Organizations and efficiency in lighthouses: the English case revisited

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PRELIMINARY DRAFT: PLEASE DO NOT QUOTE

Abstract[5]

Complex policy challenges in the infrastructure sector are seen in a fresh light when studying one of the most celebrated historical examples: lighthouses in England. We show that in 1832, the largest actor in the market, Trinity, provided services more efficiently than numerous private operators. Trinity's advantages partly came from lower revenue collection costs. Moreover, Trinity was pressured into charging lower prices, which proved illuminating to policy makers. While much of analysis shows the advantages of Trinity, we document that privates built many more lighthouses. Trinity became active only after a technological shock which increased the utility of lights. Finally, our analysis sheds light on a largely ignored provider: harbour authorities. They relied on alternative pricing and bundling strategies, achieved low operating costs, and served in markets largely ignored by Trinity and privates.

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Introduction

Markets for infrastructure services are usually thought of as natural monopolies. Large fixed costs, combined with low or close to zero operating costs, imply that it is best for only one provider to supply a market. For the same reason, regulation is thought to play a crucial role since a single firm is likely to charge an inefficiently high price. Alternatively, the government can provide infrastructure for free and use public funds to pay for it. For many practical reasons, the choice between public and private provision is rarely clear however. Technological change, improving the quality of services, complicates optimal policies further. If the incumbent provider, whether public or private, does not adopt new technologies, or build out to meet emerging demand, then perhaps there is even greater inefficiency.

When one looks at history, complex policy challenges in the infrastructure sector are seen in a fresh light. In the past, infrastructure was provided by many different types of organizations, often within the same economy and sector. The selection of the most efficient natural monopolist, as prescribed by theory, was often fraught. There are documented cases where rent-seeking incumbents used their political influence to block useful re-structuring of the market. But there were also instances where government officials did not seem to know which was the most efficient among existing providers, or did not recognize economies of scale. Optimal pricing schemes were foiled by limited understanding of marginal cost pricing and direct government provision was plagued by the high cost of public funds.

In this paper, we examine one of the most celebrated historical examples of infrastructure provision: lighthouses in England. Our focus is on static and dynamic efficiency in a context where multiple organizations provided lighthouses. We show that a particularly important moment, 1832, the largest actor in the market, Trinity, provided

equivalent services to numerous private providers of lights, but it did so by charging a lower 'price' to ships and by earning less profits. Trinity's prices came in the form of light dues, which were a unique pricing tool developed in England to make passing ships pay for lights. Trinity's low light duties led it to being selected as the primary provider of lighting services in England after 1835. As we show for the first time, Trinity's advantages partly came from lower light due collection costs. Moreover, new evidence is provided that Trinity was prodded by the government into charging lower light dues in the 1820s and this experiment helped prove that lighthouses could be provided at a lower operating margin.

While much of analysis shows the advantages of Trinity, we also provide evidence that Trinity did not build or finance most lights under its management in 1831. Rather this achievement was made by private operators, under leases from Trinity or the Crown. For a long time privates were willing to take risks, where Trinity would not. But Trinity did increase its role in building new lights after the 1780s. The invention of the Argand lamp seems to have been a technological shock which changed its behaviour. The Argand lamp increased the benefits of using lights and with time it seems to have favoured a larger organization like Trinity.

The last task of this paper is to shed light on a largely ignored provider of lighting services in England: harbour authorities. They are interesting because of their reliance on harbour duties, which only collected fees on ships entering ports, not on ships passing lights. While the inability to collect light duties would appear to be a disadvantage, harbour authorities thrived and provided numerous lights starting in the late eighteenth century. They managed this achievement by providing a more modest lighting service in a market largely ignored by Trinity. They also managed to keep their operating costs very low, in part by bundling their lighting services with other harbour services like piers and docks.

Our paper contributes to a lively theoretical and empirical literature on lighthouses. The literature begins with John Stuart Mill in 1848, who in Principles of Political Economy proposed that lighthouses are always a 'public good.' According to this eminent Victorian philosopher, lighthouses require government intervention because of the way light is freely emitted out to sea. The market could not provide lighthouses because users could not be practically excluded from the service to ensure that the lighthouse owner was paid for lighthouse services. This problem of excludability of non-paying lighthouse users meant any lighthouse businesses would naturally face the problem of passing ships free riding on the offered services. In their view, this was a classic example of market failure and some level of government intervention was required to solve it. Mill's argument made its way into canonical economics textbooks of the twentieth century, notably those by Arthur Pigou (1938) and Paul Samuelson (1964).

Coase (1974) famously disagreed with this classical view. Coase focused on England and argued that the fees collected from ships using lighthouses paid their costs. Coase also pointed to real historical examples of successful English lighthouses built by what he described as 'private enterprise' (Coase 1974 p. 375). Coase essentially argued that private and profit-making organizations could provide public goods by using the very example that Mill had originally used to prove the opposite.

Coase's arguments have drawn significant levels of criticism (and some support) by a range of scholars including economists and historians. Coase's controversial article, the Lighthouse in Economics, has at the time of our writing been cited 1,629 times according to Google Scholar and is the subject of many articles. Briefly, Van Zandt (1993) pointed out that private actors could provide public goods but only because the state ensured service fees (tolls) were paid by ships when docked in port and protected property rights. Van Zandt described the English system as a public-private or mixed system rather than a market-based

response. Bertrand (2006) argued that the involvement of private individuals in the mixed system was sub-optimal and created incentives for corruption, poor service quality, and high costs. This followed Taylor's work (2001) that highlighted a movement led by Victorian reformers in parliament in the 1820s and 1830s to abolish individual owners who had inherited or acquired lighthouses and made a fortune off the back of trade and industry and who supposedly provided a sub-optimal service by that time. For Taylor, intervention by parliament in an act of 1836 finally solved a longstanding market failure characterised by poor performance of private operators. Candela and Geloso (2018) have challenged some of these views arguing that Trinity was not as supportive of new technologies, like the lightship. They argue that private innovation was thwarted by a government favoured incumbent.

Our paper moves this literature forward by providing new data and fresh empirical analysis. This is done using a new dataset, called Light Aids to Navigation or LAN, that details all lighthouses (including beacons and light vessels) in operation in 1831 and their geo-spatial and technological attributes. The most important source is the Admiralty list of 1831, which to our knowledge has been under-utilized by scholars. We also extend this data by linking lights in the Admiralty list to more commonly used parliamentary select committee reports in 1822 and 1834. They provide a treasure of organizational, financial and regulatory data on lights.

Our emphasis on technology draws on a different and specialist strand of literature on the physical development of lighthouses. Hague and Christie (1975) provided information that was invaluable in the creation of LAN. Naish (1985) and Stevenson (1959) published historical and technical details for the better-known lighthouses in England. These authors provided crucial information about the technical abilities of various lighthouse types, which we use to assign attribute variables to the lights listed in our database, notably the range of lights in miles from the lighthouse. Our research builds on these earlier works by providing a

clearer picture of lighthouse development in time and space and by including all lights and measuring their effects in terms of their coverage using new data and digital methods. This enables us to reassess the historical role of private enterprise in the provision of public goods, and to provide lessons about this contentious political issue in the twenty-first century.

