November 18, 2025 Marine Investigation Report MIR-25-40

Contact of Containership *Dali* with Francis Scott Key Bridge and Subsequent Bridge Collapse

Patapsco River
Baltimore, Maryland
March 26, 2024

Abstract: This report discusses the National Transportation Safety Board's (NTSB) investigation of the March 26, 2024, contact of the containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse near Baltimore, Maryland. Safety Issues identified in this report include:

- improper placement of wire-label banding on terminal connection wires, preventing their secure connection into terminal blocks;
- lack of specific guidance for inspecting electrical terminal connections;
- configuration of machinery and electrical systems needed to prevent loss of propulsion and recover steering and vessel electrical power following a blackout;
- lack of effective means of emergency communications to warn motorists and notify highway workers to evacuate a bridge during an emergency;
- inadequate standards for marine safety management systems
- inadequate standards for manufacturer-provided voyage data recorder software;
- increasing vessel sizes and traffic density in US ports; and
- vulnerability of bridges over navigable waterways to strikes by large ocean-going vessels.

The NTSB makes new safety recommendations to the US Coast Guard; the Federal Highway Administration; the American Association of State Highway and Transportation Officials; the Harbor Safety Committee National Steering Team; to multiple bridge owners; the American National Standards Institute; American

National Standards Institute Accredited Standards Committee on Safety in Construction and Demolitions Operations A10; Nippon Kaiji Kyokai (ClassNK); WAGO Corporation (electrical component manufacturer); HD Hyundai Heavy Industries; and Synergy Marine Pte Ltd. In March 2025, the NTSB issued four urgent safety recommendations to the Federal Highway Administration, US Coast Guard, US Army Corps of Engineers, and to multiple bridge owners.

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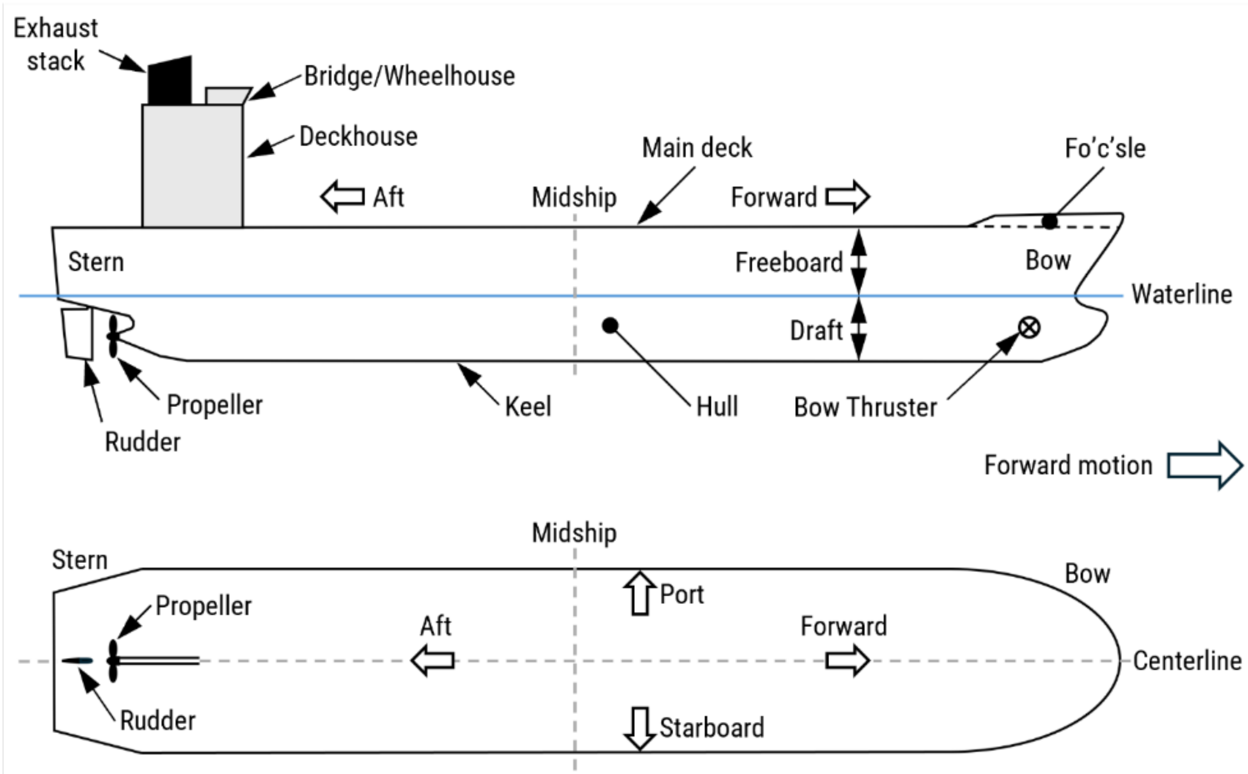
Acronyms and Abbreviations

Abbreviation	Name
AASHTO	American Association of State Highway and Transportation Officials
ABS	American Bureau of Shipping
AC	alternating current
ACONIS	Advanced Control and Integration System
AF	annual frequency of collapse
AIS	automatic identification system
ANSI	American National Standards Institute
ASSP	American Society of Safety Professionals
BGE	Baltimore Gas and Electric
CFR	*Code of Federal Regulations*
ClassNK	Nippon Kaiji Kyokai
DG	diesel generator
DOT	Department of Transportation
DWT	deadweight tonnage
ECR	engine control room
EDG	emergency diesel generator
FHWA	Federal Highway Administration
HFO	heavy fuel oil
HHI	HD Hyundai Heavy Industries
HR	high-voltage step-down transformer breaker
HSC	harbor safety committee
HSCC	Port of Baltimore Harbor Safety and Coordination Committee
HV	high voltage
IACS	International Association of Classification Societies

Abbreviation	**Name**
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISM Code	International Safety Management Code
JRC	Japan Radio Co., Ltd
LR	low-voltage step-down transformer breaker
LV	low voltage
MDTA	Maryland Transportation Authority
MGO	marine gas oil
NOAA	National Oceanic and Atmospheric Administration
NTSM	nonredundant steel tension member
NTSB	National Transportation Safety Board
PMS	power management system
SMS	safety management system
SOLAS	*International Convention for the Safety of Life at Sea*
SUPSALV	Supervisor of Salvage and Diving (US Navy)
TR	step-down transformer
UC	unified command
VDR	voyage data recorder
VIR	vessel inspection report
VLSFO	very low sulfur fuel oil

General Nautical Terms

This report uses nautical terminology to describe vessels and their related operations. The following illustration of a typical commercial vessel provides an overview of commonly used nautical terms.



Executive Summary

What Happened

On March 26, 2024, about 0129 local time, the 984-foot-long Singapore-flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, when it experienced losses of electrical power, propulsion, and steering and struck Pier 17, the southern pier that supported the central span of the Francis Scott Key Bridge (Key Bridge). A substantial portion of the bridge subsequently collapsed into the river, and portions of the pier, deck, and truss spans collapsed onto the vessel's bow and forwardmost container bays.

A seven-person road maintenance crew and one inspector were on the bridge when the vessel struck it. Six of the highway workers died as a result of the bridge collapse. One highway worker survived the collapse with serious injuries, and the inspector escaped unharmed. One of the 23 persons aboard the *Dali* sustained a minor injury. Damage to the *Dali* exceeded $18 million. Cargo damages were undetermined.

At the time of this report, replacement costs for the bridge are estimated at $4.3 billion to $5.2 billion, and the bridge is anticipated to open to traffic in late 2030. Over 34,000 vehicles, 10% of which are trucks, that formerly traveled over the Key Bridge every day must now take alternate routes around and through the Port of Baltimore, increasing congestion and travel times. The Key Bridge was also the primary route for vehicles carrying hazardous materials. These vehicles, which are prohibited from using the tunnels under the Baltimore waterways, must now make extended detours around the port.

What We Found

On March 26, after getting underway from Seagirt Marine Terminal in the Port of Baltimore, Maryland, the *Dali* experienced two electrical power outages (blackouts). We found that the initial underway blackout was caused by a series of electrical-related events that began when a signal wire (Wire 1), one of many in the main switchboard, electrically disconnected from its terminal block. The terminal block, a small, insulated plastic block, connected Wire 1 to another wire within the vessel's high-voltage switchboard. When Wire 1 electrically disconnected, one of the high-voltage breakers connecting the high-voltage bus to its step-down transformer—a mechanism that lowered voltage carried from the main, high-voltage, electrical bus before transferring it to the low-voltage bus—opened. The breaker opening interrupted power to the step-down transformer between the high-voltage electrical bus and the low-voltage electrical bus, which resulted in a low-voltage blackout.

Installed on each signal wire were labeling bands (wire-label banding), which were small silicone sheaths made of thermoplastic material that was heat-shrunk around the wire and had its associated terminal block printed on it. We found that Wire 1's label band (wire-label banding) covered all of the ferrule's blue insulated collar, increasing the ferrule's overall circumference, preventing the wire from being fully inserted into its terminal block—leaving Wire 1 vulnerable to becoming electrically disconnected.

We found that if infrared thermal imaging, an inspection technique that allows inspectors to identify possible points of failure in electrical components not visible to the human eye, had been used to inspect the *Dali*'s high-voltage switchboard connections as part of the vessel's preventative maintenance program, the loose Wire 1 may have been identified.

The low-voltage bus powered the low-voltage switchboard, which supplied power to vessel lighting and other equipment, including steering gear pumps, the fuel oil flushing pump and the main engine cooling water pumps. We found that the loss of power to the low-voltage bus led to a loss of lighting and machinery (the initial underway blackout), including the main engine cooling water pump and the steering gear pumps, resulting in a loss of propulsion and steering.

As a result of our investigation, we identified four safety concerns that, while not causal to the initial underway blackout, were related to preventing a loss of propulsion and recovering steering and vessel electrical power following a blackout.

- The configuration of the main engine to shut down due to low cooling water pressure.
- The use of the flushing pump as a fuel service pump for the electrical diesel generators.
- The operation of the vessel's low-voltage step-down transformer high-voltage breakers in Manual mode rather than Automatic.
- The effect of emergency diesel generator radiator damper positions on the generator's ability to start.

The first of these safety concerns was the configuration of the main engine to shut down due to low cooling water pressure. We found that this as-built configuration, which met classification standards at the time the vessel was constructed, endangered the vessel because the engine shut down when its cooling pump lost power following the initial underway blackout. Without the main engine running, the vessel's maneuverability was reduced.

The second safety concern was the operation of the flushing pump as a service pump for supplying fuel to online diesel generators. The online diesel generators running before the initial underway blackout (diesel generators 3 and 4) depended on the vessel's flushing pump for pressurized fuel to keep running. The flushing pump, which relied on the low-voltage switchboard for power, was a pump designed for flushing fuel out of fuel piping for maintenance purposes; however, the pump was being utilized as the pump to supply pressurized fuel to diesel generators 3 and 4.

Unlike the supply and booster pumps, which were designed for the purpose of supplying fuel to diesel generators, the flushing pump lacked redundancy. Essentially, there was no secondary pump to take over if the flushing pump turned off or failed. Furthermore, unlike the supply and booster pumps, the flushing pump was not designed to restart automatically after a loss of power. As a result, the flushing pump did not restart after the initial underway blackout and stopped supplying pressurized fuel to the diesel generators 3 and 4, thus causing the second underway blackout (low-voltage and high-voltage).

The day before the accident, on March 25, the *Dali* had experienced two blackouts while in port. The second in-port blackout on March 25, was ultimately caused by the flushing pump, not restarting after a loss of power, supplying insufficient fuel pressure to online diesel generators. This was also the cause of the second underway blackout on March 26.

Although not causal to the initial underway blackout, we found that the crew's operation of the flushing pump as the service pump for online diesel generators was inappropriate because the necessary fuel pressure for diesel generators 3 and 4 would not be automatically reestablished after a blackout. We found that operational oversight by Synergy, the *Dali*'s operator, was inadequate because it did not discontinue crews' ongoing use of the flushing pump as a service pump for the diesel generators aboard the *Dali* and at least one other vessel we identified.

The third safety concern we identified was the operation of the vessel's high-voltage breakers for the low-voltage step-down transformers in Manual mode rather than in Automatic mode. As discussed above, the step-down transformer lowered the voltage from the main, high-voltage bus to the low-voltage bus. In Manual mode, the high-voltage breakers' had to be manually closed after a blackout. In Automatic mode, high-voltage breakers for the vessel's other step-down transformer would connect and automatically restore low-voltage power within

10 seconds (Automatic) after a blackout. Aboard the *Dali*, there was no regulation or vessel operational guidance to set the breaker control mode to Automatic or Manual. Because the breakers' control modes were set to Manual when the initial underway blackout occurred, one of the high-voltage breakers, along with its corresponding low-voltage breaker, opened, and a crewmember had to manually close these breakers to restore power. We found that keeping the high-voltage breakers' control modes set to Automatic rather than Manual would not have prevented either underway blackout, but it would have shortened the duration of the initial underway blackout from 58 seconds to 10 seconds, providing more time for the crew to attempt to recover critical systems, such as propulsion, as the vessel approached the Key Bridge. Despite the delay caused by the step-down transformer needing to be manually restarted, we found the engineering crew's response to restoring low-voltage power after the first underway blackout timely.

The fourth safety concern was the effect of the emergency diesel generator radiator damper positions on the generator's ability to start within 45 seconds, as required by international regulations. After a loss of LV power, the emergency diesel generator is designed to start and power essential onboard systems such as navigation and communication equipment and emergency lighting. After the initial underway blackout, the *Dali*'s emergency diesel generator took 70 seconds to connect. We found this was because the generator damper actuator's limit switch, which detected whether the damper was open or closed, did not indicate open in the required time due to unknown circumstances. Due to the system design, any delay in the opening of the radiator damper (or its limit switch indicating it as not open) would postpone the emergency generator starting.

Proactive safety management, when done correctly, is predictive, designed to anticipate and address safety issues before they occur, and utilizes continuous data analysis to improve policies and procedures. The NTSB has previously advocated for the benefits of, and made recommendations to implement and improve, safety management systems (SMS) across all modes of transportation, because an effective SMS can help organizations proactively identify risks to reduce and prevent accidents and accident-related loss of lives, time, and resources. The International Maritime Organization's (IMO) International Safety Management Code (ISM Code), establishes the standard for SMSs in the marine industry. The commercial aviation industry's SMS model provides a robust framework for achieving effective safety management that supports a systematic, top-down, proactive approach. The four components of the aviation SMS are *safety policy, safety risk management, safety assurance*, and *safety promotion*. While the requirements of the ISM Code include some elements of a comprehensive, proactive safety management system, we found that ISM Code does not fully encompass the four critical components found in the aviation model.

After the initial underway blackout, the *Dali*'s heading began swinging to starboard toward Pier 17, which was only 200 feet outside the channel.[1] We found that the pilots and the bridge team attempted to change the vessel's trajectory, but the vessel's loss of propulsion so close to the Key Bridge rendered their actions ineffective. About a minute after the vessel first lost power, the pilot contacted a shoreside dispatcher to notify them of the emergency and instruct them to close the Key Bridge to traffic. Maryland Transportation Authority (MDTA) Police officers were stationed on both ends of the bridge conducting traffic control duties as part of the ongoing maintenance project. The officers immediately stopped all traffic from entering onto the bridge, and as a result, the bridge was cleared of traffic about 48 seconds before the vessel struck the bridge. We found that the quick actions of the pilots, the pilots' shoreside dispatcher, and the MDTA, to stop bridge traffic prevented a greater loss of life from the bridge collapse.

The Key Bridge, like many other bridges, was not equipped with a warning system to prevent motorists from driving onto the bridge in the event of a hazard. We found that, in lieu of police officers or highway workers capable of quickly stopping traffic, motorist warning systems preventing motorists from entering onto a bridge are a critical countermeasure that can save lives and may be a component of an effective bridge protection strategy. Methods to prevent motorist deaths resulting from bridge collapses have been promoted since the 1970s. Since the 1980s, while working with American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration has promoted the use of various technologies to mitigate motorist deaths and injuries in various publications and guide specifications. We also found that owners of bridges over navigable waterways frequented by ocean-going vessels would benefit from updated guidance on motorist warning systems.

The seven highway workers and inspector on the Key Bridge at the time were not notified of the *Dali*'s emergency situation before the bridge collapsed. We found that, had they been notified about the same time the MDTA police officers were told to block vehicular traffic, the highway workers may have had sufficient time to drive to a portion of the bridge that did not collapse. Further, we found that effective and immediate communication to evacuate the bridge during an emergency is critical to ensuring the safety of bridge workers.

[1] In nautical terminology, *starboard* is the direction to the right, and *port* is the direction to the left. General nautical terms such as these are used throughout this report when referring to vessels and their operations. A summary of these terms can be found in the General Nautical Terms section of this report found on page xiii.

As a result of our investigation and past investigations the NTSB has performed, we identified as a safety issue the vulnerability of bridges over navigable waterways to strikes by large ocean-going vessels.[2] On March 18, 2025, we issued a report, *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies*, related to this safety issue. In our report, we found that, had the MDTA conducted a vulnerability assessment of the Key Bridge as recommended by the 1991 and 2009 AASHTO *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, the MDTA would have been aware that the bridge was almost 30 times greater than the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.[3] Further, had the MDTA conducted the vulnerability assessment using AASHTO's Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge. Finally, we found that owners of numerous bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.

Recovery and analysis of the *Dali*'s voyage data recorder (VDR) data was integral to our investigation. However, our investigators encountered significant challenges that highlighted the need for robust standards for manufacturer-provided VDR software. We found that although the VDR model installed on board the *Dali* generally complied with IMO regulations and International Electrotechnical Commission (IEC) standards, significant deficiencies in data accessibility, audio usability, and playback software functionality revealed a critical disconnect between published technical standards and practical investigative and organizational needs to identify safety issues and solutions, and for operators and regulators to ensure safety. We found that the monoaural audio configuration of the *Dali*'s VDR system, which mixed multiple microphones into shared channels, significantly impaired the NTSB's ability to isolate and analyze critical bridge conversations, distinct voices, and sounds from the alarms and background noise. This configuration reduced the recording's intelligibility and limited the effectiveness of audio enhancement tools. Furthermore,

[2] See section 1.16 of this report for discussion of past NTSB accident investigations involving vessel contacts with bridges and resulting recommendations.

[3] The Maryland Department of Transportation State Highway Administration was a member of the development committee the 2009 AASHTO *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*. MDTA was a member of the Bridges and Structures Subcommittee for the AASHTO *LRFD* [Load Resistance Factor Design] *Bridge Design Specifications*, which references the 2009 *Guide Specifications*.

audio information from both sides of the electric telephone was not recorded during the accident, which prevented the NTSB from hearing the engine room's responses to bridge communications during the accident. We found that the lack of recording of parametric information (such as speed, thrust, steering, GPS position, automatic identification system data, and chart plotter information) by the VDR during a vessel power loss can inhibit proactive monitoring of these data by organization and adversely impact the investigation into an accident and make it more difficult for operators to use the data to improve safety of operations.

Finally, we investigated the wider issue of large containerized cargo ships, which have grown significantly in size and capacity in recent decades, calling more often at ports such as Baltimore. The increased size of vessels and increased cargo volumes presents challenges for existing port infrastructure that may not have been built with consideration of the larger vessels and greater traffic density. We found that increasingly larger containerized cargo vessels, such as the *Dali*, pose increased risks and challenges to maritime safety due to their reduced maneuverability in proximity to existing port and waterway infrastructure that was not designed to accommodate vessels of such size. We also found that as cargo vessel designs continue to evolve with the latest available standards and technology, increased redundancy to maintain critical systems, such as the main engine and steering, can mitigate risks in restricted waters.

We determined that the probable cause of the contact of the containership *Dali* with the Francis Scott Key Bridge was a loss of electrical power (blackout), due to a loose signal wire connection to a terminal block stemming from the improper installation of wire-label banding, resulting in the vessel's loss of propulsion and steering close to the bridge. Contributing to the crew's inability to recover propulsion from the loss of electrical power was the limited time available due to the *Dali*'s proximity to the bridge. Contributing to the collapse of the Francis Scott Key Bridge and the loss of life was the lack of countermeasures to reduce the bridge's vulnerability to collapse due to impact by ocean-going vessels, which could have been implemented if a vulnerability assessment had been conducted by the Maryland Transportation Authority as recommended by the American Association of State Highway and Transportation Officials. Also contributing to the loss of life was the lack of effective and immediate communications to notify the highway workers to evacuate the bridge.

What We Recommended

We recommended that Synergy, the vessel manager that provided the crew and operated the vessel, work with its classification society to obtain approval to implement the use of infrared thermal imaging for routine monitoring of electrical components, including to detect inadequate signal wire connections. We recommended WAGO, the manufacturer of the terminal block, add a warning in its product data sheet accompanying WAGO terminal block 280-681 (the model of the terminal block Wire 1 connected to), as well as any other terminal block models or similar products that incorporate wire-label banding it manufactures to explain that improperly placed wire-label banding can impede proper insertion of wire into a terminal block. We also made a recommendation to HD Hyundai Heavy Industries Co., Ltd. (HHI), the vessel's builder to incorporate proper wire-label banding installation methods into its electrical department's standard operating procedures to ensure that wire-label banding installed on a wire does not impede the proper insertion of wire into a terminal block.

In addition, we recommended that Nippon Kaiji Kyokai (ClassNK), the *Dali*'s classification society, share the circumstances of the accident with the International Association of Classification Societies and urge them to distribute this report to their members, highlighting:

a) the importance of avoiding placement of wire-label banding such that it impedes proper insertion of the wire in a terminal block,
b) the benefits of using infrared thermal imaging as part of a preventative maintenance program for routine monitoring of electrical components to detect inadequate signal wire connections,
c) the potential risks that partially open radiator dampers can pose to emergency generators starting, and
d) the need for members to review their rules on acceptable emergency generator start design.

As seen with the *Dali*, the loss of steering pumps and auxiliary systems supporting the main engine can result in the loss of steering and propulsion, which is critical to maintaining the ship's position while operating within narrow channels and close to port infrastructure. We recommended that the US Coast Guard conduct and publish the results of a study that examines the availability, feasibility, and safety benefits of redundant means to ensure that large single-propulsion-engine cargo vessels maintain propulsion and steering when maneuvering in restricted waters.

We issued several recommendations related to recovery following a blackout. To eliminate vessel crews' use of the flushing pump as a fuel oil service pump and reduce the risk of subsequent blackouts, we recommended that Synergy develop, implement, and monitor for compliance an SMS policy and procedure to ensure that vessel crews are using the fuel oil service pumps as designed for the diesel generator fuel supply systems installed on board its vessels. To avoid unnecessary main engine shutdowns during blackouts, we recommended that Synergy identify ships it operates that are equipped with an engine like the *Dali*'s and ensure they are not configured to automatically shut down due to low cooling water pressure. We also recommended that HD Hyundai Heavy Industries that they identify all active HD Hyundai Heavy Industries-constructed vessels with Hyundai-MAN B&W 9S90ME C9.2 engines installed, which are configured to Germanischer Lloyd rules and are designed to shut down on low cooling water pressure, and alert the current vessel owners of this configuration and the circumstances of this accident. Additionally, to improve crews' ability to recover from blackouts, we recommended that Synergy develop, implement, and monitor for compliance and effectiveness an SMS policy and procedure to ensure that vessel crews are setting high-voltage breakers' control mode to Automatic, unless the transformer breakers are being manually controlled for maintenance. Finally, we recommended that Synergy identify ships it operates with similar arrangements to the *Dali* and notify crews of those vessels that partially open radiator dampers can delay or prevent the emergency diesel generator from starting automatically.

An effective SMS can help organizations reduce and prevent accidents and accident-related loss of lives, time, and resources. We recommended that the Coast Guard propose to International Maritime Organization that it revise the International Safety Management Code and associated guidelines to fully incorporate safety policy, safety risk management, safety assurance, and safety promotion into its safety management system requirements.

We issued two recommendations to increase the safety of workers on bridges over navigable waterways. First, we recommended that the American National Standards Institute's Accredited Standards Committee on Safety in Construction and Demolitions Operations A10 revise *ANSI/ASSP A10.47, Work Zone Safety for Roadway Construction*, to include an effective and immediate means of emergency communications to alert workers performing roadway work on bridges over navigable waterways, which should consider the presence of law enforcement for traffic control. We also recommended that the Harbor Safety Committee National Steering Team share with harbor safety committees nationwide the importance of having a procedure, including immediately available emergency contact information, for pilots to initiate contact with shoreside support in an emergency requiring shoreside action to ensure timely and efficient action by first responders and port stakeholders.

In our March 18, 2025, report related to this investigation, we issued four urgent recommendations to safeguard bridges from contact by large ocean-going vessels. We recommended that the Federal Highway Administration, in coordination with the Coast Guard and US Army Corps of Engineers, establish an interdisciplinary team and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. We also identified 68 bridges that were:

1. Over navigable waterways that are frequented by ocean-going vessels,
2. Built before 1996 (bridges under design or initial construction in 1991 were likely not built to AASHTO's Guide Specifications), and
3. May not have undergone a vulnerability assessment based on recent vessel traffic.

We recommended that 30 bridge owners identified in the report as managing bridges over navigable waterways frequented by ocean-going vessels whose bridges were likely not designed and built to the 2009 AASHTO *Guide Specifications* determine their bridges' AASHTO Method II annual frequency of collapse and inform the NTSB whether the probability of collapse is above the AASHTO threshold. We recommended that these bridge owners develop and implement a comprehensive risk reduction plan if this annual frequency exceeded the AASHTO threshold. We have received responses from all of the bridge owners, and this report includes the classifications for each response.

We issued three recommendations to address motorist warning systems on bridges. We recommended that 20 bridge owners who, in response to the March 2025 NTSB Urgent Safety Recommendation H-25-2, found their bridges above the AASHTO threshold or who indicated that they have not yet completed their Method II calculations should, as part of their short-term bridge risk reduction and mitigation strategy to protect the traveling public, evaluate and, if appropriate, incorporate a motorist warning system capable of activating when a threat is identified and immediately warn and stop motorists from entering onto the bridge.

We recommended that AASHTO lead the efforts to update their 2009 *Guide Specifications* to include guidance in the selection of motorist warning systems with consideration of cost and other asset management principles. Evaluated changes should include hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure and would both warn and prevent motorists from entering a bridge once a threat is detected.

We also recommended that the Federal Highway Administration (FHWA) work with AASHTO to research and implement hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure and would both warn and prevent motorists from entering a bridge once a threat is detected.

Finally, as a result of this investigation, we issued two recommendations related to improving VDR systems' functionality and ease of use during investigations. First, we recommended that the Coast Guard notify IMO of the VDR technical issues encountered during our investigation into the contact of containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse, and submit to the IMO a concrete proposal to require:

1. the recording of mandatory data inputs from systems that remain powered during a blackout,
2. the recording of engine room communications to the bridge,
3. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
4. performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary VDR data into open industry standard formats.

Second, we recommended that the ANSI propose to the IEC Technical Committee 80 to revise *IEC 61996-1 ed. 2* to require:

1. the recording of mandatory data inputs from systems that remain powered during a blackout,
2. the recording of engine room communications to the bridge,
3. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
4. updating the performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary VDR data into open industry standard formats.

1 Factual Information

1.1 Accident Narrative

1.1.1 Synopsis

On March 26, 2024, about 0129 local time, the 984-foot-long Singapore-flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, with 21 crewmembers and two pilots on board, when it experienced a loss of electrical power, propulsion, and steering and struck Pier 17, the southern pier that supported the central span of the continuous through-truss of the Francis Scott Key Bridge (Key Bridge) (see figure 1 and figure 2).[4] A substantial portion of the bridge subsequently collapsed into the river, and portions of the pier, deck, and truss spans collapsed onto the vessel's bow and forwardmost container bays. A seven-person road maintenance crew and one inspector were on the bridge when the vessel struck it. Six of the highway workers died as a result of the bridge collapse. One of the highway workers survived the collapse with serious injuries, and the inspector escaped unharmed. One of the 23 people aboard the *Dali* sustained a minor hand injury. Damage to the *Dali* was estimated to exceed $18 million. Cargo damages were undetermined. At the time of this report, replacement costs for the bridge are estimated at $4.3 billion to $5.2 billion.[5]

[4] In this report, all times are eastern daylight time, and all miles are nautical miles (1.15 statute miles).

[5] Visit ntsb.gov to find additional information in the public docket for this NTSB accident investigation (case number DCA24MM031). Use the CAROL Query to search safety recommendations and investigations.

Figure 1. Containership *Dali* in 2019. (Source: Buggi Porschien, vesselfinder.com)

Figure 2. The Francis Scott Key Bridge in 2004. (Source: MDTA)

1.1.2 Event Sequence

1.1.2.1 Departure

On March 23, 2024, at 1512, the *Dali* moored at the Seagirt Marine Terminal in Baltimore Harbor (see figure 3). The ship had departed from Busan, South Korea, on February 22 and made two other US port calls (Newark, New Jersey, from March 19 until March 21, and Norfolk, Virginia, from March 22 to March 23) before arriving in Baltimore. The *Dali* was on a regular run, delivering cargo along the US east coast while also loading cargo for export.

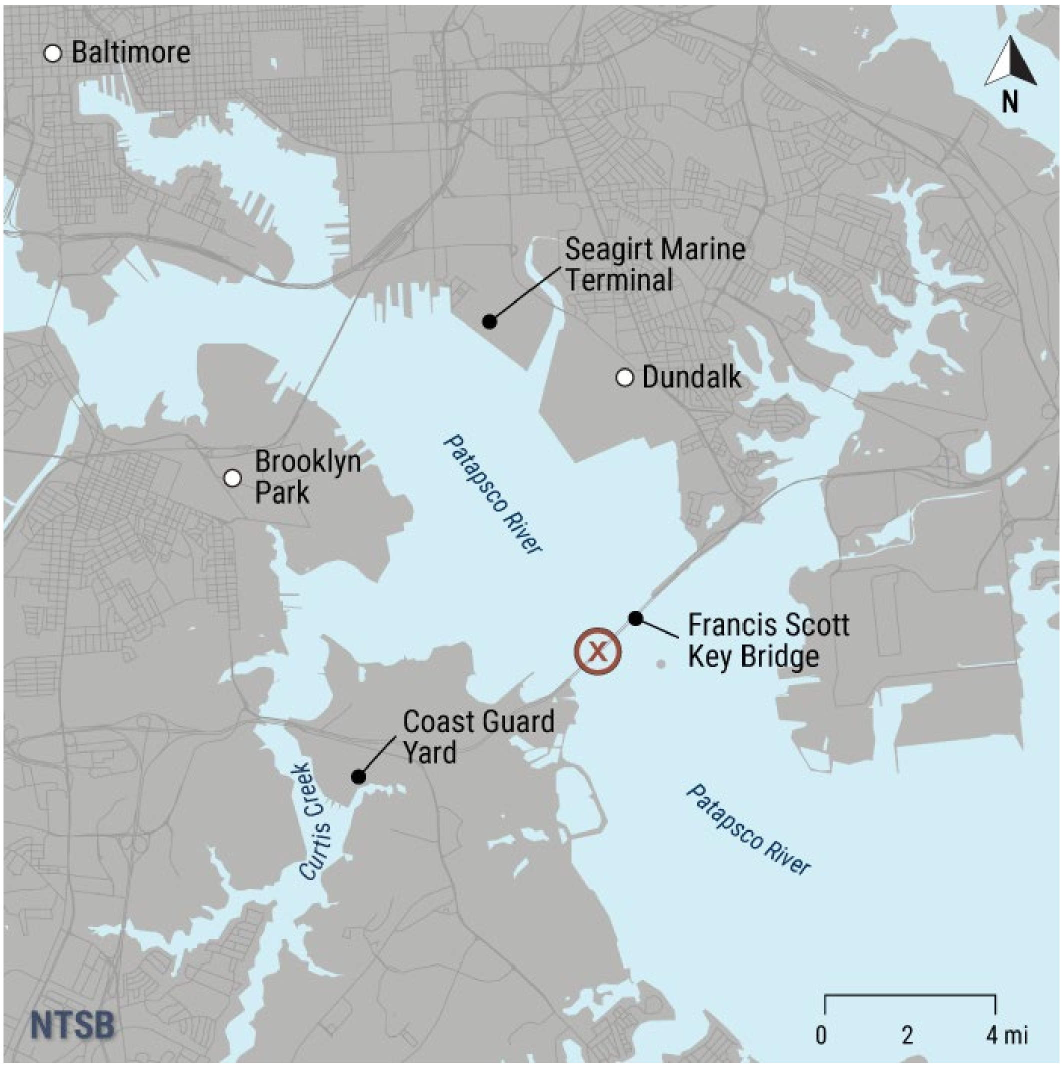


Figure 3. Map of the area surrounding the Francis Scott Key Bridge. (Background source: Google Maps)

On the evening of March 25, cargo operations were completed at 2306, and the crew of the *Dali* (21 crewmembers) was preparing the vessel to depart from Seagirt Marine Terminal to begin a 27-day transit to Colombo, Sri Lanka. The vessel was loaded with 55,671 metric tons of cargo within 4,679 containers (8,544 twenty-foot equivalent units, or TEU).[6]

About the same time the *Dali* was preparing to depart, seven highway workers employed by Brawner Builders were repairing potholes on the nearby Francis Scott Key Bridge (Key Bridge).[7] Owned and operated by the Maryland Transportation Authority (MDTA), the Key Bridge was a steel arch continuous through-truss bridge that carried four lanes of traffic across the lower Patapsco River and outer Baltimore Harbor/Port.[8] Also on the bridge was one inspector employed by Eborn Enterprises, Inc., a subconsultant to MDTA. Due to the road work, the bridge's right, southbound lane was closed to traffic, and MDTA Police units were stationed at either end of the bridge for traffic calming.[9] Before the roadwork started, the inspector had exchanged phone numbers with the MDTA Police units on scene and spoken with the Maryland State Operations Center to request permission to begin bridge lane closures. The inspector had also exchanged contact information with the road maintenance crew. He was the only point of contact on the bridge between MDTA Police units and the road maintenance crew.

At 2322, the *Dali* crew tested the vessel's steering gear and logged the test as "satisfactory." In addition, the engine department staff completed their engine room departure checklist, which included readying the main engine. The vessel's bridge

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[6] *Twenty-foot equivalent units* (TEU) measure the carrying capacity of a containership based on the number of 20-foot-long containers the vessel is capable of loading (standard shipping container lengths are 20 and 40 feet).

[7] Brawner Builders was contracted by the Maryland Transportation Authority.

[8] (a) The Key Bridge carried Maryland 695 over the Patapsco River from Baltimore to Dundalk, Maryland. The bridge was opened to traffic in 1977. According to the MDTA, the overall length of the bridge was about 9,086 feet between the north and south abutments. (b) A *steel arch continuous through-truss bridge* is a bridge comprised of steel *trusses*, with *spans* carrying traffic through these trusses and the horizontal trusses connecting the vertical trusses. (c) A *truss* is "jointed structure made up of individual members primarily carrying axial loads arranged and connected in triangular panels" (FHWA 2022). (d) A *span* the horizontal space between two supports of a bridge structure.

[9] *Traffic calming* is "the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behavior, and improve conditions for non-motorized street users" (Lockwood 1997).

team completed a separate bridge departure checklist.[10] About midnight, on March 26, the engine room watch changed over, and the third engineer and an oiler assumed the watch.[11] Additionally, the chief engineer and electrician reported to the engine control room (ECR).[12]

Because the *Dali* was a foreign-flagged vessel, traded internationally, and was departing the Port of Baltimore (a port in Maryland), a Maryland State Pilot was required to be aboard for the vessel's voyage out to sea.[13] About 0005, two pilots—an Association of Maryland Pilots senior pilot and a pilot-in-training—boarded the *Dali*.[14] A pilot is retained by the ship to provide local knowledge of the waterway, familiarity with tides and currents in the area, understanding of local procedures, and a thorough knowledge of the topography of the waterway. Pilots usually operate by issuing maneuvering instructions (such as heading, rudder angle, and speed orders) to the vessel's crew under the supervision of the master, the officer in charge of the navigation watch, or both.

About the same time the pilots boarded the vessel, the master called for standby engines.[15] A few minutes later, about 0009, the pilots and master conducted

[10] The predeparture checklist is available in the public docket for this investigation (case number DCA24MM031).

[11] (a) A *third engineer* (or *third assistant engineer*) is an engineering officer who monitors the operation of engineering machinery and equipment and repairs engine room machinery and auxiliary equipment. (b) A *marine oiler* is an engine room watchstander assisting the credentialed engineers with monitoring and maintaining the vessel's machinery systems.

[12] (a) A *chief engineer* is the most senior engineering officer of a vessel's engine department and oversees operation and maintenance of the propulsion machinery and other onboard mechanical and electrical systems. (b) Aboard the vessels it managed, Synergy required that an engineer, oiler, and the chief engineer (and, at the chief engineer's discretion, the electrician) be present in the engine room while the vessels were transiting restricted waters under pilotage. (*Restricted waterways* are areas where navigation and/or access are limited due to safety, security, or environmental concerns often require pilots with local knowledge to guide the vessels into or out of port safely.)

[13] See *United States Coast Pilot 3*, Chapter 3, Section 203.

[14] This report uses "senior pilot" to refer to the unlimited-license pilot, and "pilot-in-training," per the *Code of Maryland Regulations* naming convention, to refer to the other pilot, who was completing on-the-job training under the senior pilot's supervision. This individual is referred to as the "training pilot" in the NTSB Voyage Data Recorder (Audio) Group Chairman's Factual Report.

[15] A *master* is the person having command of a vessel, and as such is responsible for all aspects of the vessel and its crew, passengers, and cargo.

a master/pilot exchange to discuss the *Dali*'s planned voyage.[16] During the master/pilot exchange, the senior pilot asked about the vessel's condition, and the master reported that the ship was in good working order. The master/pilot exchange was completed at 0030.[17]

About 0036, the *Dali*, with the senior pilot at the conn, began maneuvering off the dock with two tugs assisting. Figure 4 shows the *Dali*'s helm and navigational equipment at night. The *Bridget McAllister*, a 78-foot-long, 5,080-hp tugboat with a 65-ton bollard pull, was secured on the *Dali*'s port side aft.[18] The *Eric McAllister*, a 98-foot-long, 5,150-hp tugboat with a 66-ton bollard pull, was secured on the *Dali*'s port bow. The vessel's draft on departure was 12.15 meters (39.86 feet) fore and aft. The ship and its containerized cargo displaced 112,383 metric tons of water as loaded at departure.[19] The master, second mate, and helmsman were present on the vessel's bridge and on watch per the vessel operating company's policy for maneuvering.[20]

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[16] A *master/pilot exchange* is required at the start of pilot transits and includes discussion of the vessel's navigational equipment, any limitations of maneuverability, available engine speeds, berthing maneuvers, intended course and speed through the waterway, anticipated hazards along the route, weather conditions, composition of the bridge team and deck crew both forward and aft including bow lookout, and so on.

[17] To *have the conn* means to direct or control a vessel's movements at sea.

[18] (a) *Bollard pull* is a measure of the pulling capability of a vessel at zero speed and is typically required for ship assist tugs. It is determined by connecting the tested vessel to a pier bollard with a line and calculating the force (measured in metric tons) developed using a load cell. (b) In nautical terminology, the *port* side is the direction to the left. A summary of general nautical terms can be found in the General Nautical Terms section of this report on page xiii.

[19] The weight of the water that a vessel displaces as it floats is equal to the weight of the vessel and is known as the vessel's *displacement*.

[20] (a) A *second mate* (or *second officer*) on a merchant vessel is the third in command (after the master and chief mate) and whose main responsibilities include navigation, watchkeeping, and safety. (b) A *helmsman* executes rudder orders from the vessel's master (or pilot) and steers the vessel, maintaining the vessel's course and communicating the ship's heading and rudder positions to the master (or pilot).

Figure 4. The *Dali*'s helm and conning area, including bow thruster and main engine controls, located on the centerline the navigational bridge, looking forward. The overhead lighting would have been off while the vessel was underway while dark outside.

When the *Dali* began maneuvering away from Seagirt Marine Terminal, two of the vessel's four alternating current, diesel engine-driven generators, DG3 and DG4, were online for departure and connected to a 6,600-volt high-voltage (HV) main electrical bus (see figure 5; see section 1.7 for more details about the vessel's machinery and electrical systems).[21] A third diesel generator, DG2, was in standby and could be started and connected if needed, either manually or automatically via

[21] An *electrical bus* is a physical part of an electrical switchboard. (The term "bus" is a shortened form of bus bars, which are the metal bars physically located within the switchboard.) The bus connects the power produced by generators to systems/devices that require electrical power. Components such as circuit breakers and transformers transfer the electrical power that the bus distributes to the systems/devices requiring electrical power.

the power management system (PMS).[22] According to the crew, at the time of departure, the vessel's fourth diesel generator, DG1, was off, had been placed in manual local control by the crew, and could not start automatically because it was in the process of warming up.[23] The electric motor-driven bow thruster and all three steering gear pumps (nos. 1, 2, and 3) were online as well.[24]

[22] The PMS allowed the engineering crew to prioritize and designate the order that standby diesel generators would start. Additionally, the PMS monitored *electrical bus* load compared to online diesel generator capacity, and, if system load exceeded preset limits or diesel generator capacity, the PMS started the next priority diesel generator and connected it to the *bus*. Finally, the PMS detected cases of a failure or underperformance of an online diesel generator and initiated a start of the next diesel generator.

[23] Synergy policy, which only required that two diesel generators be online during maneuvering in restricted waters and did not specify whether generators had to be in standby, complied with applicable international regulations. For more information these guidelines, see International Maritime Organization, *International Convention for the Safety of Life at Sea*, part 1, chapter II-1 (Construction: Structure, Subdivisions and Stability, Machinery and Electrical Installations), part D (Electrical Installations) and part E (Additional Requirements for Periodically Unattended Machinery Spaces).

[24] (a) A *bow thruster* is a propulsor on the ship's hull, below the waterline near the bow, that assists with ship maneuverability at slower speeds. A summary of general nautical terms can be found in the General Nautical Terms section of this report on page xiii. (b) A *steering gear pump* is a hydraulic pump, driven by an electric motor, that supplies pressurized hydraulic fluid to move the rudder. On the *Dali*, steering gear pump nos. 1 and 2 were powered from the low-voltage (LV) bus, while pump no. 3 was powered from the emergency bus. Steering gear pump no. 3 could be operated at two speeds: (1) at high speed, when normal LV power was supplying the emergency *bus*, or (2) low speed, when the emergency generator breaker was closed.

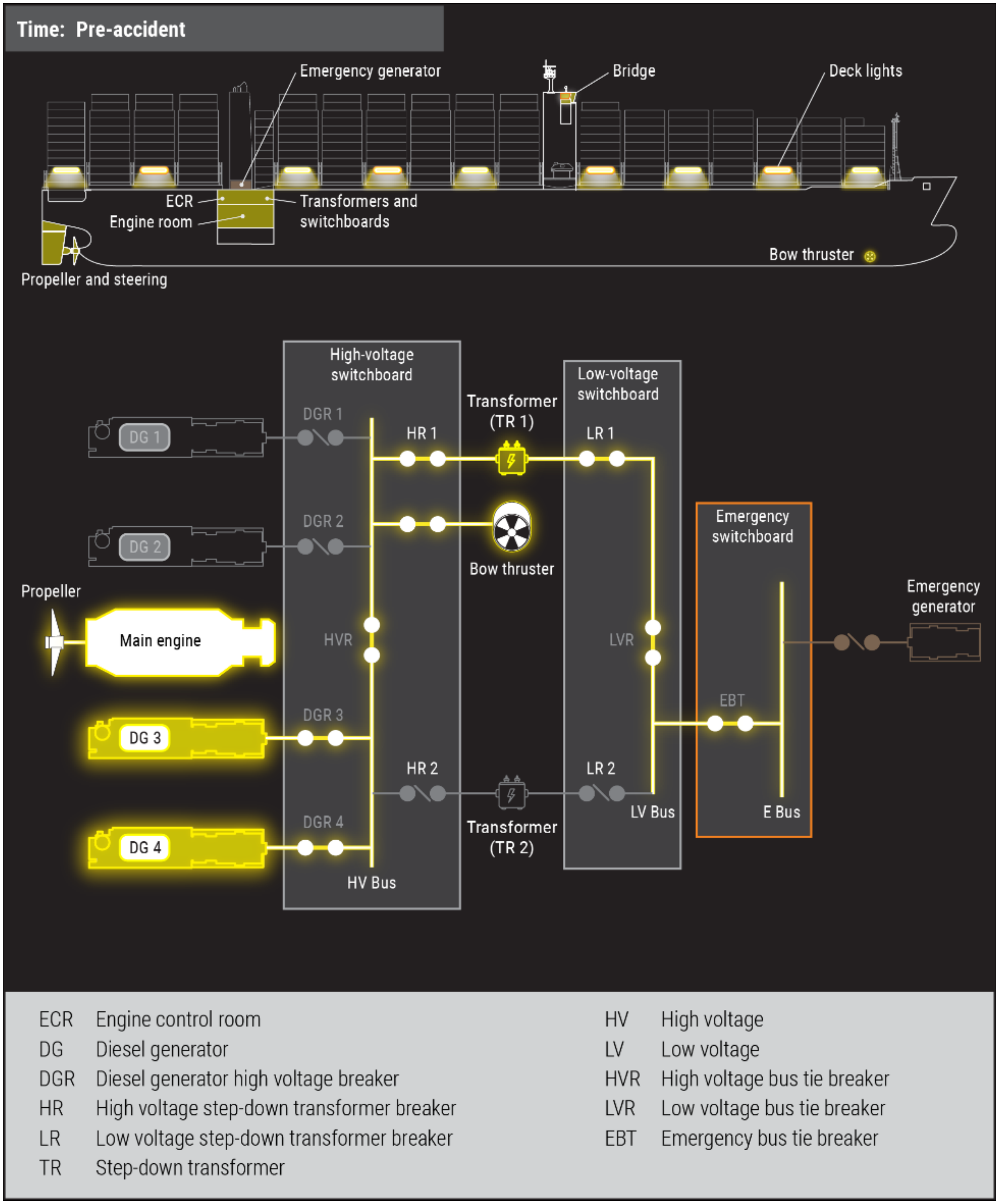

Figure 5. Configuration of *Dali* plant at time the *Dali* left the dock at Seagirt Marine Terminal on March 26, with DG3 and DG4 energized. (DG1 was offline, while DG2 was in standby.)As the vessel maneuvered away from the terminal and out through the Seagirt Marine Terminal West Channel, about 0048, the senior pilot told the master to have one

crewmember standing by on the bow until the vessel transited through the Key Bridge. At this time, the bosun was on the bow, as was an able seafarer.[25]

Both tugs continued to assist the *Dali* through the Seagirt Marine Terminal West Channel, traveling at a speed about 4 knots (4.6 mph) as the vessel headed for the Fort McHenry Channel in the Patapsco River (see figure 6). At 0107, with the vessel turning to port to enter the Fort McHenry Channel, the *Bridget McAllister* was let go. At 0108, with the vessel steady and heading southwesterly (outbound) down the main channel, the *Eric McAllister* was let go. According to the senior pilot, it was common procedure to release the tugs at this location.

[25] (a) The *bosun* (or *boatswain*) is the highest-ranking unlicensed crewmember in the deck department. (b) An *able seafarer* is a skilled and experienced member of the ship's deck department, proficient in seamanship, watchstanding, handling cargo, and deck maintenance. Able seafarers are credentialed per Standards of Training, Certification and Watchkeeping, specifically Rating Forming Part of a Navigational Watch endorsement (STCW II/4) and the Able Seafarer Deck endorsement (STCW II/5).

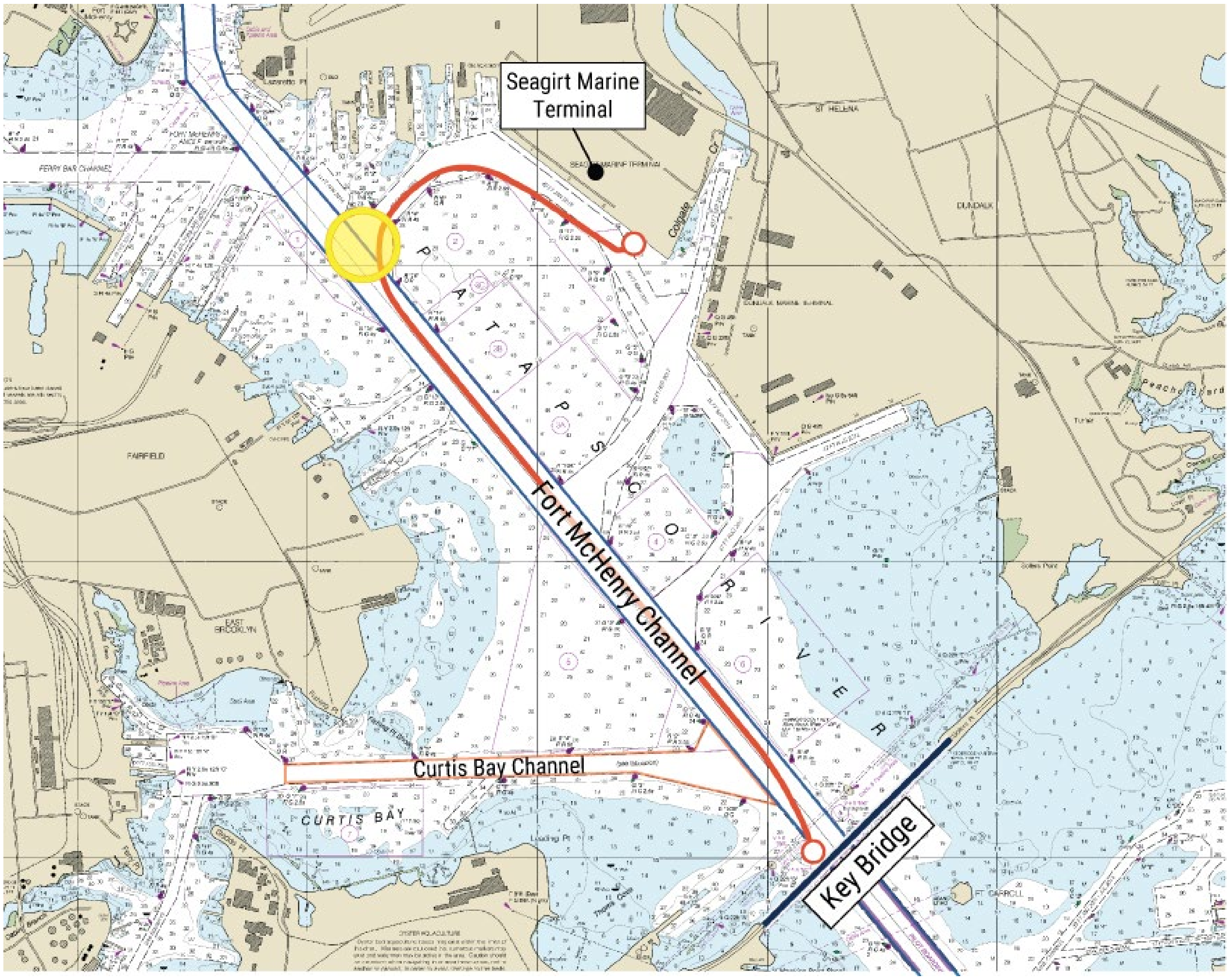

Figure 6. Navigation chart showing Baltimore Harbor, including Seagirt Marine Terminal, the Fort McHenry Channel, Curtis Bay Channel, and the Key Bridge. The yellow circle indicates where tugs used for maneuvering out of Seagirt Marine Terminal were usually let go. The red trackline represents the *Dali* after it departed Seagirt Marine Terminal and approached the Key Bridge. White circles at each end of the trackline mark the location of the vessel's automatic identification system antenna (above the vessel's bridge) at departure and at 0125:00. (Source: National Oceanic and Atmospheric Administration [NOAA] Chart 12281)

In the Port of Baltimore, it was practice to let go of the tugboats used in maneuvering when the vessel was steady in the Fort McHenry Channel, barring any extenuating circumstances that would compel the pilot to retain the tugboats. Furthermore, tugboats not classed as escorts needed to be let go before the vessel they were aiding reached a speed that exposed the tugboats and their crews to greater risks while operating in the vessel's wake and areas of low pressure near the hull.[26] Coal bulkers departing the CSX terminals west of the Fort McHenry Channel operated at speeds slow enough that the tugs could effectively contribute to vessel maneuverability. Since coal bulkers typically turned to join the Fort McHenry Channel before achieving a sufficient speed for the vessel's steering and propulsion to fully maintain directional control, the tugs' contribution to a bulker's maneuverability allowed for a safer and more controlled turn than if the vessel did so without a tug.

At 0108:58, the senior pilot ordered the engine slow ahead, which would increase vessel speed to a range around 8–10 knots (9.2–11.5 mph) (see figure 7). About the same time, the *Dali*'s master informed the crewmembers on the bow that only one person needed to remain forward, so the bosun remained on the bow while the able seafarer headed aft to rig the pilot ladder in preparation for the pilots' departure from the vessel.

Engine Telegraph (Ahead)	RPM	Estimated Ship's Speed (kts)	
		Loaded	Ballast
NAV FULL	80.05	21.9	23.5
FULL	60	16.8	18.1
HALF	53	14.5	15.7
SLOW	35	10.0	10.9
DEAD SLOW	27	8.1	8.8
STOP			

Figure 7. The *Dali*'s main engine maneuvering table, which shows ahead engine orders and the vessel's corresponding speeds under two operating conditions: loaded and ballast. The *Dali,* although not fully loaded, was nearer to a loaded than ballast condition when it departed. (One knot is equivalent to 1.15 mph.)

[26] At the time of the casualty, there were four escort tugs in the harbor. These escort tugs were classed by the American Bureau of Shipping (ABS), a vessel classification society. (For more information about classification societies, see section 1.6.1 and section 1.8.) Moran Towing owned and operated three: *Mark Moran*, *Lynne Moran*, and *April Moran*. McAllister owned and operated one, the *Eric McAllister*, the forward tug used in the undocking and maneuvering operations that was let go at 0108. An additional ABS-classed tug, *Isabel McAllister*, has been added to McAllister's fleet postcasualty, and the *Eric McAllister* has since left the Port of Baltimore to join the company's fleet in Charleston.

Once the vessel was steady in the channel and on a heading of 140°, the pilot-in-training assumed the conn from the pilot. At 0121, the senior pilot told the pilot-in-training to keep the vessel's speed at 10 knots (11.5 mph) or less.

1.1.2.2 Electrical Power Losses aboard *Dali* and Contact with Key Bridge

At 0125:00 (-4:09), as the vessel approached the intersection of the Curtis Bay Channel and the Fort McHenry Channel, the *Dali* experienced a loss of low-voltage (LV) power and an LV switchboard blackout (see figure 8).[27] The blackout resulted in a loss of steering (steering gear pump nos. 1, 2, and 3), the majority of vessel lighting, and auxiliary equipment essential for the operation of the vessel, such as fuel pumps, cooling water pumps, and bow thruster auxiliary pumps. The bow thruster, which was not being used at the time, also shut down because its auxiliary pumps had shut down. At the time of the blackout, the *Dali* was underway at 8.9 knots (10.2 mph) on a heading of 142°, and its bow was about 3,200 feet (or 3.3 ship lengths) away from the Key Bridge.[28]

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[27] This section contains time notations in parentheses, such as 0125:00 (-4:09), which indicate the time, in minutes and seconds, until the *Dali* contacted the Key Bridge.

[28] Throughout this report, given distances from the vessel to the Key Bridge are measurements from the *Dali*'s bow/stem to the northeast corner of Pier 17 of the bridge. A summary of general nautical terms can be found in the General Nautical Terms section of this report on page xiii.

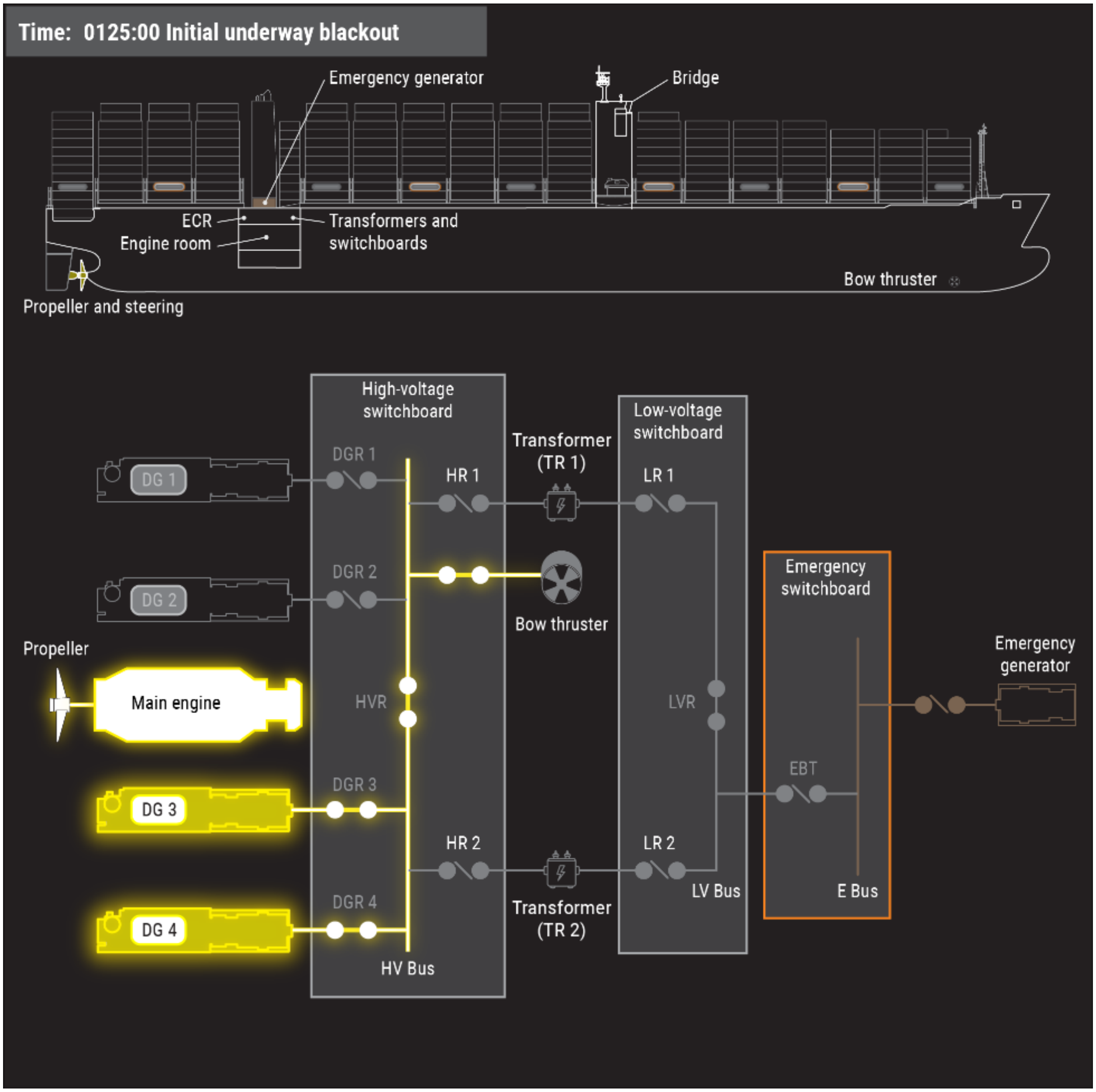

Figure 8. Configuration of *Dali* plant at 0125:00, the time of the initial loss of power (blackout) while the vessel was underway.

See figure 9 for the path of the *Dali* from the time it lost power at 0125:00 until it contacted the Key Bridge. Events referenced in the figure are discussed throughout the rest of this section.

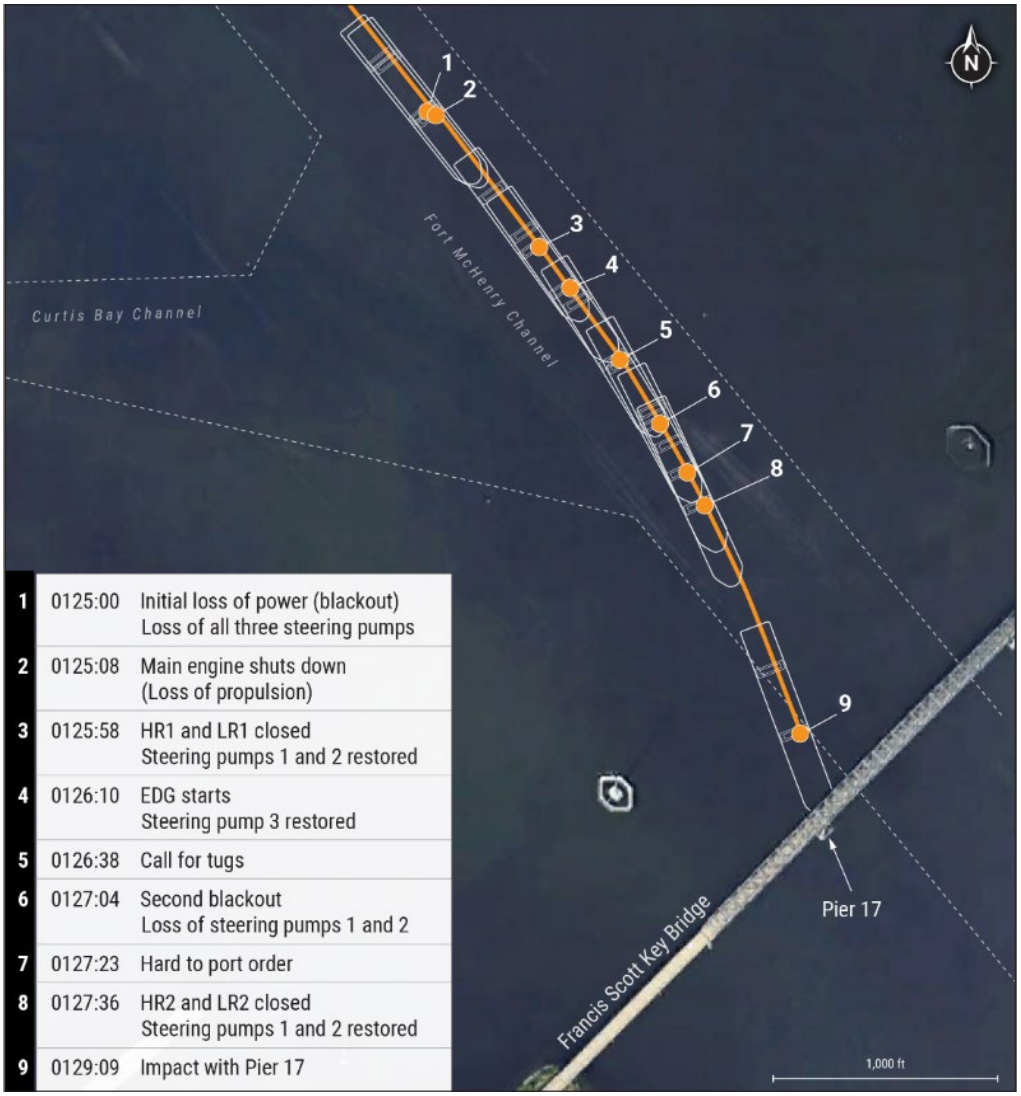

Figure 9. Trackline of the *Dali* after it departed Seagirt Marine Terminal and approached the Key Bridge. Each dot marks the location of the vessel's AIS antenna (above the vessel's bridge) at a given time. (Background source: Google Earth)

Shortly after the blackout, at 0125:03 (-4:06) , the voyage data recorder (VDR) stopped recording parametric data; the vessel's automatic identification system (AIS) continued to transmit location, speed, heading, course, and rate of turn data.[29]

[29] (a) In the context of a VDR, *parametric data* refers to numerical or digital data automatically collected from shipboard sensors and systems, such as GPS position, speed, heading (the direction the vessel's bow is pointing), engine and rudder orders, wind speed and direction, depth, and other navigation and control parameters that describe the vessel's operational state and movements over time. (b) The VDR installed on the *Dali* did not provide, nor was it required to provide, a backup power source to the unit that records parametric data. For this reason, when the blackout occurred, the VDR recorded no parametric data. However, transmissions from the AIS were able to provide some parametric data that the VDR did not capture during this period. (c) *AIS* is a maritime navigation safety communications system that provides vessel information automatically to appropriately equipped shore stations, other ships, and aircraft; automatically receives such information from similarly fitted ships; monitors and tracks ships; and exchanges data with shore-based facilities.

Additionally, at 0125:08 (-4:01), the main engine shut down, and propulsion was lost (see figure 10).

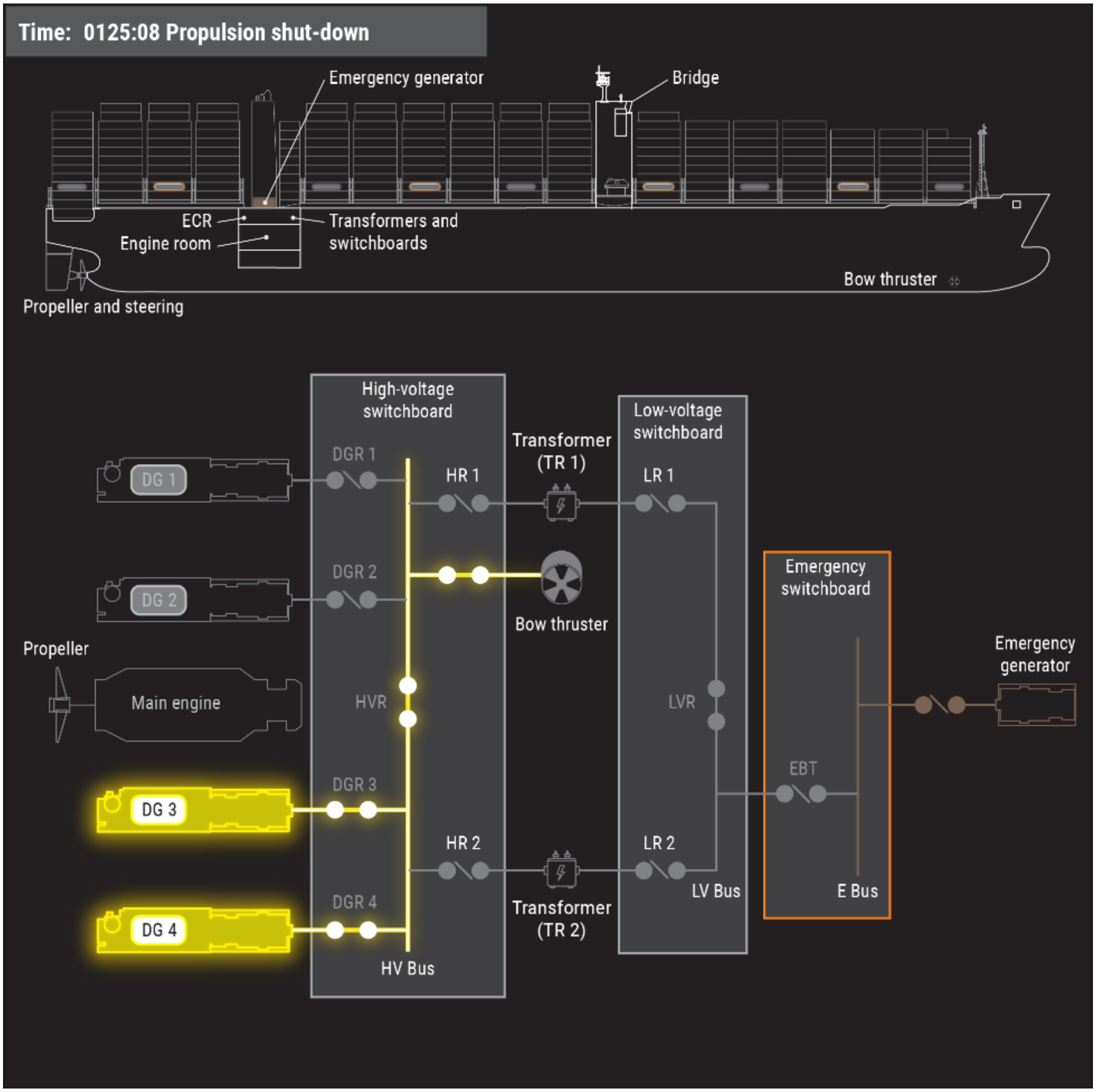

Figure 10. Configuration of *Dali* plant at 0125:08 after the main engine shut down.

