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Marine Vessels as Substitutes for Heavy-Duty Trucks in Great Lakes Freight Transportation

Bryan Comer

Rochester Institute of Technology, Rochester, NY

James J. Corbett

University of Delaware, Newark, DE

J. Scott Hawker and Karl Korfmacher

Rochester Institute of Technology, Rochester, NY

Earl E. Lee

University of Delaware, Newark, DE

Chris Prokop and James J. Winebrake

Rochester Institute of Technology, Rochester, NY

ABSTRACT

This paper applies a geospatial network optimization model to explore environmental, economic, and time-of-delivery tradeoffs associated with the application of marine vessels as substitutes for heavy-duty trucks operating in the Great Lakes region. The geospatial model integrates U.S. and Canadian highway, rail, and waterway networks to create an intermodal network and characterizes this network using temporal, economic, and environmental attributes (including emissions of carbon dioxide, particulate matter, carbon monoxide, sulfur oxides, volatile organic compounds, and nitrogen oxides). A case study evaluates tradeoffs associated with containerized traffic flow in the Great Lakes region, demonstrating how choice of freight mode affects the environmental performance of movement of goods. These results suggest opportunities to improve the environmental performance of freight transport through infrastructure development, technology implementation, and economic incentives.

INTRODUCTION

Energy use and emissions from freight transport are increasing at a more rapid rate than other types of transportation,^{1,2}

IMPLICATIONS

Freight transportation is a growing contributor to local air pollution and greenhouse gas emissions. Mode-shifting (e.g., moving cargo from truck to rail or ship) is one opportunity for reducing this environmental burden. This paper discusses the environmental, economic, and time-of-delivery tradeoffs for moving freight from land-side transport to water in the Great Lakes region. These tradeoffs have important implications for transportation and air quality planners working to improve cargo flows along goods movement corridors.

and freight transport represents a non-negligible component of local air pollution and greenhouse gases (GHGs).^{3–6} One way to address these growing impacts is through careful consideration of routes along an intermodal freight system.^{7,8} Route selection based on environmental criteria, as opposed to the traditional criteria of cost and time of delivery, could help identify environmentally sustainable ways to move freight throughout the United States and abroad.⁸

This paper applies the Geospatial Intermodal Freight Transport (GIFT) model discussed in Winebrake et al.⁸ to evaluate environmental, economic cost, and time-of-delivery tradeoffs associated with containerized freight transport in the Great Lakes region of North America. GIFT consists of an intermodal (rail, highway, and waterway) network that is characterized not only by distance and time of delivery, but also by operating costs, energy (Btu), and emissions (carbon dioxide [CO₂], carbon monoxide [CO], particulate matter [PM₁₀], nitrogen oxides [NO_x], volatile organic compounds [VOCs], and sulfur oxides [SO_x]).^{9,10} For this paper, GIFT has been expanded to include integration of U.S. and Canadian road, rail, and water networks and has been improved via the use of a “hub-and-spoke” intermodal connection feature. Here, GIFT is applied to examine the tradeoffs associated with a shift from heavy-duty trucks to ships for freight transport in the Great Lakes region, with particular attention given to cross-border freight flows between the United States and Canada.

BACKGROUND

Energy and Environmental Impacts of Freight Transport

The growing literature surrounding the important role that freight transportation plays in economic development has also highlighted the increasing energy and environmental impacts associated with cargo movement.^{1,3,4,8,11–13} For example, the United States annually

spends approximately 6–7% of its gross domestic product (GDP) on freight transport, and U.S. reliance on the freight transportation system has been growing considerably for some time.^{14,15}

Notwithstanding the recent decline in goods movement because of negative economic growth in 2008, long-term trends of U.S. domestic (ton-miles) t-mi of goods transported via multiple freight modes (i.e., trucks, trains, ships, planes) have steadily increased.^{14–16} For instance, under its “reference case” scenario, the U.S. Energy Information Administration (EIA) projects total vehicle miles traveled (VMT) for freight trucking to increase from 224 billion VMT to 378 billion VMT between 2006 and 2030, an average annual increase of 1.9%. Likewise, rail freight transport is expected to increase from approximately 1718 billion ton-miles (BTM) to 2193 BTM (1%/yr) over the same period, whereas domestic marine freight is expected to increase from 659 to 839 BTM (1%/yr).¹⁷ With increasing freight transport activity and accompanying energy use, GHG emissions will also increase. In 2007, freight transport (including rail, truck, air, and domestic shipping) was responsible for approximately 660 teragrams of CO₂ (Tg CO₂) in the United States, or approximately 9% of total CO₂ emissions.¹⁸ This is consistent with other industrialized countries, such as Canada where freight transport represents approximately 9% of total GHG emissions.¹⁹