BACKGROUND

To begin we briefly review features of navigational lights and the evolution of technologies in England. Many lights in the seventeenth century consisted of two or even three lights built in a line on the seashore facing the water (Naish 1985, 68-76). 'Leading' lights, when viewed in alignment by the navigator, often showed safe passage into harbour or the correct position to start on a safe "road" between sandbanks. Most used wood or candles to emit light. Their luminosity and reliability were low.

The next type were large single light structures used for general navigation or that marked specific dangers. These 'lighthouses' were designed to maximise visibility in areas further out to sea. An example is St Agnes which illuminated the entrance to the English Channel for ships in the Atlantic trades. Some lighthouses developed in the eighteenth century used coal-fired lights as opposed to candles. Coal fires and the smoke they emitted could be seen from 5-6 miles or more, whereas candles had a range of 1-2 miles (Naish 1985, 157). However, coal fires were susceptible to wind and rain (Hague & Christie 1975, 147). There were also significant fuel costs attributable to the shipping of coal to remote places (Naish 1985, 97). There was also the danger from fire to the lighthouse itself (Naish 1985, 88).

Lighting technology changed dramatically with the Argand lamp. In 1784 the Swiss inventor Ami Argand patented his smokeless oil lamp. This featured a hollow wick and glass chimney that produced a smokeless and steady flame (Naish 1985, 105; Hague & Christie 1975, 154;

Taylor 2001, 754). The efficiency of the lamp was improved further by the addition of parabolic reflectors to amplify and focus light beams (Stevenson, 231). The Argand lamp is described as 'one of the most important events in lighthouse history' (Stevenson 1959, p. 61). This is made apparent by the problematic systems it replaced. Firelight from coal could not easily be reflected or focused into beams using the parabolic reflectors. Such fires produced a large amount of smoke, which obscured light and covered reflectors in soot. Standard oil lamps had the same effect (Stevenson 1959, 61). Naish (1985 p. 105) estimates that Argand lamps were installed in 80-90% of British lights between 1782 and 1823. In optimal conditions, lighthouses with Argand lamps could generate visibility 20 miles out to sea.

Light vessels or lightship was another important innovation. According to Candela and Geloso (2018) the were different from lighthouses in being manned seamarks anchored in a vessel at a specific point...The main advantage of lightships is that they could be placed in areas where it was impossible for lighthouses to act as efficient seamarks (pp. 485-486). The first lightship was the Nore in 1732, but it was not until the nineteenth century that they became common. Candela and Geloso argue that the light vessel's slow diffusion was not related to its utility, but rather to Trinity's resistance to a technology that threatened its monopoly. Turning to the related issues, we now provide more background on the complex mix of norms, laws, and organizational forms operating in England at this time.

While many observers consider navigation lights as public goods, best provided by a government, it is well known that the English government did not play a direct role in building, financing, or managing its early lights. From the sixteenth century, English governments in London were run by ministers representing the monarchy. Public funds were very limited and their interests were mainly focused on war and maintaining internal order. But governments were willing to grant patents to those who would build lights in exchange

for monopoly rights to commercially exploit the light.[6] Unlike other types of patents, which expired after a number of years, most light patents continued indefinitely.

Channeling the debate among later economists, governments recognized that ships passing lights must be made to pay for their construction costs and maintenance. It became common, at least from the seventeenth century, for so-called light duties to be authorized by patents. Patentees would hire agents to collect light duties in various ports, sometimes they were customs officers, already employed in the activity of charging dues for the government. Funds were directed to patentees based on how many ships passed their lights, paying fixed tonnage rates per ship. Rates generally distinguished between British and foreign vessels, being higher on the latter. The light ships passed along their journey was inferred from ship manifests, which stated the port of origin and destination. They were then charged for lights that serviced the route and the money was paid out to lighthouse owners after a commission rate was taken for the work of collection. The rate of light duties and the commission rates of agents will be featured in our analysis later.

Patentees came in various organizational forms. Trinity House Deptford, or Trinity for short, was one of the earliest and most famous. Trinity was a guild dating from the year 1566. Its original purpose was to improvise the safety of navigation in English coastal waters. Trinity's revised 1685 charter appointed a Master, Wardens and Assistants, and eighteen elder brethren, prescribed the form of their election, and named the seamen and mariners belonging to the guild, called younger brethren. Amongst other duties, it declared that the Masters, Wardens and Assistants of the Corporation, managed schooling children in the 'Art of Navigation'. Powers of appointing Pilots and Leadsmen in and out of the river Thames,

[6] The original patents survive in the 'patent rolls' available in Chancery records series at the National Archives, Kew. Other government papers discussed local petitions and the patents and can be viewed on Gale's: State Papers Online: The Government of Britain, 1509-1714, website.

subject to the approval of the Lord High Admiral, were granted, including ancient tolls Loadmanage and Primage. Trinity had the power of holding its own courts. All profits were to be spent on charity, namely Trinity's almshouses and pensions. The only tolls mentioned in the charter were the fairly obscure ones like 'loadmanage', Primage, lastage, ballastage, etc - not light duties that were granted by specific patents for lights.

Trinity's role in providing lights evolved with time. It held a few of the early patents awarded in the seventeenth century, but at this time it more often challenged others. Trinity did not respond to several petitions for the need to have lights to protect ships from dangers. In some of these cases, individuals or groups proposed to build lighthouses (Hague & Christie 1975, 24; Harris 1969, 184). Trinity usually objected, arguing that its charter gave it the sole right to collect light dues, but this was disputed by various governments. As a result, several patents granting light dues were awarded to individuals or groups other than Trinity. These organizations have been described by Coase and others as private and entrepreneurial, because it appears they were willing to take risks to profit from lighthouses. Many of these private lights remained independent of Trinity's control until the early 1830s.

Trinity's role in English lighthouses increased around the time of the Glorious Revolution of 1688. Trinity switched to working with private groups in efforts to build more lights (Stevenson). In this system, privates leased lights from Trinity who obtained them from the government. Leases extended several years and often they were renewed multiple times, which effectively meant the lessees had a sense of ownership. Lessees were expected to take financial risks and solve technical problems. The famous case of the Eddystone lighthouse provides an example of this partnership.

Eddystone was motivated by petitions from shippers who called for the illumination of a dangerous reef in the English channel, near the port of Plymouth. There were enormous

engineering challenges to building a lighthouse on a partially submerged reef situated 9 miles from land. Nevertheless between 1696 and 1699 an engraver called Henry Winstanley managed to build a wooden lighthouse on the rocks, a world first (Stevenson, pp.113-130). He quickly replaced it with a second structure. Winstanley had negotiated a deal with Trinity House in June 1696 to do this, under which he would receive all profits for the first 5 years after showing a light, after which they would share them equally for a further 50 years (Stevenson, p. 114). Winstanley's lighthouse was swept away with him inside in the great storm of 1703.

