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Technological Dynamism in a Stagnant Sector:

Safety at Sea during the Early Industrial Revolution

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Abstract

Against the consensus that sailing ship technology was stagnant during the early Industrial Revolution, we find striking improvements in safety at sea. Between 1760 and 1825, the risk of being wrecked for Atlantic shipping fell by one third, and of foundering by two thirds, reflecting improvements in seaworthiness and navigation respectively. Seaworthiness improved through replacing the traditional stepped deck ship with stronger flushed decked ones derived from Indian designs, and the increasing use of iron reinforcement. Improved navigation owed little to precise longitude estimation and stemmed mostly from accurate charts and instruments, and accessible manuals of navigational technique.

1 Introduction.

That oceanic shipping was technologically stagnant before steamships is an orthodoxy in economic history dating back to the work on Atlantic freight rates by North (1968) and Harley (1988). More recent studies, surveyed by Kelly and Ó Gráda (2017), have analysed sailing speed and found that it improved to varying extents. However, advances in safety at sea—a third and vital facet of maritime technology, given the hazards of shipping in the age of sail—have not been studied until now. This paper describes the large innovations that took place in ship design and navigation before and during the early Industrial Revolution, and shows how these led to striking falls in the risks of sinking and shipwreck for Atlantic shipping.

Specifically, we analyse the losses of British and Irish registered ships between 1760 and 1826 provided by *Lloyd's List*. Although losses relative to tonnage stayed fairly constant for coastal shipping, the loss rate of oceanic shipping decreased sharply: we find a fall of one third in rates of shipwreck and of two thirds in founderings. These two improvements largely reflect advances in navigation and seaworthiness respectively.

What were the sources of improved seaworthiness? From medieval times, European ships had a stepped pattern of a forecastle and poop above a waist deck, a design well suited to defence but with two key structural deficiencies. First, the ship took on water each time it shipped a sea, flooding the lower decks, and potentially causing the vessel to sink or capsize.

Secondly, the flimsy, poorly attached deck of a traditional European ship resulted in a hull that was structurally weak. From the 1760s, starting with the East India Company (EIC), ships began to be built with a single, strong, well-cambered flush deck with watertight hatches that could be battened down against heavy seas. The stiffer hulls that resulted were less prone to leak and occasionally disintegrate in heavy seas. This vital but little known advance—absent, for instance, from the standard survey of maritime technology by Naish (1958)—is shown by Parkinson (1937, 134–141) to have come from direct contact with Indian ship design: the EIC effectively duplicated the hull pattern of a Bengal rice ship. The process of strengthening hulls continued through the Napoleonic period with an increasing use of iron, first to attach decks securely to hulls, and then to brace ships more generally.

When it comes to navigation, the popular impression—echoed even by Landes (1983, 145–157)—is that the fundamental problem vexing seamen in the eighteenth century was the estimation of longitude, and that this was "solved" in 1759 with John Harrison's H4 chronometer. In reality, chronometers remained too expensive and unreliable to be used widely until the middle third of nineteenth century. Mariners, besides, faced far more immediate perils from poor charts, weak compasses, and general ignorance of basic navigational techniques. Until the 1780s, British sailors largely relied on reprints of crude seventeenth century charts but, starting in 1786 with John Hamilton Moore's series of *New and Accurate Charts*, these were superseded by detailed, privately produced charts.

Just as important were affordable and understandable textbooks of navigational techniques, largely based on worked examples, and again pioneered by Moore with his *New Practical Navigator* of 1772. Beginning with basic arithmetic and geometry, these worked all the way up to longitude estimation by lunar distances. The vital contribution of these manuals lay in the instruction they gave in basic navigational techniques such as correcting speed estimates for current and leeway, estimating compass deviation, and keeping a journal of daily course based on mid-latitude sailing to derive a reliable estimate of position. Although most ships still navigated by dead reckoning based on speed and compass heading until the 1830s, it was a far more sophisticated and reliable dead reckoning than the crude guesswork of the 1770s.

Given the limitations of chronometers, the only practicable way to estimate longitude at sea was from the observed angle between the moon and a fixed star: the method of lunar distances. However, the problem of predicting the moon's orbit, under the influence of both the sun's gravity and the earth's, famously defeated Newton, and was only solved in the 1760s by the German astronomer Tobias Mayer using equations devised by Euler (who was awarded £300 by the Board of Longitude at the same time that Harrison received his chronometer prize).

With efforts by Galileo to market the motion of the moons of Jupiter as a means of calculating longitude, by Hooke and Huygens to develop portable sea watches (arguably the most important scientific contribution to practical technology before the eighteenth century, leading as it did to the mass production of watches: Kelly and Ó Gráda, 2016), and by Halley to understand compass deviation, the quest to improve navigation stands as the earliest and most direct instance of Mokyr's (2016) argument that at the heart of the European Enlightenment lay a drive to create scientific knowledge for practical ends.

The rest of the paper is as follows. Section 2 outlines the existing literature on freight cost and sailing speed that has been the exclusive concerns of economic historians concerned with shipping. Sections 3 and 4 describe the marked advances in shipbuilding and navigation that occurred during the eighteenth and early nineteenth centuries while Section 5 shows uses data from *Lloyd's List* to show how these advances led to large falls in ship losses that are reflected in lower insurance rates.

