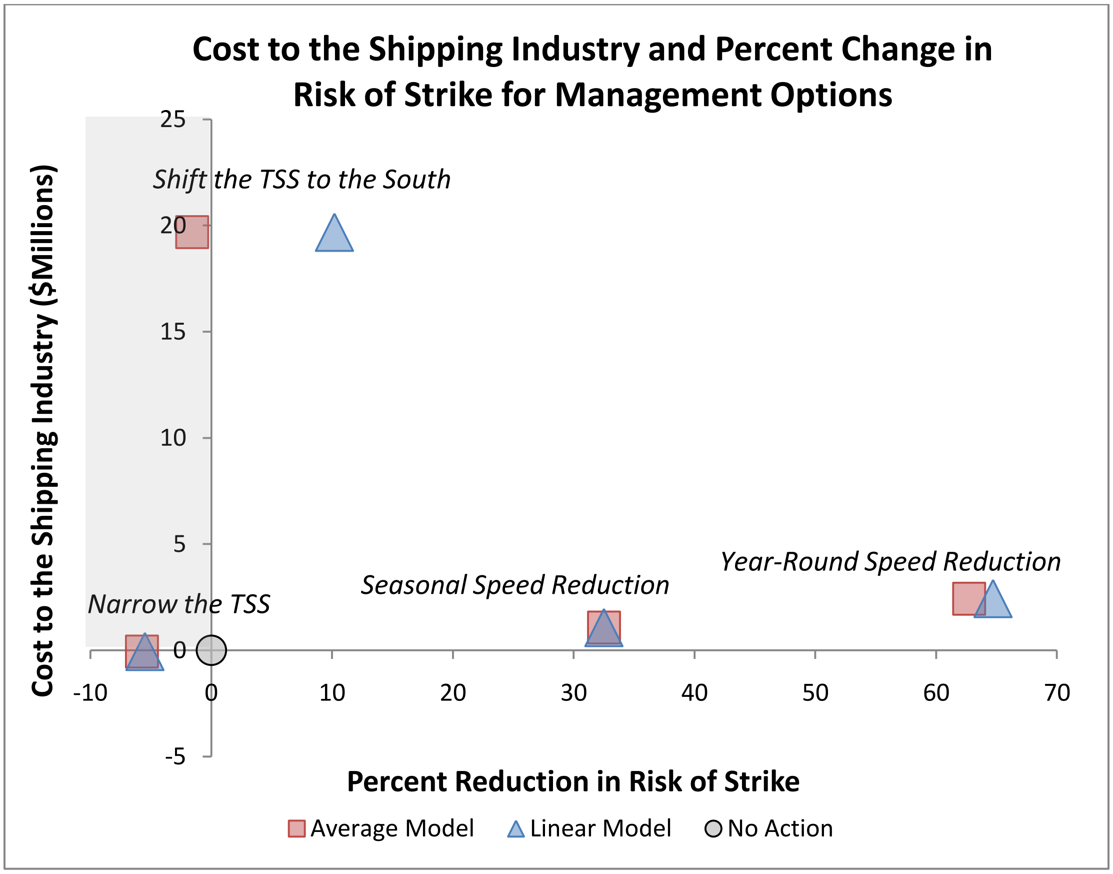


Figure 15: Compares both the reduction in relative risk of a lethal strike and the costs to the shipping industry of management options evaluated in this analysis. The risk reduction calculated using the Average Distribution Model (red boxes) and the Linear Model (blue triangles) is compared to the minimum cost of each management option, which assumes each vessel operator chooses whether to make up lost time based on the least-cost option. The gray box indicates a quadrant in which there is a cost to the industry and an increase in risk. The gray dot (0, 0) represents the change in risk and cost if no action is taken, assuming no change in current conditions. An acceptable management option should fall to the right of this point, representing a reduction in risk and either a cost or savings to the industry. The model results indicate that a year-round or seasonal speed reduction may provide the greatest risk reduction at a relatively low cost.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

8.1 WHALES

OBSERVATION DATA COLLECTION

While thorough data collection may prove costly, expansion of monitoring efforts to cover the entire Santa Barbara Channel region would greatly increase the amount of whale observation data available and allow for improved estimates of whale abundance and distribution in the region, especially to the south of the northernmost Channel Islands. Expansion of the CINMS SAMSAP aerial monitoring program or focused surveying efforts by other programs may improve these estimates.

The adoption of a standardized linear transect monitoring procedures across all survey efforts conducted throughout the Channel region could allow for more observation sighting information from separate data sets to be easily combined and used for modeling the risk of vessel strikes to whales.

POPULATION & ABUNDANCE ESTIMATES

The limited geographic distribution of whale observations recorded through SAMSAP aerial monitoring, combined with the lack of a robust whale distribution model specific to the Channel region, hindered our ability to accurately predict both the number and location of large whales in and around the Santa Barbara Channel. Efforts to develop more thorough whale distribution models are currently underway, and will play an integral role in improving estimates of large whale densities and seasonal migration patterns in the Channel region. It is also necessary to continue to evaluate how environmental variables, including ocean depth, bathymetric slope, distance to shore, sea surface temperature, krill density and upwelling, affect the distribution and abundance of whale species in this region. Through these research efforts, scientists and managers may gain a better understanding of whale behavior and spatial and temporal distribution in the Channel region, enabling more informed management and policy decisions.

STRIKE DETECTION RATES

While studies have attempted to estimate the probability of a vessel striking a large whale, it is likely that the annual number of whales struck and killed by ships is larger than the number of those actually detected (Kraus *et al.*, 2005; Vanderlaan *et al.*, 2009). This underestimation is attributed largely to the fact that each whale killed as a result of a strike may not necessarily be discovered or positively identified as being struck (Kraus *et al.*, 2005). In order to better understand the detection rate of whales strikes, and in doing so develop more informed management options, future models analyzing the probability of detection should consider incorporating oceanographic information on currents, tides and bathymetry; seasonal, yearly and decadal oceanographic patterns; and biological characteristics such as whale buoyancy and distribution. Results of modeling the probability of detection will help better inform estimates of actual risk and the total number of ship strikes in the region.

8.2 SHIPPING INDUSTRY DATA

DYNAMIC MANAGEMENT AREAS

As a result of the East Coast Port Access Route Study, NMFS adopted a dynamic management area requiring commercial ships to slow to 10 knots or less in specific areas along the eastern seaboard during certain periods of the year when right whale concentrations are high (Abramson *et al.*, 2009; NMFS, 2008). Although we did not analyze the effects on the shipping industry of a dynamic management area within the study region, it may be insightful to refine our economic model in the future to do so. In particular, we heard anecdotally from experts in the shipping industry that unanticipated delays could lead to a series of missed or delayed port calls, including, in certain cases, a missed transit through the Panama Canal (T.L. Garrett, pers. communication, Nov. 2, 2010). In extreme cases, shipping experts believed that the costs of a series of delayed or missed port calls could be substantial, with some captains estimating the cost to be as high as $250,000 (T.L. Garrett, pers. communication, Nov. 2, 2010). At the same time, shipping experts opined that the likelihood of a ship incurring such extraordinary costs on a particular transit is relatively low (T.L. Garrett, pers. communication, Nov. 2, 2010). Despite the low risk, our economic model would ideally be refined to incorporate a variable that would account for such costs to the extent that NOAA and the USCG consider instituting a dynamic management area in the region in the future.

CHANGES IN COST DUE TO CHANGES IN THE RISK OF A COLLISION

An additional issue outside the scope of our analysis is whether a particular management option will affect the risk of a vessel-to-vessel collision, thereby potentially increasing the risk of human loss, environmental damage, and economic costs. In particular, narrowing the traffic separation zone within the existing TSS decreases the distance between the northbound and southbound traffic lanes, and thus may affect the risk of a collision. Similarly, the Department of the Navy has raised concerns that shifting the TSS to the south would increase the risk of collisions involving Very Large Crude Carriers (VLCCs), which voluntarily travel at significantly slower speeds through the region to avoid faster-moving vessel traffic within the Channel (Department of Navy, 2010). Accordingly, any future assessment should consider whether a given management option would change the risk of a vessel-to-vessel collision. Among other things, future research could consider whether recent advances in navigational capabilities counterbalance any increase in the collision risk due to narrowed traffic lanes (Silber & Bettridge, 2010).

8.3 MANAGEMENT OPTIONS

APPARENT CONSTRAINTS ON ALTERING THE EXISTING TSS

As indicated, we were unable to significantly alter the current TSS configuration due to existing physical constraints, including the proximity of Anacapa Island to the current lanes and the presence of numerous oil and gas platforms in the Channel (Santa Barbara Channelkeeper, 2006). Nonetheless, it may be possible to improve upon our proposal by both narrowing the TSS and incorporating one or more additional "turns" into a newly-configured TSS. Doing so would seem particularly worthwhile in light of the substantial concerns raised by the Department of the Navy and others regarding the feasibility of shifting the traffic lanes to the south (Department of Navy, 2010). Accordingly, efforts should be made to explore whether it is possible to configure an alternative TSS within the Channel that would (1) decrease the risk of a whale strike by reducing areas in which shipping lanes overlap with high whale concentrations, and (2) account for existing physical constraints in the region that may compromise maritime safety. To the extent a new configuration is developed in the future, it is possible to use our risk and economic models to estimate the effects of such a change.

INCORPORATING THE RESULTS OF THE PORT ACCESS ROUTE STUDY

The USCG anticipates that it will publish the results of its Port Access Route Study in June 2011 (USCG, 2010b). Among other things, it is possible the USCG will propose modifications to the existing TSS in the Channel, including alternative vessel routing solutions, such as area(s) to be avoided (USCG, 2010a). To the extent the USCG does so, we encourage concerned parties to use the economic and risk models developed during this project to assess the ecological and economic impacts to whales and the shipping industry of any proposed changes to vessel traffic routing schemes in the Channel region.

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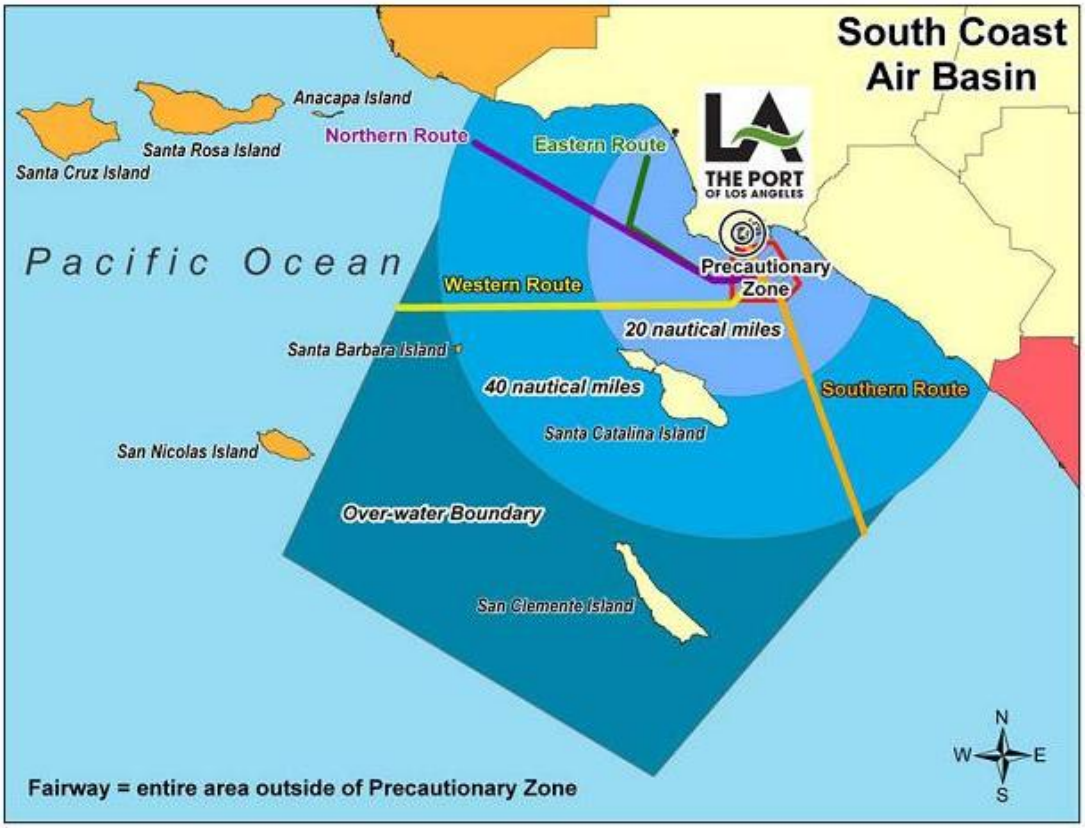
APPENDIX 1. LALB PRECAUTIONARY ZONE AND VSR PROGRAM AREAS