The master ordered the bosun, who was on the bow, to stand by the anchor. The senior pilot assumed the conn from the pilot-in-training and asked whether the ship still had steering; the second mate and helmsman stated that it did. However, due to the blackout, none of the three steering gear pumps were powered, and the rudder, which was midships at the time of the blackout, could not be moved.[30] The senior pilot ordered the helmsman to maintain a heading of 141°, and, according to AIS data, the vessel was steady on a heading of 141°.

About 0125:27 (-3:42), the master instructed the bosun to keep the bow stopper up and remain standing by at the anchor brake.[31] At 0125:47 (-3:22), the helmsman told the senior pilot that the vessel's heading was swinging to starboard and that he had the helm hard over to port to maintain a heading of 141°.

At 0125:58 (-3:11), 58 seconds after the blackout, the electrician, who was in the ECR at the time of the blackout, discovered that the vessel still had HV power but LV power was blacked out. To regain LV power, he manually closed the HV step-down transformer breaker 1 (HR1) and LV step-down transformer breaker 1 (LR1), restoring power to the LV switchboard (see figure 11).[32] Normal LV power, supplied by the LV switchboard, was restored to steering gear pump nos. 1 and 2, vessel lighting, auxiliary equipment for the main engine and electrical generators, and other equipment powered from the LV switchboard. Additionally, the VDR resumed recording parametric data. The emergency bus remained unpowered following the loss of LV power.[33] The fuel oil flushing pump, which had been used to supply fuel to the two online generators (DG3 and DG4), did not automatically restart when power was restored because the flushing pump was not configured to restart automatically following the loss of power.[34] The main engine remained off throughout the remainder of the accident voyage.

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[30] *Midships* refers to a rudder angle input on the helm (or steering system in use) to the position indicating zero degrees, which should position the rudder in line with the vessel's centerline. A summary of general nautical terms can be found in the General Nautical Terms section of this report on page xiii.

[31] On the *Dali*, the "bow stopper," typically called a riding pawl, clamped down the anchor chain to secure it during transit or while the vessel was at anchor, thereby preventing stress on the anchor windlass (which raised and lowered the anchor).

[32] See section 1.7.1.1 for more information on the vessel's machinery and electrical systems.

[33] See section 1.7.1.2 for more information about the emergency bus, the emergency switchboard, and the emergency diesel generator.

[34] The DG fuel supply system also included an air-motor-driven emergency MGO fuel pump that was designed to supply sufficient fuel to start one of the DGs when recovering from a power outage. This pump was designed to start automatically following the initial loss of power at 0125:00 but was not capable of serving as the lone fuel supply pump for the DGs.

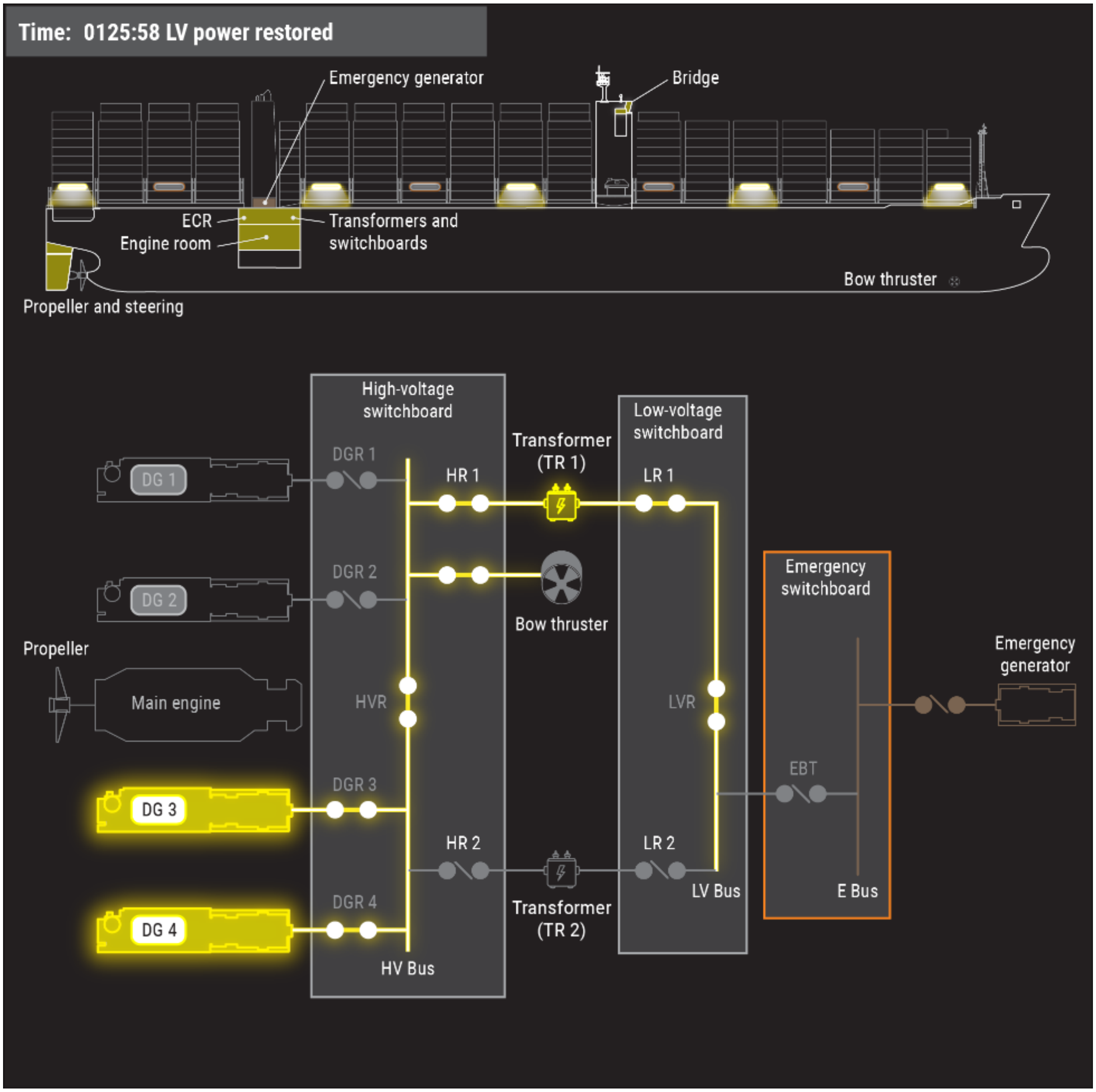

Figure 11. Configuration of *Dali* plant at 0125:58 when LV power was restored.

At 0125:59 (-3:11), the senior pilot called the Association of Maryland Pilots dispatcher via phone. The senior pilot told the dispatcher to contact local authorities and tell them to shut down the Key Bridge; the call lasted about 7 seconds. At this time, the vessel was 2,430 feet (about 2.5 ship lengths) from the Key Bridge, closing at a speed of 8.5 knots (9.8 mph). Although electrical power and steering were restored, the *Dali*'s heading was now drifting to starboard, 5° off course, and the ship was without propulsion.

At 0126:10 (-2:59), 70 seconds after the blackout, the emergency diesel generator (EDG) connected to the emergency bus, supplying power to the emergency switchboard, including steering gear pump no. 3 (see figure 12).[35] Two seconds later, at 0126:12 (-2:57), the senior pilot ordered port 20° rudder and the helmsman eased the rudder to port 20°.

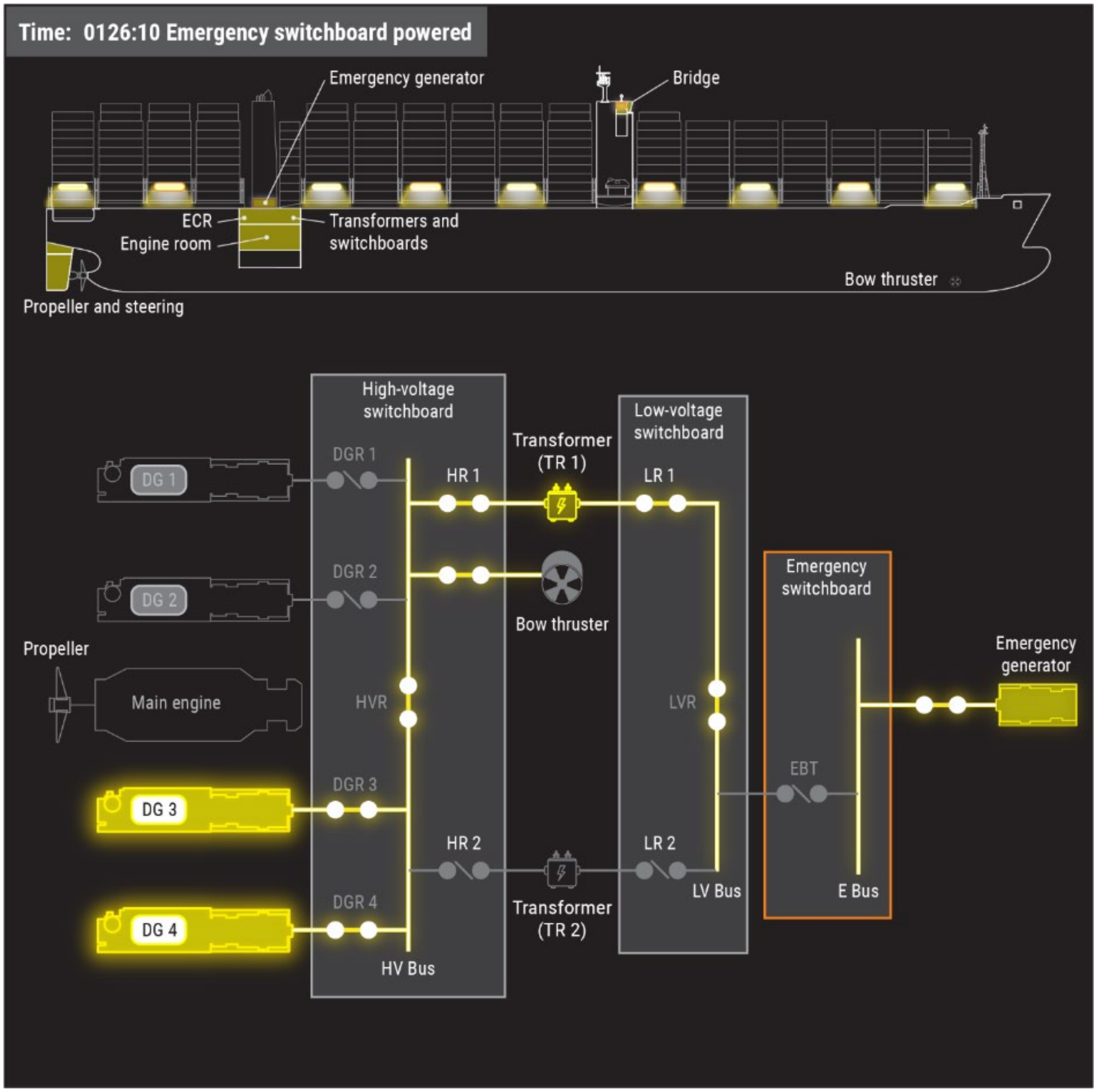

Figure 12. Configuration of *Dali* plant at 0126:10 when the emergency switchboard was powered by the EDG.

[35] Once the EDG came online, it powered the emergency *bus* throughout the accident.

At 0126:18 (-2:51), the vessel, now with all three steering gear pumps running, reached a rate of turn of 7.5° per minute to starboard, which was the maximum rate of turn reached as it approached the bridge.

At 0126:38 (-2:31), the senior pilot requested tugboat assistance by radio. At 0126:44, the pilots' dispatcher called the MDTA duty officer to notify him that the Key Bridge needed to be closed to traffic due to a nearby ship that had lost steering.[36] About the same time, the *Eric McAllister* captain responded to the senior pilot. After the senior pilot explained the *Dali*'s power loss, the tugboat started heading toward the *Dali*.

At 0127:02 (-2:07), with the vessel at 7.9 knots (9.1 mph) and about 1,500 feet (1.5 ship lengths) from the Key Bridge, the senior pilot ordered the port anchor let go.[37] Two seconds later, the vessel's PMS detected an electrical frequency drop from the online diesel generators (DG3 and DG4) and started diesel generator 2 (DG2) automatically as a backup. Before the PMS could synchronize DG2 to the HV bus, the PMS automatically disconnected DG3 and DG4 from the HV bus due to their underperformance, causing both high-voltage step-down transformer breaker 1 (HR1) and low-voltage step-down transformer breaker 1 (LR1) to open automatically. The vessel then experienced both an HV and LV switchboard blackout; all pumps, lighting, and other equipment powered by the two switchboards shut off due to the loss of power (see figure 13). The emergency bus remained powered during this second blackout, supplying power to the emergency switchboard, steering gear pump no. 3, and other equipment and lights connected to the emergency switchboard.

[36] The Association of Maryland Pilots' single-point emergency contact protocol required the pilot dispatcher to contact the US Coast Guard in case of emergency. On the contact list for emergency shutdowns of the Bay and Key Bridges, the dispatcher saw the phone number for the MDTA. Reverting to previous training, the dispatcher contacted the MDTA before contacting the Coast Guard. Immediately after the Key Bridge collapse, the pilots' association changed its protocol so that dispatchers contact the MDTA first when informed by a pilot of an emergency requiring the shutdown of a bridge; after notifying the MDTA, the dispatcher informs the Coast Guard.

[37] To *let go the anchor* means to release the anchor brake, letting the anchor and its cable freefall under the force of their combined weight until the anchor hits the seabed.

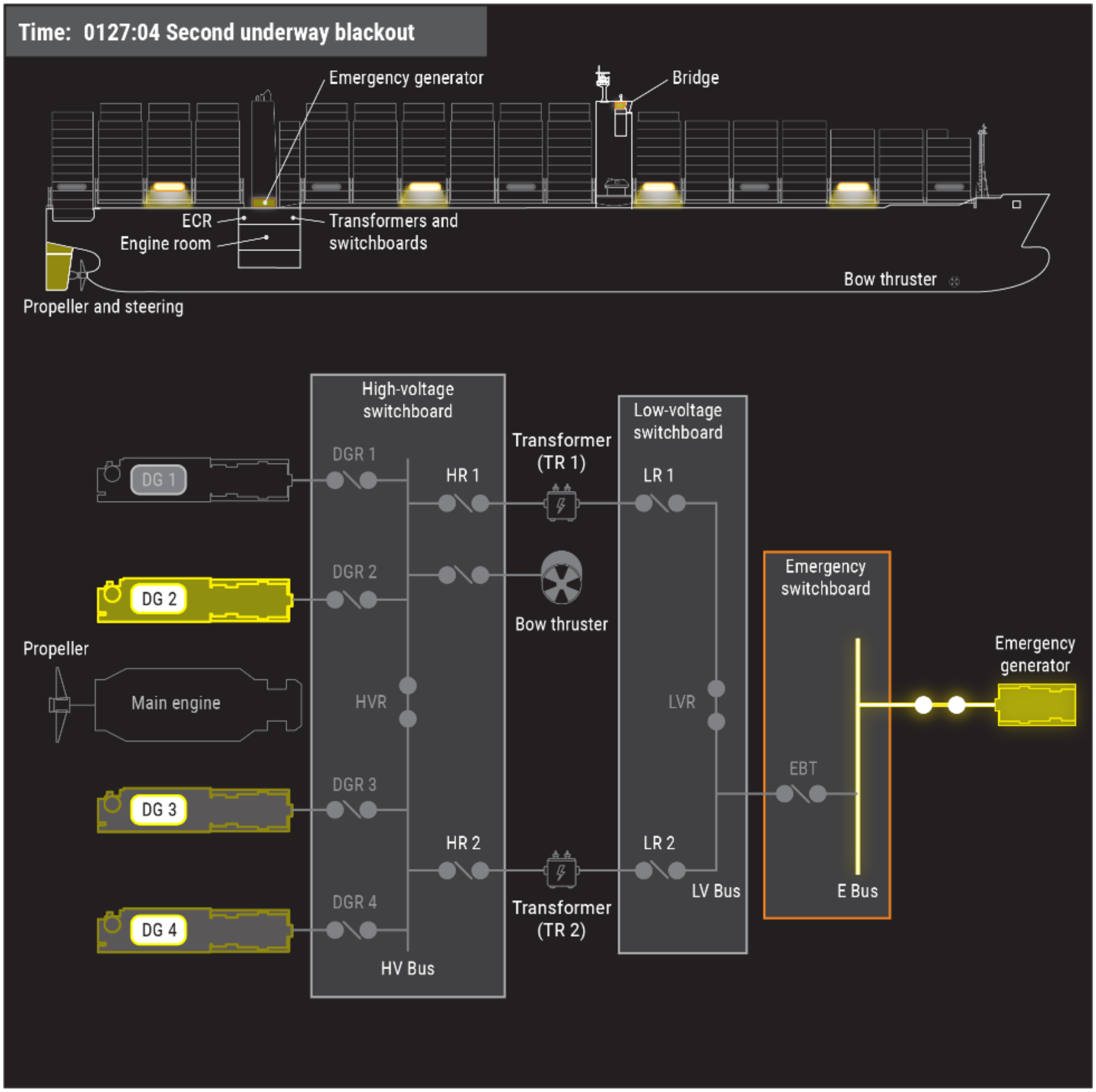

Figure 13. Configuration of *Dali* plant at 0127:04 when the vessel lost power (blackout) for a second time while underway.

Within 3 seconds of the second blackout, at 0127:07 (-2:02), the PMS synchronized DG2, powering the HV bus (see figure 14). The LV bus remained blacked out because the HR1 and LR1 breakers remained open.

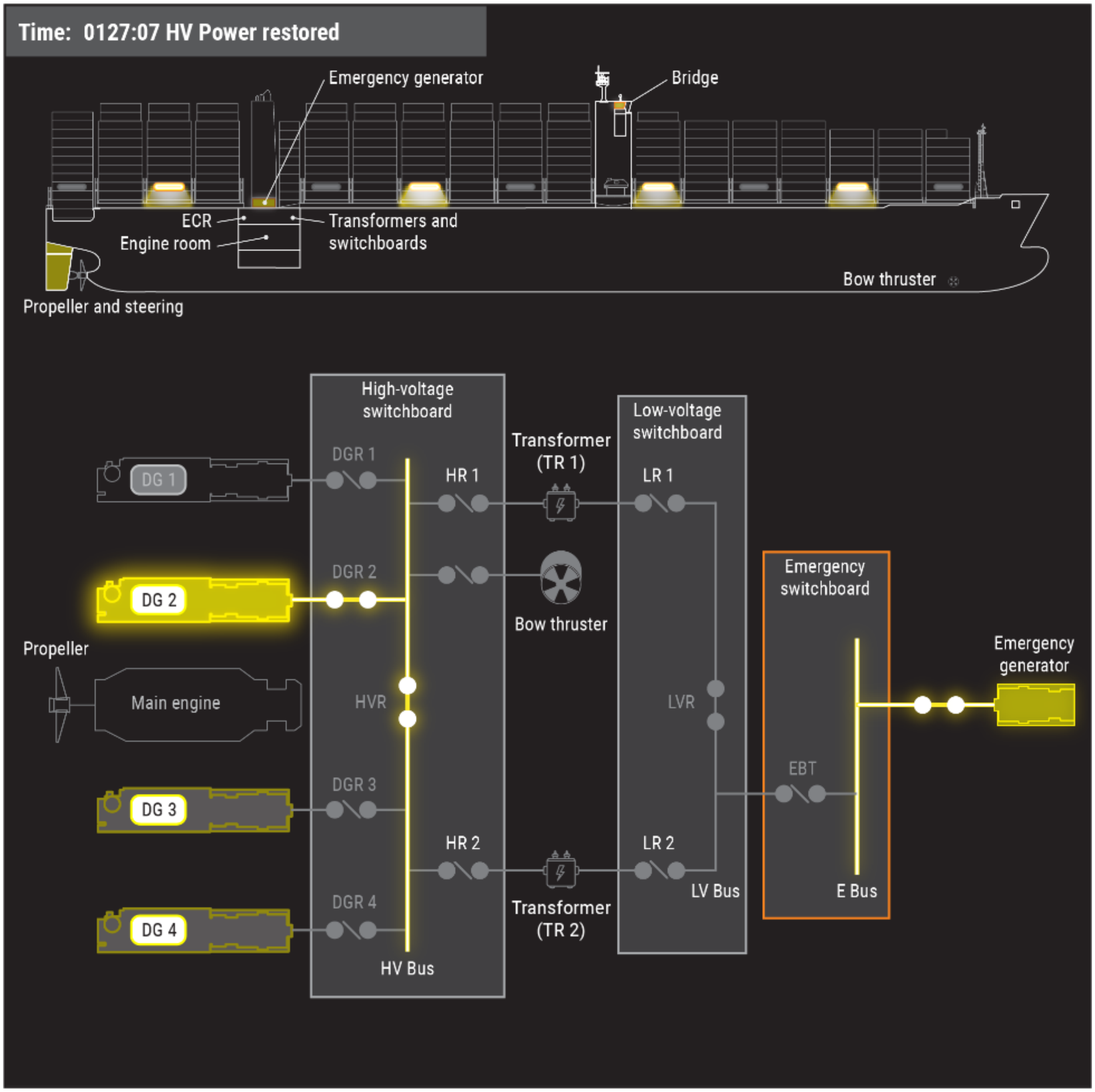

Figure 14. Configuration of *Dali* plant at 0127:07 when HV power was restored.

At 0127:23 (-1:46), the *Dali* was 14° off course. The senior pilot gave a hard port command, and shortly after, the helmsman reported the helm was on hard port. A few seconds later, the pilot-in-training made a sécurité call over VHF radio.[38]

At 0127:36 (-1:33), the electrician in the ECR manually closed HR2 and LR2, the other available HV and LV step-down transformer breakers, and power was restored to the LV bus, which reestablished power to the LV switchboard, steering gear pump nos. 1 and 2, the majority of vessel lighting, the main engine and electrical generator auxiliaries, and other equipment connected to the LV switchboard (see figure 15).[39] The main engine remained off because it needed to be restarted manually. About this time, the electrician and chief engineer instructed the third engineer to go down several decks to the purifier room and manually restart the flushing pump that had been supplying fuel to DG3 and DG4.

[38] A *sécurité call* is a VHF radio transmission of important safety-related information for vessels in the broadcast area. The vessel or station transmitting the message begins by saying "Sécurité, Sécurité, Sécurité," and follows with specific safety information.

[39] The vessel LV power configuration remained unchanged, and the system operated without incident from this point until postaccident examinations began on April 1. (See section 1.14.)

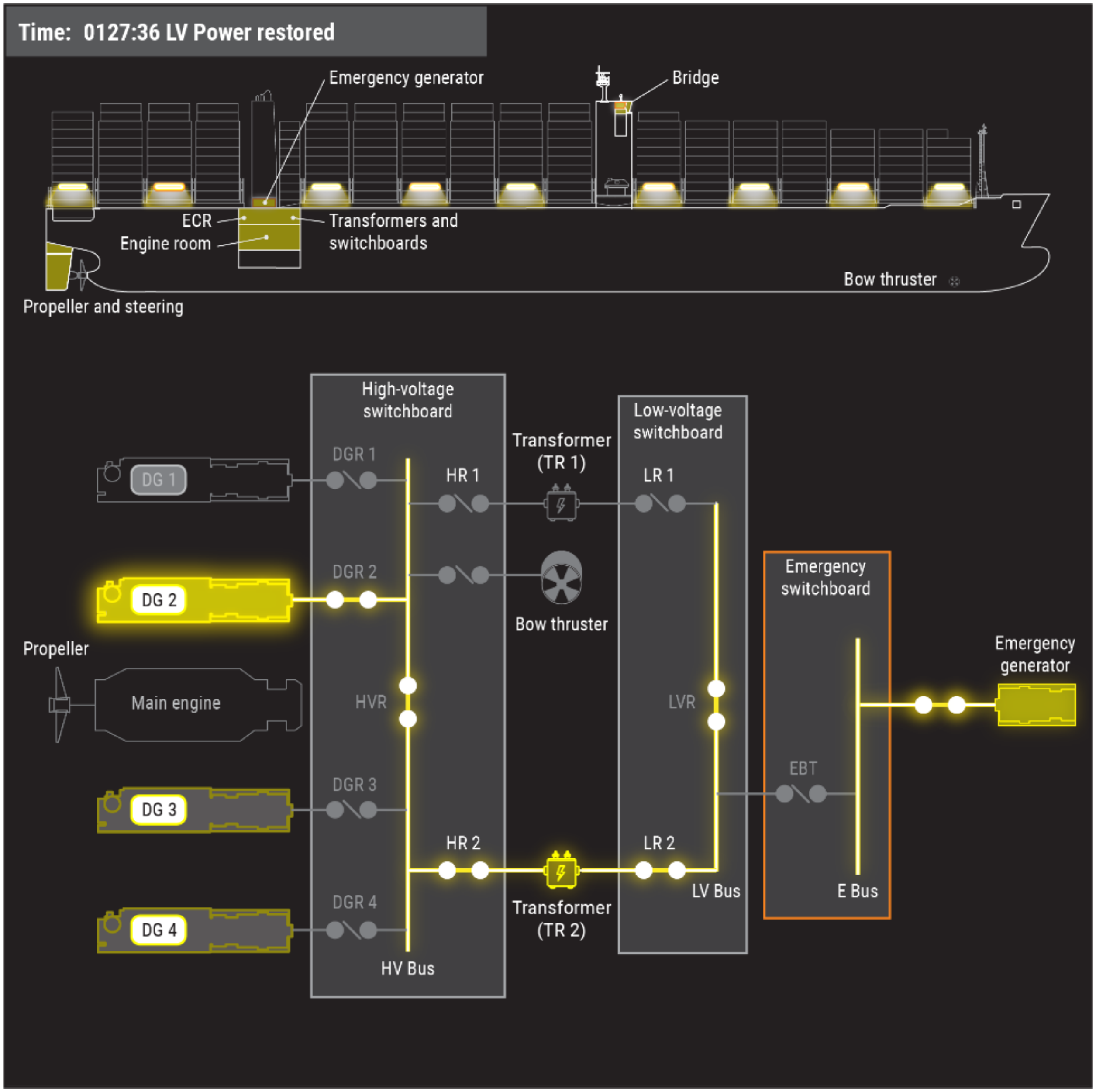

Figure 15. Configuration of *Dali* plant at 0127:36 when LV power was restored.

At 0127:46 (-1:23), the ship was about 939 feet (less than one ship length) away from the Key Bridge, on a heading of 156.6°, on a course over ground of 154.1°, and at a speed of 7.5 knots (8.6 mph). The senior pilot ordered "full to port" on the bow thruster. The second mate engaged the bow thruster control knob, but the bow thruster was unavailable because its auxiliary pumps, which relied on LV power to operate, had shut down during the initial blackout at 0125:00.

Meanwhile, at 0127:53 (-1:16), the MDTA duty officer contacted the MDTA officers that had been stationed at either end of the Key Bridge for traffic calming and instructed them to shut down the bridge to traffic.

At 0127:55 (-1:14), in response to the master's previous order to let go the anchor, the bosun reported to the bridge team and the pilots that he was unable to open the brake to let go the anchor.

About 0127:56 (-1:13), the third engineer restarted the flushing pump, returning fuel oil pressure for DG3 and DG4 to normal.

At 0128:10 (-0:59), the bow of the *Dali* crossed out of the charted Fort McHenry Channel, 656 feet (200 meters) from the bridge, and began to ground in the mud near Pier 17 of the Key Bridge at 7.2 knots (8.3 mph).[40]

At 0128:21 (-0:48), the MDTA unit stationed at the north end of the Key Bridge moved his vehicle across both lanes, blocking all southbound traffic, and the MDTA unit on the south end blocked the northbound lanes. About the same time, the MDTA duty officer asked the officer on the north end about the maintenance crew on the bridge. The officer at the north end replied that he would drive to warn the crew once another officer was on scene to relieve him.

At 0128:26 (-0:43), as the vessel continued toward Pier 17 of the bridge, the master again ordered the bosun to let go the anchor. At 0128:42, the bosun confirmed he had been able to manually release the brake and let go the anchor. The senior pilot, the master, the second mate, and the helmsman made final attempts to slow the vessel or change its course by again attempting to use the bow thruster (which had not yet been restarted) and confirming that the anchor had been dropped. The ship's rate of turn to starboard had eased, until it reached zero about 0128:49 (-0:20), and the *Dali* started coming to port. However, at 0129:09, the *Dali*'s starboard bow struck the northwest column of Pier 17 of the Key Bridge at a speed of 6.4 knots (7.4 mph) (see figure 16).

[40] The Key Bridge was supported by 37 piers. Vessels transiting the Key Bridge via the Fort McHenry Channel passed between Pier 17 and Pier 18.

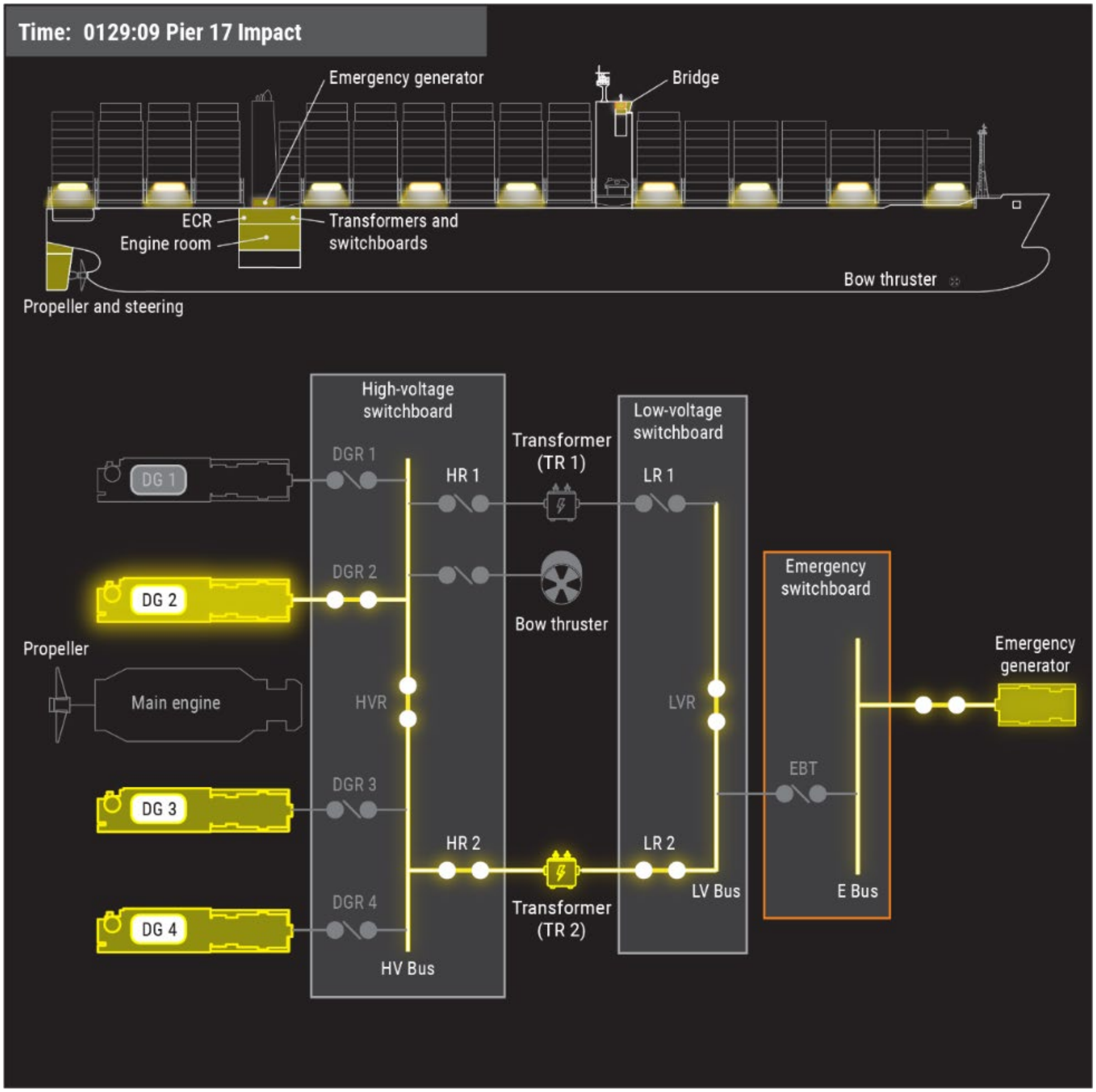

Figure 16. Configuration of *Dali* plant at 0129:09 when the vessel struck Pier 17 of the Key Bridge.

Using the calculation for equivalent static force on a pier, found within the 2009 *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, the *Dali*'s estimated impact force was over four times greater than the lateral capacity of Pier 17 (5,509 kips, according to calculations provided by the Federal

Highway Administration [FHWA]).[41] The initial impact to the column occurred about 20 feet above the waterline; the fender system on Pier 17 was likely impacted about the same time.[42] The inspector, who had been walking the length of the bridge to check on drying cement and had just reached his vehicle parked on Span 22, heard a "crumbling thunder noise" and began running northbound on the bridge.

At 0129:22, about 13 seconds after the initial impact, Pier 17 collapsed. Within seconds, the main spans (Spans 17, 18, and 19); Piers 19, 20, and 21; and Spans 20, 21, and 22 had collapsed. As the bridge deck collapsed into the water and onto the bow of the *Dali*, an able seafarer, who had been on the bow at the time of the bridge collapse, sustained a minor injury while escaping the falling debris. About the same time, one of the MDTA Police units stationed at the bridge broadcasted to dispatch that the bridge had collapsed.

At the time of the collapse, the highway workers and inspector who had been performing work on the bridge deck were within the southbound right lane, which was closed to vehicular traffic. The seven highway workers were on break in their vehicles on Spans 18 and 20. Two highway maintenance vehicles were on Span 20, four highway maintenance vehicles were on Span 18, and one highway maintenance vehicle was on Span 22 (see figure 17).

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[41] (a) According to the 2009 American Association of State Highway Officials (AASHTO) *Guide Specifications*, "The determination of the impact load on a bridge structure during a ship collision is extremely complex and depends on many factors such as the structural type and shape of the ship's bow, the degree of water ballast carried in the forepeak of the bow, the size and speed of the ship, the geometry of the collision, and the geometry and strength characteristics of the bridge pier." As such, the *Guide Specifications* provide a calculation based on *deadweight tonnage* and ship velocity to estimate a ship's equivalent static force on a pier, which was used to estimate the impact force on Pier 17. (b) The equivalent static force of the *Dali* at the time of impact was calculated using a vessel deadweight tonnage of 66,229 tons (based on the *Dali*'s draft at the time of impact) and a speed of 7.4 mph (10.9 feet per second). (c) One kip equals 1,000 pounds.

[42] (a) A *fender* (or *fendering system*) is a protective structure located directly on a bridge or on a protective element independent of the bridge (such as a *dolphin*), designed to fully or partially absorb the design impact loads, or deflect or redirect an aberrant vessel away from the bridge. (b) A *dolphin* (or *bridge dolphin*) is "a group of piles driven close together, or a caisson placed to protect portions of a bridge exposed to possible damage by collision with river or marine traffic" (FHWA 2022). See section 1.5.2 for more information about the Key Bridge's dolphins.

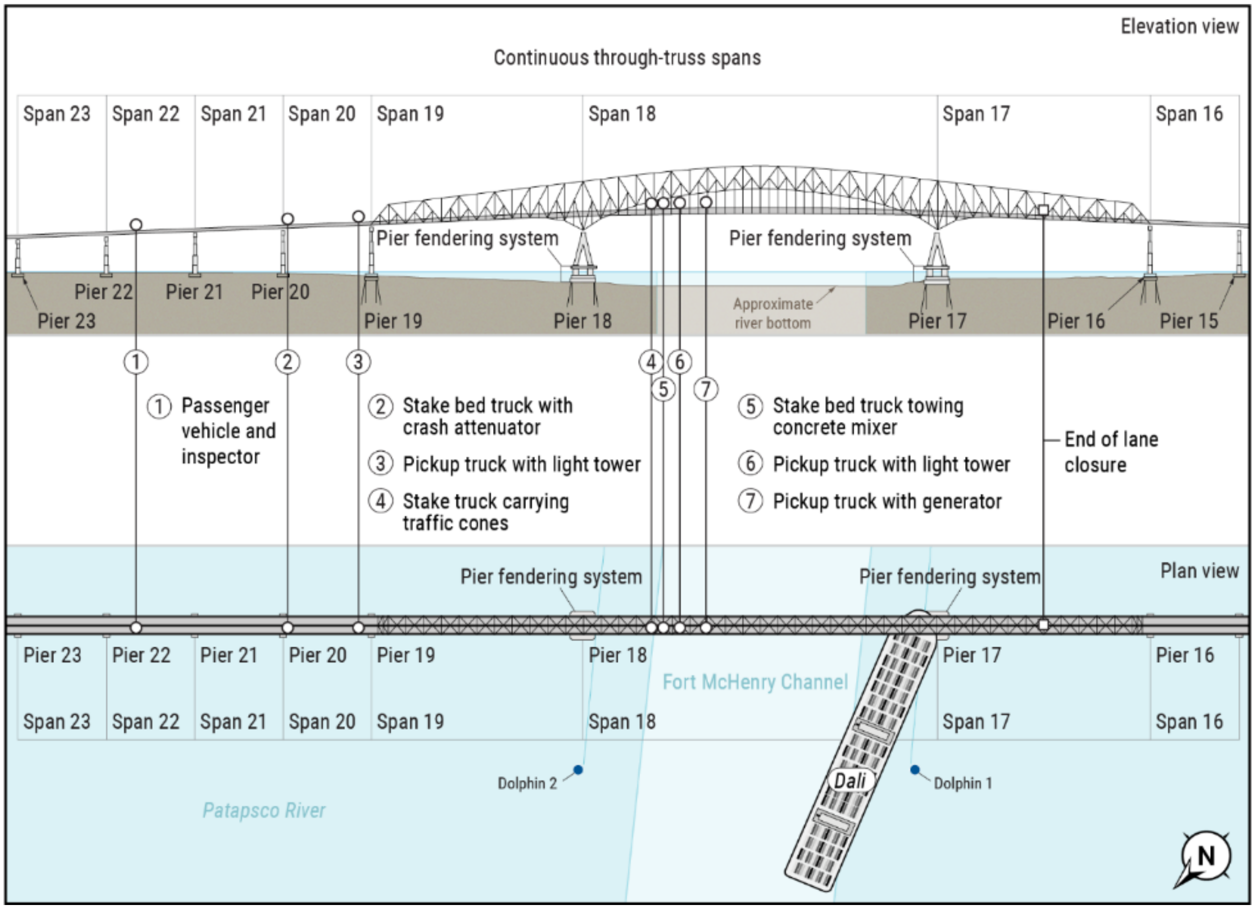

Figure 17. *From top*: Elevation view and plan view of the main spans of the Key Bridge, showing locations of highway maintenance vehicles at the time of the vessel's impact.

The seven highway workers fell with the bridge spans into the water when the central spans collapsed. One worker was able to escape through an open window of his vehicle. He swam to nearby debris and floated there until he was rescued near Pier 20 by an MDTA Police marine unit at 0155. The worker was transported by a Baltimore City medic to the University of Maryland Shock Trauma Center in downtown Baltimore, where he was treated for a serious injury.

The inspector was able to run to Span 23 before the collapse of the span he was walking on; he then called the Maryland State Operations Center to report the collapse. He arrived unharmed on the north abutment and met the MDTA officers.[43] See Appendix C for a timeline table of the accident events.

[43] An *abutment* is a structure designed to support the vertical and lateral forces from the ends of an arch or span, such as a bridge.

1.2 Response

1.2.1 Search and Rescue

Within seconds of the bridge's collapse, at 0129:37, the pilot-in-training called the US Coast Guard to notify them of the bridge collapse and the possibility of people in the water.

About 0134, the Coast Guard issued an urgent marine information broadcast requesting assistance from passing traffic. The tug *Eric McAllister*, whose crew the senior pilot contacted for help at 0126, was the first vessel on scene, arriving at 0140. Two other tugs, the *Bridget McAllister* and the *Timothy McAllister*, arrived soon after. Baltimore Harbor fell under the area of responsibility of Coast Guard Station Curtis Bay, which was located at the Coast Guard Yard on Curtis Creek in Baltimore (see figure 3). The first Coast Guard boat, a Station Curtis Bay response boat-medium, *CG45661*, was underway within 10 minutes. The *CG45661* and its crew traveled the 4 miles to the scene at a speed of 38 knots (43.7 mph), arriving on scene about 0151. In addition to the Coast Guard boat, an MDTA boat from their facility at the north end of the Key Bridge arrived at 0155.

Because of the possibility of mass casualties, the sector command center for Coast Guard Maryland-National Capitol Region, whose area of responsibility included the accident site, requested assistance from Station Annapolis in Annapolis, Maryland; the patrol boat *Mako*, homeported in Cape May, New Jersey; and Air Station Atlantic City in Egg Harbor Township, New Jersey. Other responding agencies included the Maryland State Police, Baltimore County Fire Department, Baltimore City Fire Department, and Maryland Department of Natural Resources, as well as first responders from Anne Arundel County, Maryland, and the Harford County, Maryland, Department of Emergency Services.

Responders searched for survivors until 2027 that day, when the Coast Guard suspended the active search for survivors and transitioned efforts to recovery. The following day, March 27, the bodies of two of the highway workers were recovered from a submerged vehicle. Between April 5 and May 7, the bodies of the other four highway workers were located. All the victims were found inside vehicles.

1.2.2 Unified Command

The Coast Guard, Maryland Department of the Environment, and Witt O'Brien's (a contracted emergency response company representing Synergy Marine Pte Ltd, the *Dali*'s operating company) established a unified command (UC) on the morning of March 26.[44] The Captain of the Port (Commander, Sector Maryland–National Capital Region, Coast Guard) filled the role of the federal on-scene coordinator and acted as the federal representative in the UC.[45] The Maryland Department of the Environment served as the state on-scene coordinator.[46] Witt O'Brien's served as the qualified individual on behalf of Synergy Marine Pte Ltd.[47]

1.2.3 Oil and Hazardous Materials

Of the 4,679 containers on board the vessel at the time of the accident, 56 were identified as containing dangerous goods (hazardous materials). The containers were located throughout the ship. The cargo containers in Bays 5, 6, and 7, which included 14 hazardous materials containers, were displaced and damaged when the ship struck the Key Bridge or during the subsequent collapse of the bridge deck onto the ship (see figure 18).

[44] (a) A *unified command* is a type of incident command used when there is more than one agency with incident jurisdiction. Under a UC, each participating partner maintains authority, responsibility, and accountability for its personnel while jointly managing and directing incident activities. Agencies work together through the designated members of the UC to analyze information and establish a common set of objectives and strategies. (b) Response organizations included in the UC were: the Coast Guard (which deployed its Atlantic Strike Team and its Salvage Engineering Response Team), the US Army Corps of Engineers, the Maryland Department of the Environment, MDTA, Witt O'Brien's, and the Maryland State Police. Assisting and coordinating agencies included the National Transportation Safety Board, US Customs and Border Control, the Federal Bureau of Investigation, US Navy Supervisor of Salvage and Diving (SUPSALV), the Maryland Department of Transportation, the Maryland Port Administration, the Maryland Natural Resources Police, the Maryland Air National Guard, Baltimore City, Baltimore County, NOAA, the Cybersecurity and Infrastructure Security Agency, the Maryland Department of Emergency Management, the Pipeline and Hazardous Materials Safety Administration, and the US Environmental Protection Agency.

[45] A *federal on-scene coordinator* is the federal official predesignated by the Environmental Protection Agency, the Coast Guard, or other federal agency, to coordinate and direct responses under the National Oil and Hazardous Substances Pollution Contingency Plan, or the government official designated by the lead agency to coordinate and direct removal actions. See Title 40 *Code of Federal Regulations (CFR)* 300 for more information about the National Oil and Hazardous Substances Pollution Contingency Plan.

[46] A *state on-scene coordinator* directs and manages the response actions of state agencies during a large-scale oil- or hazardous materials-release emergency.

[47] A *qualified individual* is trained in the responsibilities of implementing a vessel response plan.

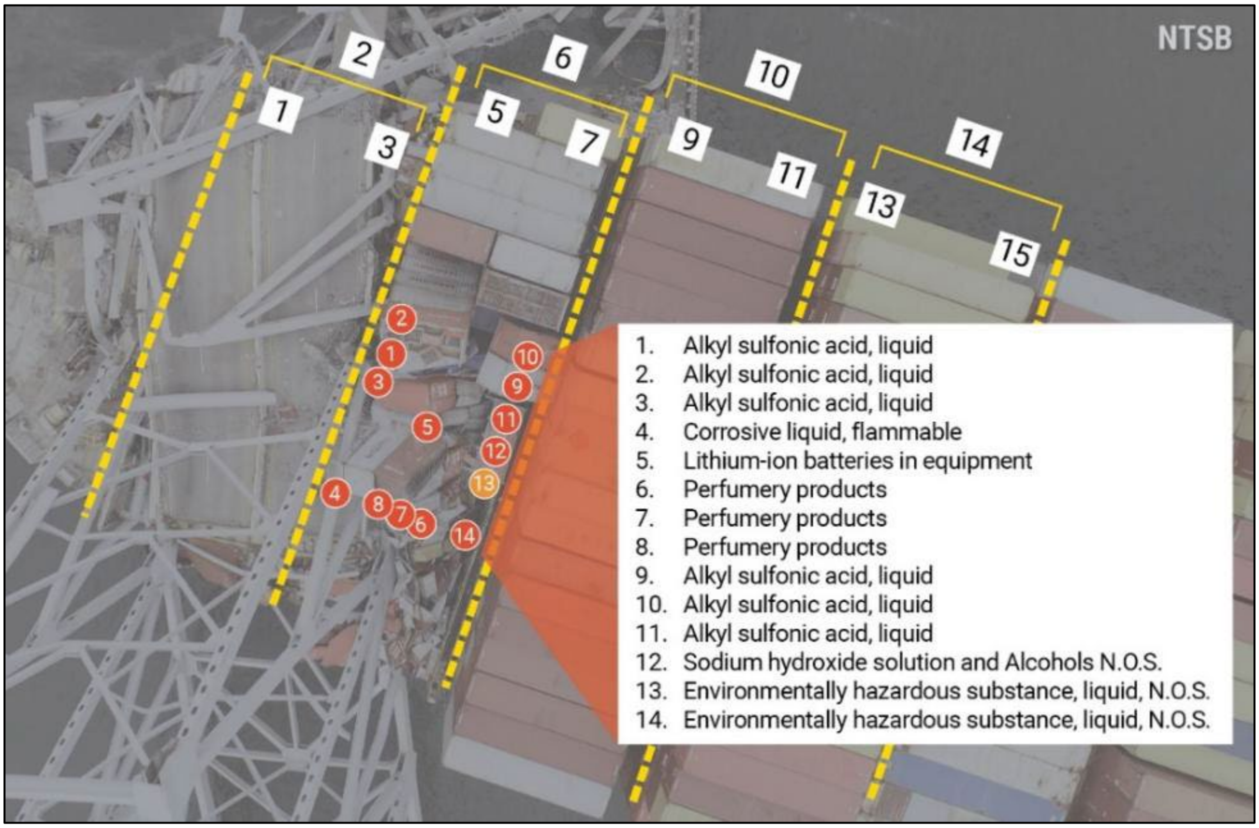

Figure 18. Overhead view of the forward portion of the *Dali* showing the approximate locations of cargo bays and the 14 impacted hazardous materials shipping containers. Yellow dashed lines with numbers in squares show the approximate locations of cargo bays and orange circles with numbers mark the approximate location of the 14 impacted hazardous materials shipping containers. Hazardous material container no. 13 was in a portable tank, stored in the hold, below the deck.

After the accident, a persistent light oil sheen was visible in the Patapsco River, on the starboard side of the ship. According to the Coast Guard, this sheen was likely from damage to the bow thruster; however, a postaccident damage report released by ClassNK did not indicate any mechanical damage to the bow thruster.[48] There were no reports of oil released from the *Dali*'s bunker tanks, and no damage was found to the vessel's cargo holds or ballast tanks. The source of the sheen was never confirmed.

Responders deployed a containment boom around the ship and coordinated containment of the oil causing the sheen, as well as a mix of hazardous and

[48] ClassNK's postaccident damage report identified damage to the bow thruster's electrical components, which do not contain oil.

non-hazardous substances on board, to prevent their release from the vessel into the environment.[49] Preventative measures included establishing collection points for spilled material and the use of scupper plugs, sorbent material, pumps, and hoses to contain any released material.[50] No hazardous substances from containers on the ship reached the environment.

1.2.4 Gas Transmission Pipeline

The Baltimore Gas and Electric (BGE) Harbor Crossing Intrastate Transmission Pipeline is a 24-inch diameter, 200-pounds per square inch, natural gas pipeline built in 1974, buried 50 feet west of, and parallel to, the bridge. Owned by BGE, the pipeline services the MDTA facilities at the Key Bridge, as well as some customers in Anne Arundel County. The pipeline is marked on nautical charts for the area (electronic and paper).

On the morning of March 26, a responder from the Pipeline and Hazardous Materials Safety Administration notified the National Transportation Safety Board (NTSB) that the pipeline was secure and not losing pressure.

On March 27, the UC contacted BGE to notify the company that a dive salvage team surveying the damage discovered that the area where the vessel had run aground was close to the pipeline. Later the same day, BGE closed valves on each side of the Patapsco River. On March 28, the BGE manager of gas transmission engineering, who had been working with MDTA to assess the pipeline's physical integrity during wreckage clearing operations, told the NTSB that BGE's monitoring system showed no anomalies after the bridge collapse.

On March 30, the UC reported that it was working with BGE to reduce the pressure in the pipeline and inert the pipeline.[51] On June 28, BGE announced that the pipeline had been reconnected, stating that "the inerted pipeline operated as expected and showed no pressure deviations" during salvage operations (BGE 2024).

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[49] A *containment boom* is a temporary floating barrier used to contain an oil spill.

[50] A *scupper* is an opening cut through a ship's bulwarks (vertical plating that extends the side of the ship above its weather decks) that allows water collecting on a weather deck to flow overboard.

[51] To *inert* a pipeline means to fill a pipeline with an inert gas, such as nitrogen, to displace potentially flammable or hazardous materials. This process is done to make the pipeline safe for work like maintenance, repair, or removal.

1.2.5 Salvage and Clearing of Debris

The US Army Corps of Engineers, Baltimore District, which operates and maintains the Fort McHenry Channel, worked with the US Navy Supervisor of Salvage and Diving (SUPSALV) to facilitate salvage and debris removal from the Fort McHenry Channel (US Navy 2024).[52] SUPSALV led a team of contractors in support of the salvage efforts. One of these contractors, Donjon Marine, provided pollution, salvage, and heavy-lift support such as cranes and barges. Another contractor, Emergency Ship Salvage and Marine, provided survey boats and operators to survey the area using sonar equipment. In addition to these federal assets and their contractors, Resolve Marine served as the vessel salvor, and Skanska served as the MDTA's non-navigation channel response team.

The bridge strike and subsequent collapse resulted in steel and concrete wreckage and debris falling into the Patapsco River and blocking the channel and all ship traffic into and out of the port. On May 13, salvors used explosives to remove sections of the collapsed bridge from the *Dali*. Salvage crews ultimately removed about 50,000 tons (equivalent to about 100 million pounds) of material from the riverbed (US Navy 2024).

On May 20, the *Dali* was refloated, removed from the channel, and returned to Seagirt Marine Terminal to offload cargo and additional debris. After the *Dali* was removed from the channel, on May 21, the UC created a limited access channel to allow vessels to enter and leave the port of Baltimore (US Coast Guard 2024-a). The limited access channel had a depth of 50 feet, width of 400 feet, and vertical clearance of 214 feet. On June 4, the last large piece of steel truss was removed from the Federal Channel. On June 10, the Fort McHenry Channel was reopened for vessel traffic.

[52] The Corps of Engineers' responsibilities as pertaining to salvage and debris removal are detailed in Title 33 *United States Code* 415.

1.3 Injuries

There were seven highway workers and one inspector on the Key Bridge at the time of the accident. Six highway workers died as a result of the bridge collapse. One of the highway workers survived the collapse with serious injuries. One of the *Dali* crewmembers sustained a minor laceration and inhalation injuries. The inspector was not injured in the collapse. Table 1 shows the injuries sustained in the accident.

Table 1. Injuries sustained in the *Dali*/Key Bridge accident.

Type of Injury [a]	Dali Crew	Maryland Pilots	Highway Workers	Total
Fatal	0	0	6	6
Serious	0	0	1	1
Minor	1	0	0	1
None	20	2	1	23

a. The NTSB uses the International Civil Aviation Organization (ICAO) injury criteria in all of its accident reports, regardless of transportation mode. Under this criteria, injuries are classified as fatal, serious, minor, or none. A serious injury is a non-fatal injury that requires hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received; results in a fracture of any bone; causes severe hemorrhages, nerve, muscle, or tendon damage; involves any internal organ; or involves second- or third-degree burns, or any burn affecting more than 5 percent of the body surface. (49 *CFR* 830.2) A minor injury is any injury that does not meet the conditions for classification as a serious injury.

1.4 Damage

1.4.1 *Dali*

The *Dali* suffered damage that was heavily concentrated on the starboard-side forward bulwark and bow above the waterline—the result of contact with the Key Bridge pier and the subsequent collapse of the bridge spans onto the vessel's bow (see figure 19).

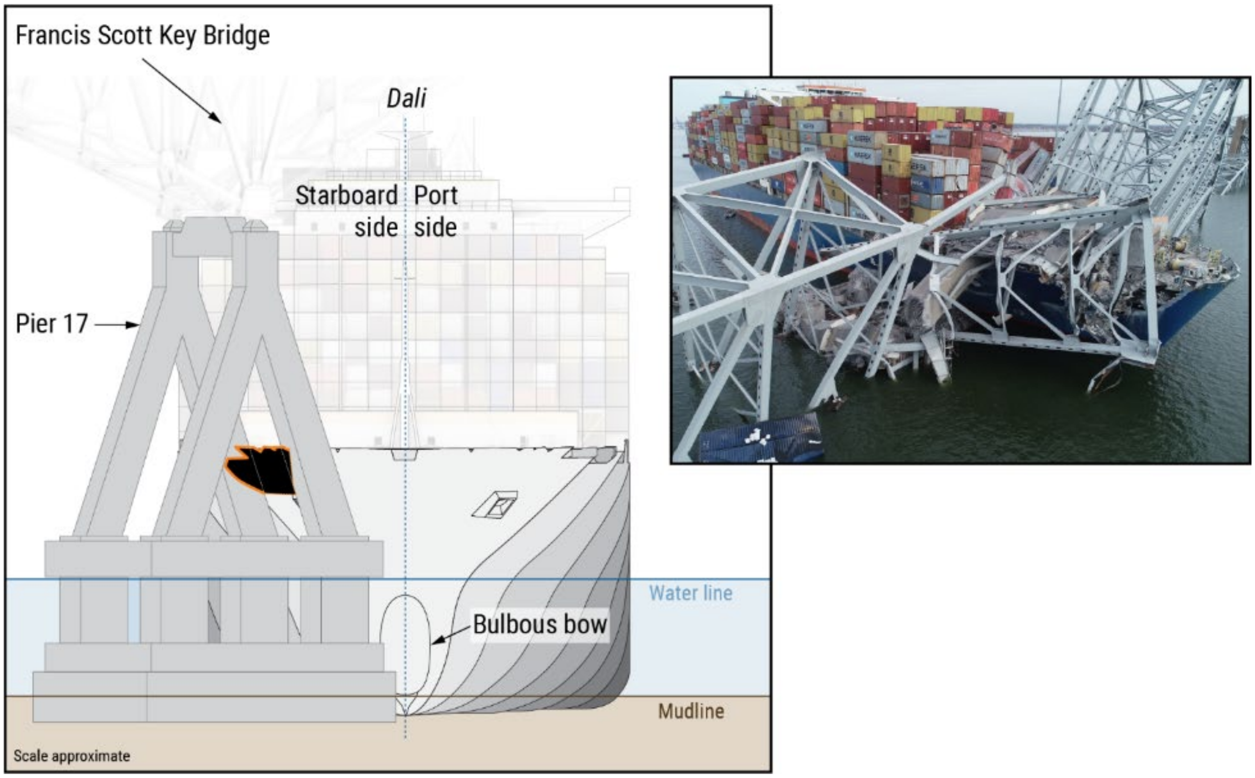

Figure 19. Representation of *Dali*'s starboard-side bow striking Pier 17. Inset shows damage to the vessel's starboard-side bow, with the bridge lying on the fo'c'sle deck, breakwater and container hold no. 1.

Following the bridge removal and salvage in Baltimore, on June 24, the *Dali* departed Seagirt Marine Terminal, bound for Talton Marine Terminals in Norfolk, to offload cargo and conduct further hazardous material salvage and overall vessel repairs. On June 26, the *Dali* arrived at Talton Marine Terminals, and was moved to International Gateway Terminal in Portsmouth, Virginia, for further cargo offloading.

On September 19, at 1300, the *Dali* departed International Gateway Terminal for Fujian Huadong Shipyard in China. Final repairs were completed at Fujian Huadong Shipyard, and, on January 16, 2025, ClassNK verified that repairs were satisfactory, allowing the ship to be returned to service. The ship was returned to service the same day and made its first port call on January 21. Damage to the *Dali* exceeded $18 million. Cargo damages were undetermined.

1.4.2 Key Bridge

The Key Bridge partially collapsed when the starboard bow of the *Dali* struck Pier 17. Pier 17 had a lateral capacity of 5,509 kips, according to calculations provided by the FHWA; the estimated impact force of the *Dali* at the time of contact was over four times the capacity of the pier. As a result of the impact, Pier 17 failed and collapsed, resulting in the collapse of spans 17–22.[53] Pier 19 collapsed down to the lower intermediate strut, and both intermediate struts on Pier 20 and Pier 21 were destroyed; the piers collapsed down to the approximate level of the water (see figure 20).[54] The strut on Pier 18 sustained contact damage from the collapsing superstructure (see figure 21).[55]

Figure 20. Damage to Spans 18 and 19, and Piers 18–22.

[53] See section 1.1.2.2 for further discussion of AASHTO's *Guide Specifications*' calculation and the *Dali*'s impact force.

[54] A *strut* is a structural component connecting two columns that can be horizontal, vertical, or inclined, and can resist both axial and lateral loads.

[55] A *superstructure* is a bridge structure that receives loads from the deck, such as traffic or pedestrian loads, and in turn, transfers those loads to the substructure.

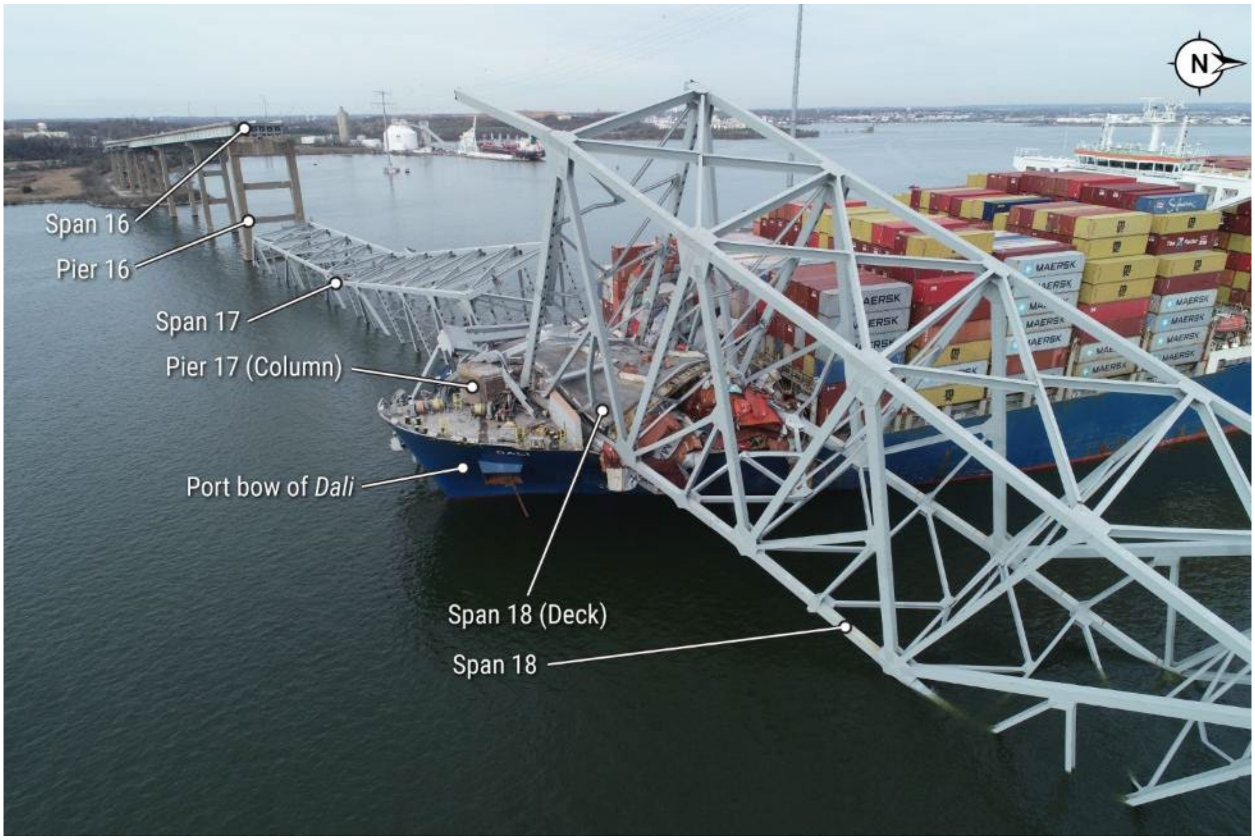

Figure 21. Damage to Spans 16–18 and Pier 17, as seen looking toward the port side of the *Dali*.

Both fendering systems surrounding Pier 17 and Pier 18 were damaged during the collapse of the truss spans of the bridge when components of the truss spans impacted portions of the fenders as the components fell into the water (see figure 22). The most significant damage to Pier 17 occurred on the opposing side of the channel, while the fender on the channel side remained largely intact. The most significant damage to Pier 18 occurred on the channel side, where portions of the fender were no longer present. Components of the truss spans came to rest in the areas of the damaged and missing fender sections. At the time of this report, replacement costs for the bridge are estimated at $4.3 billion to $5.2 billion, and the bridge is anticipated to open to traffic in late 2030. See section 1.5.5 for more information about the bridge's replacement designs.

Figure 22. *Left to right*: Damage to fendering surrounding Pier 17 and Pier 18.

1.5 Bridge Information

1.5.1 General

The Key Bridge was a continuous steel through-truss bridge located in Baltimore, Maryland, and carried Maryland 695 over the Patapsco River, from Baltimore to Dundalk, Maryland.[56] The bridge was owned and operated by the MDTA and opened to traffic on March 23, 1977. According to the MDTA, the overall length of the bridge was about 9,086 feet between the north and south abutments. The maximum vertical clearance for the Key Bridge above the main navigational channel, the 700-foot-wide Fort McHenry Federal Channel, was 185 feet.[57]

The bridge was designed with nonredundant steel tension members (NSTM).[58] A bridge requires NSTM inspection if it contains one or more non-load path redundant steel tension members, components, or connections. The FHWA defines an NSTM by the following three criteria:

[56] On April 29, 2024, the FHWA approved a request from the state of Maryland to redesignate a segment of Maryland 695, including the Francis Scott Key Bridge, as part of the interstate highway system.

[57] *Vertical clearance*, also known as *charted height*, is the vertical distance between the water level at mean high water and the lowest point of the bridge structure span over a navigation channel, indicating how much space a vessel has to pass underneath without hitting the bridge.

[58] In 2022, the FHWA started using the term nonredundant steel tension member, replacing the previous term, fracture critical member.

- it is made of steel;
- it is fully or partially in tension;
- failure of the component would likely cause the bridge to partially or fully collapse.

NSTMs must be inspected within arms-length of the inspector every 24 months or less in accordance with the NSTM inspection criteria and procedures.[59]

The substructure of the Key Bridge consisted of two reinforced concrete abutments at each end of the bridge and 36 vertical piers (31 two-column rigid frame reinforced concrete piers, two rigid frame reinforced concrete piers, and three solid wall piers) (see figure 23 and figure 24).[60]

Figure 23. *Left to right*: South abutment (looking south), and north abutment (looking north). (Background sources: MDTA)

[59] See 23 *CFR* 650.305.

[60] The *substructure* of a bridge supports the *superstructure* and transfers loads from it to the foundation; main components are abutments, piers, footings, and pilings.

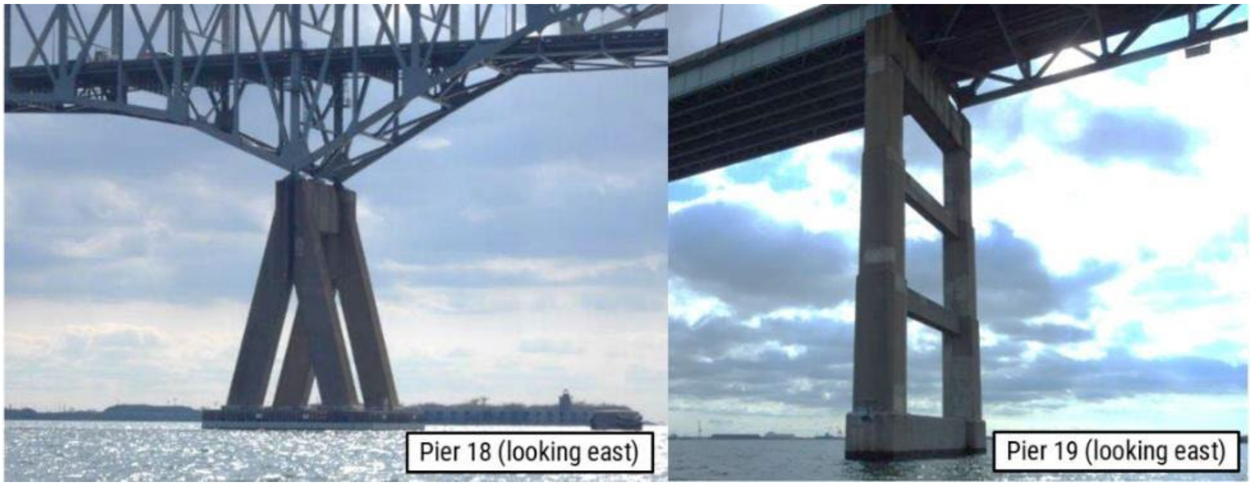

Figure 24. *Left to right*: Rigid-frame reinforced concrete pier, and two-column pier. (Background sources: MDTA)

The superstructure of the bridge consisted of seven painted continuous steel girders that ran longitudinally along the length of the bridge and supported the bridge between the vertical piers (see figure 25).[61]

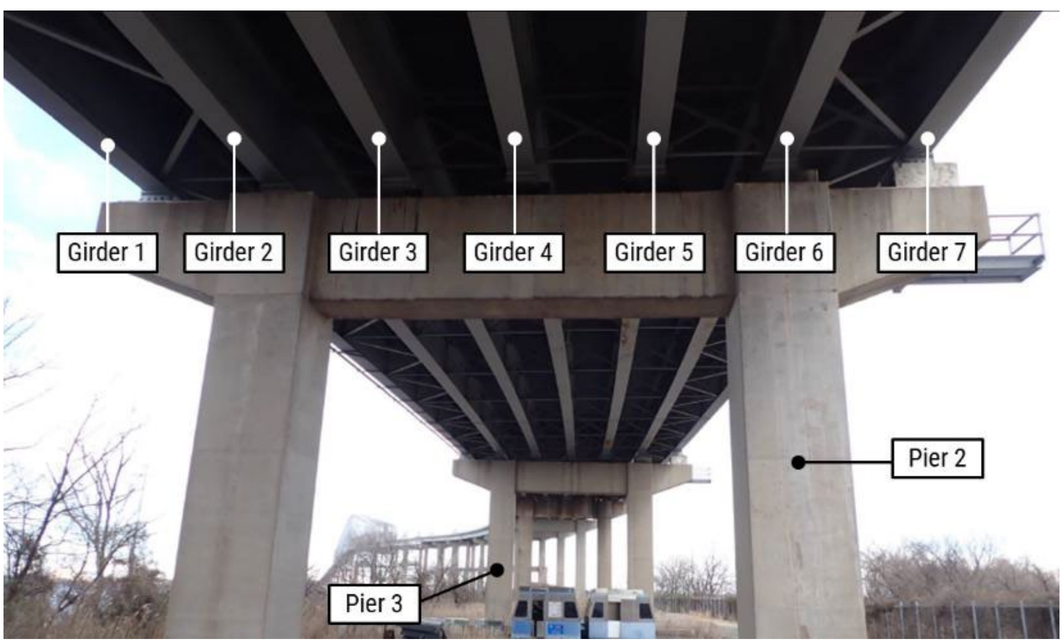

Figure 25. Painted continuous steel girders. (Background source: MDTA)

[61] A *girder* is a horizontal structural member supporting vertical loads. Larger girders are typically made of multiple metal plates welded or riveted together.

