THERE'S NO SUCH THING AS FREE SHIPPING: THE SIGNIFICANT RISK LARGE VESSELS POSE TO U.S. BRIDGES

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ABSTRACT

The collapse of the Francis Scott Key Bridge in Baltimore, Maryland in March 2024 raised major concerns surrounding bridge safety in the United States. This work presents the first comprehensive, data-driven investigation of large-vessel allision[1] risk for all major bridges in the United States and shows that the risk of a ship strike is high for 54 bridges. The study follows the American Association of State Highway and Transportation Officials Method II vulnerability assessment approach and is based on detailed large vessel traffic analysis for 357 bridges across the United States. Each bridge was identified from the National Bridge Inventory by screening all 624,170 bridges in the database and performing an initial traffic assessment of 4,464 bridges using Automatic Identification System (AIS) ship-tracking data. The study further shows that the aggregated risk of vessel allision across the full portfolio of bridges in the United States is very high, with an allision event expected once every 2.3 years – a trend that is unfortunately consistent with historical records. Importantly, the study only assesses allision risk and does not investigate the probability of collapse for individual bridges, which would require detailed structural analysis. These conclusions motivate the need for detailed collapse risk assessments for numerous bridges across the United States and investment in appropriate protective measures where necessary.

1 Introduction

On March 26, 2024, the Francis Scott Key (FSK) Bridge in Baltimore, Maryland, USA, collapsed when the cargo ship *Dali* lost power and drifted off course, striking Pier 17 of the bridge [1]. At approximately 300 meters in length and with dead weight tonnage over 116,000 tons, there is little doubt that even a major bridge like the FSK would, without protection, collapse under direct impact from such a massive cargo ship. This raises critical questions on the likelihood of an impact and the measures in place (both shipping practices and structural protections) to avoid such a catastrophic strike.

In the United States, the American Association of State Highway and Transportation Officials (AASHTO) establishes the design standards for major bridges, including provisions for ship allision risk[1]. Indeed, the FSK Bridge was designed according to the 1969 version of the AASHTO standards [2]. Critically, the 1969 design standards did not include provisions for vessel impact, as collapse from such an event was perceived as exceedingly rare. Nonetheless, the FSK Bridge was originally constructed with four 28-foot-diameter dolphin structures and crushable concrete and timber fendering systems around the piers of its main span to protect portions of the bridge from vessel impact [1].

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[1] Allision is the maritime term used for a moving vessel striking a stationary object

Following the vessel-impact-induced collapses of the Sunshine Skyway Bridge in Tampa Bay, FL and the Almö Bridge in Sweden in 1980, it became increasingly clear that provisions for vessel impact were needed in bridge design specifications. Following studies by the National Transportation Safety Board (NTSB) [3] and Federal Highway Administration (FHWA) [4], AASHTO adopted the *Guide Specification and Commentary for Vessel Collision Design of Highway Bridges* [5] in 1991. Subsequently, in 1994, AASHTO introduced vessel impact vulnerability calculations into the Load-and-Resistance Factor (LRFD) Bridge Design standard [6], which was the first design code to require risk-based design for vessel impact. AASHTO also recommended that bridge owners conduct a ship impact vulnerability assessment in accordance with the *Guide Specification* for existing bridges, but neither AASHTO nor the FHWA can require bridge owners to perform a risk analysis if the bridge was constructed prior to 1991 [1]. Consequently, the FSK Bridge and many other pre-existing bridges across the U.S. have not been assessed for ship impact risk[2].

The *Guide Specification* provides three methods for conducting vessel impact vulnerability assessment[3]. Except under special circumstances, bridges designed after 1994 (per the AASHTO LRFD standard [6]) are required to use Method II, which outlines a detailed risk assessment. Method II provides the basis for our study and will be discussed in detail in Section 3.5. According to Method II, AASHTO stipulates that, for critical/essential bridges, the annual probability of bridge *collapse* from ship impact should be less than 1 in 10,000 [7]. However, there are hundreds of critical/essential bridges in the United States, such as the FSK Bridge, constructed before AASHTO's standards were developed and for which critical risk assessments have not been performed. Furthermore, published studies addressing specific bridge allision risk in the U.S. remain limited. Consolazio and Kantrales [8] analyzed 13 bridges in Florida, focusing solely on barge impacts, trying to recalibrate the likelihood of barge aberrancy by using a larger and more recent data set. They found that the likelihood of a barge going aberrant was roughly half that of AASHTO's prescribed value, attributing it to improved GPS technology and the introduction of AIS technology to barges. Horteborn [9] analyzed nine truss bridges in the U.S. Rather than using the AASHTO methodology, they use a risk analysis method based on Monte Carlo simulations of ship movement. The FSK was included in this analysis and had the highest likelihood of allision among the bridges considered.

Finally, historical precedent suggests that the collapse risk of U.S. bridges far exceeds the standards established by AASHTO. Scheer [10] documented 31 bridge collapses in the U.S. due to vessel allisions from 1837 to 2009, with the vast majority occurring since the 1960s. This comprises nearly half of the 64 cases the author documented *worldwide* during the same period. Similarly, Chen and Duan [11] note that there were 17 bridge collapses due to vessel allisions in the United States from 1960 to 2011, again representing almost half of the 36 that occurred worldwide in the same time period. The study by Wardhana and Hadipriono [12] noted 503 cases of bridge failures in the U.S from 1989 to 2000, of which 10 were attributed to allisions involving barges, ships or tankers. Taken together, these resources highlight that vessel allision-induced bridge collapse occurs far too frequently.

With this knowledge, following the FSK Bridge collapse we established the following hypotheses:

1. The probability of collapse of the FSK Bridge was underestimated because the probability of a major allision was underestimated.
2. The probability of an allision of this magnitude occurring somewhere in the United States is much higher than intended by current codes/standards. (In other words: If it didn't happen to the FSK Bridge, it was likely to happen to a different bridge.)

To test these hypotheses, we conducted a comprehensive investigation of *ship allision risk* for bridges spanning major navigation channels in the U.S. Importantly, we investigate allision risk and do not investigate collapse risk because collapse analysis requires detailed structural modeling for each individual bridge. Conducting structural collapse analysis on hundreds of bridges whose design dimensions, materials, and specifications are not publicly available is not possible in the scope of this work. To the best of our ability, we conducted risk assessment in accordance with Method II from the *Design Specification* [7], noting where deviations were necessary.

This work presents the findings of our investigation with the following noteworthy contributions:

- We conducted a conservative ship traffic analysis, starting from the 624,170 in the National Bridge Inventory, to identify 357 major bridges with potentially significant large vessel traffic.
- We estimate large vessel traffic under these 357 major bridges in the U.S. and determine that 105 of these bridges see traffic levels that are high enough to potentially pose a significant risk.
- We demonstrate the strong relationship between annual vessel traffic under major U.S. bridges and allision risk, which is expected.

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[2] The NTSB identified 68 bridges with "unknown level of risk of collapse from a vessel collision [1]."

[3] Detailing these three methods is beyond our scope. For further information, see the latest version of the *Guide Specification* [7].

- We perform vessel allision vulnerability assessment for these 105 bridges and identify 54 bridges with high risk of allision.
- We aggregate the individual risks across the 54 high-risk bridges to estimate that we should expect an allision with one of these bridges once every 2.3 years.

The above conclusions highlight the considerable risk that large vessels pose to major U.S. bridges; a risk that has been historically underestimated, insufficiently addressed, and has resulted in catastrophic bridge failures – the FSK collapse being only the latest. They further reinforce the importance of performing more detailed risk assessments for select bridges across the U.S. that include structural collapse analysis and provide critical insights into which bridges most need further investigation. Finally, they serve as an essential step toward identifying bridges and waterways that require additional protections, retrofits, or modified shipping practices, and encouraging the requisite investments to ensure the safety and functionality of critical infrastructure in the U.S.

2 Results

To assess vessel allision risk for major U.S. bridges, we cross-referenced ship tracking data from Automatic Identification System (AIS) [13] with the National Bridge Inventory [14], a database of more than 620,000 bridges maintained by the U.S. Department of Transportation. Using these databases, we identified 357 U.S. bridges for which large vessel traffic could pose a risk[4]. The details of this cross-referencing process are outlined in Section 3.6. Next, we conducted detailed traffic assessments for each of these 357 bridges, analyzing the exact number of large vessels that passed under each bridge between 2015 and 2024. Subsequently, the traffic data were used to identify 105 bridges with sufficiently high traffic levels to constitute a potential risk. We then applied the AASHTO Method II vulnerability assessment methodology to estimate the average annual ship allision risk for these 105 bridges and identify 54 bridges with potentially "high risk" of vessel allision. The results of our traffic assessment and the corresponding risk are detailed in this section. Finally, we use these results to estimate the aggregate risk of ship allision for the portfolio of high-risk bridges in the U.S.