2 Literature Review.

Despite the fundamental role of sailing ships in the early industrial world, economic historians have paid little attention to their technology. and then only to shipping cost and sometimes sailing speed. In the classic study in the literature, North (1968) found that on the North Atlantic route freight rates fell steadily from 1600 to 1850. Asserting that technological progress in shipping had negligible, he attributed these falling prices to the increased specialization permitted by larger markets, the development of backhaul freight (either colonial produce or immigrants), lower turnaround times, and smaller crews allowed by the suppression of piracy. Harley (1988) however showed that North's price falls were largely due to denser packing of cotton bales and that, when a more reliable price index was estimated, freight rates were constant before steamships in the 1850s. A more recent literature, surveyed by Kelly and Ó Gráda (2017), finds increases in the sailing speed of ships, ranging from almost none for the Dutch East India Company from 1595 to 1795, to one third for the British East India Company between 1760 and 1830. However, the issue of safety at sea appears to have received no attention in the literature before now.

Besides shipping technology, our results bear directly on the concept the Industrial Enlightenment, and the complementary importance of artisan skill. The influential work of Mokyr (2016) has explored the idea of an Industrial Enlightenment where European science, driven by an ideal of creating useful knowledge, made major contributions to the development of technology. As Section 4 shows, the earliest and most direct example of this process is the quest starting in mid-seventeenth century to improve astronomical knowledge specifically to advance navigation.

The Paris and Greenwich Observatories were established for the stated purpose of providing astronomical data for reliable navigation tables; and many of the major figures of seventeenth and eighteenth century science—including Galileo, Newton, Hooke, Huygens, Euler, Rømer, and Laplace—were directly engaged in improving navigation. In fact, Wepster (2009, 13) argues that the annual Académie des Sciences essay prize, which alternated between a topic in general astronomy and one in navigation, played just as important a role in advancing navigation as the prizes offered by the British Board of Longitude.

However, while exemplifying the Enlightenment culture of useful knowledge, navigation also illustrates the important complementary input of artisan skills. In fact, most of the innovations that came to dominate navigational practice by the 1840s were due to ordinary watchmakers and seamen.

The two most important early contributions to practical navigation—accurate charts and accessible navigational textbooks—were both pioneered by the retired mariner turned navigational instructor John Hamilton Moore. Even with longitude estimation, the complicated lunar distances of astronomers (whom Harrison disparaged as "professors" and "priests": Gould, 1923, 68) were eventually superseded by the artisan technology of chronometers. A decisive breakthrough in positional estimation, that had been overlooked by generations of astronomers, occurred in 1837 when an American sea captain Thomas Sumner realised when sailing in overcast weather that an educated guess of latitude combined with a chronometer reading gave a line along which the ship's position lay. This could be combined with a similar line estimated a little later to give exact position. Similarly, the production of affordable, accurate sextants was made possible by the 1771 invention of the dividing engine (which underlay the development of all subsequent measuring instruments) by the instrument maker Jesse Ramsden.

Our findings of marked technological improvements in maritime technology are in keeping with growing misgivings about the consensus that the technological progress of the late eighteenth century was largely confined to cotton spinning, iron making, and steam engines, with other sectors mired in stasis. The innovations in ship design and navigation that we describe here support the view of a more broadly based advance across many manufacturing sectors proposed by Berg and Hudson (1992) among others, with sectors such as brewing, pottery, glass, hydraulics and mechanical engineering showing signs of technological dynamism at this time. For a survey see Mokyr (2009, 131–144), and more recent studies of rapid progress in gas lighting by Tomory (2012) and watchmaking by Kelly and Ó Gráda (2016).

3 Technology: Structural Innovation.

There were two ways for technology to improve safety at sea during the late eighteenth and early nineteenth centuries: structural and navigational. Improved navigation means fewer wrecks from unexpected landfalls; while structural improvements will reduce sinkings in rough weather.[1]

3.1 Flush Decks and Iron Reinforcing.

Naish (1958) claims that by the early eighteenth century the European sailing ship was a mature technology (albeit one that was able to compete successfully with steam ships on long distance routes until the second half of the nineteenth century: Harley 1971) and most subsequent improvements, except copper sheathing of hulls, were incremental. But that ignores the most important structural innovation of the late eighteenth century, pioneered by the East India Company: ships with a single, flush deck.

Since the middle ages, European ships had been built with a stepped design—a raised deck at each end, separated by a low waist deck—that offered an effective fighting platform but suffered from two fundamental flaws. First, the low waist deck caused the vessel to ship water each time it dipped in a heavy sea, flooding the lower decks and leading to the danger of foundering or capsizing. Secondly, these hulls were structurally weak.

A ship's hull can be viewed as a hollow beam whose top is the deck. A weak deck insecurely attached to the hull results in a flimsy vessel that will flex up and down (hog and sag) markedly in heavy seas, causing the

[1]Other technological innovations, such as the copper plating of hulls, and better sails and hydrodynamics improved sailing speed but not safety.

ship to leak badly and, in sufficiently bad conditions, to snap its masts and possibly disintegrate.

From 1769, under the influence of its surveyor (chief architect) Gabriel Snodgrass the East India Company gradually moved to adopt a ship with a single, convex flush deck that could be made watertight by battening down hatches, and was far sturdier in heavy seas than traditional European designs (Snodgrass 1797; Parkinson 1937, 135–138). This grew from direct contact with Indian design—Snodgrass spent his early career as a company shipwright in Bengal—where most of the EIC ships intended for the Country Trade with other Asian ports were built in traditional Indian shipbuilding centres. Parkinson summarises Snodgrass's design philosophy as a desire to build vessels "as nearly as possible like a Bengal rice-ship."