The superstructure also included 34 bridge spans between the vertical piers with the support of the girders and three truss spans not supported by girders. There were 25 shorter/shallower spans over land, nine longer/deeper multibeam plate girder spans over water, and three continuous steel through truss spans that crossed the primary navigation channel of the Patapsco River (see figure 26). Each span was covered with a deck, the surface that vehicles drive on, which consisted of reinforced concrete with stay-in-place forms in all spans.[62] There were four lanes, two for each direction of travel. The annual average daily traffic for calendar year 2023 was 34,121 vehicles per day, and the percentage of trucks on the bridge was 10%. The bridge was not posted for any load restrictions.

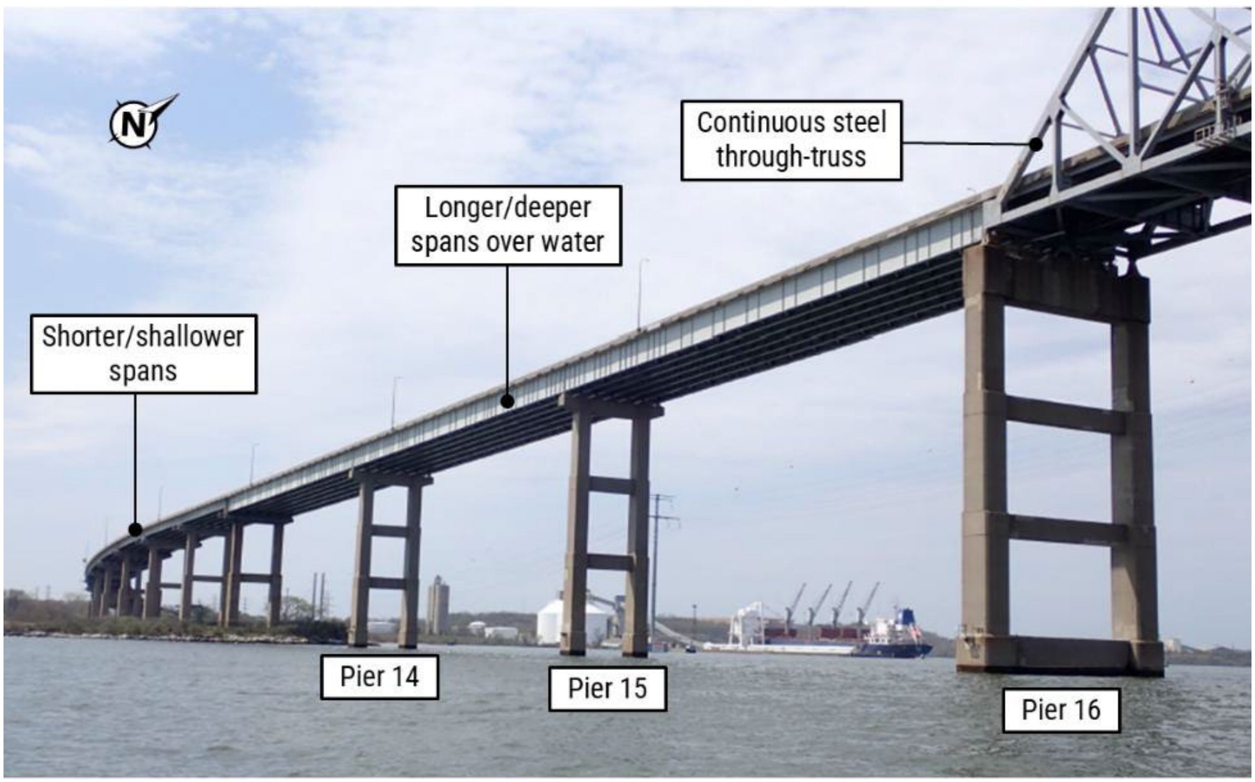

Figure 26. The three types of spans at the Key Bridge. (Background source: MDTA)

1.5.2 Key Bridge Pier Protection

The Key Bridge was designed according to the 1969 edition of the American Association of State Highway and Transportation Officials (AASHTO) *Standard Specifications for Highway Bridges* (AASHTO 1969). Although this guidance did not

[62] A *stay-in-place* form is a corrugated metal pan that spans between *girders* or stringers, which supports the wet concrete as it is placed for the deck and is not removed after the concrete has cured.

mention the risk of vessel strikes or a need for bridge protections, the Key Bridge was designed and built with physical protection systems to protect portions of the bridge exposed to possible damage by marine traffic. These protection systems (including four dolphin structures, each with rubber fenders, and crushable concrete and timber fendering systems around Pier 17 and Pier 18) were in place when the bridge opened in 1977 (see figure 27).[63] Dolphins are frequently used to protect bridge piers because they can slow, stop, or redirect an aberrant vessel (AASHTO 2009).[64]

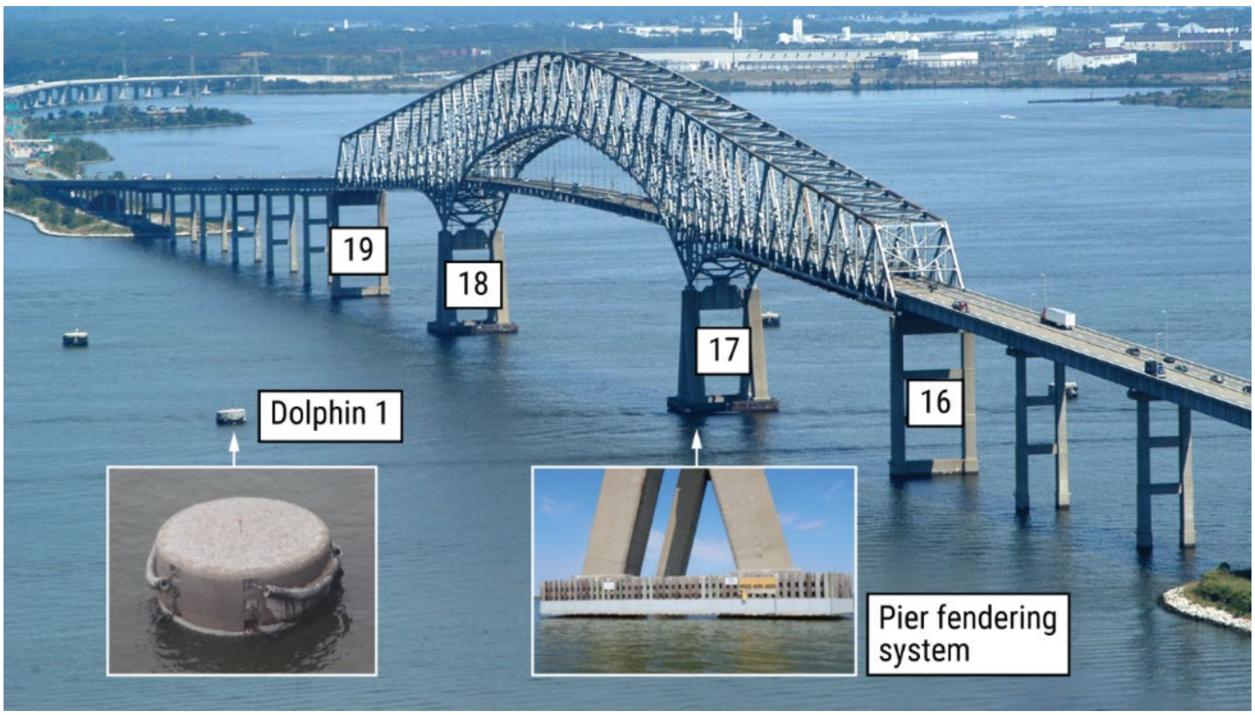

Figure 27. The Key Bridge and the physical protection systems (Dolphin 1 and the pier fendering system) protecting Pier 17 from vessels transiting outbound under the Key Bridge. (Background source: MDTA)

The Key Bridge dolphins were constructed according to project-specific design criteria and, according to the MDTA, have retained these original specifications. Each dolphin was composed of 25.46-foot-diameter driven, steel sheet

[63] *Rubber fenders* are "usually placed on the outer perimeter of the dolphin to act as an anti-sparking surface to prevent metal-to-metal contact in the event of collision with a steel-hulled vessel carrying flammable products." Further, "the circular shape of the dolphins can help deflect aberrant vessels away from the pier." Finally, crushable concrete and timber *fendering systems*, such as those around Pier 17 and Pier 18, have been frequently used for protecting piers from minor vessel impact forces "because of their relatively low cost." (AASHTO 2009).

[64] An *aberrant vessel* is a vessel that has lost control or has unexpectedly gone off course.

pile ring filled with tremie concrete and a 28-foot-diameter reinforced concrete cap (see figure 28).[65]

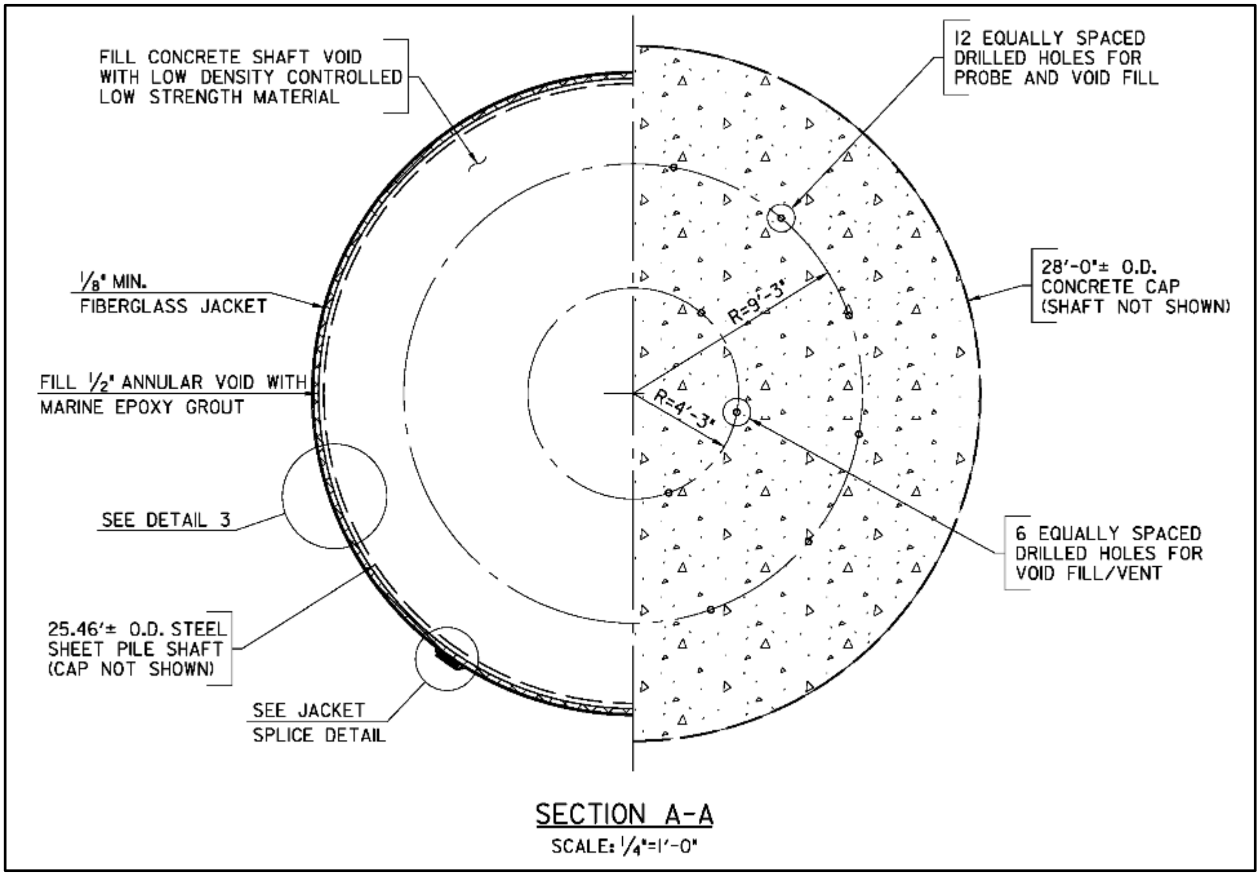

Figure 28. Typical plan view of a Key Bridge dolphin. (Source: MDTA)

[65] *Tremie concrete* is concrete placed by gravity feed from a hopper through a vertical pipe extending from above the surface of the water to the underwater floor.

Attached at various locations on each dolphin were 17-foot-long preformed rubber fenders (see Figure 29).

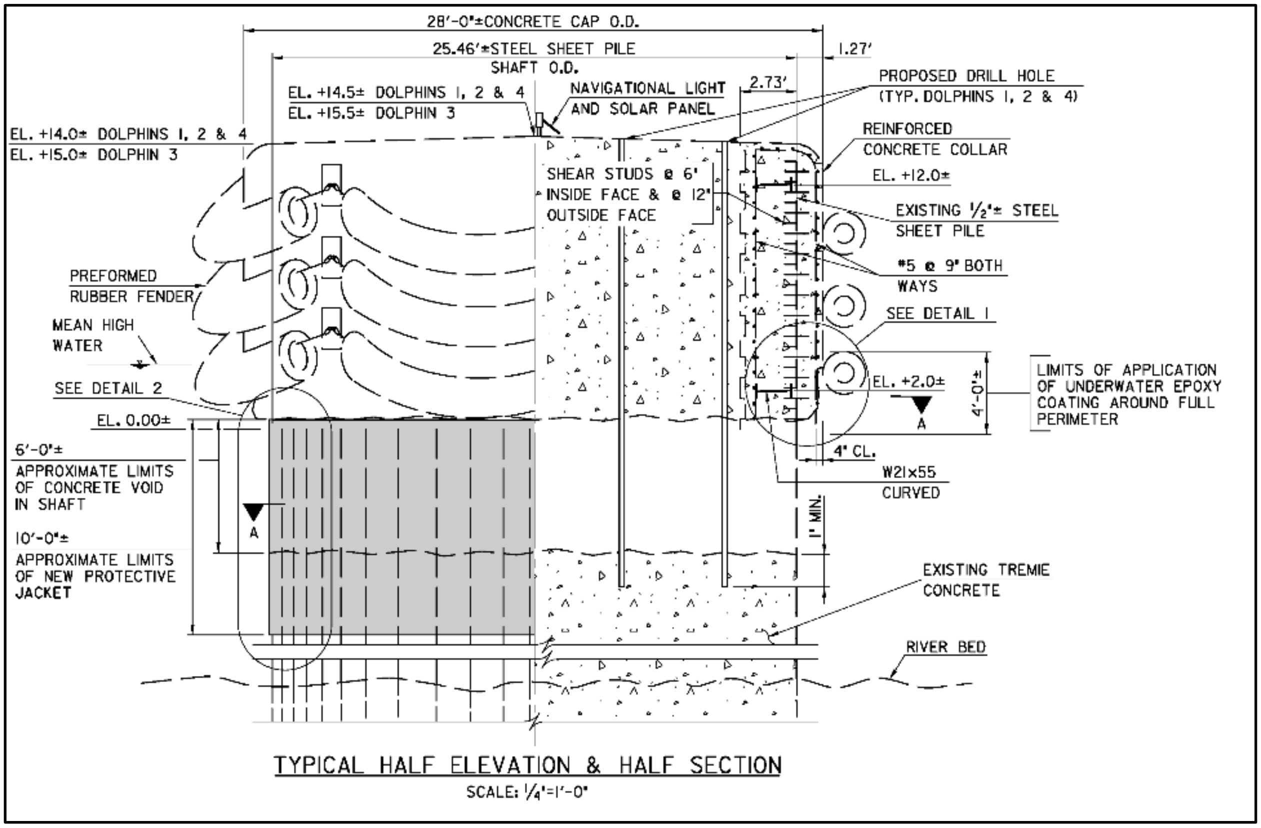

Figure 29. Typical half-elevation/section view of a Key Bridge dolphin. (Source: MDTA)

The centers of Dolphin 1 and Dolphin 2 were located 489 feet west of the centers of Pier 17 and Pier 18, respectively (see figure 30). All dolphins were about 550 feet clear of the centerline of the Fort McHenry Channel. None of the four dolphins were contacted by the *Dali* during the accident. The clear space between the two piers was 1,100 feet wide (550 feet from the centerline), and the Fort McHenry Channel width was 700 feet (350 feet from the centerline). Thus, there was only 200 feet from the edge of the channel to the edge of either Pier 17 or Pier 18.

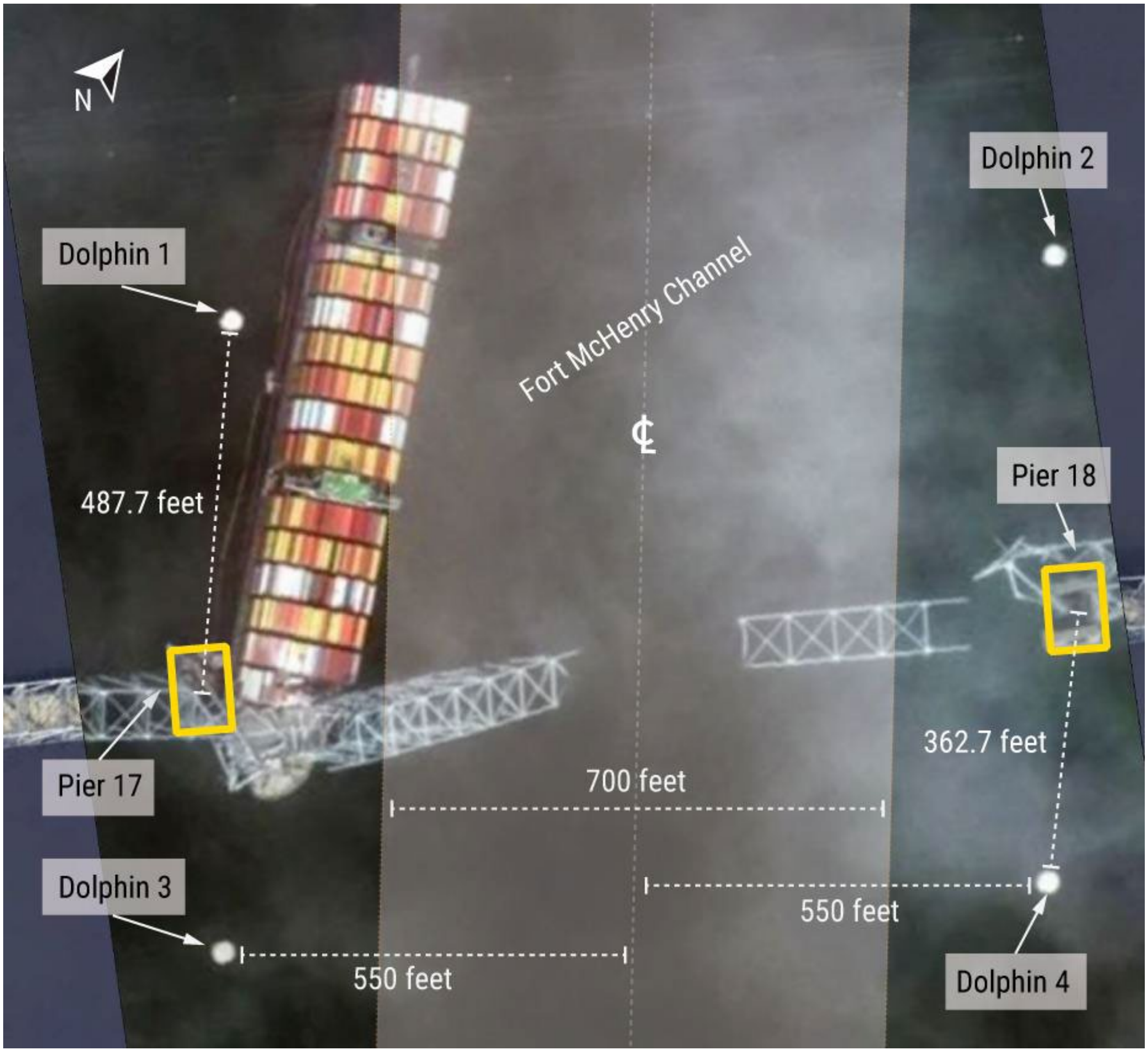

Figure 30. Overhead view of the collapsed Key Bridge and the *Dali*. Locations of dolphins relative to the vessel, bridge, and Fort McHenry Channel are depicted. (Background sources: MAXAR and Google Earth)

In addition to dolphins, crushable concrete box and timber fender systems surrounded Pier 17 and Pier 18 (see figure 31 and figure 32). The crushable concrete fender systems were composed of hollow, thin-walled, concrete box structures attached to the piers. The timber fender, which was composed of vertical (6-by-12-inch, 12-by-12-inch, and 14-by-16-inch) and horizontal (12-by-12-inch) timber members in a grillage geometry, was attached to the outer face of the concrete box fender. Timber fenders are frequently used for bridge protection because of their relatively low cost and good energy absorption characteristics; however, for the relatively large collision impact loads associated with design vessels in the *Guide Specifications*, the resulting timber fenders would have to be extremely large and might be uneconomical in most circumstances (AASHTO 2009). There were also steel plates secured to the vertical timber, near the base of the fender.

Figure 31. Pier 17, looking north, showing the fender system. (Source: MDTA)

Figure 32. Pier 17, looking north, showing the interior side of the fender system. (Source: MDTA)

In accordance with the National Bridge Inspection Standards, the Key Bridge and its pier protection systems were subject to regular safety inspections by nationally certified bridge inspectors.[66] These periodic safety inspections, which included the dolphins for the Key Bridge, are intended to assess and document the physical and functional condition of a bridge and its components, and identify any changes from previously recorded conditions to ensure that any structural deficiencies posing an imminent threat to public safety are corrected (FHWA n.d.-a).[67] According to the FHWA (FHWA n.d.-b), inspections are "necessary to maintain safe bridge operation and prevent structural and functional failures." The Key Bridge's most recent inspections in March 2021 and May 2023 found the condition of the deck, the superstructure, and the substructure as being in satisfactory condition, and the pier protection was rated as in place and functioning properly.

[66] See 23 *CFR* 650 Subpart C.

[67] See 23 *CFR* 650.313(q)(1)(i).

1.5.3 Pier Protection on Other Bridges

1.5.3.1 Sunshine Skyway Bridge

An example of a bridge with more robust pier protection than was present at the Key Bridge is the Sunshine Skyway Bridge near Tampa Bay, Florida (see figure 33). The main piers are protected by islands, whereas the five approach piers on each side of the main piers are protected by a dolphin system. The use of dolphins to protect the high-level approach piers was a result of a risk analysis, which indicated that the high-level approach piers were vulnerable to a catastrophic vessel contact. The 60-feet-diameter dolphins were designed to withstand a contact from either a loaded 23,000-deadweight tonnage (DWT) or an empty 87,300-DWT bulk carrier. The 54-feet-by–4-inch-diameter dolphins were designed to withstand an impact from a loaded 25,000-DWT barge. or an empty 70,000-DWT vessel. The 47-foot-diameter cells were designed to withstand impacts from a loaded 15,000-DWT barge or an empty 35,000-DWT ship. All design impact speeds were 10 knots. The sheet piling was driven through a sand overburden (10–40 feet thick) and then 5–10 feet into a stiff limestone stratum known as the Hawthorne Formation.

Figure 33. Aerial view of the Sunshine Skyway Bridge showing the dolphin and island protection system. (Source: Mark Luther, University of South Florida Center for Maritime and Port Studies)

1.5.3.2 Delaware Memorial Bridge

In 2019, due to previous accidents with the Delaware Memorial Bridge, the Delaware River and Bay Authority performed studies to determine the required protection requirements and protection methods. These studies recommended that a separate protection system be installed to protect the bridge. The new protection system consisted of eight 80-feet-diameter steel sheet pile cell dolphins (see figure 34 and figure 35). The dolphins were to be filled with rock and topped with a concrete cap. The cost was about $90 to $100 million to construct the eight dolphins.[68]

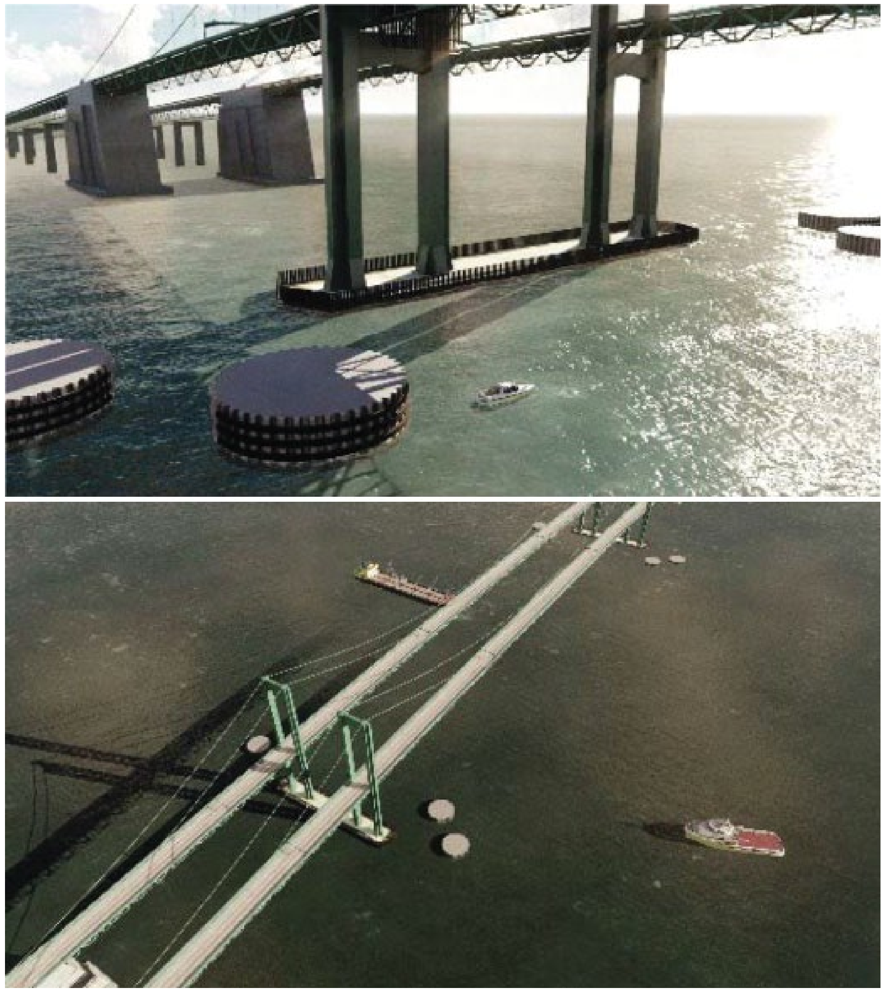

Figure 34. *Top to bottom*: Rendering of four of the proposed eight new dolphins added to the protection system for the Delaware Memorial Bridge. Rendering of an aerial view of the eight proposed new dolphins. (Source: Richard E. Pierson Construction Co., Inc)

[68] It should be noted that this section does not imply appropriate protection measures and costs from one bridge directly transfers to another. Each bridge has its own conditions that affect the design of appropriate protection systems.

Figure 35: Rendering of the proposed eight new dolphins added to the protection system for the Delaware Memorial Bridge. (Source: Richard E. Pierson Construction Co., Inc)

1.5.4 1977 Contact by Containership *Blue Nagoya*

The contact by the *Dali* was not the first time the Key Bridge was struck by a vessel. The Key Bridge's pier protection was struck in 1980 when the 390-foot-long, Japan-flagged containership *Blue Nagoya*, which had a displacement, or weight, about one-tenth that of the *Dali*, collided with Pier 17 following a loss of steering about 600 yards from the bridge; see figure 36 for a size comparison of the *Blue Nagoya* to the *Dali*. The vessel was stopped by the crushable concrete and timber fendering system at Pier 17, and the bow overhang contacted the pier's A-frame (National Research Council 1983; AASHTO 2009). As a result of the contact, minor surface damage occurred on Pier 17's columns, and the pier's fender was destroyed. The crushable concrete and timber fendering around the pier was reconstructed according to the original project-specific design criteria, and the minor damage to the columns was repaired.

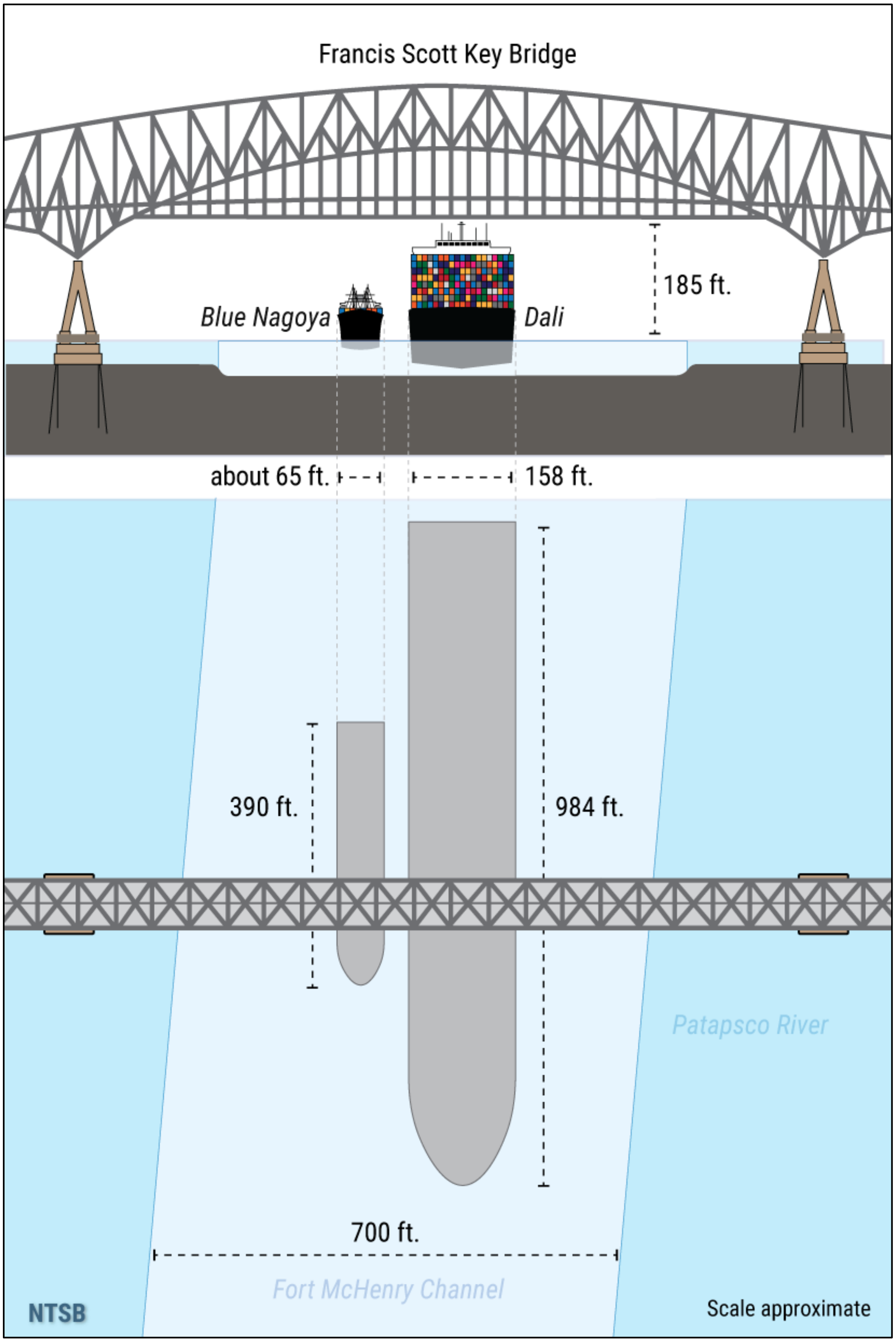

Figure 36. The comparative sizes of the *Blue Nagoya* and the *Dali* relative to the Key Bridge.

1.5.5 Replacement

In February 2025, the design concept of the replacement for the Key Bridge was announced. The design concept is for a 2-mile-long, cable-stayed bridge with a minimum vertical clearance of 230 feet (see figure 37) (MDTA 2025). Cable-stayed bridges are considered redundant, referring to the ability of the structure to carry loads even after one of its members has failed, preventing collapse.

Figure 37. Rendering of the cable-stayed replacement for the Key Bridge. (Source: Key Bridge Rebuild, MDTA)

The total length of the cable-stayed main span will be 3,300 feet and will have two main-span pylons, with a horizontal distance of 1,600 feet between the two pylons. The proposed pier protection for the cable-stayed bridge is still under development and may include islands protecting the main span and side span piers. While pier protection designs have not been finalized as of the time of this report, the MDTA has stated—

> The bridge piers will be protected by pier protection structures, which will be designed per the latest American Association of State Highway and Transportation Officials (AASHTO) specifications and follow best practices for modern vessel collision protection. Additionally, the main span length of the bridge has been increased to provide additional clearance from the shipping channel. (MDTA 2025)

1.5.6 Previous Bridge Collapses Investigated by the NTSB

The NTSB has investigated other bridge collapses resulting from vessel impacts, including the Sunshine Skyway Bridge (Tampa Bay, Florida) in 1980, the Queen Isabella Causeway bridge (South Padre Island, Texas) in 2001, and the Interstate 40 bridge (Webber Falls, Oklahoma) in 2002.

The Sunshine Skyway Bridge was struck by the 609-foot-long bulk cargo carrier *Summit Venture* on May 9, 1980. As a result of the impact, a support pier was destroyed, and about 1,297 feet of bridge deck and superstructure fell from a height of about 150 feet into the bay (see figure 38).[69] A Greyhound bus, a small pickup truck, and six automobiles fell into the bay, and 35 persons died. Repair costs were estimated at about $30 million for the bridge.

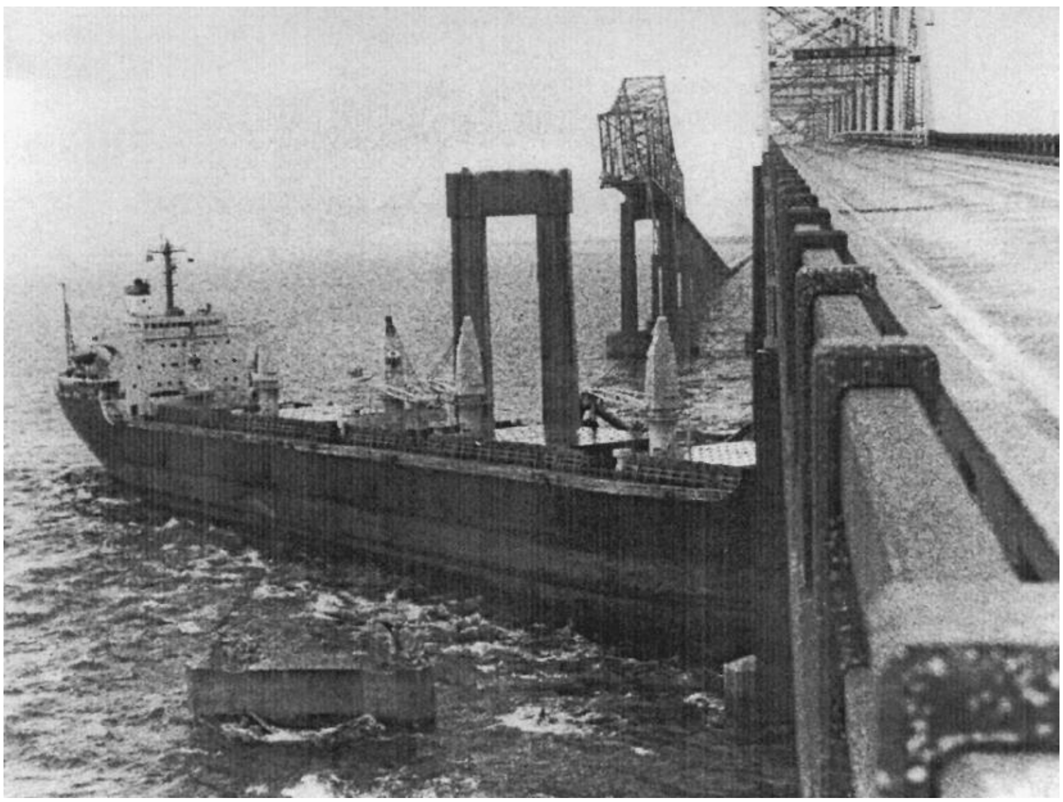

Figure 38. View of the collapsed western span of the Sunshine Skyway Bridge, looking to the north.

[69] See *Ramming of the Sunshine Skyway Bridge by the Liberian Bulk Carrier* Summit Venture, *Tampa Bay, Florida, May 9, 1980*.

The Queen Isabella Causeway bridge was struck by barges being pushed ahead by the towing vessel *Brown Water V* on September 15, 2001. The length of the towing vessel and its tow was 851 feet. The impact caused two sections of the causeway (approximately 160 feet long and 85 feet above the water) to collapse (see figure 39.[70] Ten passenger vehicles either fell with the collapsing sections or drove off the end of the remaining structure of the roadway, resulting in eight fatalities. A third adjacent section of the causeway collapsed later that day. The accident closed the 2.37-mile-long bridge, which was the only vehicular span linking the mainland to South Padre Island. More than 19,000 vehicles per day typically traveled the causeway.

Figure 39. View of the collapsed Queen Isabella Causeway bridge pier and adjacent undamaged piers looking to the northeast.

[70] NTSB docket number HWY01IH036.

The Interstate 40 bridge in Webbers Falls, Oklahoma, was struck by barges being pushed ahead by the towing vessel *Robert Y. Love* (see figure 40). The length of the towing vessel and its tow was 700 feet. The impact caused the collapse of a 503-foot-long section of the bridge, which fell into the Arkansas River and onto barges below.[71] According to witnesses, highway traffic continued to drive into the void in the bridge created by the collapsed spans. By the time traffic was stopped, eight passenger vehicles and three trucks had fallen into the river or onto the collapsed portions of the bridge. The accident resulted in 14 fatalities and 5 injuries and caused an estimated $30.1 million in damage to the bridge, including the operation of detours, and $276,000 in damage to the barges.

Figure 40. Collapsed portion of the Interstate 40 bridge, with dolphins protecting the piers.

1.6 Vessel Information

1.6.1 General

The *Dali*, a 984-foot-long, steel-hulled cargo vessel (containership), was built by HD Hyundai Heavy Industries Co., Ltd. (HHI) in 2015. Singapore-based Grace Ocean Pte Ltd bought the vessel in 2016. Singapore-based Synergy Marine Pte Ltd

[71] See *U.S. Towboat* Robert Y. Love *Allision With Interstate 40 Highway Bridge Near Webber Falls, Oklahoma May 26, 2002*.

was the vessel manager, providing the crew and operating the vessel for the owner. The vessel operated in the container liner trade between Asia and the US east coast.

The American Bureau of Shipping (ABS) classed the *Dali* at the time of its delivery. Nippon Kaiji Kyokai (ClassNK) began classing the *Dali* in February 2017, after Grace Ocean bought the vessel. Table 2 shows the vessel particulars for the *Dali*.

Table 2. Vessel particulars for the *Dali* at the time of the accident.

Vessel	*Dali*
NTSB Vessel Group	Cargo, General (Containership)
Owner/Operator	Grace Ocean Pte Ltd/Synergy Marine Pte Ltd
Flag	Singapore
Port of registry	Singapore
Year built	2015
Official number	400884
IMO number	9431848
Classification society	Nippon Kaiji Kyokai (ClassNK)
Length (overall)	983.9 ft (299.9 m)
Breadth (max.)	158.1 ft (48.2 m)
Draft (casualty)	39.9 ft (12.2m)
Tonnage	95,128 GT ITC
Deadweight tons (casualty)[a]	80,230 metric tons[b]
Engine power; manufacturer	1 × 55,626 hp (41,480 kW); Hyundai–MAN B&W 9S90ME-C9.2 direct drive diesel engine

a. Deadweight refers to the carrying capacity of a vessel (weight of cargo, fuel, water, food, parts, and other consumables but excluding the weight of the ship itself). Regulations dictate the maximum amount a vessel can carry while at sea. Having an extra 100 metric tons of deadweight means the vessel can load 100 metric tons more of cargo, fuel, water, or other consumables.

b. Deadweight tons at the time of the accident.

1.6.2 Vessel Layout

Containers were stored on the *Dali* in 18 bays and 7 cargo holds and on the deck. Three of these cargo holds were designated for carrying hazardous materials.

The *Dali* had two superstructures, or houses: one forward (accommodation space) between cargo hold nos. 3 and 4, and one located aft (engine casing/stack), between cargo hold nos. 6 and 7 (see figure 41).

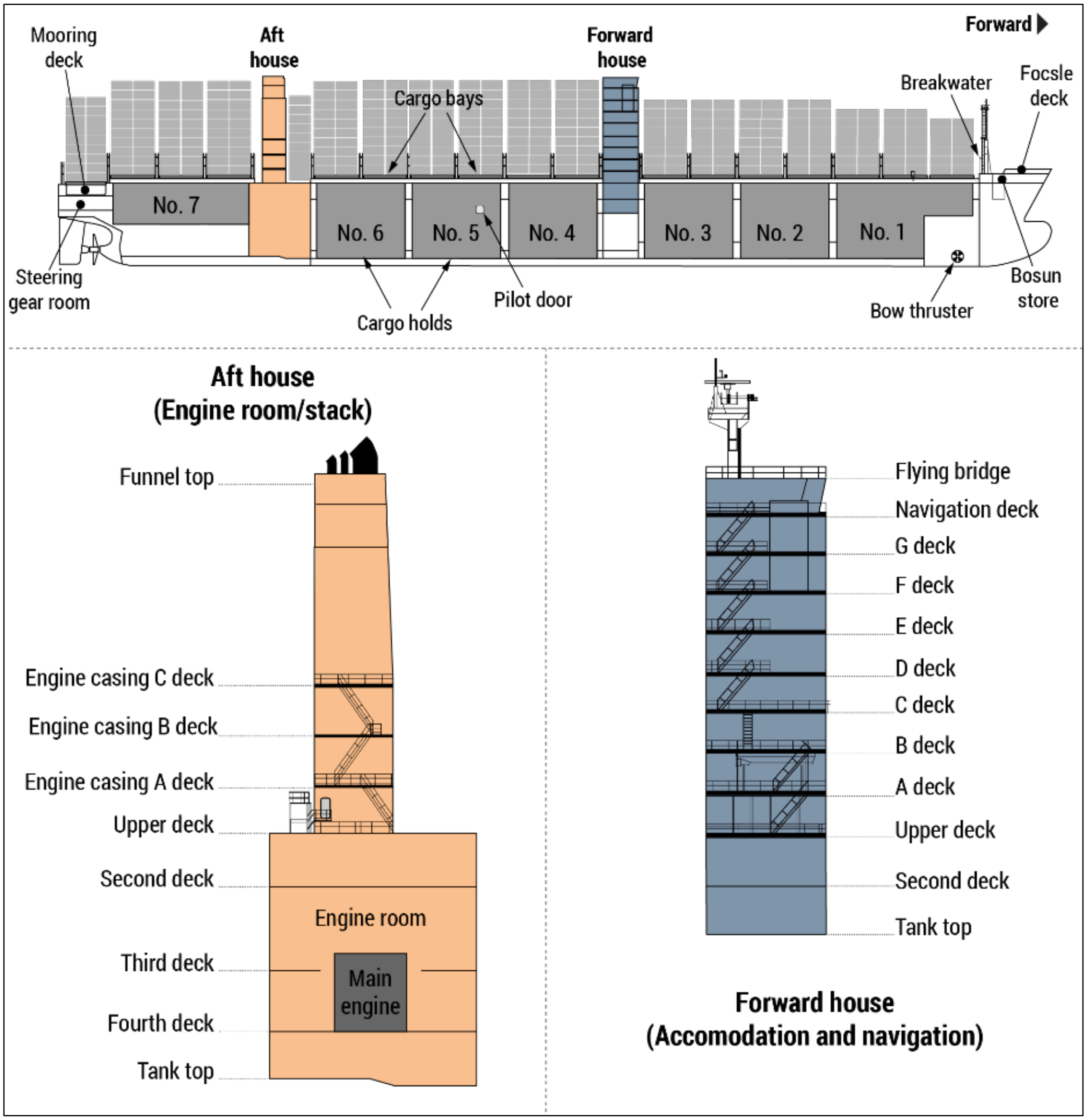

Figure 41. Profile view of the *Dali*, showing cargo holds and bays. Insets show the decks of the aft and forward houses.

1.7 Vessel Machinery and Electrical Systems

1.7.1 Electrical Power

1.7.1.1 Overview

The ship's power was normally supplied by one or more of four alternating-current (AC) generators, which were each driven by a diesel engine. At least one generator had to be operating and supplying the vessel with power for the ship's main engine to run. Diesel generators 1 and 4 (DG1 and DG4) were rated for 4,320 kilowatts, and diesel generators 2 and 3 (DG2 and DG3) were rated for 3,840 kilowatts. The generators were connected to a 6,600-volt-AC high-voltage (HV) bus. This main electrical bus powered the HV switchboard, which supplied power to various shipboard equipment, such as the main engine lube oil pumps, bow thruster motor, scrubber system, and refrigerated cargo system.

The generators also provided power to a 440-volt-AC low-voltage (LV) bus and switchboard, as well as a 440-volt-AC emergency bus and switchboard (see section 1.7.1.2). The LV bus powered the LV switchboard, which supplied power to vessel lighting and other equipment, including steering gear pumps, the fuel oil flushing pump and the main engine cooling water pumps. The LV bus was connected to the HV bus via two redundant step-down (voltage-lowering) transformers (TR1 and TR2) (see section 1.7.1.3).[72] Breakers were located on either side of the step-down transformers: HR1 and HR2 on the HV side, LR1 and LR2 on the LV side (see figure 42). Breakers HR1 and LR1 were associated with TR1, while breakers HR2 and LR2 were associated with TR2.

[72] A *transformer* is an electrical device that transfers electrical current from one or more circuits to another or multiple circuits. A *step-down transformer* is a type of transformer that lowers the voltage from the first circuit(s) before transferring it to the other circuit(s).

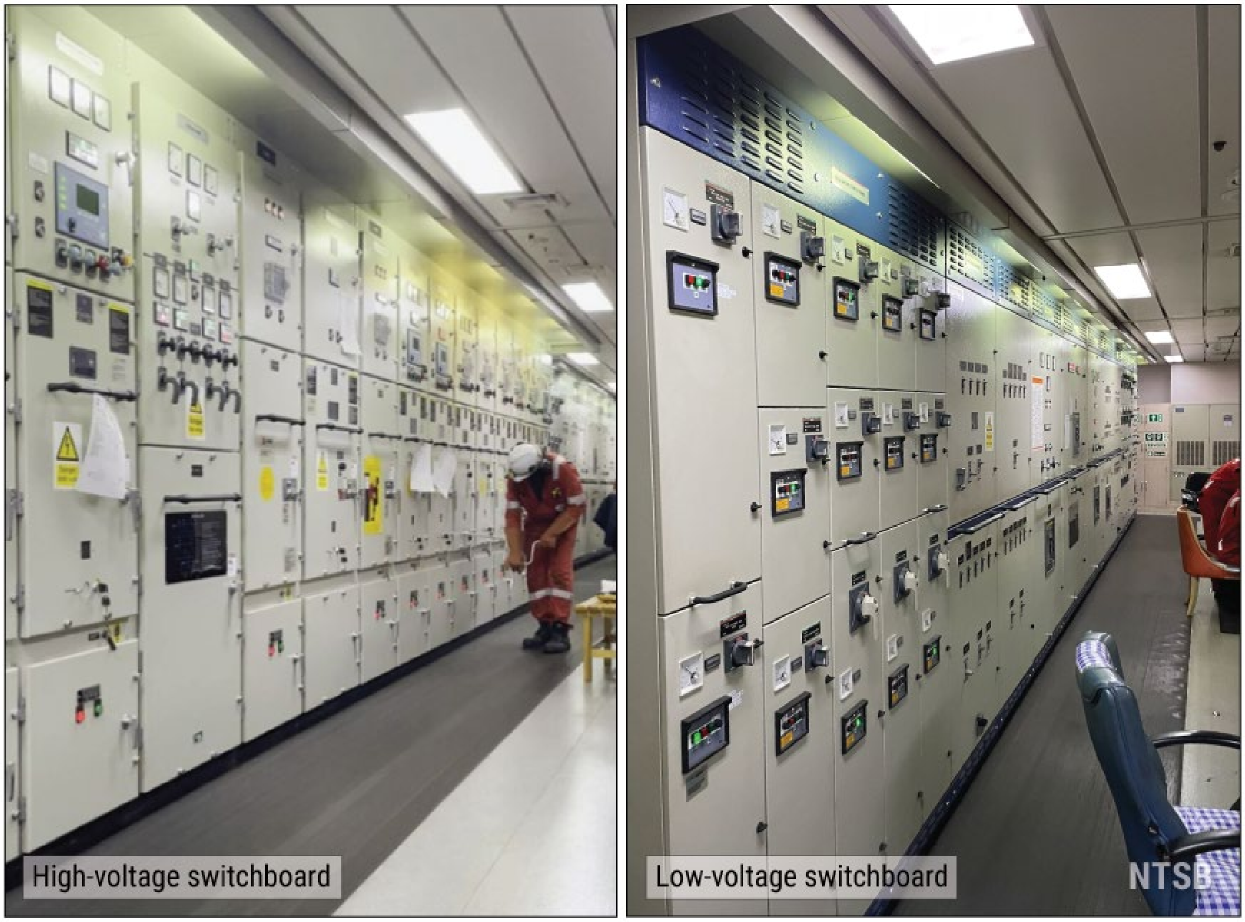

Figure 42. *Left to right*: The *Dali*'s HV switchboard (which housed the HV bus) and breakers, and the LV switchboard (which housed the LV bus) and breakers.

The LV bus also could be split with an installed bus tie breaker in order to isolate equipment that had failed or needed maintenance. The bus was designed to be operated with the LV bus tie breaker closed, which was the configuration during the accident voyage. With the LV bus tie breaker closed, one step-down transformer (TR1 or TR2) was designed to be used between the HV bus and the LV bus, with its associated breakers.

Our investigation revealed that one step-down transformer, TR2, and its associated breakers, HR2 and LR2, had been in use exclusively for at least 7 months before the accident. Although *Dali* personnel did not know the last time TR1 and its associated breakers, HR1 and LR1, had been used, a breaker counter reading for LR2 was similar to that of LR1, indicating that TR1 had been used about the same number of times as TR2.[73] Turnover notes, preventative maintenance program records, and emails did not indicate that the prior crews were aware of any operational issues with TR1 or its associated breakers.

1.7.1.2 Emergency Diesel Generator

The vessel had an emergency diesel generator (EDG), which was independent from the other generators. The EDG was a 200 kilowatt, 440-volt-AC, 3-phase generator, driven by a 4-stroke, 6-cylinder, 247-kilowatt, 330-hp diesel engine. The EDG would activate automatically during a loss of normal LV power (blackout) and provide power to only the emergency switchboard, which powered essential onboard systems, such as navigation, communication, and emergency lighting. However, the EDG alone did not produce enough electrical power to operate the auxiliary pumps to run the main engine.

The EDG's diesel engine was equipped with an electric start with a backup spring starter. An engine control panel monitored and controlled the emergency generator. Normally, the emergency switchboard was powered by the vessel's DGs through a breaker, called the emergency bus tie breaker. In accordance with International Maritime Organization (IMO) regulations, the EDG was designed to start automatically and be fully powered within 45 seconds of the loss of power to the emergency switchboard.[74] Additionally, ClassNK told the NTSB, "if the design can ensure that power can be supplied from the emergency generator within 45 seconds, then it is considered to be acceptable."

Three conditions had to be met to enable the EDG to start automatically in the standby start configuration:

1. the emergency switchboard three-position selector switch was set to Normal;
2. the engine control panel on the engine was set to Automatic mode; and
3. the EDG ventilation control panel—located in the EDG room—was set to Automatic mode.

[73] The breaker counter counted the number of times the breaker was turned on and off.

[74] (a) IMO is the global standard-setting authority for the safety, security, and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is universally adopted and implemented. IMO measures cover all aspects of international shipping, including ship design, construction, equipment, manning, operation, and disposal. (b) See International Maritime Organization Rule 43 - Emergency source of electrical power in cargo ships.

If these three conditions were met when the emergency switchboard lost power, the emergency bus tie breaker would automatically open, isolating the emergency bus from the LV bus. When the bus tie breaker opened, it would initiate an auto-start sequence in the EDG auto-ventilation control panel. The EDG's radiator damper would receive a signal to open.[75] Once a limit switch found within the damper's actuator indicated that the damper was open, the generator would start, come up to speed, and automatically power the emergency switchboard.[76]

Before the *Dali* left the dock on March 26, the crew completed a departure checklist, which indicated that the EDG had been tested within the last 12 hours and was set to the standby start configuration. Crewmembers also stated that the EDG was set to standby start configuration, which meant that all three conditions were met. Additionally, no issues related to the EDG's ability to start were noted in the vessel's preventative maintenance program or previous crew's turnover notes.

NTSB investigators determined that, after the vessel initially lost power while underway on March 26, the EDG took 70 seconds to start and power the emergency bus. This was apparent because the vessel's integrated control and monitoring system recorded two alarms that corresponded with the EDG connecting and powering the emergency bus, and, on the VDR there were sounds similar to automatic power changeover emanating from the navigation equipment distribution panel on the bridge.[77] Investigators heard similar sounds during postaccident testing on May 15, 2024, when they simulated an LV blackout to load test the EDG.[78] During testing, the EDG successfully started and connected to the emergency bus in less than 45 seconds.

[75] A *radiator* cools an engine while the engine is running. A *radiator damper*, also called a louver, is the part of the radiator that allows air flow through the radiator in order to cool the engine.

[76] A *limit switch* is an electromechanical device used to detect the presence or position of an object. On the *Dali*, the limit switch within the EDG radiator damper's actuator detected whether the damper was open or closed.

[77] Most navigation equipment, navigation lights, the VDR, and bridge operation equipment used on the bridge received power from the navigation equipment (N1) distribution panel. The N1 panel received power from a normal 440-/220-volt transformer, fed from the LV switchboard and a 220-volt power supply from the emergency switchboard. Installed in the N1 distribution panel was an automatic power changeover unit. The automatic power changeover unit was designed to switch power sources upon loss of either normal LV power or emergency supply power.

[78] During postaccident testing, the chief engineer reported that no work had been done on the EDG, emergency switchboard, or associated equipment after the accident.

1.7.1.3 Low-Voltage Step-Down Transformer Changeover

The *Dali*'s HR breakers, which linked to the LV step-down transformers, had two control modes to assist the crew in changing over transformers for maintenance or operational purposes: Automatic and Manual. When the HR breakers were in Automatic mode during maintenance work, the transformers automatically changed over once initiated by the crew without causing a blackout. When the HR breakers were in Manual mode during maintenance work, the crew had to first open the online HR breaker, which would cause an LV blackout, before closing the other HR breaker, which would restore LV power.

A secondary advantage of operating the HR breakers in Automatic control mode was that, upon an unexpected loss of LV power, such as the *Dali*'s initial underway blackout on March 26, the vessel's other step-down transformer would automatically connect after about 10 seconds, restoring power to the LV bus (this changeover was tested by investigators following the accident; see section 1.14.1). If the control mode was set to Manual during an unexpected loss of LV power, the crew would have to identify the problem, and then manually close the HR and respective LR to restore LV power.

When LV power was initially lost during the accident, crewmembers had to close HR1 manually. The NTSB examined the control modes the day after the accident; the control modes for both HR1 and HR2 were set to Manual.

ABS (the vessel's classification society at the time the vessel was delivered to its original owner), Synergy, and HHI did not have requirements applicable to the setting (Manual or Automatic) of the *Dali*'s HR breakers' control modes; the control mode setting was at the crew's discretion.[79]

[79] According to ABS, "automatic operation of the transformers/interlocks is not required." HHI's electric power system nameplate on the main switchboard did not specify a default position for the breakers' control modes.

1.7.2 Propulsion System

1.7.2.1 Main Engine

1.7.2.1.1 Overview

A single, slow-speed, 55,626-hp (41,480-kW) Hyundai-MAN B&W 9S90ME C9.2 diesel engine provided propulsion for the *Dali*.[80] The main engine was directly connected to a single, right-turning propeller and required compressed air directed into its cylinders to start and change direction (see figure 43). The *Dali's* main engine was built by HHI in their engine manufacturing facility in Ulsan, South Korea. After construction, HHI installed the engine aboard the *Dali* in their nearby shipyard.

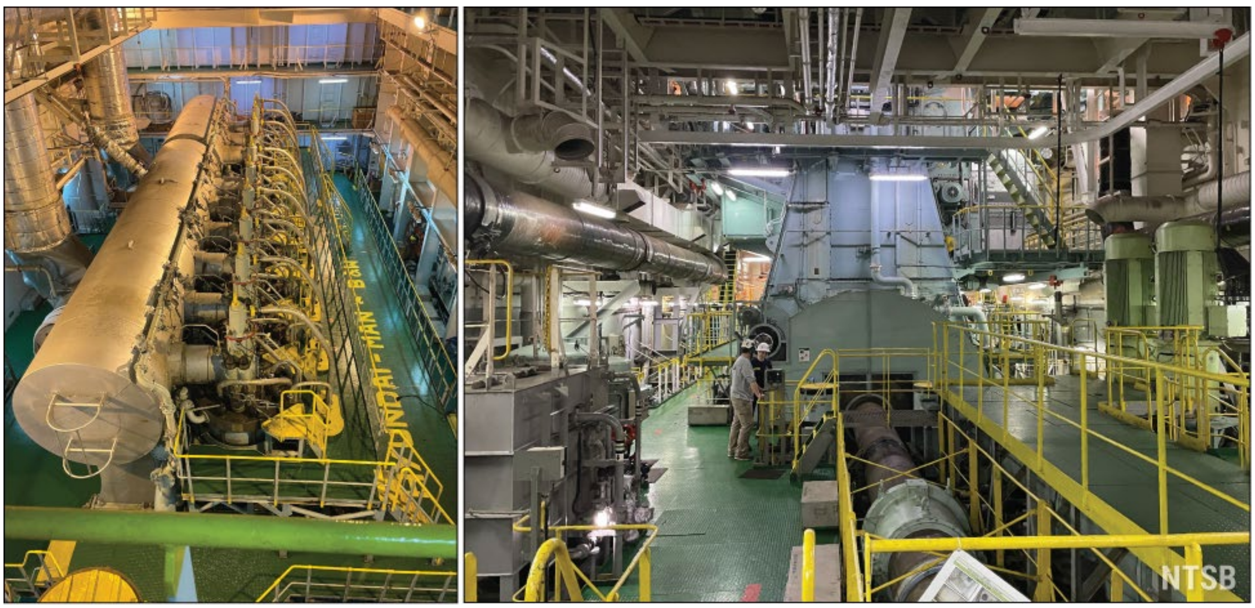

Figure 43. *Left to right*: The *Dali*'s main engine room (looking aft), showing the vessel's engine. NTSB investigators examining the lower level of the vessel's engine room (looking forward).

The main engine telegraph, engine safety system, and remote propulsion control for the engine was managed by a Kongsberg AutoChief 600 propulsion control system.[81] The main engine control system and engine safety system

[80] MAN B&W, now Everllence, designed the engine and owned the designs as intellectual property. Everllence sold HHI a license to manufacture the engine, provided technical support in the construction and manufacturing process, and provided supporting guidance documentation.

[81] An *engine telegraph*, or simply *telegraph*, is a electromechanical device used to transmit and receive orders between a ship's bridge and the engine room.

(interfaced into the AutoChief 600 system) monitored main engine conditions and could perform an automatic shutdown in order to protect the engine from system abnormalities (see section 1.7.3 for information about alarms on the day of the accident).[82]

1.7.2.1.2 Engine Shutdowns

The engine safety system and main engine control system both featured “non-cancellable” and “cancellable” shutdowns accompanied by an associated alarm. A non-cancellable shutdown could be triggered by engine overspeed or low lube oil pressure, while a cancellable shutdown could be triggered by low cooling water pressure.

Non-cancellable shutdowns could not be overridden by the crew because these shutdowns would affect essential engine functions. A non-cancellable shutdown required the crew to remedy the triggering condition before the engine could resume.

A cancellable shutdown could be overridden by the crew to allow the main engine to continue to operate. Aboard the *Dali*, this override function could only be performed at the station that was controlling the main engine at the time the alarm shutdown was triggered.[83] Once the alarm was triggered, the crew had 6 seconds to push a button on the maneuvering station to cancel, or override, this alarm to keep the engine running (the prewarning time was set by the engine manufacturer, HHI). If the crew cancelled the shutdown, the engine remained running at 40% of its rated speed. On the *Dali*, the maximum rated engine speed was 80 rpm, so the engine slowdown speed would be 32 rpm, or about “slow ahead” (see figure 7).

HHI stated the cancellable function was intended to avoid unnecessary shutdowns caused by false alarms or sensor errors during operation by allowing bridge or ECR personnel time to determine whether something is an actual emergency. The time before a cancellable shutdown was meant for executing countermeasures, such as running the standby system, before the engine shut down.

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[82] ClassNK rules permit safety devices to shut down main propulsion machinery “in cases which could lead to complete breakdown, serious damage or explosion.” Class rules do not explicitly require safety devices to shut down main propulsion machinery based on a loss of main engine cooling water pressure; they rely on the manufacturer’s design philosophy to determine if a loss of main engine cooling water pressure would lead to complete breakdown, serious damage, or explosion.

[83] When the *Dali* initially lost power on March 26, the bridge station was controlling the main engine.

According to HHI, at the time of construction, the owner (before Grace Ocean) requested the engine comply with the rules of Germanischer Lloyd (GL), a classification society. These rules required the engine be configured with a low cooling water pressure shutdown. HHI configured the main engine shutdown parameters when the engine was installed aboard the *Dali*. These parameters were based on recommendations by Everllence (formerly MAN B&W), the engine designer, and GL rules.

By 2015, when the vessel was delivered, the vessel owner chose ABS to class the vessel. Unlike GL rules, ABS rules at that time did not require the main engine to shut down due to low cooling water pressure. ABS did, however, permit main engines like the *Dali*'s to be configured to shut down due to additional conditions, such as low cooling water pressure, but only if configured with an "override." To meet this requirement, HHI reconfigured low cooling water pressure shutdown as a cancellable shutdown. The engine designer, Everllence, told NTSB investigators that they had not "specified or encouraged" that the type of main engine aboard the *Dali* be configured to shut down due to low cooling water pressure, and that it was only a GL class requirement at the time of vessel construction.

After the accident, on March 29, a representative from Kongsberg downloaded the AutoChief 600 data from the accident voyage. Kongsberg later produced a report and determined that, on the day of the accident, the main engine had shut down due to low main engine cooling water pressure, a cancellable shutdown event.

1.7.2.1.3 Engine Restart

The main engine could be restarted manually by controls located on the bridge or in the ECR. Before the main engine could restart, power needed to be available from the HV switchboard to operate the main engine lubricating oil pumps.[84] Power also needed to be available from the LV switchboard to operate critical engine components, including automatically restarting the main engine hydraulic oil pumps and cooling water pumps. Once the HV and LV switchboards' power was restored and the main engine lever was moved to a "stop" position, the main engine hydraulic oil pumps and lubricating oil pumps would automatically restart without delay.[85] Due to their sequential start function, any main engine cooling

[84] There were two lubricating oil pumps. Only one was required to be operating to restart the main engine; the other was left in standby.

[85] There were maneuvering control stations on the bridge and in the ECR. The engine start sequence could only be restarted once the station that had control returned the lever to stop.

water pumps that were running before a loss of power would start 45 seconds after the restoration of the LV switchboard, regardless of whether the engine controls were moved to a stop position. Then, if all other conditions had normalized, the main engine would start when the lever was manually moved forward or astern.

1.7.2.2 Bow Thruster

The *Dali* was equipped with a four-blade, controllable-pitch Kawasaki Heavy Industries Ltd bow thruster. The bow thruster, a propulsor on the ship's hull near the bow, assisted with ship maneuverability while the vessel moved at slower speeds. The bow thruster motor was powered by the HV switchboard, and its hydraulic oil service pump was powered by the LV switchboard. A starter panel, located on the second deck transformer room in the engine room, distributed power to the bow thruster. According to vessel documentation, the bow thruster was not effective at vessel speeds greater than 5 knots (5.8 mph).

1.7.3 Control and Monitoring Systems

The *Dali* was equipped with an integrated control and monitoring system, known on board the vessel by its brand name, Advanced Control and Integration System (ACONIS). This system monitored main propulsion, power generation, and auxiliary systems on the vessel. The ACONIS was equipped with human-to-machine interface stations, which allowed operators to control machinery functions, view equipment running status and tank levels, and acknowledge alarms. The stations' monitors provided operators with "mimics," which presented visual representations of the actual onboard vessel machinery and machinery systems (see figure 44).

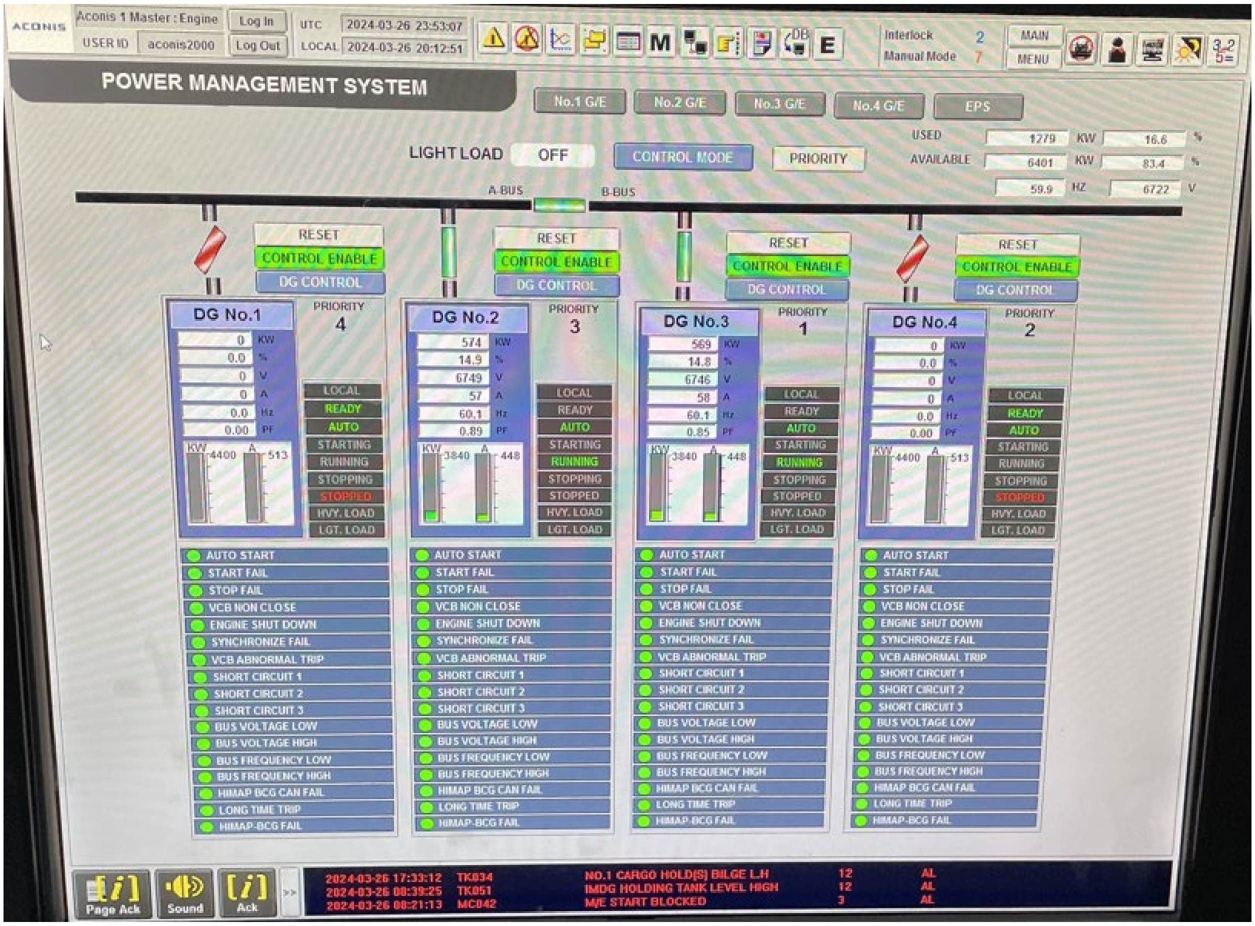

Figure 44. ACONIS mimic of the vessel's PMS, which monitored electrical bus load compared to online diesel generator capacity.

