St. Lawrence Seaway: Overview of Safety, Efficiency, Operational, and Environmental Issues

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16. Abstract

This report is the first in a series of two reports focused on identifying opportunities for application of Intelligent Transportation System (ITS) technology – or equivalent – to address challenges and/or opportunities in the St. Lawrence Seaway. This paper summarizes current condition, challenges faced, and potential opportunities for application of ITS on the St. Lawrence Seaway. It also documents existing applications of technology on the Seaway. A subsequent paper in this series presents applications of ITS – or more broadly, Information and Communications Technology (ICT) – and other novel technologies in maritime transportation operations elsewhere in the world. It also documents some initial parameters of several candidate applications for the St. Lawrence Seaway.

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The contents of this paper reflect the research findings and recommendations of the Volpe Center authors, and not necessarily the opinions of the other organizations mentioned above.

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List of Abbreviations

Abbreviation	Term
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
ATON	Aid-to-Navigation
CCG	Canadian Coast Guard
ConOps	Concept of Operations
DIS	Draft Information System
DGPS	Differential Global Positioning System
DOT	U.S. Department of Transportation
ECDIS	Electronic Chart Display and Information System
EPA	U.S. Environmental Protection Agency
GLPA	Great Lakes Pilotage Authority (Canada)
GLSLB	Great Lakes-St. Lawrence Basin
GPS	Global Positioning System
IMO	International Maritime Organization
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LPA	Laurentian Pilotage Authority (Canada)
MARAD	U.S. Maritime Administration
NCFRP	National Cooperative Freight Research Program
PSC	Port State Control
SLSDC	Saint Lawrence Seaway Development Corporation (U.S.)
SLSMC	St. Lawrence Seaway Management Corporation (Canada)
SLSPA	St. Lawrence Seaway Pilots Association (U.S.)
TMS	Traffic Management System
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
VHF	Very High Frequency (a radio frequency band from 30 MHz to 300 MHz)
WGLPA	Western Great Lakes Pilotage Association (U.S.)

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1. Introduction

The St. Lawrence Seaway is a binational waterway along the border between Canada and the United States that connects the Atlantic Ocean to the Great Lakes. Though the St. Lawrence Seaway System proper extends from Montréal to the middle of Lake Erie, it serves the broader Great Lakes-St. Lawrence Seaway System spanning the entire St. Lawrence River and all five Great Lakes. First opened to navigation in 1959, the St. Lawrence Seaway carries about 40 million metric tons of cargo annually and generates billions of dollars in employment, purchases, and tax revenue in both the U.S. and Canada [1].

The St. Lawrence Seaway is an economic generator for an area of the U.S. containing about one quarter of the U.S. population, and offers significant environmental benefits through the movement of cargo by water. A single Seaway-size vessel can carry the same amount of cargo as more than 300 rail cars or 960 trucks, making ship-born transport of cargo seven times more fuel-efficient than truck and marginally more efficient than rail [2]. Moreover, moving cargo on the St. Lawrence Seaway means removing trucks from congested highways and arterials, or reducing the demand on an increasingly busy rail corridor.

The St. Lawrence Seaway is a vital transportation resource for the region, for the U.S., and for Canada—as such, its safe and efficient operation is of the utmost importance. It is within this context that the U.S. DOT's Volpe National Transportation Systems Center (Volpe Center) has initiated a project to examine opportunities to improve Seaway operations through the application of Intelligent Transportation Systems (ITS) technology.

1.1. Project Context

In September 2015, the U.S. DOT Volpe National Transportation Systems Center (Volpe Center) initiated a project with the ITS Joint Program Office (ITS JPO), in coordination with the Saint Lawrence Seaway Development Corporation (SLSDC) and The St. Lawrence Seaway Management Corporation (SLSMC), to evaluate opportunities to apply ITS technology to the St. Lawrence Seaway. The project will ultimately culminate in the development of a Concept of Operations (ConOps) documenting one or more high-potential applications to be considered for implementation on the St. Lawrence Seaway.

1.2. Report Purpose

This paper is the first of two foundational resources for the project and is focused on summarizing current conditions, documenting operational challenges, and identifying preliminary opportunities to apply ITS concepts or technology to improve efficiency on the St. Lawrence Seaway. It serves as an informational resource for St. Lawrence Seaway stakeholders, the SLSDC, the SLSMC, and the ITS JPO, as well as a context-setting document for subsequent phases of the project.

The second framing paper will explore applications of ITS and other technologies in marine transportation generally, and outline a series of new or existing candidate applications for consideration by Seaway stakeholders in mid-2016.

The information contained in this paper is primarily drawn from a review of available literature, supplemented by interviews with key Seaway officials in both the U.S. and Canada. It is also supported by insights gained through a focus group meeting held in January 2015 with a group of Seaway stakeholders representing shipping and port operations interests in the region.

2. Overview of the St. Lawrence Seaway

This section presents an overview of the St. Lawrence Seaway, summarizing its location and physical constraints, its functional role in the Great Lakes region, groups responsible for maintaining and operating it, and stakeholders who work along it.

2.1. Physical Overview

The St. Lawrence Seaway officially extends from Montréal, southwest along the St. Lawrence River, through Lake Ontario and into the middle of Lake Erie (see figure 1). It consists of dredged portions of the St. Lawrence River and five short canals connected by seven locks, with an additional eight locks in the Welland Canal between Lake Ontario and Lake Erie. The U.S. controls two locks (Snell and Eisenhower) while the rest are controlled by the Canadian government. Sailing from Montréal to Erie, PA, ships travel close to 400 nautical miles in a typical transit time of about two days [2]. Traveling through all 15 locks also covers a vertical distance of more than 180 meters, to accommodate the change in water level as it rises from the Gulf of Saint Lawrence up to Lake Erie.

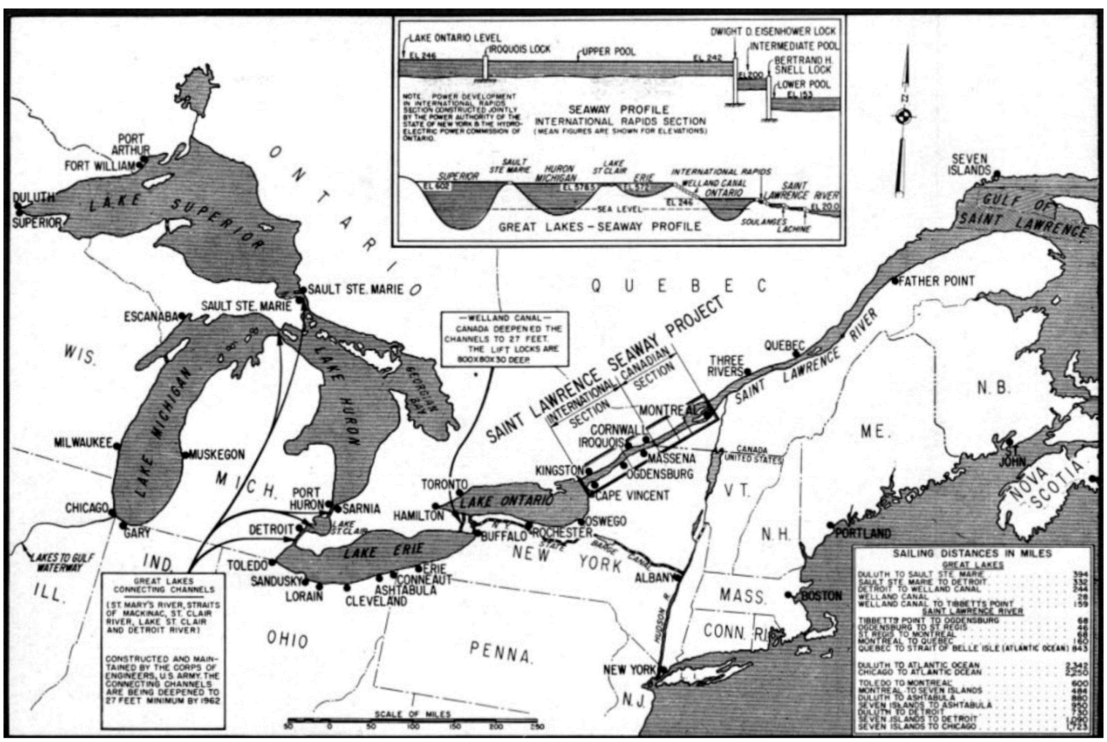

Figure 1: Map of St. Lawrence Seaway upon its opening to navigation in 1959
(Source: *All Hands, U.S. Navy,* September 1959, p. 9)

The St. Lawrence Seaway operates on a seasonal basis, due to weather conditions and maintenance requirements. The navigation season typically spans mid-March through late-December, although the specific dates of opening and closing are contingent upon temperatures and icing conditions, which present a variety of challenges for lock operation.

The SLSDC and SLSMC publish specific operating guidelines annually for vessels transiting the Seaway and add additional requirements during Seaway opening and closing periods when ice is often present in the system. These additional requirements typically apply during opening period (late March/early April) and during the closing period (late November through the month of December), as ice conditions are more common, necessitating changes in lockage procedures. Floating aids to navigation are removed prior to the closing and are not recommissioned until after the Seaway is opened due to ice conditions. The temporary operating procedures increase reporting requirements, require SLSDC/SLSMC approval for certain transits, and introduce specific vessel requirements and restrictions.

2.1.1. Locks

The 15 locks comprising the St. Lawrence Seaway have dimensions that vary slightly but each has a minimum useable length of 766 feet, width of 80 feet, and depth over the sill at the lock entrance of 30 feet."[1] These dimensions allow each lock to accommodate ships measuring up to 740 feet in overall length and 78 feet in beam; these are known as "Seawaymax" vessels. With just two feet of lateral clearance and 26 feet of longitudinal clearance between a Seawaymax vessel and lock structures, the current lock system leaves little room for accommodating larger ships (See figure 2).

Figure 2: Vessel Maneuvering into a Lock
(Source: SLSDC Facebook Page)

Ships enter and exit Seaway locks under their own power. Depending on the individual lock, ships are secured within the lock chamber either manually with mooring lines or automatically by a hands-free vacuum mooring system (see section 4.2.3). Each lock is equipped with at least one set of heavy, steel gates at each end of the lock chamber; some locks are equipped with two sets of gates for safety and redundancy. The lower lock gates are protected from possible damage by a moving vessel through use of a "ship arrestor," a large diameter steel cable or multiple smaller diameter cables that are lowered temporarily by a boom and secured to braking machinery within each lock wall while a ship is entering the lock chamber and maneuvering into place. The upper gates are protected by a concreate wall/bumper at each lock.