Snodgrass further increased the shear strength of hulls by doubling the thickness of planking, making the sides of ships vertical (again like Bengal ships) instead of sloping inwards, and, most importantly, by replacing the oak knees used to attach decks to hulls with stronger and stiffer iron ones. *Lloyd's Register of Shipping*, which lists each ship's construction and condition, first noted the presence of iron bracing in 1818, and by 1830 around 20–25 per cent of ships are reported to use iron.

As the nineteenth century progressed increasing amounts of iron were used to reinforce wooden hulls, most notably with diagonal bracing between ribs. In other words, the transition from the flimsy wooden ships of the mid-eighteenth century to the solid iron ones of the mid-nineteenth was a gradual, evolutionary process.

4 Technology: Navigational Innovation.

Safe navigation requires reliable charts, compasses, and the means to determine longitude and latitude, and all of these improved to varying extents. Equally importantly, it requires seamen with sufficient knowledge to apply these tools.

4.1 Latitude and Longitude.

It was known since the middle ages that the latitude of a ship can be calculated, at least approximately, by the altitude of the Pole Star above the horizon or, as the Portuguese learned when sailing south towards the equator in the fifteenth century, the height of the noonday sun. Traditionally, sailors used astrolabes or staffs to estimate the height of the sun or a star, a difficult exercise on a rolling deck. Systematic readings only became possible with John Hadley's octant from 1730, which worked by moving the reflection of the sun or a star down until it lined up with the horizon, allowing the angle between them to be read accurately (Cotter, 1968, 57–91). Lighter, and far more accurate sextants became practical through one of the most important innovations of the early Industrial Revolution: Ramsden's

1771 dividing engine which allowed compact and precisely cut graduated scales to be mass produced at low cost.

Longitude is the difference between the time in some reference port and the ship's local time. Local time can be calculated once latitude has been measured, and it was known from the early sixteenth century that reference time can be measured in two ways: either mechanically by a clock that tells the time in the home port; or astronomically by the position of the moon against the background of fixed stars.[2]

Against the widespread view that the problem of longitude was solved by Harrison's 1759 H4 chronometer, the fact that chronometers were the most complicated artefacts of their time made them too expensive and, more importantly, too unreliable for widespread adoption (Dunn, 2014, 104–125). Of the 22 chronometers brought on the circumnavigation of HMS *Beagle* of 1831–1836 only 11 still worked at the end of the voyage (another four were left with a surveying expedition) despite being kept in a special cabin and having a professional instrument maker on board to maintain them (FitzRoy, 1839, 325–331). The accuracy of a chronometer not only changed with variations in temperature, humidity, barometric pressure

[2] Abortive efforts were also made to estimate longitude by variations in magnetic deviation. Another astronomical timekeeper, that Galileo attempted to market as soon as he discovered them, is the position of Jupiter's moons. The need for a large telescope, despite repeated efforts to develop stabilized marine chairs, made this impractical at sea but observing these satellites became a standard means for map surveyors on land to estimate longitude precisely. Moreover, by failing to account for the gravitational interaction between the moons Galileo's tables were inaccurate; and it was while observing Jupiter's moons at the Paris observatory in 1676 to make usable longitude tables that Rømer made the fundamental discovery that light has a finite velocity.

(making surviving chronometer logs that record these a useful source for climatologists), metal fatigue and the quality of lubricating oils, but with the way it was wound: the exquisite care needed in winding chronometers remained a constant anxiety for junior officers, as shown by the standard manual of Shadwell (1855).[3]

One more limitation of chronometers was that the necessary estimate of local time required an exact calculation of the ship's latitude. Overcast weather made this impossible until Sumner devised the method of position-line navigation in 1837. This remained the basis of British navigation for a century after, despite being superseded by the French "New Navigation" of the 1870s.

Harrison's chronometer design started from an ordinary pocket watch to which he kept adding parts until it kept sufficiently accurate time, resulting in a chronometer that was complex, delicate, and expensive. Starting in the late 1750s, Pierre Le Roy (whom Gould (1923, 86) credits as the effective inventor of a practical timekeeper for navigation) instead designed a chronometer from first principles. Further improvements by John Arnold (whose chronometers were bought in substantial numbers by the East India Company), and Thomas Earnshaw led by around 1810 to a design that changed little until chronometers became obsolete in the second half of the twentieth century. Although issued to the Royal Navy in limited num-

[3]On the difficulties of maintaining early precision instruments on the move see Baker (2012).

bers from the 1790s, only 7 per cent of British warships had a chronometer in 1802 (Rodger, 2004, 382–383). Few merchant ships used chronometers before the mid-nineteenth century (Cotter, 1968, 29), trusting instead the traditional way of "running down the latitude": sailing directly north or south until they reached the latitude of their destination, and then sailing due east or west until they reached it.

The other approach to longitude estimation at sea, that of lunar distances, uses the fact that the relatively rapid movement of the moon across the sky allows it to function like a minute hand against the clock dial of fixed stars. This means that with appropriate tables the angle between the edge of the moon and a known fixed star can be used to calculate the time in the reference port. So, for example, if on July 27 1809 the adjusted angle between the edge of the Moon and Antares was 67°13'3", after looking up the *Nautical Almanac* for that day the navigator knew that the time at Greenwich was 18 minutes and 39 seconds after midnight.

The Paris Observatory was founded in 1667 for the explicit purpose of obtaining an accurate star map for lunar navigation, as was the London Royal Observatory (for "rectifying the tables of the motions of the heavens ... so as to find out the so much desired longitude of places for the perfecting the art of navigation") in 1675. However, because the moon is affected by the sun's gravity as well as the earth's, modelling its path accurately enough for reliable navigational tables leads to a challenging three body problem that defeated the geometrical approach of Newton (Wepster, 2009, 8–25) and whose eventual solution led to an unedifying priority dispute between Clairaut, d'Alembert, and Euler (Bodenmann, 2010).