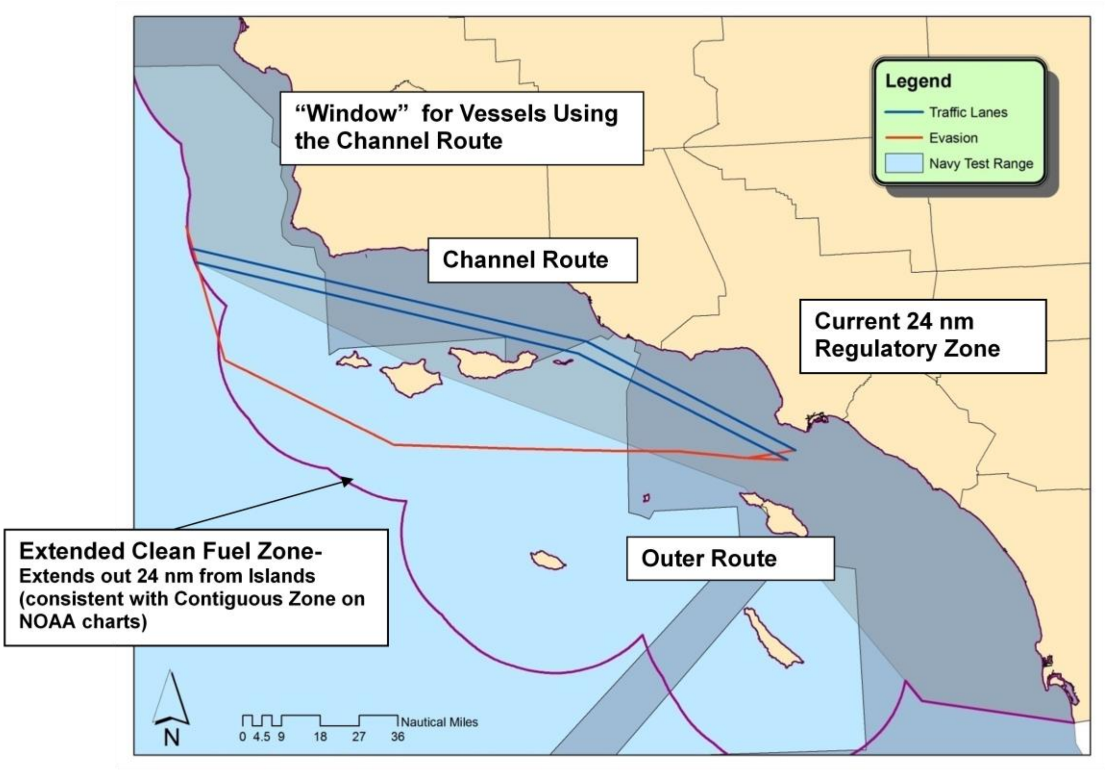
Figure 16: Port Complex of Los Angeles-Long Beach Precautionary Zone and Vessel Speed Reduction Incentive Program Areas.



Source: (Port of Los Angeles Board of Harbor Commissioners, 2009)

APPENDIX 2. CARB PROPOSED EXTENDED CLEAN FUEL ZONE

Figure 17: CARB proposed extended clean fuel zone.



Source: (CARB, 2010)

APPENDIX 3. ESTIMATING THE RELATIVE RISK OF A LETHAL STRIKE

WHALE OBSERVATIONS

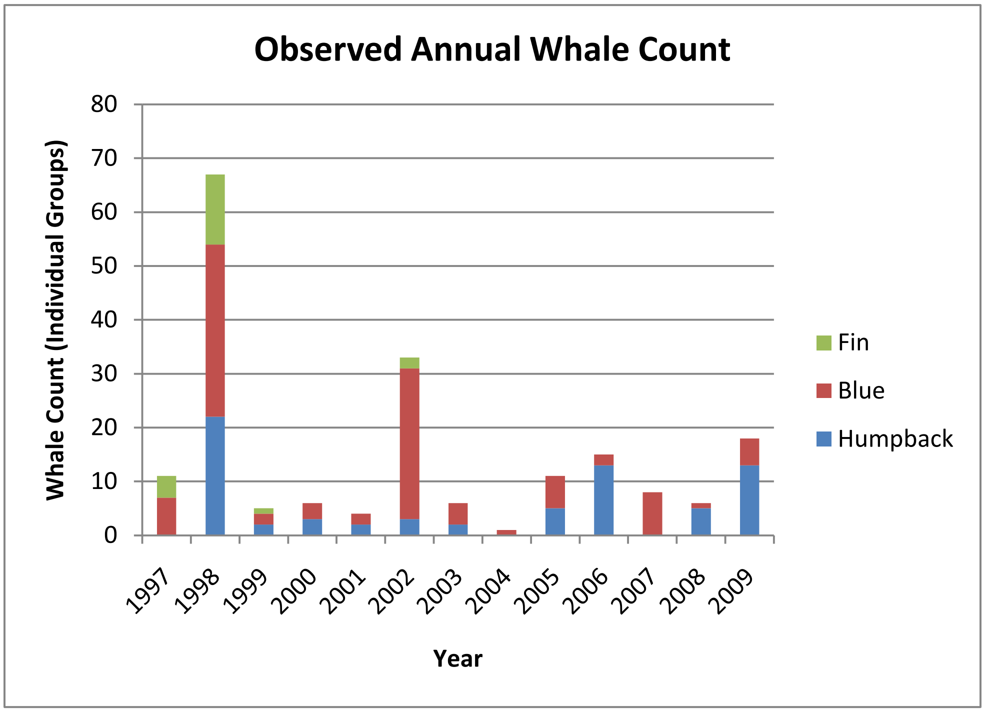


Figure 18: Annual whale counts of individual groups observed during aerial surveys conducted by the SAMSAP at CINMS.

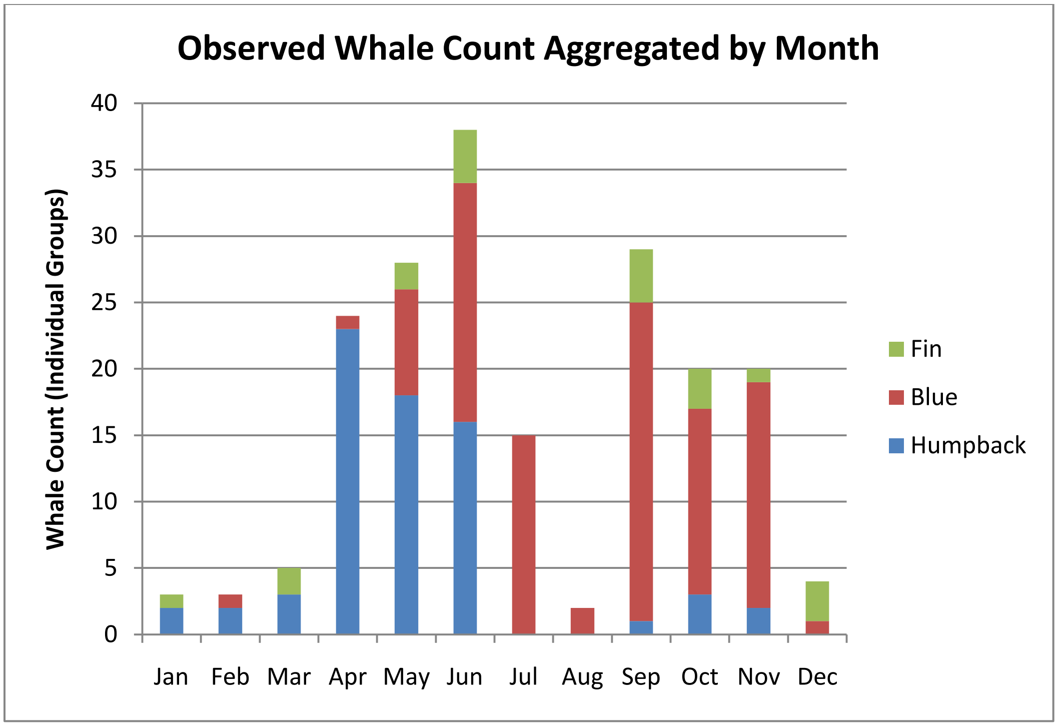


Figure 19: Aggregated monthly whale counts of individual groups observed during aerial surveys conducted by the SAMSAP at CINMS between 1997 and 2010

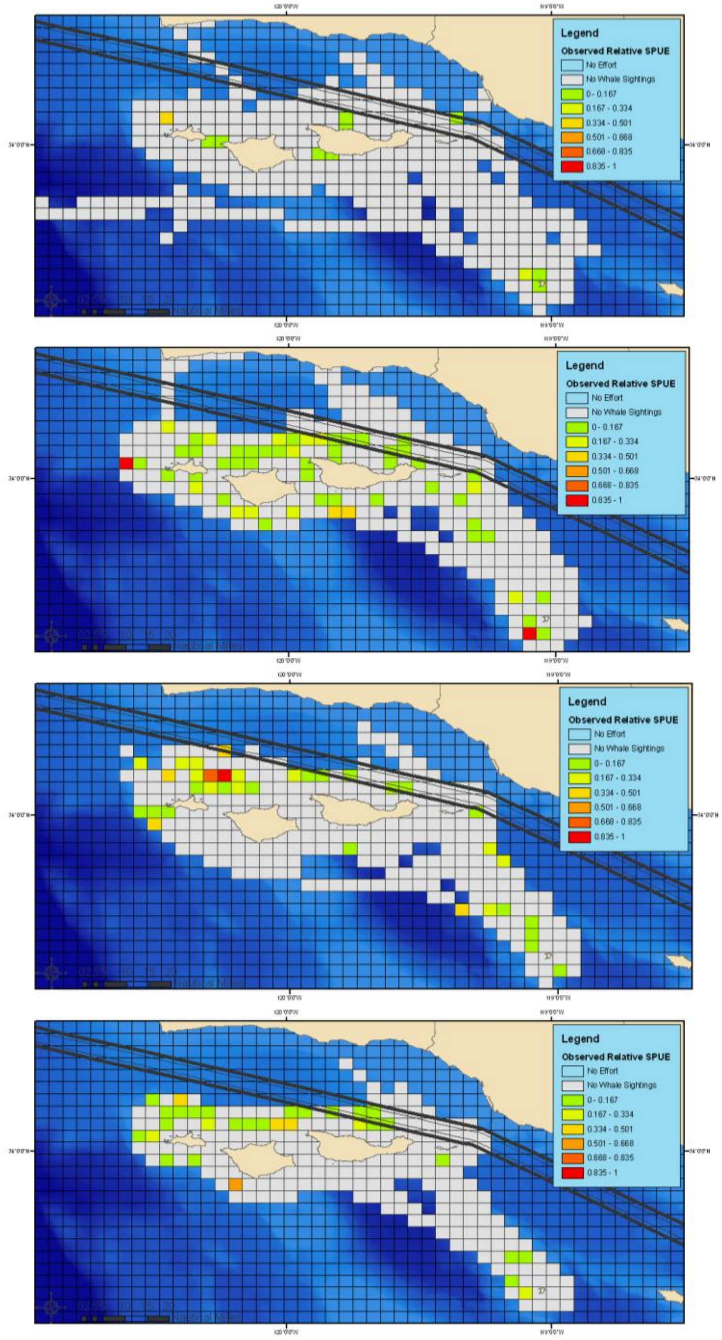


Figure 20: The observed sightings per unit effort (SPUE) for quarters 1, 2, 3 and 4 (shown top to bottom) made relative across all four quarters. The relative probability of a SPUE ranges between zero (0) and one. Red indicates high probability, green indicates low probability, and gray indicates cells that were surveyed but where no whales were observed. The gray cells have a relative probability of zero (0). The existing TSS is shown in black outline.