These mimics also provided an alarm list for the machinery and machinery systems. The ACONIS was equipped with an alarm monitoring system, which alerted operators when monitored equipment fell out of preset parameters, retained historical alarm events, and monitored values.[86]

The *Dali's* main engine manufacturer, Hyundai-MAN B&W, used a diagnostic program called CoCoS-EDS, which retained historical main engine events for engine performance evaluation.

[86] The NTSB recovered the ACONIS historical alarm events for March 25 and March 26 and used these alarms to understand the sequence of events on those dates. Further details can be found in the public docket for this investigation (case number DCA24MM031).

1.7.4 Main Engine and Diesel Generators Fuel System

1.7.4.1 Overview

The *Dali* carried an estimated 1.8 million gallons of fuel in dedicated fuel tanks. This fuel included heavy fuel oil (HFO), very low-sulfur heavy fuel oil (VLSFO), and marine gas oil (MGO). The vessel was burning MGO at departure. (This fuel was tested after the accident; see section 1.14.3.)

When the vessel was built, the main engine fuel system and diesel generator (DG) fuel systems operated independently, and their purposes were segregated. The main engine supply and circulating pumps provided fuel to the main engine, and the DG fuel supply pumps and booster pumps provided fuel to the four DGs. Both the main engine's and DGs' circulating, supply, and booster pumps were redundant, meaning that each system had two pumps.[87] Additionally, the DG fuel supply system included an MGO flushing pump and an air-motor-driven emergency MGO fuel pump. The flushing pump was designed for use as a maintenance pump for flushing alternative grades of fuel out of the fuel piping. The air-motor-driven emergency MGO fuel pump was designed to supply sufficient fuel to start one of the DGs when recovering from a power outage, but was not capable of serving as the lone pump to supply fuel to the DGs (see section 1.7.4.3).

The main engine and DG fuel pumps were all powered from the LV switchboard. The pumps' motor controllers, located at two group starter panels on either side of the LV switchboard, were configured so that once electrical power was restored after an outage, the pumps that had been running before the outage would automatically return to operation without human intervention.[88]

1.7.4.2 Modification

In 2015, when the vessel was built, it complied with IMO emissions requirements. In 2020, emissions requirements changed, and to comply with these requirements, Grace Ocean (the owner of the *Dali*), with approval from ClassNK,

[87] One pump was for normal operation, and the other was on standby and would start automatically if fuel pressure dropped too low.

[88] (a) A *group starter panel* is an electrical enclosure that houses a group of individual control panels designed to start/stop essential motors and fans. (b) The motor controllers that were configured with an LV release were also configured with a sequential start, or a predetermined time start delay (after power restoration). Essential vessel machinery, such as the steering gear pumps and the DG3 and DG4 fuel oil booster and supply pumps were configured to start immediately after power was recovered.

installed an exhaust gas scrubber system, which would clean—or "scrub"—certain pollutants from exhaust gas before being released into the atmosphere.[89] The scrubbers allowed the vessel to burn HFO in the main engine, DG1, and DG2 and remain compliant with emissions requirements. To complete the installation, Grace Ocean modified the fuel and engine exhaust systems for the main engine, DG1, and DG2. Because DG3 and DG4 did not have a scrubber system installed, they could only burn VLSFO and MGO. To facilitate the use of the scrubber system, fuel piping in the main engine circulating system was modified, and the main engine fuel oil supply pumps and circulating pumps were resized for higher capacity, so they could supply fuel to DG1, DG2, and the main engine simultaneously.

[89] The *International Convention for the Prevention of Pollution from Ships* (*MARPOL*), which was adopted by the International Maritime Organization in 1973, covers the prevention of pollution of the marine environment by ships from operational or accidental causes. *MARPOL* "Annex VI," *Regulations for the Prevention of Air Pollution from Ships*, states, "To improve air quality and reduce ship emissions, Annex VI limits the sulfur content and particulate matter of fuel oil used or carried for use onboard ships. Global limits of sulfur content in fuel oil used or carried for use is 0.50% m/m, while inside ECAs, the limit for fuel for which is burned is 0.10% m/m. A scrubber or exhaust gas cleaning system reduces particulate matter and sulfur oxides from engine exhaust systems prior to atmosphere release." These requirements became effective January 1, 2020.

The DG fuel system was also modified; the suction and return piping from/to the HFO service tank was blocked, which prevented HFO from being supplied to, and burned by, DG3 and DG4 (see figure 45). With these changes, the DG supply and booster pumps were only capable of supplying DG3 and DG4 with VLSFO and MGO.

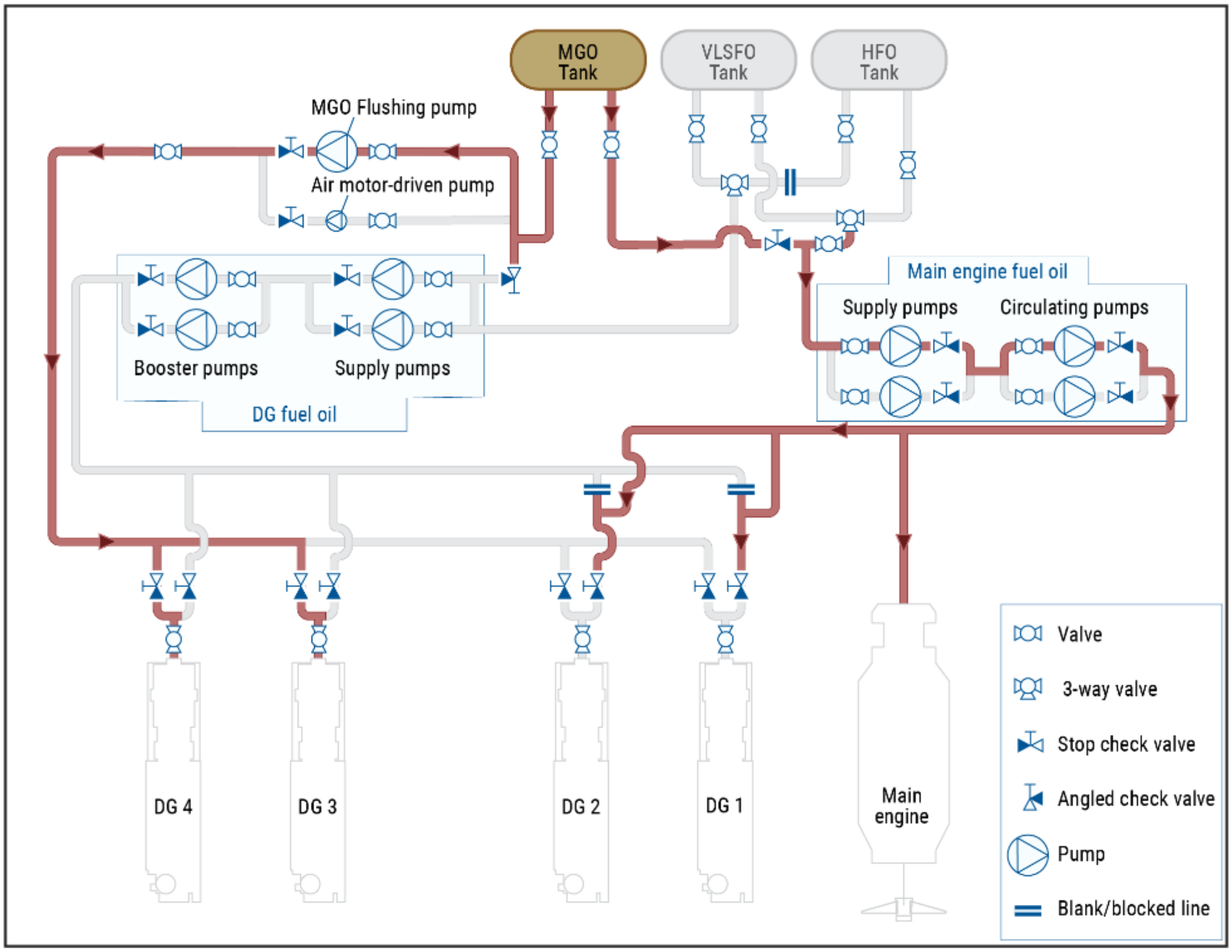

Figure 45. Simplified diagram of *Dali*'s main engine and DG fuel oil service system. The lineup in use at the time of the accident is shown in red.[90]

1.7.4.3 Flushing Pump

The DG MGO flushing pump was part of the vessel's original fuel system and not modified when the scrubber system was installed. The flushing pump was only

[90] See the public docket for this investigation (case number DCA24MM031) for the main engine and generator engine fuel oil modification class-approved drawing.

capable of taking suction from the MGO service tank, meaning that the pump would deliver only MGO to the DGs.

The flushing pump was powered by the LV switchboard. If the flushing pump was running before a blackout, a crewmember would have to manually restart it once power was restored. (The main engine supply and circulating pumps and the DG supply and booster pumps, on the other hand, would restart automatically once power was restored if they were in use before the blackout.) To restart the flushing pump, a crewmember would have had to go down two levels in near-total darkness with a flashlight, from the engine control room on the second deck to the purifier room on the fourth deck, where they would locally restart the pump.[91]

At the time of the accident, the flushing pump was utilized as a primary fuel supply pump to DG3 and DG4, and the as-designed DG supply and booster pumps were not being used. The chief engineer at the time of the accident and the previous chief engineer, who had worked aboard the *Dali* from September 2023 to January 2024, indicated that the flushing pump had been utilized as a primary MGO supply pump for DG3 and DG4 when they had each joined the vessel, and both chose to continue using it. A chief engineer is ultimately responsible for all machinery on a vessel, including the flushing pump.

After the accident, ClassNK stated that, "from the viewpoint of classification requirements," the flushing pump "could not be considered" for supplying fuel to the DGs due to its inability to automatically restart after a blackout. When asked by NTSB investigators whether the flushing pump was acceptable as the primary source of fuel delivery to the generators, a Synergy technical manager responded, "no, [because] only one pump is there."

1.7.4.4 Nonoperational System Components

As part of the vessel examination after the accident, the NTSB found that the DG supply and booster pumps, DG auto-backflush filter, DG MGO cooler, and

[91] Certain auxiliary pumps that both the vessel's manufacturer and its classification society deemed "critical" to the vessel were designed to restart automatically following an interruption in power. Such "critical" auxiliary pumps included the steering gear pumps; the main engine lube oil, fuel oil, cooling water, and hydraulic pumps; and the diesel generators' primary fuel pumps. The fuel oil flushing pump for DG3 and DG4 did not have an automatic-restart function and required the vessel crew to manually restart the pump after a power loss.

viscorators were not in use.[92] The previous chief engineer told the NTSB that these components had been secured and not used "for quite some time," although he did not know the exact length of time. In a January 2024 email he sent from the vessel to shoreside fuel supply representatives (with Synergy's vessel technical manager included in copy), he stated, "system [DG3 and DG4 supply and booster pumps] is not in use all pumps heaters etc isolated after piping modification and permanently kept on LSMGO [flushing pump] line."

After the accident, the previous chief engineer told the NTSB that he was concerned with the type and condition of the residual fuel contained in the DG3 and DG4 fuel system piping and components. He stated that there may have been biological growth in the piping that could adversely affect the rest of the system if the fuel was circulated and used. He estimated that disassembling and cleaning the nonoperational system components and pipework and returning the system to operation would have taken a "few days." He said that he would not have had time to complete this job due to his workload. Both the previous chief engineer and the chief engineer at the time of the accident opted to continue running the flushing pump in that arrangement because fuel piping associated with DG3 and DG4 supply and booster pumps contained non-MGO fuel and would need to be flushed and cleaned out before use.

1.7.5 March 25 In-Port Electrical Power Losses

On March 25, the day before the casualty, the crew was performing in-port maintenance in advance of that evening's planned departure. While working on the diesel engine exhaust scrubber system for DG2 (the only generator connected to the HV bus and supplying power to the vessel at that time), a crewmember mistakenly closed the inline engine exhaust damper, which effectively blocked the engine's cylinder exhaust gases from traveling up its stack and out of the vessel.[93] The blockage caused DG2's engine to stall and slow down, preventing DG2 from generating sufficient power to the HV bus. Sensing this underfrequency, or underperformance, the vessel's power management system (PMS) opened the online generator's main breaker, resulting in a loss of power to the HV bus. HR2 and LR2, which were connected to LV step-down transformer TR2, opened, blacking out the LV bus and causing a full-vessel blackout. Immediately after opening the breaker, the

[92] A *viscorator*, or *viscosity controller*, monitors the viscosity of fuel oil and regulates the viscosity indirectly by controlling the temperature of the fuel by regulating a fuel's heating source. *Viscosity* is a measurement of a fluid's resistance to flow.

[93] An *exhaust damper actuator* is a motor that opens and closes an exhaust damper.

PMS started and connected DG3, which had been in standby, to automatically take over for the now-offline DG2.[94] (Appendix D details the events of the March 25 blackouts.)

Shortly after the PMS connected to DG3, the electrician changed over the LV step-down transformers from the one that had been in use for several months (TR2) to the other transformer (TR1). (The electrician told the NTSB that this was common practice while working on other vessels, both for him and across the industry.) The electrician achieved this changeover by manually closing TR1's breakers, HR1 and LR1, rather than HR2 and LR2, which had opened. This changeover restored the vessel's power.

When power was restored, certain auxiliary pumps restarted automatically according to their design. The flushing pump, which was being used to supply MGO fuel for DG3 (the diesel generator that had just come online), required a manual restart, as designed.

DG3 ran for about 5 minutes. Before the crew could manually restart the flushing pump, DG3's speed began to decrease due to insufficient fuel pressure. The decrease in speed caused DG3 to underperform, preventing it from generating sufficient power to supply the HV switchboard. When the PMS sensed this decrease in power, it opened DG3's breaker, which resulted in a loss of power to the HV bus. HR1 and LR1 opened, again blacking out the LV bus and causing the second full-vessel blackout on March 25.[95]

In the meantime, the crew had reopened DG2's engine exhaust damper manually. DG2 automatically restarted and connected to the HV bus. DG2 was able to run by consuming residual fuel in the supply lines. While recovering from this second blackout, the electrician again closed HR1 and LR1. Closing HR1 and LR1 powered the LV switchboard, which restarted the fuel pumps for DG1 and DG2 automatically. TR1 and its associated breakers, HR1 and LR1, remained in use when the ship departed on March 26.

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[94] The PMS allowed the operators to prioritize and designate the order that standby DGs would start. For instance, a single DG could be prioritized as the main DG, and the other three offline DGs assigned in descending order. Operators could also manually configure DGs using controls on the HV switchboard; this process was independent of the ACONIS.

[95] According to HHI's postaccident report, the "fuel oil supply to DG No. 3 and DG No. 4 stopped, preventing them from generating enough power to supply to the HV Switchboard. The PMS, as designed and intended, detected the drop in power and disconnected the two DGs from the HV Switchboard."

1.8 Vessel Regulatory Oversight

Classification societies are non-governmental organizations that survey ships for compliance with design, construction, and maintenance requirements. They issue engineering standards or rules that ships built. Once a ship is built, a classification certificate is issued, which shows which rules the ship is built to and will operate under, along with any necessary additional notations. Classification certificates are maintained through surveys, including semi-quintennial drydocking.

As recognized organizations, classification societies also conduct surveys and issue certificates showing compliance with international conventions on behalf of the flag state administration.[96] ClassNK issued certificates to the *Dali* on behalf of Singapore for compliance with the International Safety Management Code (ISM Code), the *International Convention for the Safety of Life at Sea* (*SOLAS*), the Load Line Convention, and the International Tonnage Convention, among others. For more information about the ISM Code, see section 1.10.[97]

Because vessel owners choose their classification society, they are often based on factors such as geographic proximity to the operators or the shipyard where the vessel is being built. Because certain classification societies are recognized organizations for certain flag states, vessel owners may consider the convenience of classing their vessels with a classification society approved by their flag.

1.9 Company Oversight

At the time of the accident, Synergy, the vessel manager that provided the crew and operated the vessel, managed 55 ships under Panama, Republic of the Marshall Islands, Hong Kong, Liberia, and Singapore flags, including the *Dali*. Synergy provided technical oversight, assistance, and guidance to its vessels.

[96] For commercial maritime shipping, a *recognized organization* is an organization authorized to act on behalf of a flag-state. Flag states may delegate classification societies to perform certain flag-state vessel inspection and certification functions.

[97] (a) The main objective of *SOLAS* is to specify minimum standards for the construction, equipment, and operation of ships, compatible with their safety. The first version of the *SOLAS* Convention was adopted in 1914 in response to the *Titanic* disaster. The current version in force is the 1974 Convention, as amended on numerous occasions. (IMO 1974) (b) The ISM Code is also known as the International Management Code for the Safe Operation of Ships and for Pollution Prevention.

1.9.1 Shoreside Communication and Assistance

The *Dali*, like most modern vessels, had satellite phone, email, and internet capabilities. The *Dali* was also equipped with a remote equipment monitoring system, which allowed Synergy's shoreside support personnel to monitor real-time vessel operations, data, and analytics. The satellite-based communication methods paired with the remote equipment monitoring system connected *Dali*'s staff to a dedicated shoreside expert that Synergy employed to provide each of its vessels with shoreside assistance. These company staff, which included technical superintendents and managers, communicated with the *Dali* at least daily.

1.9.2 Inspection and Maintenance

1.9.2.1 Biannual Inspections and Vessel Inspection Reports

Synergy vessel technical managers and superintendents (port engineers) conducted vessel inspections as a part of the company's internal audit of its vessels. Inspections occurred twice per year, with at least one intended to be completed while the vessels were underway. The managers would board the vessel for at least a week (often staying longer than 2 weeks) to conduct an examination of the entire vessel. The inspections covered a broad range of areas and topics, including hull condition, safety equipment, accommodation spaces' cleanliness, and engine room equipment conditions. The inspector had a list of specific items to examine while on board.

One section under the auxiliary machinery category was for auxiliary engine (DG) inspection. This section required the inspector to—

> Check fuel oil and lubricating oil systems (including pumps, purifiers, filters, heaters and piping) maintained in satisfactory condition, free of any leakage & oil accumulation. Safety and alarm devices operational / function properly for the machinery. Meters & gauges in good working order:
>
> - HFO Purifiers & control systems
> - LO [lube oil] Purifiers & control systems
> - FO [fuel oil] Heaters & steam lines, control systems
> - ME [main engine] Fuel oil Supply & booster pumps
> - AE [auxiliary engine] Fuel oil Supply & booster pumps [the as-designed DG fuel pumps]
> - Hot filters / Auto-back flush filters for ME

- FO Transfer pump & shifter pumps / filters
- DO [diesel oil] Transfer pumps / filters - Steam pipe & valves / insulation condition in place, free of oil.

Synergy required its inspectors to produce a vessel inspection report (VIR) at the conclusion of an inspection. In addition to noting observations made during the inspection, the inspector could include photographs of general equipment, the vessel's layout, and deficiencies identified. NTSB investigators reviewed the four most recent VIRs produced for the *Dali* before March 26, and no additional observations were noted about the operational status of the DG fuel oil supply and booster pumps. While there were no notes about the flushing pump or its operation, these items were not listed as items to check. VIRs from both August 2023 and February 2024 included photographs of the flushing pump, but no contextual notes or description accompanied the images. The August 2023 VIR included a photograph of the flushing pump pressure gauges with suction and discharge pressure registered.

1.9.2.2 High-Voltage Switchboard Preventative Maintenance

HHI (the manufacturer of the HV switchboard and its components) provided the NTSB with the recommended preventative maintenance program schedule for the HV switchboard, which was supplied to the original owner of the *Dali* upon delivery of the vessel. HHI recommended annual cleaning inside and outside of the panel and inspection of electrical terminal connections. HHI also provided the NTSB with a periodic inspection list specific to the HV breakers (HR1 and HR2). The periodic inspection list recommended checking connections between the breakers' electrical terminals and conductors once every 3 years but did not specify how to perform the checks.

When asked how they ensure quality control when manufacturing the switchboards aboard vessels and installing control wiring, HHI stated—

> [The] typical method used in practice in installation of conductors at factories and shipbuilding is shaking off the lines [manually manipulating the control wires] after installing the same along with other tedious manual inspections. Then, there are FATs [factory acceptance tests], on-board tests, and sea trials conducted, attended and approved by both a shipowner and a Classification society before the delivery of a vessel.

HHI also stated that they did not have any specific materials, instructions, or training for their electrical installation technicians related to the installation of HV switchboards.

As part of its preventative maintenance program Synergy required both 6-month and 30-month HV switchboard inspections. The 30-month inspection included checking bus bars and link fastenings for cracking, breaking, and deformation, as well as checking cables and bus bars for discoloration, damage, and looseness. The 6-month work order card, which was completed on March 23, 2024, 3 days before the accident, included inspecting inside the panels for “loosening and falling off of small items such as screws, nuts, etc.” Terminal boxes and the condition of crimp terminals were also inspected, and crimp terminals were renewed as needed.[98] The completed work orders for both the most recent 6-month and 30-month inspections aboard the *Dali* indicated that the inspections had been completed as per the job description, and no abnormalities were reported.

1.9.3 Flushing Pump Practices

Vessel crewmembers and Synergy personnel interviewed following the accident stated that there were no vessel-specific or company policies related to the use of the flushing pump aboard *Dali* and other similarly equipped Synergy-operated vessels. Per customary industry practice, the *Dali*’s crew used the prior crew’s turnover notes, the vessel’s computerized preventative maintenance program’s records, and past email communications to learn the current and historic operating particulars of the vessel’s plant.

When Synergy learned about the use of the flushing pump as a standalone fuel pump aboard the *Dali* and a sister vessel after the accident, one Synergy technical manager spoke with the crews of the vessels he oversaw about flushing pumps. The technical manager instructed the crews that use of the flushing pump as a standalone fuel source without redundancy was an inappropriate and unacceptable application of the pump and therefore should not be used in that manner. As of the date of this report, these instructions had not been formally entered into company-wide policy and procedure.

[98] A *crimp terminal* is a solderless electrical connector, typically made of metal, that permanently attaches to the end of a wire by using a crimping tool to compress and deform the terminal around the stripped wire.

1.10 Safety Management System

1.10.1 Marine Safety Management Systems

A safety management system (SMS) is a systematic approach to managing safety, including the necessary organizational structures, accountabilities, policies, and procedures. IMO's ISM Code establishes the standard for SMSs in the marine industry.[99] Companies that own or operate vessels subject to the *SOLAS*–including the *Dali*–must develop, implement, and maintain an SMS in compliance with the ISM Code.[100] A Document of Compliance is issued by a flag state administration to every company that fulfills the ISM Code's requirements, and a Safety Management Certificate is issued to every ship with a valid SMS.

The ISM Code defines a safety management system as "a structured and documented system enabling Company personnel to implement effectively the Company safety and environmental protection policy." The code states that the safety management objectives of companies that own or operate vessels subject to the code should:

1. Provide for safe practices in ship operation and a safe working environment;
2. Assess all identified risks to its ships, personnel and the environment, and establish appropriate safeguards; and
3. Continuously improve safety management skills of personnel ashore and aboard ships, including preparing for emergencies related both to safety and environmental protection.

The ISM Code also states that an SMS should ensure compliance with mandatory rules and regulations, and that applicable codes, guidelines, and standards recommended by IMO, classification societies, and other maritime industry organizations are to be considered.

[99] The ISM Code in its current form was adopted in 1993 by the IMO and took effect on July 1, 1998, following the enforcement of the 1994 amendments to the *SOLAS* Convention, which introduced Chapter IX into the Convention. The code has since been amended five times, most recently in 2013.

[100] The ISM Code is incorporated into US law through Title 46 *United States Code* Chapter 32, which requires the secretary of the department in which the Coast Guard is operating (Department of Homeland Security) to implement SMS regulations that conform with the ISM Code.

According to the ISM Code, an SMS must include the following six functional requirements:

1. A safety and environmental protection policy;
2. Instructions and procedures to ensure safe operation of ships and protection of the environment in compliance with relevant international and flag state legislation;
3. Defined levels of authority and lines of communication between, and amongst, shore and shipboard personnel;
4. Procedures for reporting accidents and non-conformities;
5. Procedures to prepare for and respond to emergency situations; and
6. Procedures for internal audits and management reviews.

A vessel's owner or operating company develops marine SMSs. Each vessel has an individual SMS, and the vessel's master is charged with implementing the company's SMS aboard the vessel. According to the ISM Code, the company should clearly define and document the master's responsibility with regard to implementing the safety and environmental protection policy of the company, motivating the crew in the observation of that policy, issuing appropriate orders and instructions in a clear and simple manner, verifying that specified requirements are observed, and periodically reviewing the SMS and reporting its deficiencies to the shore-based management.

The ISM Code states that a company's SMS "should include procedures ensuring that non-conformities, accidents, and hazardous situations are reported to the company, investigated, and analyzed," and the company "should establish procedures for the implementation of corrective action, including measures intended to prevent recurrence."

According to the ISM Code, each company must ensure all personnel involved in an SMS have an adequate understanding of relevant rules, regulations, codes, and guidelines; receive appropriate training on the SMS; and are able to communicate their responsibilities and duties according to the SMS. The code also requires companies to carry out internal audits on board and ashore at least once every 12 months to verify compliance with SMS regulations.

Compliance with the ISM Code is the minimum requirement for operators of *SOLAS* vessels. Companies may, and regularly do, incorporate additional SMS components or supplemental guidance, policy, or procedures into their system.

1.10.2 Synergy's Safety Management System

Synergy provided guidance, policy, and procedures to its vessel crews via an SMS in accordance with the ISM Code. Synergy's SMS covered a broad range of operational and procedural guidance and framework for both routine and emergency operations, including watchstanding, equipment and systems operations, fuel changeover and management, and emergency response, among other topics. It specified crewmember duties and responsibilities and delineated supervisory and subordinate chains of command. Synergy's SMS also required the company to identify risks and plan responses for a range of possible emergency situations, specifying crewmember duties and responsibilities. Finally, the SMS required procedures for identifying and correcting nonconformities and included an audit process for management to ensure policies and procedures were being followed. Synergy had obtained a Document of Compliance on March 27, 2020, and the *Dali* received a Safety Management Certificate on February 6, 2022.

1.10.3 Commercial Aviation Safety Management System Model

The commercial aviation industry also has requirements for SMSs, as prescribed by the International Civil Aviation Organization's (ICAO) Convention on International Civil Aviation - Annex 19 – Safety Management.[101] The ICAO defines SMS as "a systematic approach to managing safety, including the necessary organization structures, accountability, responsibilities, policies, and procedures." The ICAO's SMS requirements extend to operators, manufacturers, maintenance organizations, airports, and other entities directly involved in aviation. These requirements are scalable based on the size and complexity of an operation.

The ICAO's SMS framework in Annex 19 establishes 4 components, sometimes referred to as "pillars," and 12 elements required for SMS implementation—

1 Safety policy and objectives
   1.1 Management commitment – senior leadership must actively support and commit to safety initiatives. Safety policy must include reporting procedures and indicate behaviors that are unacceptable, and it must be signed by a designated "accountable executive," communicated throughout the organization, and be periodically reviewed.

[101] Annex 19 was first adopted by the ICAO Council in February 2013 and took effect in November 2013. Amendment 1 to Annex 19, the second phase of implementation, took effect in July 2016 and was applicable in November 2019.

- 1.2 Safety accountability and responsibilities – clearly define roles and responsibilities for safety across all levels of the organization for all employees. Each organization must identify the accountable executive, who is accountable on behalf of the entire organization for the implementation and maintenance of an effective SMS.
- 1.3 Appointment of key safety personnel – appoint a safety manager who is responsible for the SMS implementation and maintenance.
- 1.4 Coordination of emergency response planning – establish an emergency response plan for accidents and incidents and ensure the plan is integrated and coordinated with relevant stakeholders.
- 1.5 SMS documentation – develop and maintain a SMS manual that describes safety policy, objectives, requirements, accountability, responsibilities, and authorities for SMS processes and procedures. SMS operational records must be developed and maintained.

2 Safety risk management
- 2.1 Hazard identification – establish processes to reactively and proactively identify safety hazards in operations.
- 2.2 Safety risk assessment and mitigation – establish processes to analyze and assess risks associated with identified hazards and implement controls to reduce them to acceptable levels. These can include predictive methods of safety data analysis.

3 Safety assurance
- 3.1 Safety performance monitoring and measurement – track safety performance indicators and targets to evaluate the effectiveness of safety risk controls.
- 3.2 The management of change – assess safety implications of changes before implementation and manage safety risks that may arise from these changes.
- 3.3 Continuous improvement of the SMS – use audit results, feedback, and performance data to refine and enhance the SMS.

4 Safety promotion
- 4.1 Training and education – provide safety training to ensure personnel are competent to perform their SMS duties.
- 4.2 Safety communication – develop a formal means of communication that ensures personnel are aware of the SMS, conveys safety-critical information, explains actions taken to improve safety, and explains why safety procedures are introduced or changed.

The four-component SMS model has been adapted across various modes of transportation and industries, including in US public transportation agencies and in the pipeline industry.[102]

1.11 Vessel Personnel

1.11.1 Experience

The two pilots aboard the *Dali* on March 26 were employed by the Association of Maryland Pilots.[103] The senior pilot held a Coast Guard-issued credential as a master, unlimited tonnage upon inland waters. The pilot-in-training held a Coast Guard-issue credential as a master, unlimited tonnage upon oceans. The senior pilot was an unlimited-licensed pilot in the Chesapeake Bay, and the pilot-in-training did not hold any pilotage license at the time of the casualty. The pilot-in-training was completing on-the-job training under the senior pilot's supervision.

The *Dali* crew composition met the requirements of the vessel's minimum safe manning document, which was valid at the time of the accident, in accordance with International Convention on Standards of Training, Certification and Watchkeeping for Seafarers regulations.[104] All 21 *Dali* crewmembers were credentialed for the positions they filled on board the vessel. Of those on the vessel's bridge at the time of the casualty, the master held a certificate of competency as a master of a foreign-going ship (on ships of 500 gross tonnage or more) issued by the Government of India and endorsed by the Government of Singapore, the second mate held a certificate of competency as a second mate of a foreign-going ship (officer-in-charge of a navigation watch on ships of 500 gross tonnage or more) issued by the Government of India and endorsed by the Government of Singapore,

[102] See *49 CFR* 673 Subpart D and American Petroleum Institute Recommended Practice 1173.

[103] Pilots are regulated by the state of Maryland under the Department of Labor State Board of Pilots. The Maryland State Board of Pilots oversees the selection of pilots-in-training and their training upon selection, pilot licensure, and regulation of all Maryland pilots. See *Code of Maryland* Title 11, Stat. 11- 303 and *Code of Maryland Regulations* 09.26.02.01.

[104] A *minimum safe manning document* is issued by a flag state administration and lists the minimum number of officers and ratings required on the ship and their credentials per the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers and national regulations. As the *Dali*'s flag state, Singapore was responsible for the ship's registration, nationality, and the enforcement of regulations. The Maritime and Port Authority of Singapore issued a minimum safe manning document to the *Dali* on April 13, 2020.

and the helmsman held a certificate of proficiency as an able seafarer deck issued by the Government of India.

Ten of the 21 crewmembers were part of the engineering department.[105] Of those in the engine room during the casualty, the chief engineer held a certificate of competency as a marine engineer officer class 1 (chief engineer officer on ships) issued by the Government of India and endorsed by the Government of Singapore, the third engineer held a certificate of competency as an engineering officer of the watch issued by the Maritime & Coast Guard Agency of the United Kingdom and endorsed by the Government of Singapore, and the electrician held a certificate of proficiency as an electrical-technical rating issued by the Government of Sri Lanka.[106]

All of the engineering crewmembers were on their first contract with the *Dali*—meaning they had not previously sailed on the *Dali* before joining the crew. Crewmembers' time on board ranged from 1–8 months.[107] All but two of the engineering crewmembers had joined the ship in Sri Lanka on October 18, 2023. The first engineer joined in Baltimore, at an earlier port call, on December 21, 2023, and the chief engineer joined in Malaysia on January 28, 2024. Many crewmembers, including the chief engineer, were familiar with working aboard similar types of vessels (such as containerships).

1.11.2 Toxicological Testing

Coast Guard regulations require employers to conduct drug and alcohol testing for those crewmembers directly involved in a "serious marine incident."[108] Per these regulations, employers must "take all practicable steps to have each individual engaged or employed on board the vessel who is directly involved in the incident chemically tested for evidence of drug and alcohol use as required in this part," with "directly involved" defined as "an individual whose order, action or failure to act is

[105] The engineering crew included the *chief engineer*, second engineer, *third engineer*, fourth engineer, electrician trainee marine engineer, trainee electrical officer, motorman, fitter, and two *oilers*.

[106] The *Dali*'s minimum safe manning document did not require an electrical specialist—either officer or rating—on board the vessel.

[107] Sailing with new crew and high crew-turnover rates is common for international shipping vessels due to shipping industry factors, including long periods between a vessel's port calls, terms of crew contracts, and rest and rotation requirements.

[108] See [46 *CFR* 4.06-3](46 CFR 4.06-3).

determined to be, or cannot be ruled out as, a causative factor in the events leading to or causing a serious marine incident."

Regulations also outline timeframes for alcohol and drug testing. Alcohol testing—

> must be conducted within 2 hours of when the [accident] occurred, unless precluded by safety concerns directly related to the incident. If safety concerns … prevent the alcohol testing from being conducted within 2 hours … then alcohol testing must be completed as soon as the safety concerns are addressed.

Collection of specimens for drug testing—

> must be conducted within 32 hours of when the [accident] occurred, unless precluded by safety concerns directly related to the incident. If safety concerns … prevent the collection of drug-test specimens from being conducted within 32 hours … then the collection of drug-test specimens must be conducted as soon as the safety concerns are addressed.

On March 26, at 0232, the *Dali* master and chief engineer tested the entire crew, including themselves, for alcohol, per company procedure. All tested negative. Between 1617 and 1804, a third-party testing provider went aboard the *Dali* to test the entire crew for alcohol and drugs.[109] All tested negative for both. The crewmember who was injured and had been tested at 0232 with the rest of the crew, had already been taken ashore for medical treatment when the third-party testing provider arrived on board. This crewmember was not tested by the third-party testing provider.

At 0317, the senior pilot and pilot-in-training were relieved by another pilot from the Association of Maryland Pilots. The two pilots were taken ashore where, at 0530, both were administered tests for alcohol and other drugs. Both tested negative.

[109] Crewmembers were tested for ethyl alcohol, amphetamine, barbiturates, benzodiazepines, cocaine metabolite, opiates (morphine), phencyclidine (PCP), THC (marijuana) metabolite, methadone, methaqualone, and propoxyphene.

1.12 Waterway and Environmental Conditions

The accident occurred in Fort McHenry Channel, where the dredged depth was about 50 feet. The Fort McHenry Channel, which ran within the Patapsco River along the length of the Port of Baltimore and under the Key Bridge, was a navigation channel maintained by the Corps of Engineers. In 2023, a total of 3,775 transits between Pier 17 and Pier 18 were recorded (1,902 inbound and 1,873 outbound). (NOAA AccessAIS n.d.). The channel was 700 feet wide and 4 miles long, with a vertical clearance of 185 feet under the Key Bridge (see figure 46). The main navigational channel near the bridge was straight.

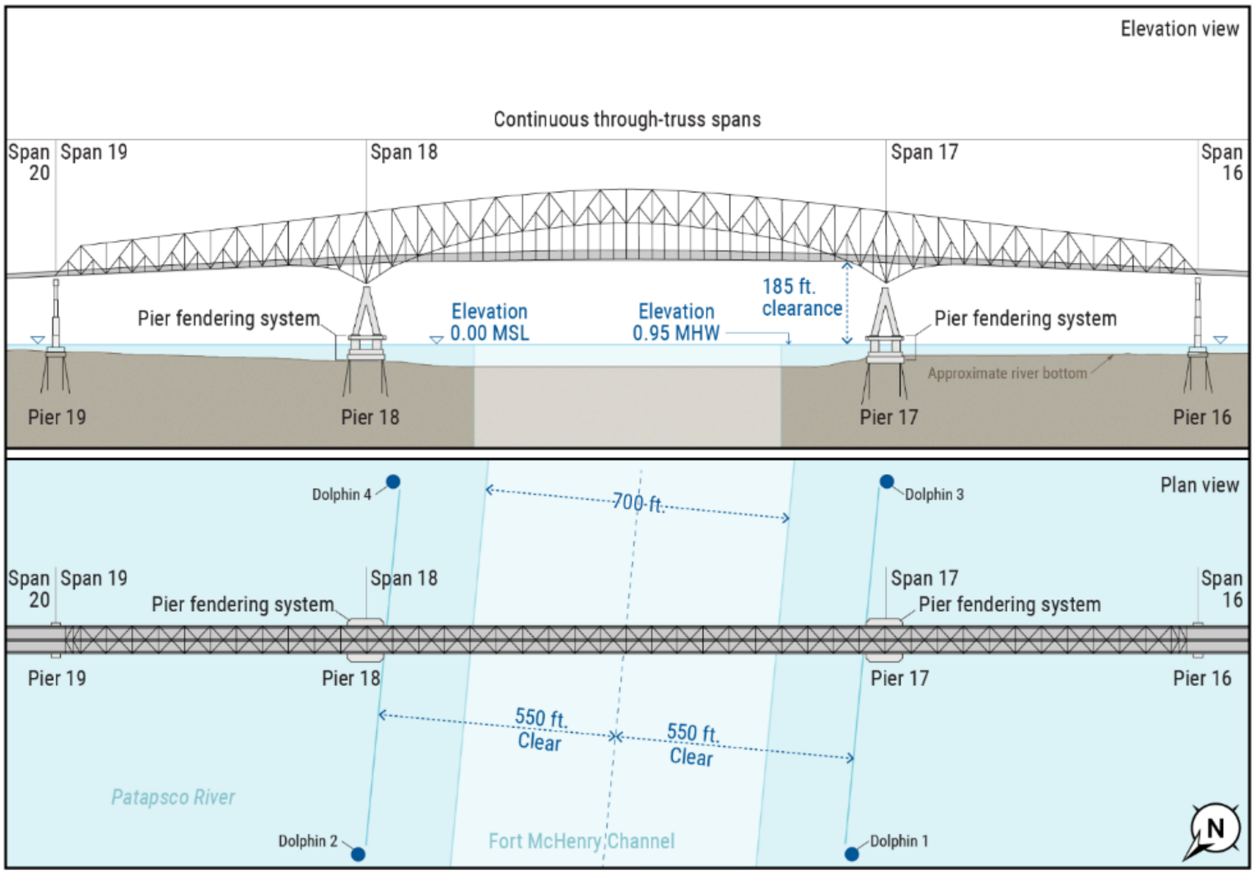

Figure 46. *From top*: Elevation view (from north looking south toward bridge) and plan view of the main spans of the Key Bridge over Fort McHenry Channel.

On March 26, low tide was predicted to be at 0224, and there was negligible current at the time of the accident. Winds were calm at less than 1 mph, and skies were overcast with 10-mile visibility. The recorded air temperature was about 44°F, and the water temperature was about 48°F. On the previous evening (March 25), sunset occurred at 1924, civil twilight ended at 1950, and moonrise occurred at 2057.

1.13 Electronic Data

1.13.1 Voyage Data Recorder Unit and Functionality

The *Dali* was equipped with a Japan Radio Co., Ltd (JRC)-brand JCY-1900 VDR. The VDR recording control unit was housed in the ship's bridge and contained an internal battery to power the VDR and bridge microphones during a loss of ship's power. This internal battery provided the VDR cabinet power to continue recording information from the bridge-mounted audio microphones. The VDR installed on the *Dali* did not provide, nor was it required to provide, a backup battery-operated power source to the unit that recorded parametric data.

The VDR's electrical power was normally supplied from the LV switchboard. If LV power was lost, the VDR was equipped with a changeover switch that would change the unit over to emergency switchboard power. However, the emergency diesel generator (EDG) had to start and automatically come online to power the emergency switchboard. For this reason, when the first underway blackout occurred on the *Dali* at 0125:00 on March 26, no parametric data were recorded, even if data were coming from data sources with their own redundant backup power. Parametric data that may have had a backup power source but were not recorded after the initial underway blackout included AIS data, rate of turn, speed, course, heading and GPS location. Parametric data that would not be recorded regardless of backup power included rudder position, certain alarms, and the bow thruster.

When power was restored to the LV bus 58 seconds later, the VDR resumed recording parametric data. When the LV bus lost power at 0127:04 (second underway blackout), the VDR continued to record both bridge audio and parametric data because the EDG had been started, and the emergency bus was powered by that time.[110]

The *Dali* had four primary means of internal communication that could carry two-way conversations; none were connected to the VDR's audio recording system. The four primary systems were:

- a dial (electric) telephone,

[110] The International Electrotechnical Commission (IEC) standard requires that, "the VDR shall be capable of operating from the ship's main and emergency source of electrical power." The IEC is an international standards organization that oversees the development and publication of standards for all electrical technologies and electronics.

- a sound-powered telephone,
- public address (talk back), and
- portable walkie-talkies.[111]

Electric and sound-powered telephones were located at fixed locations on the vessel, including the bridge and the engine room. The VDR only recorded the bridge side of electric and sound-powered telephone conversations that were within working range of a bridge microphone. Voices of personnel using the portion of the phone external to the bridge could not be detected. Walkie-talkies were the primary means of communicating with personnel while they moved about the ship. The bridge VDR recorded walkie-talkie communication within working range of a bridge microphone (see table 3).

Table 3. Audio channels recorded on *Dali*, the mixed bridge microphones, the audio quality, and the number of output WAV files for each 30-minute segment.

Channel Number	Microphones Contained	Audio Quality	Number of WAV Files Produced per 30-minute Segment
Channel 1	Helm station	Fair	30
	Port conning station	Fair	30
Channel 2	Starboard conning station	Fair	30
	Port chart table	Fair	30
Channel 3	Port wing console	Fair	30
	Starboard wing console	Fair	30
Channel 4	Starboard chart table	Good	30
Channel 5	VHF radio no. 1	Excellent	30
Channel 6	VHF radio no. 2	Excellent	30

[111] A *sound-powered telephone* is a shipboard telephone system in which the power comes from the sound pressure of the speaker's voice and requires no external power source.

1.13.2 Data Retrieval

NTSB engineers retrieved data during the on-scene investigation using the bridge-mounted USB console, which provided an interface for accessing VDR data. This yielded a 6-hour segment of data centered around the accident.

To access the full 30 days of recorded VDR data, a certified marine electronics technician, who was contracted through the vessel operator, attempted to download data directly from the VDR cabinet. Despite assistance from the VDR's manufacturer, JRC, the technician was unable to retrieve the data on board. As a result, the NTSB removed the VDR's memory components and transported them to the JRC Americas facility in League City, Texas. Using an exemplar VDR unit and proprietary JRC software that was not available on the *Dali*, JRC representatives and NTSB engineers completed a full Ethernet download of the cabinet data. Because the VDR recorded data in a proprietary format, investigators had to use the VDR manufacturer's playback software to review the data. However, the playback software was inadequate to perform the investigation, so investigators used the supplied software to, instead, export the data so that it could be used in other commercially available software and NTSB software. These extracted audio VDR data were converted using JRC's playback software, yielding monoaural audio mixed together from multiple bridge microphones.

1.14 Postaccident Testing

1.14.1 Troubleshooting

Between April 1 and April 29, 2024, NTSB and Coast Guard investigators, along with representatives from Grace Ocean (the vessel owner), Synergy (the vessel operator), HHI (the vessel builder), Singapore (the vessel flag state), and ClassNK (the vessel classification society), conducted postaccident mechanical and electrical examinations on board the vessel to determine the cause of the blackouts. HHI technical representatives were on scene as subject matter experts for the vessel's HV switchboard and its physical components. HHI also assisted with the equipment changeovers and troubleshooting.

On April 1, investigators, HHI technical representatives, and vessel crewmembers attempted to close the HV breaker, HR1, for step-down transformer TR1 and place the transformer online to reconfigure the electrical system to the same state as during the initial phases of the accident. HR1 was unable to close, and investigators were informed that an HHI circuit breaker specialist would need to be present to troubleshoot the reason HR1 did not close. HHI downloaded the historic alarm monitoring system data, main engine, and switchboard data from the day of the accident and shared it with investigators.

On April 10, investigators and the HHI circuit breaker specialist examined breakers HR1 and HR2, and associated components within the HV switchboard (see figure 47). HR1 functioned successfully several times during testing. However, when investigators attempted to changeover between LV step-down transformers TR2 and TR1, HR1 experienced a trip and alarm and failed to close. This trip had not occurred during the accident events. At the time, HHI determined that the trip was unrelated and could be attributed to an internal fault in the transformer, and was a "false alarm triggered by a high inrush to overcurrent created by the repeated changeover test procedures." Examinations were concluded without resolution or confirmation of what caused the initial underway LV blackout on March 26. HHI again downloaded electronic data and shared it with parties. Both of TR1's breakers, HR1 and LR1, were left in the closed position, energizing TR1 to see if the power outage would repeat.

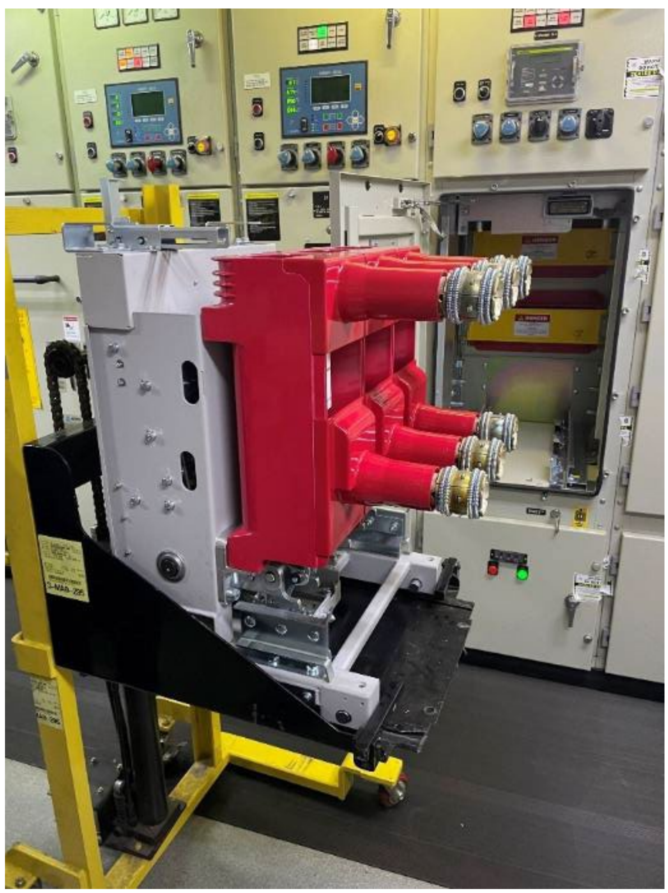

Figure 47. HR1 disconnected and removed from HV switchboard for inspection on April 10, 2024.

On April 12, without pre-alarm or warning, the vessel experienced another LV blackout, similar to the initial March 26 blackout, which was recorded by the ACONIS and other onboard monitoring systems. The ship's crew recovered LV power by connecting TR2, and TR2 remained in operation until April 22, when a third HHI envoy of engineers arrived to restart troubleshooting efforts alongside investigators.

On April 24, HHI electrical engineers, with investigators present, installed two power analyzers to monitor electrical conditions of LR1 (see figure 48).

Figure 48. Power analyzers installed on LV switchboard.

The engineers physically racked out and examined breakers HR1 and LR1 and downloaded additional HV switchboard data, which was shared with the parties (see figure 49).[112] TR1 was put back online, and the vessel crew started various equipment to test variable electrical loads, but the power analyzers detected no system abnormalities.

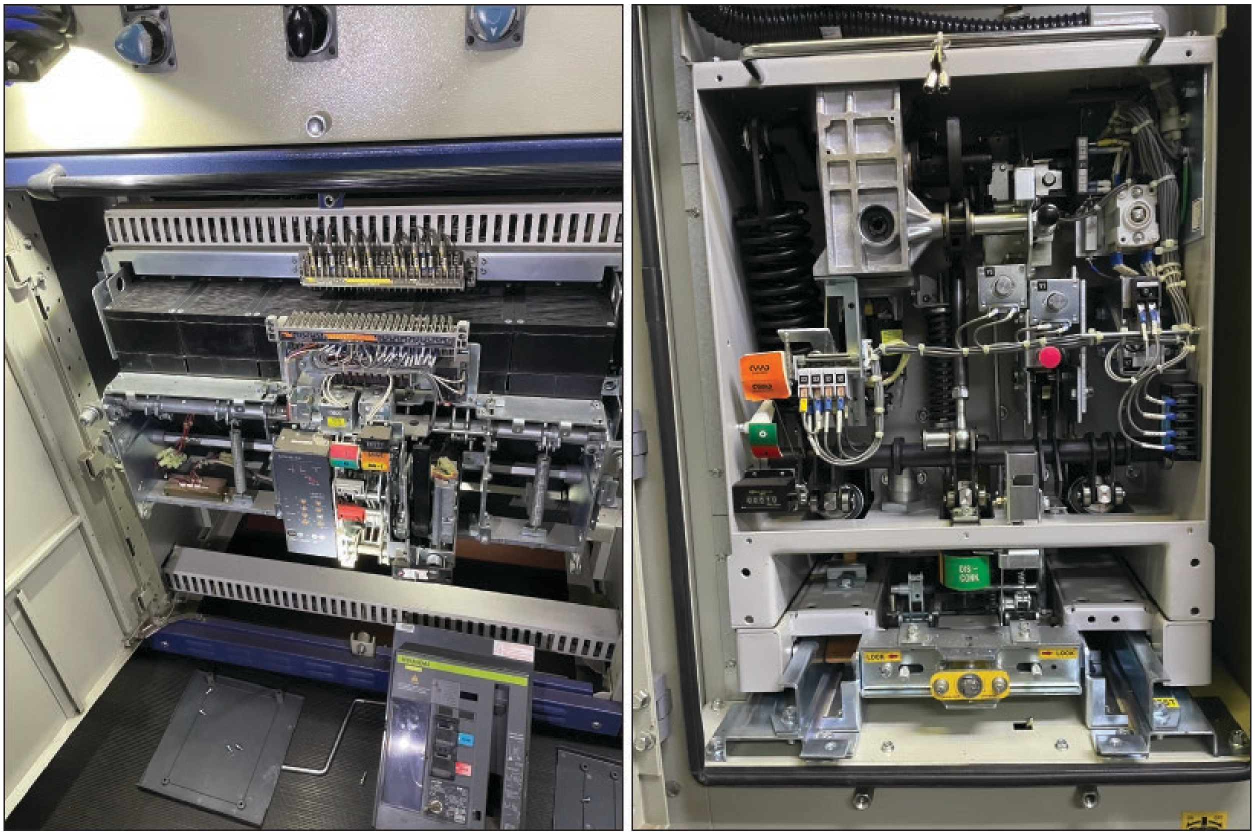

Figure 49. *Left to right*: The *Dali*'s LR1 breaker (face cover removed) during examination, and the *Dali*'s HR1 circuit breaker racked out in the test position during examination.

1.14.2 HR1 Control Circuit and Loose Signal Wire Discovery

Between April 24 and April 29, breakers HR1 and LR1 remained in the closed position, with all systems running. On April 29, about 0612, HR1 and LR1 tripped without warning or preceding alarms, causing a loss of LV power under similar circumstances to the March 26 and April 12 blackouts. When these breakers tripped, the LV step-down transformer breakers' control mode was set to transfer

[112] *Racking out* of a breaker is a procedure where a circuit breaker is mechanically removed from the bus to safely conduct maintenance or inspection.

automatically if HR1 opened, so the system automatically switched from TR1 to TR2 by closing HR2 and LR2.

HHI engineers racked out LR1 and conducted point-to-point individual wire checks and a visual inspection of the circuits; they found no issues on LR1.[113] The spectrum power analyzer captured data that suggested that the fault occurred upstream of TR1. With the satisfactory inspection of LR1 and the results found on the spectrum power analyzer, the team shifted troubleshooting efforts to HR1.

HHI engineers attempted to manually close HR1 but were unsuccessful. HR1 was racked out for visual and point-to-point wire checks, and the engineers discovered that the undervoltage release (UVR) device for HR1 was de-energized.[114] Under normal opening or protective tripping situations, the UVR would temporarily de-energize, causing HR1 to mechanically disconnect the path of electricity from the HV bus to the LV step-down transformer, TR1. The control circuit's path to energize the UVR passed through a series of auxiliary contacts, which were normally closed (see figure 50). For HR1 to remain connected to the main HV bus and powering the LV bus, these auxiliary contacts must remain closed.

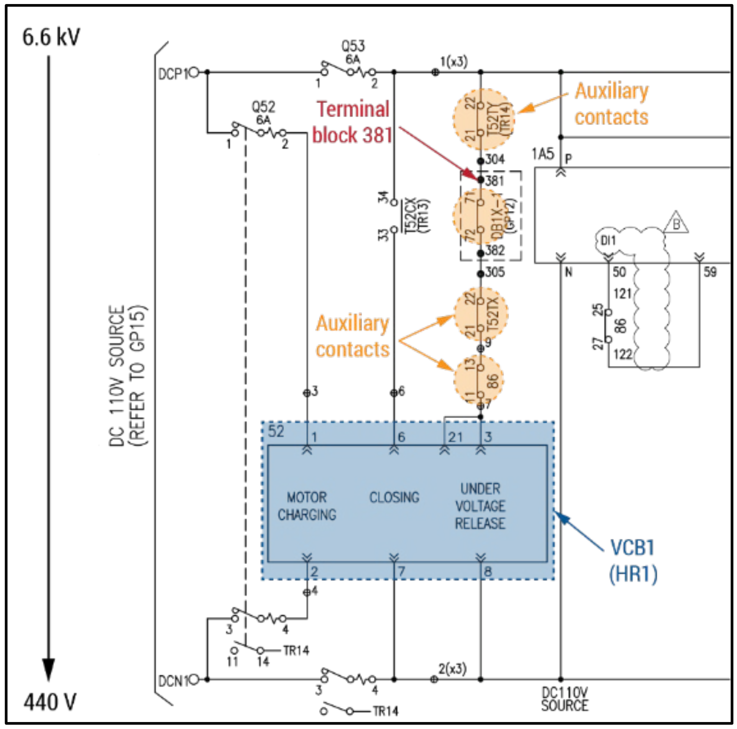

Figure 50. HR1 UVR control circuit, showing HR1 (blue), terminal Block 381 (red), and auxiliary contacts (orange). (Background source: HHI)

The engineers physically inspected the relay's auxiliary contacts in series with the UVR and found no issues. HHI engineers then conducted point-to-point signal wire checks and discovered an inadequate, or loose, connection in the circuit,

[113] A *point-to-point wire check*, also known as a *continuity check*, is a method of electrical testing that determines whether a circuit is open or complete.

[114] An *undervoltage release* is a device that opens a circuit breaker when voltage falls below a predetermined voltage threshold.

specifically on one of the wires installed in a WAGO 280-681 three-conductor terminal block (Terminal Block 381), which was in one of the HV switchboard control panels (see figure 51).[115] In this report, the wire on the right side of terminal block in figure 51 will be referred to as Wire 1, and the wire on the left will be referred to as Wire 3.Wire 1 was removed and re-installed back into the terminal block, and the UVR was then energized. With the UVR energized and Wire 1 now solidly in the terminal block, HR1 connected to the HV bus successfully and as designed. TR1 was energized, and LR1 was connected, energizing the LV bus and switchboard.

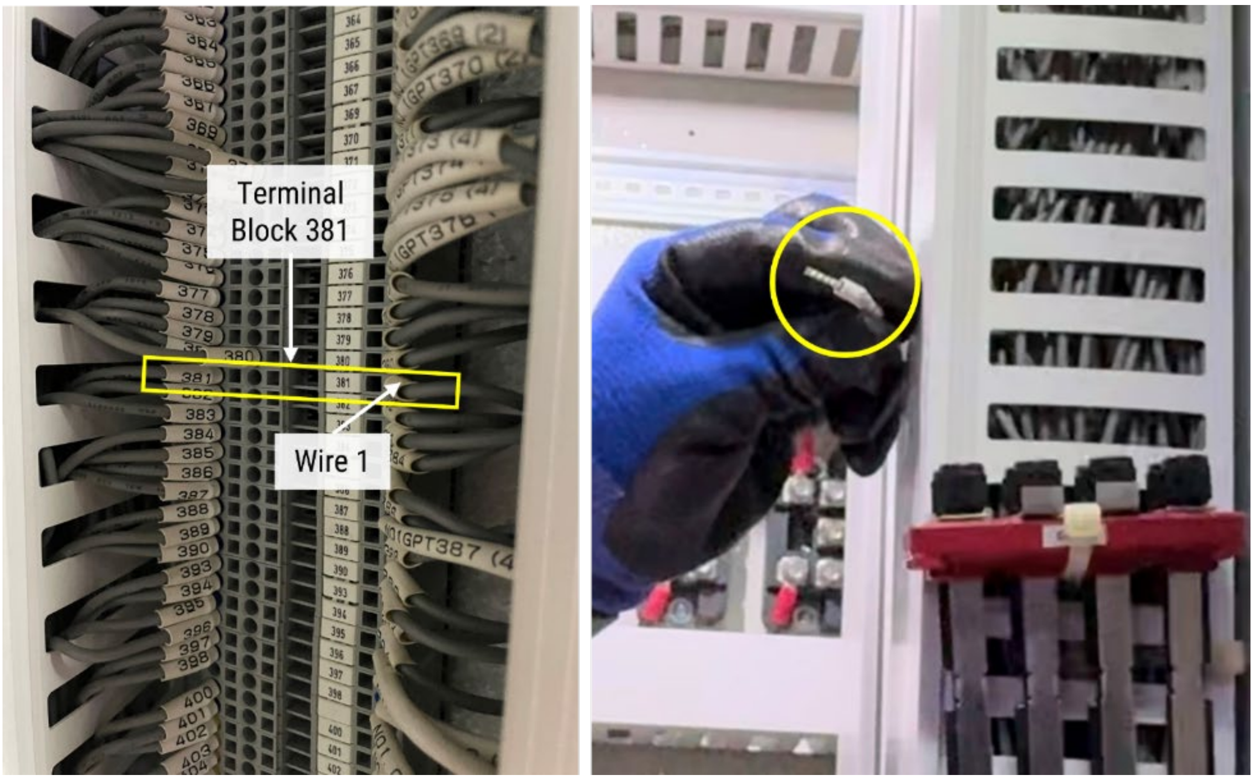

Figure 51. *Left to right*: Terminal Block 381 shown amongst a stack of other terminal blocks, and HHI field engineer displaying Wire 1 after discovering its loose and inadequate connection to Terminal Block 381.

Following this discovery, Synergy arranged for a third-party service engineer to inspect and test of the HV and LV circuit breakers and switchboards of three vessels, the *Dali*, the *Cezanne*, and the *Saltero*. The inspections included checking the condition of the control wiring and protective relays. The inspection found that all

[115] A *terminal block* is an insulated block that connects two or more wires together. Terminal blocks are readily available commercial components used in electrical connection panels in various applications, including on vessels such as the *Dali*. The *Dali* had thousands of terminal blocks throughout the vessel.

circuit breakers and switchboards were in good working order. No loose wires were found.

Investigators decided to recreate the LV blackout event, which had now occurred three times, including the day of the accident. With TR1 energized and HR2's control mode set to Automatic, Wire 1 was pulled from Terminal Block 381. The HR1 and LR1 breakers opened instantly after the wire was removed, causing an LV blackout. HR1 opened because the now-removed Wire 1 was part of an electrical circuit that delivered 110-volt direct-current voltage to HR1's UVR device, which must remain energized for HR1 to remain closed.[116] During this testing, Wire 1 was removed and reinserted several times to facilitate troubleshooting and testing of the circuit and to verify if this loose connection was causing the electrical blackouts.

Because the control mode for HR1 was set to Automatic, after about 10 seconds, HR2 and LR2 automatically connected, energizing the LV bus. After this test, investigators reviewed the HV switchboard protection relays (including HR1's protection relays) alarm event logs; no trip events were recorded during the test.[117] Following the examination and the recovery of evidence described in section 1.14.2.1, and as of the publication of this report, the vessel has not reported another HR1 trip.

[116] During normal operations, if an operator wanted to intentionally open HR1 for maintenance or other purposes, they would need to shift the operator breakers' control mode to Manual and rotate the breaker control switch to Open. This process would open an auxiliary contact that was inline of the electrical path to the UVR device, de-energizing the UVR device and opening HR1.

[117] A *protection relay* is an electrical device that monitors a power system for abnormal conditions, such as faults, and automatically sends a signal to trip a circuit breaker to isolate the faulty section of the circuit.

1.14.2.1 Evidence Recovery

On May 15, the NTSB, with the assistance of the ship's crew and Synergy, disconnected Terminal Block 381 and took it to the NTSB Materials Laboratory for examination, leaving wires that had been connected to Terminal Block 381 in the control circuit (see figure 52).

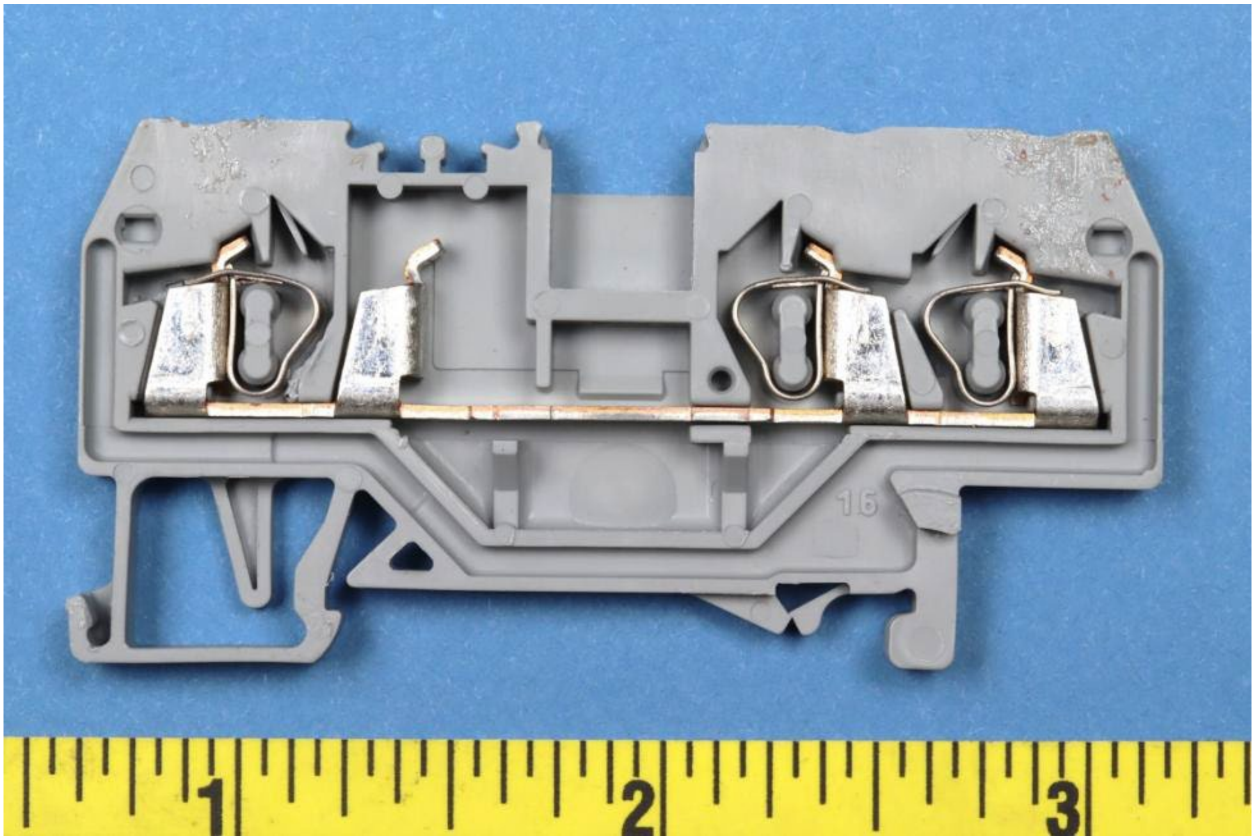

Figure 52. Terminal Block 381 after being disconnected and removed from the *Dali* (the wires have been removed).

On May 18, the NTSB, with the assistance of the ship's crew and Synergy, disconnected two lengths of control wiring from the control circuit installed in one of the HV switchboard control panels (see figure 53). Both wires were identified and had been labeled with wire-label banding as "381."[118]

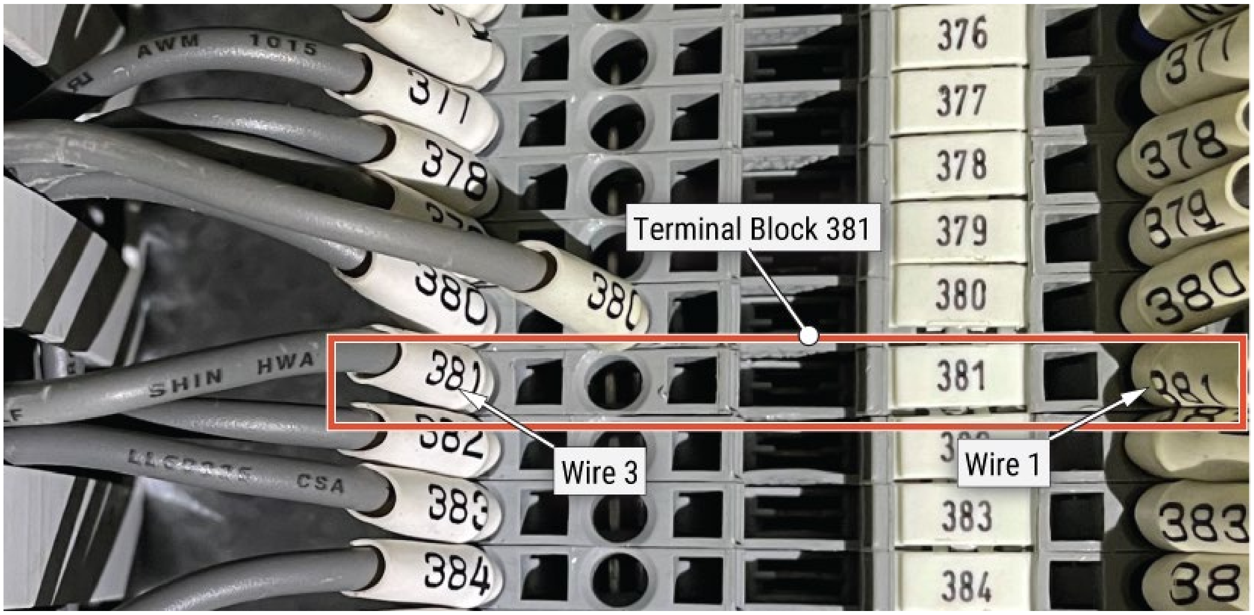

Figure 53. Signal wires Wire 1 and Wire 3 identified in Terminal Block 381.

[118] *Wire-label banding* is tubing made of thermoplastic material that is heat-shrunk around a wire and includes markings for identification.

The two signal wires were about 10 centimeters (4 inches) and 5 centimeters (2 inches) in length. The team then cut back the signal wires from the ferrule end.[119] Wire 3's wire-label banding covered most of the blue insulated collar of the wire ferrule, and Wire 1's wire-label banding covered the entirety of the ferrule collar (see figure 54). The two lengths of wire were taken to NTSB Materials Laboratory for examination.