2.1 Traffic Assessment

Naturally, the volume of large vessel traffic is the leading factor in ship allision risk for major bridges. High volumes of large vessel traffic accordingly increase risk. This is reflected in Figure 1, which plots the average annual traffic of large vessels vs. annual allision probability for the 54 bridges with the highest allision risk. The expected linear trend in log-log space stipulated by the AASHTO methodology is shown along with the individual risk-traffic pairs for each bridge. Of course, there is scatter around the trend due to individual bridge risk factors such as span length and the existence of pier protection systems. We note that the AASHTO trend conservatively predicts probability of allision for bridges with less traffic, but several bridges with higher traffic, including the FSK Bridge, have higher probability of allision than the trend. Two notable bridges are specifically highlighted in this graph, indicating that the FSK Bridge, for example, had a higher than expected allision risk (again due to bridge-specific risk factors), while the Verrazzano Narrows Bridge has a significantly lower than expected allision risk despite its very high traffic volume.

The linear trend in Figure 1 highlights the importance of accurately estimating the volume of traffic under major U.S. bridges as a critical component of risk assessment. AIS traffic data provide a valuable source of risk information for bridge owners, offering a simple metric to determine whether more detailed risk analysis is necessary. Using this information alone, we were able to reduce the scope of our necessary risk assessments by determining that, of the 357 bridges with large vessel traffic, 252 bridges did not see large enough volumes of traffic to constitute a significant allision risk.

The AIS data, spanning from 2015 - 2024, also provided us a limited window into the change in large vessel traffic under major U.S. bridges over the past decade. Figure 2 shows the average traffic each year under the 10 bridges with the highest risk, normalized by the mean traffic in the ten-year span. These data show a peak in traffic in 2017, followed by years of reduced traffic in 2018 and 2019 and a sharp decrease in traffic in 2020 during the Covid-19 pandemic. Ship traffic has increased rapidly since the pandemic and reached new highs in 2024. If this trend continues, allision risk will increase accordingly, generally following the trend observed in Figure 1.

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[4] Large vessels are defined as vessels exceeding 150 meters in length, excluding tug boats and barges. See Methods Section 3.2 for details.

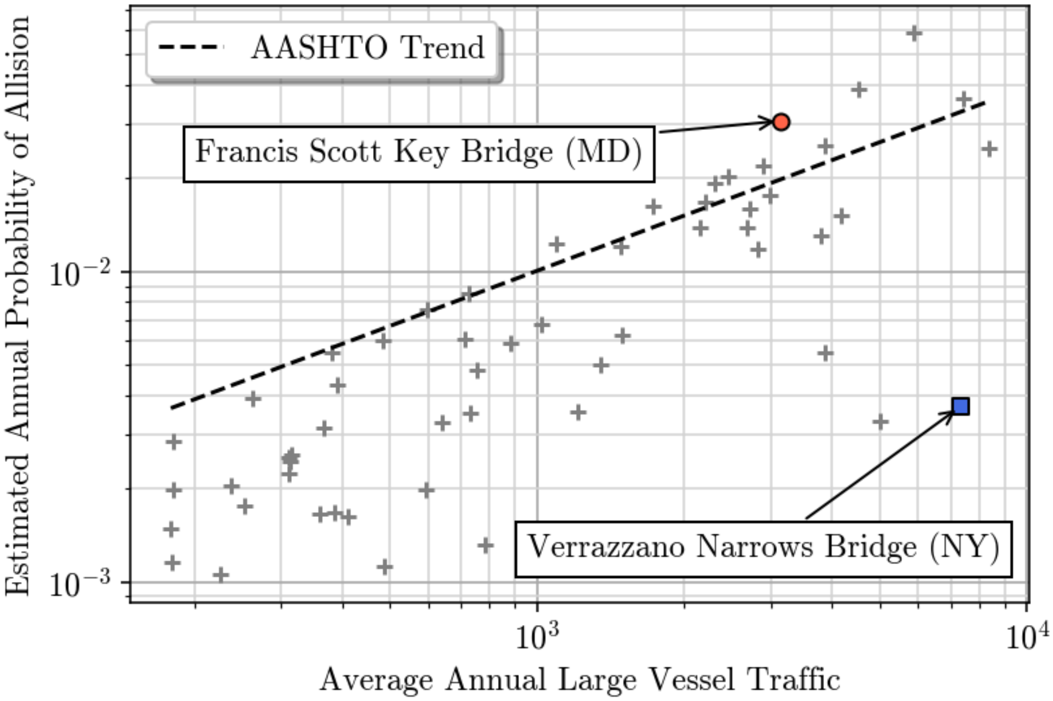

Figure 1: Average annual large vessel traffic vs. annual probability of allision for the 54 bridges with the highest allision risk. The dashed black line plots the average linear trend compiled from these 54 bridges, as stipulated by the AASHTO Method II vulnerability assessment methodology . The AASHTO trend is estimated by noting that, in the guideline, annual frequency of allision is linearly dependent on traffic volume (see Section 3.5). Taking the log of both quantities yields a linear curve in log-log space with slope one. The dashed line is the ordinary least squares best fit curve for the data transformed to log space to yield a curve with slope one.

2.2 Bridges with the Highest Allision Risk

In total, we performed detailed traffic assessments for 357 bridges. From these, we identified 105 bridges with sufficiently high volumes of large vessel traffic to pose a significant risk. We then estimated probability of allision for these 105 bridges using the AASHTO Method II vulnerability assessment approach. The details of this assessment are provided in the Section 3. In total, we identified 54 bridges that we consider to be at high risk of a potential allision event, having a probability of allision greater than 1 in 1000 (i.e. having an allision return period of less than 1000 years). The complete list of these 54 bridges is provided in Appendix A.

Table 1 lists the ten bridges with the highest probability of allision. Two allision probabilities are included – a low estimate and a high estimate – arising from differences in the measurement of the footprint of each bridge's piers. Some piers have island protections or fenders, which increase the area an aberrant ship could strike, but reduce the likelihood that an allision would result in collapse. Details describing these low and high estimates are provided in Sections 3.5.3 and 3.6.4. We see from Table 1 (and the corresponding results in Appendix A) that the probability of large vessel allision for many major U.S. bridges is very high, with expected annual allision probability as high as once in 17 years (low estimate). Of particular interest, the expected allision probability for the FSK Bridge was approximately once every 33 years, making it highly vulnerable to allision. Furthermore, we note that the allision probabilities reported in this work may be underestimated, as multiple conservative simplifications were made (these assumptions are detailed in Section 3). For example, increases in ship aberrancy probability due to complex bridge or waterway geometries were not considered, and the analysis was limited to a small number of the most vulnerable piers for each bridge instead of including all piers. Appendix B discusses this in more detail.

Of course, an allision event does not imply collapse. Many allisions may be glancing impacts or less substantial events. Nonetheless, in the event of an allision, the bridges on the list in Table 1 must have a probability of collapse between 1.7% and 5.6% in order to meet the AASHTO standard. In other words, the bridges must have a very high probability of surviving an impact, which implies that they must either have very high load capacity or have a very low probability of a direct impact (we did not assess the probability of direct vs. glancing or indirect impacts). For reference, the

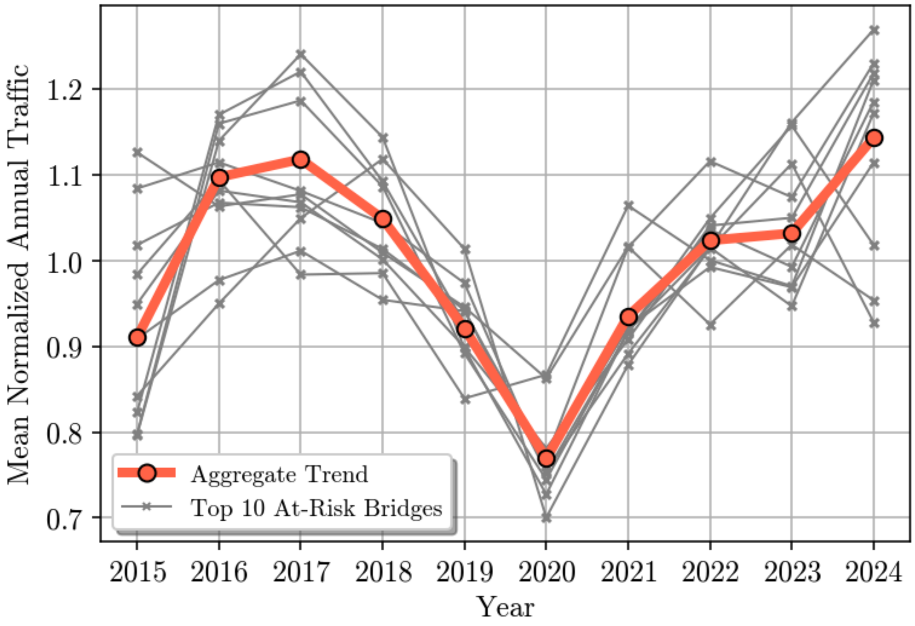

Figure 2: Large vessel traffic under the 10 most at-risk bridges for the period 2015 - 2024. The solid red line shows average vessel traffic each year while the thin gray lines show vessel traffic for each of the 10 individual bridges. All data are normalized by the average traffic over the 10-year span to show the overall trend.