WHALE DISTRIBUTION MODEL

Table 9: Regression coefficients and corresponding p-values for Linear Predictive Model run for each quarter (see Eq. 7).

QUARTER 1

REGRESSION COEFFICIENTS		***P-VALUES***
β_0	$1.51x10^{-2}$	0.23
β_1	$1.79x10^{-6}$	0.68
β_2	$-9.8x10^{-5}$	0.57
β_3	$-1.80x10^{-2}$	0.45

QUARTER 2

REGRESSION COEFFICIENTS		***P-VALUES***
β_0	$4.67x10^{-3}$	0.93
β_1	$-2.83x10^{-5}$	0.11
β_2	$3.14x10^{-4}$	0.67
β_3	$-1.70x10^{-1}$	0.07

QUARTER 3

REGRESSION COEFFICIENTS		***P-VALUES***
β_0	$2.83x10^{-2}$	0.64
β_1	$1.38x10^{-5}$	0.39
β_2	$-1.17x10^{-4}$	0.87
β_3	$1.49x10^{-1}$	0.11

QUARTER 4

REGRESSION COEFFICIENTS		***P-VALUES***
β_0	$4.08x10^{-2}$	0.40
β_1	$1.55x10^{-5}$	0.24
β_2	$-1.47x10^{-4}$	0.81
β_3	$1.07x10^{-2}$	0.88

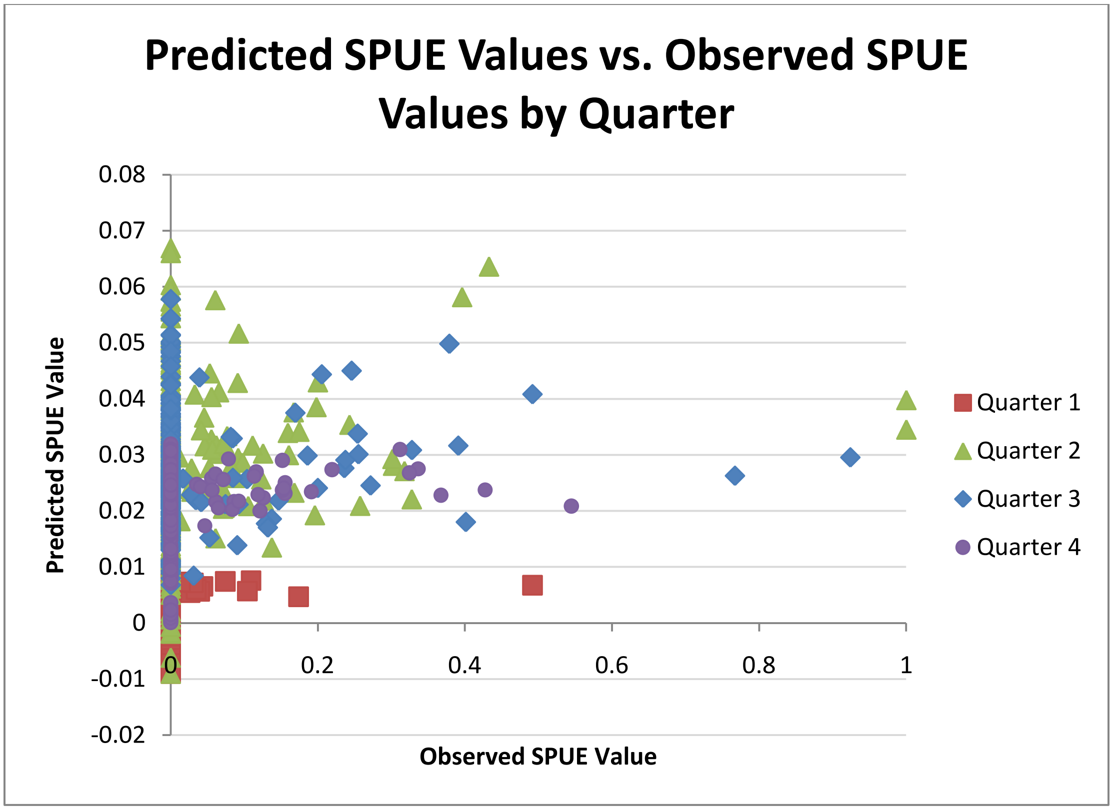


Figure 21: Predicted SPUE values generated from Linear Predictive Model graphed versus observed SPUE values generated from SAMSAP data.

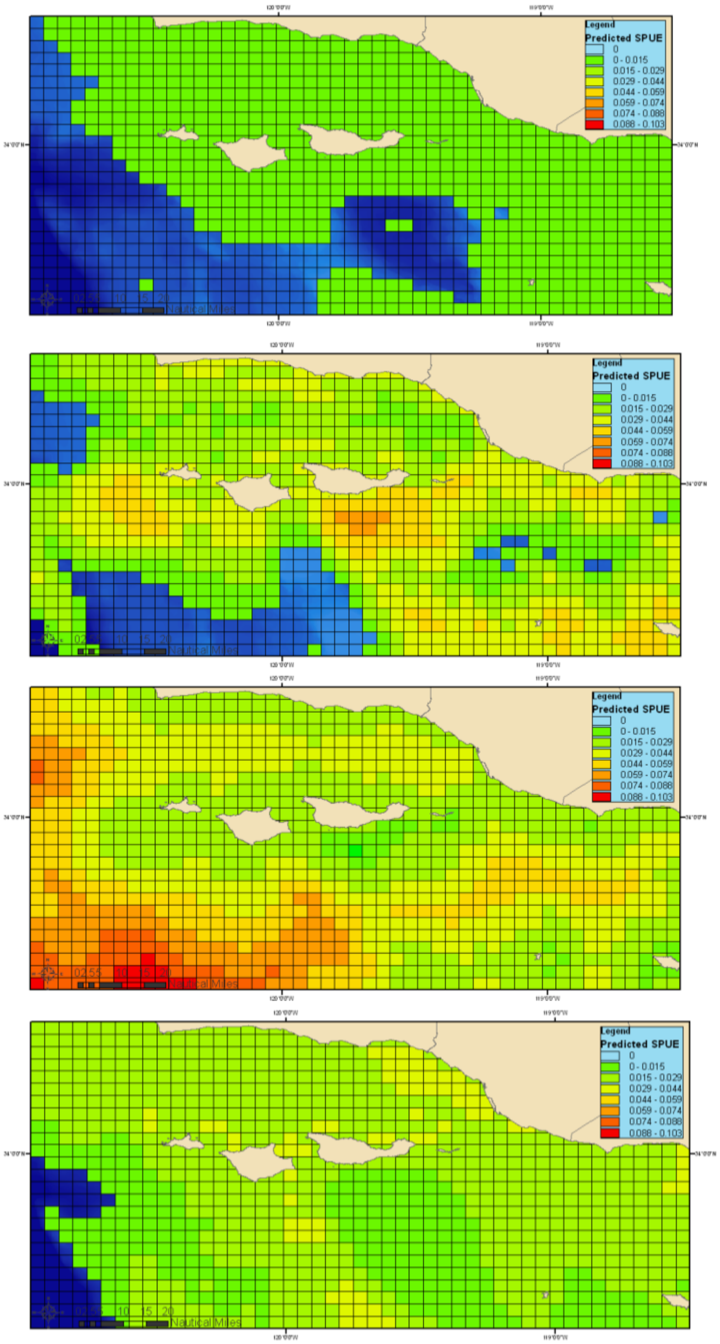


Figure 22: Predicted whale distribution generated using the Linear Predictive Model for quarters 1, 2, 3, and 4 (shown top to bottom). Red indicates higher relative probability of whale presence, while green indicates lower probability of whale presence. Cells where whale presence was predicted to be zero (0) are hollow (and thus show the underlying bathymetry in blue).

APPENDIX 4. ECONOMIC MODEL

Parameters

ΔTC = Change in Total Cost (of a *transit* for any given ship)

ΔVC = Change in Voyage Costs

ΔOC = Change in Operating Costs

ΔNC = Change in cost associated with a potential delay from Navy operations

α = Additional economic costs not otherwise captured by voyage costs, operating costs, or costs associated with a potential delay from Navy operations

Distance and speed

- $\mathbf{s^*}$ = design speed

Region A is the study region potentially affected by a management option (i.e., within the Channel or on the south side of the northern Channel Islands). Within Region A, the following parameters may be affected:

- $\mathbf{s_{a,1}}$ = initial average operating speed (knots)
- $\mathbf{s_{a,2}}$ = regulation speed (knots)
- $\mathbf{d_{a,1}}$ = distance traveled through the region under the current scenario (nautical miles)
- $\mathbf{d_{a,2}}$ = distance traveled through the region under new management scenario (nautical miles)

Region B is an area outside of the study region over which a ship may alter its speed to make up for time lost as a result of a management option implemented in Region A. Only when operator behavior is accounted for, and we assume that vessels will make up for anticipated delays by speeding up elsewhere, does Region B become incorporated into the equation. This is represented by the second half of the ΔFC_{ME}*,* ΔFC_{AE} *and* ΔLC *equations.*

- $\mathbf{s_{b,1}}$ = initial average operating speed in Region B (knots)
- $\mathbf{s_{b,2}}$ = new speed in Region B in response to regulation (knots)
- $\mathbf{d_b}$ = distance over which speed is altered to make up time (nautical miles)

Voyage cost parameters

- **P_{ME}** = total power of main engine(s) (hp or kW)
- **P_{AE}** = total power of auxiliary engine(s) (hp or kW)

Fuel

- **fp_1** = Region A: fuel price per ton in the Channel (\$/ton): price of IFO-380 before CARB; price of MGO after CARB regulations
- **fp_2** = Region A: fuel price per ton outside of the Channel (\$/ton): price of IFO-380
- **fp_B** = Region B: fuel price per ton (\$/ton)
- **SFC_{ME1}** = Region A: specific fuel consumption factor for main engine in the Channel (g/kWh): SSD/RO before CARB; SSD/MGO after CARB regulations
- **SFC_{ME2}** = Region A: specific fuel consumption factor for main engine outside of the Channel (g/kWh): SSD/RO
- **SFC_{ME2}** = Region B: specific fuel consumption factor for main engine (g/kWh)
- **SFC_{AE1}** = Region A: specific fuel consumption factor for auxiliary engine in the Channel (g/kWh): MSD/RO before CARB; MSD/MGO after CARB regulations
- **SFC_{AE2}** = Region A: specific fuel consumption factor for auxiliary engine outside of the Channel (g/kWh): MSD/RO
- **SFC_{AE2}** = Region B: specific fuel consumption factor for auxiliary engine (g/kWh)
- **ΔFC_{TOT}** = total change in fuel cost
- **ΔFC_{ME}** = change in fuel cost from main engine operation
- **ΔFC_{AE}** = change in fuel cost from auxiliary engine operation