Responding to the idea that mode shifts can help achieve reduction targets for energy and emissions,²⁰ this paper examines the potential for freight emissions reduction, particularly of CO₂, through a shift from carbon-intensive modes of freight transport (trucks) to a less carbon-intensive mode (marine vessels) in the Great Lakes region.

Freight Transport in the Great Lakes Region

The Great Lakes region includes the entire St. Lawrence Seaway System (SLSS), which extends as far east as the Gulf of St. Lawrence and as far west as the Port of Duluth, encompassing all five major Laurentian Great Lakes (Ontario, Erie, Huron, Michigan, and Superior).²¹ This region is home to approximately 10 and 30% of the populations of the U.S. and Canada, respectively. The region is considered one of “the world’s largest manufacturing and consumer markets”²² and is a critical artery of commerce for the United States. The Great Lakes region also plays a key role in international trade with goods entering the St. Lawrence Seaway from the Atlantic Ocean and goods entering from the west at ports such as Duluth and Thunder Bay, MN.²²

In 2008, approximately 114 million short tons of cargo were transported on the Great Lakes.²³ Most waterborne cargo in the Great Lakes is carried by a fleet of dry-bulk cargo ships and “self-unloaders.” The latter type of ship is essentially a dry-bulk carrier with integrated lifts and conveyors to facilitate unloading without extensive shore-side infrastructure.²⁴ Tug boats are often used to push a few barges, which can be used on the lakes as well as on most of the waterways that communicate with the Great Lakes. Increasingly, integrated tug-barge combination ships are being used in which the flat area of the

barge is included in an extended section of the tug-boat hull.²²

Notably absent from the discussion of Great Lakes waterborne freight traffic is containerization, which is currently a negligible component of Great Lakes shipping (with the exception of some regular activity at the Port of Montreal associated with transatlantic shipments). Currently, almost all containerized freight in the region is carried by land-based modes of transportation, often by heavy-duty diesel trucks. However, there appears to be interest and room for growth for on-water, containerized freight transport to reduce highway and rail congestion in the Great Lakes region. One estimate suggests that on-water goods movement could capture as much as 4% of containerized intermodal traffic in the Great Lakes region by 2050 so long as it is competitive with truck and rail.²² This waterborne activity would work in conjunction with land-side modes using intermodal freight transportation facilities to enable modal transfers if necessary.

MODELING APPROACH

In this paper, the GIFT model is used to evaluate the economic cost, time of delivery, and environmental impacts associated with modal choices of freight transport (by truck, rail, or ship). GIFT is a network optimization model that operates on an ArcGIS 9.3 software platform. The model applies a Dijkstra shortest-path algorithm included in ArcGIS’s Network Analyst to evaluate U.S. and Canadian freight movements from origin to destination.²⁵

GIFT includes two unique elements that make it useful for evaluating intermodal shipments. First, GIFT includes an intermodal network that links publicly available U.S. and Canadian unimodal network datasets (currently rail, highway, and waterway) through nodes identified at ports, railyards, and other intermodal facilities. This allows the user to model the transfer of goods from one mode to another.

Second, GIFT includes energy, environmental, economic, and speed attribute information (by mode) on each segment and node of the intermodal network. Attributes such as emissions of various pollutants (e.g., CO₂, PM₁₀, NO_x, SO_x, CO, and VOCs), energy consumption (e.g., Btu), time, and economics (US\$) have been incorporated into GIFT through a custom emissions calculator and graphical user interface that allows for user-defined inputs to be entered into the model. Each segment of the network takes on calculated attribute values based on the characteristics of the transport mode, segment speed, and other factors. Moreover, transfers between modes (occurring at railyards, ports, and other intermodal transfer facilities) accrue time, cost, and emissions “penalties” using a hub-and-spoke approach that links each mode’s network to the facility hub through creation of “spokes.” Once the network includes such attribute data, the analyst can solve the network transportation problem for different single objective functions, such as least time, least cost, and least emissions (or a weighted multiobjective function applying a combination of these attributes). The GIFT model has been discussed in previous work, and the reader is referred to that literature for details about model development.^{8–10}

By analyzing the network using energy and environmental objective functions, tradeoffs among these goals and more traditional ones (cost and time of delivery) can be explored. Policy analysis can also be studied to determine how such policies (e.g., taxes, low-carbon fuel mandates, or subsidies) would affect the overall energy and environmental character of freight transport. In this paper, tradeoffs associated with freight mode choice are examined with particular focus on time of delivery, emissions, and operating cost.

