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An economic analysis of shipping costs related to potential changes in vessel operating procedures to manage the co-occurrence of maritime vessel traffic and whales in the Channel Islands region

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ABSTRACT

The Channel Islands region off the coast of southern California provides habitat to endangered whale populations and is home to the nation's two busiest ports: Long Beach and Los Angeles. The increase in number, size, and speed of ocean going vessels raises the potential for lethal vessel strikes on whales, and potentially the recovery of whale populations. This vessel strike issue has prompted several suggested changes in vessel operations, including vessel re-routing and speed reductions, to reduce the occurrence and lethality of vessel strikes. However, these changes may affect vessel transit times and costs to the shipping industry. This study characterizes the 2015 maritime shipping industry within the Channel Islands region and estimates the shipping costs associated with five alternative vessel operating procedures. Results suggest that shipping costs will decrease with re-routing vessels (1.6%–3.4%), but increase with vessel speed reductions (1.3%–2.0%), and that these changes will vary significantly across vessel categories. These differences can be explained by predicted changes in transit time and fuel consumption. The results of this study will not only provide local and federal management with additional information on the possible effects of each vessel operating procedure, but also provide a well-detailed framework for conducting future analyses.

1. Introduction

The Channel Islands region of southern California (Fig. 1) provides habitat to populations of blue, fin, humpback, sei, and gray whales. Four of these species are listed as endangered at the federal and state levels, and all are protected under the Marine Mammal Protection Act of 1972 and National Marine Sanctuaries Act of 1972. This region is also home to the nation's two busiest ports: Los Angeles and Long Beach (LA/LB). In 2017, the LA/LB Port Complex represented 9.6% of the vessel tonnage, and 24.8% of the value of imported and exported goods moving through United States ports. According to the Bureau of Economic Analysis (U.S. Department of Commerce, 2018), the nominal cargo value at the LA/LB District increased from $225 billion in 2003 to $398 billion in 2017 (77% increase), and cargo weight increased from 94 to 133 million metric tons (42% increase).

As shown in Fig. 1, there is currently one designated traffic separation scheme (TSS) for this busy shipping region. However, vessels also navigate on the south-side of the Channel Islands, outside the internationally designated area-to-be-avoided (ATBA), when there are not live fire exercises conducted by the US military in the Pacific Missile Test Range (Sea Range at Point Magu). Additionally, there are two voluntary 12-knot vessel speed reduction zones (VSRs) within 20 and 40 nautical miles of the LA/LB Port Complex. The array of formal and informal routing options for vessels means that whales and vessels likely co-occur throughout this region, which may lead to fatal vessel strikes on whales.

Vessel strikes on whales are rarely witnessed, so it is difficult to determine mortality rates. However, the US Marine Mammal Commission inventories stranded and dead whales detected in the US and, in the fall of 2007, four blue whales were found dead in the Channel Islands Region (Marine Mammal Commission, 2008). The cause of death was attributed to vessel strikes and an "unusual mortality event" (UME) was declared (Marine Mammal Commission, 2008).

Due to the difficulty related to accurately inventorying vessel strikes on whales, modeled mortality estimates are generally higher than estimates derived from stranding records (Rockwood et al., 2017; Cassoff et al., 2011). Based on these models, blue whales are at substantial risk of vessel strikes in the Channel Islands Region (Rockwood et al., 2017). Because whales are long-lived species with low reproductive rates, additive mortality from vessel strikes could be detrimental to

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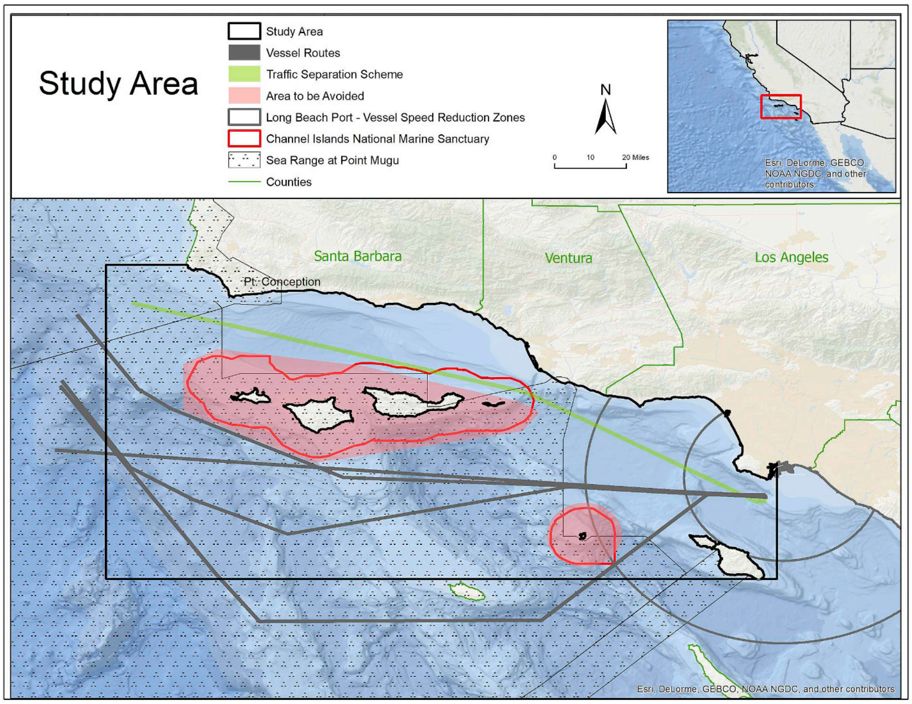

Fig. 1. Study area.

populations.