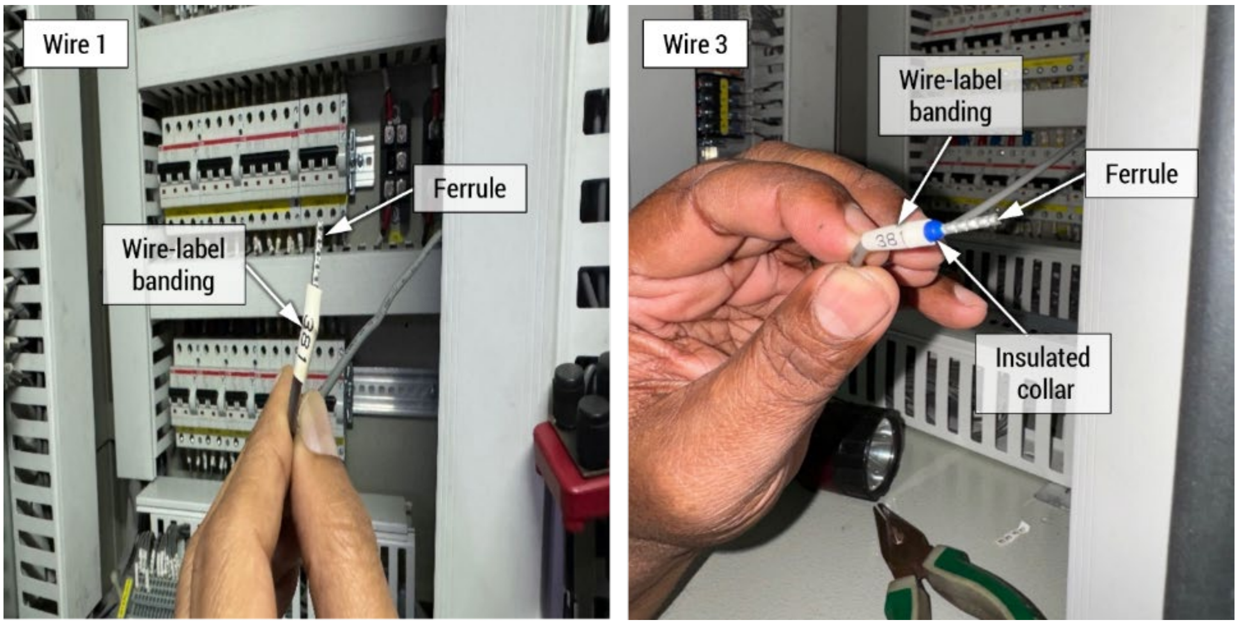

Figure 54. *Left to right*: Wire 1 disconnected from Terminal Block 381, and Wire 3 disconnected from Terminal Block 381. The blue insulated collar is partially shown on Wire 3.

[119] The *ferrule end* is a small metal tube slipped over stripped wire and permanently crimped into place.

On June 7, an NTSB investigator and the Synergy party coordinator boarded the Synergy-operated containership *Cezanne* at Port Newark Container Terminal in Newark, New Jersey, to compare the *Dali*'s operational parameters with those of a similar vessel with different crewmembers. In order to compare signal wiring used aboard the *Dali* to that of the *Cezanne* and to have a controlled exemplar wire to be used in testing, the NTSB, with the assistance of the ship's crew, collected a piece of control power wiring, 10 centimeters (about 4 inches) long, from one of the HV switchboard control panels on the *Cezanne* (see figure 55). The wire was taken from an indicator light; it was the same style and ferrule crimp as that of the wires removed from the *Dali* on May 18, and removing it did not interfere with vessel operations.

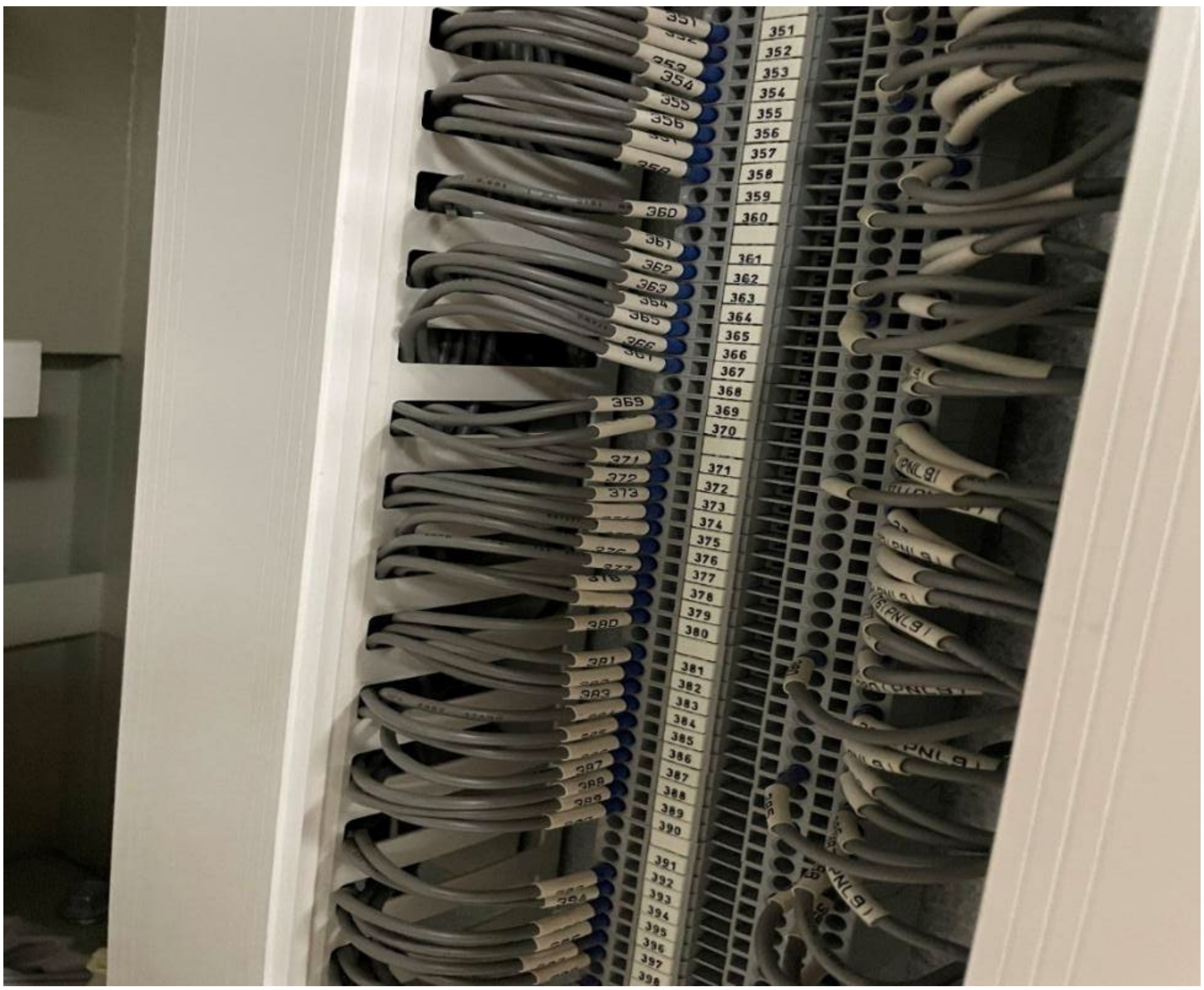

Figure 55. The *Cezanne*'s HV control panel, with terminal blocks with signal wires attached.

1.14.2.2 Materials Laboratory Testing

NTSB engineers used x-ray radiography to nondestructively view the inside of the *Dali*'s Terminal Block 381's cages (see figure 56).[120] We observed no wire debris or other obstructions within either cage.

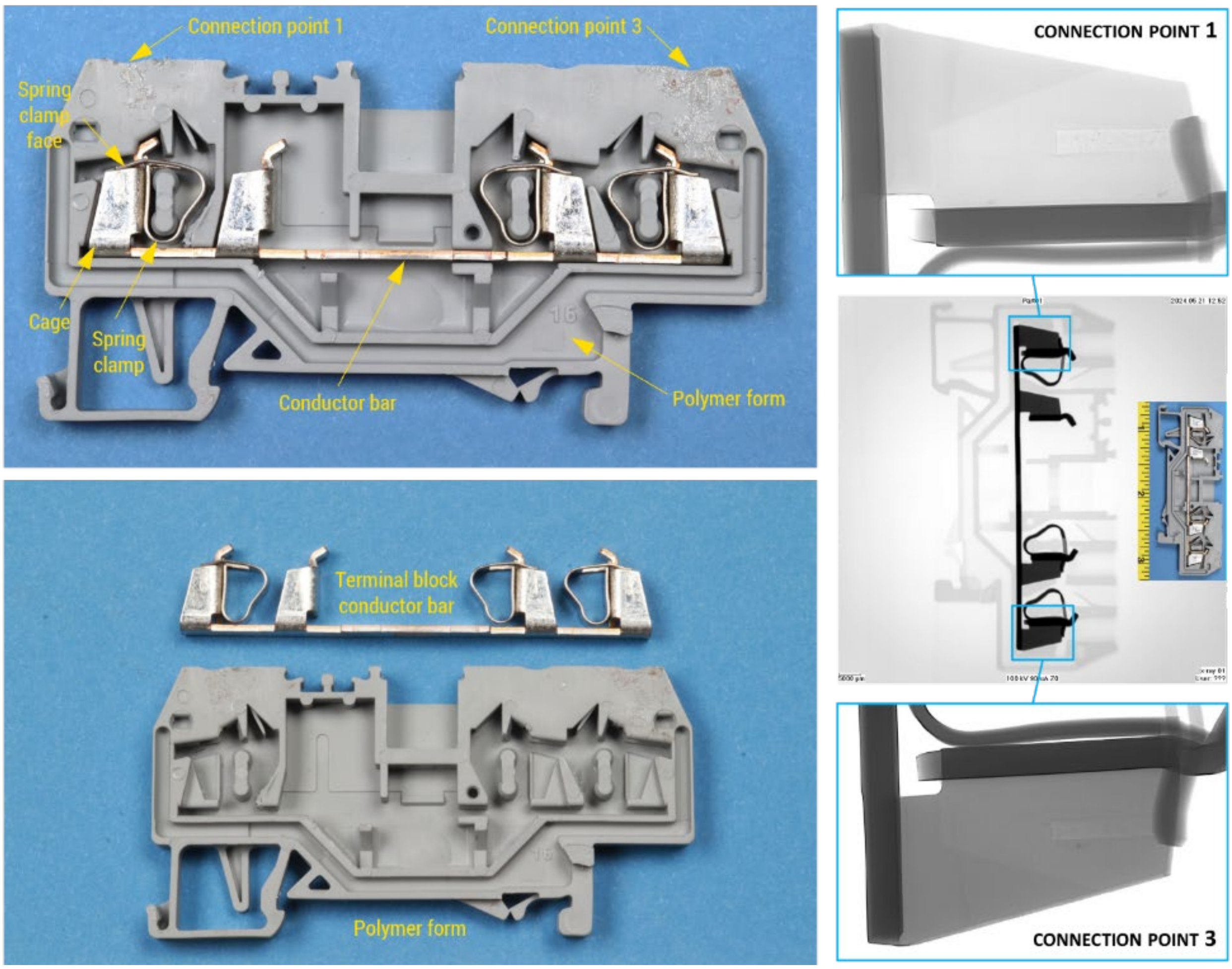

Figure 56. *From top*: An exemplar terminal block, assembled and disassembled. *Right*: X-ray of Terminal Block 381 and its connection points. (Inset shows actual terminal block.

[120] A *cage*, which is a component of the connection points in the terminal block, is connected to the conductor bar at the bottom. The cage has two walls and is comprised of a front that holds the wire ferrule within the cage and a side against which the spring clamp presses the ferrule. The spring clamp has an opening on the top face through which the ferrule is inserted. A cage tab extending upwards from the cage side guides the ferrule into place when it is installed through the spring-clamp opening.

NTSB engineers then disassembled the conductor bar to examine the polymer form.[121] Examination revealed several superficial scrape marks and scratches, consistent with those created by inserting a tool into the operating ports during spring-clamp actuation.[122] Additionally, a distinct gouge—consistent with normal contact from the spring-clamp gate during actuation of the spring clamp—was visible in the gate channel of Connection Point 1.[123] Both of these types of marks were consistent with wire installation. Terminal Block 381 showed no other signs of damage or evidence that it would not function as designed.

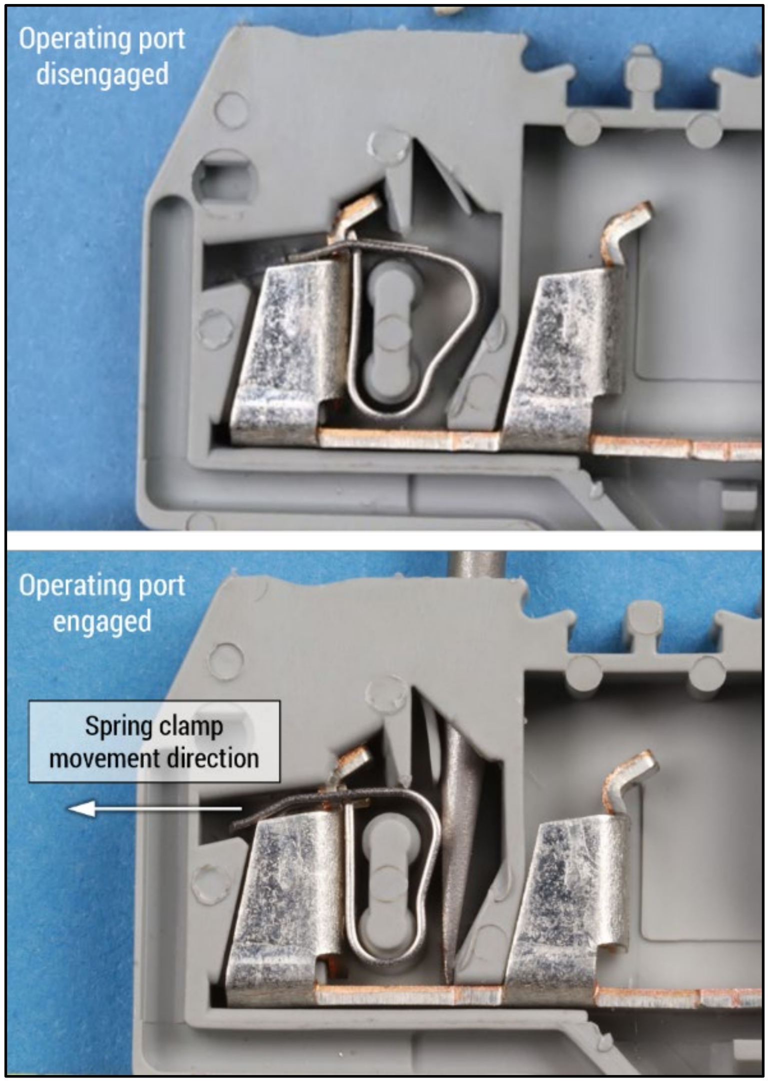

Figure 57. *From top*: The operating port of an exemplar terminal block with nothing inserted (disengaged), and the operating port of an exemplar terminal block when a tool is inserted, resulting in spring-clamp movement.

The NTSB obtained several new, unused terminal blocks identical to those used on the *Dali* (WAGO model 280-681) to serve as exemplars. Actuation of the spring clamps on the exemplar terminal blocks resulted in similar damage to the polymer forms we observed on Terminal Block 381 (see figure 57). A single actuation of the spring clamp and the subsequent contact created distinct gouges in the gate channel of the connection points. After

[121] A terminal block polymer form acts as an insulator to the metal conductor bars that the wires connect into.

[122] Spring clamps can be opened using a specialized operation tool designed for opening spring clamps or with a common screwdriver.

[123] Each connection point consists of a spring clamp assembled to a cage.

using tools to actuate the spring clamps, we also noted resultant scratches, and ridges from scratching, in the operating ports.

We also found multiple linear gouges on the Wire 1 ferrule during lab testing (see figure 58). The gouge mark at the end of the ferrule would have originated from the wire's insertion into the terminal block when the vessel was first built. Examination of Wire 3 found a similar single gouge on its ferrule, further up the ferrule, indicating it was able to be inserted further into the spring clamp gate of the terminal block. The other four linear gouge marks on Wire 1 were consistent with the onboard testing performed after the accident.

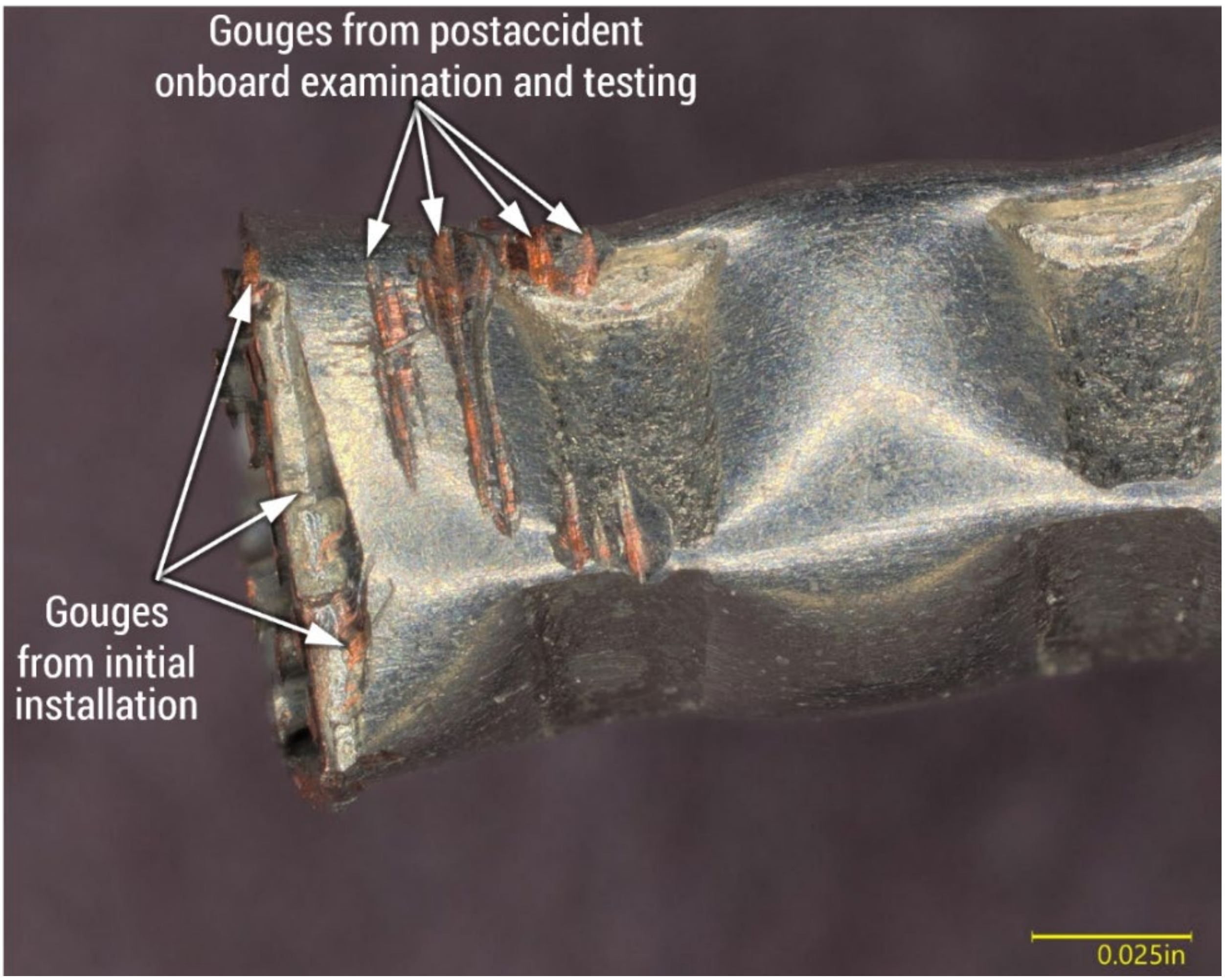

Figure 58. Digital microscope images of one side of the Wire 1 ferrule from Terminal Block 381 with multiple distinct linear gouges (white arrows).

In addition to the linear gouges and depressions in Wire 1, we observed that Wire 1's white wire-label banding had been installed in a way that covered all of the ferrule's blue-colored insulated collar (see figure 59). The application of wire-label banding increased the circumference of the wire.

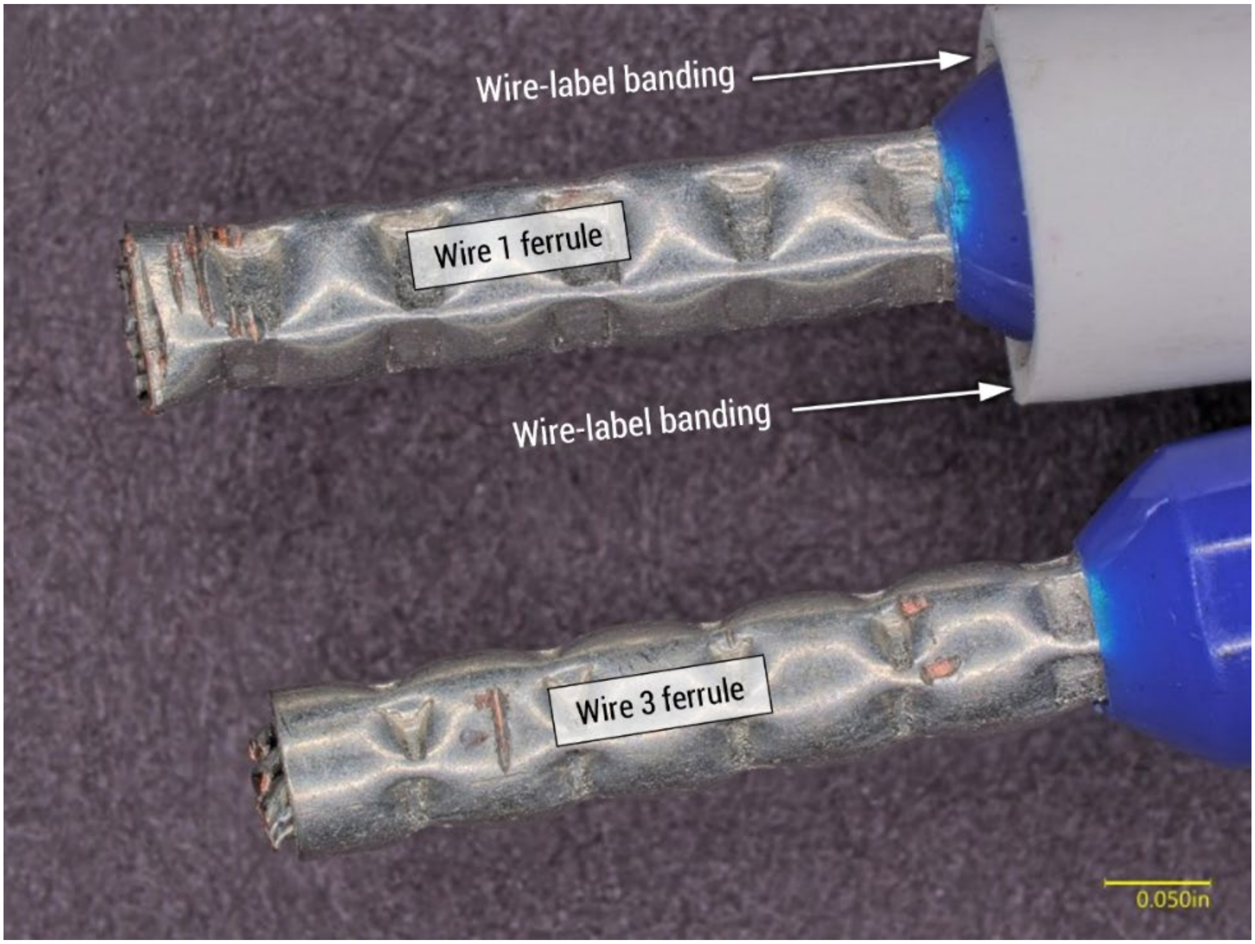

Figure 59. Close up of the Wire 1 and Wire 3 ferrules, with wire-label banding on Wire 1. Wire 3 does not have wire-label banding because the banding was removed and reused on another terminal block wire when Wire 3 was removed from the vessel.

NTSB engineers inserted Wire 3 and Wire 1 into an exemplar terminal block to the maximum depth possible into the cage areas of the connection points. The ferrule on Wire 3 could touch the bottom of the cage area, while the ferrule on Wire 1 could not be inserted as far due to the still-assembled wire-label banding restricting movement into the connection point (see figure 60).

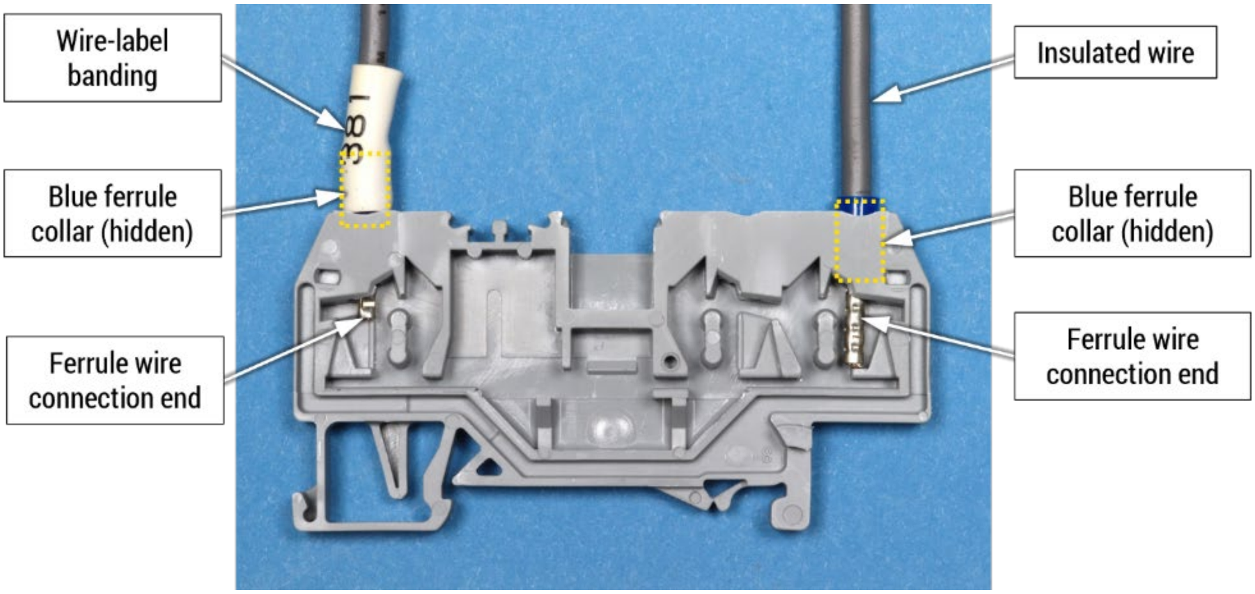

Figure 60. Wires 1 and 3 from Terminal Block 381, inserted inside the corresponding connection points, in a disassembled polymer form from an exemplar terminal block. Both wires were inserted to the maximum depth possible, without force, into the cage areas of the connection points.

NTSB engineers found a depression on the very end of Wire 1's ferrule, which indicated inward pinching that distorted the ferrule end's shape and compressed adjacent wire strands. Inward-moving scrape marks towards the center of the wire were also observed during the examination. Engineers also found material had collected at the end of the ferrule (see figure 61).

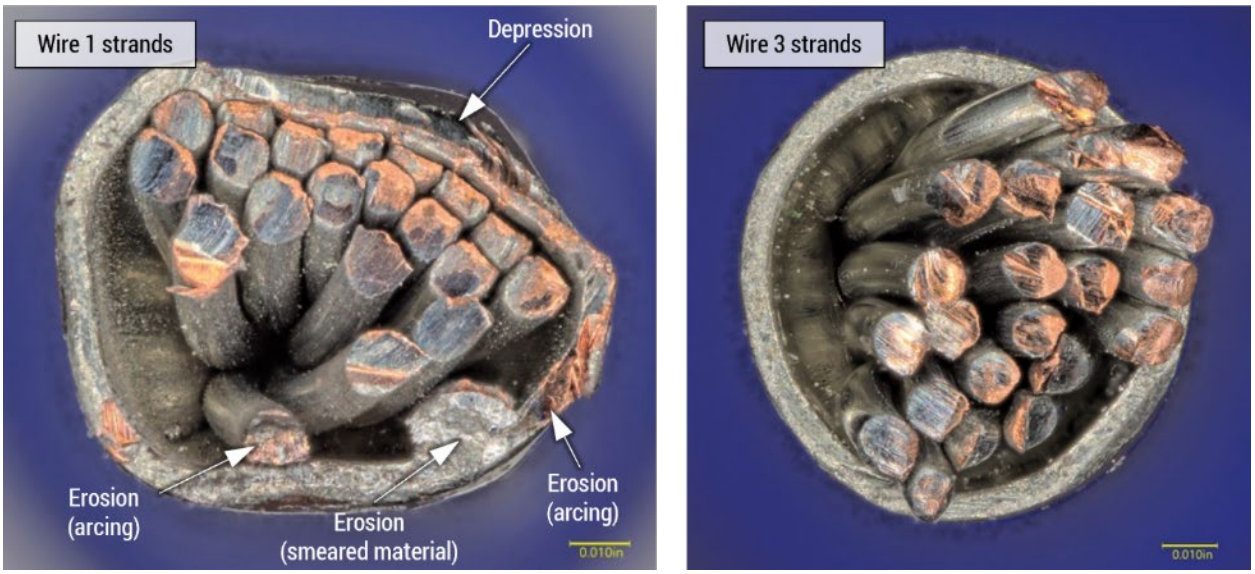

Figure 61. *Left to right*: Digital microscope images of end views comparing the ferrules from Wires 1 and 3 from Terminal Block 381, showing depression in one corner of the Wire 1 ferrule, as well as erosion consistent with arcing and smeared material.

Arcing damage was present on both the Terminal Block 381 spring-clamp gate face of the Connection Point 1 cage and the end of the Wire 1 ferrule, indicating an intermittent electrical connection (see figure 62).[124]

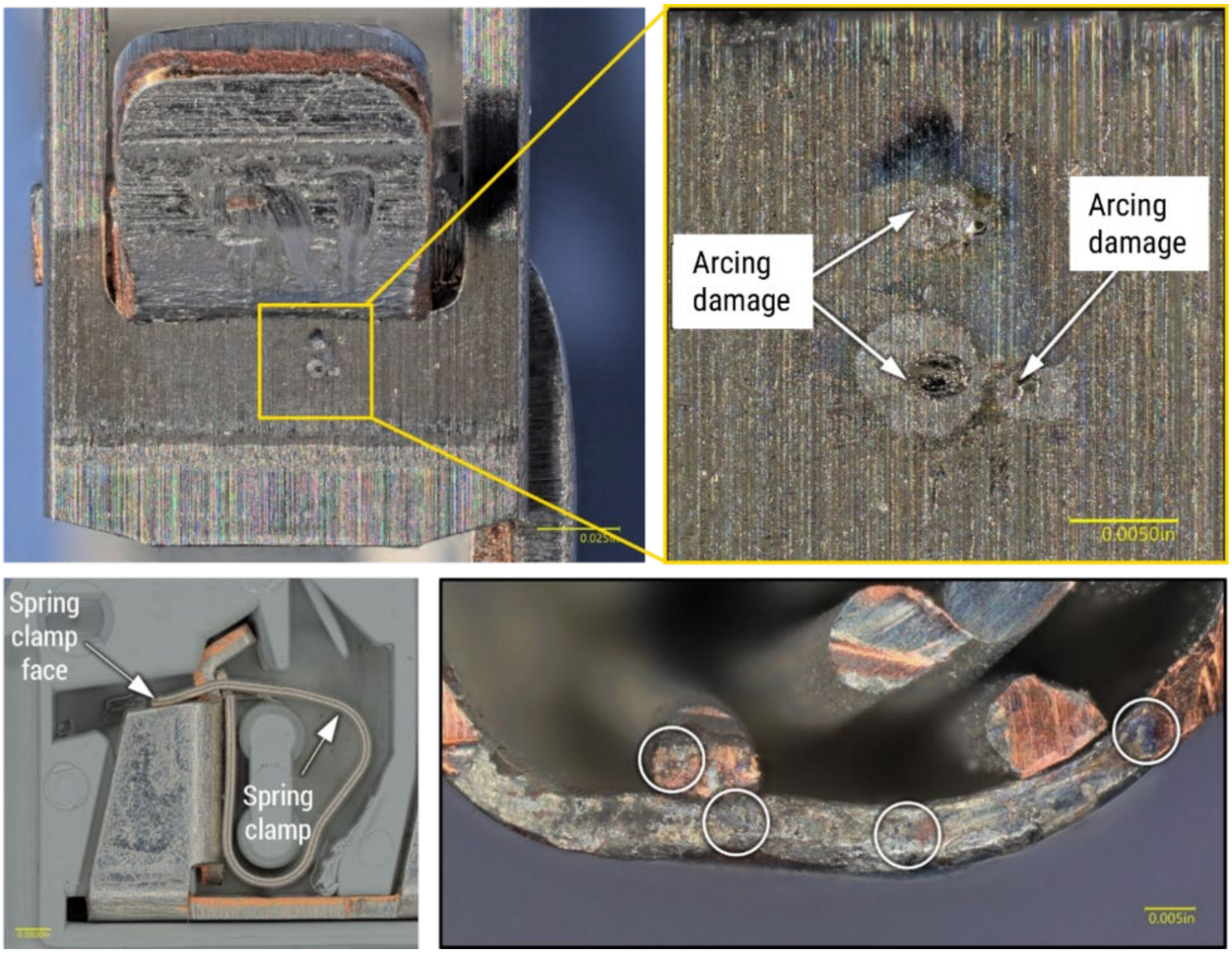

Figure 62. *Clockwise from top left*: Electrical arcing damage on the spring-clamp gate face from Connection Point 1 in Terminal Block 381, and erosion (circled) consistent with arcing on the ferrule edge and one adjacent strand face of the Wire 1 ferrule. Spring clamp shown in exemplar terminal block for reference.

1.14.3 Fuel Testing

The last time the *Dali* crew switched fuel was on the evening of March 21 (5 days before the accident), when they switched to burning MGO in all engines upon

[124] *Arcing* occurs when electricity is discharged ("arcs") across a gap in a circuit (the case of Wire 1 and the face of the closed spring clamp) or between electrodes.

entering US territorial waters (12 miles off the Atlantic coast), as required by emission regulatory requirements.

On March 28, the representatives of the vessel owner, Grace Ocean, took samples of the MGO that was being burned at the time of the accident. At NTSB direction, the owner transferred the samples to an independent laboratory. The test results did not identify any concerns related to the quality of the fuel.

On April 11, additional fuel samples were taken from all fuel tanks and various fuel supply manifolds on board the vessel; samples were tested by an independent laboratory. The *Dali* had taken on various amounts of all three types of fuel (VLSFO, MGO, and HFO) in Newark, New Jersey, on March 19. Fuel-sample analysis results indicated that the MGO fuel bunkered in Newark, which was the same type of fuel in use during the accident events, complied with international standards and regulations. The test results did not identify any concerns related to the quality of the fuel.

1.15 Coast Guard Marine Casualty Data

Investigators requested, and the Coast Guard provided the NTSB with, reportable marine casualty data for 2002 through 2023.[125] The data set was obtained from the Coast Guard's Marine Information for Safety and Law Enforcement database and included records from 94,218 completed casualty investigations. Of these, 2,405 (2.6%) included the loss of power as the initiating event. An additional 11,196 (11.9%) corresponded with a loss or reduction of vessel propulsion or steering as the initiating event.

There were 3,838 casualties involving both bridges and allisions (4.1% of the reported 94,218 records).[126] Of these, the NTSB identified 328 bridge strikes involving large ocean-going vessels.[127] NTSB investigators reviewed the Coast Guard reports for the 328 bridge strikes involving large ocean-going vessels, and identified

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[125] Regulations for reportable marine casualties are detailed in 46 *CFR* Subchapter A. Coast Guard investigators document each marine casualty event as a sequence of individual events, with corresponding locations, involved vessels and personnel, and other details.

[126] The Coast Guard refers to accidents where vessels strike a stationary object(s) as "allisions," whereas the NTSB refers to such accidents as "contacts."

[127] For the purpose of this analysis, large ocean-going vessels included bulk carriers, general dry cargo ships, passenger ships, refrigerated cargo ships, roll-on/roll-off cargo ships, tank ships, and warships.

a total of 15 (4.6%) over 22 years that cited loss of power or propulsion as an issue in the bridge strike. Another three (0.9%) bridge strikes were attributed to steering problems (see figure 63 and table 4). In 79 of the 328 cases (24.1%), there were no causal issues mentioned in the report, or the report stated the causal issue was unknown. The remaining 231 cases cited issues other than power/propulsion loss or steering problems.

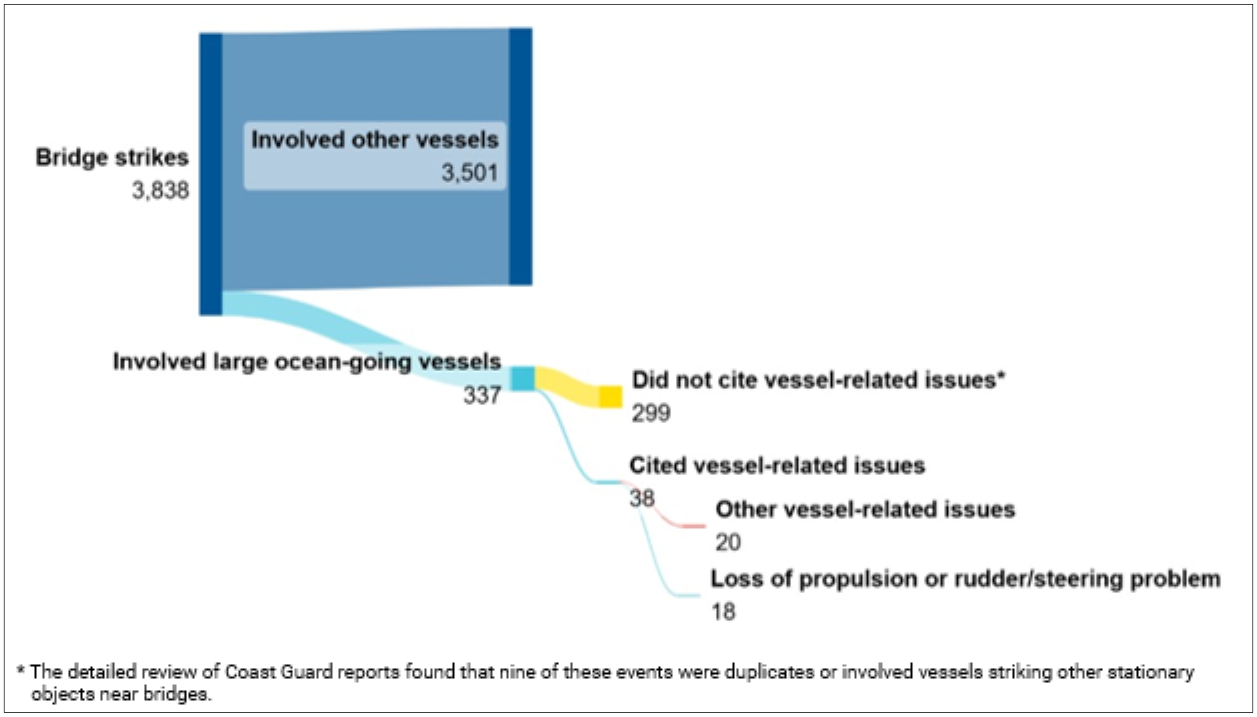

Figure 63. A depiction of the relative proportions of bridge strikes involving large ocean-going vessels and the proportion of those that involved loss of propulsion, rudder/steering problems, or other vessel-related issues.

Table 4. Operation-, environment-, vessel-, and bridge-related issues cited in the reports of large-class vessel bridge contacts between 2002 and 2023.

Type of issues cited	Number of bridge allision (contact) reports citing[a]	Percentage of bridge allision (contact) reports citing
Operations-related issues		
Clearance-related	77	23.5%
Maneuvering-related	69	21.0%
Towing maneuver-related	18	5.5%
Miscommunication	12	3.7%
Attempting to avoid collision with other vessel	7	2.1%
Bridge operation-related	5	1.5%
Distraction	3	0.9%
Inexperience	2	0.6%
Other operation-related	4	1.2%
Environment-related issues		
Current	23	7.0%
Wind	20	6.1%
High water	6	1.8%
Other environment-related	2	0.6%
Vessel-related issues		
Loss of propulsion/power	15	4.6%
Incorrect vessel documentation	10	3.0%
Vessel adrift/unmoored	9	2.7%
Rudder/steering problem	3	0.9%
Other vessel-related	1	0.3%
Bridge-related issues		
Materials hanging below bridge	6	1.8%
Incorrect bridge documentation	4	1.2%
Bridge mechanical failure	1	0.3%
Other bridge-related	1	0.3%
Other issues		
Unknown or not available	79	24.1%

a. Some cases cited multiple issues across different categories.

1.16 Vulnerability of Bridges over Navigable Waterways to Strikes from Large Ocean-going Vessels

1.16.1 Background

As a result of the NTSB's investigation into the vessel strike and collapse of the Sunshine Skyway Bridge in Tampa Bay, Florida (NTSB 1981) we issued multiple recommendations to address identified safety concerns. Among those recommendations, we asked the Federal Highway Administration (FHWA), in cooperation with the Coast Guard, to—

> develop standards for the design, performance, and location of structural bridge pier protection systems which consider that the impact from an off-course vessel can occur significantly above as well as below the water surface (Safety Recommendation M-81-20).[128]

As part of their response to this recommendation, the FHWA indicated that a study to perform laboratory tests of bridge protection models had been initiated and was nearly complete. In 1988, a pooled-fund research project sponsored by 11 states and the FHWA led to the development of a proposed design code for bridge engineers to use in evaluating structures for vessel collision. This effort resulted in the American Association of State Highway and Transportation Officials' (AASHTO) adoption of its first edition of the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* in 1991 (AASHTO 1991). The second edition, titled *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, was released in 2009 (AASHTO 2009). AASHTO's 1991 *Guide Specification* introduced the vulnerability assessment calculation, which is used to estimate the annual frequency of bridge collapse (AF) based on the bridge pier/span geometry,

[128] (a) The NTSB classified Safety Recommendation M-81-20 Closed—Acceptable Action in December 1984. (b) The NTSB made Safety Recommendation M-81-15 to the US Coast Guard, asking, "In cooperation with the Federal Highway Administration, develop standards for the design, performance, and location of structural bridge pier protection systems which consider that the impact from an off-course vessel can occur significantly above as well as below the water surface." The NTSB classified Safety Recommendation M-81-15 Closed—Acceptable Action in September 1987. (c) In response to M-81-20, the FHWA also shared an existing research study, "The State of the Art: Bridge Protective Systems and Devices." Final Report 1979. Report no. CG-N-1-80. Prepared for US Department of Transportation, sponsoring agency US Coast Guard Office of Navigation, performing organization University of Maryland Department of Civil Engineering. Washington, DC.

ultimate resistance of the pier (or span), waterway characteristics, and the characteristics of the vessel fleet transiting the channel (AASHTO 2009).[129]

The FHWA requires that new bridges on the National Highway System be designed to minimize the risk of a catastrophic bridge collapse from a vessel collision given the size, speed, and other characteristics of the vessels navigating the channel under the bridge; the requirements were adapted from AASHTO's 2009 *Guide Specifications* using a vulnerability assessment calculation. AASHTO's 1991 *Guide Specification* introduced the vulnerability assessment calculation, and AASHTO reiterated the value of performing this calculation in its 2009 *Guide Specifications*.[130] AASHTO also recommended that bridge owners use the vulnerability assessment calculations to evaluate bridges built before 1991 to identify bridges at risk of a catastrophic collapse in the event of a vessel collision and to "be aware of high-risk safety needs requiring immediate or short-term action, as well as information to prioritize and budget for the long-term needs for bridge rehabilitation or replacement."

Neither the FHWA nor AASHTO can require a bridge owner to complete a vulnerability assessment for a bridge designed before the release of the 1991 guidelines. The MDTA had not performed, nor was it required to perform, a vulnerability assessment to evaluate the Key Bridge's risk of a catastrophic collapse from a vessel collision. However, AASHTO recommended that states, like Maryland, perform such vulnerability assessments to evaluate and address risk.

1.16.2 AASHTO *Guide Specifications*

The 2009 AASHTO *Guide Specifications* provide three methods for conducting bridge vulnerability assessments. Unless a bridge over a navigable waterway with commercial vessel traffic was "designed in accordance with the previous 1991 edition of the AASHTO Guide Specification," the bridge "should be evaluated using a vulnerability assessment in accordance with the Method II risk analysis procedures contained in the current guide specifications."

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[129] *Annual frequency* is the probability of a bridge collapse due to vessel collision [contact] in a year's time.

[130] When discussing bridge design, the term *collision* refers to a vessel hitting a bridge or bridge structures. This use differs from the maritime definition of *collision*, which involves two moving vessels striking one another. Throughout this section, which focuses on bridge design, *collision* is used to refer to a vessel hitting a bridge or bridge structures.

The AASHTO Method II vulnerability assessment calculation is used to determine the AF, which is the probability of a bridge collapse due to vessel collision in a year's time. The total AF is based on the sum of the AFs for each pier that is vulnerable to a vessel collision from both inbound and outbound traffic. This vulnerability assessment calculation allows bridge owners to calculate their bridge's level of risk and determine whether that risk is below the acceptable threshold established by AASHTO. A bridge design with a risk level below the acceptable threshold would minimize the risk of a collapse but does not guarantee that a collapse from a vessel collision will not occur. Likewise, a risk level above the acceptable threshold does not mean a collapse from a vessel collision is a certainty. The Method II vulnerability assessment calculation, shown in Appendix A, uses data specific to each bridge and waterway, including:

- characteristics of the vessel traffic passing under the bridge,
- vessel transit speeds,
- vessel loading characteristics,
- waterway and navigable channel geometry (including intersecting channels),
- water depths,
- environmental conditions,
- bridge geometry,
- pier protection systems, and
- ultimate lateral capacity of the bridge piers

The 2009 AASHTO *Guide Specifications* further define how these data are used to calculate each factor in the vulnerability assessment calculation related to:

- the vessel frequency distribution transiting under the bridge,
- the probability that a vessel will go off course,
- the probability that a vessel will hit a bridge pier if it is off course,
- the probability of a bridge collapse once a collision has occurred, and
- the protection factor due to the presence of structures, such as dolphins or islands, that may protect a pier from collision

The AASHTO *Guide Specifications* classify bridges over navigable waterways as either critical/essential or typical. Bridges that "serve as important links" in the Strategic Highway Network are classified as critical/essential; the Key Bridge had this classification. Bridges not deemed critical/essential are classified as typical. The 2009 AASHTO *Guide Specifications* provide acceptable threshold values for a bridge's vulnerability assessment calculation. For bridges classified as critical/essential, the threshold is computed as an AF value of 0.0001. For bridges classified as typical, the threshold is computed as an AF value of 0.001.

1.16.3 Key Bridge Vulnerability

1.16.3.1 Port of Baltimore Harbor Safety and Coordination Committee Proceedings

Before the accident, several members of the Port of Baltimore Harbor Safety and Coordination Committee (HSCC) raised concerns about the Key Bridge's vulnerability. Formed in the 1980s, this guidance committee, which has no regulatory or enforcement authority, "offers a forum to address matters related to the efficiency and safety of the Marine Transportation System associated with the [Port of Baltimore] and its approaches." Members of the committee, which meets quarterly, included representatives from the Association of Maryland Pilots, the Baltimore Marine Exchange, the Maryland Department of Transportation, the Maryland Port Administration, the Corps of Engineers, the Coast Guard, and other area stakeholders.[131]

According to meeting minutes, a March 2006 discussion about a vessel striking the Severn River Bridge in Annapolis, Maryland, included the broader topic of bridge protection and increasing vessel sizes. During this meeting, a representative from the Maryland Department of Transportation mentioned AASHTO's 1991 *Guide Specification*, stating that since all bridges in the area were built before 1991, the bridges were not subject to the guidelines. Following statements by representatives from the Association of Maryland Pilots about the importance of bridge protection, the MDTA representative stated that the Key Bridge was not designed to withstand contact by a large vessel. Over the coming years, the issue of pier protection was discussed at several HSCC meetings, and action items related to the topic have been listed in meeting minutes since the March 2006 meeting.

1.16.3.2 NTSB Francis Scott Key Bridge Vulnerability Assessment

As noted previously, AASHTO recommended that states, like Maryland, perform vulnerability assessments to evaluate and address risk even if their bridges predated the guidelines. Following the *Dali* collision, the NTSB conducted a vulnerability assessment of the bridge using the AASHTO Method II calculation to understand its level of risk at the time of its collapse. The calculated AF considered

[131] Representatives of federal agencies act in advisory capacity and are non-voting members of the committee.

the factors listed above to assess whether this value was below AASHTO's acceptable threshold value for a critical/essential bridge's probability of collapse. We calculated and summed the AFs for both inbound and outbound vessel traffic for Piers 16, 17, 18, and 19, which are shown in table 5. These piers provided support to the portion of the bridge over the Fort McHenry Channel. A comparison of the AFs of the piers in table E-1 shows that a vessel collision with Pier 17 or Pier 18 was the largest contributor to the Key Bridge's overall AF.

Table 5. AF summary for the Key Bridge.

Pier	Inbound AF	Outbound AF	Total AF
16	0.000024	0.000024	0.000048
17	0.000687	0.000743	0.001430
18	0.000693	0.000749	0.001442
19	0.000001	0.000000	0.000001
Total	0.001405	0.001516	0.002921

Since the Key Bridge's opening in 1977, engineering and shipping advances—such as the 2016 Panama Canal expansion—have led to far larger vessels visiting, and increased vessel traffic volume to and from, the Port of Baltimore. Therefore, incorporating current vessel traffic parameters (and other environmental/waterway factors) into the AASHTO Method II vulnerability assessment calculation to evaluate the Key Bridge's specifications, the NTSB determined that if the MDTA had calculated the AF for the Key Bridge before the collapse, it would have identified that the bridge's risk level was almost 30 times greater than the AASHTO risk threshold for critical/essential bridges (0.0001).

The 2009 AASHTO *Guide Specifications* are a resource for state Departments of Transportation (DOTs) and other bridge owners to better understand the overall safety of bridges within their inventory to "minimize their susceptibility to damage from vessel collisions." For the Key Bridge, factors that contributed to this risk in the calculated vulnerability assessment included the piers adjacent to the main navigation channel and the channel size, which provided off-course vessels with little time for path correction before colliding with the bridge. Further, the locations and size of the dolphins did not fully protect Pier 17 and Pier 18 from a collision from an off-course vessel, and the speed and size (dimensions and weight) of modern vessels such as the *Dali* highlighted that the bridge piers were not strong enough to withstand a collision from a large ocean-going vessel.

Although some factors are challenging to modify for existing bridges, the process of calculating vulnerability assessments enables owners to make informed decisions to manage their assets, identify their bridges that may be susceptible to damage from a vessel collision, and appraise and prioritize vessel collision protection projects alongside other projects addressing highway asset needs and risks. When a bridge owner performs vulnerability assessments of structures in its inventory in accordance with the Method II calculation outlined by the 2009 AASHTO *Guide Specifications*, it is better equipped to understand the overall vulnerability of the bridges within its inventory.

1.16.4 NTSB Recommendations on Safeguarding Bridges from Vessel Strikes

In March 2025, the NTSB issued a safety recommendation report titled *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies*, which addressed bridge vulnerability safety issues identified during the early stages of our investigation of the contact of the *Dali* with the Key Bridge (see Appendix E) (NTSB 2025). The report focused on the vulnerability of bridges over navigable waterways to strikes from large ocean-going vessels, as well as the need to safeguard bridges from vessel strikes by developing and implementing risk reduction plans, identifying short- and long-term strategies to reduce risk, and considering the safety of vessels and structures in waterways.

In the report, the NTSB concluded that, had the MDTA conducted a vulnerability assessment of the Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 AASHTO *Guide Specifications*, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred. Further, the NTSB concluded that had the MDTA conducted a vulnerability assessment of the Key Bridge using AASHTO's Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.

Like the Key Bridge, other bridges throughout the United States were designed before AASHTO's 1991 *Guide Specification* for bridge design was issued. To understand the scope of the risk posed by bridges nationwide with designs predating AASHTO's *Guide Specification*, the NTSB requested that the FHWA identify bridges that cross navigable waterways and are used by ocean-going vessels like the *Dali*, as well as gather information about protection devices (if any) in place for those bridges. The FHWA coordinated with state DOTs to identify 176 bridges in 26 states that cross waterways used by ocean-going vessels.

The NTSB subsequently filtered the results according to whether a bridge—

- was built before 1996. We recognized that although the AASHTO *Guide Specification* was available in 1991, bridges under design or initial construction at that time were likely not built to its specifications. Therefore, we determined that bridges placed into service before 1996 were likely not designed and built to the current specifications.
- had a vertical clearance of at least 80 feet. We used the typical vertical clearance height for ocean-going vessels (80 feet) based upon the typical minimum mast clearance height of a loaded bulk carrier and loaded tanker.
- had substructures (such as piers) in a waterway. The only bridges considered in this report were those with piers in a waterway, because piers on land have natural protection from a horizontal vessel impact.

Applying these conditions to the 176 bridges reduced the number to 95. The NTSB also queried the FHWA Long-Term Bridge Performance InfoBridge web portal to identify 224 bridges owned by the Corps of Engineers. The same parameters used to filter the 176 bridges in the FHWA report were applied to these 224 bridges, resulting in 6 bridges that met the above criteria. Therefore, a total of 101 bridges—95 identified in the FHWA report and 6 owned by the Corps of Engineers—met the NTSB criteria.

Next, we evaluated the vessel traffic transiting under the 101 bridges between January 1, 2019, and September 31, 2024, to determine whether a bridge’s average annual transits by ocean-going vessels were sufficient to result in a measurable amount of risk in the vulnerability assessment calculation. This evaluation was accomplished using a similar methodology to the one used to determine the vessel traffic for the Key Bridge. As a result, we identified 72 bridges (in 19 states, managed by 30 separate bridge owners) over navigable waterways frequented by ocean-going vessels that were likely not designed and built to the 2009 AASHTO *Guide Specifications*. The information that the FHWA collected in coordination with state DOTs regarding protection devices helped us to identify that the owners of 4 of the 72 bridges had performed a recent vulnerability assessment and were either implementing a plan to reduce their bridge’s vulnerability or would be doing so in the near future. Therefore, the NTSB identified 68 bridges in the March 2025 report that had not undergone a vulnerability assessment based on recent vessel traffic.

Calculating a bridge's AF can help owners understand their bridges' vulnerability of collapse from a vessel collision and the aspects of bridge design or vessel traffic that contribute to this vulnerability, especially for bridges with an AF above the AASHTO threshold. In the report, the NTSB concluded that the 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels were likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.[132] As a result, the NTSB issued Safety Recommendation H-25-3, which asked the 30 owners of the bridges to calculate the AASHTO Method II AF for the bridge(s) identified for which they are responsible and inform the NTSB whether the probability of collapse is above the AASHTO threshold.

Awareness of which aspects of bridge design or vessel traffic affect the probability of a collapse can aid in the development of risk reduction strategies. The NTSB stressed that each of the strategies must be evaluated as part of a holistic safety evaluation of potential benefits and unintended negative outcomes. The NTSB believed that the bridge owners were in the best position to assess potential strategies for reducing the risk of a bridge collapse from a vessel collision, but that owners would also benefit from the guidance of the federal agencies that oversee the overlapping aspects of bridge infrastructure, vessel operations, and waterway management.

Per the 2009 AASHTO *Guide Specifications*, bridge risk reduction evaluations should be developed by an interdisciplinary team that includes representatives from the Coast Guard, the Corps of Engineers, and other federal agencies. The FHWA plays a key role in risk reduction based on its expertise and technical guidance in bridge design, construction, inspection, evaluation, management, and preservation. The Coast Guard has a role in the regulation of vessel operations, including

[132] The owners were: the Bay Area Toll Authority, the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Florida Department of Transportation, the Georgia Department of Transportation, Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the New Orleans Public Belt Railroad, the MDTA, the Massachusetts Department of Transportation, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City Department of Transportation, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Port Authority of New York and New Jersey, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Pennsylvania Turnpike Commission, the Rhode Island Turnpike and Bridge Authority, the Harris County Toll Road Authority, the Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation.

controlling or supervising vessel traffic (when necessary). Finally, the Corps of Engineers is responsible for maintaining the navigability of waterways leading to and within ports by planning, constructing, and managing dredging projects to ensure sufficient channel depths for vessels.

Because of the need to ensure a holistic safety approach and timely guidance to bridge owners on the risks posed by these interconnected factors, the NTSB issued Safety Recommendation H-25-1, which asked the FHWA, in coordination with the Coast Guard and Corps of Engineers, to establish an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision.

In Safety Recommendation H-25-2, the NTSB also recommended that the Coast Guard and Corps of Engineers support the FHWA in establishing an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision.

Finally, to ensure a comprehensive approach to the safety of the traveling public, bridges and structures, waterways, and vessel traffic, the NTSB issued Safety Recommendation H-25-4 to the 30 owners of the bridges identified in the report. With Safety Recommendation H-25-4, the NTSB asked that, if the calculations that the bridge owners performed in response to Safety Recommendation H-25-3 indicated that a bridge had an AF greater than the AASHTO threshold, that the bridge owners develop and implement a comprehensive risk reduction plan that included, at a minimum:

- guidance and assistance from the FHWA, Coast Guard, and Corps of Engineers interdisciplinary team identified in Safety Recommendations H-25-1 and H-25-2, and
- short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision.

The recommendations issued in that report, as well as their classification, are provided in section 2.8 of this report.

2 Analysis

2.1 Introduction

On March 26, 2024, about 0129 local time, the 984-foot-long Singapore flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, when it experienced a loss of electrical power, propulsion, and steering, and struck the southern pier supporting the central truss spans of the Francis Scott Key Bridge. A portion of the bridge subsequently collapsed into the river, and portions of the deck and the truss spans collapsed onto the vessel's forward deck. A seven-person road maintenance crew employed by Brawner Builders—which was contracted by MDTA—and one inspector employed by Eborn Enterprises, Inc., a subconsultant to the MDTA, were on the bridge when the vessel struck it. The inspector escaped unharmed, and one of the construction crew members survived with serious injuries. Six highway workers died during the collapse. One of the 23 persons aboard the *Dali* sustained a minor hand injury.

This analysis discusses the following safety issues:

- Improper placement of wire-label banding on terminal connection wires, preventing their secure connection into terminal blocks (section 2.2.1)
- Lack of specific guidance for inspecting terminal connections (section 2.2.2)
- Configuration of machinery and electrical systems needed to prevent loss of propulsion and recover steering and vessel electrical power following a blackout (section 2.3)
- Lack of effective means of emergency communications to warn motorists and notify highway workers to evacuate a bridge during an emergency (section 2.5.3)
- Inadequate standards for marine safety management systems (section 2.6)
- Inadequate standards for manufacturer-provided voyage data recorder software (section 2.7)
- Increasing vessel sizes and traffic density in US ports (section 2.8)
- Vulnerability of bridges over navigable waterways to strikes by large ocean-going vessels (section 2.9)

Having completed a comprehensive review of the circumstances that led to the accident, the investigation excluded the following as causal factors:

- *Environmental or waterway conditions.* At the time of the *Dali* accident voyage, the weather and waterway conditions were calm. The current was negligible in the harbor, and there were no weather warnings. The vessel was operating in darkness, but this is a routine occurrence for commercial merchant mariners and pilots.
- *Vessel complement and mariner credentialing*. The *Dali* crew composition met the requirements of the vessel's minimum safe manning document, which was valid at the time of the accident, in accordance with International Convention on Standards of Training, Certification and Watchkeeping for Seafarers regulations. All 21 *Dali* crewmembers were credentialed for the positions they filled on board the vessel. Additionally, the operational stations were crewed in accordance with company procedure. While a vessel is transiting restricted waters, it is critical to have a sufficient number of qualified personnel on duty and available to respond to shipboard-system failures and emergencies. Synergy's navigation manual within the vessel's safety management system (SMS) includes watchstanding conditions for both the vessel's bridge and engine room. During the *Dali*'s March 26 voyage, both of these stations were manned in accordance with SMS's policy and responded to the accident. Further, while transiting the Fort McHenry Channel toward the Key Bridge, the vessel had at least one licensed and certified pilot on board for the southbound passage to the sea buoy, as was required by Maryland state law.
- *Impairment of the Dali crew or pilots due to alcohol or other tested-for drugs.* The master and chief engineer tested all *Dali* crewmembers, including themselves, for alcohol within 2 hours of the accident, and all results were negative. A third party conducted additional breathalyzer tests (per the Coast Guard) about 12 hours postaccident, and all results were negative. Urine samples were also collected from the *Dali* crew and tested for alcohol and other drugs. The results of toxicology testing were negative for all crewmembers. The senior pilot and pilot-in-training were tested about 4 hours after the accident and their results were negative for alcohol and other drugs.
- *Fuel quality or switchover of fuels*. The crew switched to burning MGO in all engines 5 days before the accident and was burning MGO fuel at the time of the blackout. After the accident, samples of the MGO fuel used aboard the *Dali* at the time of the accident, as well as the fuel bunkered in the days before the accident, were analyzed. The results indicated that the MGO fuel complied with international standards and regulations and did not identify any concerns relating to the quality of the fuel.

- *Vessel's Ability to Get Underway After In-Port Blackouts*. While in port the day before the accident, on March 25, the *Dali* experienced a blackout caused by the mechanical blocking of DG2's exhaust gas stack when an engineering crewmember inadvertently closed the exhaust stack's damper. The second in-port blackout occurred when the generator's fuel pressure dropped because the flushing pump lacked the capability to restart on its own after a loss of power. Once the damper was opened, the cause of the initial March 25 blackout was resolved. Once the flushing pump was manually restarted, fuel pressure was restored. The crew continued preparing for the vessel's departure that evening. The March 25 in-port blackouts did not result from equipment failure or defect and did not result in damage to DG2. The blackouts did not materially or adversely affect the vessel's ability to get underway and proceed to sea.
- Presence of Non-Redundant Steel Tension Members in the Key Bridge's Continuous Steel Through-Truss. The continuous steel through-truss spans of the Key Bridge's superstructure utilized non-redundant steel tension members (NSTM) and per FHWA requirements NSTMs must receive an arms-length inspection every 24 months or less. The last such inspection before the collapse occurred in May of 2023 and did not reveal any deficiencies. The *Dali*'s contact with Pier 17, one of two rigid frame reinforced concrete piers used to support the continuous steel through-truss superstructure, generated impact forces over four times greater than the lateral strength of the pier. The presence of NSTMs within the bridge's continuous steel through-truss did not contribute to the collapse of the bridge as the impact of the *Dali* to the bridge's substructure exceeded the lateral capacity of two of the four columns at Pier 17, causing its failure and loss of support to the bridge's superstructure. The NSTMs were not a factor since a critical component of the load path was removed when Pier 17 collapsed, and the piers did not have NSTMs.

Thus, the NTSB concludes that none of the following were factors in this accident: (1) environmental or waterway conditions; (2) vessel complement and mariner credentialing; (3) impairment of the *Dali* crew or pilots due to alcohol or other tested-for drugs; (4) fuel quality or switchover of fuels; (5) vessel's ability to get underway after in-port blackouts; or (6) the presence of non-redundant steel tension members in the Key Bridge's continuous steel through-truss.

2.2 Loss of Power (Blackouts)

While underway and approaching the Key Bridge on March 26, the *Dali* experienced an LV power loss, resulting in the initial blackout and loss of propulsion and steering. Shortly after power was restored, a second blackout (HV and LV power) occurred. After the accident, investigators conducted extensive testing between April 1 and April 29 to find the cause of these blackouts.

2.2.1 Improper Placement of Wire-Label Banding

After the accident, investigators arranged the vessel's electrical distribution system in the same configuration it was in at the time of departure on March 26 by performing a changeover between the vessel's step-down transformers, TR1 and TR2, to close HV breaker HR1. Investigators left HR1 closed so it powered the LV bus via TR1—mirroring the switchboard configuration on the day of the accident, aiming to replicate the blackout.

After 2 days, while the system remained in this configuration, an LV blackout occurred. Similar to the initial accident blackout on March 26, the ACONIS (the onboard system that monitored main propulsion, power generation, and auxiliary systems on the vessel) did not provide a warning before the blackout or record any alarms that could be directly attributed to the cause of the blackout. HHI representatives connected power-analysis equipment for ongoing monitoring, and a few days later, another LV blackout occurred without advance ACONIS warnings or alarms.

NTSB and Coast Guard investigators, along with representatives from Grace Ocean, Synergy, HHI, Singapore, and ClassNK, evaluated the data captured by the power-analysis equipment and determined that the latest LV blackout was caused by the HR1 breaker unexpectedly opening. HHI engineers then attempted to close HR1 but were unsuccessful. Further troubleshooting led engineers to discover a loose signal wire (Wire 1) on Terminal Block 381.

Wire 1 was part of an electrical pathway that delivered 110 direct current control circuit voltage to HR1's undervoltage release (UVR) device. The UVR device opens a circuit breaker when the control circuit voltage falls too low. For HR1 to close and remain closed, the UVR device must remain energized. When Wire 1 became loose, the electrical pathway the UVR device was interrupted, and the UVR device de-energized. This led to an unintended trip of HR1.

Under normal operating circumstances, when an operator wanted to intentionally open breaker HR1 for maintenance or other purposes, they would shift the operator switch to Manual and then rotate the breaker control switch to "open," which would open the control circuit. This would interrupt the control circuit voltage, de-energizing the UVR, which would open HR1.

When Wire 1 became disconnected and HR1 opened, it was as if an operator had rotated the breaker control switch to "open," causing HR1 to intentionally open. Therefore, the vessel's PMS, which typically registers alarms when conditions are abnormal, did not initiate warnings or alarms when HR1 opened unexpectedly because it did not sense any conditions that fell outside safety parameters.

After re-inserting Wire 1 into Terminal Block 381 to create a secure connection, the engineers closed HR1 successfully. HHI engineers then disconnected Wire 1, resulting in HR1 opening, causing a vessel blackout similar to the initial blackout on the accident voyage, including no warnings or alarms. Therefore, the NTSB concludes that the initial March 26 low voltage blackout was caused by Wire 1 electrically disconnecting from Terminal Block 381 within the HV switchboard, which resulted in high-voltage breaker HR1 opening, interrupting power to step-down transformer TR1 and the LV bus.

NTSB investigators attempted to determine how Wire 1 became disconnected and how HR1 was able to function sporadically with Wire 1 being loose. They removed Terminal Block 381 and portions of the two wires (Wire 1 and Wire 3) that had been connected to the block for examination at the NTSB Materials Laboratory.

The NTSB observed electrical arcing damage on the terminal block's spring-clamp gate face of the Connection Point 1 cage as well as the end of the Wire 1 ferrule, indicating a defective electrical connection (see figure 61). Arcing damage occurs when electricity is discharged ("arcs") across a gap in a circuit. The terminal block showed no evidence that it would not function as designed, despite the arcing damage. Arcing damage could only have occurred on the terminal block's spring-clamp gate face if Wire 1 had become disconnected, creating a gap between Wire 1 and the face. However, if the tip of the ferrule rested on the spring-clamp gate, it would make an electrical connection as if the wire were properly seated in the gate, allowing the HR1 breaker to close, and electrical power to the LV switchboard. The intermittent electrical connection between the loose Wire 1 and the terminal block's spring-clamp gate face would have enabled HR1 to function sporadically.

We also found a depression on the end of the Wire 1's ferrule that indicated inward pinching that distorted the ferrule end's shape and compressed adjacent wires (see figure 61). This depression indicated that the ferrule's end had been inserted into the spring-clamp gate. During the examination, we observed inward-moving scrape marks towards the center of the wire, indicating that the wire ferrule had backed out of the spring-clamp gate. We also found material had collected at the end of the ferrule, consistent with the wire scraping and dragging along the side of the cage as the wire backed out of the cage (see figure 62).