Trinity house would not answer the call to rebuild at Eddystone and a new lighthouse was built by another enterprising person, this time a London silk-mercer, John Rudyard, who between 1706 and 1708 built the third Eddystone light. Trinity's Elder Brethren came to an agreement to apply for an Act of Parliament authorising the rebuilding of the lighthouse and new light duties granted to him by a lease for 99 years at an annual rent of £100. Rudyard's business partner, Lovett, provided the capital (from his wife's dowry) to build the lighthouse. He and Rudyard would receive all profits given the exceptional risk of the undertaking. £5000 was invested, for with a return of £700 per annum expected. Trinity obtained an Act of Parliament in 1706, and work began that July. This lighthouse was more successful than its predecessors, yet eventually it burnt down in 1759.

Rudyard's lighthouse was replaced by what became known as Smeaton's lighthouse. Smeaton was successful in making the new structure more durable. His innovation was the use of prefabricated, interlocking stone blocks that could be more rapidly assembled on the reef in the short period when the weather permitted (Hague & Christie 1975, 125-126). At the time of its building, 50 years remained on the original lease Rudyard obtained from Trinity, and with its agreement, private investment was again found to rebuild the lighthouse (Stevenson, p. 123). This arrangement lasted until 1807, when the expired and ownership

reverted to Trinity. From that point on Trinity managed Eddystone light and undertook further improvements, like installing Argand lamps.[7]

By the early nineteenth century Trinity had taken over many lights formerly on lease, and it also built several lights on its own. It also began to collect substantial light dues, which it partly used to fund its administration and charitable activities. Concerns about corruption caught the attention of governments, as did the growing profits earned by private lighthouses, operating under patents from the 1600s. By this time, government action was undertaken with the consultation of parliament through select committees or SCs. These cross-party groups of MPs or peers were tasked by the Commons or Lords with inquiring into and reporting on specific issues. SCs were often supported by reform-minded government ministers, which became more common after the Napoleonic wars ended in 1815 (Taylor 2001).

There were two important Select Committees reports, published in 1822 and 1834. Both stressed the importance of lighthouses to shipping, as well as the need for them to be well funded. But the reports also stressed the need to reduce light duties. The 1822 SC report focused on Trinity's light dues, which as we will see led to significant changes. The 1834 SC report focused on reducing the dues of the remaining private providers. It recommended more centralisation of control in Trinity, which it noted as charging lower light dues. The SCs recommendations were implemented by an act of 1835, which forced the remaining privates to sell to Trinity.

The 1834 SC report also noted the further fragmentation of managing authority outside of Trinity and privates. It pointed to so-called harbour authorities as another major provider of English lights. The 1834 SC did not criticize harbour authorities to the same extent as privates and their lights were not included in the list that was forced to sell to Trinity

[7] See 'Eddystone Lighthouse, Smeaton Tower', http://www.engineering-timelines.com/scripts/engineeringItem.asp?id=67, accessed on 25 Jan. 2021.

following the 1835 Act. Harbour authorities were commonly established by local acts of parliament, which covered other harbour and pier improvements. There were various subtypes, including commissions, trusts, and joint stock companies. Commissions and trusts were the most common and will be our focus here.

When considered in the broader literature on transport infrastructure, commissions and trusts were widely used organizations with a public or civic constituency (Bogart and Richardson 2011). According to Jackson (1983), commissions and trusts built lights to improve local navigation and port infrastructure to improve the commerce of the town and prevent accidents at sea. The Trustees of the Liverpool Docks are a prominent example. They managed six lighthouses and one light vessel in 1831. They were the first English lighthouse authority to adopt parabolic reflectors (Stevenson). The *Liverpool County History* summarizes the evolution of its governance:

Under the first Dock Act, 1708, the mayor, aldermen, bailiffs, and Common Council became the trustees of the proposed dock, and were empowered to construct the dock and to levy dues. They managed the first and successive docks through committees. By an Act of 1811, however, they were separately incorporated. The control of the docks by a closed corporation, which was in no way representative of the ratepayers or of those who used the docks, led to much discontent and discussion, and in the end produced a new Act, that of 1825, whereby, though the trust remained unaltered, the committee was changed by the inclusion of eight members elected by dock ratepayers. An Act of 1851 raised the number of the committee to twenty-four, half of whom were to be dock ratepayers.[8]

[8] See 'Liverpool: The docks'.

This account shows tension between different local interests over time. In Liverpool, the ratepayers – many of whom used the port – eventually gained greater say and a degree of ownership through enfranchisement and a shift away from oligarchy.

Harbour authorities relied on a very different source of revenue than Trinity and privates. They typically funded lighthouses using so-called harbour duties, which were levied on ships entering a specific port, like Liverpool. Harbour duties were different from light duties because they were not collected at ports throughout England and they were not based on which ships passed lights. Moreover, harbour duties were meant to pay for multiple services, like piers and docks. Thus shippers were paying for a 'bundled service': safe passage into the harbour and the infrastructure provided in the harbour. Bundling was not new in English navigation aids. As Candela and Geloso (2018) argue, services from lightships were originally bundled with pilotage into port, and provided one mechanism for addressing market failure. While the bundling lighthouses with harbour infrastructure appears to have been successful here too, it did not resolve an outstanding problem: some ships passed harbour lights in their journey to another harbour and they did not pay light dues to help maintain these lights. This suggests that harbour authorities will provide less visible lights, which is something that we confirm.

Looking forward, we will study the services and efficiency of different organizations in 1831 using rigorously compiled and highly complete new data, and then after, we look back further to show how the system performed in previous decades. The next section introduces the data.

DATA SOURCES

This paper draws on a new dataset called LAN, covering navigation lights and various of their attributes across England and Wales from 'medieval' times to 1911.[9] LAN improves on earlier datasets which cover coastal lighting in England and Wales in a partial manner.[10] None comprehensively detail recorded light establishments big and small, nor longitudinally over this time frame. Nor do they give visibility range for a complete list of historical lighthouses. LAN includes several geospatial elements, like latitude and longitude, that record the coverage of different lights.

Here we employ LAN to analyse 114 lights operating in 86 locations in 1831. The main source is the Admiralty, which published the first of its lists detailing all UK coastal lights in 1832.[11] The list is organized by location has several light attributes, including (i) visibility range in miles under ideal conditions, (ii) height of light in feet, and (iii) date of construction. Importantly, the Admiralty List appears to be comprehensive and includes all lights of various forms and locations in 1831. In the name, it also identifies lights that were light vessels, one of the main technological innovations noted earlier.

The Admiralty List does not identify ownership or managing authority, and so we extend the LAN dataset for this paper. Following previous scholars, we turn to the parliamentary SC reports investigating British lights in 1834, numbering over 600 pages of witness testimony with reports and appendixes.[12] It inquired after lighthouses, light-vessels, buoys, and beacons under various organizations; their revenues, and expenses, circumstances behind ownership and leases, level of light duties, and ideas for further reforms. Importantly, the SC report was

[9] See Alvarez-Palau et. al. 2020.