NTSB found that the probability of collapse given an impact for the FSK Bridge was approximately 10%, concluding that the bridge did not meet the AASHTO standards [1]. This, again, highlights the importance of detailed structural assessments for these critical bridges, which is beyond the scope of this work. Some of the bridges in Table 1 may satisfy the AASHTO specifications, while others certainly will not. Only a detailed structural analysis can provide this critical insight.

2.3 Aggregated Allision Risk for U.S. Bridges

The individual allision probabilities shown in Table 1 (and Appendix A) imply that allision risk for many U.S. bridges is very high. The overall risk to the U.S. strategic highway network is compounded when we consider that there are 54 bridges with allision probability higher than 1 in 1000. Using the low estimates of allision probability for these 54 bridges (Table 3) and assuming that ship allision events occur independently with Poisson process arrivals, we estimate that the annual probability of at least one allision event is approximately 0.435. That is, our analysis suggests that we should expect one of these 54 bridges to be struck by a vessel once every 2.3 years. Details of these estimates can be found in Methods Section 3.7.

The aggregated annual allision risk for these 54 bridges is noticeably very high, but it is also consistent with historical precedent. Per Chen and Duan [11], the U.S. saw a bridge *collapse* due to vessel impact once every 2.4 years during the 41 year period from 1960 to 2011. However, we do not consider barge or small vessel allisions and therefore limit the scope of our analysis to the 54 bridges most vulnerable to large vessel impact. Again, our estimate also does not imply collapse, but the overall allision risk for U.S. bridges appears undesirably high nonetheless.

Our results conclude that the annual probability of an allision event occurring in the U.S. is quite high. With this in mind, it is worth revisiting the standard established by AASHTO. To do so, we calculated the aggregated collapse risk for U.S. bridges in the hypothetical case that the bridges we identified as having high traffic all meet the standard established by the AASHTO Method II vulnerability approach. To reiterate, this method states that the annual collapse frequency for critical/essential bridges should be less than 1/10,000. In total, we calculated detailed probability of allision estimates for 105 bridges with sufficiently high traffic volumes to pose a credible threat. Even if each of the 105 bridges (including the 54 we identify as potentially "high risk") were to meet the standard of having an annual probability of collapse of 1/10,000, the overall annual collapse probability for the collection of bridges would still be approximately 0.01. This means that we should expect one of these 105 bridges to collapse due to a vessel allision approximately once every 100 years *even if we meet the AASHTO standard*. This, in turn, defines the implied risk

Table 1: Top 10 U.S. bridges most at-risk of allision. Notes: *This entry is a pair of parallel bridges. †This bridge is in a turning or transition region as defined in [7, pg.72]. ‡This bridge has a strong curve or bend.

Bridge Name	**Low Estimate** Allision Probability (Return Period, years)	**High Estimate** Allision Probability (Return Period, years)
Huey P. Long Bridge (LA)†	0.0588 (17)	0.0619 (16)
Hale Boggs Memorial Bridge (LA)†	0.0387 (26)	0.0399 (25)
Crescent City Connection (LA)†	0.0362 (28)	0.0406 (25)
Francis Scott Key Bridge (MD)	0.0305 (33)	0.0305 (33)
Fred Hartman Bridge (TX)†	0.0251 (40)	0.0674 (15)
Buffalo Bayou Toll Bridge (TX)†	0.0250 (40)	0.0329 (30)
Arthur Ravenel Jr. Bridge (SC)†	0.0219 (46)	0.0406 (25)
Rainbow and Veterans Memorial Bridge (TX)*	0.0204 (49)	0.0206 (49)
Astoria Megler Bridge (OR-WA)	0.0193 (52)	0.0244 (41)
William Preston Lane Jr. Memorial Chesapeake Bay Bridge (MD)*‡	0.0177 (56)	0.0231 (43)

tolerance of the AASHTO standards; using the current threshold, one collapse every $\sim$100 years is deemed acceptable. Whether this tolerance is sufficient is a question for AASHTO, federal transportation officials, and our government leaders. Regardless, our analysis implies that we are not meeting this standard and that both the risk to individual bridges and the aggregate risk over the portfolio of major bridges in the U.S. is unacceptably high and calls for action at all levels, from local bridge owners to federal investments in further quantifying and reducing this substantial risk.

3 Methods

This section outlines, in detail, the methods employed to develop the allision probability estimates presented in Section 2.

3.1 Data Set

All calculations were performed using data collected from the Automatic Identification System (AIS). AIS was developed to improve vessel safety at sea [13]. By equipping ships with a transceiver, they can broadcast their location, size, and speed to other vessels, allowing easier navigation and collision avoidance. Archives of this AIS data are made publicly available by the National Oceanic and Atmospheric Administration (NOAA), the Bureau of Ocean Energy Management (BOEM), and the United States Coast Guard Navigation Center [15]. The data is hosted by Marine Cadastre, who also provide helpful tools for working with the data.

As of writing, the entire dataset spans from 2009 to 2024, tracking the movement of all non-military vessels in coastal U.S. waters and many inland waterways [16]. Marine Cadastre also provides a data dictionary which describes each ship characteristic reported in the data, shown in Table 2. However, much of the older data is harder to read, format, and preprocess appropriately for statistical analysis (e.g., filtering for erroneous reporting or missing entries). Thus, the analysis in this work considers ten years' worth of data, from 2015 to 2024.

Table 2: Components of an AIS ship broadcast. Note: 1 azimuth = 1 degree measured clockwise from north

Ship Property	Entries	Explanation	Example
Identification	MMSI	Unique 9-Digit ID Number [17]	636024494
	Vessel Name	The name of the vessel	AREQUIPA QUEEN
	IMO	Unique 7 digit number preceded by 'IMO'	IMO9758765
	Call Sign	Call sign as assigned by FCC	5LSW5
Position	Latitude	(decimal degrees)	39.68576
	Longitude	(decimal degrees)	-75.51953
	BaseDateTime	Time of Broadcast	2024-12-31T01:27:10
Velocity	SOG	Vessel speed (knots)	9.793239374
	COG	Instantaneous travel angle (azimuths)	196.5
	Heading	Angle ship is pointing (azimuths)	196
Dimensions	Length	(meters)	183
	Width	(meters)	33
	Draft	The vertical distance from the molded baseline amidships to the waterline (meters) [18]	8
Type	Vessel Type	Integer noting the vessel type according to [19]	70
	Cargo	Integer noting type of cargo ship carries	70
Miscellaneous	Status	Integer noting navigation status as defined by the COLREGS	0
	Transceiver Class	Class of AIS transceiver	A

3.2 Vessel Selection

Not all ship traffic poses a major threat to bridge safety. For example, the Old Highway 80 Railroad Bridge in Vicksburg, Mississippi has reportedly been hit more than 200 times [20] without collapsing due to the small size of the vessels (barges) involved. Clearly, traffic from very small ships poses a much lesser threat to bridges than larger vessels. However, it is difficult to determine, based on simple metrics of vessel size alone, which ships pose a major threat to bridges. There are two dominant factors that complicate this question. First, ship mass (displacement) directly influences the force of impact but is not reported in the AIS data. Therefore, we require a surrogate for ship mass that can provide insight into which vessels pose the greatest risk. Meanwhile, on the structural side, each bridge is different. Bridges have different design specifications, materials, structural forms, protection systems, and age. This means that the structural capacity to withstand an impact varies tremendously. For this reason, we do not address collapse risk and focus only on allision risk.

Since mass (displacement) is not available in the data, length is used as a proxy. As ship length increases, the mass (displacement) increases cubically. A common measure to standardize vessel heaviness across length is known as the displacement length ratio (dlr) defined by

$$dlr = \frac{d}{\left(\frac{L}{100}\right)^3} \tag{1}$$

where d is the displacement in tons (2240 lbs.) and L (ft.) is the waterline length. To be conservative, we assume that all vessels of interest in this study (i.e., "large vessels") are also "heavy," having $dlr = 300$. Next, we consider ships of the Handymax class (mid-size dry bulk carriers) and larger, having dead weight tonnage (which is approximately equal to displacement) $d > 35,000$ tons. Using Eq. (1) under these assumptions corresponds to ships of length $L \approx 490$ ft. For simplicity, we approximate this by $L = 150$ m and apply this as the threshold ship length of interest. We therefore consider traffic for vessels having $L \geq 150$ m throughout this study.