We could not determine whether Wire 1 backed out of the spring-clamp gate before or at the time of the initial underway blackout because HR1 functioned sporadically after the accident. Additionally, TR1, the step-down transformer associated with HR1, which had been put in use the day before the accident after the second in-port blackout, had not been in use for at least 7 months, and the crew would have had no indication of a problem with Wire 1 during that time that the transformer was not in use.[133]

[133] It is common industry practice to switch between step-down transformers about twice each year. Although *Dali* personnel did not know the last time TR1 and its associated breakers, HR1 and LR1, had been used, a breaker counter reading for LR2 was similar to that of LR1, indicating that TR1 had been used about the same number of times as TR2. Following the Key Bridge collapse, Synergy instituted a biannual step-down transformer switching policy for its vessel, similar to industry practice. See section 1.7.1.1 for more information about historical use of, and switching between, TR1 and TR2.

If the connection was made by the wire ferrule resting on the closed gate face, any shipboard movements or vibrations could have moved the wire, resulting in an interruption in the connection and causing electrical arcing (see figure 64). With TR1 online, any interruption in the Wire 1's connection would have caused the HR1 breaker to open, resulting in an LV blackout.

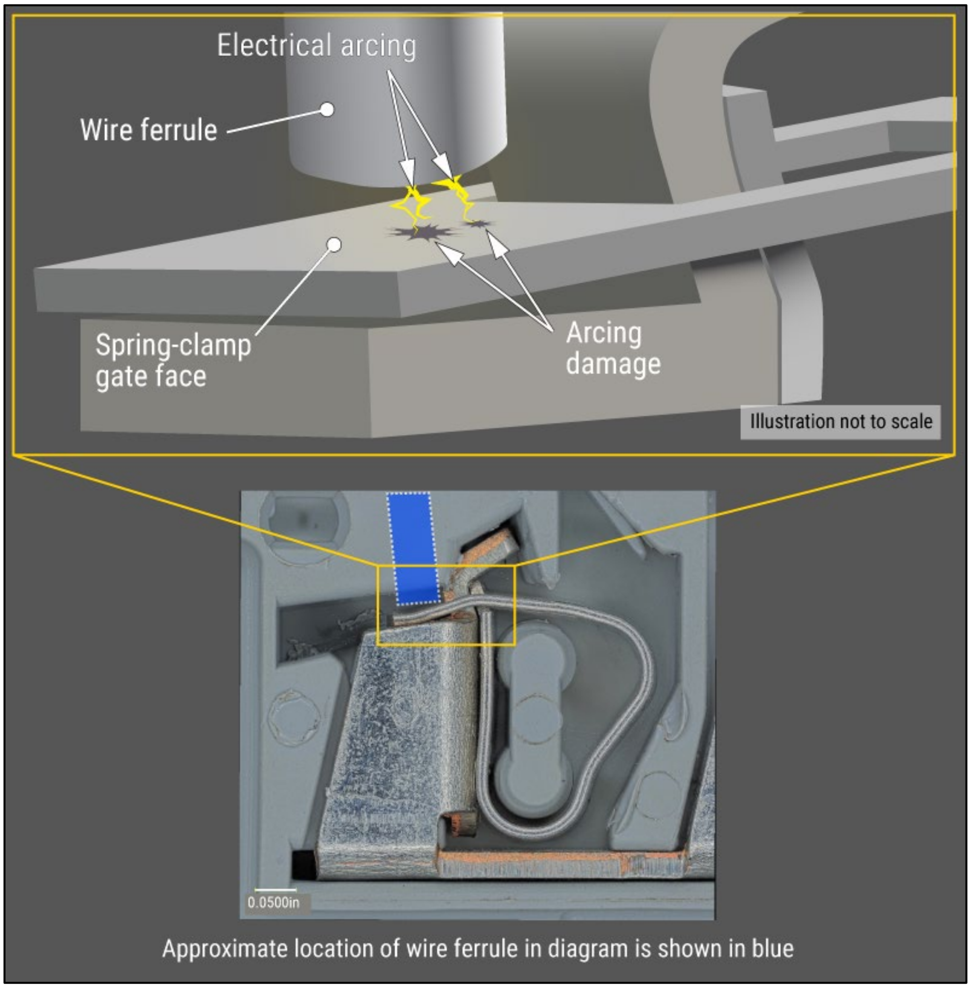

Figure 64. How arcing could occur within the gap between the wire ferrule (shown as backed of the spring-clamp gate, with the spring-clamp gate disengaged) and the spring-clamp gate face after the wire ferrule, creating arcing damage with Terminal Block 381 for comparison.

During the vessel's construction at HHI, each wire in the HV switchboard control panel was labeled using banding sleeves called wire-label banding. Printed on each wire-label banding sleeve was a number that corresponded to a specific terminal block, which was a mechanism that connected wires while maintaining circuit connectivity. The wire-label banding helped ensure that the wires were connected to the appropriate circuits via the proper terminal block. We observed that Wire 1's wire-label banding covered all of the ferrule's blue insulated collar, increasing the ferrule's overall circumference (see figure 65). Although the wire and ferrule sizing were appropriate for the terminal block, the increased circumference prevented the ferrule from being fully inserted into the spring-clamp gate. Therefore, the NTSB concludes that the position of the wire-label banding on the ferrule of Terminal Block 381's Wire 1 prevented Wire 1 from being fully inserted into the terminal block spring-clamp gate, causing an inadequate connection and leaving Wire 1 loose and vulnerable to becoming electrically disconnected.

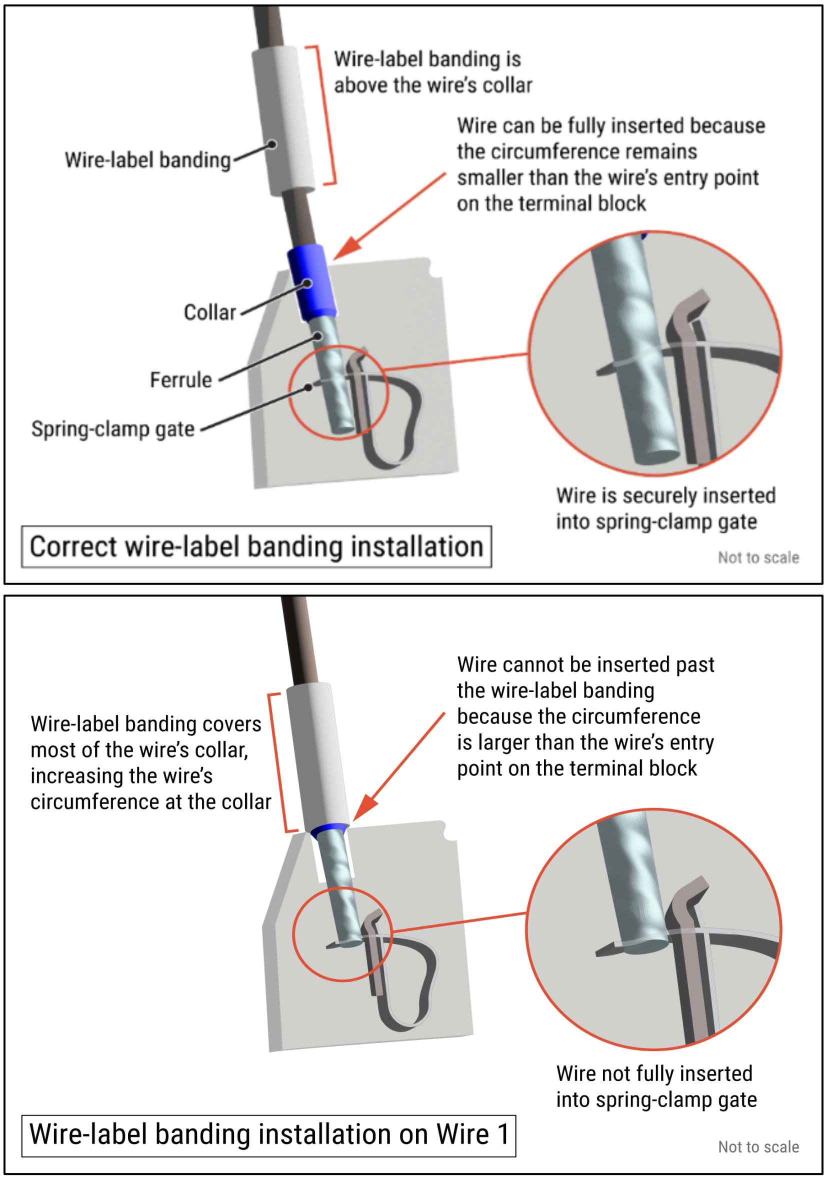

Figure 65. *Top to bottom*: Correctly installed wire-label banding compared to Wire 1's wire-label banding installation, showing how placement of wire-label banding affects the way wires are seated in their terminal blocks.

WAGO has a product data sheet for the terminal block model (280-681) used on the *Dali* (WAGO n.d.). The product data sheet includes information about the terminal block, including instructions on properly inserting a wire and how to mark a terminal block, and should be referenced by vessel manufacturers during design and building. The NTSB recommends that WAGO add a warning in your product data sheet accompanying WAGO terminal block 280-681 (model), as well as any other terminal block models or similar products that incorporate wire-label banding you manufacture, to explain that improperly placed wire-label banding can impede the proper insertion of a wire into a terminal block. The NTSB also recommends that HHI incorporate proper wire-label banding installation methods into its electrical department's standard operating procedures to ensure that wire-label banding installed on a wire does not impede the proper insertion of the wire into a terminal block.

2.2.2 Switchboard Inspections and Infrared Thermal Imaging

Synergy (the vessel's operator) required both 6-month and 30-month main switchboard inspections aboard the *Dali* as part of its preventative maintenance program. The 30-month inspection guidance provided broad instructions for the crew to check bus bars and link fastenings for cracking, breaking, and deformation, as well as cables and bus bars for discoloration, damage, and looseness, but not how to inspect control (signal) wiring termination, such as the connection of Wire 1 into Terminal Block 381, specifically. The 6-month inspection, which had last been completed on March 23, 2024, included inspection of terminal boxes, checking the condition of crimp terminals, and renewing crimp terminals when necessary. The work order did not provide specific guidance for inspecting each crimp terminal. The inspection guidance did not specify how to complete these checks, nor did it specify review of all control (signal) wires in the HV switchboard. HHI, the manufacturer of the HV switchboard, breakers, and associated components, recommended periodically checking terminal connections but did not provide practical guidance for inspecting the terminal connections within the HV switchboard.

Wire 1 was one of two wires connected to Terminal Block 381, which was one of thousands of terminal blocks within the HV switchboard and throughout the vessel. Checking thousands of terminal connections by hand would be extremely labor intensive. It would also prove operationally challenging, as the vessel's electrical systems would have to be secured, or turned off, while trained crewmembers or technicians inspected the individual connections to prevent electrical shock to personnel and inadvertent interruptions of power to equipment. Furthermore, continued manipulation of the small and delicate wiring and components during inspections could introduce additional risk due to human error and could lead to the connections' premature failure over time, which could result in blackouts, loss of steering, and/or failure of other critical equipment and systems.

Infrared thermal imaging is an inspection and maintenance technique that allows inspectors to identify possible points of failure that may not be visible to the human eye, without touching the electrical components being examined. Infrared thermal imaging is already used widely for inspections in the maritime shipping industry and is a condition-based monitoring technique approved by various classification societies. Thermal imaging uses an infrared camera to observe the surface temperature of a conductor (in this case, a signal wire) as an electrical current passes through it (see figure 66). It can be used to identify inadequate termination of conductors, such as Wire 1 into Terminal Block 381, as well as overloaded circuits by detecting increased local temperatures in electrical systems. It can also help detect faults early, before they become serious problems. Infrared thermal imaging also promotes operator safety, as it limits the need to touch, manipulate, or remove conductors.

Figure 66. Exemplar infrared thermal imaging camera being used on control circuitry. The lighter colors indicate warmer temperatures. (Source: ThermoElite Inc.)

Before the accident, Wire 1 was not inserted fully into Terminal Block 381, with the ferrule's end touching the spring-clamp gate face, as evidenced by the arcing damage found on these components during NTSB Materials Laboratory testing. Contact between Wire 1's ferrule end and the gate's face (versus full insertion into the spring-clamp gate) still would have allowed Wire 1's electrical current to pass through the terminal block spring-clamp gate and to the other wire that was connected to the terminal block. However, the electrical current would flow across a far smaller surface area than if Wire 1 had been fully inserted into Terminal Block 381's spring-clamp gate. Heat from electrical current flow dissipates more slowly from a smaller conductive surface area than it does from a larger conductive surface area. In this case, the tip of Wire 1 touching the face of the spring-clamp gate would have provided a smaller conductive surface, and the partial connection would have produced an elevated temperature relative to a fully inserted connection. This elevated temperature might have been detected using infrared thermal imaging.

This condition-based monitoring technique is approved by various classification societies. Many companies, organizations, shoreside power plants, and individual vessels have their crews or outside companies conduct thermal imaging surveys and inspections of various electrical components, such as switchboard control panels, terminal blocks, bus bars, motor controllers, and power conductors. For example, the National Fire Protection Association recommends thermal imaging surveys be conducted as part of annual electrical maintenance surveys (*NFPA 70B*). Additionally, in December 2024, the American Club, a protection and indemnity association for vessel owners and charterers, released a safety alert for its members, explaining the value of thermal imaging inspections (The American Club 2024).[134] The safety alert stated, "members should consider equipping their vessels with thermal imaging equipment/instruments to be used by the crew on a regular basis following appropriate familiarization and training" (The American Club 2024). Further, WAGO Corporation, the manufacturer of Terminal Block 381, uses thermal imaging during their production and quality assurance processes to ensure that its components are not defective. According to WAGO, thermal imaging could be effective for identifying an incorrectly installed conductor.[135] Although infrared thermal imaging is used widely in the maritime shipping industry and is approved by

[134] *Protection and indemnity* is a type of marine insurance coverage that protects shipowners and carriers against various liabilities and risks that can arise during maritime operations.

[135] During commissioning testing, WAGO uses infrared thermal imaging in accordance with International Electrotechnical and Underwriters Laboratories testing standards.

various classification societies, there is no requirement throughout the shipping industry to use the technology.

The NTSB concludes that if infrared thermal imaging had been used to inspect wire connections within the HV switchboard before the accident as part of the *Dali*'s preventative maintenance program, the loose signal wire may have been identified. Therefore, the NTSB recommends that Synergy, with classification society approval, implement into its preventative maintenance program and SMS the use of infrared thermal imaging for routine monitoring of electrical components, including the means to detect inadequate signal wire connections.

The International Association of Classification Societies (IACS) comprises 12 classification societies. Each member maintains a set of rules and standards for classing vessels, and the 12 IACS member societies class over 90% of the world's merchant shipping tonnage.[136] IACS is a forum for coordination amongst member class societies to discuss and agree on consistent application of international regulations and to consider other safety issues. ClassNK, which classed the *Dali*, is one of these 12 member societies. Therefore, the NTSB recommends that ClassNK share the circumstances of the contact of the containership *Dali* with the Key Bridge and subsequent bridge collapse with IACS and urge them to distribute report MIR-25-40 to their members, highlighting the importance of avoiding placement of wire-label banding such that it impedes the proper insertion of a wire in a terminal block, and the benefits of using infrared thermal imaging as part of a preventative maintenance program for routine monitoring of electrical components to detect inadequate signal wire connections.

2.3 Additional Shipboard Systems Related to Recovery from a Loss of Power

Modern ocean-going vessels are complex pieces of engineering. They are essentially floating cities designed to transport goods and people, and to complete difficult tasks while transiting across the ocean.[137] These vessels and their machinery spend years continually operating in challenging environments. Crews on board these vessels are tasked not only with navigating these vessels but also maintaining the safe and continual operation of the vessel's supporting machinery, which includes

[136] See https://iacs.org.uk/about-us/ for more information about IACS.

[137] For more information, see the NTSB specialist study, "Vessel size increase and associated safety risks: a review of the scientific literature," in the public docket for this investigation (case number DCA24MM031).

not only the propulsion engine, electrical generation, and steering systems, but also all vessel systems that support the people who run them. Some examples of vessel systems include lighting, HVAC, accommodation systems (including potable water, sewage, and galley), electronics, and lifesaving equipment. These vessel systems are often integrated and need to function continuously.

Like most modern equipment, vessels are dependent on electricity to maintain their functionality. Therefore, the loss of power via an unexpected blackout has broad implications for the vessel. Given the complexity of a vessel's machinery and how integrated its systems are, recovery from an unexpected blackout is complicated and can be time-consuming. There is no standard for recovery time for a full-vessel blackout, including the loss of both LV and HV power like the *Dali* experienced. A recovery can take anywhere from minutes to days in some cases, depending on the cause of the blackout and the availability of equipment, replacement materials, and technical expertise.

In the review of the *Dali*'s machinery and electrical systems, the NTSB identified the following safety concerns that, although not causal to the initial underway blackout, are related to preventing a loss of propulsion and recovering steering and vessel electrical power following a blackout:

- The configuration of the main engine to shut down due to low cooling water pressure.
- The use of the flushing pump as a fuel service pump for the electrical diesel generators.
- The operation of the vessel's LV step-down transformer high-voltage breakers in Manual mode rather than Automatic.
- The effect of emergency diesel generator (EDG) radiator damper positions on the generator's ability to start.

2.3.1 Main Engine Shutdown

During the initial underway loss of LV power on the *Dali* that began at 0125:00, the HV switchboard remained powered, supplying power to the main engine lube oil pumps. However, the main engine cooling water pumps, another critical engine component, lost power during the blackout because they were powered by the LV switchboard. Because the engine was configured to shut down when the main engine control system and engine safety system detected a loss of cooling water pressure at 0125:08, the main engine shut down. This was a "cancellable" shutdown preceded by alarms. To cancel a shutdown, within 6 seconds of the shutdown alarm sounding, a crewmember had to press a button on the station controlling the engine, which was the bridge at the time of the casualty. However, given the flood of other alarms triggered by the initial loss of LV power sounding simultaneously, and the blackout conditions, it is unrealistic to expect that the bridge team could have successfully canceled the engine shutdown in this short period. The main engine remained shut down for the remainder of the accident.

During the first underway blackout, lighting and other machinery, including the *Dali*'s steering gear pumps, were lost because they were powered by the LV switchboard. Two steering gear pumps were restored 58 seconds later when the crew restored LV power. The crew regained control of the rudder, but with the main engine shut down, they could not effectively steer the vessel because the main engine was unavailable to rotate the propeller and provide wash across the rudder. If the engine had not shut down due to loss of cooling water pressure, it would have remained running in a slowdown condition (about slow ahead, the speed at which it was running at the time of the blackout) until it ran out of fuel or the second underway blackout occurred. In this condition, the engine would have been available to provide propulsion for maneuvering. The NTSB concludes that the loss of power to the LV bus led to a loss of lighting and machinery, including the main engine cooling water pump and the steering gear pumps, which resulted in a loss of propulsion and steering.

The engine was originally configured to shut down due to low cooling water pressure because of the vessel's owner at the time of manufacturing required the engine to meet the requirements of Germanischer Lloyd, a classification society. When the subsequent vessel owner opted to use the rules of a different classification society (ABS), this configuration was no longer required. To meet ABS rules, HHI altered the engine configuration to make the low cooling water pressure shutdown cancellable. HHI stated that the ability to cancel a shutdown due to low cooling water pressure was not intended for emergency situations but rather momentary false alarms or sensor error, which was not the case in the *Dali* accident. Further, the designer and licensor of the *Dali's* main engine, Everllence (formerly MAN B&W), stated that they had not "specified or encouraged" that the engine aboard the *Dali* be configured to shut down due to low cooling water pressure.

Therefore, the NTSB concludes that the as-built configuration of the *Dali*'s main engine to automatically shut down due to low cooling water pressure met classification standards at the time the vessel was constructed; however, it endangered the vessel because it prevented the main engine from being available following the initial underway blackout, thus reducing the vessel's maneuverability.

The ability of a ship's crew and pilot to maintain main propulsion in a channel while in a maneuvering condition is imperative. Engines like the *Dali*'s can be re-configured at any time to adjust engine shutdown parameters, thus preventing engine shutdowns that affect a vessel's maneuverability. Therefore, the NTSB recommends that Synergy identify ships it operates that are equipped with a Hyundai-MAN B&W 9S90ME C9.2 engine and ensure that they are not configured to automatically shut down due to low cooling water pressure. The NTSB also recommends that HHI identify all active HHI-constructed vessels with Hyundai-MAN B&W 9S90ME C9.2 engines installed, which are configured to Germanischer Lloyd rules and are designed to shut down on low cooling water pressure, and alert the current vessel owners of this configuration and the circumstances of this accident.

Large cargo vessels are designed for economy to meet the competitive nature of the global shipping industry. These vessels have been optimized to traverse oceans with minimal fuel consumption and crew cost. Today, efficient large cargo ships, such as containerships, product tankers, vehicle carriers, and dry bulk carriers are most often fitted with a single rudder and a single slow speed diesel main engine directly driving a propeller. A loss of shipboard electrical power can result in an immediate loss of steering pumps for up to 45 seconds (the time required by IMO regulations for the emergency diesel generator to supply emergency power). A loss of electrical power may also stop auxiliary pumps, such as lube oil and fuel pumps, needed to operate large diesel engines. As seen with the *Dali*, the loss of auxiliary systems supporting the main engine can result in the loss of propulsion, which is critical to maintaining the ship's position while operating within narrow channels and close to port infrastructure. Designing vessels to maintain propulsion and steering, even temporarily, following a supporting machinery or electrical system casualty ensures bridge teams and pilots have the ability to take necessary action, such as maneuvering to anchor the vessel or avoid other nearby vessels or infrastructure. Therefore, the NTSB concludes that, as cargo vessel designs continue to evolve with the latest available standards and technology, increased redundancy to maintain critical systems, such as the main engine and steering, can mitigate risks in restricted waters. Therefore, the NTSB recommends the US Coast Guard conduct and publish the results of a study that examines the availability, feasibility, and safety benefits of redundant means to ensure that large single-propulsion-engine cargo vessels maintain propulsion and steering when maneuvering in restricted waters. See section 2.8 for more information about the impact of increasing vessel sizes and traffic density in US ports.

2.3.2 Engineering Crew Response to Initial Blackout

When the *Dali* initially lost LV power, the vessel's ACONIS did not provide the engineering crewmembers with any warnings or initiating alarms that alerted them of the impending LV blackout. Despite this sudden blackout, which resulted in numerous alarms sounding immediately, simultaneously, and continuously, the crewmembers in the ECR—now working in near darkness—were able to determine that only the LV bus had lost power and that the HV bus was still powered. At 0125:58, the electrician manually closed HR1 and LR1, the HV and LV step-down transformer breakers, thus restoring power to the LV bus and equipment powered from the LV switchboard—all within 58 seconds of the initial loss of power. The NTSB concludes that the engineering crew's initial response to restoring LV power after the first underway blackout was timely.

2.3.3 Configuration of Flushing Pump as a Service Pump

The fuel oil flushing pump, which was being utilized to supply fuel to the two online generators (DG3 and DG4), stopped supplying pressurized fuel to the generators when the initial underway blackout occurred. The pump was not designed to restart automatically when power was restored and required a manual restart. About 0127:02, the fuel pressure for DG3 and DG4 dropped, and they could not maintain speed at their electric load, which caused an underfrequency, or underperformance, condition. The vessel's PMS, which monitored the generators, detected the low frequency and automatically started DG2 as designed. However, before DG2 could synchronize to the HV bus, the PMS automatically disconnected DG3 and DG4 from the HV bus due to their underperformance, leading to both the HR1 and LR1 breakers opening automatically, and resulting in the vessel's second underway blackout.

The day before the accident, on March 25, the vessel experienced two blackouts while in port as the crew performed maintenance on the vessel. As with the second underway blackout, the second in-port blackout resulted from the PMS automatically disconnecting the online generator that was supplying power to the vessel at the time due to the generator's underfrequency condition.

The NTSB concludes that the second underway blackout on March 26, and the second in-port blackout on March 25, during which both the HV and LV buses lost power, were caused by insufficient fuel pressure to the online diesel generators resulting from the inability of the flushing pump to automatically restart following a loss of power.

As built, the main engine fuel system and generator engine (DG) fuel supply system were segregated from one another. The main engine supply and circulating pumps provided fuel to the main engine. The DG fuel supply pumps and booster pumps provided fuel to the four generator engines.

In 2020, Grace Ocean installed exhaust scrubbers on the main engines, DG1, and DG2 to comply with the IMO emissions standards. As part of the installation, Grace Ocean modified the DG fuel supply system so that the supply and booster pumps could only provide fuel to DG3 and DG4. DG1 and DG2 would operate using the same fuel the main engine used. In the modified configuration, the flushing pump could also be used to supply fuel to DG3 and DG4. The flushing pump was only capable of taking suction from the MGO service tank, meaning that the pump would deliver only MGO to the DGs. Unlike the *Dali*'s DG fuel supply and booster pumps, the flushing pump lacked redundancy and was not designed to restart automatically once power was restored after a blackout. The manual restart process occurred in the purifier room, where the manual restart controls were located, two decks below the ECR.

According to the chief engineer and previous chief engineer, for at least 7 months leading up to the accident, the crew exclusively used the flushing pump to supply fuel to DG3 and DG4. The crew believed that the DG supply and booster pumps and the associated piping contained other fuel (VLSFO or HFO) that was not compliant with emissions regulations in certain geographic areas, and that the pumps and piping may have contained bacterial growth that could have contaminated the entire fuel system (a common occurrence with stagnant marine fuels). The crew explained that cleaning the system to use the supply and booster pumps would have taken several days, so they and the previous chief engineer chose to keep the DG fuel supply system configured to run DG3 and DG4 solely with the flushing pump.

Because the flushing pump lacked redundancy and the capability to automatically restart and reestablish fuel supply to DG3 and DG4, those generators would not automatically recover from an initial blackout. In the moments after the initial underway blackout, the engineering crew had to diagnose the reason for the loss of power and steps needed to restore propulsion. Compared to an automatic restart (DG supply and booster pumps), manual restart required the crew to locally restart the pump two decks below the ECR, prioritizing manpower that otherwise could have been used to assist in tasks required to restore propulsion, and increasing the risk of a second blackout occurring. This was evident after the initial underway blackout; DG fuel supply pressure recovery was delayed, and the vessel subsequently experienced a second blackout (loss of HV power). Had the crew used the DG supply and booster pumps as designed, the vessel likely would not have experienced a second blackout, either underway or in-port, because these pumps would have restarted and sustained the necessary fuel pressure following the initial blackouts (see figure 67).[138] Additionally, according to ClassNK, the vessel's classification society, the flushing pump "would not be considered" for supplying fuel to the DGs "from the viewpoint of classification requirements" because it could not automatically restart after a blackout. Thus, the configuration of the flushing pump as the sole fuel supply pump to DG3 and DG4 on the *Dali* would not have been acceptable to ClassNK. Therefore, the NTSB concludes that the crew's operation of the flushing pump as the service pump for online diesel generators was inappropriate because the necessary fuel pressure for DG3 and DG4 would not be automatically reestablished after a blackout per the fuel system's design.

[138] See the public docket for this investigation (case number DCA24MM031) for the main engine and generator engine fuel oil modification class-approved drawing.

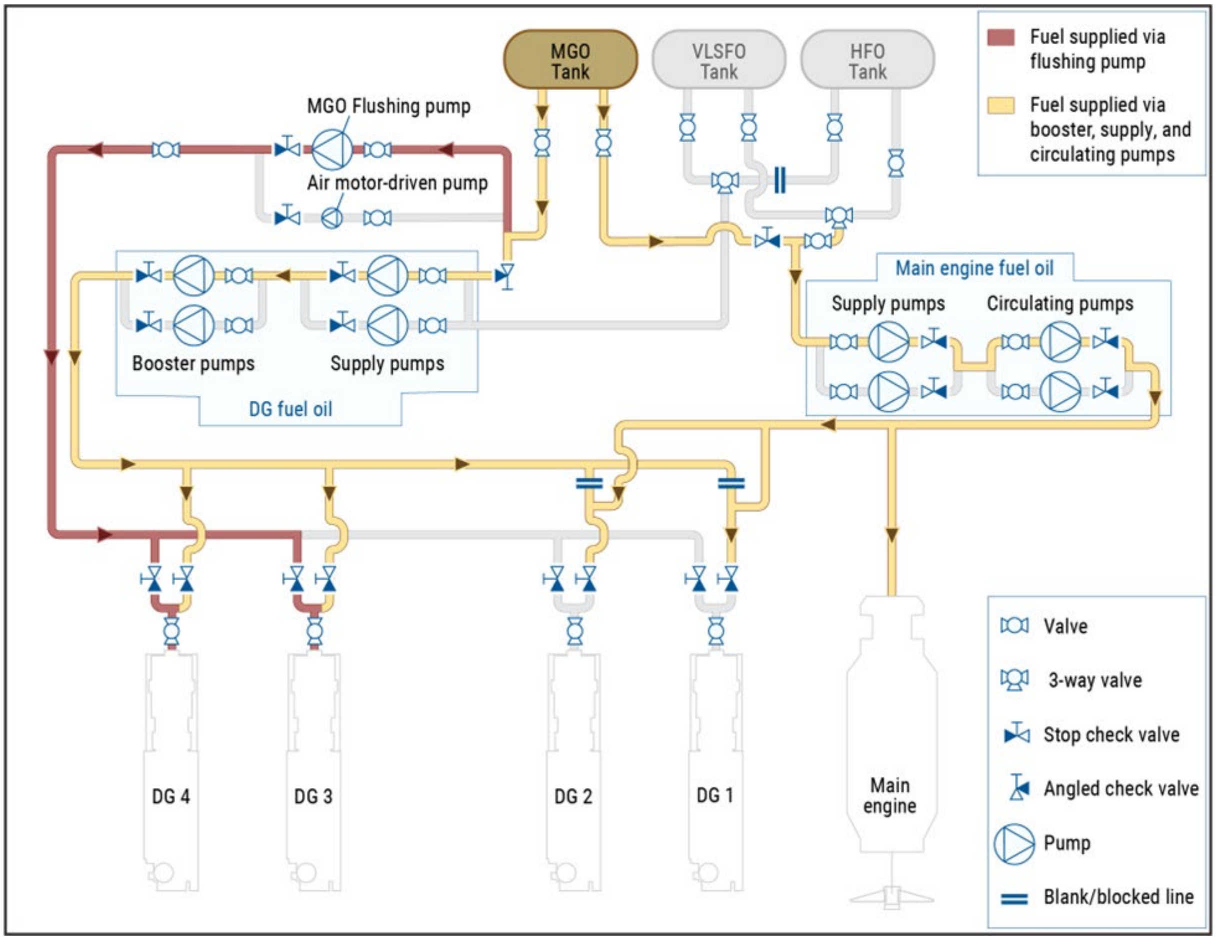

Figure 67. Simplified diagram of *Dali*'s main engine and DG fuel oil service system. The flow of fuel from MGO tank to DG3 and DG4 via supply and booster pumps is shown in yellow, while the flow of fuel from the tank to DG3 and DG4 via the flushing pump is shown in red.[139]

Synergy provided technical oversight, assistance, and guidance to its vessels' operators through a number of means. The *Dali* was equipped with a remote equipment monitoring system, which allowed Synergy's shoreside support personnel to monitor real-time vessel operations, data, and analytics. The satellite-based communication methods paired with the remote equipment monitoring system connected *Dali*'s staff to a dedicated shoreside expert that Synergy employed to provide each of its vessels with technical assistance. These experts, which included technical superintendents and managers, were in touch with the *Dali* crew at least daily. Despite these communications, the superintendents and managers were unaware that the flushing pump on the *Dali* was being used as a service pump to

[139] See the public docket for this investigation (case number DCA24MM031) for the main engine and generator engine fuel oil modification class-approved drawing.

supply fuel to DG3 and DG4. A technical manager stated that, because the flushing pump was a single pump, its use as a service pump would not have been acceptable.

In addition, a team of experienced Synergy technical managers and superintendents provided oversight of Synergy's vessels through internal biannual vessel inspections. These comprehensive inspections lasted at least a week or longer and covered a broad range of areas and topics, including the vessel's machinery and electrical systems. However, the *Dali's* technical manager, who completed these inspections, said he had not been aware that the flushing pumps were being used as service pumps to supply fuel to the generators. Additionally, following the accident, the NTSB learned that the crew aboard at least one other Synergy-operated vessel was also using—at least occasionally—a flushing pump as the DG3 and DG4 fuel supply pump.

The *Dali* crew had used the flushing pump to supply fuel to DG3 and DG4 for several months before the accident. However, Synergy did not identify that crews aboard the *Dali* and at least one other vessel in its fleet were using the flushing pump as a primary fuel service pump, nor did it take steps to address this practice despite continuous connectivity and communications with vessels, frequent vessel inspections, and having an SMS, which requires a vessel operator to identify risks and plan responses. Therefore, the NTSB concludes that Synergy's operational oversight was inadequate because it did not discontinue crews' ongoing use of the flushing pump as a service pump for the diesel generators aboard the *Dali* and at least one other vessel.

Synergy provided guidance, policies, and procedures to its vessels crew via an SMS. The company's SMS covered a broad range of operational and procedural guidance/framework, including watchstanding, machinery and systems operations, fuel changeover, and emergency response. Synergy's SMS contained, among other documents, a fuel management plan. However, the SMS did not mention the flushing pumps or service pumps, nor did it specify the appropriate method to supply fuel to the diesel generators. An SMS requires a company to identify risks and plan responses. After the accident, one Synergy technical manager spoke with the crews of the vessels he oversaw about the flushing pump and explained that use of the flushing pump as a standalone fuel source without redundancy was an inappropriate and unacceptable application of the pump and therefore should not be used in that manner. The instructions conveyed during these conversations—to stop using the flushing pump as a primary fuel supply pump—have not been formally entered into company-wide policy and procedure. Therefore, the NTSB recommends that Synergy develop, implement, and monitor for compliance and effectiveness an SMS policy and procedure to ensure that vessel crews are using the fuel oil service pumps as designed for the diesel generator fuel supply systems installed on board its vessels.

2.3.4 Low-Voltage Step-Down Transformer Changeover

The *Dali*'s LV switchboard, which supplied power to vessel lighting and other equipment, including two steering gear pumps, was powered by the LV bus. The LV bus was connected to the HV bus via two redundant step-down transformers, with breakers located on either side of the transformers. The HV breakers, HR1 and HR2, which linked to the LV step-down transformers, had two control modes: Manual and Automatic. Synergy left the operation control mode for the *Dali*'s HR breakers to the crew's discretion.

On the day of the accident, the HR1 and HR2 breakers' control modes were set to Manual. The initial underway blackout on March 26 occurred when Wire 1 disconnected from its terminal block and HR1 and its corresponding LV step-down transformer breaker, LR1, opened. The crew was able to manually close HR1 and LR1 within 58 seconds, restoring power without reliance on the emergency diesel generator (EDG).

Had HR2's control mode been set to Automatic instead of Manual at the time of the initial underway blackout, HR2 and LR2 would have automatically closed about 10 seconds after HR1 opened, shortening the initial underway blackout by about 48 seconds by restoring power through step-down transformer TR2 and powering the LV bus and LV switchboard, including vessel lighting and steering (steering gear pump nos. 1 and 2). With the steering gear pumps operable, the rudder would have been available for use 10 seconds after the blackout. However, the main engine would still have shut down after the initial underway blackout due to low cooling water pressure, and the crew would have had to restart the main engine after LV power was restored.

During maneuvering situations in channels, where immediate hazards (grounding, traffic, objects) are in proximity, response time is critical to avoiding an accident. Therefore, vessel systems should be configured to ensure maximum redundancy and the quickest possible recovery from the failure of critical systems (such as generators or steering systems). In the *Dali* accident, the crew may have had critical systems available to help control the vessel's speed and heading sooner if they had been able to both (1) initiate the main engine restart sequence and (2) return power to the steering gear pumps shortly after the initial underway blackout. However, the main engine restart sequence time would have remained similar, regardless of the HV breakers' control mode position. Additionally, the use of

Automatic control mode would not have prevented the second underway blackout, as the flushing pump, which was being used inappropriately, would still need to be manually restarted after the initial underway blackout. Therefore, the NTSB concludes that keeping the HV breakers' control modes set to Automatic rather than Manual would not have prevented either underway blackout, but it would have shortened the duration of the initial underway blackout from 58 seconds to 10 seconds, providing more time for the crew to attempt to recover critical systems, such as propulsion, as the vessel approached the Key Bridge.

Documented procedures, such as procedures for setting HV breakers' control modes to Automatic while the *Dali* was underway, would typically be included in an SMS. Although Synergy, the vessel's operator, had an SMS, it did not include a policy or procedure for setting the HV breakers' control modes. A policy or procedure would provide guidance for when it was appropriate for crewmembers to set HV breakers' control modes to Automatic, such as during normal operating conditions, versus Manual, such as when conducting maintenance. Therefore, the NTSB recommends that Synergy develop, implement, and monitor for compliance and effectiveness a safety management system policy and procedure to ensure that vessel crews are setting HV breakers' control mode to Automatic, unless the transformer breakers are being manually controlled for maintenance.

2.3.5 Emergency Diesel Generator and Emergency Switchboard

The *Dali* was equipped with an EDG able to power essential onboard systems, such as navigation, communication, and emergency lighting, via the emergency switchboard during a loss of LV power. IMO regulations required the EDG to be able to automatically start and power the emergency switchboard within 45 seconds of the loss of normal LV power. However, the EDG did not connect to the emergency switchboard until 70 seconds after the *Dali*'s initial underway blackout. Because the 45-second requirement was not achieved after the vessel's initial underway blackout, the NTSB analyzed the electrical schematics for the emergency switchboard and generator control circuitry to identify potential causes for the delay.[140]

According to the *Dali* crew, and confirmed by the departure checklist for the day, the EDG was in the standby start configuration when the vessel got underway on March 26. If the EDG was not in the standby start configuration, during the initial underway blackout, the crew would have had to go from the ECR to the EDG, in

[140] The emergency generator was tested in the presence of ClassNK and NTSB multiple times after the accident. Each time, the emergency generator successfully started and connected to the emergency bus within the required time.

darkness and with numerous alarms sounding, and configure the EDG to the standby start configuration within the 70 seconds before the EDG connected to the emergency switchboard. It is improbable that they would have had time to do so. Therefore, investigators concluded that the EDG was likely in standby start configuration at the time of the initial underway blackout, with the three required automatic-start conditions met.[141]

With the EDG in standby start configuration, when the emergency switchboard lost power, the EDG's radiator damper, which controlled air flow through the radiator to regulate the EDG's temperature, should have received a signal to open as part of the auto-start sequence. Once a limit switch within the damper's actuator detected that the damper was open, the EDG should have started, come up to speed, and connected to the emergency switchboard automatically. Due to the system design, any delay in the opening of the radiator damper (or its limit switch indicating it as not open) would postpone the start of the EDG, prolonging the time before the emergency switchboard could be powered.[142] In the case of the EDG's radiator damper on the *Dali*, if the actuator's limit switch did not indicate the damper was open, the EDG start sequence would not initiate, thus preventing it from starting automatically. Given that the EDG did not automatically connect to the emergency switchboard, the radiator dampers must not have opened in time.

Investigators tested the EDG after the accident, and it connected within the expected 45 seconds. However, the exact physical state of the EDG dampers, their actuators, and linkages at the time of the accident is unknown. Radiator damper components can be prone to jamming and restricted movement. If the damper's components had jammed, the damper actuator's limit switch would not have indicated open, and the EDG would not have connected and powered the emergency switchboard. The NTSB concludes that it is likely that the EDG's failure to connect and power the emergency switchboard within 45 seconds, as required by IMO regulations, was due to the EDG radiator damper actuator's limit switch not indicating open in the required time due to unknown circumstances.

[141] In order for the EDG to be in standby start configuration, (1) the emergency switchboard three-position selector switch must be set to "normal," (2) the engine control panel on the EDG set to automatic mode, and (3) the EDG ventilation control panel, which is located within the EDG room, is set to automatic.

[142] On the *Dali*, the *limit switch* (an electromechanical device used to detect the presence or position of an object) within the EDG radiator damper's actuator detected whether the damper was open or closed.

LV power was restored 58 seconds after the initial underway blackout, meaning that the vessel went without steering gear pumps available for 13 seconds more than the 45 seconds required by regulation for an EDG to start. These 13 seconds were likely not enough for the crew to maneuver the vessel given the lack of propulsion and the *Dali*'s proximity to the bridge. However, it is critical that an EDG starts as quickly as possible in order to recover steering following a loss of power and aid in maneuvering situations.

ClassNK rules and IACS requirements only address ventilation dampers for emergency generator rooms, but do not address radiator dampers specifically (ClassNK n.d.; IACS 2016). Simply put, dampers for the rooms holding the equipment are regulated, but dampers for the equipment itself are not. According to ClassNK, a design that ensures the emergency generator can supply power within 45 seconds is "considered to be acceptable."

Limit switches, which are already used in various damper designs aboard vessels, can be used as remote indicators or alarms that notify crewmembers of a damper's position. For instance, if an engine start design was planned so that the damper open command operated in parallel with the engine start rather than in series (like the *Dali*'s), a limit switch could alert crew if the damper fails to open—while still allowing the emergency generator engine to start.

The NTSB recommends that Synergy identify ships it operates with similar arrangements to the *Dali* and notify crews of those vessels that partially open radiator dampers can delay or prevent the emergency diesel generator from starting automatically. The NTSB also recommends that ClassNK share the circumstances of the contact of containership *Dali* with the Key Bridge and subsequent bridge collapse with IACS, and urge them to distribute report MIR-25-40 to their members, highlighting the potential risks that partially open radiator dampers can pose to emergency generators starting, and the need for members to review their rules on acceptable emergency generator start design.

2.4 Crew and Pilots' Response

When the *Dali* initially lost power (LV blackout) and propulsion on March 26, the vessel was underway at 8.9 knots (10.2 mph) on a heading of 142°. At the time of this blackout, the *Dali* was about 3,200 feet (3.3 ship lengths) from the Key Bridge.

Before the blackout, the helmsman steered to maintain a heading of 141°, which resulted in the ship's head yawing, from a maximum of 1.6° per minute to port to 1.1° per minute to starboard.[143] When the *Dali* lost power at 0125:00 (the initial underway blackout), the vessel's heading was 142°; the rate of turn was minimal (0.7° per minute to starboard); and the rudder was amidship. Over the next minute, the rate of turn to starboard increased to 4.5° per minute (to a maximum value of 7.5° per minute to starboard at 0126:18).

The increasing rate of turn after the initial underway blackout could have been influenced by the vessel's rotational momentum. To turn a ship or change its heading underway, initially, rudder must be applied (move the rudder to port or starboard), accompanied by propulsion.[144] When the rudder is applied, the rudder lift force creates a moment that diverts the vessel from its original heading. Once there is an angular difference between the centerline or heading and the vessel's course, lift is developed on the hull. A turn, or heading change, is typically initiated by a change in the rudder angle, but the hull lift force makes the vessel turn. With the *Dali* rudder amidship, forces that caused the yawing would have continued to act on the ship and accelerate the heading deviation to starboard (increased rate of turn).

Ships maneuvering in confined waters (e.g., close to a canal bank, riverbank, or shoal) can experience bank effect. While making headway, water flow down the side of a ship creates positive pressure forward of the pivot point and negative pressure aft.[145] In a channel, such as the Fort McHenry Channel, the resultant forces can attract a ship's stern toward the bank, called bank suction, and push the bow away from the bank. Generally, the faster the ship sails, the greater the suction at the stern.[146]

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[143] When a vessel *yaws*, it is rotating about its vertical axis, which causes the bow to move from side to side. In calm seas with minimal current, yaw can develop when rudder is applied.

[144] At low speeds, the availability of propulsion is critical for effective shiphandling, as the was (thrust) over the vessel's rudder allows it to perform as designed and reliably change the vessel's course over ground. At higher speeds, depending on the vessel's design characteristics, a rudder (working together with the hull) can change the vessel's course over ground absent propulsion if the speed is sustained. This is also assuming there are no environmental factors of wind or current and only applies to a vessel moving forward.

[145] When a vessel is underway and steering and propulsion are applied, a turning moment is created, and the vessel will pivot around a point, known as the *pivot point*. The actual location of the point varies depending on the shape of the hull, speed, and other factors, but a common tenet is that, for a vessel moving forward under its own power, the location is about one-third of the length of the vessel aft of the bow.

[146] The *Shiphandler's Guide* explains: "To a ship running in shallow water, with adjacent but gently shelving mud or sand banks, such as low-lying estuarial areas … the effect can be far more insidious and violent" (Rowe 2007).

A vessel will tend to continue straight in a channel with symmetrical banks when its hull is in equilibrium and there are no other external forces, such as wind and current, acting on the vessel. When navigating the center of the channel, the *Dali* would have had about 270 feet of bank clearance on either side of the hull. During the accident transit, before the loss of power, the vessel was slightly to port of the channel's center and within 1° of the channel's base course. Therefore, the hull was in relative equilibrium, meaning there was a balance of pressure acting on the vessel's hull below the waterline from either side of the channel.

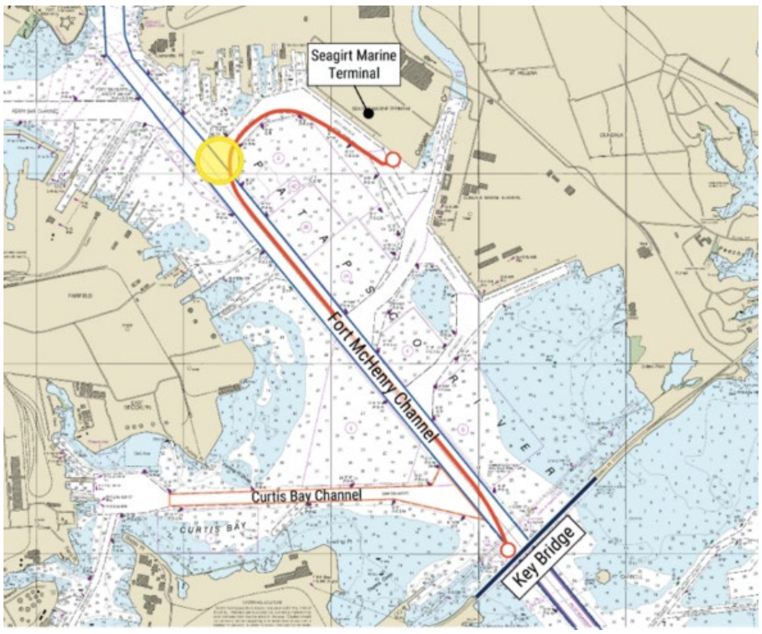

Figure 68. The red trackline represents the *Dali* after it departed Seagirt Marine Terminal and approached the Key Bridge. (This image also appeared as figure 6.) (Source: NOAA Chart 12281)

As the *Dali* proceeded toward the Key Bridge in the Fort McHenry Channel, it approached the entrance to the Curtis Bay Channel to starboard (see figure 68). The water adjacent to the channel on the vessel's port side was 9.1 meters (29.9 feet) deep, whereas the Curtis Bay Channel was dredged to the same project depth as the Fort McHenry Channel at 53 feet (see figure 69). Thus, the vessel had entered a section of the channel with asymmetrical banks. As the *Dali* transited this area, the positive pressure against the starboard side of its hull would have diminished. Subsequently, the positive pressure remaining on the port side between the bank and the hull would no longer be met with equal pressure from the opposing bank. With the forces against the hull no longer in equilibrium, the vessel's bow would have moved to starboard, away from the bank on the port side.

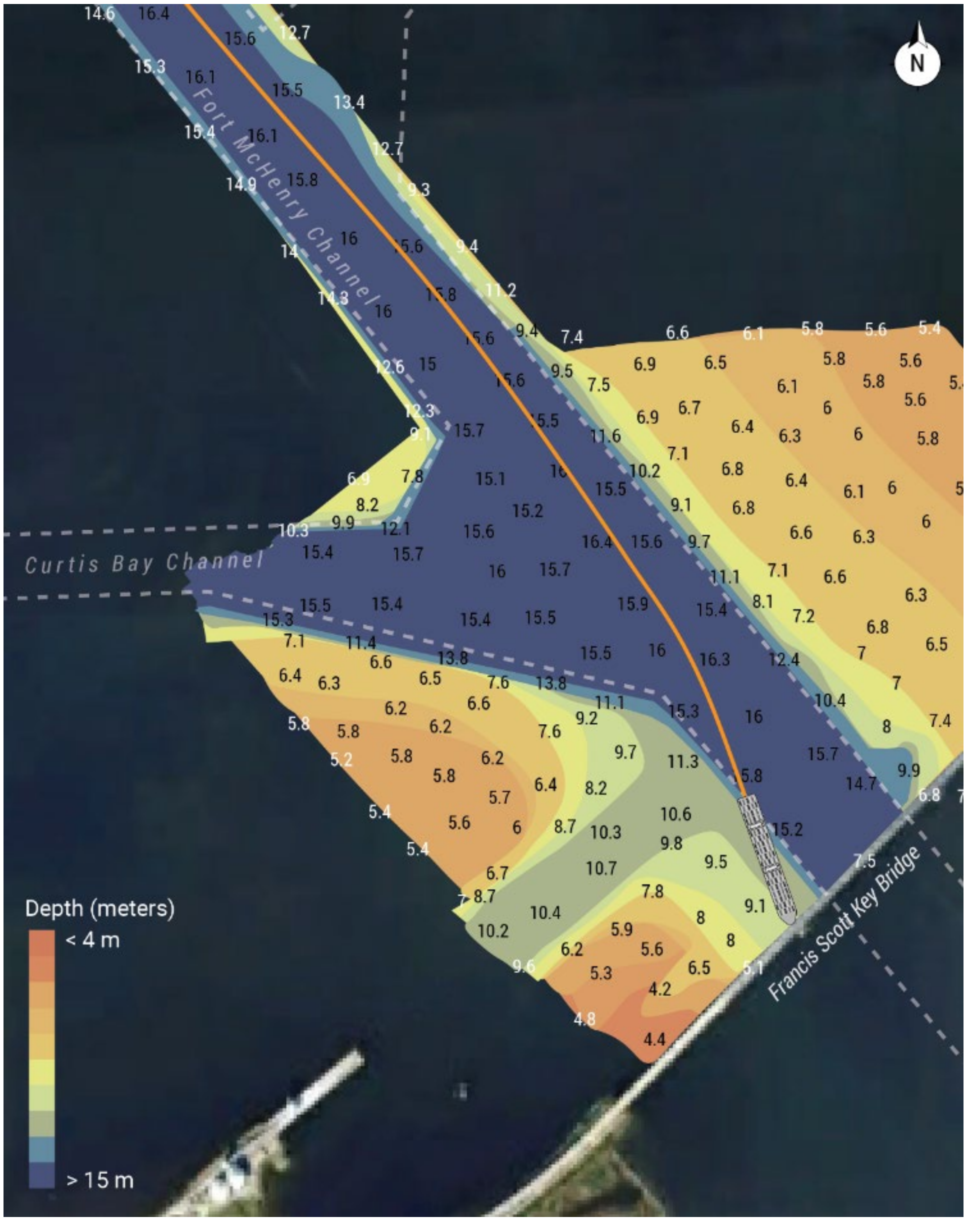

Figure 69. Depths (in meters) of Patapsco River in and near the Fort McHenry Channel and Curtis Bay Channel. The *Dali* (not to scale) and its trackline are shown; the vessel's draft at the time was 12.15 meters (39.86 feet) fore and aft. (Background source: Google Earth, NOAA)

Steering gear pump nos. 1 and 2 became available at 0125:58 (-3:11) after LV power was restored, and pump no. 3 became available at 0126:10 (-2:59) after the EDG restored power to the emergency bus.[147] However, from the moment the vessel

[147] This section contains time notations in parentheses, such as 0125:58 (-3:11), which indicate the time, in minutes and seconds, until the *Dali* contacted the Key Bridge.

lost power initially until the vessel struck the bridge, the vessel's propulsion remained unavailable because the main engine was not restarted.

The senior pilot knew that harbor tugs (*Eric McAllister* and *Bridget McAllister*) were nearby—since they had been involved in the undocking and maneuvering operations—so he instructed the pilot-in-training to retrieve the senior's VHF radio at 0126:22 (-2:47). At 0126:38 (-2:31), the senior pilot called for tug assistance, and the *Eric McAllister* responded about 30 seconds later. However, with the *Dali* moving at least 8 knots (9.2 mph), and the tug 3.5 miles from the containership, the *Eric McAllister* would not have been able to intervene in time.[148]

At 0127:02 (-2:07), with the vessel transiting about 7.9 knots (9.1 mph) and 1,500 feet (1.5 ship lengths) from the Key Bridge, the senior pilot ordered the port anchor let go; the master relayed the order to the bosun, via UHF radio, and the bosun began the process to drop anchor. The senior pilot stated that he knew the anchor would not stop the ship but he believed that the port anchor could possibly be used to get the vessel's heading to tend (start moving) to port.

The senior pilot ordered hard to port at 0127:23 (-1:46), and shortly after, the helmsman reported the helm was on hard port. According to VDR parametric data, the rudder reached hard port at 0127:54. The senior pilot's intention with this rudder order was to try to regain control of the vessel's heading, as he was tracking the increasing rate of turn to starboard. Although the rudder responded to the helm command, the rudder was less effective because the vessel did not have propulsion.

At 0128:59, the VDR recorded the sound of anchor chain running—about 10 seconds before the *Dali* struck the Key Bridge. Even if the crew had been able to let go the port anchor immediately after the senior pilot's 0127:02 order, there likely would not have been enough distance between the vessel and the bridge and time for the anchor to pay out to have reduced the vessel's forward momentum or appreciably changed the vessel's heading. Further, it would have been extremely difficult and unsafe for the bosun—with the chain paying out and at the vessel's speed—to apply the brake so that the anchor would have any holding power to alter the trajectory of the bow.[149]

At 0127:46, the senior pilot attempted to maneuver the vessel by ordering full to port on the bow thruster, which the second mate executed. As shown in the VDR

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[148] The *Eric McAllister* would have taken 16 minutes to transit the 3.5 miles to the *Dali*.

[149] For more information, see the *Vehicle Performance Specialist's Study* in the public docket for this investigation (case number DCA24MM031).

parametric data, this effort had no effect because the bow thruster was not running at that time, as it had not been restarted after the initial underway blackout. In general, bow thrusters are most effective at slow vessel speeds. According to vessel documentation, the *Dali's* bow thruster was not effective at speeds greater than 5 knots (5.8 mph).[150] When the senior pilot attempted to use the bow thruster, the vessel was transiting at 7.5 knots (8.6 mph). Therefore, even if the vessel's bow thruster had been restarted, it would not have been effective until the vessel slowed.

Only 4 minutes 9 seconds passed between the initial underway blackout and the vessel striking the Key Bridge. Based on a review of the VDR data, the bridge team and pilots maintained clear, concise communication before and during the emergency. The vessel's initial rate of turn and bank effect would have caused the vessel's heading to tend to starboard. The bridge team and pilots tried to use available resources to change the vessel's trajectory: the rudder and bow thruster to change the vessel's heading; the anchor to get the vessel's heading to tend to port; and a call to nearby harbor tugs to try to intervene. However, the vessel ultimately struck Pier 17 of the Key Bridge. The NTSB concludes that the actions of the pilots and the bridge team in response to the emergency were executed in a timely manner, but the vessel's loss of propulsion close to the Key Bridge rendered their actions ineffective.

2.5 Communications

2.5.1 Ship and Shoreside Emergency Communications

At 0125:59, the senior pilot contacted the Maryland pilot dispatcher via cell phone to inform him that the *Dali* had lost steering and was headed toward the Key Bridge. The senior pilot requested that traffic be cleared from the bridge. This call was about 7 seconds long, with the dispatcher asking only one clarifying question to confirm he was referring to the Francis Scott Key Bridge. About this time, the vessel was 2,430 feet (about 2.5 ship lengths) from Key Bridge Pier 17, approaching at a speed of 8.6 knots (9.9 mph).

While obtaining the Coast Guard's contact information per the single-point emergency contact protocol, the dispatcher saw the MDTA phone number and called it at 0126:44, just 35 seconds after talking to the senior pilot. This conversation lasted

[150] For the *bow thruster* be 100% effective, the vessel's draft would have to be 5.0 meters (16.4 feet). At the time of the vessel's departure from Seagirt Marine Terminal, the vessel's draft was 12.15 meters (39.9 feet) fore and aft.

22 seconds. At that time, MDTA police were stationed on both the north and south ends of the Key Bridge to perform traffic calming due to the roadwork being performed that night. Because the police were already stationed at either end of the bridge, they were able to stop all traffic at 0128:21. When the *Dali* struck Pier 17 of the bridge 48 seconds after the traffic was stopped, there were no vehicles traveling over the bridge.

The senior pilot also instructed the pilot-in-training to make a sécurité call over VHF radio. The pilot-in-training broadcast the call at 0127:25, alerting other nearby vessels to the nature of the *Dali*'s emergency.

The NTSB concludes that the pilots', the pilot dispatcher's, and the MDTA's quick actions to stop bridge traffic prevented a greater loss of life from the bridge collapse.

The Association of Maryland Pilots had a procedure in place in case of emergency, including initiating contact with shoreside support when land-based action was required. The successful use of this procedure during this accident demonstrated the importance of quickly establishing communication with shoreside support staff to mitigate the risk of loss of life or damage.

Harbor safety committees (HSC) like the Port of Baltimore HSCC serve as a forum for ports' stakeholders to discuss and coordinate issues of port safety and operations. The membership of each HSC is unique to each port, and local pilot associations are commonly active members. The HSC National Steering Team is organization of maritime professionals and key federal agency representatives at the national level that serves as a guiding body that HSCs nationwide can turn to for assistance (Coast Guard 2025). The mission of the HSC National Steering Team is "to provide information, guidance, and inspiration to support the establishment, development, and sustained excellence of HSCs." Therefore, the NTSB recommends that the HSC National Steering Team share with HSCs nationwide the circumstances of the contact of the containership *Dali* with the Key Bridge and subsequent bridge collapse, highlighting the importance of having a procedure, including immediately available emergency contact information, for pilots to initiate contact with shoreside support in an emergency requiring shoreside action to ensure timely and efficient action by first responders and port stakeholders.

2.5.2 Motorist Warning Systems

Protecting bridges from collapse due to vessel strikes is a multitiered process comprised of numerous potential countermeasures, including protecting a bridge through physical structures to prevent a vessel contact due to changes to vessel traffic that may reduce the risk of contact. Countermeasures focusing on the physical protection of a bridge are a long-term countermeasure and can be extremely costly. However, fully protecting a bridge against extreme events such as vessel or vehicle impacts is not always possible, and additional short-term countermeasures are needed to prevent the potential loss of life to motorists when a bridge collapse occurs.

Since the 1970s, the NTSB has investigated multiple bridge collapses and issued numerous recommendations to further the protection of bridges from vessel strikes, to prevent motorist deaths resulting from the collapse, and to minimize unaware motorists driving off the damaged bridge following the collapse. In December 1980, in response to NTSB safety recommendations from the investigation into the collapse of the Sunshine Skyway Bridge, the FHWA distributed a memo titled, "Motorist Warning System on Bridges Subject to Ship Collisions."[151] This memo was followed up by a 1983 FHWA Technical Advisory titled, "Pier Protection and Warning Systems for Bridges Subject to Ship Collisions."[152] Both documents acknowledged the need to consider protection for bridge piers as well as the installation of warning systems to alert motorists in the event of a collapse. The FHWA's technical advisory provided examples of various technologies (as shown in Appendix A of the advisory) available at that time that could be used to close a bridge to highway traffic in the event of an impending vessel strike, as well as motorist warning systems that could stop motorists from entering onto a bridge following a full or partial collapse. These technologies included laser or radar systems that could detect the presence of a large vessel close to vulnerable bridge structures and a system to warn motorists due to the approaching hazard. Technologies to detect a full or partial collapse included pier vibration sensors and bridge continuity sensors.

As a result of the investigations into the 2001 Queen Isabella Causeway partial bridge collapse near South Padre Island, Texas, and the 2002 Interstate 40 bridge collapse near Webbers Falls, Oklahoma, the NTSB issued a safety recommendation to the FHWA to develop an effective motorist warning system to stop motor vehicle traffic in the event of a partial or total bridge collapse.[153] Additionally, a

[151] See Motorist Warning System on Bridges Subject to Ship Collisions - Structures - Bridges & Structures - Federal Highway Administration.

[152] See FHWA Technical Advisory T5140.19: Pier Protection and Warning Systems for Bridges Subject to Ship Collisions - Bridges & Structures - Federal Highway Administration.

[153] Safety Recommendation H-04-030, classified Closed—Acceptable Alternate Action in 2013.

complementary safety recommendation was issued to AASHTO that once such a system had been developed, AASHTO should provide guidance to the States on its use.[154]

Following the replacement of the Queen Isabella Causeway bridge, the Texas Department of Transportation (DOT) installed a motorist warning system on the new structure. This early warning collapse detection system became operational in March 2004, was upgraded in 2007, and consisted of a continuous fiber-optic cable, which, if severed, activated flashing lights to warn motorists of danger ahead (see figure 70 and figure 71).[155] The system also included traffic gates, dynamic message signs, and warning signs (see figure 72). Before this installation in Texas, the technology for these types of motorist warning systems had been found to be unreliable and problematic due to the long-term monitoring needs and the systems' inability to withstand the conditions typically found on bridges.

[154] Safety Recommendation H-04-031, classified Closed—Acceptable Action in 2013.

[155] See Focus - Showcasing an Advanced Motorist Warning System in Texas - FHWA-HRT-13-008 - November 2012 | Federal Highway Administration.

Figure 70. Fiber-optic cable installed on the rebuilt Queen Isabella Causeway bridge. (Background source: Texas Department of Transportation)

Figure 71. Red flashing motorist warning lights (*circled*) installed on the rebuilt Queen Isabella Causeway bridge. (Background source: Texas DOT)

Figure 72. Traffic gates, warning signs, and motorist warning lights installed on the rebuilt Queen Isabella Causeway bridge. (Source: Texas DOT)

In 2009, the FHWA updated the NTSB on Safety Recommendation H-04-030 and reported that technology had advanced sufficiently for research into motorist warning systems to be implemented and that several vendors believed the technology to be market ready and feasible for installation. These advancements resulted in the FHWA funding pilot projects for motorist warning systems, and in 2012, they showcased the Collapse Warning System installed on Queen Isabella Causeway bridge. In conjunction with the FHWA's actions, AASHTO, through their Subcommittee on Bridges and Structures, updated the 1991 AASHTO *Guide Specification* to include examples of vessel collision risk assessment and bridge evaluation procedures to include the use of motorist warning systems.

The collapses of the Sunshine Skyway Bridge, the Queen Isabella Causeway bridge, and the Interstate 40 bridge occurred with no advance notice of the impending vessel strikes. However, the circumstances surrounding the *Dali*'s contact with the Key Bridge provided advance warning of the approaching vessel's aberrancy and the threat to the bridge. The Key Bridge, like many other bridges, was not equipped with a warning system to alert and stop motorists from driving onto the bridge in the event of a hazard. However, on the night of the collapse, police were stationed on both ends of the bridge conducting traffic control duties in conjunction with the ongoing maintenance project to repair the bridge deck. Knowledge of the *Dali*'s aberrancy allowed the police officers advance notification of the approaching vessel and its likely impact with the bridge which in turn allowed them to stop vehicular traffic onto the bridge before the *Dali* contacting Pier 17. As stated earlier, had police officers not been present and alerted to close the bridge to vehicular traffic, the motorists would not have been warned or stopped in response to the imminent collapse. The rapid closure of the bridge to vehicular traffic by the police saved the lives of motorists approaching the bridge and demonstrates the value of quickly closing a bridge to vehicular traffic due to an imminent hazard. This event highlights the need for motorist warning systems that can be activated in advance of an impending collision, especially when police are not available to quickly stop vehicular traffic on a bridge.

The NTSB concludes that in lieu of police officers or highway workers charged with traffic control and capable of quickly stopping traffic, a motorist warning system designed to warn and stop motorists from entering onto a bridge is a possible countermeasure that can be quickly implemented to save lives and may be a component of an effective bridge protection strategy. Therefore, the NTSB recommends that bridge owners with bridges above the AASHTO threshold or who have not yet completed their Method II calculations should, as part of their short-term bridge risk reduction and mitigation strategies to protect the traveling public, evaluate the need for, and, if appropriate, incorporate, motorist warning systems capable of activating when a threat is identified and immediately warn and stop motorists from entering onto the bridge.

While progress has been made to improve the use of warning systems to alert motorists in the event of a collapse, more work needs to be done regarding guidance on these technologies and on the selection and use of such systems. In addition to strategies intended to protect bridges, the FHWA's 1983 Technical Advisory included examples of technology designed to detect and warn motorists of hazards associated with a bridge collapse. The concepts presented in the advisory are still valid today and provide for early warnings to motorists of pending bridge collapse as well as methodologies for warning and stopping motorists following a bridge collapse and alerting workers on a bridge of a hazard. However, advancements in these technologies as well as the introduction of new solutions have occurred since the advisory was published in 1983.

The FHWA has had a significant role in the development of new technologies for bridge safety, providing information to states and bridge owners on their appropriate use, and encouraging their deployment through workshops and showcase projects such as the 2012 showcase event for the Collapse Warning System installed on Queen Isabella Causeway bridge. Additionally, the FHWA has continuously worked with AASHTO in developing language to incorporate those technologies into AASHTO publications such as the 2009 *Guide Specifications*. Another example of the collaborative efforts between the FHWA and AASHTO relating to motorist warning systems is the AASHTO *LRFD* [Load Resistance Factor Design] *Road Tunnel Design and Construction Guide Specifications*. In a similar need for warning motorists of a tunnel closure, these specifications require intelligent transportation system technologies to stop traffic within a tunnel before an incident site, such as a fire, and for stopping motorists on the approach roads upstream of the incident.[156] These technologies include the use of programmable dynamic message signs to display instructions and emergency messages to motorists, and traffic stop signals to close tunnels and prevent vehicles from entering in the event of an emergency. Both are valuable tools that can be used for emergency bridge closures.

While the 2009 AASHTO *Guide Specifications* provides information on motorist warning systems, it provides little in the way of guidance in the selection of those systems. As demonstrated through their collaborative efforts to develop and implement motorist warning systems, both the FHWA and AASHTO have a role in the continued improvement and broader implementation of such systems.

The NTSB concludes that owners of bridges over navigable waterways frequented by ocean-going vessels would benefit from updated guidance on motorist warning systems including incorporation of hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure and systems that would both warn and prevent motorists from entering a bridge once a threat is detected. Therefore, the NTSB recommends that AASHTO update its *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* to include guidance in the selection of motorist warning systems. Evaluated changes should include FHWA research on hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected. The NTSB also recommends that FHWA research hazard alert and sensing technologies capable of

[156] Intelligent transportation system technologies for tunnels can include monitoring and traffic control devices internal to the tunnel as well as detection of slowed and stopped traffic, fire, and other hazards in and approaching/exiting the tunnel.

detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected. The FHWA should provide the results of its research to the AASHTO.

2.5.3 Highway Worker Emergency Communications

At the time of the collapse, there were seven employees from Brawner Builders, Inc. and one employee, an inspector, from Eborn Enterprises, Inc., a subconsultant to the MDTA on the bridge. The inspector, who was walking the bridge length, had exchanged cell phone numbers with the MDTA police officers positioned at each end of the bridge and the foreman leading the construction activities. Despite exchanging cell phone numbers between the inspector and the police officers, when the call came in for the police officers to shut down the bridge to roadway traffic, the police officers did not call the inspector. Instead, the police officers planned to drive onto the bridge to notify the workers about the *Dali*'s emergency once backup was available. The *Dali* struck the bridge before the police officers were able to contact the road work crew. Procedures for real-time communications were not established between the highway workers or the inspector and the MDTA police officers. Therefore, they did not receive information about the impending impact at the same time as the police were notified to close the bridge.[157]

At this time, the roadway workers were on a work break in their vehicles located on Spans 18 and 20 (see figure 17) and the inspector was walking on Span 22. If notified, and the workers used their vehicles to evacuate the bridge, all workers would have likely driven south to evacuate the bridge because all vehicles were facing south and some were towing generators or were too large to make a U-turn on the bridge.[158] Although unknown to the workers, Span 16 would have been the closest point of safety, which was located 2,928 feet from the northernmost construction vehicles on Span 20. The four construction vehicles on Span 18 would have been 1,694 feet from the safety of Span 16. Had the inspector or the other workers been alerted to the vessel's emergency situation at the same time the officers at either end of the bridge were notified, the inspector and the road work crewmembers would have had 1 minute 16 seconds before vessel contact (or

[157] *Real-time communications* are the instant exchange of information with minimal delay, allowing for immediate, interactive conversations between individuals.