[1] These are the minimum dimensions of each lock chamber. Some lock chambers are longer (for example, Lock 8 is 1,148 ft. long), but maximum vessel dimensions are constrained by the smallest chamber.

Locks are filled or drained by gravity, without the use of pumps, through a complex system of culverts, valves, ports and diffusers built into the lock chamber's structure (see figure 3). Each downbound ship transit through a lock results in approximately 20 million gallons of fresh water flowing eastward towards the Atlantic Ocean.

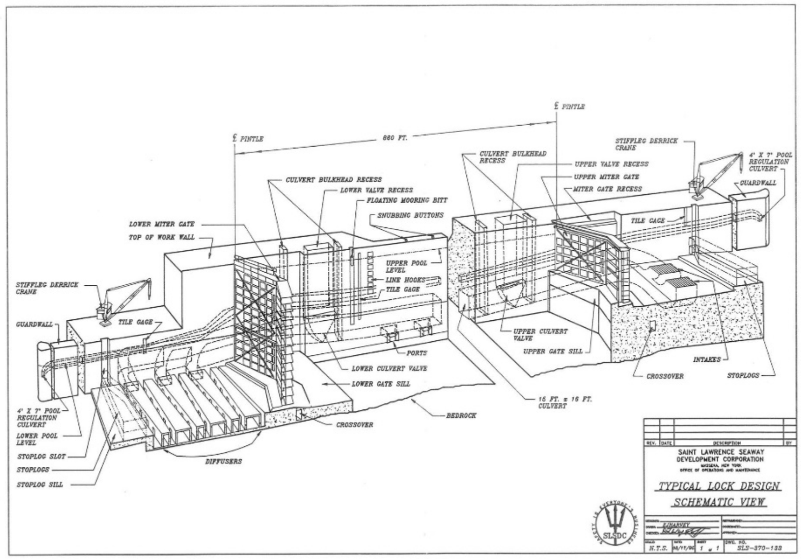

Figure 3: Typical Design of a Seaway Lock Chamber
(Source: SLSDC Facebook Page)

Twelve of the locks in the St. Lawrence Seaway are single lock systems, which limit traffic flow to one direction at a time. Only three locks—the "Flight Locks" or locks 4, 5 and 6 in the Welland Canal—are double or parallel locks. This lack of redundancy means that a failure of one of the single locks can cause cascading delays across the entire Seaway, as vessels have no means of bypassing a failed lock [3].

2.1.2. Canals

Four canals connect the St. Lawrence River, Lake Ontario, and Lake Erie to the lock systems. Three of these canals (from east to west: the South Shore, Beauharnois and Welland) are operated and maintained by the Canadian SLSMC. The fourth canal, the Wiley-Dondero Canal, is operated and maintained by the U.S. SLSDC, and spans the waterway between the Snell Lock (at its eastern end) and the Eisenhower Lock (at its western end).

In order to pass through the dredged channels, canals and locks, ships must maintain a draft of no more than 26 feet 6 inches, though ships equipped with a new Draft Information System (DIS; see section 4.2.2) are granted up to an additional three inches of draft. Ships are required to maintain a minimum under-keel clearance of one foot, and channels throughout the Seaway are maintained at a minimum depth of 27 feet below low water datum [4] [5].

2.2. Functional Context

The St. Lawrence Seaway functions as a critical link within the larger Great Lakes-St. Lawrence Seaway system, allowing passage between the Atlantic Ocean and all of the five Great Lakes. Combined with a set of locks controlled by the U.S. Army Corps of Engineers that connect Lake Huron and Lake Superior, ships can traverse the nearly 1,200 nautical miles between Duluth, MN, and Montréal, and ultimately to ports in Europe and elsewhere.

Iron ore and grain constitute the majority of cargo moved through the St. Lawrence Seaway to and from U.S. ports [1]. More generally, bulk and liquid cargo represent 90 percent of the tonnage carried by ships in the broader Great Lakes-St. Lawrence Seaway system, with carriage of manufactured goods by container or roll-on/roll-off ships limited to ten percent. Overall, various constraints impact freight movements within the Seaway including seasonality (more on these constraints in section 5) [6].

Two general types of ships operate in the Seaway, “lakers” and “salties”. Lakers are freighters up to 740 feet in length and are typically configured to carry bulk cargo (iron ore, grain, etc.). Lakers up to 1,000 feet in length can operate in the upper Great Lakes but cannot pass east of the Welland Canal. Lakers are designed specifically for operation in the Great Lakes-St. Lawrence Seaway System; although Seawaymax lakers can travel through to Montréal, they are not legally authorized to operate in open ocean waters. Salties are ocean-going vessels that can travel from the Atlantic Ocean to ports throughout the Great Lakes-St. Lawrence Seaway system; the dimensions of the Seaway lock chambers limits the size of vessels traveling west of Montréal to the Seawaymax dimensions of 740 feet in length and 78 feet in beam. Larger ocean-going vessels can travel up the St. Lawrence River as far west as Montréal.

All foreign-flagged vessels are subject to compulsory pilotage requirements when operating in the Great Lakes St. Lawrence Seaway System. Pilotage requirements apply to all waters within the Great Lakes and the St. Lawrence Seaway, as well as the Seaway canals [7] [8].

2.3. Organization and Management

The St. Lawrence Seaway is jointly operated by organizations in the U.S. and Canada. The Saint Lawrence Seaway Development Corporation is a wholly owned government corporation within the U.S. Department of Transportation that is responsible for the operation and maintenance of portions of the St. Lawrence Seaway that fall within U.S. jurisdictional limits, including the Snell and Eisenhower Locks and two of the four vessel traffic control sectors within the St. Lawrence Seaway system. As part of its responsibility for operating portions of the St. Lawrence Seaway, the SLSDC maintains approximately 100 fixed and 100 floating navigation aids. The SLSDC also supports trade development through the Great Lakes Seaway System, which contributes to regional economic and environmental development.

The St. Lawrence Seaway Management Corporation is the SLSDC’s Canadian counterpart. It is a not-for-profit corporation charged with operating the 13 locks owned by the Canadian federal government. The SLSMC also controls vessel traffic in two of the four vessel traffic control sectors.

The Maritime Administration (MARAD) is the U.S. Federal agency responsible for waterborne transportation within the U.S. DOT. Although MARAD doesn’t play a direct role in the administration of St. Lawrence Seaway, its programs promote the use of waterborne transportation and integration with other segments of the transportation system. MARAD also supports the viability of the U.S. merchant marine, and works in many other areas involving ships and shipping, shipbuilding, port operations, vessel operations, national security, environment, and safety.

The U.S. Coast Guard (USCG) and Canadian Coast Guard (CCG) also play significant roles in St. Lawrence Seaway operations. They work with both the SLSDC and SLSMC to coordinate icebreaking operations prior to the spring opening date. The CCG is also responsible for maintaining navigation aids in the Canadian-controlled canals and waterways. The SLSDC maintains navigation aids within U.S. waters of the Seaway, while the USCG maintains all other navigation aids in U.S. waters on the Great Lakes and adjacent waterways.

The USCG is responsible for registering vessels under the U.S. flag and performing safety inspections on vessels registered in the U.S., while Transport Canada exercises these functions for vessels registered in Canada. Both the USCG and Transport Canada exercise port state control (PSC) functions for foreign vessels calling on their respective U.S. or Canadian ports. The PSC program verifies that foreign flagged vessels comply with applicable international conventions, as well as national laws and regulations in their ports of call.

The U.S. Army Corps of Engineers (USACE) was involved in the initial planning and design of the St. Lawrence Seaway; with the formation of the SLSDC in 1954, the USACE ultimately served as the construction agent for the Seaway [9]. Though it is not directly involved in Seaway operations today, the USACE provides technical support when requested, through interagency agreements with the SLSDC. The USACE operates the Soo Locks at Sault Ste. Marie, MI, which links Lake Huron to Lake Superior, allowing clear passage between the Atlantic Ocean and all five Great Lakes.

2.4. Stakeholders

As with any complex transportation system, the St. Lawrence Seaway System has a wide variety of stakeholders. These include public and private entities that fall into the broad categories identified below; a detailed list may be found in appendix A. It should be noted that the Seaway is part of a large, multi-modal, bi-national regional transportation system. Freight movements—whether moving bulk commodities like grain, ore and liquid cargoes; containerized cargo; or specialized "project" cargo—may involve multiple modes during its journey from origin to destination. Furthermore, since freight is moved by commercial carriers, a natural tension exists among modal stakeholders, as each competes for business. As a result, the pool of stakeholders will vary depending upon whether viewed from the perspective of a regional, multi-modal system or a single mode, or as a public infrastructure owner vs. commercial service provider. Since this report focuses primarily upon waterborne transportation, the list of stakeholders reflects that mode.

2.4.1. Infrastructure Operators

This group of stakeholders represents the two principal public agencies of the U.S. or Canada that own, operate and maintain the locks, moveable bridges, fixed spans or tunnels crossing the Seaway, as well as entities that maintain the fixed and floating navigational aids along the waterway. Two Canadian railroad companies are also responsible for maintaining privately-owned moveable railroad bridges spanning the Seaway; operation of these structures is coordinated by Seaway.

- Canadian Coast Guard (Ottawa, ON)
- Canadian Pacific Railway (CP) (Calgary, Alb.)
- Canadian National Railway (CN) (Montréal, QC)
- Saint Lawrence Seaway Development Corporation (Washington, D.C.)
- The St. Lawrence Seaway Management Corporation (Cornwall, ON)
- U.S. Coast Guard, 9th District (Cleveland, OH)

2.4.2. Non-port federal, state, provincial or binational government entities

These are the principal public agencies of the U.S. or Canada that have varying degrees of jurisdiction over, or engagement in, the operations of the Seaway itself, within the Great Lakes-St. Lawrence Seaway region, or over the operation of Seaway users. Also included in this group is the International Maritime Organization

(IMO), an international body of United Nations with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. (See appendix A for the complete list.)

2.4.3. Vessel owners/operators

Dozens of U.S., Canadian and foreign companies own or operate commercial vessels on the Seaway. Appendix A identifies 20 significant users of the Seaway, as well as the major companies that provide liner service to Montréal and those operating exclusively within the Great Lakes as far east as Lake Erie. In general terms, Canadian- and foreign-flag cargo vessels originating from or destined for Canadian ports are the predominant users of the St. Lawrence Seaway. U.S.-flag cargo vessels primarily operate within the confines of the Great Lakes. Although few U.S. flag vessels traverse the Seaway to call on U.S. ports, recent years have seen an increase in U.S. port call in this segment.

