Vessel Collision Warning System for Vulnerable Bridges - Case Studies

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ABSTRACT: In response to the Francis Scott Key Bridge collapse, NTSB identified 68 similarly vulnerable bridges and recommended warning systems. Roebling Labs responded by developing and deploying vessel collision warning systems on four case-study bridges. The system assigns threat levels to AIS-equipped vessels by combining real-time transponder tracking, trajectory forecasting, and AASHTO impact analysis. The system provides operators information that they can use to reduce life-loss in a collapse scenario by operating traffic gates to evacuate the bridge.

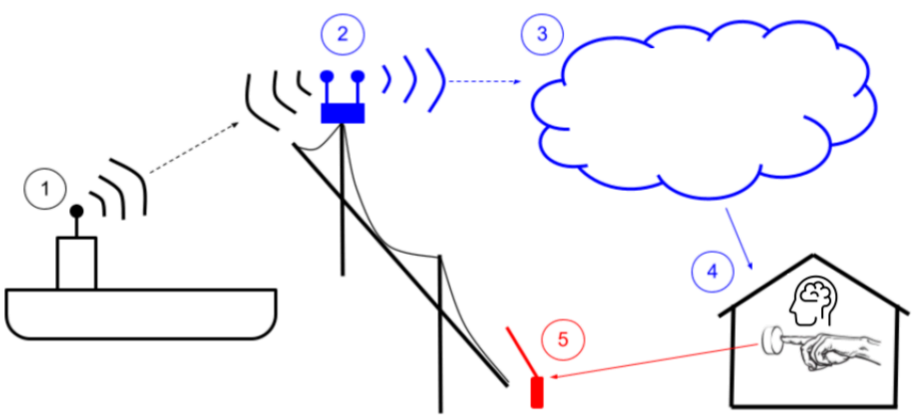

Figure 1 - Schematic - Vessel Collision Warning System

1. **Ship**: Vessels send AIS signals of identification, size, position, speed, and heading, per U.S. Coast Guard requirements since 2002.
2. **Bridge**: Hardware unit receives AIS signals and sends relevant data to the cloud.
3. **Cloud**: Cloud computer receives the data in real-time, runs threat assessment algorithms, and transmits alerts when risk scenarios are detected. Selected data is stored to investigate incidents and improve algorithm performance.
4. **Operations Center**: Staff receive system alerts via browser-based dashboard, API software integration, SMS message, or phone.
5. **Traffic Gates & Marine Radio**: Bridge operations staff evaluate and respond to alerts as appropriate to communicate with vessels and close or open the bridge to traffic

PROBLEM

The Francis Scott Key Bridge collapse, with a life-loss of six and cost to society of five billion dollars, triggered a National Transportation Safety Board (NTSB) investigation that identified 68 potentially vulnerable bridges across the U.S.A.

The NTSB applied the following criteria to identify potentially vulnerable bridges:

- Built before 1996
- Over a navigation channel serving ocean-going vessels
- Not yet received a modern risk assessment in accordance with AASHTO specifications

As of April 2026, 45 bridges remain on the NTSB's vulnerable list as risk assessments are completed.

The twenty-owner agencies responsible for NTSB-named vulnerable bridges received letters on 10 December 2025 with safety recommendations enclosed.

NTSB SAFETY RECOMMENDATION H-25-030:
"Incorporate motorist warning systems capable of activating when a threat is identified and immediately warn and stop motorists from entering the bridge." (NTSB 2025)

Standards for installing traffic gates and marine radios are well established at movable bridges, for example. However, this NTSB recommendation implies that traffic gates and marine radios now be retrofitted to existing, vulnerable long-span bridges.

Bridge owners need vessel threat information to support time critical decisions about operating traffic gates, contacting aberrant vessels, and protecting bridge users.

COSTS OF LIFE LOSS, INACTION, AND ALTERNATIVE SOLUTIONS

LIFE-LOSS COST: The annual cost of vessel-collision bridge collapse, in lives lost and dollars, for a given bridge can be estimated using the following considerations:

- Annual frequency of collapse (AF) due to vessel collision for a given bridge (AASHTO 2010).
- Average daily traffic (ADT) on the bridge
- Estimated ranges for the number of vehicles and occupants on the span at the time of the collapse and falling into the void in the minutes after the collapse.
- Value of a statistical life is $14.2 million in the U.S.A. (USDOT 2025)
  (For comparison, Denmark uses ~$5 million and China uses ~$0.5 million.)

COST OF INACTION: Depending on the above factors, vulnerable bridges may have an expected life-loss cost for vessel collision bridge collapse of many millions of dollars per year, if no action is taken.

ALTERNATIVE SOLUTIONS: Alternative solutions include bridge replacement, retrofitting protective features, a vessel collision warning system, or using freemium online services to track vessels.

The potentially vulnerable bridges identified by the NTSB in 2025 are long-span bridges. Replacement or retro-fitting construction projects at these sites would be major undertakings that are often not feasible in the near, medium, or long-term.

