Probabilistic Analysis of the Impact of Vessel Speed Restrictions on Navigational Safety: Accounting for the Right Whale Rule – Additional Material

Matteo Convertino [1,2,3*], L James Valverde, Jr [1]

[1] HumNat Lab, Division of Environmental Health Sciences, School of Public Health, University of Minnesota Twin-Cities, MN

[2] Institute on the Environment, University of Minnesota Twin-Cities, MN

[3] Bioinformatics and Computational Biology Program, University of Minnesota Twin-Cities, MN

[4] U.S. Department of Energy, Headquarters, Washington, DC

March 28, 2017

Corresponding author contact: Academic Health Center, Mayo Memorial Building, Suite 1232 12th fl., MMC807, 420 Delaware St. SE, Minneapolis, MN, 55455; email: matteoc@umn.edu

Additional Online Material

Additional Material about Event Tree Analysis

Particularly relevant to our discussion here is the fact that anchors are sometimes useful to slow or stop the way of a ship in an emergency. While, to the uninitiated, they are sometimes considered ship "brakes", unfortunately, in most instances, they fall sort of the mark. An anchor that is deployed while a ship is moving may not establish a firm hold on the bottom. If such a hold is established, it will apply a sudden force in line with the anchor chain on the bow of the vessel; if it drags, it will apply a more gradual force. In either case, the force applied to the ship is a *point force* at the extreme forward end, usually at the farthest point from both the propulsive force and from the center of gravity through which the momentum vector acts. In either case, it is likely that the anchor chain will part if the ship is going too fast. The rule of thumb commonly applied by vessel pilots is that an anchor will be ineffective when the ship is going more than one knot, because it will likely break the chain before applying any useful force to control the ship.

While the two anchors typically fitted on the bow of oceangoing ships appear to be close together, they are not interchangeable. Either one may be deployable depending on the relative orientations of the ship, its momentum, the wind, and the current; only in rare circumstances, though, are they both of use together, especially when the ship is still moving. Great damage can be incurred to the ship by dropping the wrong anchor at the wrong time, causing the ship to cross over the anchor and its chain. Therefore, the second anchor is seldom available to be used as a "second brake", should the first anchor fail to produce desired results.

This brief synopsis of the attributes of a ship's anchor system may intimate that slower speeds are better in terms of control and maneuverability, except that a ship is seldom in a suitable location to anchor when it is traversing a confined channel. As described above, the ship will succumb to wind and current when at anchor. Rarely is a modern ship in a channel of width that appreciably exceeds the length of the ship. In most cases for the major ports of the world, channels are considerably narrower than the length of the ships using it. Anchoring in a channel will result in a grounding if the ship draft exceeds the surrounding depth, and if the wind and current do not combine to hold the ship in line with the channel. This would require the combined forces of the wind and current to directly oppose the heading of the ship as it was moving through the channel. Even in those rare instances where this extremely fortuitous alignment occurs, the ship must still slow down to one knot or less, or the deployment of the anchor will apply a moment to its momentum vector and head the ship off towards the channel bank.

Just as anchors are of varying degrees of possible assistance, groundings are of varying degrees of severity. The hierarchy of possible consequences ensuing from a grounding starts with the ship being singularly impeded from completing its voyage, blocking other ships from completing their voyages, being collided with by ships that cannot avoid it, and other, more consequential impacts onboard and beyond the affected ship(s), such as oil spills due to hull ruptures from the forces of grounding. Hull breaches from grounding sometimes happen instantaneously with the grounding, and other times they develop later, as the ship is subjected to current and wind, falling tides, or pounding waves that concentrate loads on the points of contact between the ship and the ground beneath the ship. Therefore, simply stopping a ship in place when there is a problem can create far more damage than maintaining control of the ship until it can be safely stopped in an appropriate — or at least more advantageous — location.