GREAT LAKES CASE STUDY

A case study is presented that represents a containerized cargo flow scenario found in the "Great Lakes-St. Lawrence Seaway New Cargoes/New Vessels Market Assessment Report."²² This case involves moving containerized goods from Montreal, Canada to Cleveland, OH. A shipment of goods between these two locations is evaluated under different objectives and shipping options, including the following modal assumptions:

- Truck characteristics—a model year 2007 or later (MY2007+) Class 8 tractor trailer able to haul two 20-ft equivalent unit (TEU) containers at 7 t/TEU (total haul of 14 t). It is assumed that this truck has a fuel economy of 6 mpg when loaded. Further, it is assumed that the truck operates at the maximum allowable emissions standards for NO_x [1.2 grams per brake horsepower-hour (g/bhp-hr)] and PM₁₀ (0.01 g/bhp-hr) according to the Code of Federal Regulations (CFR) 40 CFR 86.007–11.
- Rail characteristics—two Tier 2 4000-hp locomotives (2005 or later build date) pulling 100 wells with 4 TEUs per well (400 TEUs total, or 2800 t).²⁶ It is assumed that these engines operate at an average efficiency of 35% and an average load factor of 70%. Further, it is assumed that the locomotives operate at the maximum allowable emissions standards for NO_x (5.5 grams per energy output [g/bhp-hr]) and PM₁₀ (0.20 g/bhp-hr) according to 40 CFR 92.8.
- Ship 1 characteristics—a 221-TEU capacity, 3070-hp container vessel called the *Dutch Runner* (1988 build date).²⁷ It is assumed that the engine operates at 40% efficiency with an average load factor of 80%. Further, it is assumed that the ship operates at the maximum allowable emissions standards for NO_x (5.4 g/bhp-hr) and PM₁₀ (0.15 g/bhp-hr) according to 40 CFR 94.8.
- Ship 2 characteristics—a 200-TEU capacity, 1550-hp tug-barge combination vessel called the *Ellie J.* (1968 build date, 2007 rebuild date). It is assumed that the engine operates at 40% efficiency with an average load factor of 65%. Further, it is assumed that the ship emits 7.94 g/bhp-hr of NO_x and 0.07 g/bhp-hr of PM₁₀.
- Fuel—the assumed fuel for this case is on-road diesel fuel with an energy content of 128,450 Btu/gal, a mass density of 3170 g/gal, and a carbon fraction of 86%.

Using these freight mode characteristics, an activity-based model is applied to generate network attribute values for energy consumption and emissions along any network

segment.⁸ For example, to calculate CO₂ emissions for trucks, eq 1 is applied.

$$\frac{gCO_2}{TEU \cdot mi} = \frac{\rho}{mpg \cdot TEU} \cdot CF \cdot 3.67 \quad (1)$$

where ρ represents fuel density in grams of fuel per gallon, mpg represents miles per gallon, CF represents the carbon fraction of the fuel (%), 3.67 represents a conversion factor to convert carbon to CO₂, and TEU is the TEU capacity of the truck. To calculate CO₂ emissions for rail and ship, eq 2 is applied.

$$\frac{gCO_2}{TEU \cdot mi} = \frac{hp \cdot \gamma \cdot \rho}{\eta \cdot mph \cdot \epsilon \cdot TEU} \cdot 2544 \cdot CF \cdot 3.67 \quad (2)$$

where hp represents the horsepower output rating of the engine(s), γ represents the average load factor for the trip, η represents the engine efficiency (out/in), mph represents the average speed for the trip in miles per hour, ϵ represents the energy content of the fuel in Btu per gallon, and 2544 represents a conversion from horsepower-hour to Btu. Similar activity-based equations are applied using the NO_x and PM₁₀ emissions factors presented above with slight adjustment. For example, NO_x and PM₁₀ emissions factors are already in units of grams per energy output (g/bhp-hr); therefore, components of the above equations needed to calculate the carbon emissions based on fuel consumption can be dropped. Table 1 presents the values of the inputs for these equations.