Lubricant Oil

- **lp_1** = Region A: lubricant price per ton inside the Channel (\$/ton): price of BN70 before CARB; price of BN40 after CARB regulations
- **lp_2** = Region A: lubricant price per ton outside of the Channel (\$/ton): price of BN70
- **lp_B** = Region B: lubricant price per ton (\$/ton)
- **LFR_1** = Region A: lubricant feed rate inside the Channel (g/kWh)
- **LFR_2 =** Region A: lubricant feed rate outside the Channel (g/kWh)
- **LFR_B** = Region B: lubricant feed rate (g/kWh)
- **ΔLC** = change in lubricant cost for the main engine

Operating cost parameters

- **Δt** = change in time at sea as a result of a management option within Region A (hours)
- **Δt_r** = duration of speed reduction within Region A (hours)
- **CC** = total crew cost based on the vessel size, type and age (hours)
- **RM** = repair and maintenance costs (hours)

Parameters of cost associated with a potential delay from Navy operations

- **NC** = cost associated with a potential delay from Navy operations
- **CU** = cost of overtime charges for cargo unloading as a result of a missed or delayed port call
- **DC** = cost of additional dockage charges as a result of a missed or delayed port call

Parameters of cost associated with Alpha

- **α** = economic costs not otherwise captured by voyage costs, operating costs, or costs associated with a potential delay from Navy operations

Basic Model

The total change in costs is the result of the change in operating costs, the change in voyage costs, and any costs incurred because of delays from Navy operations:

$$\Delta TC = \Delta VC + \Delta OC + \Delta NC$$

Calculating the change in voyage costs (ΔVC)

The change in the voyage cost is the difference in fuel and lubricant costs as a result of the change in speed for Region A and/or Region B.

$$\Delta VC = \Delta \mathrm{FC}_{\mathrm{TOT}} + \Delta \mathrm{LC}$$

$$\Delta \mathrm{FC}_{\mathrm{TOT}} = \Delta \mathrm{FC}_{\mathrm{ME}} + \Delta \mathrm{FC}_{\mathrm{AE}}$$

$\Delta \mathrm{FC}_{\mathrm{ME}}$ =

$$\left[\mathrm{fp}_2(\mathrm{P}_{\mathrm{ME}})(\mathrm{BSFC}_{\mathrm{ME2}})\left(\frac{1}{10^6}\right)\left(\frac{d_{a,2}}{s_{a,2}}\right)\left(\frac{s_{a,2}}{s^*}\right)^3 - \mathrm{fp}_1(\mathrm{P}_{\mathrm{ME}})(\mathrm{BSFC}_{\mathrm{ME1}})\left(\frac{1}{10^6}\right)\left(\frac{d_{a,1}}{s_{a,1}}\right)\left(\frac{s_{a,1}}{s^*}\right)^3\right] + \left[\mathrm{fp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{ME}})(\mathrm{BSFC}_{\mathrm{MEB}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,2}}\right)\left(\frac{s_{b,2}}{s^*}\right)^3 - \mathrm{fp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{ME}})(\mathrm{BSFC}_{\mathrm{MEB}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,1}}\right)\left(\frac{s_{b,1}}{s^*}\right)^3\right]$$

$\Delta \mathrm{FC}_{\mathrm{AE}}$ =

$$\left[\mathrm{fp}_2(\mathrm{P}_{\mathrm{AE}})(\mathrm{BSFC}_{\mathrm{AE2}})\left(\frac{1}{10^6}\right)\left(\frac{d_{a,2}}{s_{a,2}}\right)\left(\frac{s_{a,2}}{s^*}\right)^3 - \mathrm{fp}_1(\mathrm{P}_{\mathrm{AE}})(\mathrm{BSFC}_{\mathrm{AE1}})\left(\frac{1}{10^6}\right)\left(\frac{d_{a,1}}{s_{a,1}}\right)\left(\frac{s_{a,1}}{s^*}\right)^3\right] + \left[\mathrm{fp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{AE}})(\mathrm{BSFC}_{\mathrm{AEB}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,2}}\right)\left(\frac{s_{b,2}}{s^*}\right)^3 - \mathrm{fp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{AE}})(\mathrm{BSFC}_{\mathrm{AEB}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,1}}\right)\left(\frac{s_{b,1}}{s^*}\right)^3\right]$$

$\Delta \mathrm{LC}$ =

$$\left[\mathrm{lp}_2(\mathrm{P}_{\mathrm{ME}})(\mathrm{LFR}_2)\left(\frac{1}{10^6}\right)\left(\frac{d_{a,2}}{s_{a,2}}\right)\left(\frac{s_{a,2}}{s^*}\right)^3 - \mathrm{lp}_1(\mathrm{P}_{\mathrm{ME}})(\mathrm{LFR}_1)\left(\frac{1}{10^6}\right)\left(\frac{d_{a,1}}{s_{a,1}}\right)\left(\frac{s_{a,1}}{s^*}\right)^3\right] + \left[\mathrm{lp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{ME}})(\mathrm{LFR}_{\mathrm{B}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,2}}\right)\left(\frac{s_{b,2}}{s^*}\right)^3 - \mathrm{lp}_{\mathrm{B}}(\mathrm{P}_{\mathrm{ME}})(\mathrm{LFR}_{\mathrm{B}})\left(\frac{1}{10^6}\right)\left(\frac{d_b}{s_{b,1}}\right)\left(\frac{s_{b,1}}{s^*}\right)^3\right]$$

When applicable, d_{b} =

$$\frac{\left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}}\right)(s_{b,1})(s_{b,2})}{s_{b,2} - s_{b,1}}$$

Calculating the change in operating costs (ΔOC)

A change in Operating Costs (ΔOC) is the difference in hourly crew costs (CC) resulting from a change in time (Δt) at sea and maintenance and repair costs (RM) resulting from a mandatory speed reduction to 10 knots:

$$\Delta \boldsymbol{OC} = (\boldsymbol{CC})\Delta \boldsymbol{t} + (\boldsymbol{RM})\Delta \boldsymbol{t_r}$$

A change in time at sea (Δt) is expressed as a function of a change in distance (Δd) or speed (Δs) in either Region A or Region B:

$$\Delta\, \boldsymbol{t} = \left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}}\right) + \left(\frac{d_b}{s_{b,2}} - \frac{d_b}{s_{b,1}}\right)$$

Repair and maintenance costs are included only when a mandatory speed reduction causes a vessel to operate below recommended power. This hourly cost is multiplied by the duration of the speed reduction, in hours (Δt_r)

$$\Delta\, \boldsymbol{t_r} = \left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}}\right)$$

Combining these two equations, a change in Operating Costs (ΔOC) is expressed as:

$$\Delta \boldsymbol{OC} = (CC)\left[\left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}}\right) + \left(\frac{d_b}{s_{b,2}} - \frac{d_b}{s_{b,1}}\right)\right] + (RM)\left[\left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}}\right)\right]$$

Calculating the change in costs due to a potential delay from Navy operations (ΔNC)

Our model of the change in total costs (ΔTC) also includes a change in costs due to a potential delay from Navy operations (ΔNC) within the Point Mugu Sea Range:

$$\Delta \boldsymbol{TC} = \Delta \boldsymbol{VC} + \Delta \boldsymbol{OC} + \Delta \boldsymbol{NC}$$

To quantify these costs, we determined the probability of the Navy asking a ship within the Sea Range to alter course or speed by dividing the total number of Navy requests for one year by the total number of vessel transits through the Range. We then multiplied the probability of a Navy request by expected costs resulting from a missed or delayed port call. To calculate expected costs, we assumed that a delayed *ship would pay overtime charges for cargo unloading (ΔCU) as well as additional dockage charges (ΔDC), as shown by the equation below. This cost applies only under Management Option 3 (shifting the TSS to the south)*

$$\Delta \boldsymbol{NC} = \boldsymbol{Probabilty}(\boldsymbol{Navy\ Request}) * \boldsymbol{\Delta CU} * \boldsymbol{\Delta DC}$$

Calculating Alpha (α)

Based on discussions with representatives of the shipping industry, we concluded there may be some economic costs not otherwise captured by voyage costs, operating costs, or costs associated with a potential delay from Navy operations. As a result, we introduced a variable, which we call "Alpha" (α) to the change in total cost (ΔTC) equation, in an attempt to quantify these additional costs.

$$\Delta \boldsymbol{TC} = \Delta \boldsymbol{VC} + \Delta \boldsymbol{OC} + \Delta \boldsymbol{NC} + \boldsymbol{\alpha} \Delta \boldsymbol{t}$$

In our model, Alpha (α) is mathematically expressed as a constant, multiplied by a change in time (Δt) at sea due to a change in distance (Δd) or speed (Δs) in either Region A or Region B:

$$\Delta \boldsymbol{TC} = \Delta \boldsymbol{VC} + \Delta \boldsymbol{OC} + \Delta \boldsymbol{NC} + \boldsymbol{\alpha} \left[\left(\frac{d_{a,2}}{s_{a,2}} - \frac{d_{a,1}}{s_{a,1}} \right) + \left(\frac{d_b}{s_{b,2}} - \frac{d_b}{s_{b,1}} \right) \right]$$

APPENDIX 5. COST CALCULATION DETAILS

AUXILIARY ENGINE POWER AND DESIGN SPEED REGRESSIONS

AUXILIARY ENGINE POWER

To fill in missing auxiliary engine power data, we computed values based on a linear regression derived from ships with complete data. We ran a regression of auxiliary engine power against total main engine power, gross tonnage, deadweight tonnage, and combinations of these values. Our process for selecting the appropriate regression is detailed below (Table 10). We selected main engine power as our final regression for use in our model because of its goodness of fit and its simplicity. The final linear equation used in our model is as follows:

$$Auxiliary\ Engine\ Power\ = (0.1913\ \times Main\ Engine\ Power)\ +\ 287.2$$

Table 10: Linear models for predicting auxiliary engine power.

INDEPENDENT VARIABLE(S)	ADJUSTED R-SQUARED	AIC
Main Engine Power	0.7653	4110
Gross Tonnage	0.6355	4208
Gross Tonnage + Main Engine Power	0.7685	4108
Deadweight Tonnage	0.3614	4334

DESIGN SPEED

Design speed is a critical component of the fuel calculations of our model. Where design speed was not provided by Lloyd’s Register of Ships, we calculated default design speeds from a linear model. We evaluated several possible models and found that including cruise ships in our model had a significant impact on the goodness of fit (Table 11 and Table 12). Consequently, we ran the regression without cruise ship data. For cruise ships without a design speed, we used the average design speed because there was little variation in speed from one ship to another. For our final regression, we selected main engine power, gross tonnage, and an interaction term as independent variables because this combination provided the best fit for the data (Table 11). The linear equation used to fill in missing design speeds is as follows:

$$Design\ Speed = (3.390 \times 10^{-4}) \cdot ME + (2.151 \times 10^{-5}) \cdot GT - (2.742 \times 10^{-9}) \cdot ME \cdot GT + 12.93$$

$$where\ ME = Main\ Engine\ Power\ and\ GT = Gross\ Tonnage$$

Table 11: Linear models for predicting design speed with cruise ship data excluded.

INDEPENDENT VARIABLE(S)	ADJUSTED R-SQUARED	AIC
Main Engine Power + Gross Tonnage + Interaction	0.8681	1213
Main Engine Power + Gross Tonnage	0.7883	1365
Main Engine Power	0.7654	1397
Gross Tonnage	0.3968	1703
Deadweight Tonnage	0.0922	1836

Table 12: Linear models for predicting design speed with cruise ship data included.

INDEPENDENT VARIABLE	ADJUSTED R-SQUARED	AIC
Main Engine Power	0.5228	1648
Gross Tonnage	0.3725	1738
Deadweight Tonnage	0.0874	1861

CREW COST CALCULATIONS

Table 13: Estimated regular and overtime pay rates (in USD) for crew members aboard U.S.-flagged tankers and cargo ships.