With these considerations in mind, an anchor can be extremely useful to fix the position of the bow of a compromised ship, once the master or pilot has positioned the bow in a fortuitous location relative to water depth and harsh underwater features (such as rocks and buoy anchors), and relative to the prevailing forces of wind and current, as well as relative to the activity of other ships in the area, and finally, once the ship has slowed to a near stop. Taken together, these caveats lead to the supposition that an anchor — or even a pair of anchors — offers, at best, a slim chance of saving a ship confined to a narrow channel from a consequential grounding or collision.

As part of this study, the Charleston Pilots were consulted on the five propulsion channel loss of power incidents recorded amongst Coast Guard casualty records (compiled in Table S7). In two of these incidents, an anchor was deployed as a mitigating measure during the event. In one incident, the anchor was deployed after the ship was hard aground, in order to to keep it in position as the tide rose. In the other two cases, the ships remained under control for a sufficient period of time for the engineers onboard to rectify the failure. In the two cases where the anchor was deployed for a beneficial purpose during the event, the ships had drifted down to being nearly stopped. The anchors were deployed to hold the bows where the pilots had intentionally placed them. In the first case, the ship was outbound with three ships behind. All were confined to the channel due to their draft. The first ship lost engine power. The pilot drifted the ship using only the rudder to get to a location where the water beyond the channel was deep enough for the ship to leave the channel. Once out of the channel, the pilot positioned the ship where it could not swing into the channel, and he dropped the anchor to hold it there until the engine was repaired. The ship never grounded.

In the second case where the anchor was deployed for a beneficial purpose during the event, the ship was inbound and confined to the channel. The ship's engine also failed, and the pilot maintained control using only the rudder and brought the ship farther along the channel to where it was inside the jetties protecting the entrance to the port. Once inside the jetties, the ship was in a better location to sustain a grounding, where it would not be subjected to pounding forces by ocean waves. The ship was steered to be along the side of the channel where the wind was likely to hold the vessel against the bank, rather than where it could potentially blow the ship across the channel. Once at slow speed (so the anchor chain would not break), and with the ship positioned as it would eventually lay with the wind and current off to one side of the channel, the pilot ordered the anchor deployed. The ship lay there aground, though in the most fortuitous available location and orientation, until tugs arrived to take the ship to the dock. That ship also had another ship following it, and the second ship had sufficient room to safely pass the grounded vessel, thereby avoiding a forced grounding to avoid collision.

While perhaps anecdotal, it is important to note that in both of these instances, the anchor was essential *not* to gain additional *control* of a stricken vessel, but rather to *hold* a vessel where it was in a relatively safer location. In the first of these two cases, the ship did avoid grounding, and the anchor was ultimately critical to keeping the ship in a safe anchorage, precluding continued drift to an eventual grounding, or into the path of another vessel. Though this is a small number of incidents from which to draw statistically meaning inferences or conclusions, in one of five cases occurring in the dredged entrance channel described here, the anchor was instrumental in preventing the ship from grounding.[1] As noted above, this set of data is limited in size, though it is representative of five years of activity in one of the Nation's major ports.

In a 2012 incident recorded in a Coast Guard investigation, an inbound ship lost propulsion power while passing another vessel going outbound, and managed to maintained control not only through the pass, but also three-quarters of an hour longer before all steering control was lost. It had been going 15–16 knots at the time of the propulsion failure incident. The 45 minutes of continued control/maneuverability was sufficient to get the ship into the protected waters between the port's jetties, where lateral currents and ocean waves were blocked, and the ship grounded softly on one side of the channel and remained there without swinging across and blocking the channel to other ships. In another incident within the period since

[1] While it is outside the domain of this study, the Charleston Branch Pilots relayed an experience where an anchor failure occurred during a recent loss of power incident inside the harbor. The pilot was well aware that the ship was going too fast for the anchor to hold, but the situation demanded whatever force that could be mustered to slow the vessel, and the anchor was essentially used as a "sacrificial brake". This experience validates that anchor failure is, indeed, relevant to determining the incidence of consequential outcomes resulting from a loss of propulsion.