GIFT also calculates additional time, costs, and emissions associated with intermodal transfers at ports, railyards, or other facilities. Emissions are estimated from transfer activities for each of the three spokes (rail-to-hub, truck-to-hub, ship-to-hub) using an activity-based model that (1) identifies the different pieces of equipment used to move containers from one mode to another, (2) applies temporal and engine load factors for such transfers, and (3) applies emissions factors from the California Air Resource Board's OFFROAD model for each piece of equipment to estimate actual emissions for mode-to-mode transfers. Because the OFFROAD model supplies emissions factors for equipment of varying model years, the activity-based model presented here uses an average based on those emissions factors assuming a year 2007 mix of equipment. The two ships modeled in this paper are assumed to use port-side transfer equipment that includes rubber tire gantry cranes, yard hostlers, and drayage trucks. On the basis of these calculations, truck-to-ship, truck-to-rail, and rail-to-ship emissions factors were determined of 11.7, 13.3, and 6.6 kg CO₂/TEU, respectively.

Modal operating costs for each segment were derived from the "Four Corridor Case Studies of Short-Sea Shipping Services" prepared by Global Insight.²⁸ The cost data used in this analysis are \$0.87/TEU-mi for truck; \$0.55/TEU-mi for rail; and \$0.50/TEU-mi for ship. Intermodal transfer costs were obtained from a report on short-sea shipping and are a sum of the port cost and the local drayage costs outlined in that report.²⁹ A cost of \$70/TEU is assumed for each mode-to-mode transfer.

Table 1. Model inputs and assumptions

Input	Value
Truck fuel economy	6 mpg
Truck container capacity	2 TEU
Rail container capacity	400 TEU
Ship 1 container capacity (<i>Dutch Runner</i>)	221 TEU
Ship 2 container capacity (<i>Ellie J.</i>)	200 TEU
Rail total horsepower	8000 hp
Ship 1 total horsepower	3070 hp
Ship 2 total horsepower	1550 hp
Ship 1 load factor	80%
Ship 2 load factor	65%
Ship 1 engine efficiency	40%
Ship 2 engine efficiency	40%
Truck speed	Variable, depending on road classification
Rail speed	25.0 mph
Ship 1 speed	13.5 mph
Ship 2 speed	9.0 mph
Btu/hp-hr	2544
Energy density	128,450 BTU/gal
Mass density of diesel fuel	3,167 g/gal
Carbon content of diesel fuel	0.86 g C/g Fuel
Carbon-to-CO ₂ conversion factor	3.67
Truck operating cost	\$0.87/TEU-mi
Rail operating cost	\$0.55/TEU-mi
Ship 1 operating cost	\$0.50/TEU-mi
Ship 2 operating cost	\$0.50/TEU-mi
Truck spoke CO ₂ emissions	9.2 kg/TEU
Rail spoke CO ₂ emissions	4.1 kg/TEU
Ship 1 spoke CO ₂ emissions	2.5 kg/TEU
Ship 2 spoke CO ₂ emissions	2.5 kg/TEU
Intermodal transfer cost	\$35/spoke
Intermodal transfer time	1 hr/spoke

To calculate time of delivery for a given route, the travel time on each segment of the route and the time it takes to transfer between modes (if such transfers take place) are summed. For this segment time, posted speed limits for truck, average speed for rail, and ship service speed for ship are used. The speed used for rail segments

is 25 mph. The two speeds used for the ship segments are 13.5 and 9 mph, corresponding to design speeds for the *Dutch Runner* and the *Ellie J.*, respectively. A 2-hr penalty for each intermodal transfer is used.

RESULTS

The case study examines the emissions, time of delivery, and operating cost tradeoffs of freight transport according to modal choice. Optimal truck, rail, and shipping options for a Montreal, Canada to Cleveland, OH, route are compared under two cases. Case A and case B refer to cases in which the *Dutch Runner* (ship 1) and the *Ellie J.* (ship 2) are the vessels under evaluation, respectively. The model is run 3 times for each case under the following objective functions: (1) least time, (2) least CO₂, and (3) least cost. Figure 1 shows the results of the analysis based on (Figure 1a) ship 1—the *Dutch Runner*, and (Figure 1b) ship 2—the *Ellie J.* Table 2 shows the results of each model run. These results are depicted graphically in Figure 2.