On a related note, AASHTO states that "the probability of ship collision with [a] bridge is increased when the main span is less than two or three times the ship length" [7], meaning longer ships are more likely to strike a bridge. Coincidentally, the FSK Bridge had a main span of 366 meters [14], putting ships of 150 meters and larger within this critical range. This further motivates our selection of $L > 150$ m as a critical vessel length threshold.

We further exclude any vessel, even those reporting length $L > 150$ m, that is classified as a tug boat or barge. Although barge allisions are important, we do not consider them in this study because we expect that the major bridges of interest here should have sufficient lateral capacity to survive a barge strike. Moreover, barges reported with $L > 150$ m are long trains of connected barges that will disconnect upon allision and therefore will not transfer all the momentum to the bridge pier – lessening the impact force. Tug boats, meanwhile, are a safety precaution often used to avoid allision events. We assume that large vessels being tugged under the bridge have sufficiently low probability of allision, and they are therefore not considered in our analysis. Finally, the lengths of tug boats and barges are inconsistently reported in the AIS database (e.g., sometimes reporting the total length including the towed vessel, and sometimes not), with conventions differing geographically. Excluding barges and tugs from the data set avoids this variability.

Finally, there are two types of transceivers: Class A and Class B. Class B are generally weaker and send less frequent signals, leading to lower accuracy in the reported data [21]. When examining reports from class B transceivers, we found many examples of ships incorrectly reporting their details (such as a sailboat claiming to be nearly a kilometer long). Additionally, according to International Maritime Organization regulations, most large vessels are required to use Class A devices [22]. Thus, we consider only vessels using a class A transceiver; this avoids faulty data while allowing us to retain information from nearly all ships of interest.

3.3 Vessel Size Classification

The AASHTO methodology dictates that, when calculating annual frequency of collapse and its components, vessel traffic should be separated into bins by mass (displacement). As described in Section 3.2, mass (displacement) is not available, so length was also used as a proxy for determining bins. Section 3.2 already established a lower bound of 150 meters for consideration. To determine the upper bound for our bins, we analyzed the dataset and found that vessels longer than 400 meters were exceedingly rare. Hence, our largest bin includes any vessel longer than 400 meters. In-between, we chose a bin interval of 25 meters so each bin captured a reasonable amount of data without sacrificing fidelity amongst the bins. Thus, our bins are: 150 - 175 meters, 175 - 200 meters, ..., 375 - 400 meters, and > 400 meters.

3.4 Traffic Data Collection

Vessel traffic data for all the bridges is collected by cross-referencing each vessel's path, as reported by the AIS data, with the geographic span of the bridge determined from the latitude and longitude coordinates reported in the National Bridge Inventory [14] and with the assistance of Google Maps and Geographic Information Systems. Specifically, each bridge is represented as the line segment connecting the bridge's abutments adjacent to the water's edge. These segments were manually assembled using satellite imagery and entered into ArcGIS as illustrated in Figure 3.

Linear interpolation is used to determine a vessel's path from its AIS broadcasts, i.e., each path is assumed to be a series of line segments connecting consecutive broadcast points (see Figure 3). A vessel is considered to cross a bridge when any interpolating line segment along its path intersects the line segment representing a bridge. Upon intersection, the broadcast points before and after crossing (representing the intersecting line segment shown by the purple and green points in Figure 3) are automatically recorded by a computer algorithm, which performs this procedure for each bridge and all vessel paths in the data set for every day from 2015 to 2024.

There are occasionally faulty broadcasts, where the coordinates of a ship are reported incorrectly. For example, there were numerous cases of ships appearing to "teleport" hundreds of miles between broadcasts. This is handled by calculating the "effective speed" of the ship, i.e., dividing the distance traveled by the time between broadcasts. The

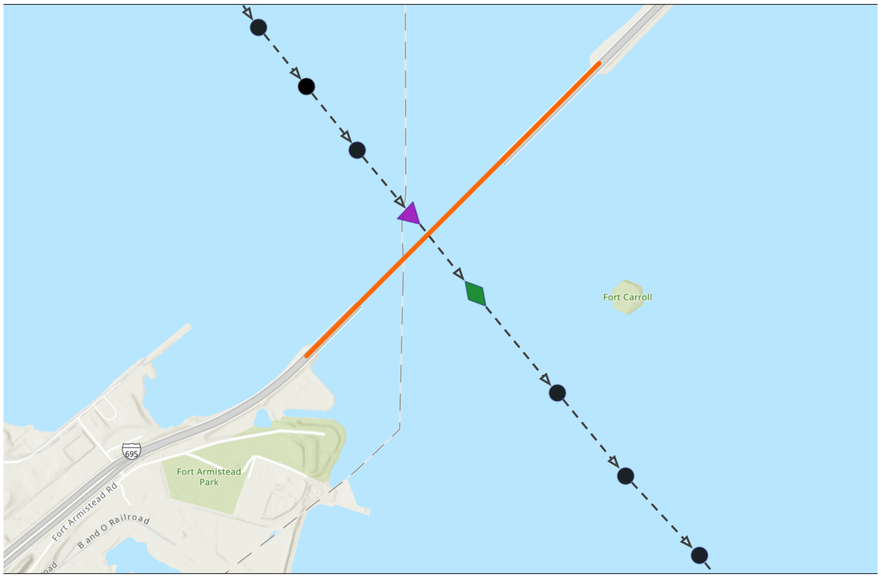

Figure 3: Illustration of AIS data points using broadcast points from a single vessel, and their intersection with the Francis Scott Key Bridge, as captured from ArcGIS. A computer program was developed to automatically detect these crossings using AIS data from all relevant vessels and major U.S. bridges. Within the program, each bridge is represented as a line segment, visualized here in orange. The purple triangle and green rhombus represent the AIS data points immediately before and after the vessel passed under the bridge, with the dashed arrows indicating direction of travel, as identified by the computer program.

fastest cargo and tanker ships reach a maximum speed of $\sim$25 knots [23], so any broadcasts with an effective speed greater than 25 knots are ignored. A second edge case arises when a ship parks beneath a bridge and continues to broadcast. This artificially inflates the traffic under some bridges. To avoid this inflation, we exclude all paths in which the vessel crosses with an effective speed less than 0.5 knots.

3.5 AASHTO Method II Vulnerability Assessment Methodology

To assess allision risk, we apply the AASHTO Method II vulnerability assessment methodology [7], which defines the annual frequency of *collapse*, AF, as $AF = \sum_{l \in \mathcal{L}} AF_l$, i.e., as the sum of the annual frequencies of collapse due to ships of individual size classes indexed by l, with the annual frequency of collapse due to a certain size class, denoted AF_l, given as:

$$AF_l = N_l \cdot PA \cdot PG_l \cdot PC_l \cdot PF_l \tag{2}$$

Here, $\mathcal{L}$ denotes the set of all size classes (see Section 3.3) and further,

N_l: annual number of vessels of size class 'l' (classified by length in this work) which can strike the bridge element

PA: probability of vessel aberrancy (considered the same for all size classes in this work)

PG_l: geometric probability of an allision between an aberrant vessel of size class 'l' and a bridge pier or span

PC_l: probability of bridge collapse due to allision with an aberrant vessel of size class 'l'

PF_l: adjustment factor to account for potential protection of the piers from vessel allision due to upstream or down stream land massses, or other structures, that block the vessel of size class 'l'

Calculating PC, the probability of collapse given allision, requires details of the structural design, materials, and construction of the bridge, as well as a detailed accounting of impact force. Structural details necessary for these estimates are not publicly available, nor is it tractable to perform detailed structural analysis for each of the hundreds of bridges to varying impact forces. For this reason, we do not estimate PC. Instead, the present work focuses on the annual frequency of *allision*, $AF_A = AF/PC$, which can be estimated using publicly available data. In addition to providing key insights into the risk to bridge infrastructure in the U.S., we hope that reporting AF_A for the most at-risk bridges will encourage bridge owners to complete a vulnerability assessment by determining PC.

In the following sections, we detail the process we employed to estimate the requisite terms in Eq. (2) in accordance with the AASHTO specifications [7]. We specifically note assumptions made, either in the AASHTO specification or in our implementation, along the way.

