Predicting the Environmental Impacts of Changing Global Maritime Freight Flows with Thawing Arctic Sea Ice

E. Miller-Hooks[a,*], A, Azadnia[b], W. Li[c], M. Henke[d]

[a] Sid & Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering
George Mason University, Fairfax, Virginia USA
miller@gmu.edu,
[b] Sid & Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering
George Mason University, Fairfax, Virginia USA
aazadnia@gmu.edu
[c] Sid & Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering
George Mason University, Fairfax, Virginia USA
wli21@gmu.edu
[d] Sid & Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering
George Mason University, Fairfax, Virginia USA
mhenke@gmu.edu
* Corresponding author

Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)
September 02-03, 2024, Crete, Greece

April 18, 2024

Keywords: Data-driven, goods transport, emissions, logistics networks, climate change

1 INTRODUCTION AND MOTIVATION

Maritime shipping is a key mode for global trade flows. Transport of goods along maritime shipping routes, while improving in efficiency in past decades, can take many weeks or even months for many origin-destination pairs. The Arctic passageways, if open, could considerably reduce the length of such voyages. Thus, as the sea ice of the Arctic waters thaw with climate change, alternative, shorter shipping lanes that use the Arctic passageways are becoming viable and attractive options.

With increased vessel traffic comes added environmental pollution and risk of accidents causing release of contaminants. The pollution may be airborne, such as particulate matter (PM) and greenhouse gases (carbon dioxide - CO_2, nitrous oxide - NO_X, methane - CH_4, and sulfur oxides - SO_X), or come as a result of release of substances into the water. The former is primarily a result of fuel consumption, while the latter may result from accidental spillage from the transfer of fuels to vessels during vessel loading, incidents, such as allisions with oil spillage, contaminants carried on the underside of the vessels, and release of bilge water containing chemicals, solvents, detergents and more, from the vessels.

This presentation will describe technologies from data-driven Bayesian networks (via the Arctic Incident Risk Estimation and Prediction Tool), Benders' branch-and-cut (via the Risk-constrained Maritime Cargo Flow Optimization Model) and emissions estimation methods that together are used to predict the environmental impacts of changing global maritime freight flows from thawing Arctic sea ice.

2 METHODOLOGY

Emissions and pollution estimates are derived from incident risk predictions, vessel flow estimates, and GHG and other emissions computations based on fuel consumption, fuel type and vessel factors, as well as other data sources on risk of oil spillage as a function of vessel traffic and more. The three key elements of the methodologies underlying these estimates are described in this section.

2.1 Risk Prediction

The Arctic Incident Risk Estimation and Prediction Tool (Li et al., in preparation for submission) was developed on concepts of data-driven Bayesian networks (BNs). The BN was trained on input from over 5,000 incidents in the Compendium of Arctic Ship Accidents (CASA) incident dataset from the Arctic Council and Protection of the Arctic Marine Environment (PAME). Causal relationships between environmental conditions and incidents, along with expert judgement, were used to construct the BN using a score-and-search K2 learning algorithm for identifying a best network structure. Once trained, the tool predicts both short- and long-term incident risks given predicted navigation conditions.

To develop predictions of incident occurrence probabilities and consequences across key subregions of the Arctic Ocean for 2020 to 2070 by season, seasonal predictions were made under changing environmental conditions on given probabilistic climate predictions obtained from the CNRM-CM6-1-HR climate model and supplemental modeling capabilities that provide high-resolution dynamic downscaling of sea ice and simulate ocean wave hazards by period. For the given climate projection, the outputs of the model are estimates of future incident risk of transiting key Arctic-based routes. The outputs also provide information on the risk of events that could lead to an oil spill.

2.2 Vessel Traffic Estimation

A Risk-constrained Maritime Cargo Flow Optimization Model (Li and Miller-Hooks, in review) for predicting changes in global cargo vessel traffic given declining Arctic sea ice predicts changes in global maritime cargo flows under the projected environmental scenarios and risks from incidents along three Arctic passageways. The outcome is seasonal future global maritime trade flows along key global routes, including routes that incorporate the Arctic passages.