It was only in 1755 that the German astronomer Thomas Mayer, developing equations devised by Euler to solve the interaction between the orbits of Jupiter and Saturn and effectively solving a least squares problem (Stigler, 1986, 11–61), computed tables accurate enough to predict longitude to one degree. In 1806 Johann Karl Burckhardt, using the refined lunar equations of Laplace, devised tables about 12 times more accurate. At the same time that the Board of Longitude finally awarded Harrison £10,000 for his watch, it also gave £3,000 to Mayer's widow, and £300 to Euler.

The practical difficulty in applying lunars lay in "clearing" the observed angle of the effects of refraction, parallax and horizon dip to calculate the true angle: a non-trivial problem in spherical trigonometry whose most elegant solution was devised by Borda (Gascoigne, 2015). Although navigation manuals provided worked examples of lunar estimates that take only about one third of a page to calculate, these may have been beyond the capabilities of most captains, and Wess (2015) notes that log book entries in EIC and Royal Navy ships before 1800 report only dead reckoning. However the widespread adoption of chronometers by the EIC from the 1790s would have required lunar estimation to correct the unreliable time pieces, and EIC logs contain a specific column, marked with a moon, for lunar estimates to be entered.

4.2 Charts and Sailing Guides.

[Figure 1 about here.]

Although precise longitude estimation may have been beyond ordinary navigators, it was indispensable for making accurate charts. A fundamental problem for navigation was the crude state of hydrographical knowledge: the standard book of charts of the British coast through most of the eighteenth century was Grenville Collins' rudimentary *Great Britain's Coasting Pilot* (first published in 1693 and frequently republished, reaching its twenty-first edition in 1792), along with somewhat less bad French and Dutch charts. Although the Royal Navy had supported the surveying work of James Cook and others in the 1760s and 1770s, it established a hydrographic department only in 1795, and did not sell its maps until 1821. Similarly, the East India Company's hydrographer, Alexander Dalrymple, produced large-scale maps based on novel surveying techniques for Company use, but not charts for use at sea Fisher (2011, 60).

However, in the late eighteenth century privately produced and crowd-sourced charts began to appear, known as Bluebacks from the colour of their heavy backing paper. Of these, the first and most important was the large chart of the English Channel by Moore who estimated that it sold "upwards of 5,000 copies" alone between its first appearance in 1786 and 1792 (Petto, 2015, 79–122). Each chart was sold with a detailed pilotage manual (such as Dessiou, 1802) that, for each port, gave times of high water, depth soundings, and guides to beacons and channel marking buoys (themselves indicative of direct government efforts to make approaches to ports safer). Moore produced charts of the Mediterranean, the Baltic, the east coast of America, and the West Indies that hardly differ from their modern counterparts, that gave longitude and latitude, precise outlines of the coast with insets for major harbours, depth soundings, and descriptions of the sea bottom.

[Figure 2 about here.]

Although Admiralty charts were sold at considerably lower prices, Bluebacks, by then mostly printed by John Norie, remained the choice of most ships' masters until well into the nineteenth century, coming as they did with detailed pilotage manuals, and being designed to be legible in dim candlelit cabins at sea, with navigational hazards clearly highlighted (Fisher, 2003).

4.3 Navigation Manuals and Improved Dead Reckoning.

These navigational innovations mattered little if mariners lacked the skills to apply them. Although state run navigational schools in continental Europe dated from the time of Prince Henry the Navigator, Britain characteristically relied on informal education. Private tutors were numerous since Elizabethan times but the earliest systematic navigation textbook was John Robertson's 1754 *Elements of Navigation* whose uncompromising reliance on spherical trigonometry, however, made it incomprehensible to most sea captains.

The first useful manual, priced at ten shillings and largely based on worked examples, was again due to John Hamilton Moore. His *New Practical Navigator* of 1772 started with arithmetic and elementary trigonometry before taking the reader successively through use of compass and log line; plotting course on charts with plane, traverse, mid-latitude and Mercator sailing; estimating tides; recording hourly course and speed on a traverse board; calculating local time and latitude; and finally calculating longitude using lunars. At the end were tables of log trigonometric functions, refraction, parallax, the sun's declination, and the right ascension of the sun and major stars. Moore's structure was kept in successive editions of the two most widely used manuals: Norie's *New and Complete Epitome of Practical Navigation* which first appeared in 1803; and its American equivalent, Nathaniel Bowditch's *American Practical Navigator* (which began as a pirated edition of Moore) from 1802 onward.

Despite teaching advanced techniques, in Moore's (1794, 186) view "the most capital part of navigation" for the young mariner was the systematic working up of a daily journal of position. This started from the traverse board of hourly speed and heading, making corrections for compass deviation and leeway, and estimating position on a chart using mid-latitude sailing. So, although it is true that most ships still navigated by dead reckoning despite advances in longitude calculation, the dead reckoning of the

1820s was far more reliable than the guesses of direction and speed entered on the inaccurate plane charts of the 1770s.

Successive editions of these manuals provide a useful way to track changes in navigational practice. The early editions of Norie are almost identical to Moore, although the exposition in general is more lucid and the algorithms for calculating lunars are considerably simpler. By 1835, however, Norie describes how to adjust for the compass deviation caused by the growing amount of iron on ships; and, instead of chronometers being placed as a short appendix after lunars, they are now discussed at length before lunars appear. Although it seems likely that educational standards of officers rose in response to the increased complexity of applied navigation, formal examinations to certify navigators and masters only began in the 1850s: Vasey (1980).