3.5.1 Probability of Aberrancy (PA)

AASHTO recommends calculating the probability of aberrancy for a given waterway based on historical records of "vessel collisions, ramming, stranding, and grounds in the waterway" [7, pg.72]. However, it is not possible to request such records from the United States Coast Guard at a national level [8, pg. 60]. When data is unavailable, AASHTO provides an approximation for calculating PA, which we use in this work:

$$PA = BR \cdot R_B \cdot R_C \cdot R_{XC} \cdot R_D \tag{3}$$

where:

- BR is the aberrancy base rate, $= 0.6 \times 10^{-4}$ for ships [7, pg.71].
- R_B is a correction factor for bridges along curves or bends in the waterway
- R_C is a correction factor for currents acting parallel to vessel transit path
- R_{XC} is a correction factor for crosscurrents acting perpendicular to vessel transit path
- R_D is a correction factor for vessel traffic density

Since each correction factor is greater than or equal to one, they all serve to increase PA and therefore increase risk. To conservatively estimate risk, we assume all correction factors are equal to 1, and therefore $PA = BR$. As a result, the true probabilities of allision for some bridges are likely to be greater than the values reported in this paper. AASHTO makes no comment about whether the time of day or ship size/weight influence PA, so we assume they have a negligible effect.

3.5.2 Geometric Probability of Allision (PG)

The geometric probability of allision given aberrancy, PG, is the probability that an aberrant ship will drift into any one of the bridge's piers. AASHTO assumes that a bridge can only be struck on one of its piers, e.g. the bridge deck is not at risk of allision. The location under the bridge where an aberrant ship will cross is modeled using a Gaussian distribution centered along the centerline of vessel transit with standard deviation equal to the ship's length. For each pier, PG is calculated as the area under this normal distribution over which a ship would strike the pier as illustrated in Figure 4. The values of PG for each pier considered (after accounting for protections as described in Section 3.5.3) are summed to determine the total PG for the bridge.

Although AASHTO prescribes that PG should be calculated for *all* piers, this was not possible within the scope of our study since some bridges have dozens of piers whose geometry can only be obtained through manual observation using satellite imagery. Instead, we restrict our analysis to the piers adjacent to each navigational channel and their nearest neighbors; these are the piers at highest risk of allision. The number of piers considered for each bridge are reported in the final results presented in Appendix A. Appendix B discusses the effect of considering an increasing number of piers, and highlights that bridges with a large number of piers may have significantly higher allision risk than estimated in our results.

The vessel transit centerline (according to AASHTO [7]) is equivalent to the geometric centerline of the channel ships use to cross under a bridge. We approximate it as the geometric center of the interval defined by all ship crossings observed under the span as illustrated by the X's in Figure 6. Figure 4 summarizes the method for calculating PG.

3.5.3 Protection Factor (PF)

The risk of allision with a bridge can be reduced using structures such as dolphins, that serve to either deflect an aberrant vessel or absorb energy prior to impact with a pier. These structures are accounted for by estimating the percentage of protection provided, PP. The protection provided decreases the probability of allision by reducing the protection factor, PF, in Eq. (2) as $PF = (1 - PP/100)$. A pier with no protection has $PP = 0$ and therefore $PF = 1$.

AASHTO [7] provides the following formula to calculate the protection provided by dolphins,

$$PP = \Phi(\theta^{+} | \mu = 0°, \sigma = 30°) - \Phi(\theta^{-} | \mu = 0°, \sigma = 30°) \tag{4}$$

with details summarized in Figure 5. Equation (4) and Figure 5 define the angular range $[\theta^{-}, \theta^{+}]$ over which an approaching vessel would strike the dolphin before striking the pier, measured from the line perpendicular to the bridge deck and centered on the pier. The integral of the circular normal distribution with $\sigma = 30°$ over this range yields the protection provided, PP. If multiple dolphins protect a pier, the union of each of their angular ranges is considered in

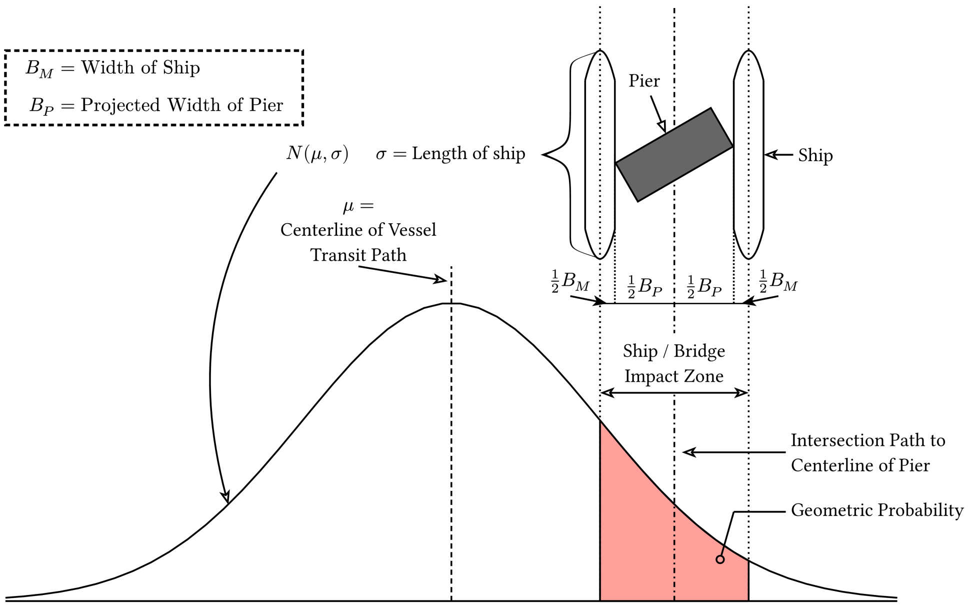

Figure 4: Graphic illustrating calculation of the Geometric Probability (PG) of ship allision (Adapted from [7, pg.74, Figure 4.8.3.3-1])

the integral for PP. From Figure 5, it is clear that PP increases for larger dolphins that are closer to the piers. Similarly, wider ships are more easily blocked by a dolphin, additionally increasing the protection provided. For each ship size class (see Section 3.5), to estimate PF_l we compute B as the average width of ships belonging to that size class, using the values of length and width reported in the AIS database. For bridge piers protected by abutments, a similar methodology is used to determine PP [7].

The other two most common types of protective structures are islands and fenders. Both islands and fenders tend to completely surround a pier and are structurally connected to the pier. As a result, allision with fenders and island will transfer energy to the pier, albeit with some dissipation. Because we do not have structural details for each bridge and the corresponding island/fender system, we report two allision probabilities: a “low” and a “high” estimate. The "high" values are calculated using the largest footprint of each pier, i.e., islands and fenders are included as part of the pier. The "low" estimates, in contrast, do not include the protection geometry within the footprint, but instead only measure the dimensions of the pier itself. Critically, the probability of collapse given allision (PC) is likely to be lower for the "high" estimates, since these systems provide some protection against collapse.

3.6 Bridge Selection

The NBI contains 624,170 bridges of all sizes and types across the U.S. A major challenge of this work was to identify the bridges at risk of large vessel allision from among this huge inventory. This section details the process by which we identified “at-risk” bridges.

3.6.1 Initial NBI Inspection: 624,170 → 4,464 bridges

The United States Department of Transportation maintains the National Bridge Inventory (NBI) [14], which is a database of bridges and associated attributes throughout the United States. The 2025 inventory includes 624,170 distinct bridges [14]. For the purposes of our study, we consider the NBI to be exhaustive, including any bridge that may be at risk of vessel allision.

While the data available for each bridge is thorough, it does not include the geographic start and end location of each bridge, nor does it include the locations and dimensions of the bridge’s piers. Determining these details requires manual data collection. To reduce this burden, bridges that have no risk of vessel allision were filtered out.

A bridge can only experience a ship allision if it spans a navigable waterway. Three features in the NBI [24] may indicate the presence of a navigable waterway:

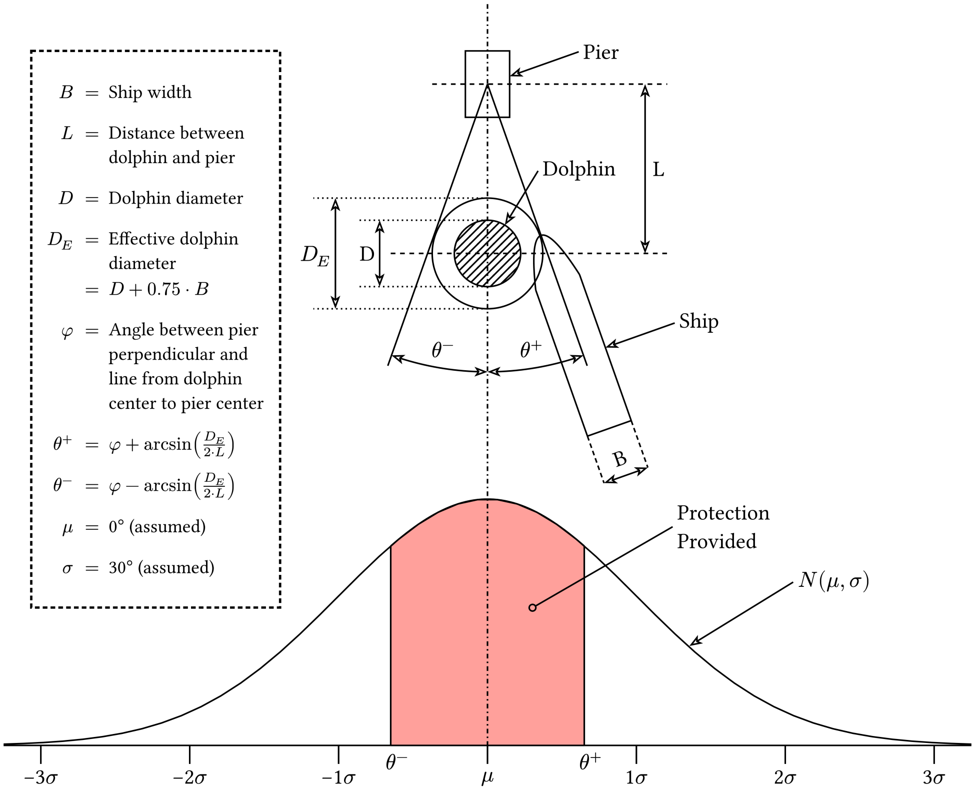

Figure 5: Graphic illustrating Protection Provided (PP) by a dolphin (Adapted from [7, pg.79, Figure C4.8.3.5-1])