	ESTIMATED ANNUAL SALARY[1]	ESTIMATED HOURLY RATE[2]	OVERTIME PAY RESULTING FROM MANAGEMENT?	OVERTIME RATE (HOURLY X 1.5)
Master	$100,000	$48.07	No	$72.12
Chief Engineer	$100,000	$48.07	No	$72.12
Chief Officer	$70,000	$33.65	No	$50.48
1st Engineer	$80,000	$38.46	No	$57.69
2nd Engineer	$72,500	$34.86	No	$52.28
2nd Officer	$57,500	$27.64	No	$41.47
3rd Engineer	$54,000	$25.96	Yes	$38.94
3rd Officer	$48,800	$23.46	Yes	$35.19
Radio Officer	$75,000	$36.06	Yes	$54.09
All Others (non-officers)	$30,000	$14.42	Yes	$21.63

[1] Estimated annual salary is the median amount reported for deep-sea vessels in Pelletier (2007)
[2] Hourly rate based on annual salary divided into 52 weeks with 40 work hours per week

Table 14: Estimated regular and overtime pay rates (in USD) for crew members aboard national flag vessels.

	ESTIMATED MONTHLY SALARY[1]	**ESTIMATED HOURLY RATE**[2]	**OVERTIME PAY RESULTING FROM MANAGEMENT?**	**OVERTIME RATE (HOURLY X 1.25)**
Master	$1,967	$40.98	Yes	$51.23
Chief Engineer	$1,760	$36.67	Yes	$45.84
Chief Officer	$1,294	$26.96	Yes	$33.70
1st Engineer	$1,294	$26.96	Yes	$33.70
2nd Engineer	$1,077	$22.44	Yes	$28.05
2nd Officer	$1,077	$23.04	Yes	$28.80
3rd Engineer	$1,030	$21.63	Yes	$27.03
3rd Officer	$1,030	$19.55	Yes	$24.44
Radio Officer	$1,077	$22.44	Yes	$28.05
All Others (non-officers)	$542	$11.29	Yes	$14.11

[1] Estimated monthly base pay (Stopford, 2009); Radio Officer assumed to have similar pay to 2nd Engineer; other salaries averaged from salaries given in Stopford (2009) Table 6.3

[2] Based on 6 eight-hour work days per week (ILO, 2006a)

REPAIR AND MAINTENANCE COST CALCULATIONS

To estimate the additional repair and maintenance cost incurred by a vessel operating at low load, we used example annual maintenance costs from Stopford (2009) (Table 15). We assumed a 25% increase in the hourly maintenance cost for operating at 10% to 40% MCR and a 50% increase for operating below 10% MCR (Table 16).

Table 15: Example vessel repair and maintenance costs (Stopford, 2009).

AGE	ANNUAL COST OF MAINTENANCE	HOURLY COST OF MAINTENANCE
5	$196,000	$22.37
10	$338,000	$38.58
20	$393,000	$44.86

Table 16: Estimated hourly repair and maintenance cost increase for operating below 40% MCR and below 10% MCR.

AGE	HOURLY MAINTENANCE COST INCREASE AT 10-40% MCR	HOURLY MAINTENANCE COST INCREASE BELOW 10% MCR
0-5	$5.60	$11.19
6-10	$9.65	$19.29
11-20	$11.22	$22.43

APPENDIX 6. CHANGE IN COST BY SHIP TYPE AND DWT

MANAGEMENT OPTION 1:
AVERAGE CHANGE IN COST PER TRANSIT FOR MANDATORY YEAR-ROUND VESSEL SPEED REDUCTION IN WHALE ADVISORY ZONE BY SHIP TYPE AND DEADWEIGHT TONNAGE (DWT)

Vessels with a cost of $0 are not affected by the management option

Average Cost Per Transit When Operators Do Not Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			$4,942	$6,224	$4,751	$5,068	$5,691	$4,535	$4,531	$4,117				$5,284
Chemical/Products Tanker		$7,393	$0		$1,873	$4,283	$4,990	$4,693						$3,236
Container		$8,780	$8,093	$5,337	$5,663	$5,534	$2,616	$863	-$1,042	-$3,656	-$1,544	-$190		$2,416
Crude Oil Tanker								$3,429			$4,109		$331	$956
Cruise	-$15,963	-$7,245												-$14,994
General Cargo		$3,877	$4,673	$3,614	$4,706									$4,443
Other Cargo	$7,605	$8,216		$135			$1,554							$6,709
Tanker		$5,943		$664	$3,897	$0					$4,568		$0	$1,679
Vehicles Carrier	$9,339	$7,906	$5,977	$5,264										$7,619

Average Cost Per Transit When Operators Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			-$271	-$125	-$318	-$259	-$239	-$33	-$217	-$437				-$201
Chemical/Products Tanker		$175	$0		$21	-$489	-$190	$157						$18
Container		$1,069	$1,521	$4,630	$3,290	$5,497	$8,341	$7,945	$10,575	$13,818	$11,856	$8,445		$7,822
Crude Oil Tanker								$19			-$186		-$78	-$79
Cruise	$9,129	$6,555												$8,843
General Cargo		-$163	-$320	-$496	-$169									-$205
Other Cargo	$272	$1,180		-$11			-$247							$695
Tanker		$9		-$33	$63	$0					-$259		$0	-$11
Vehicles Carrier	$1,228	$1,123	$969	$2,471										$1,174

MANAGEMENT OPTION 2:
AVERAGE CHANGE IN COST PER TRANSIT FOR MANDATORY SEASONAL VESSEL SPEED REDUCTION IN WHALE ADVISORY ZONE BY SHIP TYPE AND DEADWEIGHT TONNAGE (DWT)

Vessels with a cost of $0 are not affected by the management option

Average Cost Per Transit When Operators Do Not Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			$5,180	$5,536	$5,002	$5,525	$6,235	$4,343						$5,147
Chemical/Products Tanker			$0		$3,562	$4,283		$3,254						$2,986
Container		$8,615	$8,402	$5,852	$6,133	$5,567	$2,185	$658	-$251	-$2,662	-$2,218	$1,522		$2,505
Crude Oil Tanker													$0	$0
Cruise	-$7,842	-$7,245												-$7,767
General Cargo		$6,546			$4,814									$5,247
Other Cargo		$4,836		$135										$3,269
Tanker		$7,541		$0	$5,794	$0						$0		$2,610
Vehicles Carrier	$9,682	$7,509	$3,801	$5,264										$6,968

Average Cost Per Transit When Operators Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			-$261	-$254	-$276	-$30	-$76	$38						-$146
Chemical/Products Tanker			$0		$212	-$489		$340						$102
Container		$1,357	$1,303	$5,824	$3,348	$5,289	$8,497	$9,608	$9,317	$13,052	$12,993	$5,651		$7,986
Crude Oil Tanker													$0	$0
Cruise	$8,149	$6,555												$7,950
General Cargo		-$155			-$264									-$237
Other Cargo		$285		-$11										$186
Tanker		$48		$0	$94	$0						$0		$24
Vehicles Carrier	$1,863	$981	$144	$2,471										$1,103

MANAGEMENT OPTION 3:
AVERAGE CHANGE IN COST PER TRANSIT FOR NARROWING THE TRAFFIC SEPARATION SCHEME WITHIN THE CHANNEL BY SHIP TYPE AND DEADWEIGHT TONNAGE (DWT)

Vessels with a cost of $0 are not affected by the management option

Average Cost Per Transit When Operators Do Not Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			-$12	-$11	-$12	-$12	-$12	-$12	-$12	-$12				-$12
Chemical/Products Tanker		-$10	$0		-$4	-$12	-$12	-$13						-$7
Container		-$10	-$10	-$10	-$12	-$12	-$13	-$11	-$15	-$16	-$16	-$16		-$13
Crude Oil Tanker								-$13			-$12		-$1	-$4
Cruise	-$22	-$19												-$22
General Cargo		-$8	-$11	-$13	-$12									-$11
Other Cargo	-$10	-$8		-$13			-$14							-$9
Tanker		-$11		-$1	-$7	$0					-$12		$0	-$3
Vehicles Carrier	-$10	-$9	-$8	-$13										-$10

MANAGEMENT OPTION 4:
AVERAGE CHANGE IN COST PER TRANSIT FOR SHIFTING THE TRAFFIC SEPARATION SCHEME TO THE SOUTH BY SHIP TYPE AND DEADWEIGHT TONNAGE (DWT)

Vessels with a cost of $0 are not affected by the management option

Average Cost Per Transit When Operators Do Not Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			$4,820	$4,630	$4,691	$4,703	$5,012	$4,974	$4,968	$5,147				$4,792
Chemical/Products Tanker		$4,171	$0		$1,435	$4,936	$4,902	$5,300						$3,017
Container		$4,184	$4,053	$3,967	$4,838	$5,130	$5,363	$4,742	$6,235	$6,790	$6,530	$6,590		$5,364
Crude Oil Tanker								$5,355			$5,166		$610	$1,455
Cruise	$8,949	$7,739												$8,815
General Cargo		$3,403	$4,644	$5,204	$4,847									$4,505
Other Cargo	$3,995	$3,122		$5,303			$5,962							$3,817
Tanker		$4,330		$585	$3,052	$0					$5,024		$0	$1,340
Vehicles Carrier	$4,094	$3,908	$3,548	$5,420										$3,946

Average Cost Per Transit When Operators Make Up Time

Ship Type	DWT (000s)													Average
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	All Sizes
Bulk Carrier			$1,569	$2,224	$1,926	$2,398	$2,488	$3,110	$2,821	$3,255				$2,383
Chemical/Products Tanker		$2,114	$0		$845	$2,634	$3,087	$3,821						$1,935
Container		$2,480	$2,683	$3,730	$3,570	$4,932	$6,016	$5,653	$7,676	$8,932	$8,095	$7,595		$5,841
Crude Oil Tanker								$4,287			$3,697		$380	$1,037
Cruise	$13,628	$10,331												$13,262
General Cargo		$1,249	$1,631	$3,536	$2,425									$2,120
Other Cargo	$1,282	$1,597		$996			$2,009							$1,494
Tanker		$1,447		$319	$1,893	$0					$3,279		$0	$641
Vehicles Carrier	$2,409	$2,237	$2,393	$4,869										$2,389

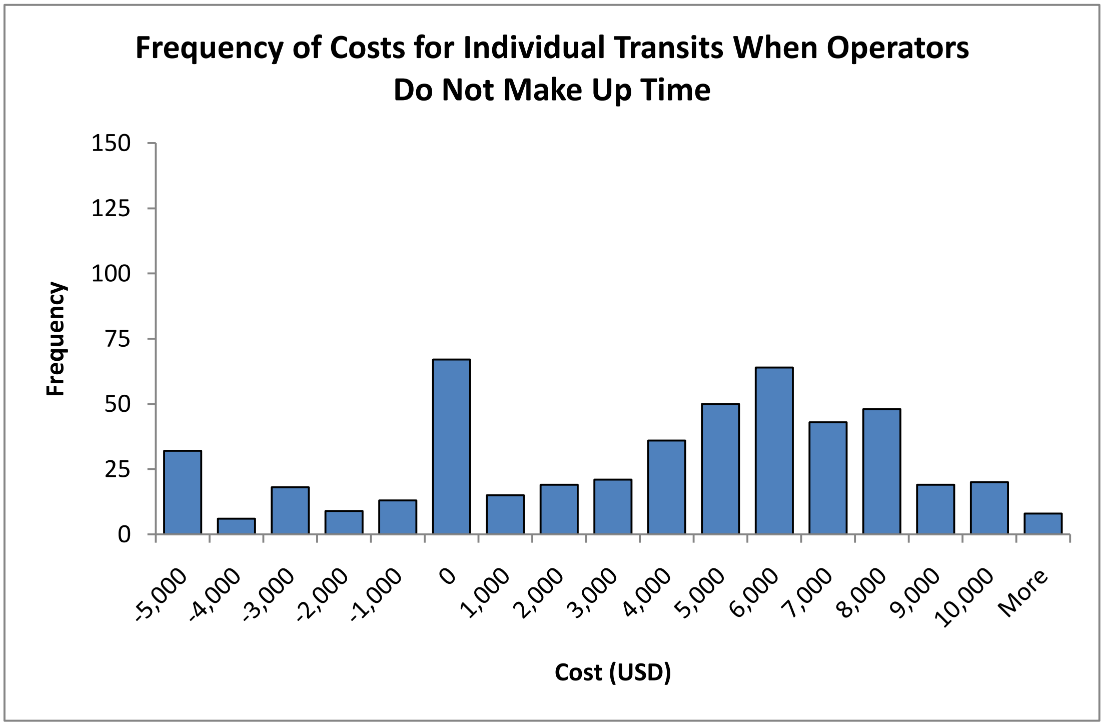
APPENDIX 7. HISTOGRAMS OF COSTS FOR INDIVIDUAL TRANSITS UNDER EACH MANAGEMENT SCENARIO