[10] The Lighthouse Directory: http://www.ibiblio.org/lighthouse/; ARLHS World List of Lights (WLOL): http://wlol.arlhs.com/index.php?mode=zones&zone=ENG; List of lighthouses in England: https://en.wikipedia.org/wiki/List_of_lighthouses_in_England#Lighthouses
(all accessed in October 2019)

[11] The 1831 list is in the British Library: Great Britain. Hydrographic Office, The Light-Houses of the British

[12] See 'Report from the Select Committee Appointed to Consider of the Means of Improving and Maintaining the Foreign Trade of the Country' and 'Select Committee to inquire into State and Management of Lighthouses'.

particularly concerned with classifying how each lighthouse was owned and managed.[13] Concerning England and Wales, the Isle of Man, and the Channel Islands, five different types are listed in the Report:

1. Under Trinity
2. In private hands, on lease from Trinity
3. In private hands, on lease from the crown
4. In private hands, held under an act of parliament
5. Local or harbour lights.

Trinity and private groups are well known in the literature. The specific lease and holding terms for 'private hands' are explained earlier. One difference is that privates under lease from the Crown or held under an Act were entirely independent of Trinity's control. The fifth group, local and harbour, is more heterogeneous, but descriptions of each in the 1834 report identifies most of them as harbour commissions created by acts of parliament.[14] One can regard the Liverpool Dock Trustees highlighted in the background as a leading example, since it was one of the first to be established.

From the rich description in the 1834 select committee report and the literature, we define 3 organizational types which financed and managed lights in a common manner. In the list above, group 1 is labelled Trinity. It is straightforward as it consists of a single authority. Group 2, 3, and 4 are combined into a single type called private. Our reading of the literature strongly suggests control lay with private groups, even if on lease from Trinity or the Crown. In other words, we do not regard the lease type as a major distinction, which is borne out in our analysis below. Lastly, we relabel all lights in group 5. as harbour authorities. We should

[13] See 1834 Select Committee report, appendix C, list of lights of the UK, p. 186.
[14] See 'Select Committee to inquire into State and Management of Lighthouses', 172-179.

stress that much of the previous literature ignores, or is unaware of, harbour authority lights. However, as we show they were important.

The 1834 SC report is also valuable in giving information on finances. For all lights under Trinity, it provides data on (i) gross revenues, (ii) collection costs for light dues, (iii) maintenance costs, and (iv) surplus for the years 1820 and 1832. Surplus is defined as gross revenue minus light due collection and maintenance costs.[15] Elsewhere in the report similar financial variables are given for most private lights, although in some cases a particular measure is missing or reported differently. Of particular value the 1834 report details the rates of light dues charged by Trinity and several privates.[16] It also lists the commission rates by port for Trinity and several privates.[17] For harbour authorities, information on revenues is typically missing. This is probably due to their reliance on harbour dues, which bundled several harbour services, beyond lights. Fortunately, maintenance costs were systematically reported for harbour authorities and we can compare these with privates and Trinity.[18]

There was another SC report in 1822 that gives financial information for Trinity lights in 1818, 1819, and 1820.[19] An earlier paper printed by the House of Commons in 1816 also gives annual surpluses for lights under Trinity between 1805 and 1815.[20] These have been digitized and are completely linked to the list of lights in the 1834 Report.

The linking between lights in the 1834 Select committee report and the 1831 Admiralty list is a key step in creating our new dataset. The linking was done by name of light or location. 131 lights in 92 locations are given in the Admiralty list for 'England' and the 'Isle of Man.'

[15] See 1834 Select Committee report, appendix I England, table 86, p. 86.
[16] For Trinity light due rates, see 1834 Select Committee report, appendix I England, table 12, p. 15.
[17] For Trinity commissions, see 1834 Select Committee report, appendix I England, table 12, p. 11.
[18] See 1834 Select Committee report, appendix D, list of private, local, and harbour lights, p. 190.
[19] See 1822 Select Committee report, appendix A, A return of the Gross Sums, p. 340.
[20] Accounts Relating to the Trinity-House of Deptford STrong, 1805-1815, table 1 account of the revenue, pp. 2-3.

We were able to successfully match 126 lights in 90 locations to the lights described in the 1834 report. But our analysis focuses on 120 lights in 86 locations because several Isle of Man lights were managed by the Commission on Northern lights in Scotland, which we do not study in its totality.

Stevenson provides a final source. In this 'encyclopedia' of lights before 1820, this author describes technologies used by individual lights, including the important innovation of parabolic reflectors and Argand lamps. Stevenson also describes which type of organization first built the lighthouse, paid for a major renovation, and if it adopted Argand. Stevenson focuses on 'general coastal lights' and admittedly ignores most harbour authorities. We match lighthouses described in Stevenson to the Admiralty list of 1831 and we match Sevenson's description to our three organizational types created from the 1834 report. The upshot is that we know which organizational type built all private and Trinity lights that were operational in 1831 and when they adopted Argand lamps.

SERVICE COMPARISONS IN 1831

By the early 1830s the organization of England's lighthouse sector was highly fragmented outside of Trinity. In this section, we start by documenting the extent of fragmentation in 1831. Then we turn to A comparison of services across three organization types, including light visibility, use of light vessels, and location.

The fragmentation of industry structure is shown by the total number of lights managed by each organizational type and the number of authorities within each (see table 1). Trinity, a single organization, managed the most at 52 lights. There were several private authorities and most managed a single light. Two was the maximum for privates. There were many harbour

authorities too. The Liverpool Dock Trustees managed the most at 7. The Commissioners for the Isle of Man managed 3. The remaining harbour authorities managed 1 or 2 lights.

Table 1: Number and types of lighthouse organizations in 1831

	(1)	(2)	(3)
Organization type	Number of lights	Num. of unique authorities	Num. of light vessels in (1).
Trinity	52	1	12
Private	17	13	0
Harbour	51	28	1

Lights vessels were a unique technology as been noted. As it turns out, there were 13 light vessels among the 120 lights in E&W. Nearly all vessels were managed by Trinity, indicating its dominance in the application of this technology in 1831. The only other light vessel was managed by Liverpool Dock Trustees, the most important harbour authority. Below we will distinguish performance outcomes by controlling for lightships, as they were quite different.

The amount of visibility provided by lights is a key service measure. The Admiralty lists provide visibility ranges in miles under ideal nighttime conditions for 118 of the 120 lights in 1831. There is a complication however, because in some cases where two leading lights were operating, only one visibility range is given in the List. We address this measurement error in two ways. First, it is assumed that the single reported range applies to one light and the second is ignored, effectively assuming its visibility was zero. Second, the single reported

range is assumed to apply to both lights, effectively doubling the single reported range. The true visibility provided by both lights will lie in between the values in assumption 1 and 2.

Trinity lights provide the most visibility range in total in 1831, regardless of which assumption we use for missing ranges (see panel A, table 2). Trinity lights also provide the most light, even if we exclude light vessels, a technology where Trinity was dominant in 1831. While the importance of Trinity is perhaps not surprising, it is remarkable that harbour authorities collectively provided a significant amount of visibility. They were much more important than the private lights, which are often given prominence in the literature. Recall that harbour authorities had more limited sources of revenues, relying solely on harbour duties. Therefore, one might have expected far less total light provision from harbours. This was not the case.