<u>Bridge replacement</u>: Existing vulnerable bridges can be replaced with a new bridge designed in accordance with modern vessel collision standards. However, this may cost billions per bridge with a lead time of many years.

<u>Retrofitting protective features</u>: Existing vulnerable bridges can be retrofitted with protective dolphins, fenders, or islands. However, these projects can cost $100 million per bridge or more with a lead time of many years. Geometric constraints may preclude this solution at many sites, or only allow for partially-effective protective features to be installed.

<u>Vessel collision warning systems</u>: A vessel collision warning system can be installed on a vulnerable bridge in less than one day while costing an order of magnitude less per year than the expected life-loss cost of inaction. Vessel collision warning systems are the focus of this paper.

<u>Freemium online services</u>: Websites such as vesselfinder.com and marinetraffic.com provide global AIS data, including limited free versions. This can be useful to bridge owners that are interested in developing situational awareness of marine traffic around their bridges, but the vessel data can be delayed by as much as an hour. While these services do show vessel information, they have no ability to warn of ship-bridge collisions.

SOLUTION - VESSEL COLLISION WARNING SYSTEM DESCRIPTION

Roebling Labs builds vessel collision warning systems for vulnerable bridges, in response to NTSB Safety Recommendation H-25-030.

The warning systems assign threat levels to AIS-equipped vessels by combining real-time transponder tracking, trajectory forecasting, and AASHTO impact analysis.

The system provides real-time risk assessment of each vessel as it approaches the bridge based on the probability of aberrancy and the consequence of collision. (See Figure 2 Risk Matrix)

The U.S. Coast Guard, since 2002, has required commercial vessels longer than 65 feet, greater than 600 Horsepower, or carrying passengers to use AIS (Automatic Identification System) transponders.

AIS was designed for vessel-to-vessel collision avoidance. Therefore the AIS transmission includes vessel information sufficient to estimate ship-bridge collision risk.

Static AIS data, transmitted at six-minute intervals, includes: vessel name, type, number, call sign, length, and width.

Dynamic AIS data, transmitted as often as 2 second intervals, includes: GPS position, speed, course, heading, arrival time, rate of turn.

The AIS transmissions do include vessel draft information, but it is considered unreliable because captains often forget to update this value for each trip depending on the weight of the cargo, if any.

Examples of important vessel properties not included in the AIS transmissions include: deadweight tonnage and air draft.

AASHTO provides data tables with typical deadweight tonnage, air draft, and draft dimensions for vessels given their length and type (AASHTO 2025). These estimates are used when calculating the consequences of collision associated with each vessel.

CONSEQUENCES OF ABERRANCY AND COLLISION

AASHTO specifications are used to calculate, in real-time, the likely consequences for each approaching vessel, at its current speed, in a hypothetical collision with each bridge element, if accessible. (AASHTO 2010 and AASHTO 2024)

To check the accessibility of each pier relative to each vessel, the system considers the vessel's draft relative to the waterway depth to estimate if grounding may occur. Pier protection dolphins or fenders are also considered, including accounting for partial protection when applicable.

Likewise, the accessibility of each span superstructure relative to each vessel, including the air draft for the hull, deckhouse, and mast, are considered.

Once it is determined that the ship can access a given bridge pier or superstructure element to collide, AASHTO specifications are used to calculate, in real-time, the impact load of the vessel at its current speed. The vessel impact force is compared to the ultimate strength of the bridge pier or superstructure element to determine a probability of collapse in the case of a collision. (AASHTO 2010 and AASHTO 2024)

PROBABILITY OF ABERRANCY

When estimating the probability of aberrancy for a vessel, it is useful to consider three categories of trajectory forecasts: committed, reachable, and probable. The committed and reachable are defined by the physics of ship maneuverability. The probable vessel trajectory is influenced by the decision-making of the vessel pilot. (See Figure 3)

COMMITTED - The committed path for each vessel is the area where the ship must pass, given its size and velocity, even if the ship's captain initiated evasive maneuvers immediately. Ships can have significant lags between the captain initiating a turn and the vessel actually beginning to turn; typically 4.5 times the length of the ship at full speed, but increasing due to environmental factors including shallow water, wind, waves, and currents. Stopping ships involves even greater lags; typically 15 times the length of the ship at full speed. (IMO-MSC 2002) (Gokarn 2025) (Nomoto 1957)

REACHABLE - The reachable zone for each vessel is where the ship could pass, given its size and velocity, even if the ship's captain initiated maximum evasive maneuvers immediately. (IMO-MSC 2002) (Gokarn 2025) (Nomoto 1957)

PROBABLE - The probable trajectory for a given vessel at a given moment is a subset of the possible extents. At most moments, it is unlikely that a captain will initiate maximum evasive maneuvers immediately. Site specific vessel history data is useful in estimating probable trajectories.

WARNING TIMES

Timing is an important consideration. How much time will bridge owners have to respond relative to the time it could take to close and evacuate their bridge?