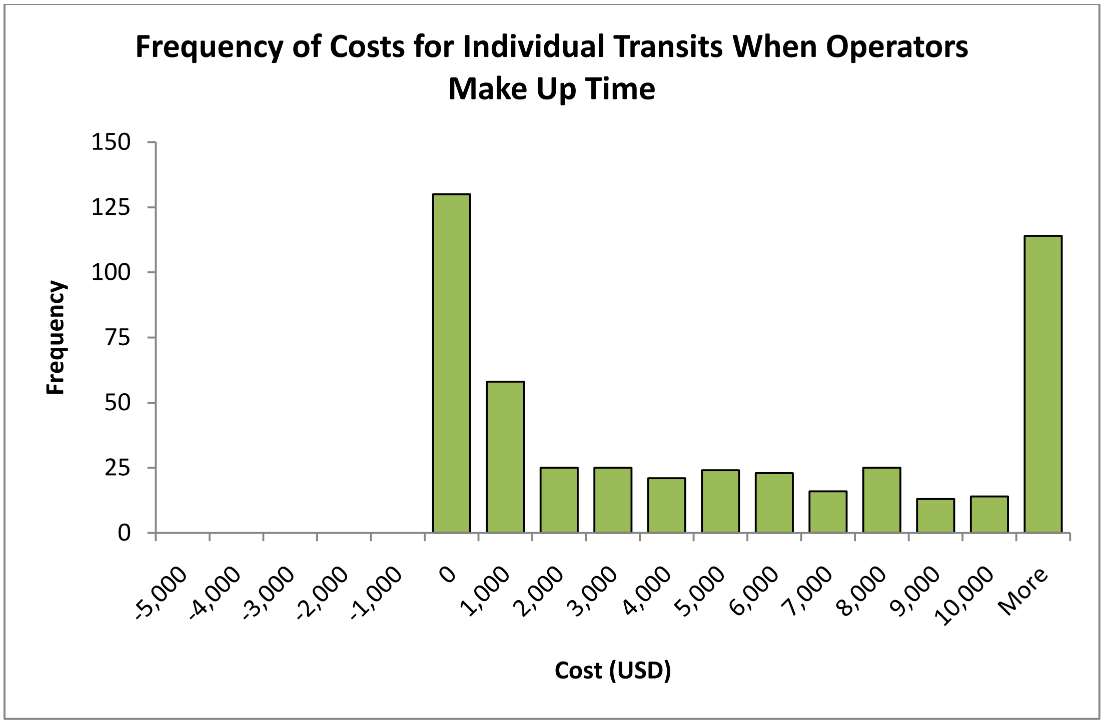
The following histograms show the cost of each management option for individual transits when operators:

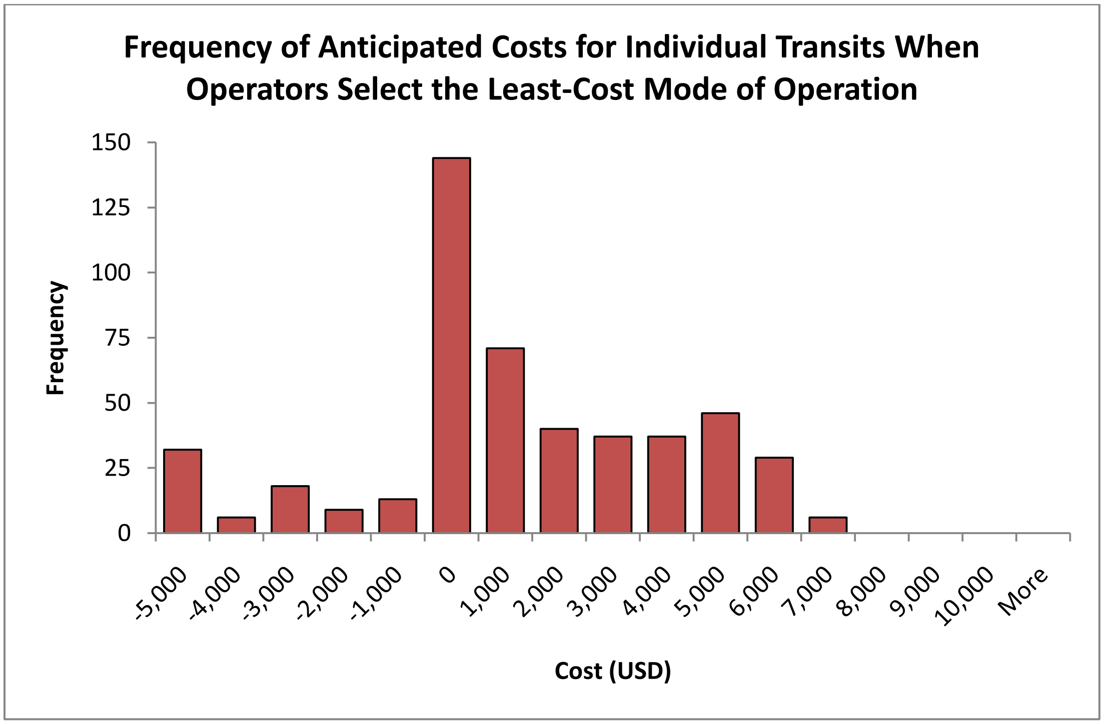
(1) Do not make up lost time resulting from management options;
(2) Make up all lost time, and;
(3) Choose the least-cost option.

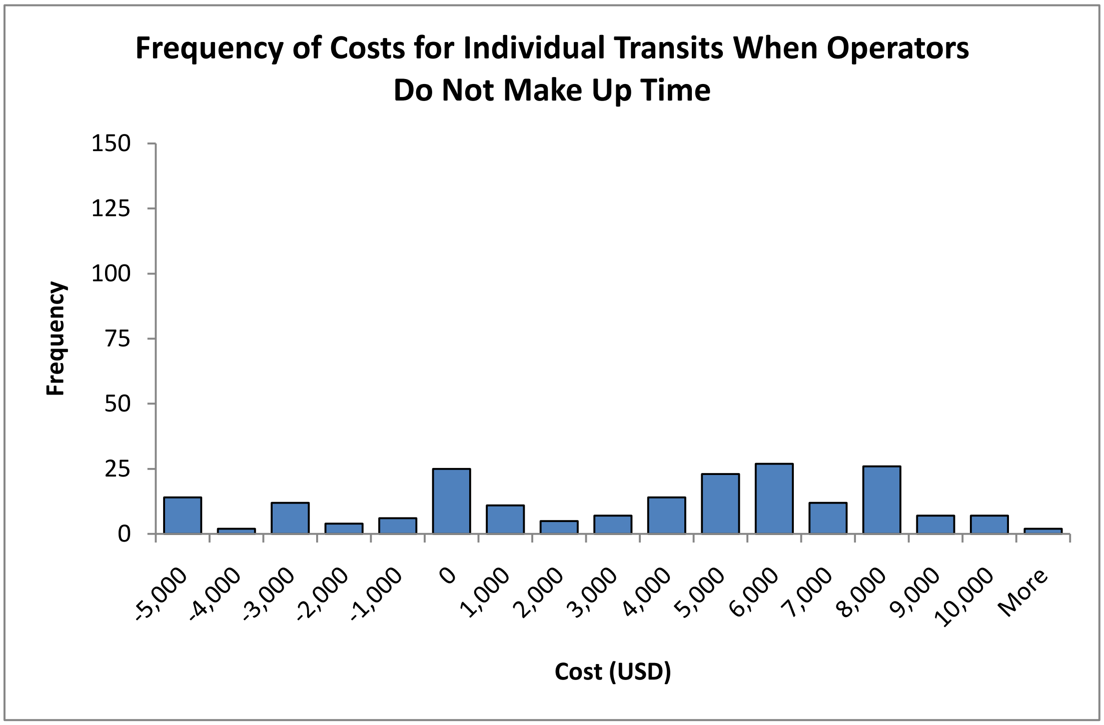
For the speed reduction (Management Options 1 and 2) and shifting the TSS to the south (Management Option 4), assuming operators choose the least-cost option results in a much lower cost to the industry than assuming all vessels behave in the same way – either making up time or not making up time. For narrowing the TSS (Management Option 3), there is no delay resulting from management, so making up lost time is not applicable.

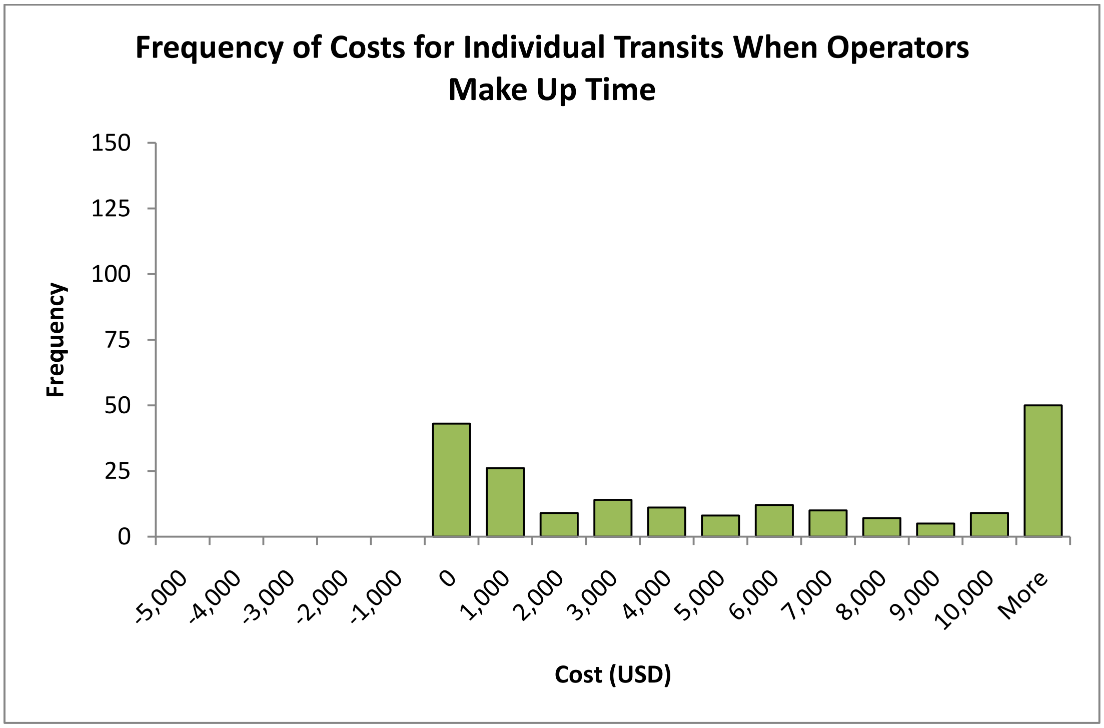
MANAGEMENT OPTION 1: YEAR-ROUND MANDATORY SPEED REDUCTION