Table 2: Light visibility range by organization type in 1831

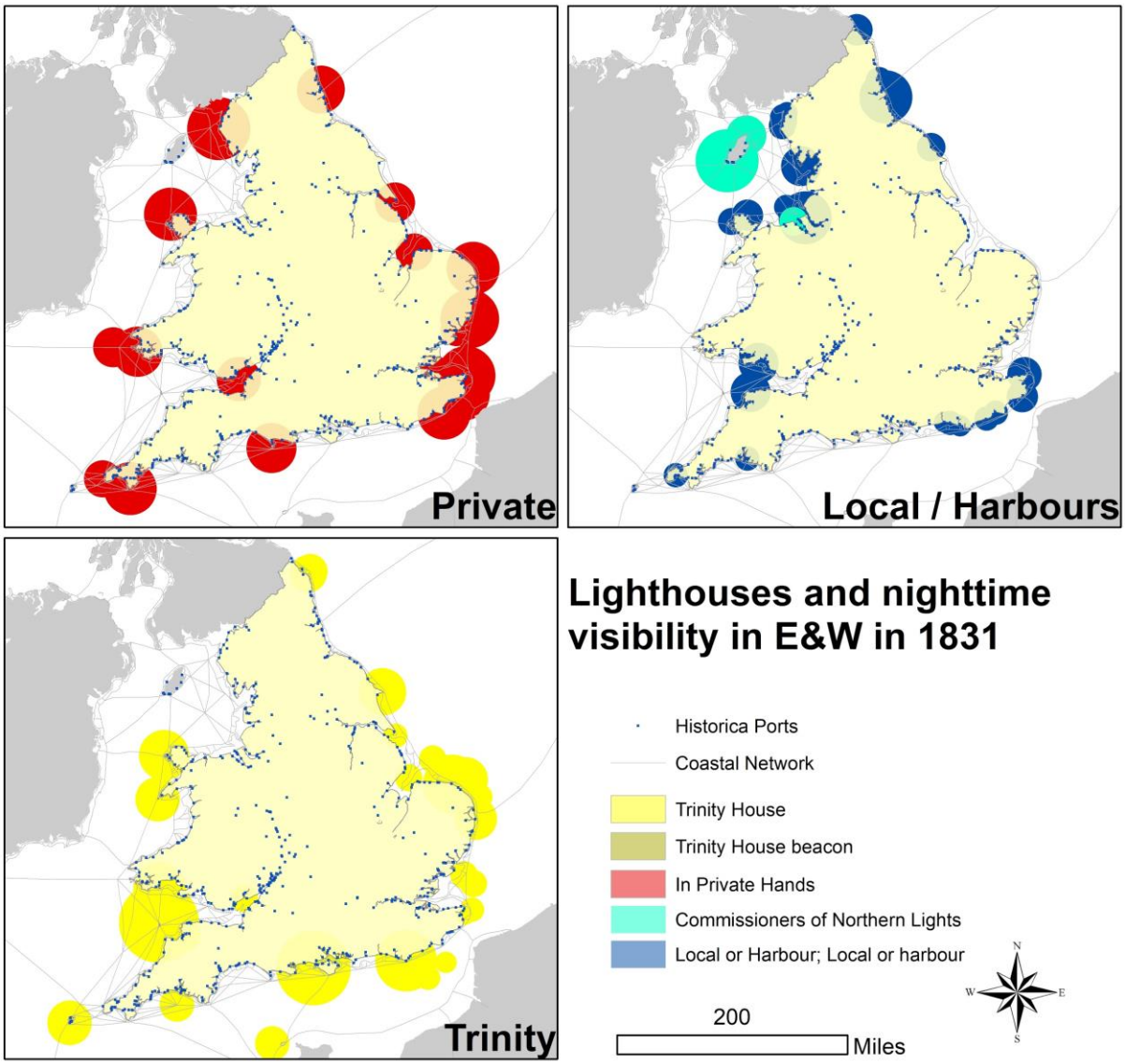
	(1)	(2)	(3)
Panel A	Total visibility range in miles, assumption 1	Total visibility range in miles, assumption 2	Total visibility range in miles, assumption 1, excluding light vessels
Trinity	659	705	540
Private	239	293	239
Harbour	402	519	393
Panel B	Av. visibility range in miles, assumption 1	Av. visibility range in miles, assumption 2	Av. visibility range in miles, assumption 1, excluding light vessels
Trinity	14.6	14.4	16.4

Privates	17.1	17.2	17.1
Harbour	10.6	10.4	10.6

Revealing similarities and differences emerge between organizational types if we shift from aggregate totals to averages (see panel B, table 2). Private lights had the greatest average visibility range considering all light types. But, once light vessels are excluded, Trinity had a similar average visibility range as privates. The reason is that light vessels generally emitted less light, indicating they served a different purpose. Therefore, if we focus on lights fixed to structures (i.e. lighthouses) Trinity and privates have similar average visibility ranges. Harbour authority lights, on the other hand, had a much lower lowest average visibility range. They were under 62% of the average height of privates.

Considering location, Trinity and privates shared more similarities, while harbour authorities again stand out as being different. The following maps show locations and visibility ranges of lighthouses under each organization type in 1831. Trinity and privates are both broadly distributed around the coast and with lights of similar range. With the exception of parts of the east and southern coasts, the visibility ranges of Trinity and private often do not overlap. This suggests Trinity and privates were differentiated spatially, even if providing a similar visibility range. By contrast, harbour authorities are more concentrated and covered less of the coastline. Harbour lights were most common in the northwest near Liverpool, at the entrance to the Bristol channel, the southeast, and near Newcastle in the northwest. With the exception of the Liverpool area, there is some overlap in location between harbours and either Trinity or privates. But this hides certain differences as we will soon see.