[158] There were only two lanes in the southbound direction, and the southbound and northbound direction was separated by a concrete barrier.

1 minute 29 seconds before bridge collapse), which may have been sufficient time to receive notification to evacuate and reach a span that did not collapse.

The NTSB concludes that had the inspector and highway workers been notified of the *Dali*'s emergency situation about the same time the MDTA police officers at each end of the bridge were told to block vehicular traffic, the highway workers may have had sufficient time to drive to a portion of the bridge that did not collapse.

According to MDTA's contract with Brawner Builders, the company that employed the roadwork crew on the Key Bridge at the time of its collapse:

> The Contractor [Brawner Builders] must provide a means of communication to the MDTA/MSP detachment/barracks as a safety requirement. Acceptable forms of communication shall consist of a mobile telephone, citizens band or portable two-way radio.[159]

Although the inspector on the bridge had exchanged mobile phone numbers with the MDTA police officers, the inspector was not notified of the imminent, life-threatening hazard created by the *Dali*. This indicates that the reliance on an informal exchange of mobile device numbers as a means of communication between the MDTA police officers and workers on the bridge was not effective in alerting the workers of the imminent hazard created by the aberrant *Dali*. A portable two-way radio may have provided a more immediate communication method. The NTSB concludes that effective and immediate communication to evacuate the bridge during an emergency is critical to ensuring the safety of bridge workers.

The American National Standards Institute (ANSI) is a private, non-profit organization that "oversees standards and conformity assessment activities in the United States" (ANSI n.d.). The ANSI-Accredited Standards Committee, with the American Society of Safety Professionals (ASSP) serving as secretariat, developed and published *Standard A10*, *Work Zone Safety for Roadway Construction*, a series of standards related to safety in construction and demolition operations, with *ANSI/ASSP A10.47-2021* covering "workers engaged in construction, utility work, maintenance or repair activities on any area of a roadway" (ASSP 2021b).

According to this standard, pre-job planning, including method statements and a job hazard analysis, will be conducted before work begins to determine appropriate needs for–

[159] MDTA contract MR-3025-0000.

- Safety issues and controls,
- Materials and logistics,
- Equipment,
- Staffing requirements,
- Traffic control plans,
- Internal traffic control plans, and
- Lighting (ASSP 2020, 2021a, and 2024).

Ship crews and pilots have means to communicate urgent information to the Coast Guard (such as dedicated VHF channels for emergency communication), whereas bridge contractors and inspectors working over navigable waterways do not have similar formal avenues to receive emergency information. Additionally, there are no regulations or standards for them to receive emergency information before or during dangerous or life-threatening events occurring relative to their work zones. Therefore, the NTSB recommends that ANSI Accredited Standards Committee on Safety in Construction and Demolitions Operations A10 revise *ANSI/ASSP A10.47, Work Zone Safety for Roadway Construction*, to include an effective and immediate means of emergency communications to alert workers performing roadway work on bridges over navigable waterways, which should consider the presence of law enforcement for traffic control.

2.6 Safety Management Systems

The NTSB has previously advocated for the benefits of, and made recommendations to implement and improve, SMSs across all modes of transportation, because an effective SMS can help organizations reduce and prevent accidents and accident-related loss of lives, time, and resources.[160] Proactive safety management, when done correctly, is predictive, designed to anticipate and address

[160] Examples include the following NTSB reports: Aviation Investigation Report AIR-25-04, *In-Flight Separation of Left Mid Exit Door Plug, Alaska Airlines Flight 1282, Boeing 737-9, N704AL, Portland, Oregon, January 5, 2024*; Aircraft Accident Report AAR-10-01, *Loss of Control on Approach, Colgan Air, Inc., Operating as Continental Connection Flight 3407, Bombardier DHC 8 400, N200WQ, Clarence Center, New York, February 12, 2009*; Railroad Accident Report RAR-10-01, *Collision of Two Washington Metropolitan Area Transit Authority Metrorail Trains Near Fort Totten Station, Washington, D.C., June 22, 2009*; Marine Accident Report MAR-20/03, *Fire Aboard Small Passenger Vessel* Conception*, Platts Harbor, Channel Islands National Park, Santa Cruz Island, 21.5 miles South-Southwest of Santa Barbara, California, September 2, 2019*; and Highway Accident Report HAR-01-01, *Motorcoach Fire on Interstate 45 During Hurricane Rita Evacuation, Near Wilmer, Texas, September 23, 2005.*]

safety issues before they occur, and utilizes continuous data analysis to improve policies and procedures.

The commercial aviation industry's SMS provides a robust model for achieving effective safety management. The four components of the aviation SMS and their elements, as outlined by ICAO, support a systematic, top-down, proactive approach. Safety policy establishes senior management's commitment to continually improve safety and defines the methods, processes, and organizational structures needed to meet safety goals. Safety risk management determines the need for, and adequacy of, new or revised risk controls based on the assessment of acceptable risk. Safety assurance evaluates the continued effectiveness of implemented risk control strategies and supports the identification of new hazards through data collection and analysis. Safety promotion includes training and communication regarding the SMS, and other actions to create a positive safety culture within all levels of the workforce.

The ISM Code's requirements for an SMS incorporate some aspects of the aviation industry's four-component SMS model. For example, safety policy is addressed through many of the six functional requirements for SMSs. Under the code, vessel owners and operators must define and document responsibilities and authorities, both on vessels and ashore, relating to safety and must develop detailed policies and procedures–including procedures for responding to emergencies and reporting accidents–for all crewmembers to follow.

However, some elements of the four-component SMS model are not included in the ISM Code requirements. For example, the safety risk management component requires hazard identification by reactive and proactive methods, as well as safety risk analysis, assessment, and control using processes that include predictive methods. While the ISM Code requires procedures ensuring that non-conformities, accidents, and hazardous situations are analyzed and corrective actions are implemented, these requirements are entirely reactive. Incorporating proactive hazard identification and predictive analysis, assessment, and control into an operator's SMS would help reduce safety hazards and risks before they happen.

As another example, the safety assurance component of the four-component model includes management of change. It requires a company to develop and maintain a process to identify changes that may affect safety and to manage the safety risks that arise from those changes. Management of change is not a requirement of marine SMSs under the ISM Code, but it is critical to ensuring any changes in an operation, such as increases or decreases in staffing levels, engineering modifications, or changes in the type of fuel used, do not compromise safety. An SMS requirement for safety assurance that includes a comprehensive management of change element would serve to strengthen the ISM Code SMS requirements.

As a final example, the ISM Code SMS requirements incorporate elements of safety promotion component, with detailed communication and training requirements associated with an SMS. However, the code does not address other critical elements of safety promotion, including the requirement for companies to provide a formal means of safety communication that conveys safety critical information and explains why particular actions are taken to improve safety and why safety procedures are introduced or changed. While many vessel owners and operators do have safety communications programs, the lack of a formal requirement in the ISM Code leaves open the possibility that mariners are not receiving the critical safety information they need. The NTSB concludes that while the requirements of the ISM Code include some elements of a comprehensive, proactive safety management system, the code does not fully encompass all four critical components of safety policy, safety risk management, safety assurance, and safety promotion.

IMO regularly reviews and revises the ISM Code based on stakeholder feedback. Proposed changes must be submitted to the Maritime Safety Committee (MSC), which oversees the ISM Code. The MSC reviews proposed amendments and, if accepted, drafts amendment text and circulates it to member states. This process occurs regularly, and in June 2025, at its 110th session, the MSC initiated a comprehensive review of the ISM Code (IMO 2025). Annex 19 to the ICAO Convention on International Civil Aviation provides a model for defining and fully encompassing all four components of a comprehensive safety management system. The NTSB recognizes that there are vast differences in the ways that the aviation and marine industries operate, and not all programs and systems can be shared between the two. However, for SMSs, the ICAO model is a universal framework that can be adapted to the marine industry, as it has been with other transportation industries, and provides a robust model for IMO's next generation of SMS. The US Coast Guard is the head of the delegation representing the United States at IMO. Therefore, the NTSB recommends that the United States Coast Guard propose to IMO that it revise the ISM Code and associated guidelines to fully incorporate safety policy, safety risk management, safety assurance, and safety promotion into its safety management system requirements.

2.7 Voyage Data Recorders

As a result of the NTSB's investigation of the 1973 collision of the containership *Sea Witch* with the oil tanker *Esso Brussels*, we issued multiple recommendations to address identified safety concerns. Among these recommendations, we asked the Coast Guard to—

> require the installation of an automatic recording device to preserve vital navigational information aboard oceangoing tankships and containerships (Safety Recommendation M-76-8).[161]

Throughout the late 1970s and 1980s, the NTSB issued additional safety recommendations to the Coast Guard to address investigators' needs for VDRs.[162] The 1994 capsizing and sinking of the passenger ferry *Estonia* in the Baltic Sea, which killed 852 people, increased industry focus on VDR requirements at IMO due to the vessel's lack of a data-recording system. The first VDR performance standard was proposed at IMO in 1997; it was adopted in 2000. The first requirement for vessels to be equipped with VDRs took effect on July 1, 2002. Since 1997, only three modifications of the original resolution—expanded carriage requirements to additional vessels, increased data-logging duration, and the addition of a limited number of additional data parameters—have been adopted.

The IMO's *International Convention for the Safety of Life at Sea* (*SOLAS*) regulation V/20 requires vessels built after 2002 to be fitted with a VDR, "to assist in casualty investigations." Per *SOLAS* regulation V/18, the VDR model must be approved by the vessel's flag administration and comply with the applicable performance requirements. As a cargo ship constructed after June 2014, the *Dali* was required to have a VDR compliant with IMO Resolution *MSC.333(90)*, the latest published international VDR performance standard for voyage data recorders, as well as additional requirements imposed by the flag administration, in this case Maritime

[161] The NTSB classified Safety Recommendation M-76-8 Closed—Unacceptable Action in September 1982.

[162] In 1978, the NTSB made Safety Recommendation M-78-2 to the Coast Guard, asking that it "Conduct a formal study in coordination with the Federal Maritime Administration and the shipping industry to determine a standard array of operational and audio data that should be recorded automatically with a view to establishing a requirement for the installation and operation of suitable equipment in U.S. vessels over 1,600 gross tons built after 1965, and to submitting an initiative to Inter-governmental Maritime Consultative Organization (IMCO) for the adoption of a similar international requirement." The Inter-government Maritime Consultative Organization became the International Maritime Organization in May 1982. The NTSB classified Safety Recommendation M-78-2 Closed—Unacceptable Action in September 1982. In 1981, the NTSB made Safety Recommendation M-81-84 to the US Coast Guard, asking that it, "expedite the study to require the installation of automatic recording devices to preserve vital navigational information aboard applicable ships." The NTSB classified Safety Recommendation M-81-84 Closed—Unacceptable Action in September 1982.

& Port Authority of Singapore (IMO 2012).[163] For installation on Singapore-flagged ships, the Maritime & Port Authority of Singapore accepts equipment approvals from nine class societies, as well as other flag administrations. The Japan Radio Co., Ltd (JRC) JCY-1900 model VDR was approved by TÜV SÜD according to the European Union Marine Equipment Directive (MED).[164] The MED requires that VDRs comply with the International Electrotechnical Commission's (IEC) standard *IEC 61996-1 Edition 2*, which specifies the minimum performance standards, technical characteristics, and testing methods for full VDR systems (IEC 2013).

After recovering the *Dali*'s VDR for analysis, the NTSB encountered issues that hampered an effective extraction, playback, and use of the data, including:

- Lack of recorded parametric data during the first blackout,
- Inability to download the full VDR dataset,
- Extremely time-consuming workflow for processing VDR data into standard commercial formats,
- Inadequate playback software,
- Lack of bridge telephone recording, and
- Lack of IMO and IEC standards to address functionality and useability standards for VDR software.

2.7.1 Recording of Voyage Data During Loss of Normal Power

2.7.1.1 Parametric Data

IMO resolution *MSC.333(90)* specifies that a VDR continue to record bridge audio for 2 hours after a loss of ship's power. However, there is no similar requirement for parametric data. The *Dali*'s VDR contained an internal battery to power the control unit recording bridge microphones during a power loss. It did not provide, nor was it required to provide, a backup power source to the unit that recorded parametric data. Several of the *Dali*'s navigational systems were powered by an uninterruptible power supply, which provides standby power until normal power is restored or emergency generator power is available. Some of these systems—including AIS, GPS, gyrocompass, alarm monitoring, and electronic chart display and information system (ECDIS)—contained sensors whose outputs are

[163] *MSC.333(90)* was amended in 2021 but did not bring significant performance changes.

[164] TÜV SÜD is a company that assesses product conformity, performs regulatory testing, and provides certification and auditing services on behalf of international governmental bodies, and private and non-profit organizations.

required to be recorded by the VDR when normal or emergency power is available. However, since neither normal nor emergency power was available, no parametric data were recorded during the blackouts even though data were coming from input data sources with their own redundant back-up power. Therefore, the NTSB concludes that the lack of recording of parametric information by the VDR during a power loss can inhibit proactive monitoring of these data by organizations and adversely impact an accident investigation.

2.7.1.2 Bridge Audio and Bridge Telephone Audio

When power was lost to the LV bus during the first blackout, the *Dali*'s VDR continued to record bridge audio from the bridge-mounted microphones. The VDR recorded only the bridge side of telephone conversations. Many vessel emergencies require communication between the bridge and other parts of the ship. Once the *Dali* lost power, the frequency of electric telephone calls, presumably to the engine room, increased, and the calls continued through the accident event.[165]

IMO standards did not require that a VDR record the communications line between the bridge and the engine room. As a result of our investigation into the October 1, 2015, sinking of the *El Faro*, we issued Safety Recommendation M-17-47 to the Coast Guard:

> Propose to the International Maritime Organization to amend resolution MSC.333(90) to specify that "normal operations" are defined as when a ship is under way using its main propulsion unit and to assess voyage data recorder problems, including not capturing both sides of internal phone calls on the bridge electric telephone and unrecorded very-high-frequency communications, and identify steps to remedy them (NTSB 2017).

In its initial July 17, 2018, response to our recommendation, the Coast Guard stated that it would propose to IMO that VDR performance standards be amended "to include all communications between shipboard control stations and both sides of all communications to the bridge." On March 25, 2019, the Coast Guard submitted a proposal to IMO to amend the organization's requirements for VDRs (US Coast Guard 2019). The Coast Guard stated that it considered its action on the recommendation complete. In our March 21, 2024, response to the Coast Guard, we stated that, to fully

[165] The bridge audio recording contained ambient conversational audio. Some conversations were conducted via telephone and thus only one side of the conversation was recorded by the VDR. See the *NTSB Voyage Data Recorder (Audio) Group Chairman's Factual Report* in the public docket for this accident investigation (case number DCA24MM031).

satisfy our recommendation, the Coast Guard must specify “normal operations” as defined in the recommendation. As a result, Safety Recommendation M-17-47 was classified Closed—Unacceptable Action. Ultimately, IMO did not update the VDR performance standard to record both sides of bridge telephone conversations.

Because only the bridge side of the phone conversations was recorded, the *Dali*’s VDR missed potentially critical information, such as the status of engine room equipment or other communication to the bridge team from the engine room crew as they worked to mitigate the emergency. Thus, the NTSB concludes that audio information from both sides of the *Dali*’s electric telephone was not recorded during the accident, which prevented the NTSB from hearing the engine room’s responses to the accident.

2.7.2 Mixed Monoaural Audio Channel Design

The JRC JCY-1900 VDR system fitted aboard the *Dali* had a mixed monoaural (also known as “mono”) audio design. This design mixed two or more audio channels into a single channel from which individual audio inputs cannot be isolated. For example, the left and right bridge wing microphones were combined into a single mono channel before recording to the unit. This practice is not prohibited by IMO Resolution *MSC.333(90)*, as long as the intelligibility of the recording can be maintained while “there is a single audio alarm anywhere on the bridge or any noise, including those from faulty equipment or mounting, or wind.” The IEC standard further specifies that the equipment “shall be capable of recording workstations with no more than 2 microphones per channel,” without stipulating that the microphones should be recorded in stereo format.

As a result of this monoaural configuration with multiple microphones per channel, it was difficult for the NTSB to isolate or analyze individual voices and sounds in the recording of the *Dali*’s bridge audio. Critical bridge conversations overlapped with unrelated background noise or audio from other stations, reducing overall intelligibility (see figure 73). Additionally, the bridge environment during the accident included multiple persistent and loud audible alarms, particularly during the blackout sequence, that frequently masked crew conversation. Because the audio channels were mixed together, alarms or specific conversations could not be filtered without also affecting other parts of the recording.

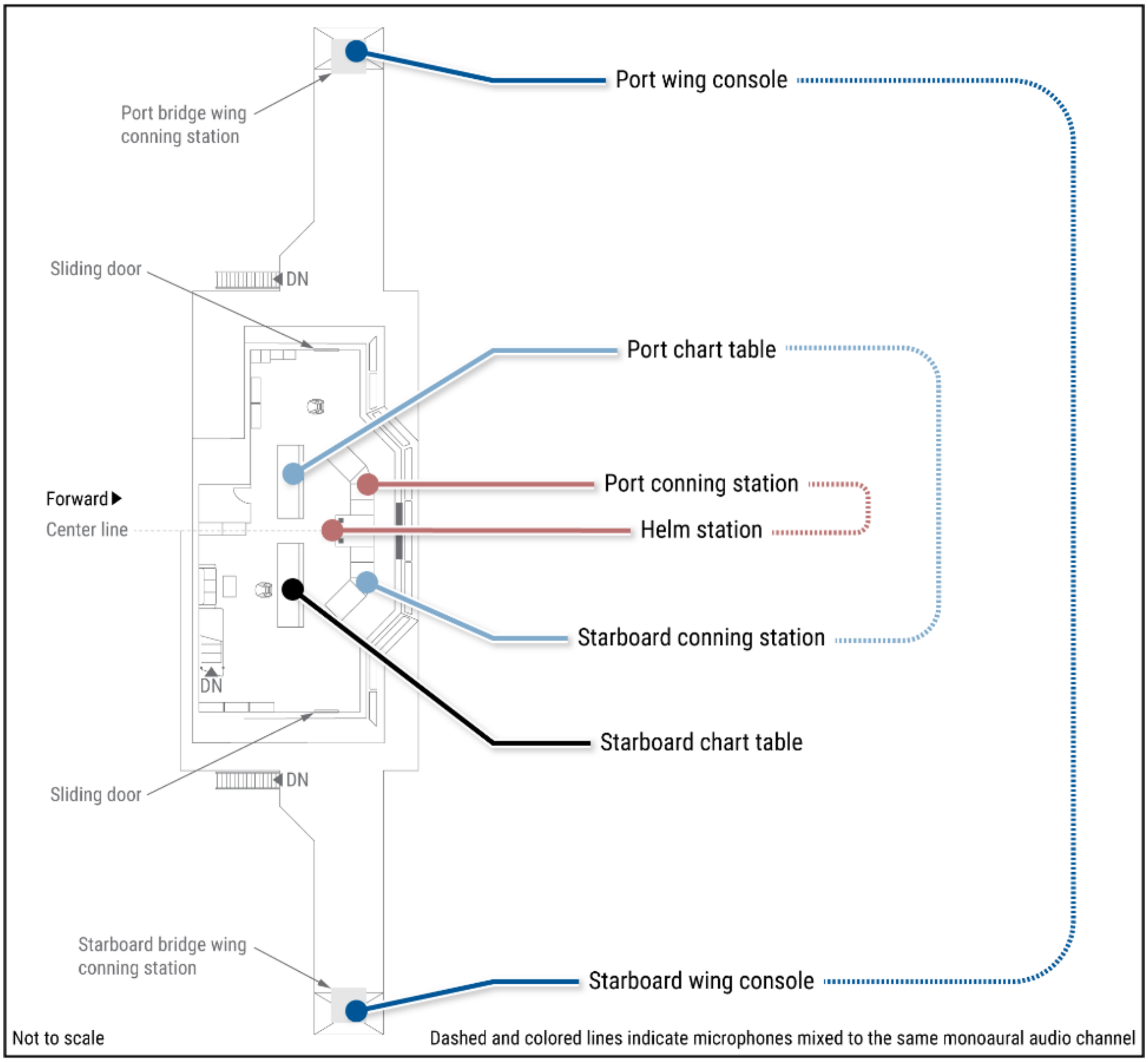

Figure 73. A plan view of the microphone locations on the *Dali*'s bridge.

Had the channels been recorded individually, or mixed into a stereo format, more postprocessing options would have been available to further enhance the quality of the bridge microphone recordings. For example, if the *Dali* VDR left and right bridge wing microphones had been recorded individually, the VDR processor would have stored them as two individual mono channels or a single stereo channel. In this scenario, postprocessing tools such as digital filters would have been more effective because there would have been less extraneous audio on a particular channel.

While the audio recordings met the IMO and IEC standards for VDR performance, they fell short in delivering the clarity needed for a detailed accident reconstruction and analysis, because they were mixed monoaurally and could no longer be isolated. Ultimately, the mixed channel design impeded the NTSB's ability to fully interpret bridge team communication during critical phases of the voyage.

Therefore, the NTSB concludes that the monoaural audio configuration of the *Dali*'s JRC-brand JCY-1900 VDR system, which mixed multiple microphones into shared channels, significantly impaired the NTSB's ability to isolate and analyze critical bridge conversations, distinct voices, and sounds from the alarms and background noise, thereby reducing the recording's intelligibility and limiting the effectiveness of audio enhancement tools.

2.7.3 Deficiencies in Voyage Data Recorder Access, Voyage Data Recorder Playback Software, and Performance Standards

While the JRC JCY-1900 VDR and the accompanying playback software complied with IMO and IEC standards, these standards do not address the software's usability for investigative authorities. The functional limitations of the software posed barriers to the NTSB's efficient extraction and analysis of VDR data from the accident in the time-critical early stages of the investigation. Rather than being able to play and review the VDR data quickly and easily, the NTSB had to use alternative means to complete a thorough analysis of the data. While the playback software was designed to meet the IEC standard, it was inadequate for the accident investigation.

IMO regulations require that VDR playback software be available to "investigation authorities."[166] Limitations of the playback software kept the NTSB from extracting any more than about 36 hours of data from before the accident. After several attempts to extract more than these 36 hours of data, the NTSB ultimately removed the VDR's memory components and transported them to the JRC Americas facility to secure the evidence.

It took the NTSB and JRC personnel using an exemplar VDR unit intended for training purposes and proprietary JRC software 36 continual hours to complete a full download of the cabinet data formatted in JRC's proprietary file format. The format required conversion using JRC's playback software and could not be replayed using

[166] The process for retrieving data from the *Dali*'s bridge-mounted USB console was time-consuming, requiring about one hour just to download the selected time window. This method, while intended for rapid access, still requires a significant amount of loading and restructuring data files to efficiently replay the data.

"open-industry standard format" (commercially available) software or NTSB investigative software.

In addition to the problems stemming from the proprietary file format, the conversion produced monoaural audio files in one-minute increments, for each mixed channel. To process a 6-hour audio segment, investigators had to use the proprietary software to convert the raw data, ultimately yielding 2,160 individual audio files. Additional software was required to arrange and combine these files for continuous playback. Because of limitations in the data and complexities in retrieving it, the NTSB reviewed specific time windows of interest, with a focus on the 24 hours leading up to the incident.

While IMO regulations require that a VDR continuously records audio for at least 30 days, the JRC software made exporting the full 30-day audio dataset with commercially available software unfeasible. This disconnect between regulatory performance standards and practical investigative needs has led to inconsistent quality among various manufacturer-provided VDR software.

The NTSB encountered challenges using the manufacturer-provided VDR software because the IEC standard lacks specificity in addressing data playback utility, functionality, and logical exportability. For instance, the software lacked fine-time audio scrubbing, a feature that is commonly included in commercially available software and allows users to rewind in second-long increments. The rewind feature in the manufacturer-provided software was imprecise, allowing users to rewind in increments of a minute or longer. Also missing from the software were audio-channel isolation and filtering that enhanced intelligibility and the quality of the audio. For the NTSB, and other investigation authorities that process VDR data, the software's deficiencies led to considerable resources being consumed and delayed investigators' ability to understand the sequence of the events and to issue timely safety recommendations aimed at preventing future accidents.

While the NTSB has the personnel, hardware, and software resources to extract and analyze VDR data under the current standards, other investigative authorities and vessel owners may not. In addition to providing accident investigation benefits, VDRs can be valuable tools in a company's SMS. Operators can review crew and vessel performance through data obtained during operations. The data can be used to study incidents, analyze vessel performance, train operators, and mitigate risk. Improvements in VDR software would improve and streamline this process, allowing operators and investigative authorities to make more timely and effective use of this safety data.

Just as VDR hardware must meet rigorous physical standards to survive an accident, the associated software must also be held to a similarly stringent functional standard to ensure that the recorded data can be effectively used. These issues revealed a critical disconnect between compliance with the published technical standards and practical investigative needs, highlighting the urgent need for operators, investigative authorities, and regulatory bodies and standard-setting organizations to modernize VDR standards to account for investigator-focused usability and functionality requirements. Therefore, the NTSB concludes that although the *Dali*'s JRC-brand JCY-1900 VDR complied with IMO and IEC standards, significant deficiencies in data accessibility, audio usability, and playback software functionality revealed a critical disconnect between published technical standards and practical investigative and organizational needs to identify safety issues and solutions, and for operators and regulators to ensure safety. The Coast Guard is the head of the delegation representing the United States at IMO. The NTSB believes IMO is the best avenue for updating VDR standards. Therefore, the NTSB recommends that the Coast Guard notify IMO of the VDR technical issues encountered during our investigation into the contact of containership *Dali* with the Key Bridge and subsequent bridge collapse, and submit to IMO a concrete proposal to require:

a. the recording of mandatory data inputs from systems that remain powered during a blackout,
b. the recording of engine room communications to the bridge,
c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
d. performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary VDR data into open industry standard formats.

The IEC's standards are developed by specialized technical committees, subcommittees, and working groups. IEC Technical Committee 80 is responsible for developing international standards related to maritime navigation and radiocommunication equipment and systems. ANSI represents the United States in the IEC, coordinating the participation of US experts in IEC technical committees, where they contribute to the development and revision of international standards. The NTSB also recommends that the ANSI propose to IEC Technical Committee 80 to revise *IEC 61996-1 ed. 2* to require:

a. the recording of mandatory data inputs from systems that remain powered during a blackout,
b. the recording of engine room communications to the bridge,

c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
d. the updating of performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary VDR data into open industry standard formats.

2.8 Increasing Vessel Sizes and Traffic Density in US Ports

When the Key Bridge opened to traffic in 1977, the largest containerships were about 700 feet long (Rodrigue and Notteboom 2024).[167] Containerships are significantly larger now: the *Dali* was nearly 1,000 feet long and displaced over 112,000 metric tons, and there are other containerships operating worldwide that extend over 1,300 feet long.[168] Additionally, containership capacity has grown exponentially, from about 500-800 twenty-foot equivalent units (TEU) in the 1950s to over 20,000 TEU in recent years—an increase of over 3,000% (CRS 2008; ERG 2020; Rodrigue and Notteboom 2024).

As early as 2006, the issue of increasing vessel sizes was a point of discussion raised during the quarterly Port of Baltimore Harbor Safety and Coordination Committee (HSCC) meetings with port stakeholders. The topic was initially mentioned as it related to port preparedness and how to protect potentially vulnerable infrastructure while accommodating larger vessels. This topic remained in the meeting minutes for several years. Although members of the HSCC included representatives from the MDTA, the US Army Corps of Engineers, US Coast Guard, and the Association of Maryland pilots, there were no outcomes from the numerous discussions regarding the potential implications larger vessels could have on critical infrastructure and port operations.

The increasing size of ships has corresponded with an increased growth in containership cargo volumes. Across all US ports, the total weight of imports and exports increased from about 1.26 billion metric tons in 2013 to about 1.47 billion

[167] For more information, see the NTSB specialist study, "Vessel size increase and associated safety risks: a review of the scientific literature," in the public docket for this investigation (case number DCA24MM031).

[168] Before containerization, ships were primarily designed for break-bulk cargo, where goods were loaded and unloaded individually. The introduction of containerships marked the beginning of a trend toward larger vessels. The expansion of the Panama Canal in 2016 allowed for the transit of larger vessels, which has further encouraged the trend toward increased ship sizes. The expanded canal can now accommodate vessels exceeding 14,000 TEUs, which were previously restricted by the canal's size limitations (Rodrigue and Notteboom 2024).

metric tons in 2023, a 16.7 percent increase. For container ships, the growth was more pronounced, with a 21.1% increase in cargo volumes, from 246 million metric tons in 2013 to about 298 million metric tons in 2023. The Port of Baltimore exhibited even more significant growth than the national average. The total weight of imports and exports at the Port of Baltimore increased by 71.7%, from about 27.6 million metric tons in 2013 to 47.4 million metric tons in 2023 (see table 6). The weight of cargo imported and exported by container vessels through the Port of Baltimore increased by 61.3% during the same period, from about 5.17 million metric tons to roughly 8.34 million metric tons.

Table 6. Total weight of vessel imports and exports in metric tons (all US ports and the Port of Baltimore, 2013–2023).

Year	All cargo (All US ports)	Containerized (All US ports)	All cargo (Port of Baltimore)	Containerized (Port of Baltimore)
2013	1.26 billion	246 million	27.6 million	5.17 million
2014	1.29 billion	257 million	26.8 million	5.46 million
2015	1.27 billion	264 million	29.5 million	5.98 million
2016	1.28 billion	274 million	28.8 million	6.51 million
2017	1.39 billion	292 million	34.7 million	7.41 million
2018	1.45 billion	311 million	39.1 million	7.87 million
2019	1.40 billion	307 million	40.1 million	8.16 million
2020	1.34 billion	306 million	33.9 million	7.82 million
2021	1.44 billion	331 million	39.6 million	9.11 million
2022	1.48 billion	330 million	40.2 million	8.57 million
2023	1.47 billion	298 million	47.4 million	8.34 million

Larger containerized cargo ships are calling more often at ports such as Baltimore. The increased size of vessels and increased cargo volumes presents challenges for existing port infrastructure that may not have been built with consideration of the larger vessels and greater traffic density. Many bridges, canals, and docks were designed decades ago when containerships were significantly smaller and vessel traffic was substantially less. As a result, larger vessels, which are inherently less maneuverable due to their sheer size and mass, often operate with very tight clearances, reducing the margin for error and increasing the risk of contact

(US Coast Guard 2019; Dillon Consulting 2020). The NTSB concludes that increasingly larger cargo vessels, such as the *Dali*, pose increased risks and challenges to maritime safety due to their reduced maneuverability in, and proximity to, existing port and waterway infrastructure that was not designed to accommodate vessels of such size.

On May 15, 2024, following the collapse of the Key Bridge, the US Coast Guard convened a Ports and Waterways Safety Board of Inquiry to evaluate the risks posed by larger commercial vessels and increased traffic density to critical port infrastructure—such as bridges, cargo terminals, pipelines, railways, and power plants—in 10 selected ports (US Coast Guard 2024b).[169] The board was directed to conduct "a holistic vulnerability assessment for each of the ten ports with supporting recommendations for port-specific risk mitigation measures and best practices for navigation safety, critical infrastructure, commercial shipping, waterways management, and environmental protection." The Board of Inquiry's final report, which had not been published at the time of this report, "shall include parameters and methodology to update waterway risk assessment tools and associated tactics, techniques, and procedures (TTP) for subsequent risk assessments of the nation's remaining ports and navigable waterways." The NTSB awaits the report from the Coast Guard Board of Inquiry and the recommendations contained within.

2.9 Assessing Bridge Vulnerability to Contact by Large Ocean-going Vessels

In this accident, the *Dali*'s loss of power and propulsion ultimately led to it striking the Key Bridge and the bridge's collapse. The NTSB analyzed reportable marine casualty data for 2002 through 2023 provided by the Coast Guard and determined that the majority were not related to loss of vessel power or propulsion or steering issues.[170] Bridge contacts often result from other factors, such as human performance or weather-related issues. For example, our investigation of the 2007 contact of the containership *Cosco Busan* with the San Francisco-Oakland Bay Bridge fendering system found that the accident was caused, in part, by "the pilot's degraded cognitive performance from his use of impairing prescription medications" as well as "lack of effective communication between the pilot and the master during the accident voyage" (NTSB 2009). Our investigation of the 2012 contact of the cargo

[169] A *Port and Waterways Board of Inquiry* is the Coast Guard's highest-level assessment for port and waterway infrastructure.

[170] In addition to pier or fender contacts, these contacts included overhead clearance contact of bridge deck or other structure.

vessel *Delta Mariner* with the Eggner's Ferry Bridge identified performance of the bridge team as a causal factor (NTSB 2013). Our investigation of the collapse of the Sunshine Skyway Bridge in Tampa Bay, Florida, in 1980, after it was struck by the bulk carrier *Summit Venture* found that the bridge strike was caused by environment-related issues, specifically the vessel's "unexpected encounter with severe weather…which overtook the vessel as it approached the Sunshine Skyway Bridge" (NTSB 1981).

In this report, the NTSB has recommended changes to vessel engineering practices to prevent losses of power and propulsion during critical maneuvering situations. However, as the examples above illustrate, bridge strikes can occur as a result of any number of factors. As demonstrated by the Sunshine Skyway Bridge collapse over 45 years ago, the outcome of vessel strikes caused by factors unrelated to engineering casualties can be just as catastrophic.[171] To address the innumerable range of potential factors leading to a bridge strike, the vulnerability of bridges must be addressed. Further, measures to assess and address the vulnerability of bridges must account for mounting threats to bridge safety, such as the increasing vessel sizes and traffic density.

The FHWA requires that new bridges on the National Highway System be designed to minimize the risk of a catastrophic bridge collapse from a vessel collision based on a vulnerability assessment calculation defined by the 2009 AASHTO *Guide Specifications*.[172] The Method II calculations in the AASHTO specifications include the sizes, speeds, and other characteristics of the vessels navigating the channel under the bridge. The annual number of vessels transiting under a bridge is also a factor in the calculation. This factor also accounts for the distribution of vessel sizes over the wide range of vessel types and sizes that may strike a portion of the bridge. Therefore, the number of vessels as well as the distribution of vessel sizes (DWT) are important considerations in the risk associated with a vessel strike on the bridge. Importantly, the AASHTO *Guide Specifications* includes future growth as part of the vulnerability assessment calculations, including the Method II calculations recommended by the NTSB in March 2025. Specifically, the specifications state: "Vessel characteristics and the design vessel selection shall include consideration of

[171] The NTSB's investigation into the collapse of the Sunshine Skyway Bridge first demonstrated the need for bridges to be protected from vessel contact, ultimately resulting in efforts by the FHWA and other organizations to develop the 1991 AASHTO *Guide Specification*.

[172] When discussing bridge design, the term *collision* refers to a vessel hitting a bridge or bridge structures. This use differs from the maritime definition of *collision*, which involves two moving vessels striking one another. Throughout this section, which focuses on bridge design, *collision* is used to refer to a vessel hitting a bridge or bridge structures.

the possibility of a growth in vessel frequency, distribution, and size over the design life of the bridge as a result of channel improvements in the waterway, or an increase in commerce on the waterway."

In addition to the requirement to evaluate new bridges, AASHTO also recommended that bridge owners use the vulnerability assessment calculations to evaluate bridges built before the release of the *1991* specifications. Calculations on existing bridges were encouraged so that owners could identify bridges at risk of a catastrophic collapse in the event of a vessel collision and "be aware of high-risk safety needs requiring immediate or short-term action, as well as information to prioritize and budget for the long-term needs for bridge rehabilitation or replacement" (AASHTO 2009). For existing bridges, the likelihood that a bridge strike results in a collapse will change throughout the lifetime of the bridge as the vessel traffic frequency and density and the size of vessels change. Therefore, conducting bridge vulnerability assessments when traffic density and vessel size change is vital.

Because the Key Bridge was built before the release of the 1991 AASHTO Guide Specification, the bridge owner, MDTA, was not required to complete a vulnerability assessment. However, MDTA should have been aware that the vulnerability assessment was recommended for existing bridges.[173] After the accident, to determine how susceptible the Key Bridge was to collapse from bridge strike by a vessel of the *Dali*'s size, the NTSB completed a vulnerability assessment using the AASHTO *Guide Specifications* Method II vulnerability assessment calculation (NTSB 2025).[174] The assessment was based on a mathematical risk model calculated using data on bridge/span geometry and design, pier protection and lateral capacity, the characteristics of vessel traffic transiting the main navigation channel, waterway characteristics, and other factors. Our assessment found that the Key Bridge's annual frequency of collapse was almost 30 times greater than the AASHTO bridge vulnerability assessment risk threshold.

On March 18, 2025, the NTSB issued the safety recommendation report *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk*

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[173] As previously footnoted, the Maryland State Highway Administration was a committee member on the 2009 AASHTO Guide Specifications development. MDTA was a member of the Bridges and Structures Subcommittee for the AASHTO *LRFD* [Load Resistance Factor Design] *Bridge Design Specifications*, which referenced the 2009 Guide Specifications.

[174] The 2009 AASHTO *Guide Specifications* provide three methods for conducting bridge vulnerability assessments: Method I is a simple to use semi-deterministic procedure; Method II is a detailed risk analysis procedure; and Method III is a cost-effectiveness of risk reduction procedure (based on a classical benefit/cost analysis) (AASHTO 2009).

Reduction Strategies, which addressed the urgent need for vulnerability assessments and risk reduction strategies to safeguard bridges from vessel strikes (NTSB 2025). We found that, had the MDTA conducted a vulnerability assessment of the Key Bridge using AASHTO *Guide Specifications*, the MDTA would have been aware that the bridge was above the AASHTO risk threshold for catastrophic collapse from a vessel collision when the *Dali* collision occurred. Additionally, we found that, had MDTA conducted a vulnerability assessment of the Key Bridge using the AASHTO Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge. We found that, at the time of our report's publication, nationally, the 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels were likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.[175]

As a result of our findings, we issued four urgent safety recommendations.[176] All recipients have responded and are taking, or have taken, action to address the urgent recommendations.

The NTSB issued Urgent Safety Recommendation H-25-1 to the Federal Highway Administration, with support from the Coast Guard and the US Army Corps of Engineers (Urgent Safety Recommendation H-25-2), to establish an interdisciplinary team to provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. All three recipients responded to the urgent safety recommendation and are taking action to fulfill the recommended actions.[177]

The NTSB also issued Urgent Safety Recommendations H-25-3 and H-25-4 to the 30 owners of the 68 bridges over navigable waterways that are frequented by ocean-going vessels, constructed before the AASHTO guidance was issued in 1991,

[175] In response to a request from the NTSB, the FHWA coordinated with state departments of transportation to identify 176 bridges in 26 states that cross waterways used by ocean-going vessels. Using the reportable marine casualty data for 2002 through 2023 provided by the Coast Guard, and cross-referencing bridge strikes from that data set with the 176 bridges identified by the FHWA, the NTSB determined that 40 of those bridges (23%) had been contacted by large ocean-going vessels between 2002 and 2023.

[176] See data.ntsb.gov/carol-main-public/query-builder/route/?t=published&n=18.

[177] Both Urgent Safety Recommendations, H-25-1 and H-25-2, are classified Open—Acceptable Action.

and have not undergone a vulnerability assessment based on recent vessel traffic.[178] We recommended that the recipients calculate the AASHTO Method II annual frequency of collapse for their bridges, and, if the calculations indicated the annual frequency was greater than the AASHTO threshold, develop and implement a comprehensive risk reduction plan.

Comprehensive risk reduction plans can include implementing countermeasures, such as protective systems and operational limitations. Bridges built or modified to incorporate protective systems can provide passive defense against ships that lose control or steer off course to prevent or redirect impact loads on bridges or reduce them to non-destructive levels. According to the 2009 AASHTO *Guide Specifications*, protective systems can include physical pier or bridge protection systems, such as fendering, dolphins, or island protection. Alternatively, operational limitations, such as speed limits for vessels, mandatory tug assistance requirements, or channel restrictions (for example, limiting vessel size or restricting transits to daylight), can improve safety near bridges, reducing the risk and consequences of a bridge strike.

We received responses from 27 recipients accounting for all bridges identified in our March 18, 2025, report.[179] Of the 27 recipients who responded, 10 have hired, or are in the process of hiring, a consultant to do the AASHTO Method II calculations,

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[178] The owners were: the Bay Area Toll Authority, the California DOT, the Golden Gate Bridge Highway and Transportation District, the Corps of Engineers, the Florida DOT, the Georgia DOT, Skyway Concession Company LLC, the Louisiana DOT and Development, the New Orleans Public Belt Railroad, the MDTA, the Massachusetts DOT, the Mackinac Bridge Authority, the New Hampshire DOT, the Delaware River Port Authority, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City DOT, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Port Authority of New York and New Jersey, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio DOT, the Oregon DOT, the Pennsylvania Turnpike Commission, the Rhode Island Turnpike and Bridge Authority, the Harris County Toll Road Authority, the Texas DOT, the Washington State DOT, and the Wisconsin DOT.

[179] Three recipients responded on behalf of bridge owners within their jurisdictions; specifically, the Louisiana DOT and Development responded for the New Orleans Public Belt Railroad, the Texas DOT responded for the Harris County Toll Road Authority, and the California DOT responded for the Bay Area Toll Authority. Safety Recommendation H-25-3 is classified Closed—Reconsidered for these recipients.

and 4 have initiated the calculations independently.[180] The MDTA, owner and operator of the Key Bridge, is one of these recipients. In the spring of 2024, after the Key Bridge collapsed, the MDTA hired an engineering consultant to complete calculations for the eastbound and westbound spans of the William Preston Lane Jr. Memorial Bay Bridge (Bay Bridge), another bridge owned and operated by the MDTA.[181] The consultant found that both spans for the Bay Bridge exceeded the AASHTO threshold.

Of the 13 recipients that have completed the calculation, eight reported annual frequencies below the AASHTO threshold.[182] As these bridges will not require a risk reduction plan, Safety Recommendation H-25-4 is classified Closed—No Longer Applicable for these recipients. Four of five recipients who have reported at least one bridge with an annual frequency of collapse over the AASHTO threshold—including the MDTA for the Bay Bridge—have reported plans to develop a risk reduction plan. Safety Recommendation H-25-4 is classified Open—Acceptable Response for these five recipients.[183] One recipient, the Delaware River Port Authority, reported an ongoing bridge rehabilitation project for the two bridges found to have an annual frequency of collapse over the AASHTO threshold. Safety Recommendation H-25-4 is classified Open—Acceptable Alternate Response for this recipient.

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[180] (a) The 10 recipients that have hired, or are in the process of hiring, a consultant to do the calculations are the Golden Gate Bridge Highway and Transportation District, the Skyway Concession Company LLC, the Mackinac Bridge Authority, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Thousand Islands Bridge Authority, the Oregon DOT, the Rhode Island Turnpike and Bridge Authority, the Washington State DOT, and the Wisconsin DOT. (b) The four recipients that have initiated calculations independently are the California DOT, the Corps of Engineers, the New Hampshire DOT, and the Texas DOT. (c) Safety Recommendation H-25-3 is classified Open—Acceptable Response for these 14 recipients, including the MDTA. Thirteen recipients reported that they have completed the calculations. Safety Recommendation is classified H-25-3 Closed—Acceptable Action for these recipients.

[181] The Bay Bridge is a dual-span bridge that carries US 50 from Annapolis, Maryland, to Stevensville, Maryland, over the Chesapeake Bay. The eastbound span consists of two lanes, and the parallel westbound span consists of three lanes; however, traffic patterns on the five lanes can be adjusted using the bridge's lane control system.

[182] The eight recipients who have completed calculations and reported frequencies below the AASHTO threshold are the Florida DOT, the Georgia DOT, the Massachusetts DOT, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City DOT, the Port Authority of New York and New Jersey, and the Pennsylvania Turnpike Commission.

[183] The five recipients that have reported at least one bridge with an annual frequency of collapse over the AASHTO limit are the Seaway International Bridge Corporation, the Louisiana DOT and Development, the Ohio DOT, the Delaware River Port Authority, and the MDTA.

For additional information on the findings and recommendations in the NTSB's *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies*, please see the full report, which has been included as Appendix E to this report.

3 Conclusions

Findings

1. None of the following were factors in this accident: (1) environmental or waterway conditions; (2) vessel complement and mariner credentialing; (3) impairment of the *Dali* crew or pilots due to alcohol or other tested-for drugs; (4) fuel quality or switchover of fuels; (5) vessel's ability to get underway after in-port blackouts; or (6) the presence of non-redundant steel tension members in the Francis Scott Key Bridge's continuous steel through-truss.
2. The initial March 26 low-voltage blackout was caused by Wire 1 electrically disconnecting from Terminal Block 381 within the high-voltage switchboard, which resulted in high-voltage breaker HR1 opening, interrupting power to step-down transformer TR1 and the low-voltage bus.
3. The position of the wire-label banding on the ferrule of Terminal Block 381's Wire 1 prevented Wire 1 from being fully inserted into the terminal block spring-clamp gate, causing an inadequate connection and leaving Wire 1 loose and vulnerable to becoming electrically disconnected.
4. If infrared thermal imaging had been used to inspect wire connections within the high-voltage switchboard before the accident as part of the *Dali*'s preventative maintenance program, the loose signal wire may have been identified.
5. The loss of power to the low-voltage bus led to a loss of lighting and machinery, including the main engine cooling water pump and the steering gear pumps, which resulted in a loss of propulsion and steering.
6. The as-built configuration of the *Dali*'s main engine to automatically shut down due to low cooling water pressure met classification standards at the time the vessel was constructed; however, it endangered the vessel because it prevented the main engine from being available following the initial underway blackout, thus reducing the vessel's maneuverability.
7. As cargo vessel designs continue to evolve with the latest available standards and technology, increased redundancy to maintain critical systems, such as the main engine and steering, can mitigate risks in restricted waters.
8. The engineering crew's initial response to restoring low-voltage power after the first underway blackout was timely.
9. The second underway blackout on March 26, and the second in-port blackout on March 25, during which both the high- and low-voltage buses lost power,

were caused by insufficient fuel pressure to online diesel generators, resulting from the inability of the flushing pump to automatically restart following a loss of power.

10. The crew's operation of the flushing pump as the service pump for online diesel generators was inappropriate because the necessary fuel pressure for diesel generator 3 and diesel generator 4 would not be automatically reestablished after a blackout per the fuel system's design.

11. Synergy's operational oversight was inadequate because it did not discontinue crews' ongoing use of the flushing pump as a service pump for the diesel generators aboard the *Dali* and at least one other vessel.

12. Keeping the high-voltage breakers' control modes set to Automatic rather than Manual would not have prevented either underway blackout, but it would have shortened the duration of the initial underway blackout from 58 seconds to 10 seconds, providing more time for the crew to attempt to recover critical systems, such as propulsion, as the vessel approached the Francis Scott Key Bridge.

13. It is likely that the emergency diesel generator's failure to connect and power the emergency switchboard within 45 seconds, as required by International Maritime Organization regulations, was due to the emergency diesel generator radiator damper actuator's limit switch not indicating open in the required time due to unknown circumstances.

14. The actions of the pilots and the bridge team in response to the emergency were executed in a timely manner, but the vessel's loss of propulsion close to the Francis Scott Key Bridge rendered their actions ineffective.

15. The pilots', the pilot dispatcher's, and the Maryland Transportation Authority's quick actions to stop bridge traffic prevented a greater loss of life from the bridge collapse.

16. In lieu of police officers or highway workers charged with traffic control and capable of quickly stopping traffic, a motorist warning system designed to warn and stop motorists from entering onto a bridge is a possible countermeasure that can be quickly implemented to save lives and may be a component of an effective bridge protection strategy.

17. Owners of bridges over navigable waterways frequented by ocean-going vessels would benefit from updated guidance on motorist warning systems including incorporation of hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for

bridge closure and systems that would both warn and prevent motorists from entering a bridge once a threat is detected.

18. Had the inspector and highway workers been notified of the *Dali*'s emergency situation about the same time the Maryland Transportation Authority police officers at each end of the bridge were told to block vehicular traffic, the highway workers may have had sufficient time to drive to a portion of the bridge that did not collapse.
19. Effective and immediate communication to evacuate the bridge during an emergency is critical to ensuring the safety of bridge workers.
20. While the requirements of the International Safety Management Code include some elements of a comprehensive, proactive safety management system, the code does not fully encompass all four critical components of safety policy, safety risk management, safety assurance, and safety promotion.
21. The lack of recording of parametric information by the voyage data recorder during a power loss can inhibit proactive monitoring of these data by organizations and adversely impact an accident investigation.
22. Audio information from both sides of the *Dali*'s electric telephone was not recorded during the accident, which prevented the National Transportation Safety Board from hearing the engine room's responses to the accident.
23. The monoaural audio configuration of the *Dali*'s Japan Radio Co., Ltd-brand JCY-1900 voyage data recorder system, which mixed multiple microphones into shared channels, significantly impaired the National Transportation Safety Board's ability to isolate and analyze critical bridge conversations, distinct voices, and sounds from the alarms and background noise, thereby reducing the recording's intelligibility and limiting the effectiveness of audio enhancement tools.
24. Although the *Dali*'s Japan Radio Co., Ltd-brand JCY-1900 voyage data recorder complied with International Maritime Organization and International Electrotechnical Commission standards, significant deficiencies in data accessibility, audio usability, and playback software functionality revealed a critical disconnect between published technical standards and practical investigative and organizational needs to identify safety issues and solutions, and for operators and regulators to ensure safety.
25. Increasingly larger cargo vessels, such as the *Dali*, pose increased risks and challenges to maritime safety due to their reduced maneuverability in, and proximity to, existing port and waterway infrastructure that was not designed to accommodate vessels of such size.

Previously Issued Findings

1. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.
2. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge using the American Association of State Highway and Transportation Officials' Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.
3. The 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the contact of the containership *Dali* with the Francis Scott Key Bridge was a loss of electrical power (blackout), due to a loose signal wire connection to a terminal block stemming from the improper installation of wire-label banding, resulting in the vessel's loss of propulsion and steering close to the bridge. Contributing to the crew's inability to recover propulsion from the loss of electrical power was the limited time available due to the *Dali*'s proximity to the bridge. Contributing to the collapse of the Francis Scott Key Bridge and the loss of life was the lack of countermeasures to reduce the bridge's vulnerability to collapse due to impact by ocean-going vessels, which could have been implemented if a vulnerability assessment had been conducted by the Maryland Transportation Authority as recommended by the American Association of State Highway and Transportation Officials. Also contributing to the loss of life was the lack of effective and immediate communications to notify the highway workers to evacuate the bridge.

4 Recommendations

New Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following new safety recommendations.

To the US Coast Guard:

> Conduct and publish the results of a study that examines the availability, feasibility, and safety benefits of redundant means to ensure that large single-propulsion-engine cargo vessels maintain propulsion and steering when maneuvering in restricted waters. (M-25-16)
>
> Propose to the International Maritime Organization that it revise the International Safety Management Code and associated guidelines to fully incorporate safety policy, safety risk management, safety assurance, and safety promotion into its safety management system requirements. (M-25-17)
>
> Notify the International Maritime Organization of the voyage data recorder technical issues encountered during our investigation into the contact of containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse and submit to the International Maritime Organization a concrete proposal to require:
>
> a. the recording of mandatory data inputs from systems that remain powered during a blackout,
>
> b. the recording of engine room communications to the bridge,
>
> c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
>
> d. performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary voyage data recorder data into open industry standard formats. (M-25-18)

To the Federal Highway Administration:

> Research hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected. Provide the results of your

research to the American Association of State Highway and Transportation Officials. (H-25-28)

To the American Association of State Highway and Transportation Officials:

Update your *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* to include guidance in the selection of motorist warning systems. Evaluated changes should include Federal Highway Administration research on hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected. (H-25-29)

To the Harbor Safety Committee National Steering Team:

Share with harbor safety committees nationwide the circumstances of the contact of the containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse, highlighting the importance of having a procedure, including immediately available emergency contact information, for pilots to initiate contact with shoreside support in an emergency requiring shoreside action to ensure timely and efficient action by first responders and port stakeholders. (M-25-19)

To the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the Maryland Transportation Authority, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Rhode Island Turnpike and Bridge Authority, the Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation:

As part of your short-term bridge risk reduction and mitigation strategies to protect the traveling public, evaluate the need for and, if appropriate, incorporate motorist warning systems capable of activating when a threat is identified and immediately warn and stop motorists from entering onto the bridge. (H-25-30)

To the American National Standards Institute:

Propose to the International Electrotechnical Commission Technical Committee 80 to revise *IEC 61996-1 ed. 2* to require:

a. the recording of mandatory data inputs from systems that remain powered during a blackout,

b. the recording of engine room communications to the bridge,

c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and

d. the updating of performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary voyage data recorder data into open industry standard formats. (M-25-20)

To the American National Standards Institute Accredited Standards Committee on Safety in Construction and Demolitions Operations A10:

Revise *ANSI/ASSP A10.47, Work Zone Safety for Roadway Construction* to include an effective and immediate means of emergency communications to alert workers performing roadway work on bridges over navigable waterways, which should consider the presence of law enforcement for traffic control. (H-25-31)

To Nippon Kaiji Kyokai (ClassNK):

Share the circumstances of the contact of the containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse with the International Association of Classification Societies and urge them to distribute report MIR-25-40 to their members, highlighting:

a. the importance of avoiding placement of wire-label banding such that it impedes the proper insertion of a wire in a terminal block,

b. the benefits of using infrared thermal imaging as part of a preventative maintenance program for routine monitoring of electrical components to detect inadequate signal wire connections,

c. the potential risks that partially open radiator dampers can pose to emergency generators starting, and

d. the need for members to review their rules on acceptable emergency generator start design. (M-25-21)

To WAGO Corporation:

Add a warning in your product data sheet accompanying WAGO terminal block 280-681 (model), as well as any other terminal block models or similar products that incorporate wire-label banding you manufacture, to explain that improperly placed wire-label banding can impede the proper insertion of a wire into a terminal block. (M-25-22)

To HD Hyundai Heavy Industries:

Incorporate proper wire-label banding installation methods into your electrical department's standard operating procedures to ensure that wire-label banding installed on a wire does not impede the proper insertion of the wire into a terminal block. (M-25-23)

Identify all active HD Hyundai Heavy Industries-constructed vessels with Hyundai-MAN B&W 9S90ME C9.2 engines installed, which are configured to Germanischer Lloyd rules and are designed to shut down on low cooling water pressure, and alert the current vessel owners of this configuration and the circumstances of this accident. (M-25-24)

To Synergy Marine Pte Ltd:

With classification society approval, implement into your preventative maintenance program and safety management system the use of infrared thermal imaging for routine monitoring of electrical components, including the means to detect inadequate signal wire connections. (M-25-25)

Identify ships you operate that are equipped with a Hyundai-MAN B&W 9S90ME C9.2 engine and ensure that they are not configured to automatically shut down due to low cooling water pressure. (M-25-26)

Develop, implement, and monitor for compliance and effectiveness a safety management system policy and procedure to ensure that vessel crews are using the fuel oil service pumps as designed for the diesel generator fuel supply systems installed on board your vessels. (M-25-27)

Develop, implement, and monitor for compliance and effectiveness a safety management system policy and procedure to ensure that vessel crews are setting high-voltage breakers' control mode to Automatic, unless the transformer breakers are being manually controlled for maintenance. (M-25-28)

Identify ships you operate with similar arrangements to the *Dali* and notify crews of those vessels that partially open radiator dampers can delay or prevent the emergency diesel generator from starting automatically. (M-25-29)

Previously Issued Recommendations

In March 2025, the NTSB issued a safety recommendation report titled *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies*, which issued the following urgent safety recommendations addressing the vulnerability of bridges over navigable waterways to strikes by large ocean-going vessels, identified during the *Dali* investigation (NTSB 2025):

To the Federal Highway Administration:

In coordination with the US Coast Guard and US Army Corps of Engineers, establish an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-1) (Urgent)

To the US Coast Guard and the US Army Corps of Engineers:

Support the Federal Highway Administration in establishing an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-2) (Urgent)

To the Bay Area Toll Authority, the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Florida Department of Transportation, the Georgia Department of Transportation, Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the New Orleans Public Belt Railroad, the Maryland Transportation Authority, the Massachusetts Department of Transportation, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City Department of Transportation, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Port Authority of New York and New Jersey, the Seaway International Bridge Corporation, the Thousand Islands

Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Pennsylvania Turnpike Commission, the Rhode Island Turnpike and Bridge Authority, the Harris County Toll Road Authority, the Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation:

> Calculate the American Association of State Highway and Transportation Officials (AASHTO) Method II annual frequency of collapse for the bridge(s) identified in Appendix B of this report for which you are responsible and inform the National Transportation Safety Board whether the probability of collapse is above the AASHTO threshold. (H-25-3) (Urgent)[184]
>
> If the calculations that you performed in response to Safety Recommendation H-25-3 indicate that a bridge has an annual frequency of collapse greater than the American Association of State Highway and Transportation Officials threshold, develop and implement a comprehensive risk reduction plan that includes, at a minimum:
>
> - guidance and assistance from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers Interdisciplinary Team identified in Safety Recommendations H-25-1 and H-25-2, and
> - short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision. (H-25-4) (Urgent)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

JENNIFER L. HOMENDY
Chairwoman

MICHAEL GRAHAM
Member

THOMAS CHAPMAN
Member

J. TODD INMAN
Member

Report Date: November 18, 2025

[184] "Appendix B" referenced in this recommendation referred to the original report it appeared in, MIR-25-10, *Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies* (see Appendix E).

Board Member Statement

Member Michael Graham filed the following concurring statement on November 19, 2025.

This report contains a host of findings related to systems, processes, configurations, and vulnerabilities surrounding this accident, issues that were either not identified or not addressed prior to the accident. As a longtime advocate of safety management systems (SMS), I believe a comprehensive SMS – one that fully incorporates all four pillars of safety policy, safety risk management, safety assurance, and safety promotion – could have identified and mitigated many of the deficiencies our team discovered aboard the *Dali*. However, the underlying issue with SMS in this accident was not with the *Dali* or Synergy, whose SMS exceeded the requirements of the International Maritime Organization's (IMO) International Safety Management (ISM) Code. Rather, the shortcomings lie within the current regulations and definitions of SMS prescribed by the IMO.

The ISM Code's definition of SMS is incomplete. It focuses primarily on compliance and policy implementation rather than a top-down, systematic, risk-based approach. While aspects of the four SMS pillars are present, such as safety policy requirements within the Code's functional elements and certain safety promotion practices involving communication and training, these provisions alone do not constitute a comprehensive SMS.

As this report highlights, existing maritime regulations are woefully insufficient – or, in some cases, silent – on key SMS components. As this final report notes, safety risk management requires hazard identification by both reactive and proactive methods, as well as safety risk analysis, assessment, and control using processes that include predictive methods. The existing ISM Code's handling of risk management is entirely reactive. To meet modern safety expectations, the Code must incorporate proactive hazard identification and predictive risk analysis, supported by robust data collection and analysis.

Similarly, the safety assurance pillar evaluates the ongoing effectiveness of risk controls and helps identify new hazards through continuous data collection and analysis. Safety assurance also includes management of change, which assesses safety implications of operational changes before they are implemented and manages any associated risks. Management of change is not currently required under the ISM Code, yet it is critical to ensuring any operational changes – such as varying staffing levels, engineering modifications, or changes in the type of fuel used – do not introduce new safety vulnerabilities.

The marine industry has a foundation for a holistic SMS, but that foundation must be strengthened and expanded to align with the comprehensive, systematic approach successfully adopted by other modes of transportation. As the IMO considers revisions to its SMS regulations, I urge them to fully incorporate all four pillars of SMS into future updates.

Appendixes

Appendix A: Investigation

The National Transportation Safety Board (NTSB) was the lead federal agency for this investigation. The NTSB learned of this accident from the Federal Bureau of Investigation on March 26, 2024, at 0216. NTSB investigators were on scene at the initial incident command post at MDTA's facility by 0525. Formal determination of the accident as a major marine casualty was received from the US Coast Guard at 0733. The NTSB, according to its Memorandum of Understanding with the Coast Guard, was the lead federal agency for the safety investigation. A team of 14 investigators, NTSB Chairwoman Jennifer Homendy, and support staff were on scene in Baltimore, Maryland, throughout March 26. The investigative team consisted of specialists in engineering, operations, survival factors, vehicle recorders, and bridge structures. NTSB investigators first boarded the *Dali* on March 26, about 1930, to conduct preliminary interviews and retrieve VDR data and audio.

Over 8 months, investigators conducted interviews of the *Dali*'s crew, the senior pilot and pilot-in-training, and first responders, and familiarized themselves with the vessel and its engine room. Additionally, the NTSB worked with parties and technical experts to troubleshoot and determine the cause of second March 25, 2024, blackout and both blackouts on March 26, 2024. The following entities served as parties to the investigation:

- Synergy Marine Pte Ltd
- Grace Ocean Pte Ltd
- Maryland Transportation Authority (MDTA)
- Federal Highway Administration
- Association of Maryland Pilots
- Nippon Kaiji Kyokai (ClassNK)
- HD Hyundai Heavy Industries Co., Ltd
- Maritime & Port Authority of Singapore

The Coast Guard convened a formal Marine Board of Investigation on March 26, 2024, tasked with investigating the contact of the *Dali* and the resulting loss of life.[185] The Marine Board of Investigation's report was not yet available at the time of this report.

[185] A *Marine Board of Investigation* is the Coast Guard's highest level of investigation.

The Coast Guard chartered a Ports and Waterways Safety Board of Inquiry on May 15, 2024. Among other things, the board was tasked with evaluating "the risks to critical port infrastructure due to larger commercial vessels and increased traffic density over recent decades for ten domestic ports or port complexes." The studied ports specifically excluded Baltimore so as not to conflict with the Marine Board of Investigation. The Ports and Waterways Safety Board's report was not yet available at the time of this report.

Appendix B: Consolidated Recommendation Information

Title 49 *United States Code* 1117(b) requires the following information on the recommendations in this report.

For each recommendation–

(1) a brief summary of the Board's collection and analysis of the specific accident investigation information most relevant to the recommendation;

(2) a description of the Board's use of external information, including studies, reports, and experts, other than the findings of a specific accident investigation, if any were used to inform or support the recommendation, including a brief summary of the specific safety benefits and other effects identified by each study, report, or expert; and

(3) a brief summary of any examples of actions taken by regulated entities before the publication of the safety recommendation, to the extent such actions are known to the Board, that were consistent with the recommendation.

To the US Coast Guard

M-25-16
Conduct and publish the results of a study that examines the availability, feasibility, and safety benefits of redundant means to ensure that large single-propulsion-engine cargo vessels maintain propulsion and steering when maneuvering in restricted waters.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.1 Main Engine Shutdown. Information supporting (b)(1) can be found on pages 154–155; (b)(2) can be found on pages 154–155; and (b)(3) is not applicable.

M-25-17
Propose to the International Maritime Organization that it revise the International Safety Management Code and associated guidelines to fully incorporate safety policy, safety risk management, safety assurance, and safety promotion into its safety management system requirements.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.6 Safety Management Systems. Information supporting (b)(1) can be found on pages 182–183; (b)(2) can be found on pages 182–183; and (b)(3) can be found on page 182.

M-25-18
Notify the International Maritime Organization of the voyage data recorder technical issues encountered during our investigation into the contact of containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse and submit to the International Maritime Organization a concrete proposal to require:

a. the recording of mandatory data inputs from systems that remain powered during a blackout,
b. the recording of engine room communications to the bridge,
c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
d. performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary voyage data recorder data into open industry standard formats.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.7 Voyage Data Recorders. Information supporting (b)(1) can be found on pages 185–191; (b)(2) can be found on page 190; and (b)(3) can be found on page 184.

To the Federal Highway Administration

H-25-28
Research hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected. Provide the results of your research to the American Association of State Highway and Transportation Officials.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.5.2 Motorist Warning Systems. Information supporting (b)(1) can be found on pages 171–178; (b)(2) can be found on pages 172–178; and (b)(3) can be found on pages 172–178.

To the American Association of State Highway and Transportation Officials

H-25-29
Update your *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* to include guidance in the selection of motorist warning systems. Evaluated changes should include Federal Highway Administration research on hazard alert and sensing technologies capable of detecting errant vessels and bridge movements that would indicate a need for bridge closure, and would both warn and prevent motorists from entering a bridge once a threat is detected.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.5.2 Motorist Warning Systems. Information supporting (b)(1) can be found on pages 171–177; (b)(2) can be found on pages 172–178; and (b)(3) can be found on pages 172–178.

To the Harbor Safety Committee National Steering Team

M-25-19
Share with harbor safety committees nationwide the circumstances of the contact of the containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse, highlighting the importance of having a procedure, including immediately available emergency contact information, for pilots to initiate contact with shoreside support in an emergency requiring shoreside action to ensure timely and efficient action by first responders and port stakeholders.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.5.1 Ship and Shoreside Emergency Communications. Information supporting (b)(1) can be found on pages 170–171; (b)(2) can be found on pages 170–171; and (b)(3) is not applicable.

To the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the Maryland Transportation Authority, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, the New York State Bridge Authority, the

Ogdensburg Bridge and Port Authority, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Rhode Island Turnpike and Bridge Authority, the Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation:

H-25-30
As part of your short-term bridge risk reduction and mitigation strategies to protect the traveling public, evaluate the need for and, if appropriate, incorporate motorist warning systems capable of activating when a threat is identified and immediately warn and stop motorists from entering onto the bridge.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.5.2 Motorist Warning Systems. Information supporting (b)(1) can be found on pages 171–177; (b)(2) can be found on pages 172–178; and (b)(3) can be found on pages 172–178.

To the American National Standards Institute

M-25-20
Propose to the International Electrotechnical Commission Technical Committee 80 to revise *IEC 61996-1 ed. 2* to require:

a. the recording of mandatory data inputs from systems that remain powered during a blackout,
b. the recording of engine room communications to the bridge,
c. the recording of multiple bridge microphone inputs such that the audio channels can be isolated or recorded independently, and
d. the updating of performance requirements for playback software that facilitates real world use, including enhanced criteria for exporting proprietary voyage data recorder data into open industry standard formats.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.7 Voyage Data Recorders. Information supporting (b)(1) can be found on pages 185–191; (b)(2) can be found on page 190; and (b)(3) can be found on page 184.

To the American Society of Safety Professionals Accredited Standards Committee on Safety in Construction and Demolitions Operations A10

H-25-31
Revise *ANSI/ASSP A10.47, Work Zone Safety for Roadway Construction* to include an effective and immediate means of emergency communications to alert workers performing roadway work on bridges over navigable waterways, which should consider the presence of law enforcement for traffic control.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.5.3 Highway Worker Emergency Communications. Information supporting (b)(1) can be found on pages 179–181; (b)(2) can be found on pages 180–181; and (b)(3) can be found on pages 180–181.

To Nippon Kaiji Kyokai (ClassNK)

M-25-21
Share the circumstances of the contact of the containership *Dali* with the Francis Scott Key Bridge and subsequent bridge collapse with the International Association of Classification Societies and urge them to distribute report MIR-25-40 to their members, highlighting:

a. the importance of avoiding placement of wire-label banding such that it impedes the proper insertion of a wire in a terminal block,
b. the benefits of using infrared thermal imaging as part of a preventative maintenance program for routine monitoring of electrical components to detect inadequate signal wire connections,
c. the potential risks that partially open radiator dampers can pose to emergency generators starting, and
d. the need for members to review their rules on acceptable emergency generator start design.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.2 Loss of Power (Blackouts) and section 2.3.5 Emergency Diesel Generator and Emergency Switchboard. Information supporting (b)(1) can be found on pages 145–153, 154–156, and 163–165; (b)(2) can be found on pages 145–153, 154–156, and 163–165; and (b)(3) can be found on pages 155–156 and 163.

To WAGO Corporation

M-25-22
Add a warning in your product data sheet accompanying WAGO terminal block 280-681 (model), as well as any other terminal block models or similar products that incorporate wire-label banding you manufacture to explain that improperly placed wire-label banding can impede the proper insertion of a wire into a terminal block.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.2.1 Improper Placement of Wire-Label Banding. Information supporting (b)(1) can be found on pages 145–150; (b)(2) can be found on page 145; and (b)(3) is not applicable.