The vessel strike issue and management response extends beyond the Channel Islands Region to the rest of the US West Coast (Monnahan et al., 2014), the US East Coast (Laist et al., 2014), the Gulf of Mexico (Soldevilla et al., 2017), and even worldwide (Cates et al., 2016; McWhinnie et al., 2018; Nanayakkara and Herath, 2017; Van Waerebeek and Leaper, 2008). As ocean going vessels have become more numerous, larger, and faster, the potential for lethal vessel strikes on whales has increased (Laist et al., 2001), putting individual whales at greater risk and possibly hindering the recovery of endangered whale populations (Monnahan et al., 2014; Moore et al., 2004; Knowlton and Kraus, 2001).

Vessel re-routing is used to reduce the probability of a strike occurring (Vanderlaan et al., 2009; van der Hoop et al., 2014). Vessel re-routing can be implemented by creating or modifying a TSS or by establishing ATBAs (see Silber et al. (2012) for in-depth review). Sometimes alone, or in combination with re-routing, VSRs are used to reduce the likelihood of lethal strikes, should collisions occur (Freedman et al., 2017; Laist et al., 2001, 2014; Conn and Silber, 2013; Gende et al., 2011; Wiley et al., 2011; Wang et al., 2007; Vanderlaan and Taggart, 2006). To protect North Atlantic Right Whales on the US East Coast, the 2008 North Atlantic Right Whale Ship Strike Reduction Rule (2008 Rule) was implemented. As a part of this rule, VSRs exist in the form of mandatory Seasonal Management Areas and voluntary Dynamic Management Areas (Speed restrictions to protect North Atlantic Right Whales, 2014). Vessels are required to travel at or below 10 knots in designated areas because of high whale densities. These mandatory actions likely decreased the probability of right whale mortality from vessel strikes (Lagueux et al., 2011) and significantly reduced the number of right whales killed by vessels (Laist et al., 2014; van der Hoop et al., 2014).

Vessel re-routing and VSRs could affect costs to the shipping industry because vessel transit times are increased, causing delayed or missed port calls (Nathan Associates, Inc., 2012; Kite-Powell and Hoagland, 2002) or avoidance of certain ports altogether (Kite-Powell, 2005). However, the economic impacts to the shipping industry along the US East Coast since implementation of the 2008 Rule have been minimal when compared with the roughly $439.3 billion (2015$) value of the US East Coast maritime trade. Nathan Associates, Inc. (2012) estimated the direct impact to the US East Coast shipping industry to be $26.2 million (2015$), and Silber and Bettridge (2012) estimated the total economic impacts to range from $57.5 million (2015$) and $82.4 million (2015$).

In 2014, the Channel Islands National Marine Sanctuary (CINMS) Advisory Council formed a Marine Shipping Working Group to address and recommend solutions to reduce vessel strikes on whales, reduce air pollution, and reduce conflicts with other ocean users in the Channel Islands region. Membership of the working group included: US Department of Defense; US Coast Guard (USCG); Channel Islands National Park; National Marine Fisheries Service (NMFS); Marine Exchange of Southern California; the Santa Barbara and Ventura Counties Air Pollution Control Districts; the shipping industry; and the tourism, research, and conservation communities. In 2016, the working group proposed a spatial management approach (Channel Islands National Marine Sanctuary Advisory Council Marine Shipping Working Group, 2016) (Fig. 2) with the following four components: (1) a TSS extension; (2) a new Western route (along the south side of the Channel Islands); (3) an ATBA expansion; and (4) a seasonal 12-knot VSR from approximately April 1st to November 15th within the study area.

From this spatial management approach, five potential vessel operating procedures were analyzed:

1. A seasonal 12-knot VSR with vessel re-routing (12RR)
2. A seasonal 10-knot VSR with vessel re-routing (10RR)
3. A seasonal 12-knot VSR (12NR)
4. A seasonal 10-knot VSR (10NR)
5. Vessel re-routing (RR)

This study estimates the change in shipping costs associated with the five vessel operating procedures designed to reduce vessel strikes within the Channel Islands region. Specifically, this study aims to characterize the 2015 shipping industry within the study area and to estimate the change in costs to the shipping industry from changes in operating procedures. In this analysis, shipping costs are defined as inventory carrying costs (ICCs) and vessel transportation costs (VTCs), both of which vary by vessel category and size, and sum to form total