- **Navigation Permit**: An entry of "N" indicates "Not applicable, no waterway". All other entries are assumed to indicate the existence of a navigable waterway.
- **Features Intersected**: This column contains "a description of the [geographic and transportation] features intersected by the structure.", for example, "MISSISSIPPI RIVER".
- **Type of Service**: This column indicates the types of service under a bridge, such as highways, railroads, and crucially, waterways.

If any of these features indicate a bridge is over water, the bridge is retained in our database. For approximately 100,000 bridges, none of these features indicated the existence of a navigable waterway, and thus were culled.

Since this work follows AASHTO Method II, which only accounts for collisions with piers (i.e., assumes that the bridge deck is not at risk of allision), we consider exclusively bridges with a substructure that can be struck. In the NBI, the **Substructure** column contains an "N" if the bridge does not have any type of substructure. All such bridges are removed, eliminating another $\sim$100,000 bridges from the set of potentially at-risk bridges.

Finally, bridges at risk must have a navigable clearance above the water. The NTSB report only considered bridges with a vertical clearance above water of 80 ft. according to the AASHTO specifications [7, 1]. However, while the NBI includes a "navigational vertical clearance" feature (item 39), it reports the minimum height above water across the *entire* bridge. This is not an indicator of navigability, making the feature unusable in this study. For example, the Dames Point Bridge (FL) is reported to have a minimum clearance above water of 1 ft, since the tail end of the bridge sits just above a waterway. By this measure, it would not appear to span a navigable waterway. However, its main span is tall enough to permit very large vessels. In place of a tighter constraint, we retain any bridge that reports a non-zero clearance above water. This was deemed appropriate (i.e., did not discard any important bridges) by manually cross-checking a limited set of bridges reporting zero navigational vertical clearance.

After applying all of these initial filters to the NBI database, we identified 4,464 bridges that can potentially accommodate large vessel traffic, and therefore may be at risk for allision. As we will see next, not all of these bridges do, in fact, accommodate large vessel traffic.

3.6.2 Initial Traffic Estimation: 4,464 → 357 bridges

Manually collecting the start and end coordinates for all 4,464 bridges would still be infeasible, since there is no straightforward way to automate the task. However, the NBI includes a single location tag along each bridge's span, which we use to obtain an initial rough estimate of traffic near each bridge. To do so, we count the number of large vessels (longer than 150 meters, see Section 3.2) that come within a "close" proximity of this location tag, defined by the larger of 1.5 nautical miles or the length of the bridge. In general, we consider that an aberrant ship may pose a significant threat to a bridge if it is within 1 nautical mile of a bridge. Hence, 1.5 nautical miles is used to be conservative. For bridges longer than 1.5 nautical miles, this minimum distance is increased since, it is possible for ships to pass under the bridge without coming within 1.5 nautical miles of the point listed in the NBI.

We consider a bridge to be "at-risk" if, on average, at least 160 large vessels enter its "close" proximity annually, based on the following assumptions:

- An aberrancy base rate of 0.6×10^{-4} for cargo and tanker ships [7]
- Approximately 10% of aberrant ships collide with a bridge
- Each bridge is designed to have an annual frequency of collapse less than 1 in 10,000 [7].

Applying this filter leaves 357 bridges that are potentially vulnerable to large vessel allision.

3.6.3 Accurate Traffic Estimation: 357 → 105 bridges

After applying initial traffic estimates, the number of bridges is now small enough that we can manually collect the coordinates defining the endpoints of each bridge. Then, detailed ship traffic for each bridge is collected as described in Section 3.4 above.

However, it is still too labor intensive to collect pier geometry and protection information for all 357 bridges. Therefore, we first conduct a highly conservative allision probability estimate to identify bridges that need to be investigated further. Using the detailed traffic estimates mentioned above, we construct a histogram of the observed ship-crossing locations for each bridge (an illustrated example is provided in Figure 6). To ensure conservativeness, we assume that piers exist at every location along the bridge where a ship has not passed (shown by the purple hatched regions in Figure 6). We then estimate the annual frequency of allision (AF_A) according to the AASHTO methodology (Section 3.5) assuming piers in all of these locations and no pier protections. If $AF_A < 1/1000$ under these conservative assumptions, then we do not consider the bridge to be at risk of a major allision. This final step reduces the set of potentially at-risk bridges to 105.

3.6.4 Precise Allision Probability Calculation: 105 → 54 bridges

The pier dimensions and protections for the remaining 105 bridges were manually estimated and used to calculate the precise "high" and "low" probabilities of allision using the AASHTO methodology outlined in Section 3.5. The footprints used for the high estimates are the largest area of a pier plus any structures (e.g. islands or fenders) attached to the pier. For example, if a pier was conically shaped, the area of the base of the pier (at its widest) is used. In contrast, the footprint used for the low estimate uses the smallest footprint of the pier above water. In the conical example, the width used is the width of the pier when it stops tapering. Hence, the low estimate is highly conservative.

As discussed in Section 2, any bridge with an annual frequency of allision (AF_A) greater than 1 in 1,000 is considered potentially high risk. We identified 54 bridges which met this high risk threshold. The 10 bridges with the largest annual frequency of allision are shown in Table 1, while all 54 of the "high risk" bridges are listed in Appendix A.

3.6.5 Additional Notes on Bridge Selection

There are several bridges that require a more specialized analysis that was not possible in this study. For example, the Bayonne Bridge (NY-NJ) has large arches that are potentially vulnerable to allisions, but without data about ship heights above water and the clearance along the length of each arch, the appropriate probabilities of allision cannot be sufficiently determined. Another example is that the Detroit Superior Bridge (OH) crosses its waterway at an extreme oblique angle, which is not accounted for in the AASHTO methodology. Such special conditions are not considered in this study. However, to the extent possible, we have noted these special conditions that arise in the 54 bridges listed in Appendix A.

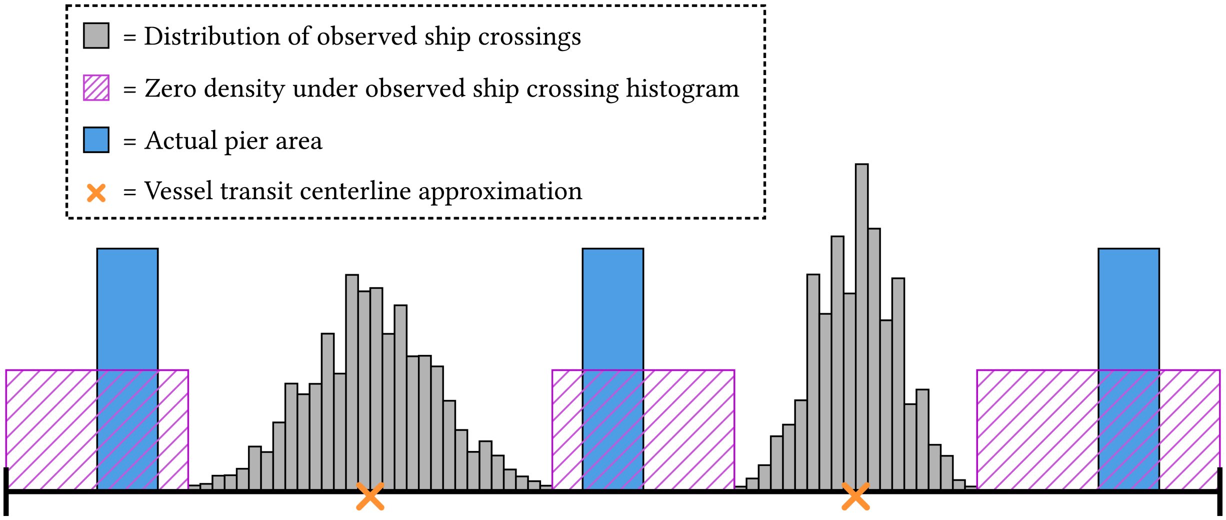

Figure 6: Illustration of the initial conservative allision probability calculation described in Section 3.6.3. Once the start and end points of a bridge are collected, the bridge is represented as a line segment, visualized here in black. The histogram of all observed ship crossings under the bridge is plotted (shown in grey). All regions under the bridge that have zero density under this histogram (shown in purple hatching) are assumed to be vulnerable to allision, as if they contained a pier. Clearly, the true pier area (shown in blue) will always be smaller than the hatched purple zero-density region. The orange crosses indicate the vessel transit centerline approximation used in Section 3.5.2.