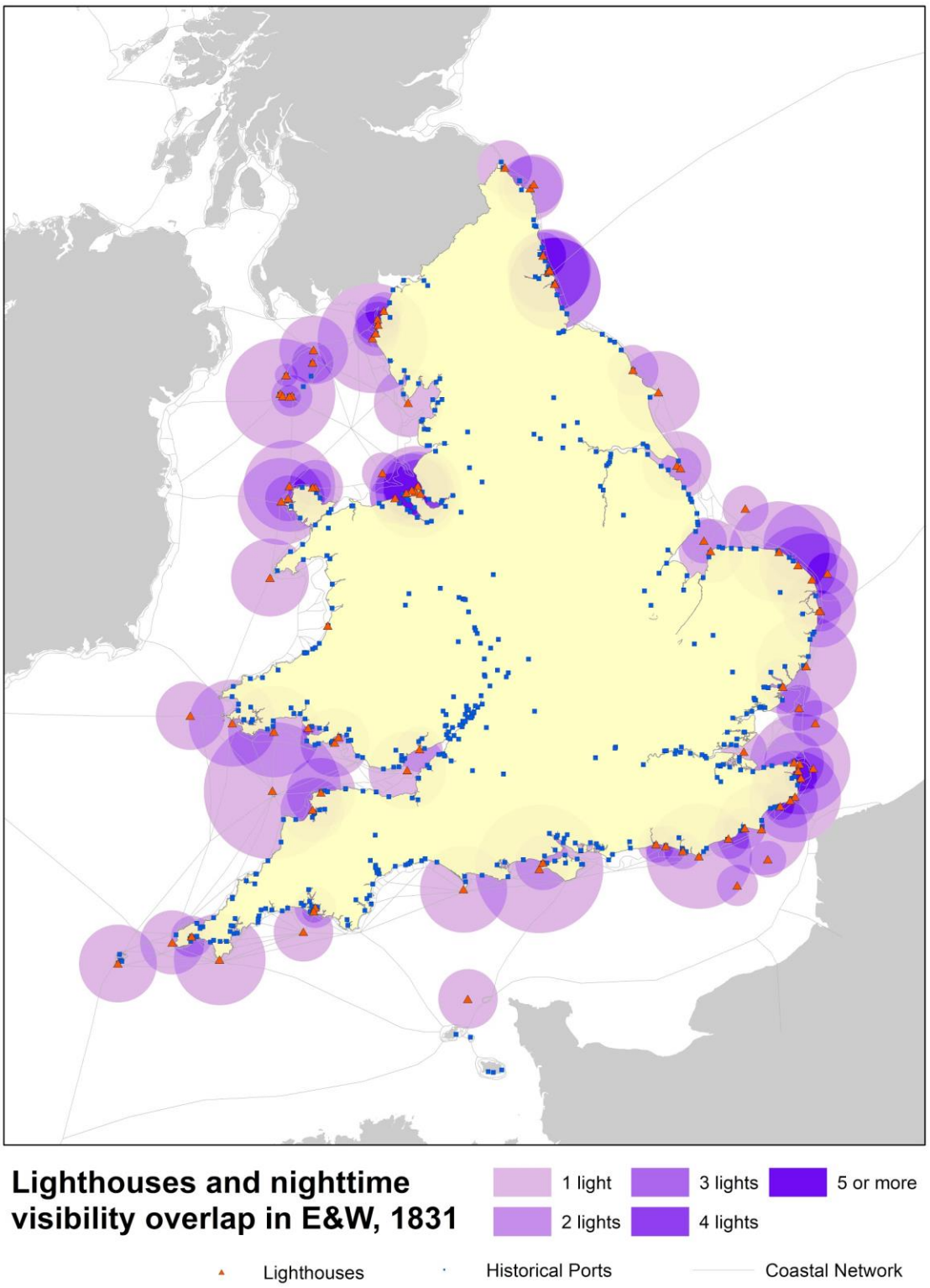
Figure 1: Light visibility ranges by Authority type



It may be surprising that harbour lights covered less of the coast as they had second highest total visibility range according to table 2. The reason is that harbour authorities were more likely to concentrate their lights in particular locations. Figure 2 shows the concentration of all lights was highest near Liverpool and the South and eastearn coast, These are two areas where harbour authorities were common. Figure 2 also shows the distribution of all ports in E&W drawn from the LAN data. This list of ports goes beyond the main customs ports, and includes all documented landing locations. It is notable that some lights that were close to ports and some that were more distant, for example on islands in the sea.

To study location more precisely, we calculate the distance between each light in 1831 and the nearest port. As their name suggests, harbour authorities were generally close to ports. On average, the nearest port was 3.1 km in distance. Note that harbour authority lights could be outside of the port footprint in locations on coastal routes to aid visiting shipping. Privates were farther away from the nearest ports, averaging a distance of 9.3 km. Trinity's average distance to the nearest port was 11.5 km if light vessels are excluded. Both serviced remote coastal zones. Light vessels averaged 19.5 km distance from ports, consistent with their use in locations difficult to build lighthouses.

Figure 2: Concentration of light in 1831



Economic functions naturally differed across England and Wales in 1831, and one might wonder if the service comparisons across organization types noted above are correlated with location and are thus biased. We can confirm that coastal location does not change our

conclusions. We run a regression of the natural log of visibility range or the natural log of distance to the nearest port on two dummy variables for private and harbour with Trinity being the omitted category. The regressions also add a dummy variable for lights being attached to vessels and a quadratic polynomial in lighthouse latitude and longitude. These results show there is no significant difference in visibility range or port distance between Trinity and privates, but harbours had 73% less visibility and 83% lower distance to the nearest ports compared to Trinity. The associated p-values for these differences are both below 0.000.[21] These results are consistent with harbour authorities serving different markets. They are also consistent with Trinity and privates serving similar markets, once we account for the fact that Trinity dominated in light vessels.

FINANCIAL COMPARISONS IN 1831

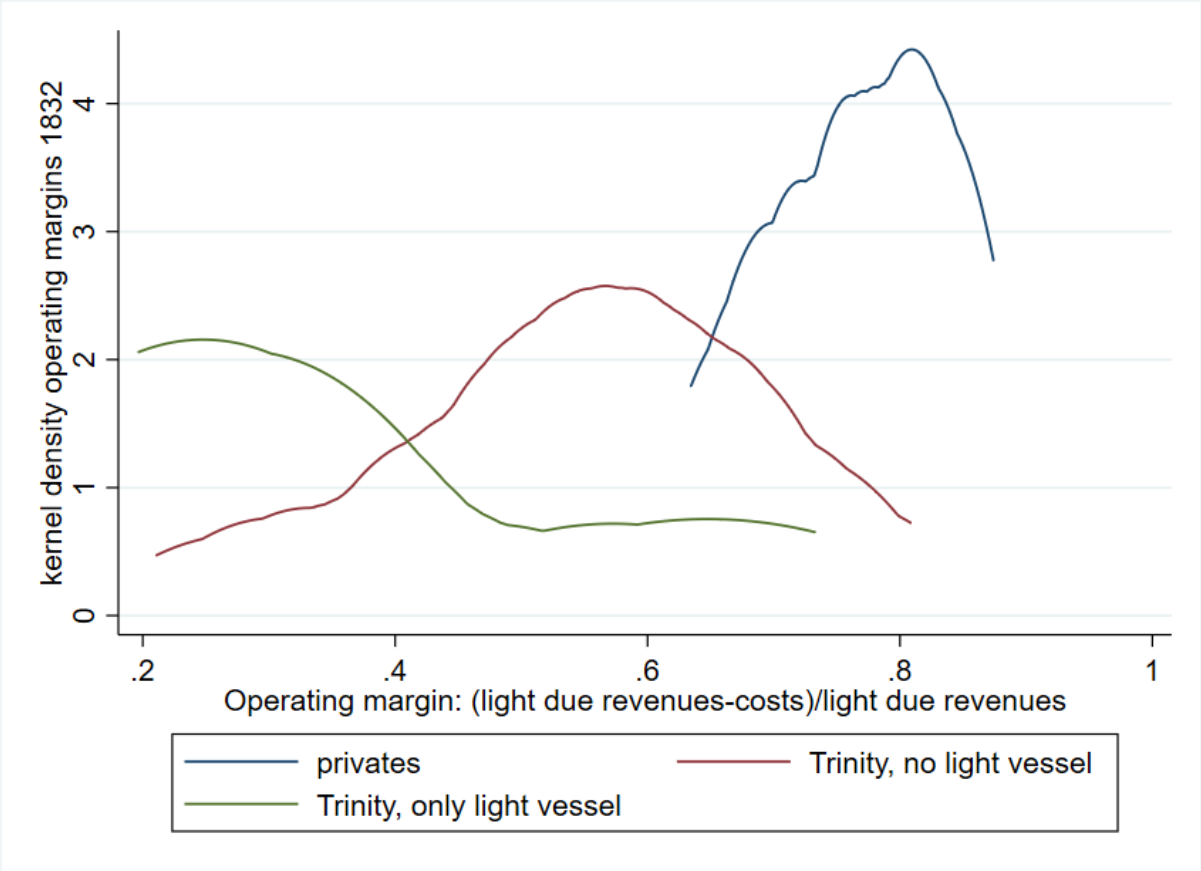
In the literature, privates are thought to have earned much higher surpluses compared to Trinity and that the reforms in 1835 were needed to address the market failure (Taylor and Bertrand). In this section, we start by confirming the higher surpluses earned by private lights in 1832. We also show that the differences in surpluses were so large that it is likely privates were earning larger economic profits. Then we go deeper and examine which aspects of revenues and operating costs were different between Trinity and privates after accounting for the heterogeneity in visibility provided by different lights. Finally, we also compare maintenance costs, the only financial outcome observed for harbour authorities. The latter will be shown to have the lowest maintenance cost per mile of visibility, which is perhaps surprising given that harbour authorities are not often discussed in the literature.