There is no single answer to this question because the timing is specific to each different bridge site, vessel, and situation.

Surprisingly, the majority (87%) of life-loss has occurred not with people who fell with a collapsing span, but with those that arrived in the minutes after the collapse and fell into the void. See Appendix A and Table 1.

Life loss can be reduced just by detecting that a vessel collision has occurred, even if forewarning were not possible. But forewarning is possible using realtime AIS data.

In rough terms, a 1200-foot-long ship (366 m) will take about one mile to turn. At a speed of 10 knots, the ship will travel that mile in about 5 minutes. Shorter ships will tend to be more maneuverable and, therefore, have shorter committed zones and provide less forewarning time.

Alarm thresholds balance forewarning time against the potential for false alarms.

Latency within the vessel collision warning system itself can be less than five seconds from receiving the AIS signal to delivering an alarm to the user dashboard. At a speed of 10 knots, commercial vessels transmit an AIS signal at 10 second intervals.

CASE STUDY 1 - CHELSEA YACHT CLUB AT TOBIN BRIDGE

Roebling Labs operates a demonstration vessel collision warning system deployed at the Chelsea Yacht Club, a site adjacent to the Tobin Bridge in Boston, Massachusetts. Operational since January 2026, including through multiple blizzards, it has tracked hundreds of vessels. Roebling Labs is actively developing and improving the threat assessment algorithms using the real-world data gathered from this site.

HARDWARE - The hardware unit is approximately the size of a shoebox with an antenna. The antenna receives AIS transmissions from vessels. A computer inside the box processes the data and a cellular modem transmits relevant data to the cloud. The box is powered from a standard 120v outlet. (See Figure 4)

DASHBOARD - The dashboard displays real-time information on local vessel traffic. In a production deployment, bridge operators use this interface to monitor approaching vessels and receive collision threat alerts. (See Figure 5)

VESSEL HISTORY SCREEN - The vessel history screen facilitates detailed searches of point-by-point data. In a production deployment, this tool supports detailed investigations of incidents, including collisions, near-misses, and false alarms. Vessel history data allows Roebling Labs to improve our threat assessment algorithm over time. (See Figure 6)

CASE STUDY 2 - NEWBURGH-BEACON BRIDGES

The Newburgh-Beacon Bridges are owned by NYSBA and were identified in 2025 as requiring updated vessel collision vulnerability assessments relative to modern safety standards. The site includes two 2,204-foot-long steel truss toll bridges over the Hudson River about 60 miles upriver from New York Harbor. The Westbound (North) bridge was built in 1963. The adjacent Eastbound (South) bridge was built in 1980 of a nearly identical design. Each bridge has 11 piers in the waterway without fenders, dolphins, or other protective elements.

The main span for each bridge is 1000 feet long with vertical clearance for navigation of 135 feet above mean water level. The Federal navigation channel for the Hudson River from New York City to Albany is authorized to a depth of 32 feet and maintained by the U.S. Army Corps of Engineers. Tides in the area range 4.3 feet from Mean Lower Low Water (MLLW) to Mean Higher-High Water (MHHW).

Roebling Labs installed a vessel collision warning system for both bridges, on a pilot basis, in March 2026. The hardware unit was installed on a catwalk platform under the roadway at midspan of the South bridge. (See Figure 7)

NYSBA operates a Command Center in Highland, NY about 15 miles upriver from the Newburgh-Beacon Bridges. NYSBA owns four other toll bridges over the Hudson River, besides the Newburgh-Beacon Bridges, with cameras and other sensors providing real-time information to the Command Center. Roebling Labs' vessel collision warning system adds to the array of real-time information that NYSBA uses to monitor and manage their sites. (See Figure 8)

NYSBA has an active project underway to install bridge closure systems at each of their five bridge sites with remote operation capabilities from the Command Center. NYSBA identified vessel collision as an important vulnerability and began a program of mitigations prior to the Francis Scott Key Bridge collapse. NYSBA has been pro-actively responding to NTSB recommendations.

CASE STUDY 3 - RIP VAN WINKLE BRIDGE

The Rip Van Winkle Bridge is also owned by NYSBA and identified in 2025 as requiring an updated vessel collision vulnerability assessment. The 5,040-foot-long cantilevered steel truss toll bridge spans the Hudson River about 120 miles upriver from New York Harbor. It was built in 1935 and has 4 piers in the Hudson River without fenders, dolphins, or other protective elements.

Roebling Labs installed a vessel collision warning system on Rip Van Winkle Bridge, on a pilot basis, in April 2026. The hardware unit was installed under the roadway on a catwalk platform near the navigable channel. (See Figure 9)

The NYSBA Command Center staff in Highland, NY about 45 miles downriver have access to real-time vessel risk assessment information and alarms.

Upon completion of the active project, NYSBA Command Center staff will be able to remotely close the Rip Van Winkle Bridge to traffic and contact vessels via marine radio.