The objective of the optimization model is a generalized cost function that accounts for fuel consumption, maintenance, insurance, port handling, delay penalties and other costs. The risk of an incident, such as a collision, allision, equipment failure, grounding or foundering, is captured in part through lower or higher sailing speeds, increased insurance premiums and accident probabilities. A risk-exposure threshold constraint eliminates overly risky paths from consideration. Additionally, Polar Code (IMO, 2022) regulations on needed vessel ice class and use of one or more ice breakers, or whether travel is even permitted, are incorporated. The method uses a smart path generation and storage approach within an exact Benders-branch-and-cut methodology. This method exploits concepts of Benders decomposition with embedded acceleration techniques, branch-and-cut, column generation, and a label-correcting algorithm with specialized fathoming rules.

2.3 Emissions and Pollution Prediction

Emissions from maritime shipping are estimated via fuel consumption and type. Fuel consumption is affected by operational speed, engine type, wind speed and direction, wave height, loading of ships and more. Emissions (in kg) per metric ton fuel burned in CO_2, NO_X, SO_X, PM, and CH_4 as a function of fuel type are estimated under varying future meteorological and sea ice conditions. Models suggested by Le et. al (2020) are employed to estimate fuel consumption of the vessels and resulting emissions based on factors provided in (IMO, 2020) according to equations (1) and (2).

For Neo-Panamax container ships with 8000-11999 TEUs:

$$FC = 0.0141 T_{ijk} S_{1k}^{3} + 32.1584 T_{ijk} + \varepsilon, \quad (1)$$

where FC denotes the fuel consumption per voyage (metric ton), S_{1k} is the operational speed of the vessel k (knots), and T_{ijk} represents the voyage time from port i to port j by vessel k (days).

For Neo-Panamax container ships with 12000-14999 TEUs:

$$FC = 0.0180 T_{ijk} S_{1k}^{3} + 32.2535 T_{ijk} + \varepsilon, \quad (2)$$

3 APPLICATION AND RESULTS

The solution technique was applied on a model of the global maritime container network associated with the world's largest carrier alliance, the 2M Alliance. The network includes 80 ports, 32 routes, 338 links and 4,110 legs, and incorporates three routes through the Arctic Ocean: the Northern Sea Route, Northwest Passage and Transpolar Sea Route. Estimates of changes in fuel consumption, related emissions and other pollutant discharge with changing conditions in the Arctic Ocean were obtained. These estimates show the increasing emissions risks to the region with improved shipping conditions over coming decades.

4 DISCUSSION

Increased emissions and other pollutants in the Arctic waters can have grave consequences for marine ecosystems and the animals and people who depend on marine life to subsist. Predictions as obtained herein can prepare nations and regions for a changing global maritime landscape and provide quantitative estimates that can be used to help protect the pristine and fragile Arctic environment.

5 REFERENCES

Le, L., Lee, G., Kim, H., & Woo, S., 2020. Voyage-based Statistical Fuel Consumption Models of Ocean-going Container Ships in Korea. Maritime Policy and Management, 47(3) pp. 304–331. https://doi.org/10.1080/03088839.2019.1684591

Li, W. & Miller-Hooks, E. A Risk-constrained Maritime Cargo Flow Optimization Model for Predicting Changes in Cargo Vessel Traffic under Thawing Arctic Passageways. In review for publication.

Li, W., Henke, M. & Miller-Hooks, E. A Bayesian Network Approach for Predicting Future Risk in Arctic Maritime Transit. In preparation for submission in May 2024.

IMO, 2020. Fourth International Maritime Organization (IMO) GHG Study 2020 Full Report. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf (last access, April 17, 2024)

Acknowledgements. This work was funded by the U.S. National Science Foundation through the Navigating the New Arctic program (Grant 1927785). The authors are grateful for the support.