Four companies stand out due to the number of vessels they operate on the Seaway: Algoma Central Corporation (operating 31 ships), Canada Steamship Lines (operating 66 ships), Canfornav (operating 41 ships) and Fednav Limited (operating 64 ships). While not all of the vessels owned by these companies operate on the Great Lakes-St. Lawrence Seaway system, many of them do, representing a significant portion of total traffic.

2.4.4. Port and terminal and shipyard owners and operators

Port and terminal owners and operators are the U.S. or Canadian public, quasi-public and private entities that own, oversee, manage or operate the commercial ports and cargo terminals in the Great Lakes-St. Lawrence Seaway system. Individual ports may be managed by a single regional, state or municipal port authority, or may simply serve as host to an independent terminal operating company. Similarly, a single port may have multiple terminal operators managing various piers and cargo facilities. The list contained in appendix A identifies the principal port and terminal owners in the region. This report does not list the hundreds of individual companies that may support cargo operations within individual ports, except in cases where a single entity (typically a private terminal operator) appears to be the sole entity operating within the geographic confines of a port.

2.4.5. Service providers

Thousands of individual businesses support the vessels that operate on the Great Lakes-St. Lawrence Seaway system, or support the maintenance and operation of the physical infrastructure (locks, canals, bridges, tunnels). These include shipyards, pilotage associations, bunkering (fueling), brokerage, freight forwarding, vessel operations, dredging, vessel maintenance and repair, chandlery, insurance, crewing, and other marine services. The list contained in appendix A is not exhaustive, but includes some of the more prominent service providers in the region.

2.4.6. Major shippers of commodities and finished products

The list found in appendix A represents many of the primary U.S. or Canadian commercial enterprises that move their bulk commodities or finished products—whether import or export—on the Great Lakes-St. Lawrence Seaway System.

2.4.7. Public and private advocacy groups

Public and private advocacy groups are the numerous organizations that serve statutory or chartered advisory or advocacy function on behalf of specific environmental causes, economic development, user groups, labor unions, or other interests within the Great Lakes-St. Lawrence Seaway region. A list of the principal advocacy groups is found in appendix A.

2.4.8. Recreational users

The Great Lakes-St. Lawrence Seaway system is a major attraction to recreational users. From sailing yachts to motor boats, anglers, kayakers and other outdoorsman, millions of people from the U.S., Canada and other nations take advantage of this natural resources each year. Hundreds of vessels travel through the canals and locks of the St. Lawrence Seaway, traveling between the Lake Erie and Lake Ontario, or between the Atlantic Ocean and the Great Lakes.

Since this report is focused primarily on the commercial or non-recreational use of the Great Lakes-St. Lawrence Seaway System, it does not address the extensive, diverse and exceptionally vibrant spectrum of recreational usage of the waterways and surrounding shoreside communities, or the many hundreds of smaller marine businesses (e.g., boat builders, yacht harbors, marinas, etc.) that operate in the region. These groups have an important role in Seaway operations and planning. While they are not identified individually, their interests as stakeholders are represented through many of the government agencies, port authorities, and public and private advocacy groups identified elsewhere in this report.

3. Overview of Existing Conditions

This section summarizes existing safety, environmental, and economic conditions within the St. Lawrence Seaway and the broader Great Lakes-St. Lawrence Seaway system. These sections rely on four key resources, which document these issues in great detail:

- ***Great Lakes St. Lawrence Seaway Study*** (available at: www.seaway.dot.gov/sites/seaway.dot.gov/files/docs/Army%20Corps%20-%20Great%20Lakes%20Seaway%20Study.pdf) [10]
- ***Safety Profile of the Great Lakes-St. Lawrence Seaway System*** (available at: www.seaway.dot.gov/sites/seaway.dot.gov/files/docs/Safety%20Profile%20-%20Full%20Report.pdf) [11]
- ***Environmental and Social Impacts of Marine Transport in the Great Lakes-St. Lawrence Seaway Region*** (available at: www.greatlakes-seaway.com/en/pdf/Impacts-Full_En.pdf) [12]
- ***The Economic Impacts of the Great Lakes-St. Lawrence Seaway System*** (available at: www.greatlakes-seaway.com/en/pdf/eco_impact_full.pdf) [1]

This section also draws from annual reports produced by the SLSDC and SLSMC, available at: www.seaway.dot.gov/publications/annual-reports and www.greatlakes-seaway.com/en/management/slsmc/reports

3.1. Safety

Marine transportation represents a comparatively safe way of transporting goods relative to available surface modes. Open water generally presents less traffic congestion than road or even rail, crew members receive extensive training, and the combination of international standards set by the IMO and Seaway-specific standards and enforcement by national agencies in the U.S. and Canada ensure that vessels transiting the Seaway are in safe condition. In addition, the U.S. Oil Pollution Control Act of 1990 requires that vessels that transport liquid bulk oil products are double-hulled which is more stringent than the requirements for transporting oil via rail. Other factors that ensure safety include the Enhanced Seaway Inspection Program, the use of vessel tracking through an Automatic Identification System (discussed later), continuous monitoring and management of waterway navigation channel depth, and the compulsory pilotage requirements covering both U.S. and Canadian waters.

Due to these and many other safety measures, the Seaway maintains an excellent safety record. Between 2002 and 2011, vessel accidents did not result in a single fatality and the vast majority of the 801 reported accidents and safety occurrences reported throughout the Great Lake-St. Lawrence Seaway System were classified at the lowest severity ratings maintained by the U.S. and Canada. Moreover, compared to freight transportation by rail in the U.S., shipment by Seaway produced 70 times fewer injuries on a per ton-mile basis [11]. The Maritime Administration (MARAD) suggests an even more significant safety gap between inland marine freight and movement of cargo by rail or truck. Nationwide data suggest that for every one fatality that occurs on inland waterways, more than 20 occur in rail freight and more than 150 occur in truck freight [13].

The Great Lakes-St. Lawrence Seaway System's overall safety performance has resulted in very few injuries and fatalities. Moreover, where there have been accident-induced spills of hazardous cargo in the System, these occurrences were minor: between 2002 and 2011 a total of 139 spills occurred, involving small quantities of product being released during loading/unloading or spills of fluids used aboard vessels (e.g., hydraulic fluid, lubricating oil, fuel oils). These spills amounted to about 3,500 gallons of fluid spilled over the ten-year reporting period, or 2½ cups for every million gallons carried by vessels in the Seaway [11].

3.2. Environmental

The Great Lakes-St. Lawrence Basin (GLSLB) comprise the world's largest fresh water system and environmental considerations play a significant part in operating the Seaway as a freight transportation network. Some of the most significant impacts of commercial navigation in the Seaway include those generated by dredging and ship wakes, as well as the past introduction of aquatic non-indigenous invasive species. A 2007 study of the GLSLB evaluated 35 environmental stressors for their relative impact based on: areal extent; temporal extent; and degree of reversibility. The authors of this study identified the following as the most sensitive navigational-related environmental stressors [10]:

- **Water management** – Operation of the Seaway involves regulation of water flows and levels for power generation, shoreline protection, and preservation of adequate channel depth. Where native flora and fauna had adapted to natural seasonal variations in water levels, fluctuations in water levels caused by regulation could have effected natural cycles.
- **Aquatic non-native invasive species** – In order to maintain stability, large ships carry water in tanks as ballast. A ship that fills its ballast tanks with freshwater overseas and releases its ballast water in the Seaway or Great Lakes threatens to introduce invasive species into the waterway, potentially jeopardizing native species and their habitat. Ballast water management requirements in the Great Lakes-St. Lawrence Seaway System are the most stringent in the world. Several strategies have been introduced to prevent non-native species from being introduced by foreign vessels, including prohibitions on foreign freshwater ballast; foreign ships can comply by discharging their freshwater ballast water in the mid-Atlantic and replacing it with saltwater. All ships travelling to Great Lakes ports from origins outside the exclusive economic zone must conduct this ballast water exchange [14]. Since the imposition of these more stringent ballast water management regulations in 2006, there has been no further introduction and establishment of a shipborne aquatic invasive species [15].
- **Channel modification** – Dredging to maintain navigation channels can increase turbidity, thereby reducing light penetration; release materials from waterway bottoms, including contaminants, nutrients, gases, and oxygen-consuming substances; impact fish and fish spawning habitat; remove important organisms living in or on the waterway bottom; and alter water flows.
- **Infrastructure development** – Construction and maintenance of ports, harbors, marinas and other infrastructure that supports the Seaway can impact environmental conditions in these areas. These activities can modify or eliminate terrestrial and aquatic habitats that are important to species breeding; damage or eliminate staging areas for migratory species; and release nutrient, toxic, or noxious substances into air and watersheds. More sustainable construction and maintenance practices are being introduced (for example, see Cat Island Chain Restoration Project being conducted by the Port of Green Bay).
- **Ships' air emissions** – The impact of ship air emissions is mixed. Ships account for less than three percent of all greenhouse gas emissions from freight transportation and marine transportation is far

more fuel-efficient – in terms of fuel consumed per ton-mile of cargo transported – than truck or rail alternatives. A 2013 study found that Seawaymax-sized vessels produce 18 percent lower greenhouse gas emissions than rail and emit about one fifth as much as truck-based freight transportation. Despite this environmental advantage in a global sense, ships operating their engines in port tend to negatively impact nearby air quality by releasing high concentrations of sulfur oxides, nitrogen oxides, and particulate matter. Regulations entering force through 2025 will gradually reduce emissions of these criteria air contaminant emissions [12].

Though these environmental impacts represent a significant consideration in Seaway operations, the waterway also plays a notable role in reducing broader environmental impacts. Inland marine transport is a significantly more fuel-efficient and less emission-intensive way of moving cargo and any cargo moved via the Seaway represents train cars and trucks that are not contributing to congestion in a busy freight corridor.

3.3. Economic

The eight states and two provinces in the Great Lakes region, if viewed as a single country, would represent the world's third largest economy after the United States and China [16]. The Seaway represents a significant source of economic activity within the region it serves. A 2011 study estimated that approximately 40 million metric tons of cargo passed through at least a portion of the Seaway in 2010, generating $12.3 billion in business revenue. The study also linked 86,000 jobs in the U.S. and Canada to the cargo that moves via the St. Lawrence Seaway, as well as $4.6 billion in various forms of consumption expenditures (direct, indirect, induced, and local) and $1.68 billion in taxes paid to all levels of government [1]. The Seaway's economic impact stems from, among other factors, two key characteristics. First, the Seaway sits within a hub of economic activity, surrounded by one quarter of North America's population and more than half of its manufacturing and service industries. As mentioned earlier, most of the cargo shipped via the Seaway is in bulk form and most of the industries that make use of bulk cargo transport via the Seaway depend upon the availability of this cost-effective service [10]. This cost effectiveness is the other key characteristic that supports the Seaway's economic impact on the region. A 2012 National Cooperative Freight Research Program (NCFRP) report found that shipping commodities to, from, or within the GLSLB via the Seaway cost roughly half of shipping by rail or, where applicable, pipeline. The report's authors estimated the truck-based shipping costs to be about four times higher than marine [6].