CASE STUDY 4 - NEWPORT PELL BRIDGE

The Newport Pell Bridge is owned by RITBA and was designated as potentially vulnerable to vessel collision by NTSB in 2025. The 11,247-foot-long (2.1 miles) toll bridge with a 1,600-foot-long suspended main span was constructed in 1969. The piers for the towers, cable bents, anchorages, and numerous approach spans are in the waterway. (See Figure 10)

Protective features include collision cells near the anchorages to protect the main cables from allision where they have low clearance to the water. The main cables also include a strut that connects them to help distribute forces in the case of an impact.

Roebling Labs is scheduled to install a vessel collision warning system on Newport Pell Bridge, on a pilot basis, in May 2026. The hardware unit will be installed on land at a maintenance building near the western abutment of the bridge, with an unobstructed range to the waterway.

RITBA is investigating options for installing traffic gates, marine radios, and integrating systems with their command center located onsite.

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APPENDIX A - LITERATURE REVIEW OF VESSEL COLLISION BRIDGE COLLAPSE WITH LIFE LOSS IN USA

Since 1974, the NTSB has investigated seven significant vessel collision bridge collapses with life-loss in the U.S.A., described below.

In sum, over the half-century from 1974 to 2024, these seven major incidents resulted in a life-loss of 114 people in the U.S.A. Of these, 99 people (87%), were not on the span at the time of the collapse, but fell into the void before authorities regained control of the site. (See Table 1)

This history indicates that there are significant opportunities to reduce life-loss by applying modern information and communication technologies to warn bridge users of vessel collisions.

The U.S. Coast Guard and American Waterways Operators jointly published a study of the ten year period between 1992 to 2001 and found 2,692 bridge allisions with a rate of 0.06% allisions per vessel trip with 94% resulting in property damage of less than $100,000 and no injuries. Sixty-one allisions were classified as severe with either life-loss, injury, missing persons, damage in excess of $500,000, or oil spilled. (USCG-AWO 2003)

In rough averages with round numbers, about 250 bridge allisions occur per year, but allisions with life loss occur only about once per decade with an average of 20 lives lost per incident.

1974 - LAKE PONTCHARTRAIN CAUSEWAY in Louisiana was struck by a tow powered by *M/V Miss Andy* causing 252 feet of span to collapse. The contributing cause was the captain falling asleep at the wheel. The life loss was 3 people including 2 people that fell into the void after the collapse. (NTSB 2004)

1980 - SUNSHINE SKYWAY BRIDGE in Florida was struck by a 609-foot-long cargo ship *Summit Venture* causing 1,297 feet of span to collapse from a height of 150 feet. A sudden storm with high winds and limited visibility were contributing causes. The life loss was 35 people including 32 people that fell into the void less than three minutes after the collapse. (NTSB 1981)

1993 - CSXT BIG BAYOU CANOT RAILROAD BRIDGE in Alabama was struck by a 490-foot-long tow powered by *MAUVILLA* causing a 3-foot displacement of a 140-foot-long steel through-girder span. The blow did not sever the continuous welded rail or trigger the traffic control signal system (TCS). Thus, the train dispatcher had no indication of a problem with the track structure. Limited visibility due to night, dense fog and the tow pilot's lack of competency to use radar navigation were contributing causes. The life loss was 47 people plus 111 injured on the Amtrak train *Sunset Limited* that derailed at a speed of 72 mph into the waterway upon arrival 8 minutes after the vessel collision. After the massive forces imparted by the train derailment, the 165-foot-long through-truss span plus an additional 500-foot-long section of timber trestle had collapsed from a height of 7 feet. (NTSB 1994)

1993 - JUDGE WILLIAM SEEBER BRIDGE in Louisiana was struck by a tow powered by *CHRIS* causing 145 feet of span to collapse. Inadequate pier protection and proximity to a busy lock were contributing causes. Two vehicles fell with the bridge, causing a life loss of 1. No vehicles fell into the void in the minutes after the collapse as this is a movable bridge with traffic gates. (NTSB 2004)

2001 - QUEEN ISABELLA CAUSEWAY in Texas was struck by a 851-foot-long tow powered by *Brown Water V* causing 160 feet of span to collapse from a height of 85 feet. The bridge's location near a bend in the navigation channel, the presence of strong cross currents, poor tow configuration (deeper draft barges placed in front), inadequate horsepower, the captain's human error, and limited nighttime visibility were contributing causes. Following the collapse, 9 vehicles entered the water through the missing bridge sections in the 15 minutes before first responders closed the bridge. The life loss was 8 people, none of which were thought to be on the spans at the time of their collapse. (USCG 2005)

2002 - INTERSTATE 40 HIGHWAY BRIDGE over the Arkansas River in Oklahoma was struck by a 402-foot-long tow powered by *Robert Y. Love* causing 503 feet of span to collapse from a height of 65 feet. The captain's loss of consciousness was a contributing cause. The life loss was 14 people. A total of 11 vehicles were found in the waterway; of these a recreational boater witnessed 8 vehicles drive into the void after the collapse and before he fired a warning flare at the roadway that a truck driver saw, stopped, and blocked the roadway with his truck. (NTSB 2004)