The most carbon-intensive mode of freight transport in this case is truck, followed by the container ship (the *Dutch Runner*), rail, and the tug-and-barge vessel (the *Ellie J.*). The *Ellie J.* performs the best with respect to CO₂ emissions. The two marine vessels are the best choice when the objective is to minimize operating costs; however, the emissions and economic benefits come at a time-of-delivery penalty. Note that the time of delivery presented does not include delays due to congestion or border crossing for any of the modes or lock delays for ships. This functionality is currently being developed within GIFT; however, such delays can be easily considered when interpreting the results. For example, the least-time transportation mode is truck, with a time of delivery of 8 hr, followed by rail with a time of delivery of 25 hr; therefore, highway congestion or border-crossing delays would need to exceed 17 hr before rail becomes the least-time solution. In addition, the origin and destination are located on truck delivery segments. If a facility at the origin or destination can directly load cargo onto ship or rail, transfer penalties associated with this routing may be reduced.

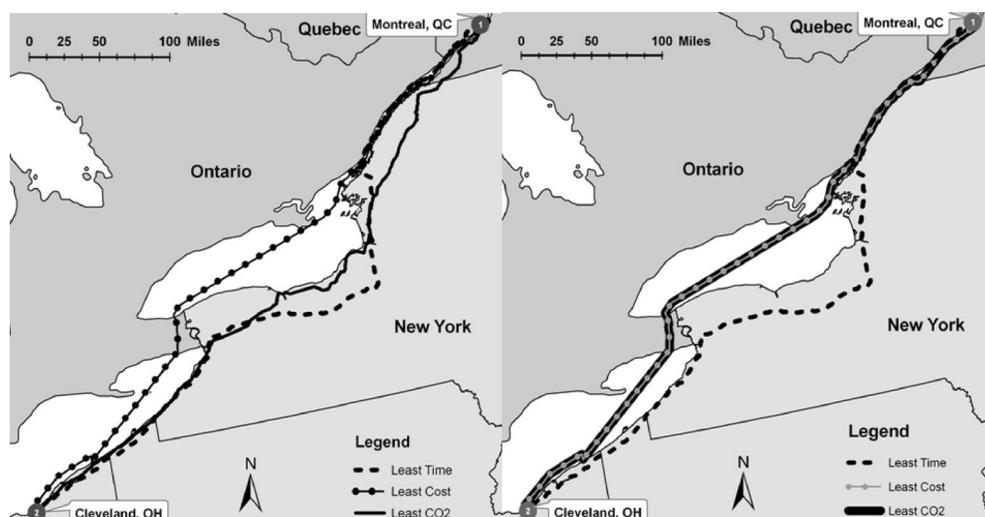


Figure 1. (a) Results of Montreal-to-Cleveland case in which the ship is the *Dutch Runner* container vessel. (b) Results of the Montreal-to-Cleveland case in which the ship is the *Ellie J.* tug-and-barge vessel.

Table 2. Results for three optimization model runs from Montreal to Cleveland.

Objective	Case A ^a			Case B		
	Least Time	Least Cost	Least CO ₂	Least Time	Least Cost	Least CO ₂
Primary mode (>90% of distance)	Truck	Ship	Rail	Truck	Ship	Ship
Total CO ₂ (kg/TEU)	460	240	190	460	160	160
Total NO _x (g/TEU)	1150/2400 ^b	4400	3800	1150/2400 ^b	4200	4200
Total PM ₁₀ (g/TEU)	10/100 ^b	130	130	10/100 ^b	90	90
Total time (hr)	8	42	25	8	60	60
Total distance (mi)	550	510	530	550	510	510
Total cost (\$/TEU)	480	400	430	480	400	400

Notes: ^aCase A refers to a case in which the ship used is based on the *Dutch Runner*, a container vessel. Case B refers to a case in which the ship used is based on the *Ellie J.*, a tug-and-barge vessel. ^bThe first value represents a Class 8 truck meeting model year 2007 emissions standards of 1.2 g/bhp-hr for NO_x and 0.01 g/bhp-hr for PM; the second value represents a Class 8 truck meeting model year 2004–2006 emissions standards of 2.5 g/bhp-hr for NO_x and 0.10 g/bhp-hr for PM.