Despite the significant economic impact of the Seaway and its cost-competitiveness, marine shipping within the GLSLB operates with capacity to spare. All port representatives surveyed for the 2012 NCFRP report mentioned above reported excess capacity and more than half indicated that they had "significant available capacity" [6]. The authors of that report suggest that physical constraints on vessel size and the seasonality of Seaway operations are significant contributing actors to the development of excess capacity.

4. Technology in the St. Lawrence Seaway

4.1. Overview

The SLSDC and SLSMC, in coordination with their core stakeholders, have been quite progressive in the deployment of new technologies to improve operational efficiency and safety of the Seaway. This section summarizes noteworthy technology applications that have been deployed in the Seaway in recent years. Though these all generally fall outside of the traditional conception of ITS, their intent and application nonetheless resemble ITS, as typically applied in surface transportation.

Several definitions of ITS exist, but all generally specify the application of information and communications technologies to improving transportation safety and efficiency; in some cases, these definitions specify applications within the realm of surface transportation. Definitions from the leading authorities on ITS in the U.S. and Canada suggest a broad yet consistent definition of ITS:

> *U.S. DOT ITS Joint Program Office – ITS involves "…the integration of advanced communications technologies into the transportation infrastructure and in vehicles. Intelligent transportation systems encompass a broad range of wireless and wire line communications-based information and electronics technologies" [17].*
>
> *ITS America – "Intelligent transportation systems and services is the application of technology to enhance the movement of people and goods" [18].*
>
> *Transport Canada – "Intelligent Transportation Systems include the application of advanced information processing (computers), communications, sensor and control technologies and management strategies in an integrated manner to improve the functioning of the transportation system…These applications bring system users, vehicles and infrastructure together into one integrated system that enables the exchange of information for better management and use of available resources" [19].*
>
> *ITS Canada – "The application of advanced and emerging technologies (computers, sensors, control, communications, and electronic devices) in transportation to save lives, time, money, energy and the environment. Even with this definition, the term 'ITS' is an elastic one, capable of broad or narrow interpretation. It covers all modes, including ground transportation such as private automobiles, commercial vehicles, and public transit, and also rail, marine, and air modes. Because these are dynamic systems, the term 'ITS' is understood to include consideration of the vehicle, the infrastructure, and the driver or user, interacting together dynamically" [20].*

Some of the technologies in use on the St. Lawrence Seaway and, more broadly in marine navigation, communications, and operations have some similarities with ITS applications being developed within other transportation modes.

4.2. Seaway Specific Technology

This section describes four technologies that have been deployed within the St. Lawrence Seaway. While they are not unique to the Seaway, the Seaway has been a pioneer in their development and deployment.

4.2.1. Automatic Identification System

The St. Lawrence Seaway was the first waterway in the world to implement mandatory carriage requirements for a vessel Automatic Identification System (AIS). As of the 2003 navigation season, all ships with gross tonnage of 300 or greater, length of more than 20 meters, or capacity for more than 50 passengers were required to be equipped with AIS in order to transit the Seaway between Montréal and Lake Erie. The SLSDC and SLSMC, in coordination with their core stakeholders, worked with the U.S. DOT's Volpe National Transportation Systems Center to develop and implement the AIS network to meet the particular operating requirements of the Seaway.

AIS combines a global positioning system (GPS) receiver and a VHF digital radio transceiver to broadcast vessel position information and other data to the Seaway's Traffic Control Center (TCC). In return, AIS-equipped ships can receive broadcasts from the TCC about prevailing weather and waterway conditions, lock order of turn, and alerts and advisories. Moreover, AIS-equipped ships can also receive communications directly from other AIS-equipped ships and are, therefore, aware of type, size, position, course, and speed of all nearby ships.

AIS data can be displayed on a stand-alone device, or fed to other shipboard navigation devices such as an Electronic Chart Display & Information System (ECDIS) or a portable pilot unit (PPU). This information increases the situational awareness of the vessel's master and other officers; assists is decision making; and reduces risk and increases safety when maneuvering in crowded, confined waterways. AIS-generated real-time ship traffic data are also available publicly at www.greatlakes-seaway.com/en/navigating/map/.

4.2.2. Draft Information System

Every vessel behaves differently while in motion, based upon hull design, loading condition, and speed, and this behavior is further influenced by weather, width of the waterway, depth of water between the ship and the bottom, and the shape or contour of the waterway. These factors influence how much the bow or stern of a vessel will settle or "squat" deeper in the water while underway. Due to this variability from ship to ship, the Seaway has historically taken a conservative approach when setting draft restrictions, in order to maintain a safe, minimum under-keel clearance. In practice, however, the maximum permitted draft of 26 feet 6 inches might be overly restrictive for certain vessels less prone to squat. These ships could theoretically be loaded with more cargo, and their speed managed more precisely in shallow water, in order to reduce squat and therefore avoid the risk of running the ship aground.

In 2012, the SLSDC and SLSMC began to allow ship operators to use a new system that enables ships to safely take full advantage of the available water column within the Seaway. The Draft Information System (DIS) merges data on current water levels, channel type and bathymetry with specific vessel characteristics, speed, and hydrodynamic behaviors to provide ship operators with an indication of current and predicted under-keel clearance (the distance between the lowest point on a ship's hull and the waterway bottom).

The DIS integrates bathymetry, water level, and ship-type characteristic data and speed in order to derive real-time estimates of squat and resulting under-keel clearance for five types of ships (New Laker, Traditional Laker, Oceangoing Laker, Oceangoing Bulker, and Chemical Tanker) [4]. The DIS also includes a "look-ahead" feature, which predicts a ship's squat and identifies areas ahead of the Seaway where minimum under keel clearance (one foot) will be violated if the vessel continues on the same course and at the same speed (see figure 4).

The ability of mariners to know and predict their vessel's under-keel clearance throughout the Seaway allows them to potentially operate at both deeper drafts and higher speeds in certain portions of the waterway—reducing the chance of grounding while operating within the Seaway's draft requirements. The DIS provides a much more precise and tailored understanding of the most important safety metric: under keel clearance.

Figure 4: Typical DIS Display
(Source: MarineLink)

Figure 5: Hand-Free, Vacuum Mooring System
(Source: Cavotec)

Since ships equipped with the DIS can actively monitor and predict their adherence to under keel clearance requirements, the SLSDC/SLSMC allow them to sit three inches lower in the water than unequipped ships (26'9", versus 26'6"). Though virtually unnoticeable to an observer on shore, these additional three inches of draft represent an additional 360 metric tons of payload that can be loaded onto Seawaymax vessels. With little impact to vessel fuel consumption, this additional capacity improves the environmental efficiency and economic viability of shipping goods by Seaway.

4.2.3. Hands-Free Mooring

The most recent technology installation within the St. Lawrence Seaway has dramatically reduced the need for manual line handling within locks for most lockages. Traditionally, ships enter a lock chamber and dedicated lock staff secure it in the correct position using wire or synthetic mooring lines affixed to cleats and bollards along the lock chamber. The hands-free mooring system uses mechanically-deployed vacuum pads mounted to steel arms, which attach to a ship with up to 20 tons of force and can move vertically with the ship (while holding it in position within the lock) as the water level raises or lowers the ship. The SLSMC estimates that the hands-free mooring system can save about three and a half minutes from each lock transit, while maintaining a more precise position in the lock chamber, particularly as water fills or drains from the lock chamber. (See figure 5.)

The hands-free mooring system is installed on eleven locks currently (all operated by the Canadian SLSMC), once deployed throughout the Seaway, the system will shorten the overall transit time in each direction by nearly an hour. Moreover, the system creates safer conditions for lock staff and ship crewmembers, who no longer have to manually handle wire rope or synthetic mooring lines, which occasionally fail and have been responsible for injuries and fatalities in the past. The SLSDC and SLSMC also suggest that the hands-free mooring system makes the Seaway more competitive and attractive to ship operators. In addition to the reduced transit times, the hands-free mooring system eliminates the need for Seaway-specific hardware, reduces the need for shore side line handlers, and can reduce the number of crew needed to operate a ship within transit requirements, thereby reducing operating costs [21] [22]. The SLSDC plans to install hands-free mooring systems in both of its locks by 2018 and the SLSMC plans to equip the rest of its locks with the system by the 2017 season [22].

4.2.4. Vessel Self-Spotting

Maneuvering large vessels in the tight confines of the Seaway's locks presents a significant challenge. A Seawaymax vessel has just 26 feet to spare fore and aft as it enters a lock chamber. Precisely maneuvering a vessel to its mooring position is a critical exercise that, if misjudged, has the potential to slow transit time or even damage lock equipment, ultimately delaying the transits of other ships due to the Seaway's predominant single lock systems. Traditionally, lock personnel relay instructions to a ship's bridge via radio as it enters a lock, which offers the pilot limited information about the ship's position.

The vessel self-spotting system, currently in use at the majority of the SLSMC locks, provides real-time information to a ship's master/pilot about its position relative to its final mooring position (previously provided verbally by the lock spotter during initial communications with inbound vessels via radio). The system uses an eye-safe 3D laser scanner at each end of the lock to measure the distance between the ship's bow and its final mooring position and displays this information on a large digital readout that is visible from the bridge. The system also broadcasts an automated message via radio when the ship is 25 meters and ten meters from its final mooring position, and when it reaches its final mooring position.

4.3. Other shipboard technologies

In addition to the four technologies described above, vessels operating in the Great Lakes-St. Lawrence Seaway system typically carry several other advanced transportation related technologies. These include advanced navigation systems for ships, communications systems, and traveler information systems.

4.3.1. Electronic Chart Display and Information System

Nearly all of the commercial cargo, tanker and passenger ships operating on the St. Lawrence Seaway are fitted with an Electronic Chart Display and Information System (ECDIS). These units integrate electronic navigational charts (maps) with other navigational data, such as position (derived from a GPS or DGPS system), speed, gyrocompass heading, radar, and water depth in a single display. These systems create a data-rich environment for officers navigating ships along the 1200-mile Great Lakes-St. Lawrence Seaway

System which improve their situational awareness of navigational hazards and other vessel traffic. System design and vessel carriage requirements are established by the IMO and are followed by both the USCG and CCG.