Early navigation manuals were plagued by inaccurate tables of logarithms and trigonometric functions. The most ambitious effort to produce reliable tables, intended for a cadastral survey of post-revolutionary France, was undertaken by de Pronys in 1794 with algorithms designed by Legendre and others. Inspired by Adam Smith's discussion of division of labour, he established "computation factory" of unemployed hairdressers—accustomed to painstaking work, but victims of the reaction against the elaborate coiffure of Bourbon times—to perform the routine calculations. However, the completed tables could not be printed because of the collapse in value of the Assignat: Grattan-Guinness (2003). Another ambitious but abortive project to develop mathematical tables for navigation was Babbage's 1822 idea of a Difference Engine.

4.4 Compasses.

In contrast to the progress in positional estimation and chart making, the improvement of the oldest and most important navigational instrument, the compass, was remarkably slow. Small compass errors translate into large, and potentially deadly, errors in estimated position: heading ten miles due west on a compass bearing that is only 6 degrees in error will leave a ship one mile north of its estimated position. Three difficulties plagued compasses: low quality iron, magnetic variation, and magnetic deviation.

Gowin Knight in 1745 devised a process to magnetize steel bars resulting in a compass needle that retained its magnetism longer than soft iron ones, and this technique became public after his death in 1776. Despite considerable efforts to improve compasses, the Ross Arctic voyage of 1818, which was intended in part to assess the performance of novel designs, found all of them to be extremely unreliable, pointing in widely different directions even before reaching high latitudes with their strong magnetic fields (Dunn, 2016).

Magnetic variation—the difference between magnetic and true north—had been familiar since Elizabethan times (and seemed at first to offer a way to measure longitude, being first systematically mapped by Halley in his voyage around the Atlantic in 1701) but was frequently ignored. The navigators of Shovell's fleet wrecked on the Scilly Isles in 1707 with the loss of 2,000 lives (the event that led directly to the establishment of the Board of Longitude) had not compensated for a 10 degree variation, as well as relying on charts that placed the islands nine miles north of their actual position. As described by Norie and Bowditch, magnetic variation may easily be compensated for by comparing the compass position of the sun at dawn with the true position in published tables.

As increasing use of iron reinforcing and cables after 1800 worsened the deviation of compasses from magnetic north, these manuals also described how to compensate by comparing the position of a compass needle when the ship was heading east-west with its position heading north-south. On iron clippers and steamships, however, compasses were useless (as illustrated by the 1854 sinking of the clipper *RMS Tayleur* with 370 drowned), and although adjustable magnets began to be tested in the 1850s the problem was not solved until Lord Kelvin's binnacle design in the 1880s. Although compass design was largely stagnant, notable improvements occurred during our in the two other traditional mainstays of navigation: log lines (for estimating speed), particularly Edward Massey's design of 1802; and rapid depth sounding, although the latter was only needed when fast steamships appeared.

Hand-held spyglasses, widely used from the seventeenth century to identify navigational hazards and safe places to land, considerably improved during the eighteenth. In 1758 John Dollond patented a lens which corrected for chromatic aberration, and formed a partnership to sell spy-glasses incorporating the new lens. With the termination of Dollond's patent in 1782, cheaper achromatic telescopes became widely available Dunn (2011, 73–76).

4.5 Lighthouses, Lifeboats, and Legislation.

The second half of the eighteenth century saw increased state efforts to improve navigational aids around coasts. The number of lighthouses on the east coast of the United States rose from three (all in Massachusetts) before 1750, to about 24 by 1800, and 85 by 1830. In the United Kingdom the numbers rose from about fifteen in the mid-eighteenth century to 57 by 1800, 118 by 1830, and 264 in 1844.[4] Steady innovation occurred in lighthouses, detailed chronologically by Stevenson (1959, 61–85): in particular the replacement of simple coal fires and candles with oil Argand Lamps illuminating parabolic reflectors; and building "wave-swept" lighthouses off shore, pioneered by Smeaton's 1759 stone Eddystone Lighthouse.

At the same time, as noted above, channel marking buoys and beacons were installed by most local harbour commissioners. The first successful purpose-built lifeboat was designed by Henry Greathead in 1789, and was soon operated by lifeboat societies in several British ports that were or-

[4] Probert (1999). Some of these numbers were compiled from Wikipedia entries.

ganised into what became the Royal National Lifeboat Institution in 1824.[5] Mortars and rockets to bring zip-lines to distressed ships appeared in the early 1800s, with every Coast Guard station being equipped with a Manby Mortar which were credited with saving over a thousand lives by mid-century (Prosser, 1885).

These innovations coincided with rising humanitarian concern at loss of life at sea that drove campaigns for state intervention, reflected in the foundation in London in 1774 of the Society for the Recovery of Persons Apparently Drowned (the Royal Humane Society from 1787) and the passage of the Burial of Drowned Persons Act in 1808. A belief that the risk of shipwreck was increasing—blamed on "bad vessels, bad navigation and drunken officers . . . in more or less equal parts" (MacDonagh, 1961, 48)—seemed to be confirmed by McCulloch's (1835) influential article on shipwrecks in the *Edinburgh Review*, and the detailed accounts of individual incidents published in the *Nautical Magazine*.