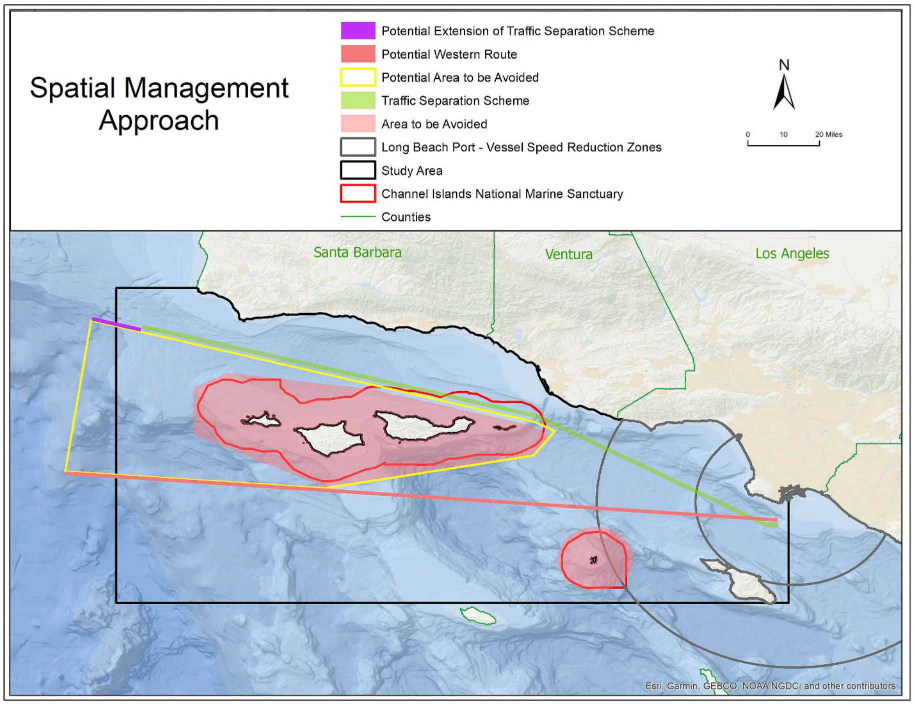

Fig. 2. Spatial management approach.

costs (TCs).

2. Data

There are two types of datasets used in this analysis, spatial and economic, which were linked by data from the Authoritative Vessel Identification Service (AVIS).

2.1. Automatic Identification System (AIS)

Automatic Identification System (AIS) data on vessel dimension, direction of travel, location, and speed were obtained from the USCG. AIS is an automatic tracking system for ocean going vessels that relays each vessel's geographic position to maritime authorities and other vessels. AIS allows regulators to track compliance with maritime regulations, assist with search and rescue endeavors, monitor fishing fleets, and oversee accident investigation. The International Maritime Organization's International Convention for the Safety of Life at Sea requires AIS transmitters for vessels 300 gross tons and greater on international voyages, cargo vessels of 500 gross tons and greater on domestic voyages, and all passenger vessels regardless of size (International Maritime Organization, 1974).

Because speed, heading, and position of a vessel are reported every 2–10 s, linear vessel track lines were generated by joining successive AIS position report points corresponding to vessel Maritime Mobile Service Identity (MMSI) numbers following Jensen et al. (2015).

2.2. USA Trade® online

Cargo value data was obtained from USA Trade® Online, the official source of United States import and export statistics. The database provides current and cumulative data on more than 9,000 export commodities and 17,000 import commodities by country.

The U.S. International Trade Commission's International Harmonized System (HS) Code classifies traded products into approximately 140 export and 140 import end-use categories and makes it possible to examine goods according to their principal uses.

Five vessel categories were evaluated in this study: Container, Tanker, Dry Bulk, Ro-Ro (wheeled cargo driven on and off the ship), and Ro-Ro/Combo. As Tanker, Dry Bulk, and Ro-Ro vessels are not specifically identified in the USA Trade® Online database, more granular analysis of commodities that tend to be transported in certain vessel categories can be extracted from the data. Additionally, the three to six-digit HS Code defined by the USA Trade® Online database makes it possible to infer the value of cargo transported by Tanker and Ro-Ro vessels. The remainder of traffic combines Dry Bulk with general vessel traffic.

Cargo values for each vessel category were calculated based on the average weight of trafficked goods transported within the LA/LB Port Complex from 2008 to 2014. This allowed for an evaluation of recessionary and recovery economic periods.

2.3. National navigation operation and maintenance performance evaluation and assessment system (NNOMPEAS)

Vessel fuel consumption and minimum engineering viability speeds (the slowest speeds at which vessels can operate without vessel operations becoming unstable) for vessel transits were obtained from NNOMPEAS. NNOMPEAS is a United States Army Corps of Engineers (USACE) tool for estimating marine transportation costs and performing economic analysis on USACE waterway projects. It is the standard source for all marine transportation cost data, and forms the basis for evaluating the benefits of proposed USACE projects.

NNOMPEAS data does not represent actual expenses to the firms for the shipment of goods because marine transportation companies do not share proprietary information such as profit margin, market-pricing decisions, and competitive pricing strategies. Rather, NNOMPEAS is a construct from a large number of variables, such as vessel length, breadth, draft, engine horsepower, crew, distance traveled, cost of fuel, engine fuel efficiency, and diameter of the propeller, all of which affect vessel operating costs. It produces the best available compilation of shipping costs and gives USACE a robust approach for comparing vessel costs across multiple years without having to consider the competitive elements of cost.

In addition to costs, NNOMPEAS provides estimates of vessel cargo carrying capacity and point estimates of fuel consumption by vessel category and size class based on variables such as fuel type, engine type and size, immersed draft, and vessel speed. Non-linear minimum and maximum fuel consumption functions were estimated to interpolate between fuel consumption point estimates. Maximum estimated cargo carrying capacity (measured in metric tonnes (mt)) and average fuel consumption were used in this analysis.

2.4. Authoritative Vessel Identification Service (AVIS)

The spatial and economic datasets were linked by data from AVIS, which provides information on vessel cargo and vessel dimensions for each vessel in the study area.