One important outcome of these results is the relative importance of vehicle, route, and operating characteristics as they pertain to energy use and CO₂ emissions. Lately, competing interests in the freight sector have argued publicly that their mode of transportation is “greener”

than other modes. These comparisons rely on top-down analyses using fleet averages that shroud the true variability that exists with respect to shipping goods. For example, at least one freight rail provider’s Web site (<http://www.csx.com>) compares average fuel consumption factors for rail with fuel consumption factors for truck to calculate carbon benefits of a modal shift. Such comparisons are inappropriate; depending on the type of freight being moved, route characteristics, transport speed, and locomotive/truck characteristics, the results of these comparisons may be very different. Here, this variability is demonstrated in the shipping sector through a comparison of freight movement with two distinctly different Great Lakes vessels. In this analysis, the *Dutch Runner* emits approximately 50% more CO₂ than the *Ellie J.* In fact, the *Dutch Runner* emits more CO₂ (240 kg/TEU) than rail (190 kg/TEU); however, the *Ellie J.* (160 kg/TEU) emits less. Additionally, Table 2 shows results of other pollutants (e.g., NO_x) and how these results may be affected based on the model year of the truck used for transport, with a factor of 2 difference shown for NO_x emissions in particular. Understanding the importance of vehicle, vessel, or locomotive vintage is particularly important given new regulations by the U.S. Environmental Protection Agency (EPA) on exhaust emissions standards from these modes. These results point to the importance of activity-based calculations when making these comparisons.

Despite the emissions differences one might expect from modal variability and the difficulty this uncertainty introduces into modal comparisons, one should not feel paralyzed. Table 2 shows that there is a significant gap between the amount of CO₂ emitted by trucks (460 kg/TEU) compared with rail or ship. This is also true for the differences in time of delivery between the three modes. Even if truck were to decrease its carbon emissions by a factor of 2 (perhaps through increased fuel efficiency or the use of low-carbon fuels), rail and/or ship would still be preferred as the low-carbon choice. The opposite is true for time of delivery. For instance, the truck could travel one-third as fast and still be the least-time choice. Future research will examine the sensitivity of the results to probabilistic uncertainties in the inputs given the characteristics of the truck, locomotive, and vessel fleets serving the Great Lakes. In particular, it is expected that sources of

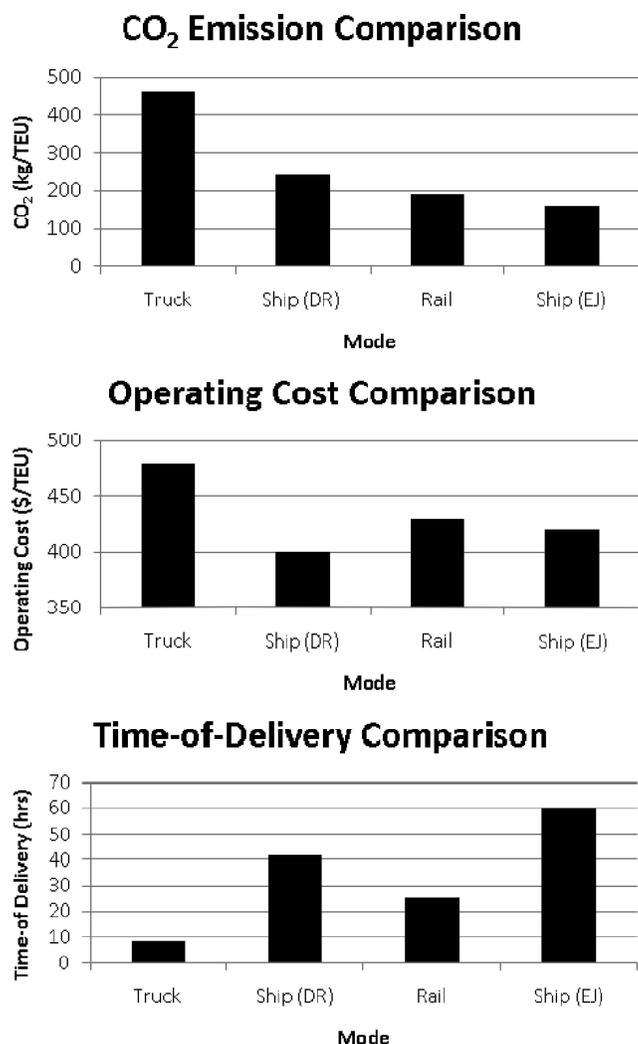


Figure 2. Results for the Montreal-to-Cleveland route based on (a) least-CO₂ objective function, (b) least-cost objective function, and (c) least-time objective function.

uncertainty will include emissions factors; speeds, especially during congested periods of the day; delays associated with locks and border crossings; fuel quality; and other factors.