From 1803, early legal efforts concerned the welfare of passengers, with most legislation on maritime safety appearing after our period, culminating in the Mercantile Marine Act of 1850 that placed all regulation of shipping under the Board of Trade. From 1835, load lines painted on hulls to prevent overloading with cargo were required by Lloyd's for all ships re-

[5] For example Dublin's port authority placed five lifeboats at locations around Dublin Bay between 1801 and 1816 (Gilligan, 1980).

gistered with them, but did not become mandatory until the campaigns of Plimsoll in the 1870s (Fink, 2011, 72).

5 Safety at Sea.

To what extent did these extensive improvements in ship design and navigational practice improve safety at sea? *Lloyd's List,* then published biweekly, gives information on all known losses of British and Irish vessels (along with some other ones) and their circumstances, and is available with several gaps from 1740, and continuously from 1760 to 1825.[6] The list also gives details of ship arrivals at all major ports used by British shipping, and details from returning captains on vessels they had encountered en route: usually welcome news such as "All well" or "Fully slaved and ready to sail."

Our concern is with two major categories of complete loss: founderings (described by such terms as "lost", "last sighted", "sunk") and abandonments, where the ship sinks in open water, usually in bad weather; and wrecks where the ship is destroyed on rocks or other coastal hazards. The other common accident was where a ship had been driven ashore—usually as it approached port, because sailing ships tried to stay as far from land

[6] Available at Hathi trust. Transcriptions are available at www.cityoflondon.gov.uk/lloydslist/ and their loss lists are available on Wikipedia: comparisons with several printed lists show the transcriptions to be accurate. The volume for 1778 is missing: we interpolate this as the average of observations from 1776 to 1780.

as possible at other times—meaning that it had been salvaged and usually suffered little loss to cargo or crew. We do not consider less common events like losses from enemy action or privateers, fires and explosions, or mutinies by slaves or crew.

[Figure 3 about here.]

We look at annual losses of British and Irish (United Kingdom after 1801) ships coming from or going to UK ports, dividing them into two categories: North America and the Caribbean; and all other areas, largely coasting traffic from within the UK or from the Baltic and Northern Germany. Losses must, of course, be adjusted for growing volumes of shipping, and two measures are available: registered tonnage and monthly arrivals in ports. Official tonnage estimates exist continuously after 1788, and a separate series assembled by Davis (1972, 27) runs from 1751 to 1775 (with a gap from 1756–1762), and one more observation for 1786.

Our other measure of shipping volume is the number of arrivals in British and Irish ports given in *Lloyd's List*. The low print quality of these publications means that totals had to be computed manually for arrivals from the Atlantic and Caribbean for January and July 1755, 1760, 1770, 1784–86, 1794, 1809,1816, 1823–25. The top panel of Figure 3 gives the average of January and July arrivals, multiplied by 12 for each of these periods. Although Davis warns that the two tonnage series are not strictly comparable, it can be seen that arrivals and tonnage (where values before 1788 are multiplied by 1.33 to match the observed values for 1786 and 1788 and missing values are interpolated using a cubic spline) show similar patterns suggesting that estimated tonnage is a reasonable estimate of shipping volume.

Figure 4 gives annual totals of founderings and wrecks, and the number relative to million tons of registered shipping, for the Atlantic routes. It can be seen that, adjusting for tonnage, Atlantic founderings fall sharply through time and wrecks at a more moderate rate.

[Figure 4 about here.]

By contrast, loss rates on European routes remain constant, suggesting that improvements in shipbuilding and navigation were worth the additional investment for expensive oceanic ships but not for smaller coasting vessels. All series peak in the late 1810s, and appear to drop markedly in the 1820s although there are too few observations to determine whether this is the start of a steeper downward trend.

In terms of risk of foundering or sinking, there were slightly under 20 wrecks and founderings a year around 1770, out of 4,000 crossings (twice the UK arrivals number), giving a risk of around 0.5 per cent per voyage, and this had fallen to around 30 losses in 10,000 voyages by the 1820s, or 0.3 per cent of voyages.

[Figure 5 about here.]

Ship losses rose in bad weather: could better conditions, especially during winter, explain some of the improvement here? The storminess of Atlantic winters is driven by the North Atlantic Oscillation (NAO): the pressure differential between the Icelandic low and the Azores high. This winter NAO has been reconstructed by Cook, D'Arrigo and Mann (2002) and shows no trends during this time. Adding estimated NAO as an extra covariate to the foundered and wrecked regressions in Table 1 showed it to have no explanatory power.

[Table 1 about here.]

Table 1 gives regressions of log losses relative to tonnage for each of the three categories and confirms what the graphs show. On the Atlantic, founderings fall by 1.9 per cent per year and wrecks by 0.7 per cent, whereas on other routes they remain constant.

5.1 Reported Survivors.

As well as the place and circumstances of each ship's loss, *Lloyd's List* mentions whether there were any survivors. Of course, it is not possible to ascertain how comprehensive these descriptions are: although there are frequent mentions of "lost with all hands", there is always the possibility that the report sometimes fails to mention the presence of survivors. Trends in reported survivals may therefore reflect changed reporting, rather than changing rates of survival. As well as the quality of a ship, survival rates also depend on the proximity of other shipping to rescue victims of the sinking, and which would have increased as shipping volumes rose.

[Figure 6 about here.]

With these large caveats in mind, Figure 6 shows that the proportion of founderings where at least one survivor is mentioned rises from about 50 per cent to 70 per cent on Atlantic routes, and from 25 to 50 per cent on coastal routes; while the number of wrecks with survivors mentioned increases from 20 to 30 per cent on Atlantic routes, and from 5 to 40 per cent on coastal routes.

A more directly informative of survival is the fraction of sinkings where the crew is reported to have abandoned the ship: the implication being that some were alive to report the loss when rescued. This rises from nothing in almost all years in the 1760s to over fifty per cent of Atlantic sinkings in the 1820s.