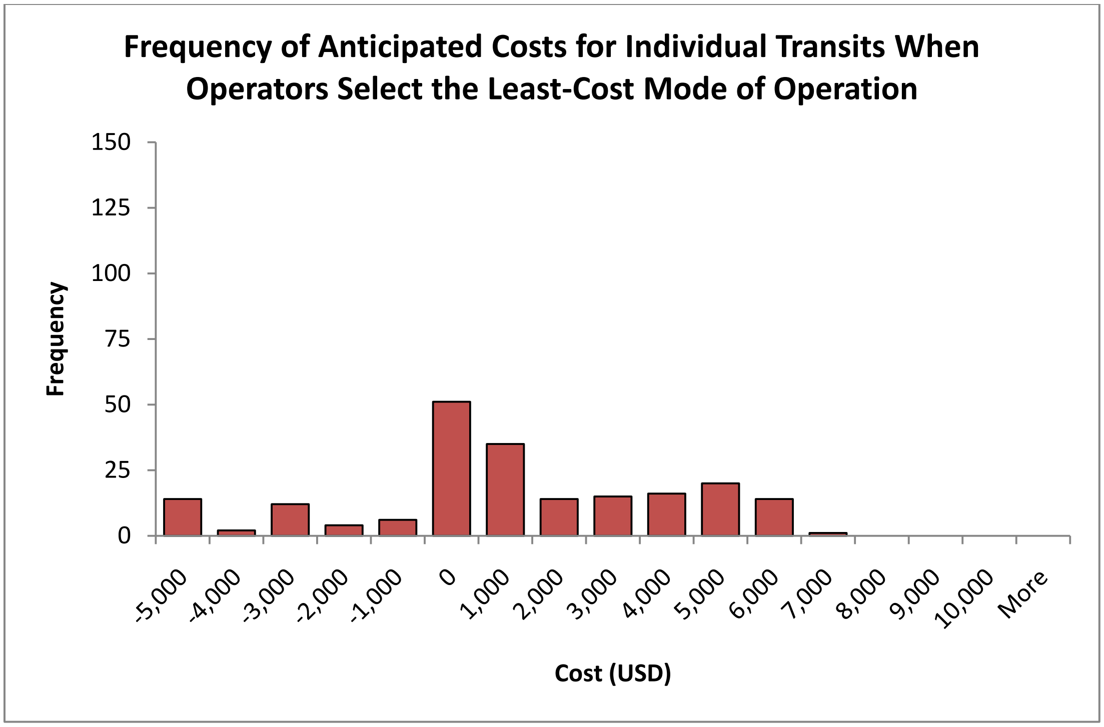



Frequency of Costs for Individual Transits When Operators Make Up Time
Frequency
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)


Frequency of Anticipated Costs for Individual Transits When Operators Select the Least-Cost Mode of Operation
Frequency
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)

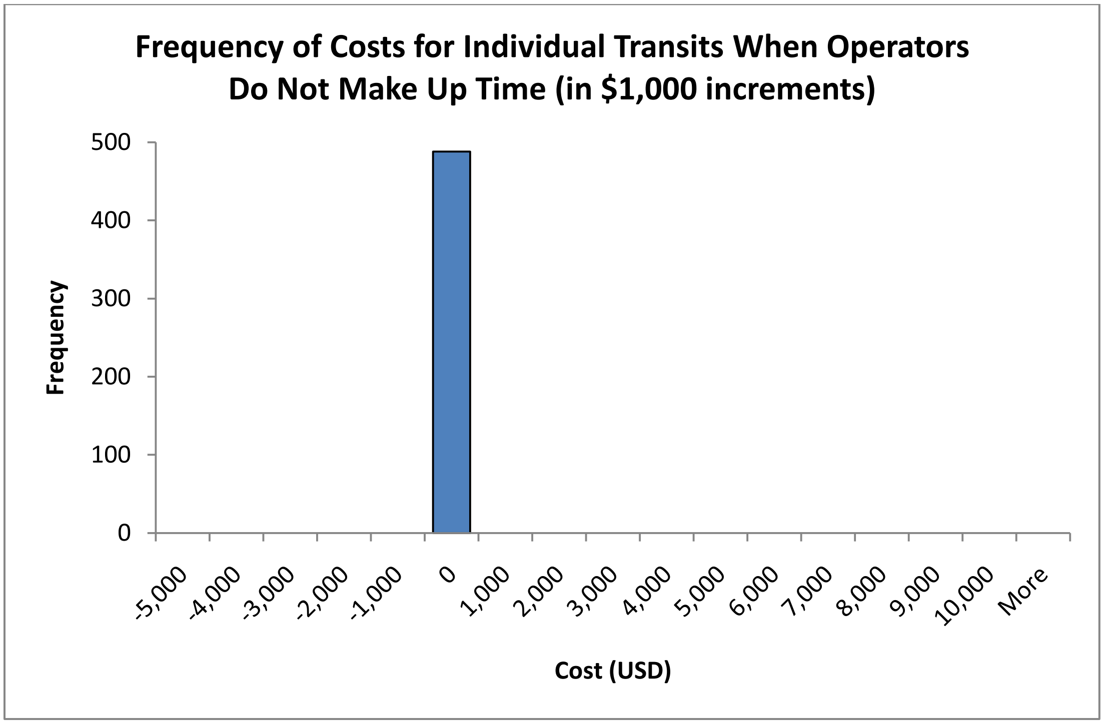

Frequency of Costs for Individual Transits When Operators Do Not Make Up Time
Frequency
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)

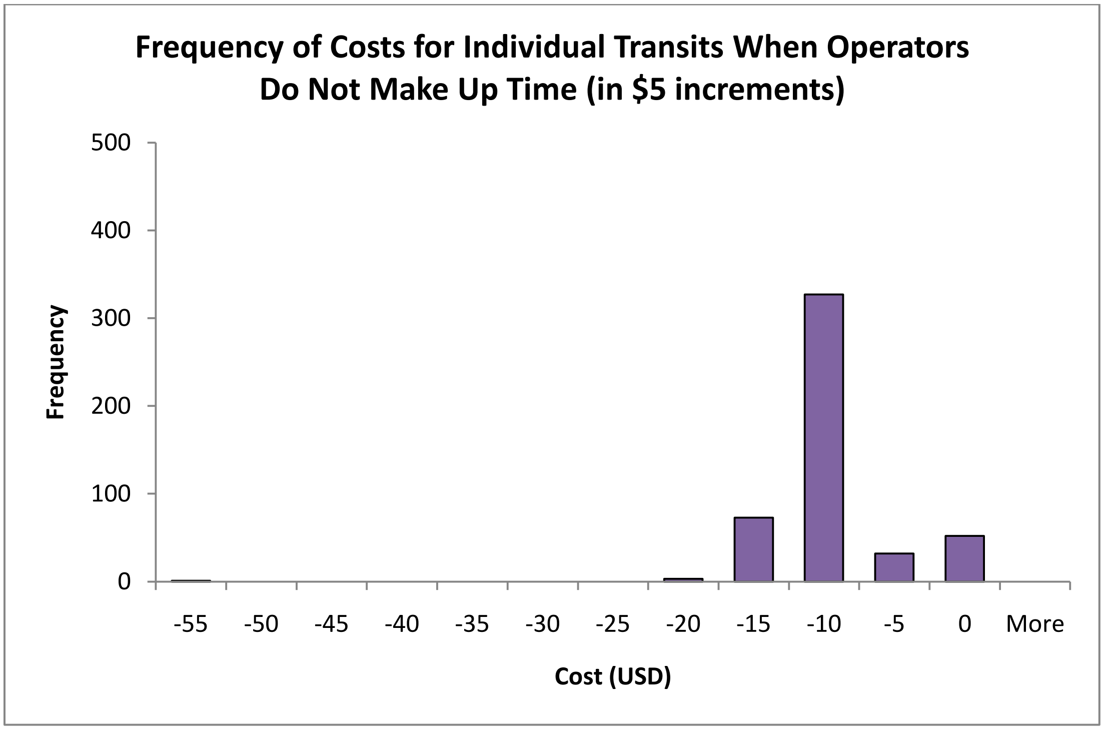

Frequency of Costs for Individual Transits When Operators Make Up Time
Frequency
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)



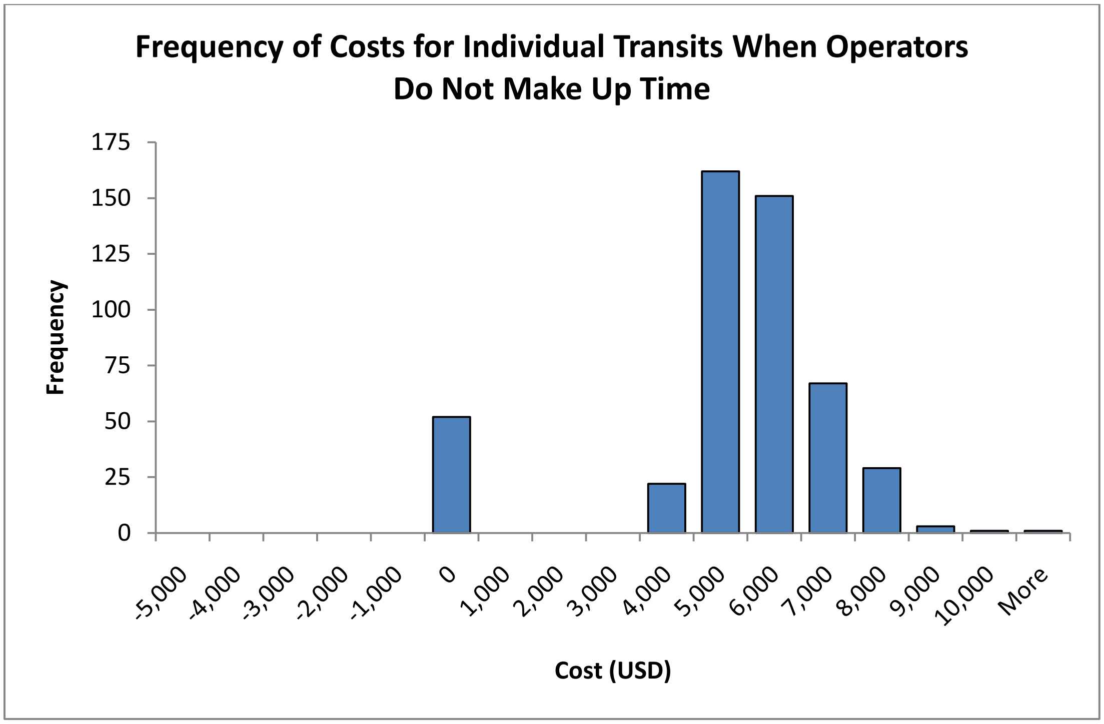
Frequency of Anticipated Costs for Individual Transits When Operators Select the Least-Cost Mode of Operation
Frequency
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)