2024 - FRANCIS SCOTT KEY BRIDGE in Maryland was struck by 984-foot-long cargo ship *Dali* causing 1,400 feet of span to collapse from a height of 145 feet. Unexpected loss of electrical power on the ship and resulting loss of maneuverability control were contributing causes. The life loss was 6 people that were construction workers filling potholes on the bridge when it collapsed. No vehicles fell into the void because police had closed the roadway before the collision in response to the ship pilot's Mayday call three minutes before impact. (NTSB 2025)

APPENDIX B - LITERATURE REVIEW AND TIMELINE OF VESSEL COLLISION WARNING SYSTEMS FOR BRIDGES IN THE USA

1974 - NTSB SAFETY RECOMMENDATION H-74-42: *"Install a warning system on those sections of the Lake Pontchartrain causeway that are vulnerable to impact by errant marine vessels. The system should activate automatically to warn motorists of danger ahead, should the causeway collapse."* (NTSB 2004)

1979 (Est.) - LAKE PONTCHARTRAIN CAUSEWAY retrofitted with a motorist warning system, including marine radar, marine radio, variable message signs, and hazard incident lighting (NTSB 2004)

1981 - NTSB SAFETY RECOMMENDATION M-81-18:

"Establish criteria to evaluate the need for installing bridge span failure detection and warning systems on existing and proposed bridges." Issued in response to the Sunshine Skyway Bridge collapse. (NTSB 1981)

1983 - FHWA TECHNICAL ADVISORY T5140.19: *Pier Protection and Warning Systems for Bridges Subject to Ship Collision with Appendix A - Alternative Surveillance and Warning Systems:* Technologies identified for further evaluation to be retrofitted on the Sunshine Skyway Bridge (surviving truss span) included a laser system (geofencing the navigable channel), CCTV, delineation lighting, dynamic traffic signaling, and traffic gates. (FHWA 1983)

1987 - SUNSHINE SKYWAY BRIDGE: Construction of the new, cable-stayed bridge included a span continuity warning system, but its operation was less than dependable. (NTSB 2004)

2002 - MARITIME TRANSPORTATION SECURITY ACT: AIS (Automated Identification System) transponders on ships become required by the U.S. Coast Guard (USCG) and International Maritime Organization (IMO). The primary purpose is collision avoidance. By sharing real-time position, speed, and course over VHF radio, AIS enables ships to see and be seen. (33 CFR § 164.46)

2004 - NTSB SAFETY RECOMMENDATION H-04-31: *"Once an effective motorist warning system has been developed, provide guidance to the States on its use."* Issued in response to Interstate 40 Bridge collapse with influence from the Queen Isabella Causeway collapse. (NTSB 2004)

2012 - SHOWCASING AN ADVANCED MOTORIST WARNING SYSTEM IN TEXAS*:* FHWA article describing the collapse warning system installed on the Queen Isabella Causeway in 2007 that included: a continuous fiber optic cable, controller, traffic gates, dynamic signs, and a telephone auto-dial system. (FHWA 2012)

2025 - NTSB SAFETY RECOMMENDATION H-25-030: *"Incorporate motorist warning systems capable of activating when a threat is identified and immediately warn and stop motorists from entering the bridge."* Issued in response to the Francis Scott Key Bridge collapse. (NTSB 2025)

2026 - ROEBLING LABS: deploys vessel collision warning systems for vulnerable bridges, as described herein. The systems assign threat levels to AIS-equipped vessels by combining real-time transponder tracking, trajectory forecasting, and AASHTO impact analysis.

APPENDIX C - LITERATURE REVIEW OF INTERNATIONAL VESSEL COLLISION WARNING SYSTEMS USING AIS

The vessel collision warning systems installed on vulnerable bridges by Roebling Labs in 2026 are believed to be the first AIS-based systems in the U.S.A.

Vessel collision warning systems for bridges using AIS have been previously operating internationally, including in Denmark and China, as discussed below.

GREAT BELT BRIDGE in Denmark has been outfitted with a Vessel Traffic Service (VTS) since approximately 1997 when the bridge began operations. In addition to AIS, the system uses radar, cameras, and drones. Until 2010, the VTS included a dedicated, on-call interceptor vessel with powerful flashing lights to contact ships that do not respond to radio. "Sniffing" equipment is even mounted on the bridge to detect and report polluting ships with non-compliant emissions.

The VTS at Great Belt Bridge has been thrice tested with one ship-bridge collision and two near misses.

Lessons learned from three decades of Danish experience described below indicate that vessel collision warning systems can provide valuable information to support decisions to evacuate a bridge and contact aberrant vessels. Also, vessel trajectory forecasting will not be effective if it causes too many false alarms. More sophisticated models are required than a straight-line extrapolation of the existing vessel course. Vessels can maneuver.