USCG developed AVIS to account for identification and measurement errors in AIS data transmission because multiple vessels using the same MMSI in the same local region can cause safety issues and make it difficult to track the history of a vessel. AVIS enables the AIS data to be linked with economic data because it provides vessel type, cargo type, and vessel dimensions, such as length, beam, draft, and dead weight tonnage, by MMSI.

To prepare the AVIS vessel data, vessels identified as "non-vessels" or "scrapped" (less than 4% of the vessel population) were removed, and the remaining vessels were parsed into five different vessel categories (Container, Tanker, Dry Bulk, Ro-Ro, and Ro-Ro/Combo) based on reported vessel and cargo type and on expert opinion. Class sizes were then defined within each vessel category to simplify the process of assigning vessel cost and revenue values during the analysis. These classifications were performed using k-means cluster analyses based on estimated vessel gross tonnage. Three size-class clusters were defined for Container, Tanker, Dry Bulk, and Ro-Ro vessels, and one size-class cluster was defined for Ro-Ro/Combo vessels due to the relative infrequency of Ro-Ro/Combo vessel movements in the study area.

2.5. Ship and Bunker

Vessel fuel prices were obtained from Ship and Bunker, the leading independent source of daily and historical bunker price indications. Bunker prices were obtained for Singapore from March 2012 to March 2016 and averaged by month. Marine gas oil (MGO) at or below 0.1% sulfur was selected as it is the least costly fuel that meets fuel sulfur content regulations in the region, and Singapore was selected because it is the largest provider of shipping fuel.

Table 1 summarizes the key variables by vessel category and size class. Tanker and Dry Bulk vessels have the greatest cargo carrying capacities and the slowest minimum engineering viability speeds. Ro-Ro and Ro-Ro/Combo vessels carry cargo with the greatest value and, along with Container vessels, have the fastest minimum engineering viability speeds.

3. Methods

For this evaluation, the shipping cost analysis estimates the potential change in ICCs and VTCs associated with the proposed changes in operating procedures within the study area. According to the Council of Supply Chain Management Professionals (CSCMP), in 2016, ICCs and VTCs combined accounted for roughly 94% of total logistics costs (CSCMP, 2017).

While there are additional ways speed and routing changes may affect the shipping industry, it is probable that shippers would eventually adjust to any predictable scheduling and operating procedure changes; therefore, the effects would not be long-term. Consequently, these changes in speed and routes for vessel operators were investigated under an "all else equal" set of conditions.

ICCs and VTCs were calculated for each vessel transit using the following equations:

$$ICC = (cargo\ value\ per\ tonne) * (number\ of\ tonnes\ carried) * (transit\ hours) * (hourly\ opportunity\ cost\ of\ capital)$$

$$VTC = (hourly\ fuel\ consumption) * (price\ per\ ton\ of\ fuel) * (transit\ hours)$$

Cargo values, the number of tonnes carried, fuel consumption, and fuel price were all derived from the data. The hourly opportunity cost of capital was calculated using an annual commercial paper rate of 4%. Finally, baseline transit hours were estimated using the AIS data, and predicted transit hours for each vessel operating procedure were estimated using the following assumptions regarding transit route (Table 2) and speed (Table 3).

Under proposed rerouting procedures, a vessel is predicted to travel along the TSS if it: 1) did so in 2015 or 2) traveled above 34°N when entering the study area. Otherwise, a vessel is predicted to travel along the Western route. Using these assumptions, transit distances are predicted to significantly decrease for each vessel category and route. This decrease is primarily due to the removal of "fanning" along the Northern route and the consolidation to a single Western route. However, it is likely that this decrease in transit distance will be offset by an increase in transit distance outside of the study area as vessels adjust their routes.

Under proposed operating procedures with a VSR, a vessel is predicted to travel at its 2015 speed if that speed was less than or equal to the target VSR speed. If a vessel's 2015 speed was faster than the target VSR speed, then it is predicted to travel at either its minimum engineering viability speed, or the target VSR speed, whichever is greater. This means that some vessels are predicted to travel faster than the target VSR speed, which relaxes the common, yet often unrealistic, assumption of 100% compliance with vessel regulations (Nathan Associates, Inc., 2012; and Silber and Bettridge, 2012).

Table 1
Summary statistics of estimated cargo carrying capacity (mt), mean import and export values (2015$/mt), and minimum engineering viability speeds (knots) by vessel category and size class.

Vessel Category	Size Class	Vessel Count	Estimated Cargo Carrying Capacity	Mean Import Value	Mean Export Value	Minimum Engineering Viability Speed
Container	Small	59	35,558	6,216	2,308	12.6
	Medium	150	58,323			13.5
	Large	119	98,584			14.0
Tanker	Small	17	27,090	690	723	7.7
	Medium	89	65,129			8.1
	Large	17	153,509			8.2
Dry Bulk	Small	40	22,952	4,067	928	7.6
	Medium	24	34,171			7.8
	Large	29	121,153			7.4
Ro-Ro	Small	4	14,453	16,435	11,122	10.4
	Medium	44	29,113			10.6
	Large	79	41,294			10.5
Ro-Ro/Combo	Medium	15	67,754	16,435	11,122	13.5

Table 2
Baseline and predicted transit distances (nm) by vessel category and route.