3.7 Aggregated Risk Estimation

Finally, we assessed the aggregated national risk of allision for these 54 bridges in Section 2.3 by assuming that: (a) allision events occur independently for each bridge with Poisson process arrivals; and (b) the Poisson processes for allisions with each bridge are independent of other bridges. In this way, we define an overall Poisson process for allision events across these 54 bridges by defining the rate as $\lambda = \sum_{i=1}^{54} AF_A^{(i)}$, where $AF_A^{(i)}$ is the annual frequency of allision for the i^{th} bridge. Then, letting X denote the number of allision events in one year, the annual probability of at least one allision event across all bridges is determined from the Poisson distribution by:

$$P(X > 0) = 1 - P(X = 0) = 1 - \exp[-\lambda] \tag{5}$$

In this way, we determine that the annual allision probability for these 54 bridges is approximately 0.435, which corresponds to return period of allision events of approximately 2.3 years.

4 Conclusion

In this work, we performed a comprehensive census of large-vessel allision risk for bridges across the United States. By combining bridge data from the NBI with publicly available ship AIS data, we estimated the risk of large vessel allision for all bridges across major waterways in the United States. The analysis revealed 54 bridges with potentially high risk for vessel allision, with estimated annual frequency of allision greater than 1 in 1,000.

For each bridge, we report a “low” estimate and a “high” estimate using different assumptions about bridge protections. In both cases, the reported probabilities are shown to be conservative estimates. These estimates highlight the significant risk that major bridges in the U.S. face from large seafaring vessels. We determine that allision events should be expected at least once every 100 years for numerous bridges, with some higher risk bridges expecting allision events once every 15 – 30 years. On average, we expect an allision event to occur in the United States once every 2.3 years, which is consistent with historical observations dating back to the 1960s.

As global shipping traffic increases and the size of maritime vessels keep growing, the probability of ship-bridge allisions will continue to increase. To prevent future disasters similar to the FSK Bridge and Sunshine Skyway bridge collapses, our work motivates the need for detailed collapse risk assessments for the bridges identified in this study and for future investments in protective measures and mitigation efforts where necessary.

Acknowledgments

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Data Availability Statement

Processed data sets and code used in this study can be found in Github at: `https://github.com/SURGroup/JHU-Key-Bridge-Data`. The data will also be archived on the DesignSafe-CI upon publication.

Raw AIS data were collected from Marine Cadastre [15] and bridge inventory date were collected from the National Bridge Inventory [14].

A Complete list of at-risk bridges

Table 3 lists the 54 bridges with a low estimate of the annual frequency of allision greater than or equal to 1/1000. Each bridge is listed with its location (latitude and longitude according to the NBI), its NBI state code and structure number, low and high estimates of AF_A, and the number of piers considered when estimating AF_A. The following notes correspond to the superscripts denoting special conditions for certain bridges.

- * This entry is a pair of parallel bridges. For this pair of bridges, risk is aggregated across the traffic facing piers of the parallel structures.
- † This bridge is in a turning or transition region as defined by [7, pg.72].
- ‡ This bridge has a strong curve or bend.
- • This bridge has a superstructure that hangs below the deck of the bridge.
- ¡ Some of the bridge piers are protected against allision by the shape of the waterway.
- ○ This bridge crosses its waterway at a strongly oblique angle, as opposed to being perpendicular to the waterway.
- ¶ This bridge moves (either a lift, swing, or bascule bridge), which may require a specialized risk analysis method.
- ※ This bridge has more piers than considered in the study

Table 3: Complete list of U.S. bridges determined to have annual frequency of allision greater than 1/1000. Superscripts are described in the text above.

Rank	Name	LAT LON	NBI State Code & Structure Number	Low Estimate High Estimate	Piers Considered
1	Huey P. Long Bridge (LA)†	29.944218 -90.169035	22 022600060100001	0.0588 0.0619	4
2	Hale Boggs Memorial Bridge (LA)†	29.943056 -90.373637	22 024504503700001	0.0387 0.0399	5
3	Crescent City Connection (LA)*†	29.938831 -90.056617	22 023602830802442	0.0362 0.0406	2

4	Francis Scott Key Bridge (MD)	39.218361 -76.526547	24 300000BCZ472010	0.0305 0.0305	4[※]
5	Fred Hartman Bridge (TX)[†]	29.702579 -95.018150	48 121020038912089	0.0251 0.0674	1
6	Buffalo Bayou Toll Bridge (TX)[†]	29.735840 -95.146235	48 121020325603075	0.0250 0.0329	2
7	Arthur Ravenel Jr Bridge (SC)[†]	32.803570 -79.920681	45 000000000009824	0.0219 0.0406	4[※]
8	Rainbow and Veterans Memorial Bridge (TX)[*]	29.980477 -93.871579	48 201240030603015	0.0204 0.0206	4
9	Astoria-Megler Bridge (OR-WA)	46.197307 -123.852505	41 07949C009 00241	0.0193 0.0244	3[※]
10	William Preston Lane Jr. Memorial (Chesapeake) Bay Bridge (MD)[*‡]	38.994453 -76.385429	24 300000AAZ050013	0.0177 0.0231	4[※]
11	Lewis and Clark Bridge (OR-WA)	46.103602 -122.962823	41 02046 02WC04892	0.0168 0.0179	3
12	Richmond Bridge (CA)[‡]	37.934980 -122.437034	6 28 0100	0.0162 0.0225	8[※]
13	Veterans Memorial Bridge (LA)[†]	30.045380 -90.672370	22 614704340200001	0.0160 0.0160	3
14	San Francisco - Oakland Bay Bridge (CA)	37.798175 -122.377886	6 34 0003	0.0152 0.0219	5
15	Commodore Barry Bridge (NJ-PA)	39.825259 -75.368401	34 4500001	0.0139 0.0251	4[※]
16	Gulfgate Bridge (TX)[•]	29.853375 -93.944687	48 201240236701001	0.0133 0.0136	2
17	Sunshine Skyway Bridge (FL)	27.620396 -82.655536	12 150189	0.0133 0.0252	4[※]
18	Delaware Memorial Bridge (DE-NJ)[*]	39.689021 -75.520379	34 3200004	0.0131 0.0169	4[※]
19	Don N. Holt Bridge (SC)[¡]	32.891083 -79.962563	45 000000000008516	0.0123 0.0157	4[※]

20	Sunshine Bridge (LA)	30.097802 -90.912524	22 614704260200721	0.0121 0.0145	3
21	Carquinez and Alfred Zampa Memorial Bridge (CA)[*,¡]	38.060925 -122.225121	6 23 0015R	0.0092 0.0117	3
22	Benicia Martinez and George Miller Jr. Memorial Bridge (CA)[*,†]	38.043779 -122.122498	6 28 0153R	0.0085 0.0127	4[※]
23	Coronado Bridge (CA)[‡]	32.688402 -117.157056	6 57 0857	0.0076 0.0102	5[※]
24	Outerbridge Crossing (NY-NJ)[†]	40.524809 -74.246767	34 3823069	0.0074 0.0137	4[※]
25	Sidney Lanier Bridge (GA)	31.119239 -81.483635	13 000000012750200	0.0068 0.0159	3[※]
26	Columbus Road Over Cuyahoga River (OH)[†,¶]	41.488002 -81.700479	39 1833758	0.0060 0.0060	2
27	Ogdensburg-Prescott International Bridge (NY-ON)	44.733903 -75.458911	36 000000005523230	0.0059 0.0059	4[※]
28	Talmadge Memorial Bridge (GA)	32.089755 -81.098129	13 000000005101690	0.0055 0.0055	1
29	Antioch Bridge (CA)	38.023999 -121.751542	6 28 0009	0.0055 0.0071	4[※]
30	John A. Blatnik Bridge (MN-WI)[†]	46.749224 -92.101006	27 9030	0.0047 0.0050	4
31	Calcasieu High Bridge (LA)[†]	30.201983 -93.280822	22 071004503001411	0.0043 0.0057	3[※]
32	South Norfolk Jordan Bridge (VA)	36.808401 -76.289514	51 000000000030717	0.0039 0.0062	4[※]
33	Verrazzano Narrows Bridge (NY)	40.606338 -74.045438	36 000000005521218	0.0037 0.0074	2
34	Dames Point Bridge (FL)[†]	30.384504 -81.556909	12 720518	0.0036 0.0038	2
35	Thousand Island Bridge - Alexandria Bay (NY)	44.302258 -75.982695	36 000000005523240	0.0035 0.0035	2