[21] These results are available upon request.

The 1834 report gives details on individual revenues, costs, and surpluses for 32 lights managed by Trinity in 1832. The report gives the same for 13 private groups managing at least one light. From these data, we calculate operating margins, defined as light due revenues minus operating costs divided by light due revenues, where operating costs include light due collection and maintenance costs. Two quick observations are worth noting. First, margins were negative in only one case. That means nearly all Trinity and private lights earned a positive revenue surplus in 1832. Second, lighthouses had to generate a positive surplus if they were going to cover their fixed capital cost, something that was also recognized by the SC committees in 1822 and 1834. What is unclear is whether a given surplus was well beyond what was needed to cover the fixed costs. The size of the operating margin addresses this issue to some degree, but it is not perfect since it does not address heterogeneity in capital costs, which is something we don't observe. We study the differences in operating margins, because they place a bound on how different capital costs would have needed to be for privates to have earned the same economic profit as Trinity.

Figure 4 plots kernel densities for the operating margin by organization type and light vessel technology. From the density plots, it is evident that Trinity lights generally had lower operating margins than private lights. It is notable that light vessels had much lower operating margins, around 0.36 on average. When all light vessels are omitted, Trinity's margins were higher, around 0.474 on average. But even so, Trinity's margins are much lower than privates, which averaged 0.768. A similar conclusion is supported by a regression of log operating margins on a dummy for Trinity lights and controlling for a light vessel status and quadratic polynomial in light latitude and longitude. The estimates imply Trinity margins were 58.7% larger on average, which is statistically significant with a p-value of 0.001.

Figure 4: Operating margins in 1832: Kernel density plots for Trinity and private lights

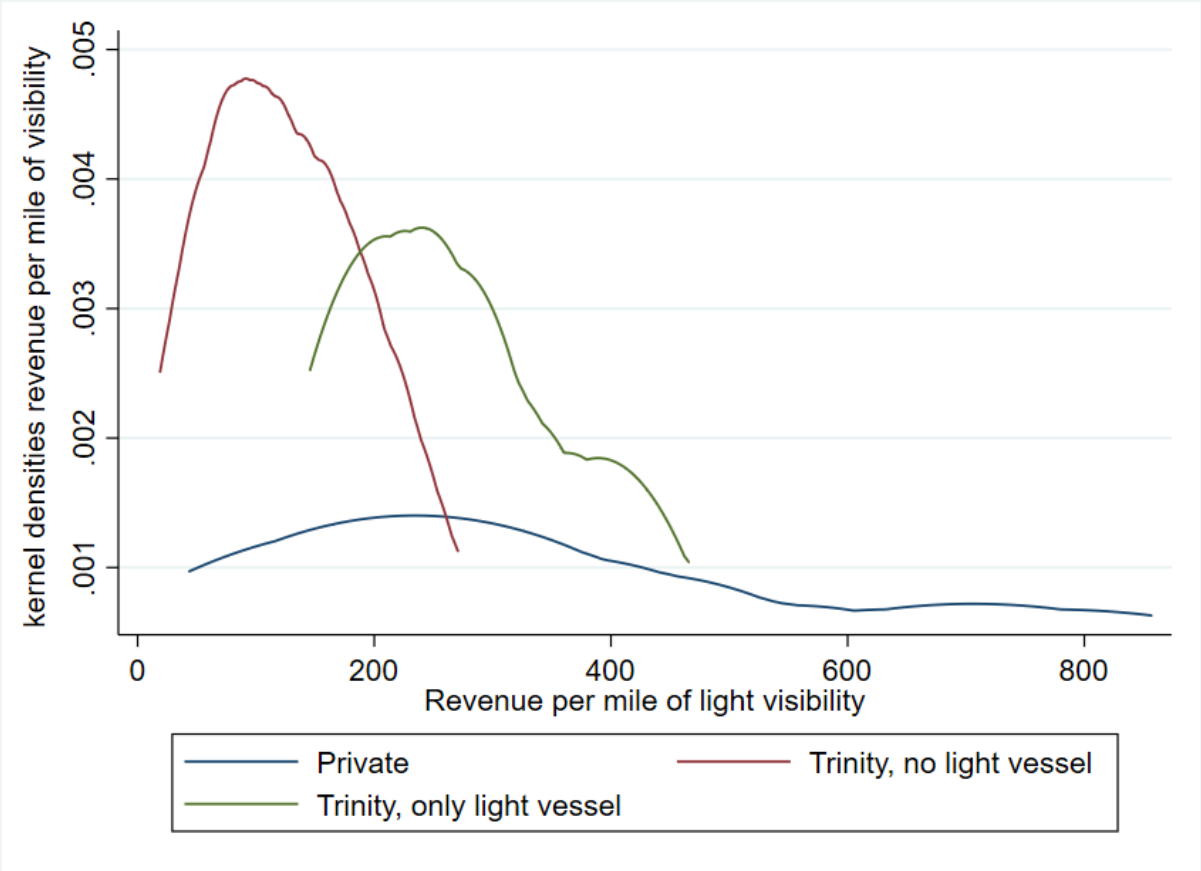


It is possible that privates had higher capital costs and thus needed to have higher operating margins to earn competitive profits. But going against that argument we have already seen that Trinity and privates provided similar visibility ranges so it is not clear their lights would have cost so much more to build. But even if we allow for some heterogeneity in private's capital costs, they would need to have been much higher to explain the 58.7% difference in operating margins. We think significantly larger capital costs for privates to be unlikely, and thus higher margins for privates really do reflect higher economic profits. This conclusion is also supported by the SCs in 1822 and 1834. For example, the 1822 SC heavily criticized six private lights (Flatholm, Smalls, Fern, Longships, Mumbles, Burnham). Strong 'disapprobation' was recorded because light duties were being misappropriated for 'private emolument, which was not in keeping with the public spirit of the light dues system.

There were two significant differences between Trinity and privates, which help in explaining their different operating margins. Privates had higher revenues (i) and they had higher light due collection costs (ii). The latter was offset to some degree by similar maintenance costs, which were the larger of the two components of operating costs. Therefore, higher collection costs still coincided with higher margins for privates.