Vessel Category	Route	Statistic	2015 Transit Distance	Predicted Transit Distance
Container	North	Mean	105.8	104.1
		SE	0.1	0.0
		Range	102.2–132.9	103.8–104.3
	West	Mean	101.9	97.7
		SE	0.4	0.0
		Range	98.0–185.6	97.6–97.7
Tanker	North	Mean	105.8	104.1
		SE	0.4	0.0
		Range	98.1–134.1	103.8–104.3
	West	Mean	108.5	97.7
		SE	1.5	0.0
		Range	98.0–258.2	97.6–97.7
Dry Bulk	North	Mean	105.0	104.1
		SE	0.4	0.0
		Range	103.4–163.5	103.8–104.3
	West	Mean	104.1	97.7
		SE	1.4	0.0
		Range	98.0–134.7	97.6–97.7
Ro-Ro	North	Mean	113.7	104.2
		SE	1.7	0.0
		Range	103.4–306.0	103.8–104.3
	West	Mean	124.7	97.7
		SE	5.4	0.0
		Range	98.0–329.9	97.6–97.7
Ro-Ro/Combo	North	Mean	106.3	103.9
		SE	0.8	0.0
		Range	103.6–116.4	103.8–104.3
	West	Mean	102.8	97.7
		SE	1.8	0.0
		Range	98.1–119.3	97.6–97.7

Table 3
Baseline and predicted transit speeds (knots) and predicted VSR compliance rates (%) by vessel category and target speed (knots).

Vessel Category	Target VSR Speed	Predicted VSR Compliance	Statistic	2015 Transit Speed	Predicted Transit Speed
Container	10	6.1	Mean	14.2	12.8
			SE	0.1	0.0
			Range	5.5–22.5	5.5–21.0
	12	29.7	Mean	14.2	12.8
			SE	0.1	0.0
			Range	5.5–22.5	5.5–21.0
Tanker	10	72.9	Mean	12.6	10.7
			SE	0.1	0.1
			Range	5.2–16.0	5.2–15.7
	12	78.5	Mean	12.6	11.9
			SE	0.1	0.1
			Range	5.2–16.0	5.2–15.7
Dry Bulk	10	66.9	Mean	11.7	10.5
			SE	0.1	0.1
			Range	7.4–14.3	7.4–13.3
	12	89.2	Mean	11.7	11.5
			SE	0.1	0.1
			Range	7.4–14.3	7.4–13.3
Ro-Ro	10	8.9	Mean	13.4	11.1
			SE	0.2	0.1
			Range	6.3–18.2	6.3–17.5
	12	86.2	Mean	13.4	11.9
			SE	0.2	0.1
			Range	6.3–18.2	6.3–17.5
Ro-Ro/Combo	10	10.3	Mean	13.3	12.8
			SE	0.5	0.4
			Range	8.6–18.6	8.6–18.0
	12	31.0	Mean	13.3	12.8
			SE	0.5	0.4
			Range	8.6–18.6	8.6–18.0

Table 4
Predicted transit times (hours) by vessel category and vessel operating procedure.

Procedure	Statistic	Container	Tanker	Dry Bulk	Ro-Ro	Ro-Ro/Combo
2015 Baseline	Mean	7.8	9.0	9.2	8.2	9.0
	SE	0.0	0.1	0.2	0.4	0.2
	Range	4.7–18.7	7.3–14.1	5.5–25.9	5.3–13.8	6.3–48.9
12RR	Mean	8.3	9.0	8.7	8.2	8.6
	SE	0.0	0.1	0.1	0.3	0.1
	Range	4.8–17.8	7.8–14.1	5.8–16.5	5.6–11.3	6.2–18.7
10RR	Mean	8.3	9.9	9.4	8.2	9.6
	SE	0.0	0.1	0.1	0.3	0.1
	Range	4.8–17.8	7.8–14.1	5.8–16.5	5.6–11.3	6.2–18.7
12NR	Mean	8.4	9.2	10.1	8.5	9.5
	SE	0.0	0.1	0.2	0.3	0.2
	Range	4.8–18.7	8.0–14.1	6.0–27.5	5.9–13.8	6.5–48.9
10NR	Mean	8.4	10.0	10.9	8.5	10.5
	SE	0.0	0.1	0.2	0.3	0.2
	Range	4.8–18.7	8.0–16.3	6.0–31.4	5.9–13.8	6.5–48.9
RR	Mean	7.6	8.9	7.9	7.9	8.1
	SE	0.0	0.1	0.1	0.3	0.1
	Range	4.6–17.8	7.3–14.1	5.3–16.5	5.2–11.3	6.1–18.7

Using these assumptions, transit speeds are predicted to significantly decrease for each vessel category under both target VSR speeds. However, predicted VSR compliance ranges from 6.1% to 89.2% due to varying minimum engineering viability speeds.

Based on these predictions, Table 4 shows the predicted transit time in hours for each vessel category under each proposed vessel operating procedure. Within the study area, transit times are predicted to significantly decrease under the re-routing only procedure and significantly increase under the two VSR-only procedures for all vessel categories. Container vessels are the only category whose transit times are predicted to significantly increase under the 12RR procedure.