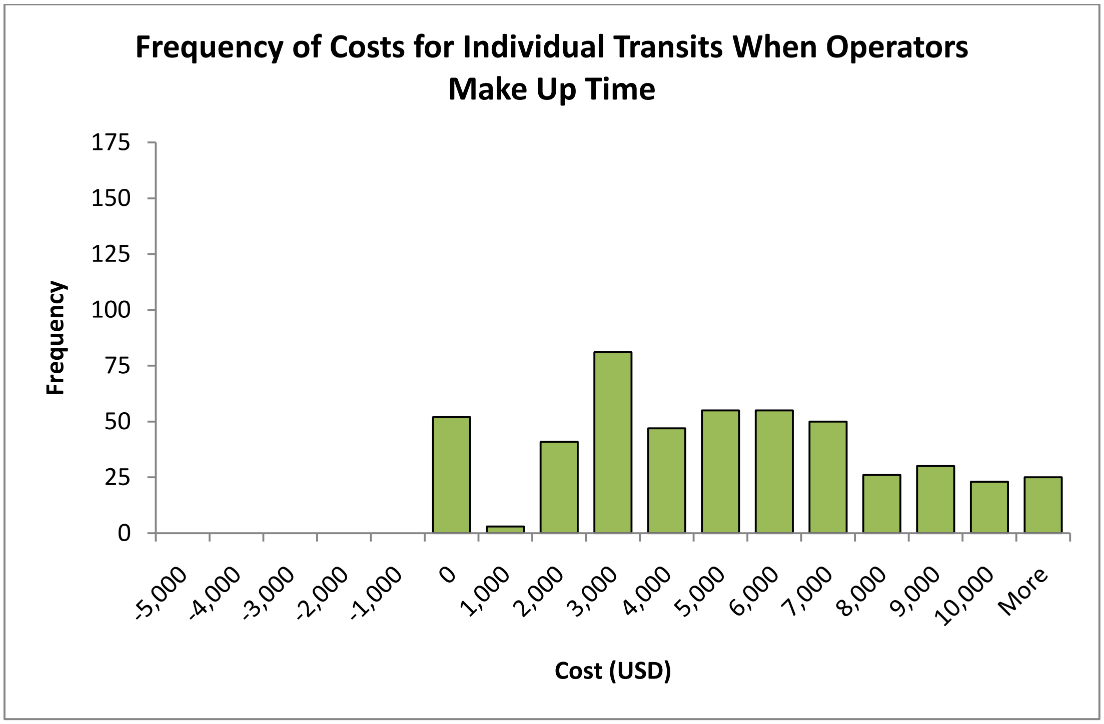
MANAGEMENT OPTION 3: NARROW THE TRAFFIC SEPARATION SCHEME WITHIN THE CHANNEL

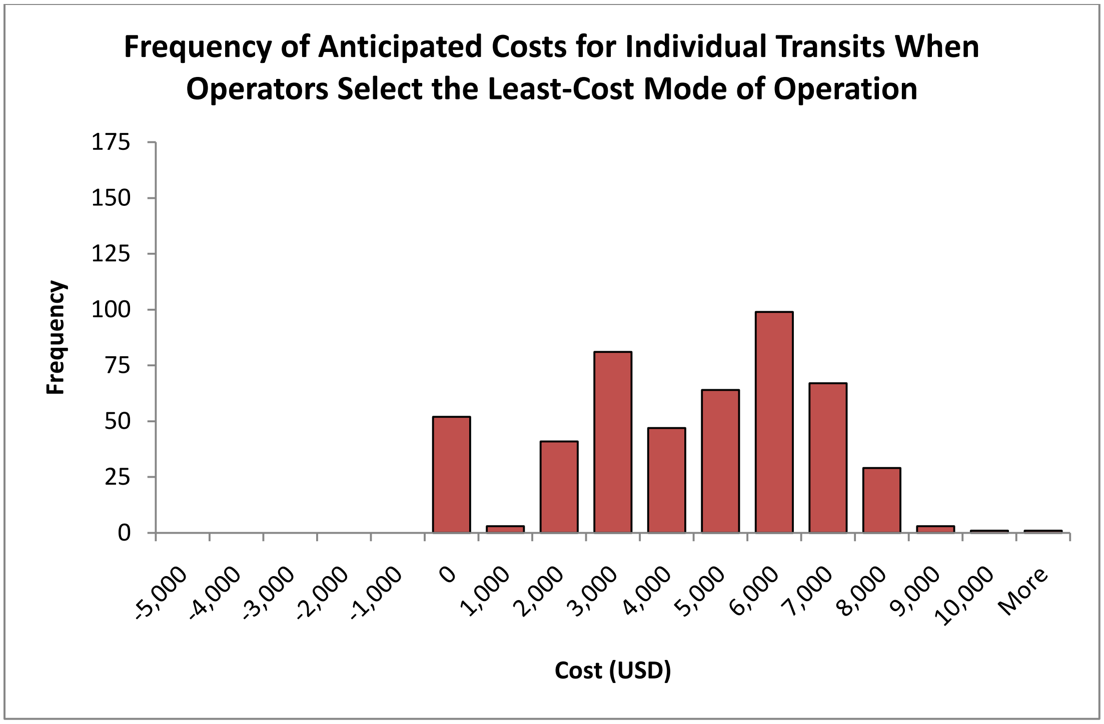

Frequency of Costs for Individual Transits When Operators Do Not Make Up Time (in $1,000 increments)


Frequency of Costs for Individual Transits When Operators Do Not Make Up Time (in $5 increments)

MANAGEMENT OPTION 4: SHIFT THE TRAFFIC SEPARATION SCHEME TO THE SOUTH OF THE NORTHERN CHANNEL ISLANDS






Frequency of Anticipated Costs for Individual Transits When Operators Select the Least-Cost Mode of Operation
Frequency
175
150
125
100
75
50
25
0
-5,000
-4,000
-3,000
-2,000
-1,000
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
More
Cost (USD)

APPENDIX 8. COMPARISON OF MANDATORY SPEED REDUCTION OPTIONS

Though our analysis focused on a year-round mandatory speed reduction and a half-year speed reduction (from April through September), we also used our models to calculate the change in relative risk of a lethal strike and cost to the shipping industry under a 3-quarter mandatory speed reduction scenario from April through December. The resulting reduction in risk under this management option achieves almost the same reduction in risk as a year-round mandatory speed reduction (Figure 23). However, the cost resulting from this three-quarter speed reduction (Figure 24) was high enough such that the percent reduction in risk per million dollars (~28% per million dollars) was lower than for the half-year speed reduction (~30% per million dollars). Although we consequently focused our analysis on the half-year speed reduction, including additional months for the speed reduction may further reduce the risk of a lethal strike if whale aggregations are high during quarter 4.

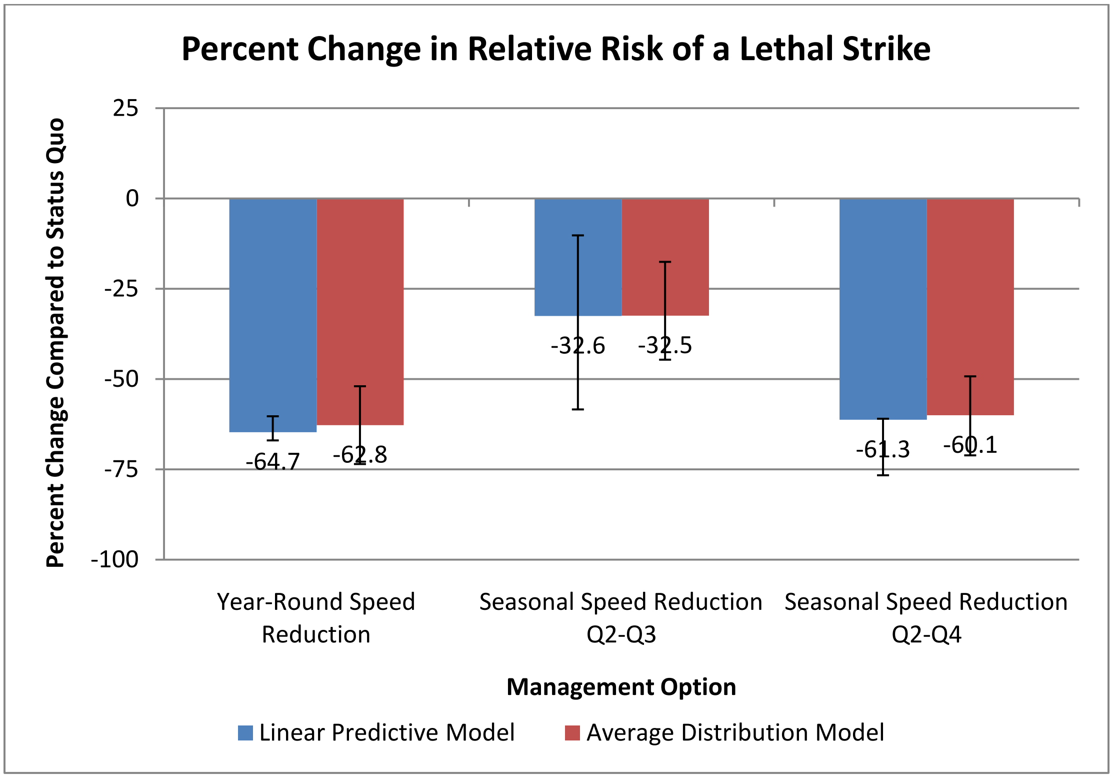


Figure 23: Percent change in relative risk of a lethal strike under a mandatory speed reduction for one year, for a half-year speed reduction (quarters 2 and 3), and for a three-quarter speed reduction (quarters 2 through 4).

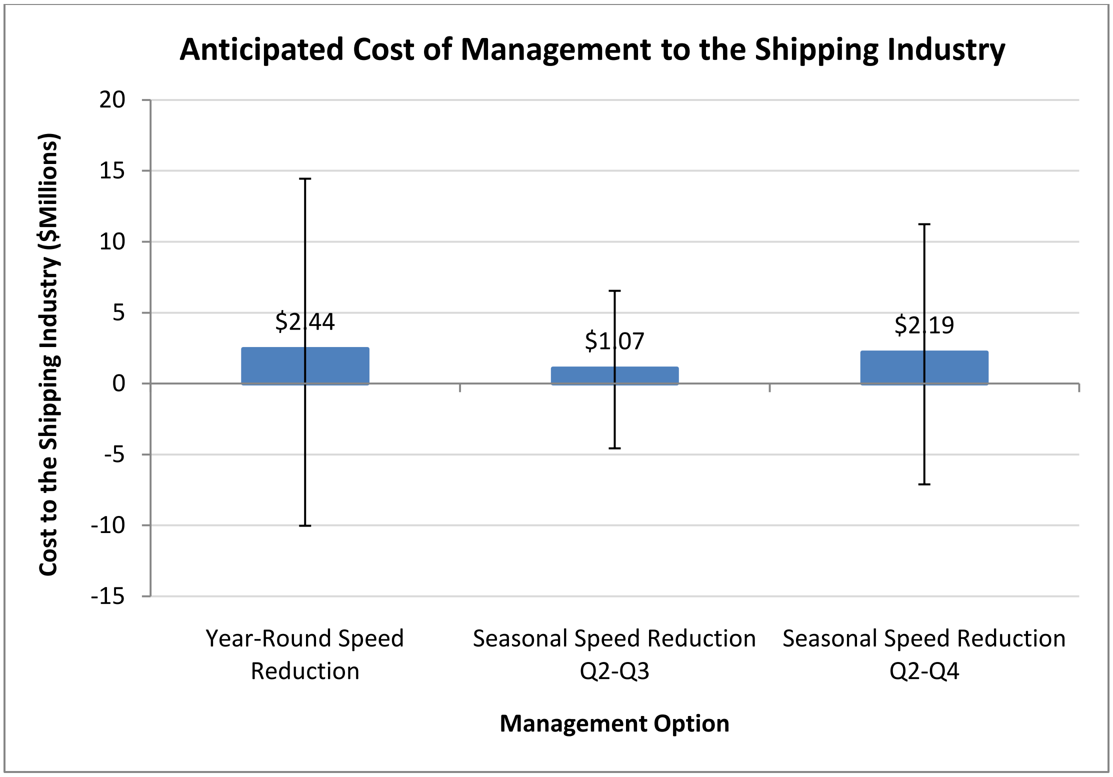


Figure 24: Total expected change in cost to the shipping industry under a mandatory speed reduction for one year, for a half-year speed reduction (quarters 2 and 3), and for a three-quarter speed reduction (quarters 2 through 4).