5.2 Insurance Rates.

To what extent does rising safety at sea show up in insurance rates? Being set by private brokers, insurance data are scarce, but they do show a downward trend that is consistent with improving safety, although may also reflect factors such as greater competition between insurers and the deepening of capital markets.

For 1782, during the American War of Independence, the rate from London to Ireland was 6 per cent, and for ships sailing in convoy (and presumably at little risk of attack) to the West Indies are 10 per cent, and to New York 15 per cent (Martin, 1876, 166, see also Solar, 2013).

These rates are considerably larger than those quoted by John (1958) for the London Assurance Company. Here there is little change in insurance rates, which were only 2 per cent each way to North America both in 1730 and 1770. This may be a consequence of what John views as the extreme conservatism of the company: it is notable that their winter rates are identical to summer rates, suggesting that they were offering insurance only to a select group of low risk, repeat customers.

In 1797 the insurance rate to Bengal and Canton was 8.4 per cent and in 1809 that rate was 7 per cent (Leonard, 2012). In 1826, addressing the House of Lords on the rent dissipation of the East India Company (focusing largely on its chartering of large, over-priced ships owned by its biggest shareholders) a shipping agent John Simpson stated that they were paying 6 per cent insurance to their favoured brokers on voyages to Calcutta and Canton, whereas other brokers would charge 4 per cent on a voyage to Calcutta, and 5 per cent to Canton (Great Britain, 1830, 599–600). For 1853–1873, Martin (1876, 399) reports average insurance premiums charged by Lloyd's of 1–1.5 per cent depending on season.

6 Conclusions.

A transport technology can improve through cost, speed, or safety. The North-Harley orthodoxy of technological stasis in oceanic shipping—which forms part of the wider narrative that technological improvement during the early Industrial Revolution was limited to cotton, iron, and steam—stems from an exclusive focus on the cost of shipping freight, mixed with a lack of curiosity about technological history. More recent studies have found steady, and sometimes substantial, rises in sailing speed during the late eighteenth century. However, the greatest advances in maritime technology during this time, as we have demonstrated here, took place in safety, with large falls occurring in the risk of sinking at sea or being wrecked on the shore.

The improvements in safety reflect advances in the design of ships and in their navigation. The most important innovation in shipbuilding was the adoption of flush decked shipped, probably based on Indian designs, and, later, iron reinforcements that made for stronger, more watertight ships. Efforts to improve the theory of navigation provide the strongest example of the Industrial Enlightenment, with many of the key scientific figures directly involved; while for practical navigation the major improvements came through better charts and improved knowledge of basic navigational skills.

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	Foundered Atlantic	Wrecked Atlantic	Foundered Europe	Wrecked Europe
(Intercept)	35.246^{***}	14.970^{***}	-1.459	1.756
	(6.947)	(4.055)	(4.309)	(3.299)
Year	-0.019^{***}	-0.007^{**}	0.002	0.001
	(0.004)	(0.002)	(0.002)	(0.002)
R^2	0.216	0.122	0.017	0.006
N	67	67	67	67
SER	0.702	0.369	0.353	0.258

HAC standard errors in parentheses.

Table 1: Regression of the log of annual losses (per million tons of shipping) on year, 1760–1826.

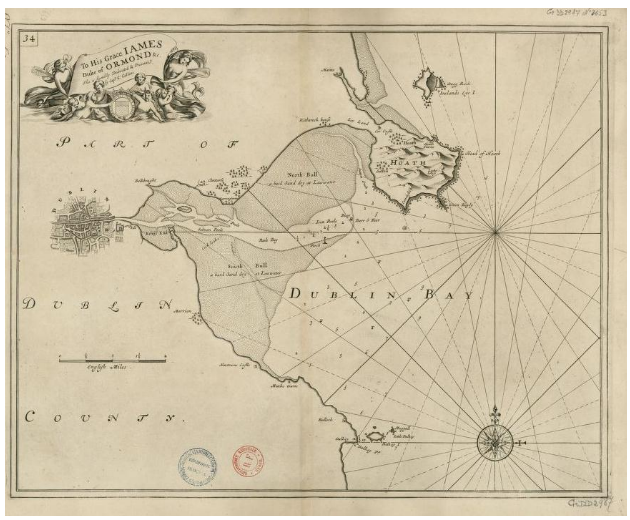

Figure 1: Grenville Collins, *Map of Dublin Bay*, 1693.

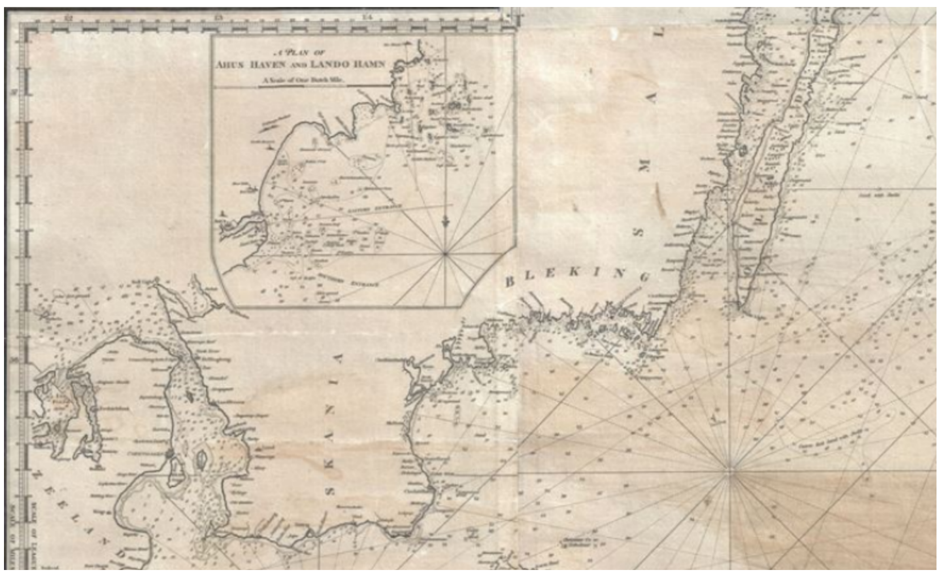

Figure 2: Detail from Moore's "New and Correct Chart of the Baltic...", 1791.