4. Results

In 2015, there were 3,038 transits within the study area (Fig. 3). The majority of transits were by Container vessels (73.7%), and the least number of transits were by Ro-Ro/Combo vessels (1.0%). Most (77.3%) transits occurred along the Northern route. The average speed through the study area was 13.8 knots with Container vessels traveling the fastest, averaging 14.2 knots, and Dry Bulk vessels traveling the slowest, averaging 11.7 knots (Fig. 4). Finally, TCs within the study area were approximately $66.7 million, with $43.6 million from ICCs and $23.0 million from VTCs. Container vessels comprise 80.1% of these TCs, Ro-Ro vessels comprise 10.9%, and Tanker, Dry Bulk, and Ro-Ro/Combo vessels each comprise less than 4%.

Predicted changes in TCs were variable across the proposed alternatives (Table 5). TCs are predicted to decrease by 1.6%–3.4% under the three proposed procedures with re-routing, and increase by 1.3%–2.0% under the two VSR only procedures. ICCs are predicted to increase under the four proposed procedures with a VSR component from 3.1% to 8.8%, and decline under the vessel re-routing only procedure by 3.7%. VTCs are projected to decrease from 2.9% to 13.4% under all five proposed procedures. Both ICCs and VTCs are anticipated to change the most for VSR only procedures and with slower target speeds.

Predicted changes in TCs also varied among vessel categories (Table 6). For example, TCs for Tanker vessels are expected to decrease under all five management procedures, and Dry Bulk vessels are the only category whose TCs are predicted to increase under the 10RR procedure.

To test if these changes are significant, mean TCs were normalized per 1,000 metric tonne per nautical mile (1,000 mt-nm) for each vessel category and compared to the 2015 baseline (Table 7). Due to the

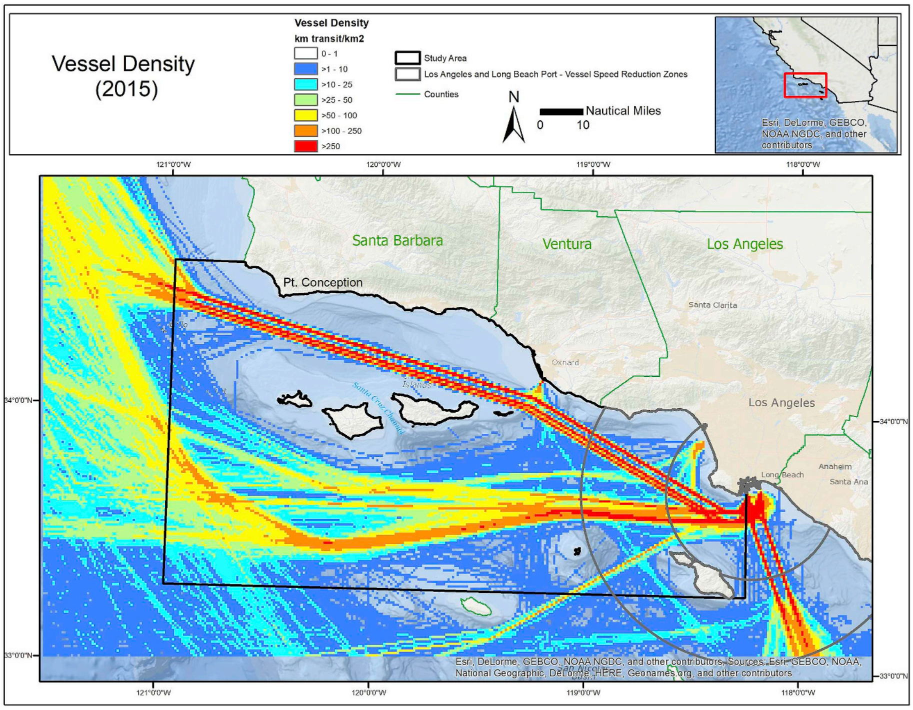

Fig. 3. Vessel density (all vessels, 2015).

decrease in transit distances, TCs per 1,000 mt-nm are predicted to significantly increase for all procedures with a VSR component for all vessel categories, except Tanker vessels.

Distance elasticity of TCs and *speed elasticity of TCs* can be calculated to measure the responsiveness, or elasticity, of TCs to a change in transit distance and transit speed. Mathematically, these are the ratios of the percentage change in TCs to the percentage change in transit distance and the percentage change in transit speed. If this ratio were greater than one, then small changes in distance or speed would cause large changes in TCs (elastic). Alternatively, if this ratio were less than one, then large changes in distance or speed would cause small changes in TC (inelastic).

As an example calculation, consider a small sized Container vessel traveling along the western route under the 12RR vessel operating procedure.

$$
\begin{aligned}
TC\,(2015) &= (\$5.32/1{,}000\ mt - nm) * (35{,}558\ mt) * (101.9\ nm) \\
&= \$19{,}276
\end{aligned}
$$