4.3.2. Global Maritime Distress and Safety System (GMDSS)

All commercial cargo, passenger and tank vessels operating in the Seaway are equipped with a GMDSS equipment suite. GMDSS is an internationally-standardized system that alerts shore-based communications and rescue agencies, as well as nearby vessels, in the event of distress or other shipboard emergency. GMDSS integrates data from communications and positioning systems to transmit detailed alert messages that include details about the specific vessel, its location, and the nature of its emergency to satellites and terrestrial stations. The use of GMDSS technology has dramatically improved maritime search-and-rescue and emergency response, by automating the emergency alert process; distributing alerts across a wider audience than stand-alone radio distress calls; and by providing actionable data.

4.3.3. Automatic Radar Plotting Aid (ARPA)

Every commercial cargo, passenger and tank vessel operating in the Seaway is equipped with an ARPA unit. Unlike conventional radar systems, ARPA units provide more precise tracking of targets, which improves situational awareness and decision making. The units display speed, relative position, true course and speed, and past and predicted tracks of “own-ship” and at least 40 separate target ships. ARPA units can be programmed to alert the navigation officer when a target ship is calculated to be on a collision course with their ship, or when a target ship is predicted to come within an established distance or closest point of approach (CPA) with their ship (e.g., within three miles). Some ARPA units allow operators to create “trial maneuvers” for their own ship, to determine what adjustments to their own ship’s speed or heading would allow for the safest passing distance between their own ship and one or more other vessels. Some ARPA units can also integrate AIS data, allowing operators to identify radar targets as specific vessels, which facilitates more productive voice communication between ships using marine band radios.

4.3.4. Navigational Telex (Navtex)

Navtex is an international, radio-frequency-based system that transmits navigational, weather and urgent marine safety information from a shoreside station to a shipboard receiver. Navtex coverage in the Great Lakes is provided by the CCG; the USCG does not operate Navtex transmissions stations in the region. Navtex data can be integrated with ECDIS units to increase situational awareness.

4.3.5. Communications systems

All commercial vessels operating in the Seaway must carry a VHF marine-band radio transceiver, and maintain a radio watch on designated safety channels at all times while the ship is underway. In addition, ships are equipped with other radio transceivers operating on designated marine bands in the satellite or terrestrial radio service.

4.3.6. Portable Pilot Units

Some of the pilot associations serving in the Great Lakes-St. Lawrence Seaway System utilize Portable Pilot Units (PPUs) to supplement shipboard navigational devices. (See figure 6.) These units typically consist of a ruggedized laptop and a dedicated DGPS antenna, and are connected to the ship's existing AIS receiver. (See figure 6.) More sophisticated units can include dedicated AIS receivers; highly accurate rate of turn generators; sensors that measure vessel roll, pitch and heave; and multiple antennae (necessary for exceptionally long ships); to achieve an extremely accurate position down to two centimeters and a heading precision within 0.01 degrees.

4.4. Other transportation technologies in use in the region

A number of other technologies are used within the Great Lakes-St. Lawrence Seaway region that are not associated with operation of the Seaway, but which incorporate data provided by the Seaway into applications used for other purposes and in other transportation modes.

4.4.1. Vessel tracking systems

The St. Lawrence Seaway uses AIS data to provide a real-time tracking system that allows shippers, vessel owners, marine service providers, local businesses, and any member of the general public to monitor vessel traffic on the Seaway (see figure 7). AIS technology is also used by other government and private entities to develop vessel tracking services.

The USCG manages a U.S. network of approximately 200 receiver sites located throughout the coastal and inland U.S. waters, while the CCG operates 96 comparable stations in Canada. These networks gather and disseminate data to increase federal Maritime Domain Awareness (MDA), particularly focusing on improving maritime security, marine and navigational safety, search and rescue, fisheries management, and environmental protection services. The USCG may share AIS data with other nations; with other federal, state and local agencies (e.g. customs, law enforcement); and with private entities that meet certain criteria (e.g., research). The USCG does not share its AIS network data with the general public.

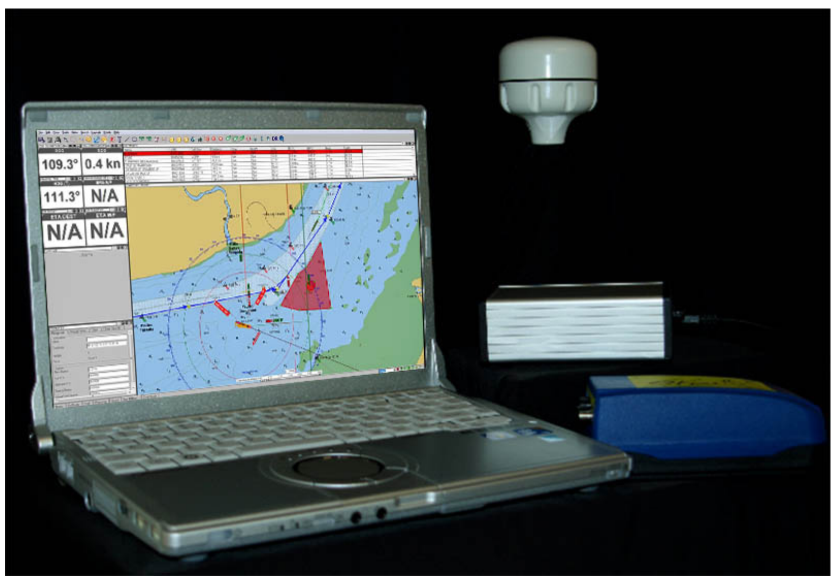

Figure 6: PPU System used by Great Lakes Pilotage Authority
(Source: NavSim)

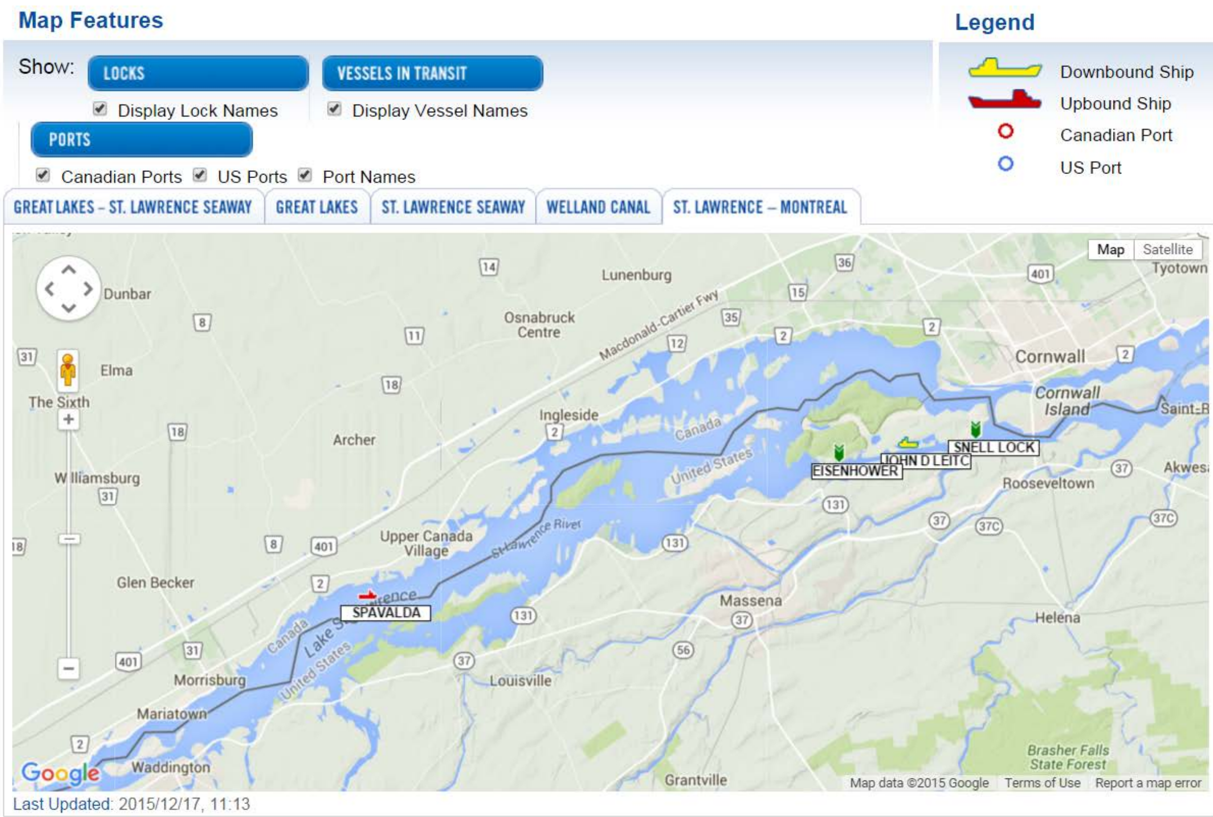

Figure 7: Screenshot of St. Lawrence Seaway On-Line Vessel Tracker
(Source: SLSDC/SLSMC binational website: www.greatlakes-seaway.com)

In addition to government vessel tracking systems, several private companies have deployed their own AIS receiver network to capture vessel traffic for commercial purposes. These systems can provide real-time information on ship position, course and speed, route details (origin and destination) and vessel registry information (owner, operator, homeport, etc.). The commercial services provide varying levels of data, with basic details typically available to the general public for free, but reserve more detailed information for those users who have paid a subscription fee.

4.4.2. Bridge status mobile applications

Two private software developers have created mobile applications that provide users with status reports of eight moveable roadway bridges that cross the Seaway over the Welland Canal (Niagara region). These mobile applications typically indicate one of three status conditions for each bridge: Available, Unavailable or Available-Raising Soon. These applications integrate raw data provided by the SLSMC website, but have no affiliation with the Seaway.[2] (See figure 8.)