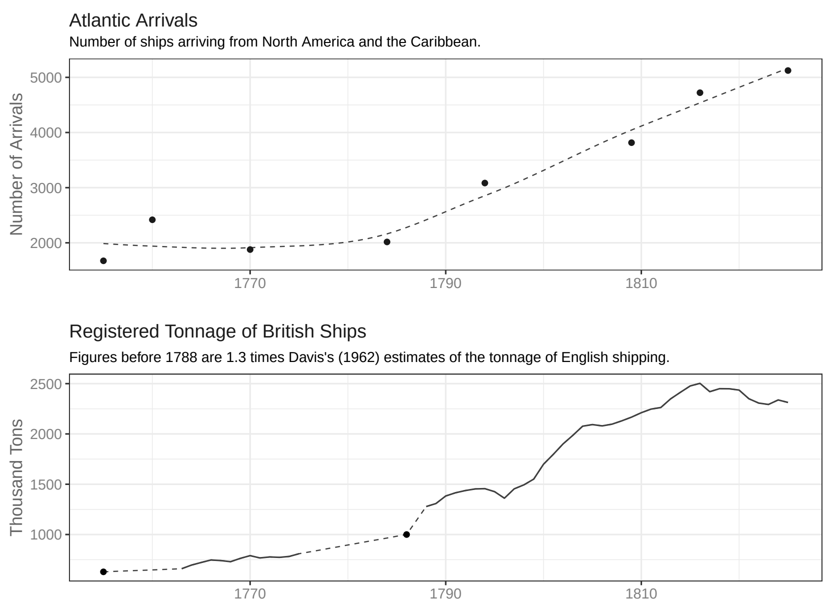

Figure 3: Estimated annual arrivals and shipping tonnage, 1750s–1825.

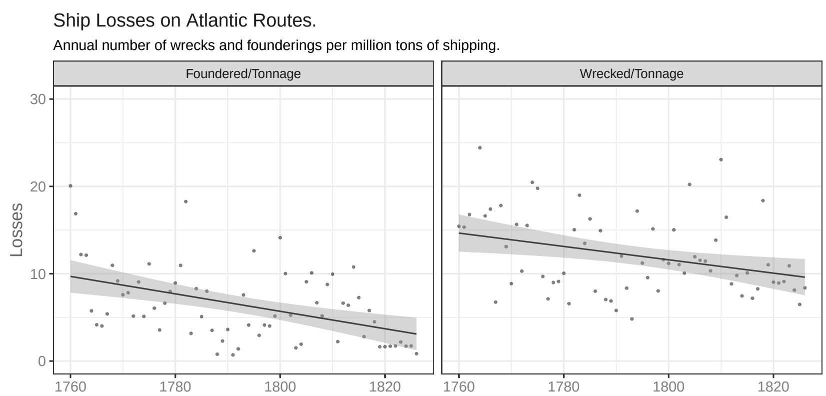

Figure 4: Annual losses on Atlantic routes relative to tonnage, 1760–1826.

Figure 5: Annual losses on European routes relative to tonnage, 1760–1826.

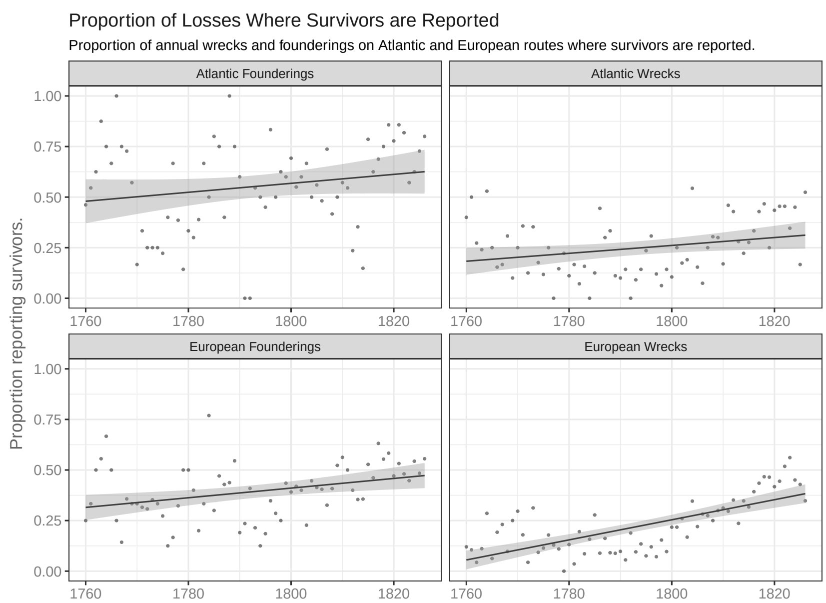

Figure 6: Percentage of losses where one or more survivors are reported.

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