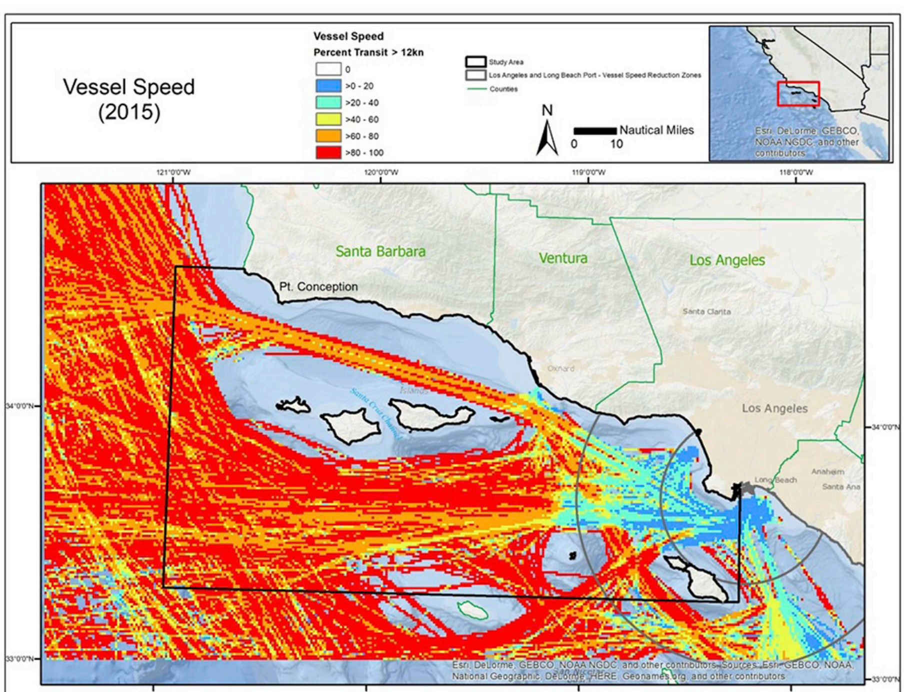

Fig. 4. Percent of transits traveling faster than 12 knots (all vessels, 2015).

Table 5
Results (2015$) by vessel operating procedure.

Procedure	Statistic	TCs	ICCs	VTCs
2015 Baseline	Total	66,658,476	43,637,547	23,020,929
12RR	Total	65,203,516	45,004,297	20,199,219
	% Change	−2.2	3.1	−12.3
10RR	Total	65,620,018	45,674,692	19,945,326
	% Change	−1.6	4.7	−13.4
12NR	Total	67,539,241	46,741,530	20,797,711
	% Change	1.3	7.1	−9.7
10NR	Total	68,018,510	47,492,598	20,525,912
	% Change	2.0	8.8	−10.8
RR	Total	64,371,003	42,019,577	22,351,426
	% Change	−3.4	−3.7	−2.9

$$TC(12RR) = (\$5.37/1{,}000\ mt - nm) * (35{,}558\ mt) * (97.7\ nm) = \$18{,}655$$

$$Distance\ Elasticity = \frac{TC(12RR) - TC(2015) / TC(2015)}{Dist(12RR) - Dist(2015) / Dist(2015)} = \frac{\$18{,}655 - \$19{,}276 / \$19{,}276}{97.7\ nm - 101.9\ nm / 101.9\ nm} = 0.78$$

Table 8 shows the distance and speed elasticities of TCs across all vessel operating procedures. The results indicate that, on average, TCs are more responsive to changes in distance than speed. Further, TCs are elastic with respect to distance and speed for Tanker vessels, elastic with respect to distance for Dry Bulk vessels, and inelastic for Container, Ro-Ro, and Ro-Ro/Combo vessels.

5. Discussion

The results suggest that shipping costs within the Channel Islands region would decrease under procedures with re-routing components, and increase under seasonal VSR-only procedures.

These results can be explained by examining the effects on ICCs and VTCs separately. First, ICCs are a function of cargo value, transit time, and capital costs. The only input affected by either component is transit time, which decreases with re-routing and increases with VSRs. The net effect is an increase in ICCs under a VSR, and a decrease in ICCs under re-routing only. Second, VTCs are a function of fuel consumption, fuel price, and transit time. Both fuel consumption and transit time are affected by the proposed management components. The effect of transit time on VTCs is the same as on ICCs; however, fuel consumption decreases with speed, and increases with time. The net effect is an overall decrease in VTCs. When combining the economic impacts of ICCs and VTCs, the decrease in VTCs only outweighs the increase in ICCs under procedures with re-routing.

Additionally, the results suggest that the effects will be different across vessel categories. For example, Tanker vessels are the only vessel category whose TCs are expected to significantly decrease under the four procedures with a VSR component. This is likely because Tanker vessels are predicted to decrease transit distance the most and are the most responsive to changes in speed. Alternatively, TCs may change the least for Container vessels. This is likely because their minimum engineering viability speeds are greater than the target VSR speeds, which highlights the importance of relaxing the assumption of 100% compliance. Container vessels also primarily traveled along the TSS in 2015, so they are relatively unaffected by the re-routing procedures.

To put these results into context, consider an individual vessel transit between Hong Kong and the LA/LB Port Complex (6,300 nm). The total cost of vessel operation including fuel, crew, capital, insurance, and related administrative overhead costs on an individual vessel transit can easily range from approximately $0.6 to over $1.1 million depending on the type of vessel, fuel, and the degree to which the vessel was loaded. The estimated changes in costs from implementation of these procedures would therefore represent a change in total vessel operating costs ranging from −0.07% to +0.07% for this hypothetical transit. Additionally, the estimated changes in costs across all vessels in the study area would represent 0.0003%–0.0006% of LA/LB Port Complex's cargo value. These results are similar, but roughly an order of magnitude smaller, to those found along the US East Coast (Nathan Associates, Inc., 2012; Silber and Bettridge, 2012), which may be partially explained by relaxing the assumption of 100% compliance.