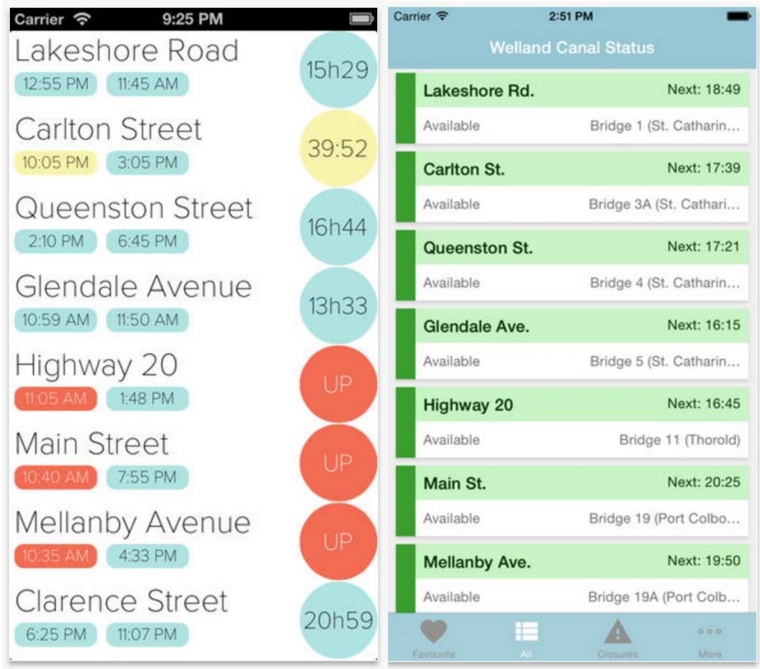

Figure 8: Bridge Status Applications
Spot (Niagara Region) (left) and Welland Bridge Status (right)
(Source: Without Software (l) and Tom Koole (r))

[2] The joint SLSDC-SLSMC website publishes bridge status for both the Niagara and Maisonneuve regions, in both desktop and mobile formats; see www.greatlakes-seaway.com/en/communities/bridge.

5. Summary of Findings

This section summarizes several of the more significant challenges facing the Seaway, revealed through an extensive literature review and discussions with SLSDC/SLSMC representatives and Seaway stakeholders. These challenges apply broadly and do not necessarily reflect issues that can be addressed through ITS or similar technologies or applications. Nonetheless, the intent of this project is for subsequent phases to address one or more of the challenges identified below.

5.1. Challenge: Multiple Jurisdictions

As a bi-lateral waterway between the U.S. and Canada, the Great Lakes-St. Lawrence Seaway system poses inherent jurisdictional challenges. The system spans eight U.S. states and two Canadian provinces, with hundreds of cities and towns bordering the system's lakes, rivers, canals and locks. Within each federal, state, provincial, county and municipal government, there are numerous agencies with varying levels of regulatory authority or other jurisdictional control over the activities that take place on or adjacent to the Seaway. Adding to this complex landscape are several bi-lateral entities that play formal and informal roles in policy development and implementation. Finally, there are dozens of advocacy groups—environmental, economic development, trade, recreational—that seek to influence policy and practice within the region. SLSDC and SLSMC representatives interviewed for this project reported excellent working relationships and coordination, but the sheer number of agencies involved in the operation of the Seaway make sustaining this coordination a challenge.

5.2. Challenge: Lack of Redundancy

One of the most significant challenges facing the St. Lawrence Seaway is the extent to which continuity of operations can be compromised by the failure of a single lock. As mentioned earlier, all locks within the Seaway – with the exception of locks 4, 5, and 6 in the Welland Canal, which comprise the Flight Locks (see figure 9) – are single units. Therefore, an equipment failure or damage from a ship collision with the lock chamber, a ship arrestor or worse—a lock gate—can suspend the movement of vessels in the Seaway until the issue is resolved.

Figure 9: Welland Canal Locks 4, 5 & 6
(Source: SLSMC)

One of the most extreme illustrations of this limitation occurred in 1985, when a 150-foot section of the lock chamber wall in Lock 7 in the Welland Canal collapsed. Repairing the damage took 24 days and delayed 130 ships from reaching their destinations [23]. Even less significant incidents can drastically impact Seaway operations. In June 2015, the cruise ship *Saint Laurent* struck a wall in the

Eisenhower Lock. During the subsequent 42 hour suspension of navigation, 15 ships were delayed and Seaway officials estimated that the financial impact of this brief shutdown exceeded $1 million.

Fortunately, the Seaway maintains a strong safety record and such incidents and resulting closures tend to be rare. Nonetheless, the U.S.-controlled locks in the Seaway over the last five years has experienced an average of 15 hours of closures per operating season due to reasons other than weather which is equal to an average reliability rating of 99.77%. The *Saint Laurent* incident illustrates the operational vulnerability of a single-lock system; this single incident more than doubled the typical downtime experienced by the U.S. locks over the course of an entire season [24].

5.3. Challenge: Seasonality

Although unanticipated shutdowns likely represent a significant concern for ships operating on the Seaway, the seasonal nature of the Seaway's operations represents a potential limitation to attracting new users. Navigation on the Seaway is suspended for approximately 90 days each winter, from late December through mid-March, due to ice conditions on the canals, rivers and in the locks. Due to the single-lock limitation (described above), which precludes closure of a single lock for routine maintenance while the system is in service, both the SLSDC and the SLSMC are forced to conduct repairs and maintenance during the winter months, often under extreme conditions (see figure 10).

Figure 10: Winter Lock Maintenance
(Source: SLSDC Facebook Page)

However brief, this recurring interruption in operations impacts vessel operators and ship traffic from serving industries that cannot afford to halt goods movement for three months or are unwilling to incur the cost of shifting shipping route and/or mode during the winter.

5.4. Challenge: Lock Physical Constraints

Seawaymax-sized vessels almost entirely fill lock chambers in their current configuration. As mentioned earlier, the largest ships allowed through the Seaway leave 26 feet of free space fore and aft and just two feet of free space laterally within the lock chamber. Seawaymax vessels fill the width of the locks to such an extent that the SLSDC and SLSMC must be vigilant about preventing ice buildup on lock walls early and late in the operating season, as ice can consume all available free space to the sides of passing ships and interfere with the vacuum mooring system.

These size constraints represent the most significant barrier to opening the Seaway to larger vessels. Larger vessels operate freely within the Great Lakes and from the Atlantic Ocean into the Port of Montréal. Lakers can measure up to 1,100 feet in length, 105 feet in beam and up to 26 feet 9 inches in draft; these are the maximum dimensions permitted to pass through the Soo Locks at Sault Ste. Marie, MI [25]. Within the St.

Lawrence River below Montréal, the Canadian Coast Guard now allows post-Panamax-sized vessels (up to 935 feet in length and 131 feet in beam) to serve the Port of Montréal [26]. Any cargo that needs to transit the Seaway must either be carried by smaller ships – which increases shipping cost per unit – or be transferred from oversized lakers or salties to a Seawaymax-sized vessel, incurring additional costs due to the transfer.

Proposals have been raised in the past to expand the St. Lawrence Seaway but all have met significant resistance and subsequently failed. Consequently, this paper assumes that lock size will remain a constant constraint for the foreseeable future. In light of this constraint, however, SLSDC representatives interviewed for this project indicated that taking fuller advantage of available draft presents the most promising opportunity to increase the amount of cargo that can be carried by each ship through the Seaway. The DIS discussed earlier has already helped in this regard, allowing equipped vessels to transit with up to an additional three inches of draft. However, opportunities exist to expand this concept further to take fuller advantage of the available water column (to be discussed further in the next section).

5.5. Challenge: Ship Dynamics within Locks

Discussions with SLSDC/SLSMC representatives revealed a potential source of delay associated with Seawaymax vessels maneuvering into and out of a lock chamber. A fully-loaded Seawaymax bulk carrier displaces approximately 10.6 million gallons (300 thousand cubic meters) of water. As the ship moves into the lock chamber, a corresponding volume of water must flow out of the lock chamber. For a laden Seawaymax vessel—with a beam of 78 feet and a potential draft of 26 feet 9 inches—that displaced water is forced through the narrow gaps between the ship's hull and the lock walls and sill. That water flow creates two problems:

First, as the displaced water begins to flow rapidly through the narrow gaps—as little as one foot on each side of the ship and 3 feet 3 inches under the ship at the lock sill—hydrodynamic forces can create areas of lower pressure which can cause the ship to be drawn closer to one of the walls of the lock chamber, or to squat lower in the water as it passes over the lock sill. This movement can result in the vessel's hull striking the lock wall or sill.

Second, as the ship moves into the lock chamber, water level builds up ahead of the ship while it struggles to move past the ship towards the stern and out of the lock chamber. This buildup is exacerbated by bow waves naturally created as the ship moves forward. As the vessel nears the forward lock gate, this build-up of water can cause the ship to surge aft just as it nears its final mooring position, making it difficult for the ship to stabilize in its desired position within the lock. Seaway officials have reported that after the ship is correctly positioned into the lock chamber, and the vacuum mooring devices attached to the ship's hull, the residual water build-up at the bow can cause temporary rearward movement of the ship; if not compensated for, this movement can exceed the load capacities of the vacuum mooring equipment, potentially causing the ship to come loose and risking damaging the vacuum mooring devices.

The vessel self-spotting system discussed earlier can help with this issue, since it increases situational awareness of the vessel's master and pilots by indicating exactly how far their ship is from its final mooring position. However, the ship's behavior is highly speed-dependent, and these effects are much more noticeable when ships enter locks at higher speeds, even within allowable limits. Entering a lock with minimal speed can drastically reduce this effect, but can reduce lateral control and add to the lockage time.[3]

In this respect, SLSDC/SLSMC representatives suggested that an optimal maneuvering speed likely exists for each vessel—based upon its design and loading condition— which maximizes entry speed into the lock chamber while minimizing the position instability issue. Avoiding minor lockage delays is crucial as even a 15-minute delay per lockage could translate into a cumulative delay of four hours if the ship encountered the same delay at each lock.

5.6. Challenge: Time Delays Due to Pilot Shortages

Five different pilot associations provide navigational services along the Great Lakes-St. Lawrence Seaway System for vessels that require pilotage. Both the U.S. and Canada have complementary rules and regulations that govern the overlapping geographic jurisdictions for each pilot association.

- The Laurentian Pilotage Authority (LPA) is a Canadian Crown Corporation and provides pilots in Canadian sections of the St. Lawrence River from Les Escoumins, Québec, westward to Montréal. This group had a pool of 181 contract pilots as of 2014, and is the largest and busiest of the pilot associations, since it serves Montréal, which is the largest container ship port on Canada's east coast.
- The Great Lakes Pilotage Authority (GLPA) is also a Canadian Crown Corporation and provides pilots in Canadian or binational waters of the Great Lakes west of Montréal, Quebec, including the Welland Canal. This group had a pool of approximately 60 pilots as of 2014.
- The St. Lawrence Seaway Pilots Association (SLSPA) is a U.S. private partnership and provides pilots in binational sections of the St. Lawrence River and Lake Ontario. This association had a pool of 11 pilots as of 2012.
- The Lakes Pilots Association (Lakes Pilots) is organized as a U.S. private corporation and provides pilots in binational sections of Lake Erie, the Detroit River, Lake St. Clair and the St. Clair River. This association had a pool of 10 pilots as of 2012.
- The Western Great Lakes Pilots Association (WGLPA) is organized as a U.S. private partnership and provides pilots in all areas of Lake Michigan and binational sections of Lake Superior, the St. Mary's River (including the Soo Locks), and Lake Huron. This association had a pool of 15 pilots as of 2015.