<u>2001 - BELLA Near Miss with the Great Belt Bridge</u>: The 717-foot-long (Estimated from 27,000 dwt) Cambodian cargo ship BELLA triggered an alarm from VTS Great Belt to close the Great Belt Bridge to roadway, rail traffic, and to deploy the interceptor vessel. BELLA had exceeded the required limits without reporting by marine radio and was on a collision course with a main pylon of the bridge. The captain later stated that BELLA had problems with the steering gear causing difficulties in maneuvering. The bridge was re-opened to road and rail traffic after 10 minutes. (Ingeniøren 2001)

<u>2005 - KAREN DANIELSEN Collision with the Great Belt Bridge</u>: The 291-foot-long cargo ship failed to turn with the channel and struck a pier and superstructure of the concrete box-girder highway bridge, wedging under before coming to a halt against the adjacent railroad bridge superstructure while shearing the ship's wheelhouse in the process. The bridges received minimal structural damage and re-opened to traffic within hours. The life loss was 1 person, the ship's chief officer, who was later found to have blood alcohol concentration three times the legal limit and is believed to have fallen asleep at the wheel at least 10 minutes before the collision.

"The task of VTS Great Belt is to supervise the Great Belt [vessel] traffic to protect the bridges spanning the Great Belt and to alarm in time to stop rail and the road traffic in case of a risk of collision with the bridges."

Despite the VTS Great Belt having a full-time staff of three people assigned to tracking nearby vessels at all times, the VTS did not become aware of the incident until receiving the Mayday call from the ship personnel's radios 6 minutes after the collision had occurred. It took the VTS an additional 4 minutes (10 minutes after collision) to sound the alarm to close the roadway and an additional 12 minutes (18 minutes after the collision) to sound the alarm to stop the trains.

The automatic alarm function had been turned off 8 years earlier because of excessive false alarms by relying solely on a 10-minute straight line projection of each vessel's current course.

A project was underway to modernize the automatic alarm functions with improved vessel trajectory forecasts and a goal to activate *"if a ship that could constitute a hazard to the bridge unintentionally approaches the bridge at a distance of less than 10 minutes sailing time."* The system update will also alarm if a vessel exceeds a speed of 7 knots in designated areas around the bridge. (BMA-DMA 2005)

<u>2016 - PERSEUS Near Miss with Great Belt Bridge</u>: The 250-foot-long (Estimated from 1872 dwt) Lithuanian cargo ship PERSEUS came close to colliding with the eastern pylon. VTS Great Belt detected the aberrancy, triggered an alarm to close the Great Belt Bridge to roadway and rail traffic. VTS Great Belt made radio contact with the Lithuanian captain and got him to correct the course. VTS staff estimated that the vessel missed colliding with the pylon by 40 meters or less, a very close call. The captain was taken into police custody and charged with operating under the influence of alcohol. Bridge staff said that the bridge was "designed to withstand a collision that is 10 times as powerful" as PERSEUS would have delivered. The bridge was re-opened to road and rail traffic after being closed for 12 minutes while the situation developed. (TV2 ØST, 2016)

CHINA: *"Three-Year Action Plan for Hidden Danger Management of Ship-Bridge Collisions"* from 2020 to 2022, by the Ministry of Transport included installing warning devices at nearly 500 highway bridges. *"For bridges whose collision resistance does not meet the requirements…where it is difficult to install collision protection facilities, reinforce, or renovate them, active warning devices should be installed, and relevant departments should strengthen on-site management."* (PRC Ministry of Transport, 2020)

The ship-bridge collision problem in China is focused on inland rivers with many smaller barges and fishing craft that do not carry AIS transponders. Therefore, the early-warning systems in China rely on a fusion of physical sensors. In addition to AIS, the systems use LiDAR sensors, phased-array radar, and computer vision. Alerts are issued directly to the vessels using VHF radio, loudspeakers, and large LED displays. Alerts are simultaneously pushed to a monitoring center dashboard and mobile apps for maritime law enforcement personnel and bridge managers. Publicly available documentation was not found regarding the performance of these early-warning devices such as near misses, false alarms, or collisions.

APPENDIX D - NAVIGATION INCIDENTS AT OR NEAR THE CASE STUDY BRIDGES

UPPER HUDSON RIVER: Several vessel aberrancies, including groundings and bridge collisions have occurred in the Upper Hudson River in recent decades. A vessel traffic service (VTS) operates in New York Harbor, but does not extend up the Hudson River to NYSBA-owned bridges. (CRC 2008)

NEWPORT PELL BRIDGE: In 1981 the fully-laden oil tanker Gerd Maersk collided with the main tower pier at a speed of 6 knots. The bow of the 18,700 DWT ship crushed inwards 11 feet. The damage to the bridge was superficial. (NRC 1982)