the promulgation of the speed rule, a ship was leading three others outbound from the Port of Charleston. It lost propulsion power and began to drift. It was also moving at 15–16 knots before the engine casualty. The speed the vessel was carrying allowed the pilot to maintain control and keep the vessel in the channel, until reaching a point where the water depth outside the channel was sufficient to accommodate the ship's draft. The pilot steered the vessel out of the channel and anchored, maintaining satisfactory control throughout the entire incident. Had this ship been traveling at a slower speed, the ship would very likely have grounded on the bank of the channel; with a following tide, the ship would have swung across the channel and fetch up aground by the bow and the stern, each on opposite sides of the channel. This, in turn, would have blocked the channel for the three vessels following, forcing them to ground or collide with the ship blocking the channel, or the ship directly ahead of them in the line.

Additional Tables

In the following, tables with values that populate the model are reported.

1	2	3	4	5	Endpoint Probabilities
Yes	Yes	Yes			0.9860
Yes	Yes	No	Yes		0.0010
Yes	Yes	No	No	Yes	1.9721E-05
Yes	Yes	No	No	No	1.9920E-07
Yes	No	Yes			0.0010
Yes	No	No	Yes		9.9501E-06
Yes	No	No	No	Yes	1.9741E-08
Yes	No	No	No	No	1.99E-10
No		Yes		Yes	0.0030
No		Yes	No		2.97E-05
No		No	Yes	Yes	2.96406E-5
No		No	Yes	No	2.994E-07
No		No	No	Yes	5.9400E-08
No		No	No	No	6.0E-10

Table S1: Endpoint Probabilities for Faulty Passage Planning Event Tree

1	2	3	4	5	6	7	8	9	Endpoint Probabilities
Yes	Yes	Yes		Yes	Yes		Yes		0.9930
Yes	Yes	Yes		Yes	Yes		No	Yes	9.8314E-05
Yes	Yes	Yes		Yes	Yes		No	No	9.9307E-07
Yes	Yes	Yes		Yes	No	Yes	Yes		0.0030
Yes	Yes	Yes		Yes	No	Yes	No	Yes	2.9287E-07
Yes	Yes	Yes		Yes	No	Yes	No	No	2.9580E-09
Yes	Yes	Yes		Yes	No	No			2.9882E-05
Yes	Yes	Yes		No					0.0010
Yes	Yes	No	Yes						0.0010
Yes	Yes	No	No						9.9805E-06
Yes	No								0.0010
No									0.0010

Table S2: Endpoint Probabilities for Faulty Piloting Event Tree

1	**2**	**3**	**4**	**Endpoint Probabilities**
Yes	Yes	Yes	Yes	0.0042
Yes	Yes	Yes	No	0.0014
Yes	Yes	No		0.5569
Yes	No			0.1875
No				0.2500

Table S3: Endpoint Probabilities for Assistance Failure Event Tree

Reported Loss of Propulsion Marine Casualties in Port of Charleston Pilotage Waters, 2009 - 2013