Within the St. Lawrence Seaway proper, pilot services are only provided by the SLSPA and GLPA. Under normal conditions of wind and weather, ships are piloted seamlessly from the mouth of the St. Lawrence River as far west as the port of Duluth-Superior in Wisconsin. However, at several times during the year, demand for pilots often exceeds supply, which may create delays that ripple throughout the system:

- During the two weeks prior to the end of the navigation season (early- to mid-December), many of the floating aids to navigation are removed or replaced with winter markers, in order to prevent damage

[3] A vessel requires some forward motion to maintain directional control through use of the rudder and propeller. A vessel traveling at a minimum speed of only one knot (approximate 1.15 miles per hour) will cover a distance of 26 feet in only 15 seconds.

during heavy winter icing conditions. During this period, SLSPA and GLPA require ships to carry two pilots.

- Similarly, in the spring, when the Seaway first opens, two pilots are required until the winter markers have been replaced with permanent buoys, and all floating aids are verified to be in—or relocated to—their charted positions.
- Finally, from mid-October through the end of the season, the number of vessels transiting the Seaway increases significantly, as shippers and carriers seek to move cargoes into or out of the region before the Seaway closes for the winter.

The USCG, which is responsible for regulating the three U.S. Great Lakes pilots associations, as well as the individual pilot associations themselves, recognize the inherent delays associated with this structural but short-term shortage of qualified pilots.

6. Opportunities for Applications of ITS

This section summarizes several opportunities for applying ITS or equivalent technology strategies, based on the challenges and other insights documented earlier in this paper. Subsequent phases of this project will further explore the extent to which these opportunities can be addressed with one or more specific ITS applications.

6.1. Maximizing Use of Available Water Column

As discussed earlier, the physical size of the lock chambers constrains the size of ships that can transit the Seaway; these are unlikely to be enlarged in the foreseeable future. However, as changes in vessel draft requirements and introduction of the DIS illustrate, opportunities still exist in maximizing use of the available water column.

The DIS allows ships with an approved DIS to be loaded with up to three additional inches of draft—which can represent up to 360 metric tons of additional cargo—by enabling more precise predictions of under-keel clearance. Seaway officials interviewed for this effort suggested that under-keel clearance of a ship underway can still vary, even for different ships of the same ship type. Specifically, ships even of the same ship type, can squat differently – that is, their hulls may sink deeper in the water differently at different speeds and in different channel types. Existing draft requirements, therefore, may be overly restrictive for a ship that tends to squat less than similar vessels. If a ship squats less than the predicted squat for that ship type, it might be able to travel faster while still maintaining a safe margin of under-keel clearance (as long as the additional speed does not increase its wake enough to worsen its impact on shoreline erosion).

The opportunity that these insights suggest is that draft and speed requirements tailored to the dynamics of individual ships could truly maximize the ability for ships in the Seaway to carry more cargo within existing physical constraints. The DIS begins to address this opportunity but can be taken farther if applied to the dynamics of specific ships rather than a type of ship. Sufficiently modelling the ship dynamics required to implement ship-specific draft and speed requirements is likely to be extensive and potentially costly, but the ability to safely carry more cargo and/or travel more quickly provides a distinct economic advantage for participating vessels.

6.2. Optimizing Lock Entry Speeds

The previous section of this report describes the maneuvering challenge presented by the dynamics of vessels entering a lock. Ships – particularly Seawaymax-sized vessels, due to the minimal space between their hull and the lock walls – can face a challenge in optimizing their entry speed. Ideally, ships should enter locks at a speed high enough to maintain maneuverability and minimize their transit time, but not so fast as to create a bow wave and buildup of water forward of the ship that can destabilize the ship's position in the lock as the water drains out.

Ships entering too quickly or too slowly, therefore, present potential concerns for both safety and transit time efficiency. In theory, then, an optimal speed likely exists for a ship entering a lock that balances these competing factors. Determining this ideal entry speed profile for each ship—based upon the vessel's design and various loading conditions--and communicating it to the pilot and/or master, presents an opportunity for improving lock transit times while maintaining or even improving safety.

6.3. Minimizing Delays Due to Pilotage Shortages

Section 5.6 of this report describes the transit delays introduced into the system when the demand for ship pilots often exceeds the availability, specifically when ships are required to carry two pilots during periods at the beginning and end of each navigation season when navigational aids are not in place. Some of these delays coincide with the periods at the start and end of the navigation season—periods when vessel traffic levels are inherently higher than normal and/or when transits can take significantly longer due to ice in the navigation channels —which can introduce delays across the entire freight supply chain.

There are potential technology solutions that could be brought to bear to alleviate the requirement for doubling up pilots. In 2014, the USCG began testing the use of AIS technology to create *synthetic* and *virtual* aids to navigation (ATONs) [27]. Virtual or synthetic ATONs using AIS technology have been deployed in Ireland and the United Kingdom [28] [29].

For a synthetic ATON, an AIS transmitter sends out a signal that mimics an existing buoy, day marker, lighthouse or other physical object. The synthetic ATON will appear at the same location as the buoy's radar signature on an ARPA unit, or at the same geographic position as the charted buoy on an ECDIS display.

In the case of a virtual ATON, the AIS transmitter broadcasts a signal that "creates" an ATON where there is no physical counterpart. The only means that a navigator will "see" a virtual ATON through an AIS-linked ARPA or ECDIS display. Virtual ATONs could be used to mark uncharted hazards (e.g. a sunken ship, an underwater structure, or other obstruction), temporary channels, or a missing physical buoy.

The use of virtual ATONs could alleviate the need for two pilots during the transition periods at the beginning and the end of the navigation season, since pilots would have access to the accurate position of ATONs, regardless of whether those ATONs were physically present, or displaced from their normal positions. Although the USCG is still in the testing and evaluation phase for its aids, the SLSDC could implement synthetic and/or virtual ATONs for the waters for which it has legal jurisdiction.

6.4. Overall System Optimization

The *Seaway Handbook*, issued jointly by the SLSDC and SLSMC and containing practices and procedures, specifies the following operational factors in providing efficient ship transits:

> *Two prime factors in providing efficient ship transits are the reduction of "dead time" at a lock, which is that period between the exit of one ship from a lock and the entry of another, and the elimination of the need to tie up at the approach walls [while waiting for another vessel to exit the lock chamber]. With the increase in traffic, new Control Centre facilities and procedures, and additional aids to navigation, it is desired to make much greater use of the "passing entry" procedures as described hereunder, when two ships meet immediately outside a lock [with one vessel exiting and the second vessel entering" and when weather conditions permit [30].*

Minimizing "dead time" at locks and maximizing the use of "passing entry" procedures represent optimization goals towards which existing tools might be applied. The existing AIS provides the SLSDC and SLSMC with real-time information about ship position, speed, and heading. Barring sources of travel time uncertainty, the AIS should enable reasonably accurate travel time estimates for a vessel transiting the Seaway. A potential opportunity exists to optimize vessel traffic throughout the Seaway in such a manner as to minimize the need for ships to wait to enter a lock. Particularly if sources of travel time uncertainty were minimized (e.g., delays due to unavailability of pilots or variability in lock transit times due to ship dynamics, both mentioned above), a speed profile could conceivably be developed that minimizes lock dead time throughout a ship's transit of the Seaway.

Achieving such an optimization represents a lofty goal, but one that nonetheless seems plausible given available technology and the characteristics of the Seaway. Detailed, real-time data on ship movements already exist and, whereas such an optimization problem would need to apply to thousands of vehicles in a surface transportation context, such an application might only need to coordinate the movements of a few dozen ships simultaneously. In this respect, this opportunity resembles an optimized air traffic control system, albeit with significantly lower vehicle speeds.

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Appendix A: Stakeholders

This appendix lists the principal stakeholders identified during the research for this report. The list is not exhaustive, but represents the major public and private entities in each category.

Infrastructure Operators

- Canadian Coast Guard (Ottawa, ON)
- Canadian Pacific Railway (CP) (Calgary, Alb.)
- Canadian National Railway (CN) (Montréal, QC)
- St. Lawrence Seaway Development Corporation (Washington, D.C.)
- The St. Lawrence Seaway Management Corporation (Cornwall, ON)
- Transport Canada (Ottawa, ON)
- U.S. Coast Guard, 9^{th} District (Cleveland, OH)

Non-port federal, state, provincial or binational government entities

- U.S. Coast Guard, Great Lakes Pilotage Division (WWM-2), Washington, D.C.
- Canada-United States Collaboration for Great Lakes Water Quality , ,
- Canadian Coast Guard (Ottawa, ON)
- Canadian Transportation Agency (Ottawa, ON)
- Environment Canada (Gatineau, QC)
- Federal Maritime Commission (Washington, D.C.)
- Fisheries and Oceans Canada, Great Lakes Environment Office (Ottawa, ON)
- Great Lakes Fishery Commission (Ann Arbor, MI)
- Infrastructure Canada (Ottawa, ON)
- International Joint Commission (Washington, D.C.)
- International Maritime Organization (London, U.K.)
- Maritime Administration (Washington, D.C.)

- Transport Canada (Ottawa, ON)
- U.S. Coast Guard (Washington, D.C.)
- U.S. Environmental Protection Agency, Great Lakes National Program Office (Chicago, IL)
- U.S. Geological Survey, Great Lakes Science Center (Ann Arbor, MI)

Vessel owners/operators

This list reflects the largest or most influential vessel owners and operators that utilize the Great Lakes-St. Lawrence Seaway system, including the port of Montréal.