TABLES

Year	Bridge Collapse	Life Loss, Total	Life-Loss, Fell With Span	Life Loss, Fell Into Void	Time to Stop Traffic
1974	Lake Pontchartrain Causeway, LA	3	1	2	Unknown
1980	Sunshine Skyway Bridge, FL	35	3	32	less than 3 minutes
1993	CSXT Big Bayou Canot, AL	47	0	47	8 minutes to train arrival
1993	Judge William Seeber Bridge, LA	1	1	0	Stopped at traffic gates before collapse
2001	Queen Isabella Causeway, TX	8	0	8	15 minutes
2002	Interstate 40 Bridge over Arkansas River, OK	14	4	10	Unknown. Less than 8 minutes.
2024	Francis Scott Key Bridge, MD	6	6	0	Stopped by police before collapse
	Total (Life Loss)	114	15	99	
	Total (%)	--	13%	87%	

*Life-Loss Split for I40 estimated by author. Boater witnessed 8 vehicles fall into the void. 11 vehicles found in the water.

Table 1 - Half-century history of life loss due to vessel collision bridge collapse in the USA

FIGURES

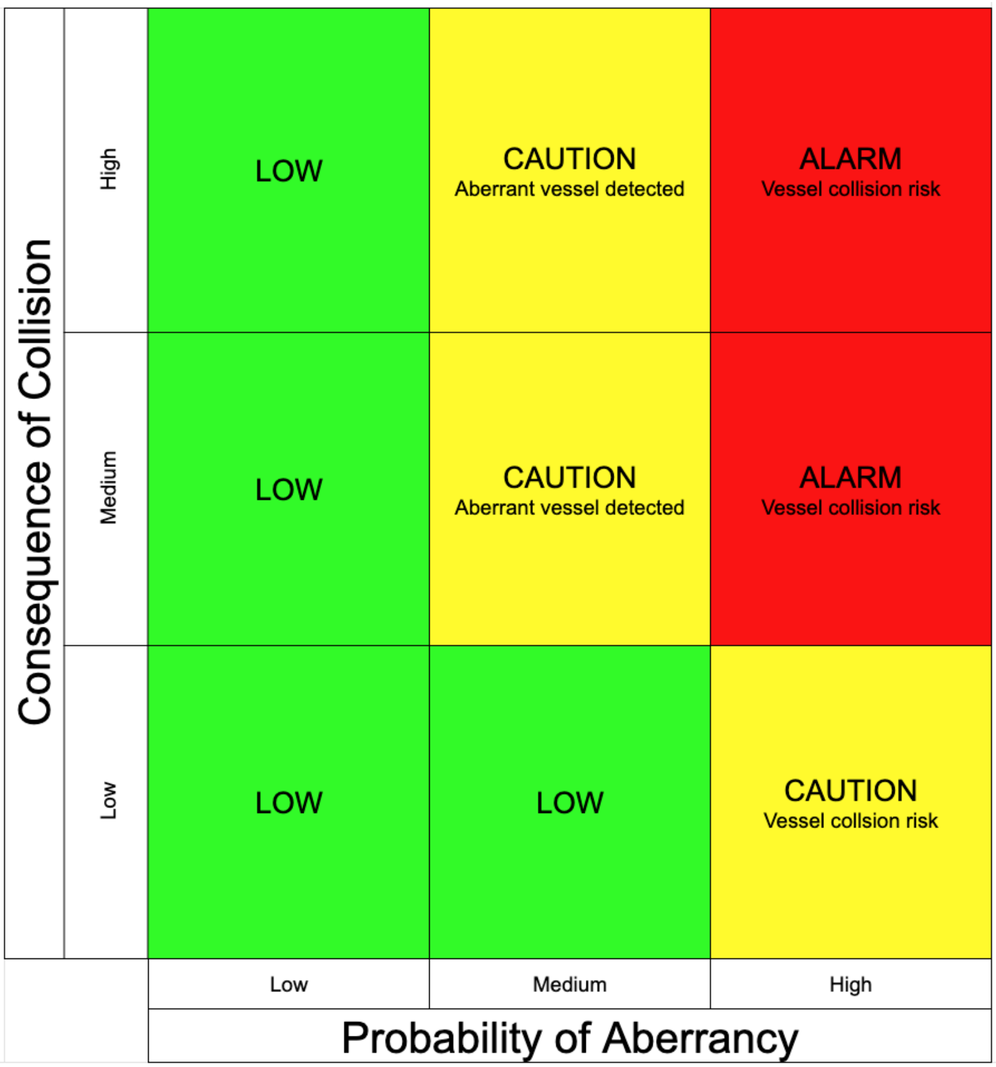

Figure 2 - Risk matrix for real-time threat assessment of AIS-equipped vessels based on the probability and consequence of collision with the bridge