36	Claiborne Pell Newport Bridge (RI)	41.504899 -71.347838	44 000000000009000	0.0033 0.0035	4[※]
37	Golden Gate Bridge (CA)	37.819772 -122.478385	6 27 0052	0.0033 0.0037	2
38	Seaway International Bridge (NY-ON)	44.989522 -74.739589	36 000000005523220	0.0033 0.0043	2
39	Wayne County River Rouge Bridge (MI)[†¶]	42.280804 -83.128775	26 000000000012214	0.0031 0.0031	2
40	Tacony-Palmyra Bridge (NJ-PA)[†¶]	40.012248 -75.043146	34 3000001	0.0029 0.0030	4[※]
41	Chesapeake City Bridge (MD)	39.529136 -75.813934	24 300000CECE01010	0.0026 0.0026	2
42	Saint Georges Bridge (DE)[†]	39.552768 -75.651054	10 000000001495034	0.0025 0.0025	2
43	Summit Bridge (DE)	39.541226 -75.738247	10 000000001494016	0.0024 0.0024	2
44	Reedy Point Bridge (DE)	39.558399 -75.582412	10 000000001496002	0.0022 0.0023	2
45	Casco Bay Bridge (ME)[†¶]	43.645047 -70.257915	23 5900	0.0020 0.0024	4
46	Burlington-Bristol Bridge (NJ-PA)[†¶]	40.082219 -74.869821	34 3000002	0.0020 0.0022	3[※]
47	Goethals Bridge (NY-NJ)[*†¡]	40.634869 -74.195888	34 3823051	0.0020 0.0024	1
48	Maurice J. Tobin Memorial Bridge (MA)[†]	42.384864 -71.047591	25 B160174X3DOTNBI	0.0018 0.0018	2
49	Benjamin Franklin Bridge (NJ-PA)[†]	39.952970 -75.134653	34 4500010	0.0017 0.0020	2
50	Horace Wilkinson Bridge (LA)[†]	30.439369 -91.194799	22 611704500900001	0.0016 0.0020	3
51	Delaware River-Turnpike Toll Bridge (NJ-PA)[†•]	40.117058 -74.830547	34 P000000	0.0015 0.0017	2

52	Betsy Ross Bridge (NJ-PA)[†]	39.984431 -75.065112	34 4500011	0.0014 0.0015	4[※]
53	Detroit-Superior Bridge (OH)[¡○]	41.493229 -81.704293	39 1800930	0.0011 0.0011	1
54	St. Johns Bridge (OR)	45.585188 -122.764550	41 06497 123 00091	0.0011 0.0012	2

B Effect of number of piers on the annual allision probability

Intuitively, it makes sense that a bridge with more piers is more likely to be struck by a ship. However, intuition also dictates that piers very far from the location where ships pass under a bridge should contribute negligibly to the allision probability. Consider the Antioch Bridge (CA): its main navigable span sits on the edge of the waterway, and four piers fit the criterion for our analysis as described in Section 3.5.2. However, there are an additional eleven piers that were not accounted for, all getting progressively further from the main span.

Figures 7a and 7b show the relationship between the distance of each pier from the main span and the cumulative annual probability of allision considering an increasing number of piers for the FSK Bridge and the Antioch Bridge (CA), respectively. Cumulative return periods are likewise shown in Figures 7c and 7d. Clearly, the incremental increase in the probability of allision decreases with distance, but there are several piers with non-negligible annual probability of allision. Including the probability from every pier leads to a 14.66% increase in the probability of allision for the FSK Bridge, and a 23.97% increase for the Antioch Bridge (CA). Our analysis considers only the piers bounding the navigable span and their nearest neighbors, shown in red in the plots. However, when performing more thorough risk analyses of individual bridges, *all* piers should be included as they tend to have small but significant impacts on the final results. This is in line with the procedure descirbed in AASHTO Method II as well.

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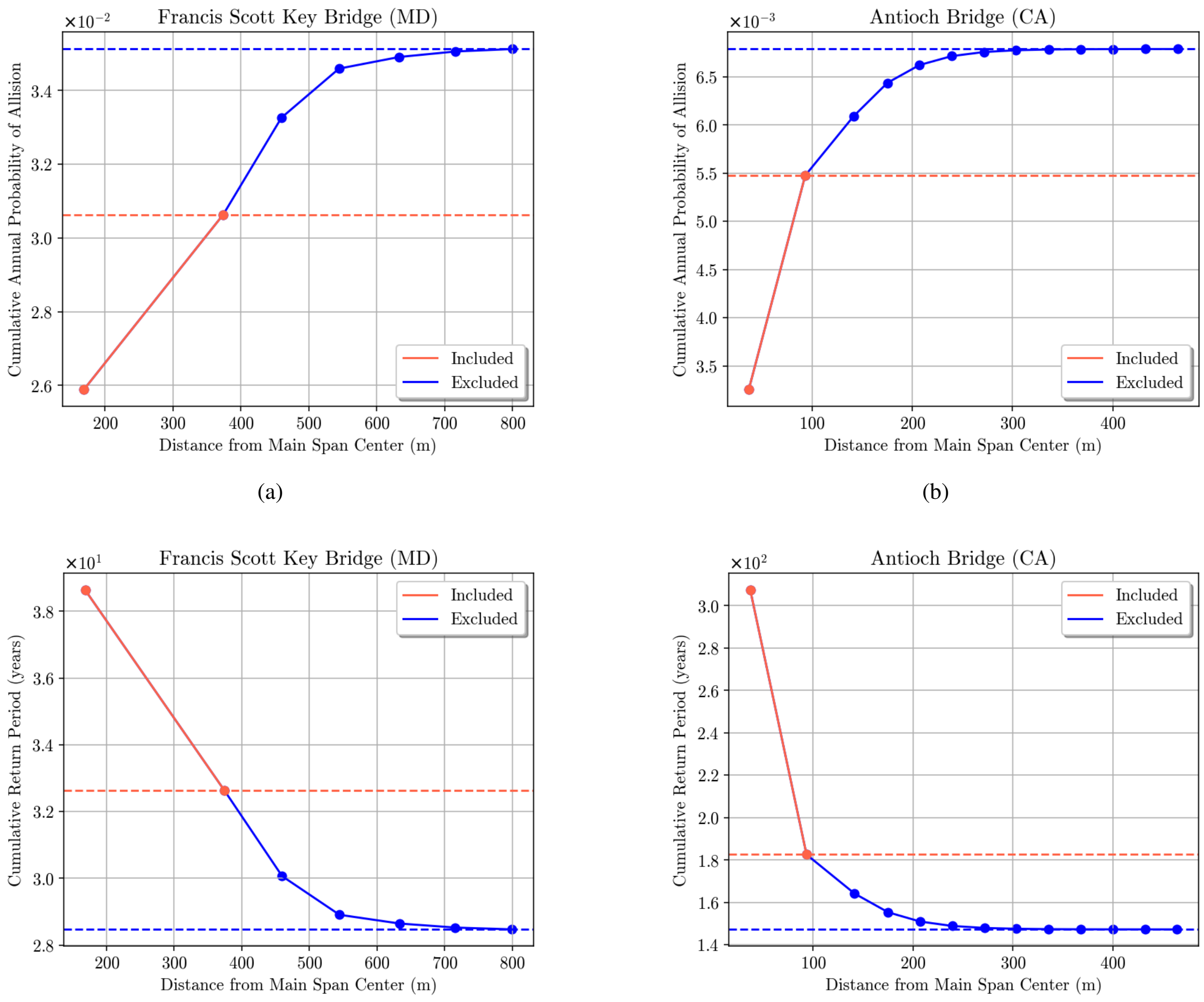

(a)

(b)

(c)

(d)

Figure 7: The cumulative annual probability of allision for increasing number of piers for the Francis Scott Key (MD) and the Antioch Bridge (CA) are plotted in subfigures (a) and (b), respectively, while the cumulative return period for increasing number of piers for the Francis Scott Key (MD) and the Antioch Bridge (CA) are plotted in subfigures (c) and (d), respectively. Each pier location is shown by a point on the graph and pairs of piers that are nearly equidistant from the main span center (i.e., within 5 m) are plotted together as a single point.

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