- Algoma Central Corporation (St. Catherines, ON)
- American Steamship Company (Williamsville, NY)
- BBC Chartering (Leer, Germany)
- Bridge Tankers (Med Maritime) (London, U.K.)
- Canada Steamship Lines (Montréal, QC)
- Canfornav (Montréal, QC)
- Fednav Limited (Montréal, QC)
- Grand River Navigation Company, Inc. (Traverse City, MI)
- Great Lakes Fleet/ Key Lakes, Inc. (CN) (Duluth, MN)
- Groupe Desgagnés Inc. (Québec, QC)
- Hansa Heavy Lift (Hamburg, Germany)
- Hapag-Lloyd (Montréal, QC)
- Lakes Shipping Company, Inc. (part of Interlake) (Middleburg Heights, OH)
- Interlake Steamship Company, The (Middleburg Heights, OH)
- McKeil Marine Limited, Hamilton, ON)
- Mediterranean Shipping Company (MSC) (Montréal, QC)
- Orient Overseas Container Line (OOCL) (Toronto, ON)
- Polsteam (Szczecin, Poland)
- Rand Logistics, Inc. (New York, NY)
- Rigel Shipping Canada Inc. (Shediac, N.B.)
- Spliethoff's Bevrachtingskantoor B.V. (Amsterdam, Netherlands)
- Wagenborg Shipping (Montréal, QC)

Public and private advocacy groups

- American Great Lakes Ports Association (Washington, D.C.)
- American Maritime Officers (Washington, D.C.)
- American Pilots Association (Washington, D.C)
- Canadian Shipowners Association (Ottawa, ON)
- Chamber of Marine Commerce (Ottawa, ON)
- Conference of Great Lakes and St. Lawrence Governors and Premiers (Chicago, IL)
- Consumer Energy Alliance - Midwest (Columbus, OH)
- Freight Management Association of Canada (Ottawa, ON)
- Great Lakes Boating Federation (Chicago, IL)
- Great Lakes Commission (Ann Arbor, MI) (binational)
- Great Lakes Maritime Research Institute (Superior, WI)
- Great Lakes Maritime Task Force (Toledo, OH)
- Great Lakes Protection Fund (Evanston, IL)
- Healing Our Waters-Great Lakes Coalition (Washington, D.C.)
- International Association of Machinists and Aerospace Workers (Lancaster, NY)
- International Longshoremen's Assoc. (ILA), Great Lakes District Council (Cleveland, OH)
- International Organization of Masters, Mates & Pilots (Cleveland, OH)
- International Ship Masters' Association (Berkley, MI)
- Lake Carriers' Association (Rocky River, OH)
- Lake Michigan Forum (Chicago, IL)
- Marine Engineers Beneficial Association (MEBA), AFL-CIO (Washington, D.C.)
- Mining Association of Canada (Ottawa, ON)
- Ontario Marine Transportation Forum (Toronto, ON)
- Regional Economic Development Council - North Country (Watertown, NY)
- Seafarers International Union (Algonac, MI)
- Seaway Task Force (Washington, D.C.)
- Shipping Federal of Canada (ShipFed) (Montréal, QC)
- St. Lawrence Economic Development Council (Québec, QC)
- St. Lawrence Shipoperators (Québec, QC)

- Supply Chain Management Association (Toronto, ON)
- The Chartered Institute of Logistics and Transport (Ottawa, QC)
- The Great Lakes and St. Lawrence Cities Initiative (Chicago, IL)
- U.S. Great Lakes Shipping Association (Cleveland, OH)
- Western Grain Elevator / Lakehead Terminal Elevators Association (Thunder Bay, ON)
- Western Transportation Advisory Council (Vancouver, B.C.)
- Wisconsin Commercial Ports Association (Green Bay, WI)

Port and terminal and shipyard owners and operators

- Becancour Industrial Park (Becancour, QC)
- Central Dock Company (Benton Harbor, MI)
- Cleveland-Cuyahoga County Port Authority (Cleveland, OH)
- Conneaut Port Authority (Conneaut, OH)
- CSX Transportation, Toledo Docks (Toledo, OH)
- Detroit/Wayne County Port Authority (Detroit, MI)
- Dock 63 Inc. (St. Joseph, MI)
- Duluth Seaway Port Authority (Duluth, MN)
- Erie-Western PA Port Authority (Erie, PA)
- Goderich Port Management Corporation (Goderich, ON)
- Hallett Dock Company (Duluth, MN)
- Hamilton Port Authority (Hamilton, ON)
- Illinois International Port District (Chicago, IL)
- Lorain Port Authority (Lorain, OH)
- Midwest Energy Resources Co. (Superior, WI)
- Montréal Gateway Terminals Partnership (Montréal, QC)
- Montréal Port Authority (Montréal, QC)
- Nicholson Terminal & Dock Company (River Rouge, MI)
- Norfolk Southern Corporation (Norfolk, VA)
- Ogdensburg Bridge & Port Authority (Ogdensburg, NY)
- Oshawa Port Authority (Oshawa, ON)
- Port Colborne (Port Colborne, ON)

- Port de Valleyfield (Salaberry-de-Valleyfield, QC)
- Port of Ashtabula (Ashtabula, OH)
- Port of Buffalo (Buffalo, NY)
- Port of Duluth-Superior (Duluth, MN)
- Port of Green Bay (Green Bay, WI)
- Port of Johnstown (Johnstown, ON)
- Port of Milwaukee (Milwaukee, WI)
- Port of Monroe (Monroe, MI)
- Port of Muskegon (Muskegon, MI)
- Port of Oswego Authority (Oswego, NY)
- Port of Sept-Îles (Sept-Îles, QC)
- Ports of Indiana (Indianapolis, IN)
- PortsToronto (Toronto, ON)
- Québec Port Authority (Québec, QC)
- Thunder Bay Port Authority (Thunder Bay, ON)
- Thunder Bay Terminals Ltd. (Thunder Bay, ON)
- Toledo-Lucas County Port Authority (Toledo, OH)
- TPG Chicago Dry Dock, LLC (Chicago, IL)
- Trois-Rivières Port Authority (Trois-Rivières, QC)
- Verplank Dock Co. (Ferrysburg, MI)
- Windsor Port Authority (Windsor, ON)

Service providers

- Algoma Ship Repair (Port Colborne, ON)
- Allied Marine & Industrial (Port Colborne, ON)
- American Bureau of Shipping (ABS) (Houston, TX)
- Basic Marine (Escanaba, MI)
- Bay Shipbuilding Company (Fincantieri Marine Group, LLC) (Sturgeon Bay, WI)
- Bell Marine & Mill Supply Ltd. (Port Colborne, ON)
- Brown County Port & Resource Recovery Dept. (Green Bay, WI)
- Burger Boat Company (Manitowoc, WI)

- Canadian Marine Pilots' Association (Ottawa, ON)
- Chantier Davie Canada Inc. (Lévis, QC)
- Cleveland Ship Repair Company (Cleveland, OH)
- Donjon Shipbuilding & Repair, LLC (Erie, PA)
- Donjon Shipbuilding and Repair, LLC (Erie, PA)
- EMS-TECH Inc. (Belleville, ON)
- Fraser Shipyards, Inc. (Superior, WI)
- Great Lakes Pilotage Authority (Cornwall, ON)
- Group Ocean (Québec, QC)
- Heddle Marine Service Inc. (Hamilton, ON)
- Hermont Marine Inc. (St. Laurent, QC)
- Hike Metal Products Ltd. (Wheatley, ON)
- Ironhead Marine, Inc. (Toledo, OH)
- Lakes Pilots Association (Port Huron, MI)
- Laurentian Pilotage Authority (Montréal, QC)
- Lloyd's Register North America, Inc. (Burlington, ON)
- Lock/Port Sales & Services Inc. (St. Catherines, ON)
- Logistec Corporation (Montréal, QC)
- Marine and Offshore Canada (St. Catherines, ON)
- Marine Clean Ltd. (Niagara Falls, ON)
- Marinette Marine Corporation (Marinette, WI)
- Mount Royal /Walsh Inc. (Montréal, QC)
- Navamar Inc. Ship Repairs (Montréal, QC)
- Nicholson & Hall Corporation (Buffalo, NY)
- Palmer Johnson Incorporated (Sturgeon Bay, WI)
- Provmar Fuels Inc. (Hamilton, ON)
- Purvis Marine Limited (Sault Ste. Marie, ON)
- RWDI Air Inc. (Toronto, ON)
- Somavrac Inc. (Trois-Rivières, QC)
- St. Lawrence Seaway Pilots' Association (Cape Vincent, NY)
- Sterling Fuels Ltd. (Hamilton, ON)

- Walter Hiltebrand Marine Services Ltd. (Welland, ON)
- Western Great Lakes Pilots' Association (Superior, WI)

Major shippers of commodities and finished products

This list is based upon analysis of membership of several advocacy and promotional groups engaged in supported commerce on the Great Lakes-St. Lawrence Seaway system, including the Chamber of Marine Commerce and the Great Lakes Maritime Task Force.

- ADM (Archer Daniels Midland Company)
- Agrium Inc.
- AK Steel Corporation
- Alcan Smelters & Chemicals (Rio Tinto)
- Aluminerie Alouette
- ArcelorMittal
- Atlantic Minerals Limited
- Badgeley Island Aggregates (Coco Group)
- Bunge North America
- Canadian Slag Services Inc.
- Cargill Limited
- Carmeuse Lime, Inc.
- CertainTeed Gypsum Canada
- CGC Inc. (Canadian Gypsum Company)
- Cliffs Natural Resources, Inc.
- Compass Minerals (Sifto Canada)
- Construction Aggregates (Fairmount)
- Consumers Energy
- CRH Canada Group, Inc. (Holcim (Canada) Inc.)
- DTE Electric
- Edw. C. Levy Co.
- ESSROC Italcementi Group
- FeX Group, LLC
- G3 Global Grain Group (formerly Canadian Wheat Board)
- Georgia Pacific

- Grain Farmers of Ontario
- Grande Cache Coal Corporation
- Greenfield Ethanol
- Hansen Mueller Company
- Hensall Global Logistics
- HTS America LLC
- International Minerals Inc.
- Iron Ore Company of Canada
- Island Construction
- K + S Windsor Salt (Canadian Salt)
- Keystone Coal Canada Inc.
- Koch Carbon, LLC
- Kraft Foods Global, Inc.
- Lafarge North America
- London Agricultural Commodities Inc.
- Louis Dreyfus Canada Ltd.
- Mondelez International
- Moran Iron Works
- Morton Salt
- Mosaic Company
- Norton Lilly International
- Nova Scotia Power
- Omnisource Corporation
- OMYA, Inc.
- Ontario Trap Rock Ltd. (Tomlinson Group)
- Ontario Wheat Producers Marketing Board
- Osborne Concrete & Stone Co.
- Oxbow Carbon and Minerals LLC
- Palmerston Grain
- Parrish & Heimbecker Ltd.
- Pittsburgh Logistics Systems, Inc.

- Potash Corporation of Saskatchewan
- Redpath Sugar Ltd.
- Richardson International
- Rio Tinto Fer et Titane
- Riverland AG
- Smelter Bay Aggregates Inc.
- Southwestern Sales Corporation Limited
- Tata Steel
- Teck Coal
- U.S. Steel Canada
- U.S. Steel Corp.
- Unimin Canada Ltd.
- United States Gypsum Corporation
- Viterra
- Votorantim Cement North America

Recreational users

Since this report is focused primarily on the commercial or non-recreational use of the Great Lakes-St. Lawrence Seaway system, we have not identified specific stakeholders in this category. (The Great Lakes Boating Federation is included as a stakeholder.)

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