What is perhaps more important than the actual values of the aggregate CO₂ emissions, time of delivery, and cost are the tradeoffs that exist. Traditionally, the most important attributes were time of delivery and cost. Truck remains the most expensive mode of freight transport in the Great Lakes region under published rate comparisons, and rail and ship may compete to be the cheapest mode, depending on the other service requirements imposed on these modes. With GIFT, tradeoffs that incorporate environmental performance metrics such as CO₂ emissions or emissions of other pollutants such as NO_x and PM₁₀ can now be examined. These tradeoffs are most prominently on display in Table 2.

CONCLUSIONS

Discussions of the competitiveness of rail and ship compared with trucks require understanding the tradeoffs associated with any mode that is chosen. Trucks are often the fastest way to move containers but emit the greatest amount of CO₂. Ships are often the cheapest way to move containers but have a relatively longer time of delivery, and some ships offer the lowest CO₂ alternative at less cost than trucking, albeit with potential penalties in NO_x or PM emissions. Environmental policy incentives to make ships more attractive and competitive with trucks must consider multiple performance metrics (e.g., not just time of travel) to incentivize freight transportation in the Great Lakes region by ship.

Some policies that could make ships a more attractive mode of freight transportation include infrastructure development, technology implementation, and economic incentives. A framework for such policies has been recently presented called IF-TOLD.³⁰ The letters of this acronym represent:

- Intermodalism/infrastructure for mode-shifting: using different transportation modes to provide freight services, such as rail or ship instead of truck or air, and including concomitant infrastructure development
- Fuels: burning low-carbon or clean fuels
- Technology: applying efficient technologies within each mode
- Operations: using best practices in operator behavior
- Logistics: improving supply-chain management
- Demand: reducing the amount of goods that are shipped, measured in ton-miles

Policy-makers can use GIFT to evaluate various IF-TOLD mechanisms, the most obvious being the benefits of intermodal transport and mode shifting in meeting policy goals. However, GIFT can also be used to explore the benefits of low-carbon fuels, the opportunities of advanced emissions control devices, and emissions impacts of supply chain logistics because of decisions related to the location of distribution centers. The model can also test the consequences of carbon taxes, fuel taxes, or modal subsidies by adjusting costs in GIFT and observing the routing impacts due to these economic instruments.

For example, to incentivize a shift to marine-based freight transport in the Great Lakes, policies could include carbon taxes, port and lock infrastructure improvement and development, and modal subsidies and grants. A carbon tax would increase the cost of shipping freight by truck because of its carbon intensity. At some price for carbon, less carbon-intensive modes such as ships would become more attractive. Port and lock infrastructure improvement and development would allow for more opportunities for container vessels to operate on the Great Lakes as well as reduce lock delays to reduce time of delivery. Modal subsidies and grants for shippers who switch from truck to ship would provide an economic incentive to utilize the Great Lakes as a freight transport corridor. Although transporting freight by ship will be slower than truck, the economic savings may help balance the "cost" of a longer time of delivery. These types of policies need to be studied and evaluated as the Great Lakes take on a greater role in international cargo transport in the coming decades.

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About the Authors

The authors consist of members of the Sustainable Intermodal Freight Transportation Research (SIFTR) project jointly run by the Rochester Institute of Technology and the University of Delaware. Bryan Comer and Chris Prokop are graduate students at the Rochester Institute of Technology. Dr. James Corbett and Dr. Earl Lee are faculty at the University of Delaware. Dr. J. Scott Hawker, Dr. Karl Korf-macher, and Dr. James J. Winebrake are faculty members at the Rochester Institute of Technology. Please address correspondence to: James J. Winebrake, Rochester Institute of Technology, Public Policy Department, Rochester, NY 14623; phone: +1-585-475-4648; fax: +1-585-475-2510; e-mail: jwinebrake@mail.rit.edu.