Calendar Year	Involved Vessel Class	Involved Vessel Service	ITC Gross Tonnage	Length (ft.)	Event Class	Event Type	Waterway Name	Latitude	Longitude	Total	Location according to Pilots:
2009	General Dry Cargo Ship	**Freight Ship**	57075	**939.5**	Fire-fighting Respons	**Emergency Response**	WANDO RIVER	**32.835023**	-79.893783	2	In Charleston Harbor
	Towing Vessel	**Towing Vessel**	1043	**129.6**	Other loss	**Vessel Maneuverability**	CHARLESTON HARBOR ENTRANCE CHANNEL	**32.81136667**	-79.91453333	1	In Charleston Harbor
	Bulk Carrier	**Freight Ship**	40121	**738**	Unintentional	**Set Adrift**	(blank)	**32.92366667**	-79.93466667	1	In Charleston Harbor
2009 Total										**4**	
2010	Barge	**Tank Barge**	13462	**559.8**	Initial - contained	**Fire**	COOPER RIVER	**32.90759**	-79.94666	1	In Charleston Harbor
	Bulk Carrier	**Freight Ship**	42887	**751.3**	Unintentional	**Set Adrift**	COOPER RIVER	**32.9**	-79.93333333	1	In Charleston Harbor
2010 Total										**2**	
2011	General Dry Cargo Ship	**Freight Ship**	65475	**857.3**	Total Loss	**Loss of Electrical Power**	ATLANTIC DEEP WATER SPUR	**32.73915**	-79.84535	1	In Entrance Channel Area
	General Dry Cargo Ship	**Freight Ship**	17821	**594.2**	Broadside	**Allision**	CHARLESTON HARBOR ENTRANCE CHANNEL	**32.73915**	-79.84535	1	In Entrance Channel Area
	General Dry Cargo Ship	**Freight Ship**	54182	**964**	Total Loss	**Vessel Maneuverability**	CHARLESTON HARBOR ENTRANCE CHANNEL	**32.73915**	-79.84535	1	In Entrance Channel Area
	General Dry Cargo Ship	**Freight Ship**	34454	**707**	Total Loss	**Vessel Maneuverability**	COOPER RIVER	**32.75882**	-79.86668	1	In Charleston Harbor
2011 Total										**4**	
2012	Ro-Ro Cargo Ship	**Freight Ship**	56978	**656**	Total Loss	**Vessel Maneuverability**	CHARLESTON HARBOR	**32.75974**	-79.91885	1	In Charleston Harbor
	Passenger Ship	**Passenger (Inspected)**	1973	**187.5**	Astern	**Allision**	ASHLEY RIVER	**32.77432**	-79.94867	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	46697	**(blank)**	Total Loss	**Vessel Maneuverability**	(blank)	**32.767**	-79.87483333	2	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	50686	**912.5**	Partial Reduction	**Vessel Maneuverability**	WANDO RIVER	**32.83588**	-79.89182833	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	66086	**905.6**	Partial Reduction	**Vessel Maneuverability**	COOPER RIVER	**32.9005965**	-79.95957633	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	50698	**912.5**	Total Loss	**Vessel Maneuverability**	WANDO RIVER	**32.92055**	-79.83682	1	North of Channel Area
	General Dry Cargo Ship	**Freight Ship**	37474	**795.2**	Partial Reduction	**Vessel Maneuverability**	CHARLESTON HARBOR	**32.81666667**	-79.91666667	1	In Charleston Harbor
					Total Loss	**Loss of Electrical Power**	CHARLESTON HARBOR	**32.81666667**	-79.91666667	2	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	12993	**440.9**	Total Loss	**Vessel Maneuverability**	COOPER RIVER	**32.90759**	-79.94666	1	In Charleston Harbor
	Ro-Ro Cargo Ship	**Freight Ship**	60942	**653**	Partial Reduction	**Vessel Maneuverability**	CHARLESTON HARBOR ENTRANCE CHANNEL	**32.73915**	-79.84535	1	In Entrance Channel Area
2012 Total										**12**	
2013	General Dry Cargo Ship	**Freight Ship**	43071	**876**	Partial Reduction	**Vessel Maneuverability**	COOPER RIVER	**32.75882**	-79.86668	1	In Charleston Harbor
	Offshore	**Offshore Supply Vessel**	243	**102.3**	Broadside	**Allision**	COOPER RIVER	**32.8555**	-79.95433333	1	In Charleston Harbor
	Towing Vessel	**Towing Vessel**	235	**102.8**	Broadside	**Allision**	COOPER RIVER	**32.8555**	-79.95433333	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	13816	**464.3**	Partial Reduction	**Vessel Maneuverability**	CHARLESTON HARBOR	**32.75233283**	-79.86692733	1	In Charleston Harbor
	Passenger Ship	**Passenger (Inspected)**	28803	**565.1**	Broadside	**Allision**	(blank)	**32.79765**	-79.92976	1	In Charleston Harbor
	Towing Vessel	**Towing Vessel**	524	**104.8**	Initial - contained	**Fire**	COOPER RIVER	**32.90759**	-79.94666	1	In Charleston Harbor
					Partial Reduction	**Vessel Maneuverability**	COOPER RIVER	**32.90759**	-79.94666	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	72760	**984.2**	Total Loss	**Vessel Maneuverability**	WANDO RIVER	**32.818055**	-79.88416333	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	49985	**900.3**	Partial Reduction	**Vessel Maneuverability**	(blank)	**32.818055**	-79.88416333	1	In Charleston Harbor
	Towing Vessel	**Towing Vessel**	524	**104.8**	Partial Reduction	**Vessel Maneuverability**	COOPER RIVER	**32.90350167**	-79.95641833	1	In Charleston Harbor
	Towing Vessel	**Towing Vessel**	417	**118.7**	Partial Reduction	**Vessel Maneuverability**	CHARLESTON HARBOR	**32.75974**	-79.91885	1	In Charleston Harbor
	General Dry Cargo Ship	**Freight Ship**	54309	**964.9**	Partial Reduction	**Vessel Maneuverability**	COOPER RIVER	**32.75882**	-79.86668	1	In Charleston Harbor
2013 Total										**12**	
Grand Total										**35**	