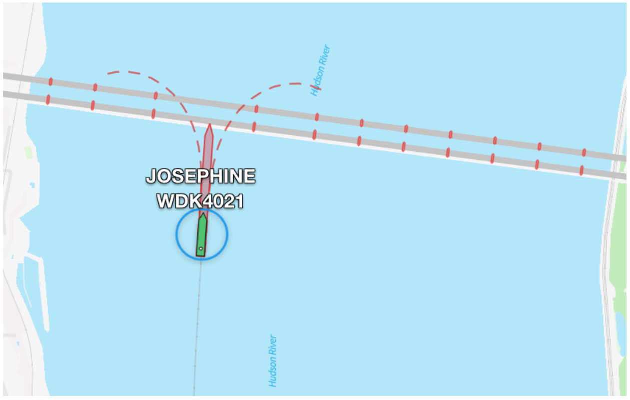

Figure 3 - Dashboard with vessel trajectory forecast. Ship "Josephine" is green. The red shaded area is the committed path, where the ship is likely to pass - due to lags before maneuvers take effect. The dashed red arcs represent the reachable extents - indicating where the ship could pass under maximum maneuvers.

Josephin is approaching the Newburgh-Beacon Bridges, but the bridge piers (red) are already beyond reach for a potential collision.

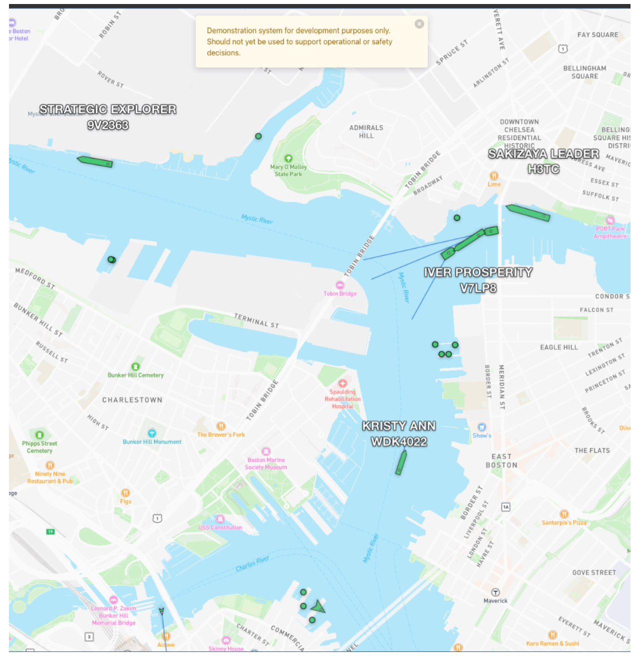

Figure 5 - Screenshot of the Dashboard for the Chelsea Yacht Club at Tobin Bridge

Figure 4 - Hardware Unit for Vessel Collision Warning System at Chelsea Yacht Club adjacent to the Tobin Bridge in Boston, MA

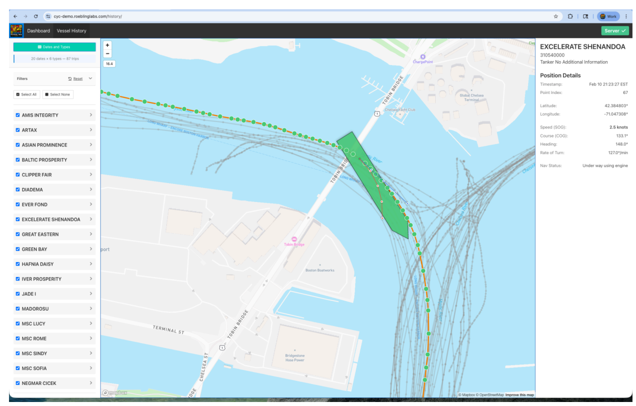

Figure 6 - Screenshot of the Vessel History search screen for the Chelsea Yacht Club at Tobin Bridge

Figure 7 - Hardware Unit for Vessel Collision Warning System (See Arrow) at the Newburgh-Beacon Bridges over the Hudson River in New York State. NYSBA Project Manager, NYSBA Bridge Mechanics, and the Author smiling after completing the installation and successfully testing functionality.

Figure 8 - NYSBA Command Center for 5 toll bridges over the Hudson River in New York State. Staffed 24/7. Vessel collision dashboard, marine radio, and traffic gate control are being deployed here.

Figure 9 - Rip Van Winkle Bridge over the Hudson River in New York State

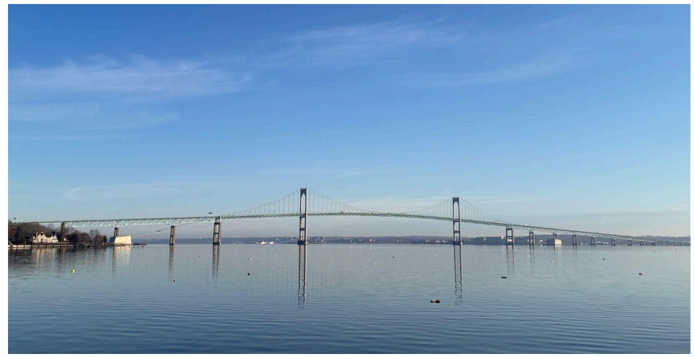

Figure 10 - Newport Pell Bridge in Rhode Island