To HD Hyundai Heavy Industries

M-25-23
Incorporate proper wire-label banding installation methods into your electrical department's standard operating procedures to ensure that wire-label banding installed on a wire does not impede the proper insertion of the wire into a terminal block.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.2.1 Improper Placement of Wire-Label Banding. Information supporting (b)(1) can be found on pages 145–150; (b)(2) can be found on page 145; and (b)(3) is not applicable.

M-25-24
Identify all active HD Hyundai Heavy Industries-constructed vessels with Hyundai-MAN B&W 9S90ME C9.2 engines installed, which are configured to Germanischer Lloyd rules and are designed to shut down on low cooling water pressure, and alert the current vessel owners of this configuration and the circumstances of this accident.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.1 Main Engine Shutdown. Information supporting (b)(1) can be found on pages 155–156; (b)(2) can be found on pages 155–156; and (b)(3) can be found on page 156.

To Synergy Marine Pte. Ltd

M-25-25
With classification society approval, implement into your preventative maintenance program and safety management system the use of infrared thermal imaging for routine monitoring of electrical components, including the means to detect inadequate signal wire connections.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.2.2 Switchboard Inspections and Infrared Thermal Imaging. Information supporting (b)(1) can be found on pages 150–153; (b)(2) can be found on pages 151–152; and (b)(3) can be found on pages 151–152.

M-25-26
Identify ships you operate that are equipped with a Hyundai-MAN B&W 9S90ME C9.2 engine and ensure that they are not configured to automatically shut down due to low cooling water pressure.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.1 Main Engine Shutdown. Information supporting (b)(1) can be found on pages 155–156; (b)(2) can be found on pages 155–156; and (b)(3) can be found on page 156.

M-25-27
Develop, implement, and monitor for compliance and effectiveness a safety management system policy and procedure to ensure that vessel crews are using the fuel oil service pumps as designed for the diesel generator fuel supply systems installed on board your vessels.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.3 Configuration of Flushing Pump as a Service Pump. Information supporting (b)(1) can be found on pages 157–162; (b)(2) can be found on pages 158–159; and (b)(3) is not applicable.

M-25-28
Develop, implement, and monitor for compliance and effectiveness a safety management system policy and procedure to ensure that vessel crews are setting high-voltage breakers' control mode to Automatic while operating, unless the transformer breakers are being manually operated or maintenance is being performed

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.4 Low-Voltage Step-Down Transformer Changeover. Information supporting (b)(1) can be found on pages 162–163; (b)(2) can be found on pages 162–163; and (b)(3) is not applicable.

M-25-29

Identify ships you operate with similar arrangements to the *Dali* and notify crews of those vessels that partially open radiator dampers can delay or prevent the emergency diesel generator from starting automatically.

Information that addresses the requirements of 49 *USC* 1117(b), as applicable, can be found in section 2.3.5 Emergency Diesel Generator and Emergency Switchboard. Information supporting (b)(1) can be found on pages 163–165; (b)(2) can be found on page 165; and (b)(3) can be found on pages 164–165.

Appendix C: Voyage Timeline

Table C-1 shows the timeline of events after the *Dali* initially lost power while underway on March 26, 2024. This timeline has been developed based on the voyage data recorder (VDR) transcript, CCTV footage, and alarms from the *Dali*'s advanced control and integration system (ACONIS) and alarm monitoring system. Confirmed times are provided. During the accident voyage, at least two verified exchanges occurred between bridge officers and the engine room during the accident event. The verification of these conversations came from comments from the master and the second mate during the crew audition of the VDR recording which occurred on August 22, 2024, at the NTSB's headquarters in Washington, District of Columbia.

Table C-1. *Dali* voyage timeline on March 26, 2024.

Time	Time Until Impact	Event
0125:00	-4:09	Approaching the intersection with Curtis Bay Channel, steering 142° with a speed of 8.9 knots (10.2 mph) First loss of power; loss of steering gear pump nos. 1, 2, and 3; and first signs of VDR data loss
0125:03	-4:06	VDR stopped recording parametric data
0125:08	-4:01	Main engine shut down
0125:11	-3:58	Master commanded bosun to go forward
0125:14	-3:55	Senior pilot asked, "Do we have steering?"
0125:16	-3:53	Second mate answered, "We have steering." Senior pilot asked the helmsman directly, "Do you have steering?"
0125:17	-3:52	Helmsman responded, "Yes sir. Yes sir."
0125:18	-3:51	Senior pilot commanded the helmsman to steer 141°
0125:24	-3:45	Senior pilot instructed the helmsman to let him know if he cannot steer
0125:27	-3:42	Master instructed bosun to stand by at the anchor brake and keep the bow stopper up
0125:35	-3:34	Master commanded the bosun to pick up the bow stopper

Time	Time Until Impact	Event
0125:47	-3:22	Helmsman stated, "Swinging to starboard, wheel on hard port sir" (to inform the senior pilot that the vessel's heading was swinging to starboard and he had the maximum possible counter rudder applied)
0125:51	-3:18	Vessel was on a heading of 143.0°, course of 141.7°, speed of 8.6 knots (9.9 mph), and had a 3.5° per minute rate of turn to starboard Vessel was located where the Curtis Bay Channel joins Fort McHenry Channel from the west The forwardmost point on *Dali* was about 763.5 meters from the Francis Scott Key Bridge (Key Bridge) (tangent line from bow), about 2.54 ship lengths
0125:58	-3:11	The electrician located in the engine control room (ECR) manually closed HR1 and LR1 Normal power (LV switchboard) restored (power to steering gear pump nos. 1 and 2 and other auxiliaries for the main engine and electrical generators) Fuel oil flushing pump did not automatically restart
0125:59	-3:10	Senior pilot called pilot association's duty dispatcher; duty dispatcher answered
0126:01	-3:08	Senior pilot told dispatcher to contact local authorities and have them shut down the Key Bridge
0126:04	-3:05	Dispatcher confirmed which bridge was to be closed
0126:08	-3:01	Senior pilot/dispatcher call concluded
0126:10	-2:59	The emergency generator connected to and powered the emergency switchboard, supplying power to steering gear pump no. 3 and other lighting and equipment connected to the switchboard
0126:12	-2:57	Senior pilot ordered port 20
0126:13	-2:56	Master confirmed port 20 Helmsman confirmed port 20
0126:15	-2:54	Senior pilot again ordered port, now shouting Helmsman again confirmed port 20
0126:18	-2:51	Vessel had developed a rate of turn of 7.5° per minute to starboard (the maximum rate of turn during the accident)
0126:20	-2:49	Senior pilot instructed the pilot-in-training to "grab my radio get to channel fourteen"

Time	Time Until Impact	Event
0126:22	-2:47	Pilot-in-training confirmed senior pilot command for radio Senior pilot ordered pilot-in-training to "grab a mac boat"
0126:29	-2:40	Senior pilot asked master if bosun was standing by forward
0126:31	-2:38	Master confirmed bosun was standing by forward
0126:34	-2:35	Helmsman confirmed that the "wheel was on port twenty" Senior pilot asked whether VHF was on channel 14
0126:38	-2:31	Senior pilot called for "mac boat" assistance over channel 14
0126:44	-2:25	Pilot dispatcher called MDTA command center, and MDTA command center answered call
0126:45	-2:24	Tug *Eric McAllister* answered senior pilot's channel 14 call
0126:46	-2:23	Pilot dispatcher notified MDTA command center that Key Bridge needed to be shut down due to a ship that lost steering
0126:47	-2:22	Senior pilot notified *Eric McAllister* that they needed assistance, that power had been lost, and that the ship was headed toward the Key Bridge
0126:53	-2:16	MDTA command center asked for further information about pilot's location
0126:55	-2:14	*Eric McAllister* confirmed the tug was on its way
0126:57	-2:12	Senior pilot stated via VHF, "that's it, hammer down" *Eric McAllister* operator turns tug around and heads toward *Dali* Pilot dispatcher explained to MDTA command center that there was a ship that had lost steering headed for the Key Bridge, and that all traffic needed to be stopped
0127:02	-2:07	Senior pilot ordered "port anchor," shouting
0127:04	-2:05	Helmsman again stated "port twenty sir" Second loss of power (both HV and LV switchboards) Both connected HR and LR breakers opened automatically (in this case HR1 and LR1 opened) All pumps, lighting, and other equipment powered by the LV switchboard shut off due to the loss of power MDTA command center confirmed they had the information from the pilot dispatcher to stop traffic to the Key Bridge

Time	Time Until Impact	Event
0127:06	-2:03	End of call between MDTA command center and pilot dispatcher
0127:07	-2:02	DG2 synchronized and powered the HV bus, but the LV bus remained blacked out
0127:11	-1:58	Senior pilot instructed the pilot-in-training to make a sécurité call[186]
0127:14	-1:55	Master continued to command (shouting) the bosun to let go the port anchor
0127:19	-1:50	Master repeated command to bosun to let go the port anchor
0127:20	-1:49	Over public address system, second mate repeated master's radioed orders to let go the port anchor
0127:23	-1:46	Senior pilot ordered hard port; helmsman confirmed
0127:25	-1:44	Pilot-in-training made sécurité call
0127:28	-1:41	Master repeated command to bosun to let go the port anchor
0127:36	-1:33	Normal power (LV switchboard) restored Steering gear pump nos. 1 and 2 restored Sound similar to automatic bus transfer switch
0127:40	-1:29	Master repeated command to bosun to let go the port anchor
0127:42	-1:27	Senior pilot shouted, "captain [master], do we have a bow thruster?"
0127:44	-1:25	Master and second mate confirmed
0127:46	-1:23	Senior pilot commanded "full to port" on the bow thruster Master read back full to port
0127:47	-1:22	Second mate read back order and executed the command on the bow thruster control knob
0127:51	-1:18	Master commanded the bosun to let go the anchor
0127:53	-1:16	MDTA dispatcher relayed the request to stop vehicular traffic to the MDTA officers who were stationed at either end of the bridge for traffic calming

[186] A *sécurité call* is a VHF radio transmission of important safety-related information for vessels in the broadcast area. The vessel or station transmitting the message begins by saying "Sécurité, Sécurité, Sécurité," and follows with specific safety information.

Time	Time Until Impact	Event
0127:54	-1:15	*Eric McAllister* radioed *Dali* to ask whether engines were lost. (Call was never answered.)
0127:55	-1:14	Bosun reported that he was unable to open the anchor brake
0127:57	-1:13	Third engineer restarted flushing pump
0128:01	-1:08	Master again commanded the bosun to open the brake quickly and let the anchor go
0128:10	-0:59	Bow of *Dali* crossed out of Fort McHenry Channel and began to ground in mud
0128:21	-0:48	MDTA unit stationed at the north end of the bridge to block traffic in the right lane during the road work moved his vehicle across both lanes, blocking all traffic MDTA unit on the south end of the bridge, who had been about to secure traffic on that side for work, blocked the northbound lanes
*	*—	MDTA duty officer inquired about the crew working on the bridge, and the officer at the north end replied that he would drive up on the bridge to warn the crew once another officer was on scene to relieve him *This conversation was not timestamped, the position of this event in the timeline is approximated.
0128:22	-0:47	Both ends of the bridge closed to traffic by MDTA police officers
0128:24	-0:45	Call between pilot dispatcher and Coast Guard concluded
0128:26	-0:43	Master commanded the bosun to let go the anchor
0128:42	-0:27	Bosun confirmed brake was open
0128:45	-0:24	Master again commanded the bosun to let go the anchor
0128:49	-0:20	*Dali*'s rate of turn reached zero
0128:51	-0:18	Helmsman stated, “Hard port, sir.” Senior pilot confirmed
0128:56	-0:13	Senior pilot commanded, “Full bow thruster to port.”
0128:57	-0:12	Second mate replied, “No, it’s not working.”
0128:59	-0:10	Master stated, “It’s not working.” Senior pilot repeated, “Not working.”

Time	Time Until Impact	Event
		Sound of anchor chain running (on VDR)
0129:00	-0:09	Master said, "Forward?"
0129:03	-0:06	Master again commanded the bosun to let go the anchor
0129:09	**Impact**	**Vessel began impacting Pier 17**
0129:15	+0:06	Bridge Span 18, with four vehicles on it, began to collapse
0129:22	+0:13	Pier 17 collapsed
0129:24	+0:15	Span 20 (two vehicles) collapsed
0129:27	+0:18	Span 21 (no vehicles) collapsed
0129	--	MDTA police unit on bridge called MDTA dispatch to report the Key Bridge had collapsed (audio not timestamped)
0129:28	+0:19	Span 22 (one vehicle, belonging to the inspector) collapsed

Appendix D: Causes, Results, and Remedies for Losses of Power (Blackouts) on the *Dali*

Table D-1. Losses of power (blackouts) on the *Dali* on March 25, 2024, and March 26, 2024.

Date and Time of Blackout	Vessel Status	Initiating Event	Result	Remedy
March 25, 1420:28	In port	Damper closed	DG2's engine stalled, preventing DG2 from generating proper electrical power. The vessel's PMS opened the online generator's main breaker, resulting in a loss of power to the HV and LV buses.	The PMS automatically started and connected DG3 to the HV bus, and the electrician manually closed HR1 and LR1, restoring LV power.
March 25, 1427:36	In port	Insufficient fuel pressure	DG3 began to underperform due to insufficient fuel supply. This decreased power output resulted in HR1 and LR1 opening and the PMS opening DG3's breaker, causing a complete vessel blackout.	The crew manually reopened DG2's engine exhaust damper, and the PMS automatically restarted and connected the DG2 to the HV bus, which restored power to the HV bus. The crew then manually closed HR1 and LR1, restoring power to the LV bus.
March 26, 0125:00	Underway	Loose terminal block wire	Loss of LV bus. Steering gear pump nos. 1, 2, and 3. Main engine shuts down.	Electrician manually closed HR1 and LR1, restoring LV power.
March 26, 0127:04	Underway	Insufficient fuel pressure	DG3 and DG4 began to underperform due to insufficient fuel supply, resulting in the PMS disconnecting both generators from the HV bus, causing a complete vessel blackout.	The PMS automatically started and connected DG2 to the HV bus. The electrician manually closes HR2 and LR2 restoring LV power.

Abbreviations:

DG2	diesel generator 2	HV	high voltage
DG3	diesel generator 3	LR1	Low-voltage step-down transformer 1
DG4	diesel generator 4	LV	low voltage
HR1	high-voltage step-down transformer 1	PMS	power management system

Appendix E: Safeguarding Bridges from Vessel Strikes: Need for Vulnerability Assessment and Risk Reduction Strategies

March 18, 2025 **MIR-25-10**

E1. Introduction

The National Transportation Safety Board (NTSB) is providing the following information to urge owners of bridges over navigable waterways frequented by ocean-going vessels, the Federal Highway Administration (FHWA), the US Coast Guard, and the US Army Corps of Engineers to act on the safety recommendations in this report.[187] We identified the need to safeguard bridges from vessel strikes as part of our ongoing investigation of the March 26, 2024, containership *Dali*'s collision with the Francis Scott Key Bridge, and the bridge's subsequent collapse.[188] We completed a vulnerability assessment—a mathematical risk model calculated using data on bridge/span geometry and design, pier protection and lateral capacity, the characteristics of vessel traffic transiting the main navigation channel, waterway characteristics, and other factors—to determine how susceptible the Key Bridge was to collapse from a vessel collision and found that it was above the acceptable level of risk established by the American Association of State Highway and Transportation Officials (AASHTO) for such a collision.[189] We also identified 68 other bridges frequented by ocean-going vessels that were constructed before the AASHTO guidance was issued in 1991, have not undergone a vulnerability assessment based on recent vessel traffic, and, therefore, have an unknown level of risk of collapse from a vessel collision.

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[187] An *ocean-going vessel* is a large ship that transits international routes and/or the Great Lakes. Examples include containerships, general cargo ships, tankers, dry bulk carriers, passenger ships, cable-laying ships, research ships, support ships, training ships, and US Navy ships.

[188] (a) Although the maritime definition of *collision* involves two moving vessels striking one another, the findings and recommendations in this report mainly concern bridge design. Therefore, this report uses the term *collision* when discussing a vessel striking a bridge. (b) Visit ntsb.gov to find additional information in the public docket for this NTSB investigation (case number DCA24MM031). Use the CAROL Query to search safety recommendations and investigations.

[189] A *vulnerability assessment* is used to estimate the annual frequency of bridge collapse based on the bridge pier/span geometry, ultimate resistance of the pier (or span), waterway characteristics, and the characteristics of the vessel fleet transiting the channel. (AASHTO, 2009, *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, 2nd ed., 180.)

In this interim report, we urge the FHWA, Coast Guard, and Corps of Engineers to form a dedicated, interdisciplinary team that provides guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. We also urge the owners of the 68 identified bridges to calculate whether the probability of a bridge collapse from a vessel collision is above the acceptable risk threshold established by AASHTO. If so, we urge them to develop and implement a risk reduction plan that includes input from the interdisciplinary team, identifies short- and long-term strategies to reduce risk, and considers the safety of the vessels and structures in the waterways.

E2. Background and Analysis

E2.1 *Dali* Collision with Francis Scott Key Bridge and Subsequent Bridge Collapse

On March 26, 2024, about 0129 eastern daylight time, the 984-foot-long Singapore-flagged cargo vessel (containership) *Dali* was transiting out of Baltimore Harbor in Baltimore, Maryland, when it experienced a loss of electrical power and propulsion and struck Pier 17, the southern pier that supported the central span of the continuous through-truss of the Francis Scott Key Bridge.[190] A portion of the bridge subsequently collapsed into the river, and portions of the pier, deck, and truss spans collapsed onto the vessel's forward deck (see figure E-1).[191] A seven-person road maintenance crew and one inspector were on the bridge when the vessel struck it. The inspector escaped unharmed, and one of the construction crewmembers survived the collapse with serious injuries. Six construction workers died as a result of the bridge collapse. One of the 23 persons aboard the *Dali* sustained a minor injury.

[190] (a) A *pier* is "a substructure unit that supports the spans of a multi-span superstructure at an intermediate location between its abutments." (FHWA, 2022, *Bridge Inspector's Reference Manual*, Report Number FHWA-NHI-21-002, FHWA National Highway Institute.) (b) A *span* is the horizontal space between two supports of a bridge structure. (b) A *truss* is a "jointed structure made up of individual members primarily carrying axial loads arranged and connected in triangular panels" (FHWA 2022).

[191] A bridge *deck* is "the portion of a bridge that provides direct support for vehicular and pedestrian traffic, supported by the superstructure" (FHWA 2002).

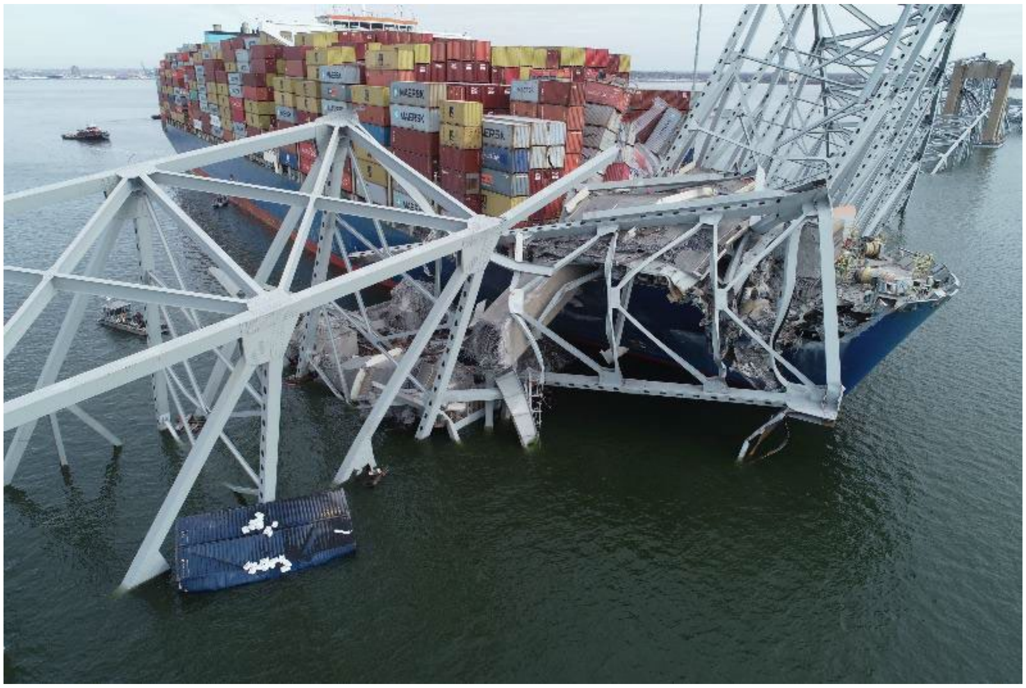

Figure E-1. The *Dali*, with portions of the collapsed Key Bridge across its forward deck and in the Patapsco River, on March 28, 2024.

E2.2 Francis Scott Key Bridge and Fort McHenry Federal Channel

E2.2.1 Francis Scott Key Bridge

The Key Bridge was located in Baltimore, Maryland, and carried Maryland 695 over the Patapsco River, from Baltimore to Dundalk, Maryland.[192] The bridge was owned and operated by the Maryland Transportation Authority (MDTA) and opened to traffic on March 23, 1977. According to the MDTA, the overall length of the bridge was about 9,086 feet between the north and south abutments.[193] The maximum vertical clearance for the Key Bridge above the main navigational channel, the 700-foot-wide Fort McHenry Federal Channel, was 185 feet.[194]

[192] On April 29, 2024, the FHWA approved a request from the State of Maryland to redesignate a segment of Maryland 695, including the Francis Scott Key Bridge, as part of the interstate highway system.

[193] An *abutment* is a structure designed to support the vertical and lateral forces from the ends of an arch or span, such as a bridge.

[194] *Vertical clearance* is the vertical distance between the water level at mean high water and the lowest point of the bridge structure span over a navigation channel, indicating how much space a vessel has to pass underneath without hitting the bridge. Also known as "charted height."

The Key Bridge was designed according to the 1969 edition of the AASHTO *Standard Specifications for Highway Bridges* (1970 and 1971 Interim Specifications).[195] Although this guidance did not mention the risk of vessel collisions or a need for bridge protections, the Key Bridge was designed and built with physical protection systems to protect portions of the bridge exposed to possible damage by marine traffic. These protection systems (including four 28-foot-diameter dolphin structures, each with rubber fenders, and crushable concrete and timber fendering systems around Pier 17 and Pier 18) were in place when the bridge opened in 1977 (see figure E-2).[196] Dolphins are frequently used to protect bridge piers because they can slow, stop, or redirect an aberrant vessel.[197]

The Key Bridge dolphins were constructed according to project-specific design criteria and, according to the MDTA, have retained these original specifications. The centers of Dolphin 1 and Dolphin 2 were located 489 feet west of the centers of Pier 17 and Pier 18, respectively (see figure E-3). All dolphins were about 550 feet clear of the centerline of the Fort McHenry Federal Channel. None of the four dolphins were contacted by the *Dali* during the collision.

[195] AASHTO, 1969, *Standard Specifications for Highway Bridges*, 1970 and 1971 Interim Specifications, 10th ed. Note that in 1969, AASHTO was called the American Association of State Highway Officials.

[196] (a) A *bridge dolphin* is "a group of piles driven close together, or a caisson placed to protect portions of a bridge exposed to possible damage by collision with river or marine traffic" (FHWA 2022). (b) A *fender* (or *fendering system*) is a protective structure located directly on a bridge or on a protective element independent of the bridge (such as a dolphin), designed to fully or partially absorb the design impact loads, or deflect or redirect an aberrant vessel away from the bridge. (c) *Rubber fenders* are "usually placed on the outer perimeter of the dolphin to act as an anti-sparking surface to prevent metal-to-metal contact in the event of collision with a steel-hulled vessel carrying flammable products." Further, "the circular shape of the dolphins can help deflect aberrant vessels away from the pier." Finally, crushable concrete and timber *fendering systems*, such as those around Pier 17 and Pier 18, have been frequently used for protecting piers from minor vessel impact forces "because of their relatively low cost." (AASHTO, Article C7.3.3, "Dolphin Protection," *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges* (2009), 114.)

[197] (a) For more information, see Article C7.3.3, "Dolphin Protection" in AASHTO's 2009 *Guide Specifications*. (b) An *aberrant vessel* is a vessel that has lost control or has unexpectedly gone off course.

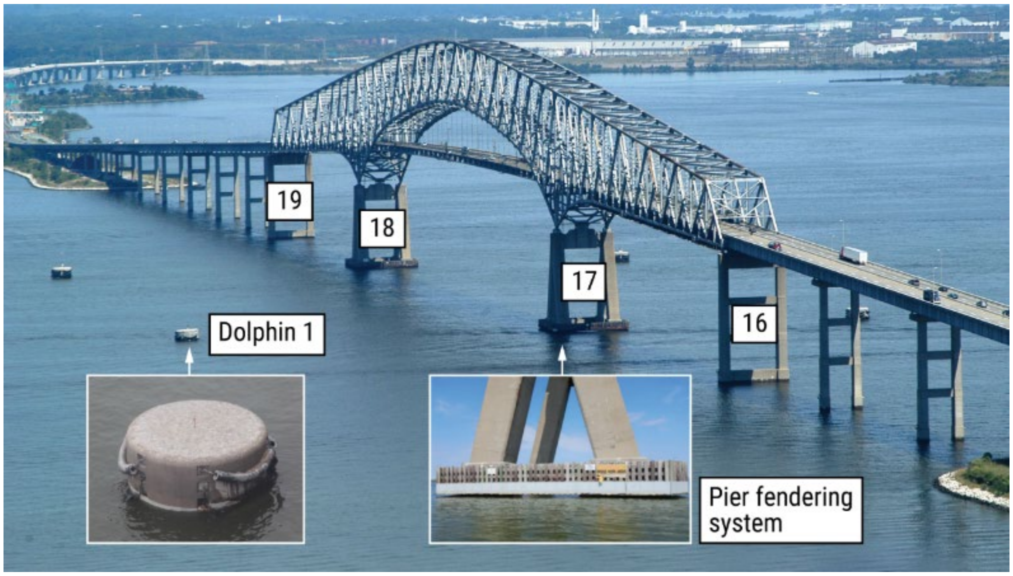

Figure E-2. The Key Bridge and the physical protection systems (Dolphin 1 and the pier fendering system) protecting Pier 17 from vessels transiting outbound under the Key Bridge. (Background source: MDTA)

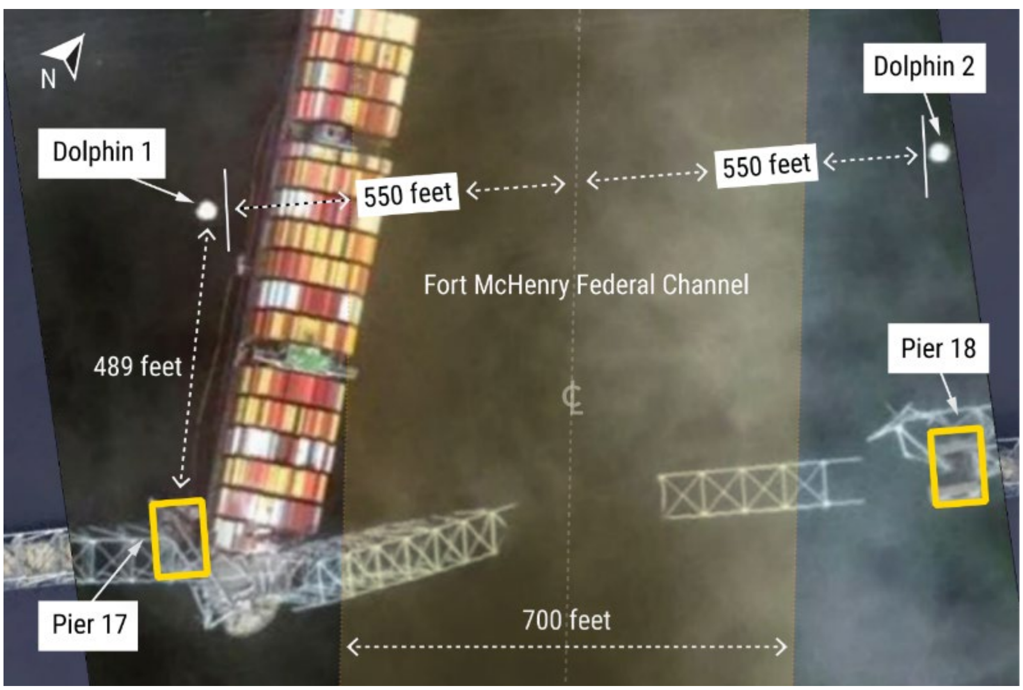

Figure E-3. Overhead view of the collapsed Key Bridge and the *Dali*. Locations of Dolphin 1 and Dolphin 2 relative to the vessel, bridge, and Fort McHenry Federal Channel are depicted. (Background sources: MAXAR and Google Earth)

In accordance with the National Bridge Inspection Standards, the Key Bridge and its pier protection systems were subject to regular safety inspections by nationally certified bridge inspectors.[198] These periodic safety inspections, which included the dolphins for the Key Bridge, are intended to assess and document the physical and functional condition of a bridge and its components, and identify any changes from previously recorded conditions to ensure that any structural deficiencies posing an imminent threat to public safety are corrected.[199] These inspections are "necessary to maintain safe bridge operation and prevent structural and functional failures."[200] The Key Bridge's most recent inspections in March 2021 and May 2023 found the condition of the deck, the superstructure, and the substructure as being in satisfactory condition, and the pier protection was rated as in place and functioning properly.[201]

The Key Bridge's pier protection was struck in 1980 when the 390-foot-long Japan-flagged containership *Blue Nagoya*, which had a displacement or weight about one-tenth that of the *Dali*, collided with Pier 17 following a loss of steering about 600 yards from the bridge; see figure E-4 for a size comparison of the *Blue Nagoya* to the *Dali*. The vessel was stopped by the crushable concrete and timber fendering system at Pier 17, and the bow overhang contacted the pier's A-frame.[202] As a result of the collision, minor surface damage occurred on Pier 17's columns and the pier's fender was destroyed. The crushable concrete and timber fendering around the pier was reconstructed according to the original project-specific design criteria, and the minor damage to the columns was repaired.

[198] See Title 23 *Code of Federal Regulations* (*CFR*) Part 650 Subpart C.

[199] (a) See 23 *CFR* 650.313(q)(1)(i). (b) FHWA, "Questions and Answers on the National Bridge Inspection Standards, 23 *CFR* Part 650, Subpart C." Updated April 5, 2024.

[200] FHWA, "National Bridge Inspection Standards." Updated November 7, 2024.

[201] (a) A *superstructure* is a bridge structure that receives loads from the deck, such as traffic or pedestrian loads, and in turn, transfers those loads to the substructure. (b) A *substructure* is a bridge structure that supports the superstructure and transfers loads from it to the foundation; main components are abutments, piers, footings, and pilings.

[202] See National Research Council, *Ship Collisions with Bridges: The Nature of the Accidents, Their Prevention, and Mitigation* (National Academy Press, 1983), 26. See also AASHTO 2009, 102.

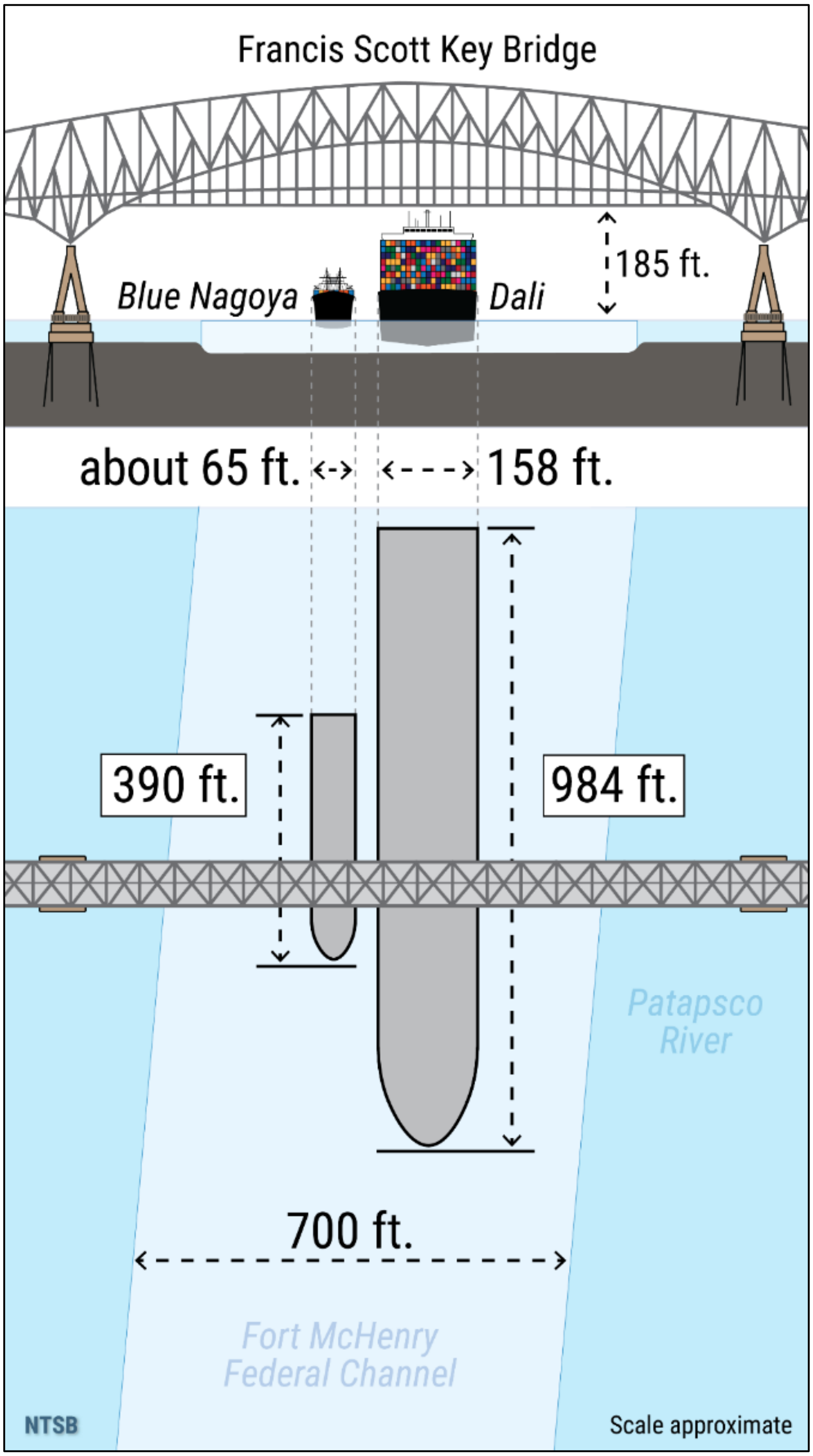

Figure E-4. The comparative sizes of the *Blue Nagoya* and the *Dali* relative to the Key Bridge.

E2.2.2 Fort McHenry Federal Channel

The Fort McHenry Federal Channel, which runs within the Patapsco River along the length of the Port of Baltimore and under the Key Bridge, is a navigation channel maintained by the Corps of Engineers (see figure E-5). The channel is 700 feet wide, 50 feet deep, and 4 miles long, with a vertical clearance of 185 feet under the Key Bridge. The main navigational channel near the bridge is straight, and there are no bends or turns.

Ocean-going vessels passed under the bridge at the centerline of the Fort McHenry Federal Channel and were required to have a Maryland State Pilot aboard.[203] In 2023, a total of 3,775 transits between Pier 17 and Pier 18 were recorded (1,902 inbound and 1,873 outbound).[204]

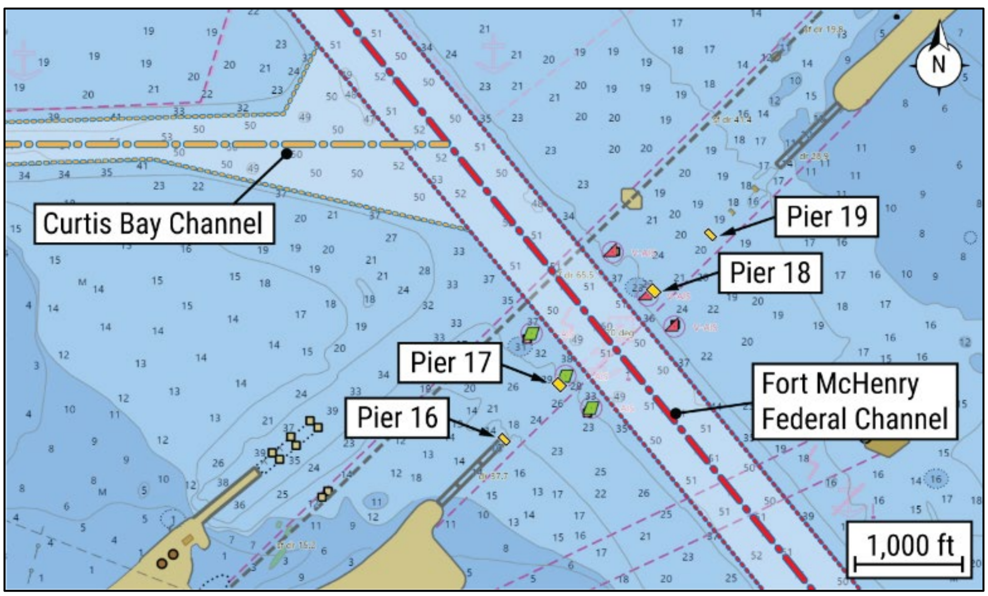

Figure E-5. Nautical chart used to evaluate the channel layout. (Background source: National Oceanic and Atmospheric Administration electronic navigational chart US5BALBB)

[203] A *pilot* is retained by the ship to provide local knowledge of the waterway, familiarity with tides and currents in the area, understanding of local procedures, and a thorough knowledge of the topography of the waterway. Pilots usually operate by issuing maneuvering instructions (such as heading, rudder angle, and speed orders) to the vessel's crew under the supervision of the master, the officer in charge of the navigation watch, or both.

[204] Per National Oceanic and Atmospheric Administration AccessAIS data. Further details can be found in the public docket for this investigation.

E2.3 Vessel Collision Vulnerability Assessment

E2.3.1 Background

As a result of the NTSB's investigation of the May 9, 1980, Liberia-flagged bulk carrier *Summit Venture*'s collision with the Sunshine Skyway Bridge, Tampa Bay, Florida, we issued multiple recommendations to address identified safety concerns.[205] Among those recommendations, we asked the FHWA, in cooperation with the Coast Guard, to "develop standards for the design, performance, and location of structural bridge pier protection systems which consider that the impact from an off-course vessel can occur significantly above as well as below the water surface" (Safety Recommendation M-81-20). In response to this recommendation, the FHWA shared an existing research study, "The State of the Art: Bridge Protective Systems and Devices," and indicated that a follow-up study to perform laboratory tests of bridge protection models had been initiated and was nearly complete.[206] In 1988, a pooled-fund research project sponsored by 11 states and the FHWA led to the development of a proposed design code for bridge engineers to use in evaluating structures for vessel collision. This effort resulted in AASHTO's adoption of its first edition of the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* in 1991.[207] The second edition, titled *Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges*, was released in 2009.[208]

The FHWA requires that new bridges on the National Highway System be designed to minimize the risk of a catastrophic bridge collapse from a vessel collision given the size, speed, and other characteristics of the vessels navigating the channel under the bridge; the requirements were adapted from AASHTO's *Guide*

[205] *Ramming of the Sunshine Skyway Bridge by the Liberian Bulk Carrier* Summit Venture, *Tampa Bay, Florida, May 9, 1980*, MAR-81-03.

[206] (a) The NTSB classified Safety Recommendation M-81-20 Closed—Acceptable Action in December 1984. (b) "The State of the Art: Bridge Protective Systems and Devices." Final Report 1979. Report no. CG-N-1-80. Prepared for US Department of Transportation, sponsoring agency US Coast Guard Office of Navigation, performing organization University of Maryland Department of Civil Engineering. Washington, DC.

[207] AASHTO, *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges*, Volume I: Final Report, 1991.

[208] AASHTO 2009.

Specifications using a vulnerability assessment calculation.[209] AASHTO's 1991 *Guide Specification* introduced the vulnerability assessment calculation, and AASHTO reiterated the value of performing this calculation in its 2009 *Guide Specifications*. AASHTO also recommended that bridge owners use the vulnerability assessment calculations to evaluate bridges built before 1991 to identify bridges at risk of a catastrophic collapse in the event of a vessel collision and to "be aware of high-risk safety needs requiring immediate or short-term action, as well as information to prioritize and budget for the long-term needs for bridge rehabilitation or replacement."[210]

Neither the FHWA nor AASHTO can require a bridge owner to complete a vulnerability assessment for a bridge designed before the release of the 1991 guidelines.[211] The MDTA had not performed, nor was it required to perform, a vulnerability assessment to evaluate the Key Bridge's risk of a catastrophic collapse from a vessel collision. However, as previously stated, AASHTO recommended that states, like Maryland, perform such vulnerability assessments to evaluate and address risk.

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[209] a) This requirement applies to bridges on the National Highway System (23 *CFR* 625.3(a)(1)). Bridges not on the National Highway System are designed in accordance with State law (23 *CFR* 625.3(a)(2)). b) Requirements contained within the AASHTO *LRFD* [Load and Resistance Factor Design] *Bridge Design Specifications*, which are defined in 23 *CFR* 625.4, were adapted from the *Guide Specifications* using the Method II vulnerability assessment. Method II is discussed further in section E0 of this report. The *LRFD Bridge Design Specifications* are intended for the design, evaluation, and rehabilitation of both fixed and movable highway bridges. The Method II risk acceptance has been included in the *LRFD Bridge Design Specifications* since their inception in 1994. c) The NTSB has addressed the AASHTO *Guide Specifications*' vulnerability assessments in two prior investigation reports related to vessel/bridge collisions. See *U.S. Towboat* Robert Y. Love *Allision With Interstate 40 Highway Bridge Near Webbers Falls, Oklahoma, May 26, 2002*, NTSB/HAR-04/05, and *Allision of Hong Kong-Registered Containership M/V* Cosco Busan *with the Delta Tower of the San Francisco–Oakland Bay Bridge, San Francisco, California, November 7, 2007*, NTSB/MAR-09/01.

[210] AASHTO 2009, 2.

[211] Per Title 23 *United States Code* 144(h)(3)(A)(ii), the FHWA's authority to require bridge assessment extends only to the evaluation of live load carrying capacity (commonly referred to as a bridge load rating).

E2.3.2 AASHTO Guide Specifications

The 2009 AASHTO *Guide Specifications* provide three methods for conducting bridge vulnerability assessments.[212] Unless a bridge over a navigable waterway with commercial vessel traffic was "designed in accordance with the previous 1991 edition of the AASHTO *Guide Specification*," the bridge "should be evaluated using a vulnerability assessment in accordance with the Method II risk analysis procedures contained in the current guide specifications."

The AASHTO Method II vulnerability assessment calculation is used to determine the annual frequency of collapse (AF), which is the probability of a bridge collapse due to vessel collision in a year's time. The total AF is based on the sum of the AFs for each pier that is vulnerable to a vessel collision from both inbound and outbound traffic. This vulnerability assessment calculation allows bridge owners to calculate their bridge's level of risk and determine whether that risk is below the acceptable threshold established by AASHTO. A bridge design with a risk level below the acceptable threshold would minimize the risk of a collapse but does not guarantee that a collapse from a vessel collision will not occur. Likewise, a risk level above the acceptable threshold does not mean a collapse from a vessel collision is a certainty. The Method II vulnerability assessment calculation, shown in Appendix A, uses data specific to each bridge and waterway, including:

- characteristics of the vessel traffic passing under the bridge,
- vessel transit speeds,
- vessel loading characteristics,
- waterway and navigable channel geometry (including intersecting channels),
- water depths,
- environmental conditions,
- bridge geometry,
- pier protection systems, and

[212] "Method I is a simple to use semi-deterministic procedure; Method II is a detailed risk analysis procedure; and Method III is a cost-effectiveness of risk reduction procedure (based on a classical benefit/cost analysis). The *Guide Specifications* require the use of Method II risk analysis for all bridges unless special circumstances exist as described in the code for the use of Methods I and III. Special circumstances for using Method I include shallow draft waterways where the marine traffic consists almost exclusively of barges, and for using Method III include very wide waterways with many piers exposed to collision, as well as existing bridges to be retrofitted" (AASHTO 2009, 2). Further, "a prerequisite for using Method III is that the annual frequency of bridge collapse is computed in accordance with Method II and brought to the attention of the [bridge] owner" (AASHTO 2009, 62).

- ultimate lateral capacity of the bridge piers.[213]

The AASHTO *Guide Specifications* further define how these data are used to calculate each factor in the vulnerability assessment calculation related to:

- the vessel frequency distribution transiting under the bridge,
- the probability that a vessel will go off course,
- the probability that a vessel will hit a bridge pier if it is off course,
- the probability of a bridge collapse once a collision has occurred, and
- the protection factor due to the presence of structures, such as dolphins or islands, that may protect a pier from collision.

The AASHTO *Guide Specifications* classify bridges over navigable waterways as either critical/essential or typical. Bridges that "serve as important links" in the Strategic Highway Network are classified as critical/essential; the Key Bridge had this classification.[214] Bridges not deemed critical/essential are classified as typical. The 2009 AASHTO *Guide Specifications* provide acceptable threshold values for a bridge's vulnerability assessment calculation. For bridges classified as critical/essential, the threshold is computed as an AF value of 0.0001. For bridges classified as typical, the threshold is computed as an AF value of 0.001.

E2.3.3 Francis Scott Key Bridge Vulnerability Assessment Acceptable Threshold

As noted previously, bridges built before 1991 were not required to undergo a vulnerability assessment; such an assessment had not been performed for the Key Bridge, which was constructed in 1977. Following the *Dali* collision, the NTSB conducted a vulnerability assessment of the bridge using the AASHTO Method II calculation to understand its level of risk at the time of its collapse. The calculated AF considered the factors listed above to assess whether this value was below AASHTO's acceptable threshold value for a critical/essential bridge's probability of collapse. We calculated and summed the AFs for both inbound and outbound vessel traffic for Piers 16, 17, 18, and 19, which are shown in table e-1.[215] These piers provided

[213] *Lateral capacity* is the maximum horizontal load a pier can withstand before failing.

[214] AASHTO 2009, 21. The Strategic Highway Network "is a designation given to roads that provide defense access, continuity, and emergency capabilities for movements of personnel and equipment in both peace and war." (US Department of Transportation, updated July 27, 2024.)

[215] Details of the vulnerability assessment calculations to determine the Key Bridge's AF can be found in the public docket for this investigation.

support to the portion of the bridge over the Fort McHenry Federal Channel.[216] A comparison of the AFs of the piers in table E-1 shows that a vessel collision with Pier 17 or Pier 18 was the largest contributor to the Key Bridge's overall AF.

Table E-1. AF Summary for the Key Bridge.

Pier	Inbound AF	Outbound AF	Total AF
16	0.000024	0.000024	0.000048
17	0.000687	0.000743	0.001430
18	0.000693	0.000749	0.001442
19	0.000001	0.000000	0.000001
Total	0.001405	0.001516	0.002921

Since the Key Bridge's opening in 1977, engineering and shipping advances—such as the 2016 Panama Canal expansion—have led to far larger vessels visiting, and increased vessel traffic volume to and from, the Port of Baltimore. Therefore, incorporating current vessel traffic parameters (and other environmental/waterway factors) into the AASHTO Method II vulnerability assessment calculation to evaluate the Key Bridge's specifications, the NTSB determined that if the MDTA had calculated the AF for the Key Bridge before the collapse, it would have identified that the bridge's risk level was almost 30 times greater than the AASHTO risk threshold for critical/essential bridges (0.0001). Therefore, the NTSB concludes that had the MDTA conducted a vulnerability assessment of the Francis Scott Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 AASHTO *Guide Specifications*, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.

The 2009 AASHTO *Guide Specifications* are a resource for state Departments of Transportation (DOTs) and other bridge owners to better understand the overall safety of bridges within their inventory to "minimize their susceptibility to damage from vessel collisions."[217] For the Key Bridge, factors that contributed to this risk in the calculated vulnerability assessment included the piers adjacent to the main navigation channel and the channel size, which provided off-course vessels with little

[216] The calculation focused on ocean-going vessels, including containerships, general cargo ships, tankers, dry bulk carriers, and other vessels (passenger ships, cable laying ships, research ships, support ships, training ships, and US Navy ships).

[217] AASHTO 2009, ix.

time for path correction before colliding with the bridge. Further, the locations and size of the dolphins did not fully protect Pier 17 and Pier 18 from a collision from an off-course vessel, and the speed and size (dimensions and weight) of modern vessels such as the *Dali* highlighted that the bridge piers were not strong enough to withstand a collision from a large ocean-going vessel.

Although some factors are challenging to modify for existing bridges, the process of calculating vulnerability assessments enables owners to make informed decisions to manage their assets, identify their bridges that may be susceptible to damage from a vessel collision, and appraise and prioritize vessel collision protection projects alongside other projects addressing highway asset needs and risks. When a bridge owner performs vulnerability assessments of structures in its inventory in accordance with the Method II calculation outlined by the 2009 AASHTO *Guide Specifications*, it is better equipped to understand the overall vulnerability of the bridges within its inventory. Therefore, the NTSB concludes that had the MDTA conducted a vulnerability assessment of the Key Bridge using AASHTO's Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.

E2.4 Other US Bridges over Navigable Waterways Frequented by Ocean-Going Vessels

Like the Key Bridge, other bridges throughout the United States were designed before AASHTO's 1991 *Guide Specification* for bridge design was issued. To understand the scope of the risk posed by bridges nationwide with designs predating AASHTO's *Guide Specification*, the NTSB requested that the FHWA identify bridges that cross navigable waterways and are used by ocean-going vessels like the *Dali*, as well as gather information about protection devices in place for those bridges (if any). The FHWA coordinated with state DOTs to identify 176 bridges in 26 states that cross waterways used by ocean-going vessels.[218]

The NTSB subsequently filtered the results according to whether a bridge:

- Was built before 1996. We recognized that although the AASHTO *Guide Specification* was available in 1991, bridges under design or

[218] The FHWA sent questionnaires to state DOTs, regarding engineering studies on pier protection and what standards were used during those studies. The FHWA used the responses to produce the report, *FHWA Bridges Crossing Waterways Utilized by Ocean-Going Vessels*, which can be found in the public docket for this investigation.

initial construction at that time were likely not built to its specifications. Therefore, we determined that bridges placed into service before 1996 were likely not designed and built to the current specifications.

- Had a vertical clearance of at least 80 feet. We used the typical vertical clearance height for ocean-going vessels (80 feet) based upon the typical minimum mast clearance height of a loaded bulk carrier and loaded tanker.[219]
- Had substructures (such as piers) in a waterway. The only bridges considered in this report were those with piers in a waterway, because piers on land have natural protection from a horizontal vessel impact.[220]

Applying these conditions to the 176 bridges reduced the number to 95. The NTSB also queried the FHWA Long-Term Bridge Performance (LTBP) InfoBridge web portal to identify 224 bridges owned by the Corps of Engineers.[221] The same parameters used to filter the 176 bridges in the FHWA report were applied to these 224 bridges, resulting in 6 bridges that met the above criteria. Therefore, a total of 101 bridges—95 identified in the FHWA report and 6 owned by the Corps of Engineers—met the NTSB criteria.[222]

Next, we evaluated the vessel traffic transiting under the 101 bridges between January 1, 2019, and September 31, 2024, to determine whether a bridge's average annual transits by ocean-going vessels were sufficient to result in a measurable amount of risk in the vulnerability assessment calculation.[223] This evaluation was accomplished using a similar methodology to the one used to determine the vessel traffic for the

[219] (a) AASHTO 2009. (b) *Mast clearance height* is the vertical distance from the top of a vessel's highest point down to its waterline. Also known as "air draft." (c) The NTSB used the vessel types listed in the AASHTO 2009 *Guide Specifications*, which had a minimum mast height of 80 feet (AASHTO 2009, 32).

[220] A total of 14 bridges built before 1996 had piers that were constructed only on land.

[221] Federal Highway Administration Office of Research, Development and Technology at the Turner-Fairbanks Highway Research Center, "Long-Term Bridge Performance (LTBP) InfoBridge." Updated November 10, 2022.

[222] Additional details about how the data were filtered can be found in the public docket for this investigation.

[223] Engineering judgement was used to determine a conservative value of 100 annual transits by ocean-going vessels as the minimum number sufficient to provide risk in the vulnerability assessment calculation. For comparison, the Key Bridge had 3,775 ocean-going vessel transits in 2023.

Key Bridge.[224] As a result, we identified 72 bridges (in 19 states, managed by 30 separate bridge owners) over navigable waterways frequented by ocean-going vessels that were likely not designed and built to the AASHTO *Guide Specifications*. The information that the FHWA collected in coordination with state DOTs regarding protection devices helped us to identify that the owners of 4 of the 72 bridges had performed a recent vulnerability assessment and were either implementing a plan to reduce their bridge's vulnerability or would be doing so in the near future. Appendix B lists the remaining 68 bridges that have not undergone a vulnerability assessment based on recent vessel traffic and therefore have an unknown level of risk of collapse from a vessel collision.

Calculating a bridge's AF can help owners understand their bridges' vulnerability of collapse from a vessel collision and the aspects of bridge design or vessel traffic that contribute to this vulnerability, especially for bridges with an AF above the AASHTO threshold. As noted, we identified 68 bridges over navigable waterways frequented by ocean-going vessels that have an unknown level of risk of collapse. Therefore, the NTSB concludes that the 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability. The NTSB recommends that the 30 owners of the bridges identified in Appendix B of this report calculate the AASHTO Method II AF for the bridge(s) identified in Appendix B of this report for which they are responsible and inform the NTSB whether the probability of collapse is above the AASHTO threshold.

Awareness of which aspects of bridge design or vessel traffic affect the probability of a collapse can aid in the development of risk reduction strategies. Each of the strategies must be evaluated as part of a holistic safety evaluation of potential benefits and unintended negative outcomes. The bridge owners are in the best position to assess potential strategies for reducing the risk of a bridge collapse from a vessel collision, but they would also benefit from the guidance of the federal agencies that oversee the overlapping aspects of bridge infrastructure, vessel operations, and waterway management. Per the 2009 AASHTO *Guide Specifications*,

[224] (a) More information can be found in the public docket for this investigation. (b) The differences between our assessment of the Key Bridge traffic and that of the 101 bridges were the use of National Oceanic and Atmospheric Administration's AccessAIS tool and that duplicate records that were transmitted within 15 minutes of each other for the same vessel were not removed and, therefore, the number of transits may have been overestimated. Generally, vessels transmit automatic identification system [AIS] data at specific intervals. There were instances where the same ship transmitted automatic identification system data because the transmission intervals were short and, as the vessel traveled through the established geofence, it transmitted multiple times (duplicate records).

bridge risk reduction evaluations should be developed by an interdisciplinary team that includes representatives from the Coast Guard, the Corps of Engineers, and other federal agencies.[225] The FHWA plays a key role in risk reduction based on its expertise and technical guidance in bridge design, construction, inspection, evaluation, management, and preservation. The Coast Guard has a role in the regulation of vessel operations, including controlling or supervising vessel traffic (when necessary). Finally, the Corps of Engineers is responsible for maintaining the navigability of waterways leading to and within ports by planning, constructing, and managing dredging projects to ensure sufficient channel depths for vessels.

Because of the need to ensure a holistic safety approach and timely guidance to bridge owners on the risks posed by these interconnected factors, the NTSB recommends that the FHWA, in coordination with the Coast Guard and Corps of Engineers, establish an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. The NTSB also recommends that the Coast Guard and Corps of Engineers support the FHWA in establishing an interdisciplinary team—including representatives from the FHWA, Coast Guard, and Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision.

Finally, to ensure a comprehensive approach to the safety of the traveling public, bridges and structures, waterways, and vessel traffic, the NTSB recommends that the 30 owners of the bridges identified in Appendix B of this report, if the calculations that they performed in response to Safety Recommendation H-25-3 indicate that a bridge has an AF greater than the AASHTO threshold, develop and implement a comprehensive risk reduction plan that includes, at a minimum:

- guidance and assistance from the FHWA, Coast Guard, and Corps of Engineers interdisciplinary team identified in Safety Recommendations H-25-1 and H-25-2, and
- short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision.

[225] AASHTO 2009, 1.

E3. Findings

1. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge based on recent vessel traffic, as recommended by the 1991 and 2009 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications*, the MDTA would have been aware that this critical/essential bridge was above the AASHTO threshold of risk for catastrophic collapse from a vessel collision when the *Dali* collision occurred.

2. Had the Maryland Transportation Authority (MDTA) conducted a vulnerability assessment of the Francis Scott Key Bridge using the American Association of State Highway and Transportation Officials' Method II vulnerability assessment calculation, the MDTA would have had information to proactively identify strategies to reduce the risk of a collapse and loss of lives associated with a vessel collision with the bridge.

3. The 30 owners of 68 bridges over navigable waterways frequented by ocean-going vessels are likely unaware of their bridges' risk of catastrophic collapse from a vessel collision and the potential need to implement countermeasures to reduce the bridges' vulnerability.

E4. Recommendations

To the Federal Highway Administration:

In coordination with the US Coast Guard and US Army Corps of Engineers, establish an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-1) (Urgent)

To the US Coast Guard and the US Army Corps of Engineers:

Support the Federal Highway Administration in establishing an interdisciplinary team—including representatives from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers—and provide guidance and assistance to bridge owners on evaluating and reducing the risk of a bridge collapse from a vessel collision. (H-25-2) (Urgent)

To the Bay Area Toll Authority, the California Department of Transportation, the Golden Gate Bridge Highway and Transportation District, the US Army Corps of Engineers, the Florida Department of Transportation, the Georgia Department of Transportation, Skyway Concession Company LLC, the Louisiana Department of Transportation and Development, the New Orleans Public Belt Railroad, the Maryland Transportation Authority, the Massachusetts Department of Transportation, the Mackinac Bridge Authority, the New Hampshire Department of Transportation, the Delaware River Port Authority, the New Jersey Turnpike Authority, Metropolitan Transportation Authority Bridges and Tunnels, the New York City Department of Transportation, the New York State Bridge Authority, the Ogdensburg Bridge and Port Authority, the Port Authority of New York and New Jersey, the Seaway International Bridge Corporation, the Thousand Islands Bridge Authority, the Ohio Department of Transportation, the Oregon Department of Transportation, the Pennsylvania Turnpike Commission, the Rhode Island Turnpike and Bridge Authority, the Harris County Toll Road Authority, the Texas Department of Transportation, the Washington State Department of Transportation, and the Wisconsin Department of Transportation:

Calculate the American Association of State Highway and Transportation Officials (AASHTO) Method II annual frequency of collapse for the bridge(s) identified in Appendix B of this report for which you are responsible and inform the National Transportation Safety Board whether the probability of collapse is above the AASHTO threshold. (H-25-3) (Urgent)

If the calculations that you performed in response to Safety Recommendation H-25-3 indicate that a bridge has an annual frequency of collapse greater than the American Association of State Highway and Transportation Officials threshold, develop and implement a comprehensive risk reduction plan that includes, at a minimum:

- guidance and assistance from the Federal Highway Administration, US Coast Guard, and US Army Corps of Engineers Interdisciplinary Team identified in Safety Recommendations H-25-1 and H-25-2, and

- short- and long-term strategies to reduce the probability of a potential bridge collapse from a vessel collision. (H-25-4) (Urgent)

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Report Date: March 18, 2025

Appendixes

Appendix E-A: American Association of State Highway and Transportation Officials Method II Vulnerability Assessment Calculation

The Method II calculation determines the annual frequency of collapse (AF), which is the probability of a bridge collapse due to vessel collision in a year's time. The equation for this calculation is as follows:

$$AF = (N)(PA)(PG)(PC)(PF)$$

where:

N = annual number of vessels classified by type, size, and loading condition which can strike the bridge element

PA = probability of vessel aberrancy

PG = geometric probability of a collision between an aberrant vessel and bridge pier or span

PC = probability of bridge collapse due to a collision with an aberrant vessel

PF = adjustment factor to account for potential protection of the piers from vessel collision due to upstream or downstream land masses, or other structures, that block the vessel

An AF is "computed for each bridge element and vessel classification. The summation of all bridge element AFs equals the annual frequency of collapse for the entire bridge structure."[226]

[226] AASHTO 2009, 69.

Appendix E-B: US Bridges Over Navigable Waterways Frequented by Ocean-Going Vessels with Unknown Levels of Risk of Collapse from a Vessel Collision

Table EB-1. US Bridges Over Navigable Waterways Frequented by Ocean-Going Vessels with Unknown Levels of Risk of Collapse from a Vessel Collision.[a]

State	Bridge Name	Bridge Owner	Classification	Year Built
California	Richmond-San Rafael Bridge	Bay Area Toll Authority	Critical/Essential	1956
California	Carquinez Bridge	Bay Area Toll Authority	Critical/Essential	1958
California	Benicia-Martinez Bridge	Bay Area Toll Authority	Critical/Essential	1962
California	Antioch Bridge	Bay Area Toll Authority	Typical	1978
California	San Mateo-Hayward Bridge	Bay Area Toll Authority	Typical	1967
California	Coronado Bridge	Caltrans	Critical/Essential	1969
California	Golden Gate Bridge	Golden Gate Bridge Highway and Transportation District	Critical/Essential	1937
Delaware	Summit Bridge	US Army Corps of Engineers	Typical	1959
Delaware	Saint Georges Bridge	US Army Corps of Engineers	Typical	1941
Delaware	Reedy Point Bridge	US Army Corps of Engineers	Typical	1969
Florida	Sunshine Skyway Bridge	Florida DOT	Critical/Essential	1986
Florida	Napoleon Bonaparte Broward Bridge (Dames Point Bridge)	Florida DOT	Critical/Essential	1989
Georgia	Talmadge Bridge	Georgia DOT	Typical	1991
Illinois	Chicago Skyway Calumet River Bridge	Skyway Concession Company LLC	Critical/Essential	1958
Louisiana	Huey P. Long Bridge	Louisiana DOT and Development and New Orleans Public Belt Railroad	Typical	1936
Louisiana	Greater New Orleans Bridge	Louisiana DOT and Development	Critical/Essential	1957
Louisiana	Israel LaFleur Bridge	Louisiana DOT and Development	Critical/Essential	1964

State	Bridge Name	Bridge Owner	Classification	Year Built
Louisiana	Crescent City Connection Bridge	Louisiana DOT and Development	Critical/Essential	1985
Louisiana	Hale Boggs (Luling) Bridge	Louisiana DOT and Development	Critical/Essential	1983
Louisiana	Horace Wilkinson Bridge	Louisiana DOT and Development	Critical/Essential	1968
Louisiana	Gramercy (Veterans Memorial) Bridge	Louisiana DOT and Development	Typical	1989
Louisiana	Sunshine Bridge	Louisiana DOT and Development	Typical	1963
Maryland	William Preston Lane Jr. (Bay) Bridge (eastbound)	Maryland Transportation Authority	Critical/Essential	1951
Maryland	William Preston Lane Jr. (Bay) Bridge (westbound)	Maryland Transportation Authority	Critical/Essential	1973
Maryland	Chesapeake City Bridge	US Army Corps of Engineers	Typical	1948
Massachusetts	Tobin Bridge (southbound upper)	Massachusetts DOT	Typical	1950
Massachusetts	Tobin Bridge (northbound lower)	Massachusetts DOT	Typical	1950
Massachusetts	Bourne Bridge	US Army Corps of Engineers	Critical/Essential	1935
Massachusetts	Sagamore Bridge	US Army Corps of Engineers	Typical	1935
Michigan	Mackinac Bridge	Mackinac Bridge Authority	Critical/Essential	1957
New Hampshire[b]	Memorial Bridge	New Hampshire DOT	Typical	1921
New Jersey[c]	Commodore Barry Bridge	Delaware River Port Authority	Typical	1974
New Jersey	Vincent R. Casciano (Newark Bay) Bridge	New Jersey Turnpike Authority	Critical/Essential	1955
New York	Verrazano Narrows Bridge (eastbound)	MTA Bridges and Tunnels	Critical/Essential	1961
New York	Verrazano Narrows Bridge (westbound)	MTA Bridges and Tunnels	Critical/Essential	1961
New York	Brooklyn Bridge	New York City DOT	Typical	1883
New York	Manhattan Bridge	New York City DOT	Typical	1909
New York	Williamsburg Bridge	New York City DOT	Typical	1903
New York	Newburgh-Beacon Bridge (eastbound)	New York State Bridge Authority	Critical/Essential	1980

State	Bridge Name	Bridge Owner	Classification	Year Built
New York	Newburgh-Beacon Bridge (westbound)	New York State Bridge Authority	Critical/Essential	1963
New York	Rip Van Winkle Bridge	New York State Bridge Authority	Typical	1935
New York	Ogdensburg-Prescott International Bridge	Ogdensburg Bridge and Port Authority	Typical	1960
New York[d]	George Washington Bridge	Port Authority of New York and New Jersey	Critical/Essential	1962
New York[d]	Outerbridge Crossing Bridge	Port Authority of New York and New Jersey	Typical	1928
New York	Seaway International Bridge	Seaway International Bridge Corporation	Typical	1958
New York	Thousand Islands Bridge	Thousand Islands Bridge Authority	Critical/Essential	1938
Ohio	CUY-00490-0010 (I-490) Bridge	Ohio DOT	Critical/Essential	1990
Ohio	CUY-00002-1441 (Main Avenue) Bridge	Ohio DOT	Typical	1939
Ohio	CUY-00006-1456 (Detroit Avenue) Bridge	Ohio DOT	Typical	1917
Ohio	CUY-00010-1613 (Carnegie Avenue) Bridge	Ohio DOT	Typical	1932
Ohio	LUC-01W02-0002 (Dr. Martin Luther King Jr. Memorial) Bridge	Ohio DOT	Typical	1914
Ohio	LUC-00002-1862 (Anthony Wayne) Bridge	Ohio DOT	Typical	1931
Oregon[e]	Astoria-Megler Bridge	Oregon DOT	Critical/Essential	1966
Oregon	St. Johns Bridge	Oregon DOT	Typical	1931
Pennsylvania[d]	Walt Whitman Bridge	Delaware River Port Authority	Critical/Essential	1957
Pennsylvania[d]	Benjamin Franklin Bridge	Delaware River Port Authority	Critical/Essential	1926
Pennsylvania[d]	Betsy Ross Bridge	Delaware River Port Authority	Typical	1976
Pennsylvania[d]	Delaware River Turnpike Bridge	Pennsylvania Turnpike Commission and New Jersey Turnpike Authority	Critical/Essential	1956
Rhode Island	Claiborne Pell Newport Bridge	Rhode Island Turnpike and Bridge Authority	Typical	1969

State	Bridge Name	Bridge Owner	Classification	Year Built
Texas	Buffalo Bayou Toll Bridge	Harris County Toll Road Authority	Typical	1980
Texas	Sidney Sherman Bridge	Texas DOT	Critical/Essential	1973
Texas	Rainbow Bridge	Texas DOT	Critical/Essential	1939
Texas	Veterans Memorial Bridge	Texas DOT	Critical/Essential	1991
Texas	Hartman Bridge (eastbound)	Texas DOT	Typical	1995
Texas	Hartman Bridge (westbound)	Texas DOT	Typical	1995
Texas	GulfGate Bridge	Texas DOT	Typical	1970
Washington[f]	Lewis and Clark Bridge	Washington State DOT	Critical/Essential	1929
Wisconsin	Leo Frigo Bridge	Wisconsin DOT	Critical/Essential	1979

[a] As discussed in the report, the four bridges with active or near-term plans are the west span of the Oakland-San Francisco Bay Bridge (owned by the Bay Area Toll Authority); the east and west spans of the Delaware Memorial Bridge (owned by the Delaware River & Bay Authority); and the Blatnik Bridge (co-owned by the Wisconsin and Minnesota DOTs).

[b] Crosses into Maine.

[c] Crosses into Pennsylvania.

[d] Crosses into New Jersey.

[e] Crosses into Washington.

[f] Crosses into Oregon.

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Accident Summary

Casualty type	Contact
Location	Patapsco River, Baltimore Harbor, Baltimore, Maryland 39°12.99' N, 076°31.75' W
Date	March 26, 2024
Time	0129 eastern daylight time (coordinated universal time -4 hours)
Injuries	6 fatal, 1 serious, 1 minor
Property damage	>$18 million est.
Environmental damage	None
Persons on board	23 (21 crewmembers and 2 pilots)

NTSB investigators worked closely with our counterparts from **Coast Guard East District** throughout this investigation.

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