Source: Coast Guard Sector Charleston, as reviewed by Charleston Branch Pilots Association

Table S6: Reported Loss of Propulsion Marine Causalities, in the Port of Charleston, 2009-2013

Loss of Propulsion Incidents versus Voyage Counts, Port of Charleston 2009 - 2013

Year	Piloted Voyages: Harbor*	Piloted Voyages: Entrance Channel*	Total Reported Propulsion Failure Incidents	Propulsion Failures: Harbor	Propulsion Failures: Entrance Channel**	Gross Rate: Propulsion Failures/ Piloted Voyages	Propulsion Failures/ Voyage: Harbor	Propulsion Failures/ Voyage: Entrance Channel
2009	4,105	3,090	3	2	1	0.073%	0.049%	0.032%
2010	4,103	3,963	2	2	0	0.049%	0.049%	0.000%
2011	4,293	4,152	4	1	3	0.093%	0.023%	0.072%
2012	4,464	4,343	12	11	1	0.269%	0.246%	0.023%
2013	4,442	4,315	12	12	0	0.270%	0.270%	0.000%
5 Yr Total	**21,407**	**19,863**	**33**	**28**	**5**	**0.154%**	**0.131%**	**0.025%**

**South Carolina requires pilots on all foreign vessels of draft greater than eleven feet and all U.S. vessels engaged in international trade. U.S. Coast Guard regulations require pilots on inspected vessels in coastwise trade greater than 100 gross tons. All piloted voyages occur in the harbor. Some piloted voyages are "shifts" within the harbor between docks and do not traverse the entrance channel. Therefore, the number of voyages in the entrance channel is the sum of ships arriving and departing, and will be a lesser number than total voyages for the port.*

***In one case the Coast Guard and the Pilots differed over the location of the casualty relative to the entrance channel or within the harbor, most likely due to a discrepancy in recording the location of the propulsion failure versus the location of the eventual grounding. For the purposes of this research, the location of the incident was considered to be in the Entrance Channel if either party designated it so. Not all loss of power incidents resulted in a grounding. An incident in which propulsion power or control was restored before a major consequence occurred is still a reportable marine casualty.*

Table S7: Loss of Propulsion Incidents versus Voyage Counts in the Port of Charleston, 2009-2013