The framework used in this study can be transferred to other regions. However, both current and expected vessel fleet composition and behavior must be taken into account. For example, vessel characteristics, such as size and cargo type, vary by port, region, and over time. Additionally, minimum engineering viability speeds vary by transit length and may not be directly transferable to longer TSS. There may also be different regulations, such as fuel regulations, which may affect vessel behavior. Therefore, a clear understanding of region-specific information is necessary to properly apply this framework elsewhere.

6. Conclusion

The goal of this study was to estimate the shipping costs associated with the five proposed vessel operating procedures designed to reduce vessel strikes, air pollution, and user conflicts within the Channel Islands region. Broadly, results suggest that costs to the shipping industry are likely to decrease with re-routing, and increase with VSRs, but that the magnitude and direction of these changes may vary by vessel category. Furthermore, the estimated cost changes are minimal compared to the value of the LA/LB Port Complex shipping industry. This information is useful to decision-makers because it enables them to balance the goal of managing the co-occurrence of whales and vessels to reduce vessel strikes, while minimizing the economic impact to the shipping industry.

Table 6
Results (2015$) by vessel operating procedure and vessel category.

Procedure	Statistic	Container	Tanker	Dry Bulk	Ro-Ro	Ro-Ro/Combo
2015 Baseline	Total	53,420,040	2,389,190	2,130,888	7,289,026	1,429,332
12RR	Total	52,956,458	2,089,272	2,097,863	6,655,005	1,404,918
	% Change	−0.9	−12.6	−1.5	−8.7	−1.7
10RR	Total	52,956,458	2,024,773	2,181,650	7,052,219	1,457,509
	% Change	−0.9	−15.3	2.4	−3.2	−1.7
12NR	Total	53,936,507	2,292,006	2,137,711	7,715,509	1,457,509
	% Change	1.0	−4.1	0.3	5.9	2.0
10NR	Total	53,936,507	2,224,267	2,223,901	8,176,325	1,457,509
	% Change	1.0	−6.9	4.4	12.2	2.0
RR	Total	52,450,377	2,181,227	2,091,609	6,270,321	1,377,469
	% Change	−1.8	−8.7	−1.8	−14.0	−3.6

Table 7
Results (2015$/1,000 mt-nm) by vessel operating procedure and vessel category.

Procedure	Statistic	Container	Tanker	Dry Bulk	Ro-Ro	Ro-Ro/Combo
2015 Baseline	Mean	5.32	1.69	4.12	5.11	8.13
	SE	0.13	0.06	0.24	0.10	0.37
	Range	0.69–65.64	0.24–11.56	1.03–15.51	2.47–12.94	4.70–15.16
12RR	Mean	5.37	1.55	4.29	5.73	8.29
	SE	0.13	0.05	0.25	0.11	0.36
	Range	0.69–65.64	0.24–11.46	1.03–15.80	3.11–12.94	4.70–15.16
	t-value(df)	0.28(2238)	−0.97(357)	0.03(165)	2.07(245)	0.32(28)
	p-value	0.78	0.33	0.97	0.04	0.75
10RR	Mean	5.37	1.55	4.29	5.73	8.29
	SE	0.13	0.05	0.25	0.11	0.36
	Range	0.69–65.64	0.24–11.46	1.03–15.80	3.11–12.94	4.70–15.16
	t-value(df)	0.28(2238)	−1.69(357)	0.46(165)	4.15(245)	0.32(28)
	p-value	0.78	0.09	0.64	0.00	0.75
12NR	Mean	5.37	1.61	4.13	5.41	8.29
	SE	0.13	0.06	0.25	0.10	0.36
	Range	0.69–65.64	0.24–11.56	1.03–15.51	2.99–12.94	4.70–15.16
	t-value(df)	0.28(2238)	−0.97(357)	0.03(165)	2.07(245)	0.32(28)
	p-value	0.78	0.33	0.97	0.04	0.75
10NR	Mean	5.37	1.55	4.29	5.73	8.29
	SE	0.13	0.05	0.25	0.11	0.36
	Range	0.69–65.64	0.24–11.46	1.03–15.80	3.11–12.94	4.70–15.16
	t-value(df)	0.28(2238)	−1.69(357)	0.46(165)	4.15(245)	0.32(28)
	p-value	0.78	0.09	0.64	0.00	0.75
RR	Mean	5.32	1.69	4.12	5.11	8.13
	SE	0.13	0.06	0.24	0.10	0.37
	Range	0.69–65.64	0.24–11.56	1.03–15.51	2.47–12.94	4.70–15.16
	t-value(df)	0.00(2238)	0.00(357)	0.00(165)	0.00(245)	0.00(28)
	p-value	1.0000	1.0000	1.0000	1.0000	1.0000

Table 8
Distance and speed elasticities (absolute values) of TCs by vessel category.

Vessel Category	Statistic	Distance Elasticity	Speed Elasticity
Container	Mean	0.61	0.09
	SE	0.16	0.00
	Range	0.45–0.94	0.08–0.09
Tanker	Mean	1.67	1.13
	SE	0.26	0.41
	Range	1.19–2.09	0.45–2.31
Dry Bulk	Mean	1.18	0.48
	SE	0.15	0.19
	Range	0.95–1.47	0.21–1.03
Ro-Ro	Mean	0.64	0.56
	SE	0.23	0.13
	Range	0.24–1.04	0.19–0.79
Ro-Ro/Combo	Mean	0.68	0.45
	SE	0.19	0.02
	Range	0.50–1.06	0.42–0.48

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