To illustrate further, figure 5 plots kernel densities for revenue per mile of visibility for privates and Trinity in 1831. Revenues are divided by visibility range in order to partly account for the different qualities of service across lights. The density plots show that Trinity had lower revenues per visibility mile than privates, if one omits light vessels. This conclusion is supported by a regression of log revenues per mile on the same control variables as before. Trinity revenues per mile are estimated to be 205% larger after accounting for latitude and longitude, a difference that is statistically significant with a p-value of 0.001. The differences between Trinity and private are smaller when light vessels are not controlled for, but again light vessels were a different technology and apparently required higher revenues to operate.

Figure 5: Revenues per mile of visibility in 1832: Kernel density plots for Trinity and private lights



Light revenues were largely determined by light due rates and by the volume of tonnage being charged. Of special interest is the rate since it was determined by the organizations in charge. We have digitized information on the levels of light due rates for British vessels in pence per ton mile. The data is not as comprehensive across lights (n=31) due to missing information, but it does show that Trinity's average light due rate was just over half that of privates when lightships are excluded (0.38 pence per ton vs. 0.71 pence per ton). The difference is slightly smaller when lightships are included (0.39 vs. 0.71). Thus, a lower light due rate rate was ultimately a key factor in Trinity's lower operating margins compared to privates. In the next section, we will explore the sources of lower rates further.

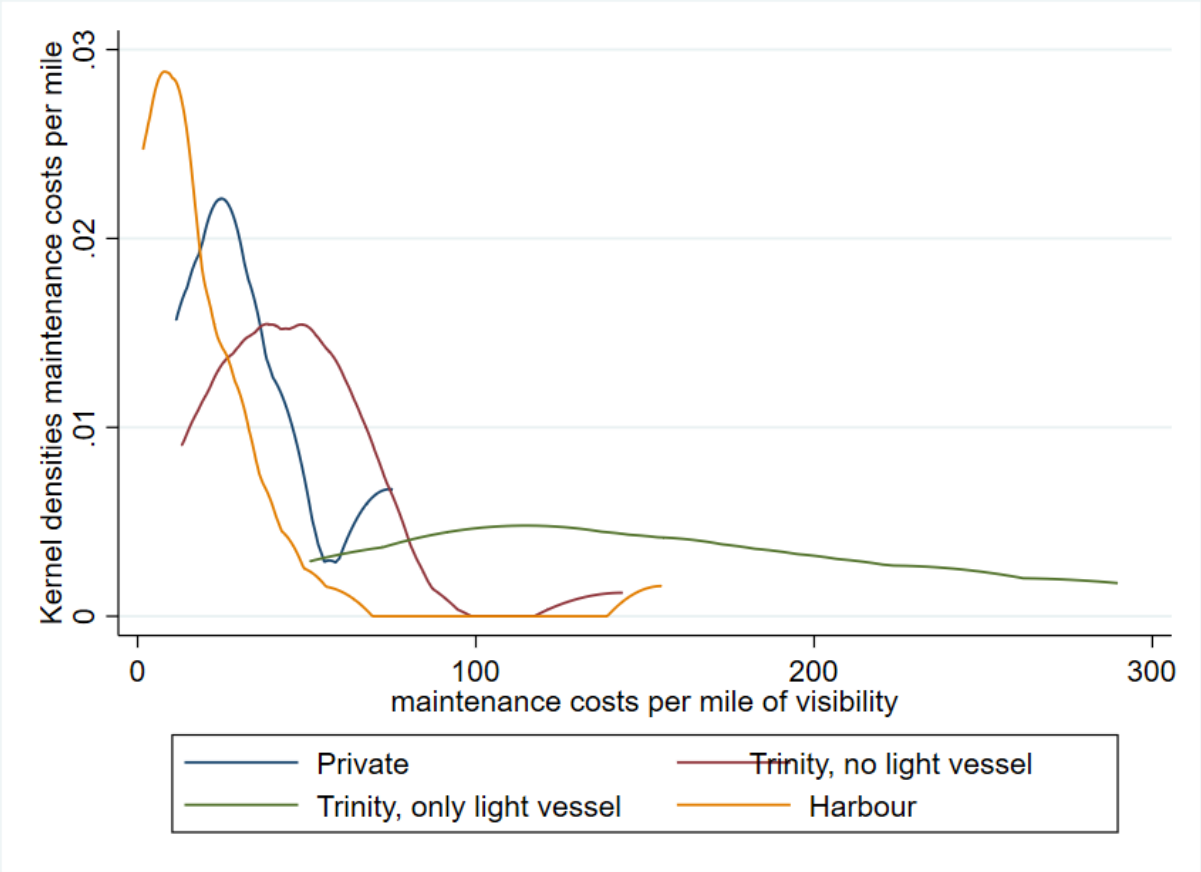
Lower light due collections costs were another financial advantage for Trinity over privates. We have this information for 11 private groups managing at least 1 light and 32 lights managed by Trinity. To make comparisons, we again divide by the visibility range to address

the different qualities of service. The calculations show that private light due collection costs per mile were 159% higher on average. After controlling for light vessels and location in a regression, private light due collection costs are estimated to have been 250% higher.

The sources also indicate that Trinity paid lower commission rates to its agents. The commission rates charged in each port and by different lights have been digitized and linked with our comprehensive list of ports drawn from LAN (the match rate is 100%). The data reveal that Trinity's average commission rate was 8.05% and for all privates, the average commission rate was 17.5%. Interestingly, Trinity and privates often had agents in different ports, so some of the differences in commission rates may be due to port-level heterogeneity. To address this we compare rates in ports where Trinity and privates both collected commissions. The data show Trinity commission rates were lower on average.

The last financial outcome of interest concerns maintenance costs. They are available for 11 private authorities managing at least 1 light and individually for 32 lights managed by Trinity. Maintenance costs are available for 29 harbour lights, where six lights come under Liverpool commission and three under the Isle of Man commission. As above, maintenance costs are divided by visibility to account for differences in service quality across lights. Figure 6 shows that harbour authorities generally had lower maintenance costs per mile compared to Trinity, regardless of whether light vessels are distinguished. Harbours also have lower maintenance costs relative to privates, although the differences are smaller. The differences between harbours and Trinity and privates hold in a regression controlling for light vessels and the flexible polynomial in latitude and longitude. They also hold if we control for multiple lights managed by Liverpool or Isle of Man. In short, the estimates reveal that harbour maintenance costs per mile of visibility were 72% lower than Trinity.

Figure 6: Maintenance costs per mile of visibility in 1832: Kernel density plots for Trinity, private, and harbour lights



The differences observed in the data suggest harbour authorities were the low cost providers of light services, if one ignores the cost of collecting dues or duties. Why would this be? Harbours perhaps faced lower wages since they drew upon a large labor market near ports. Being near ports, might also imply that harbours had lower fuel costs as well since oil and coal were often stockpiled there. However, when we flexibly control for distance to ports, the cost difference for harbours remains large, and so it is not simply being near ports. One remaining explanation is that harbour authorities had lower revenues and thus to cover costs they were pressured to be more cost efficient.

GOVERNMENT POLICY AND TRINITY'S RATES

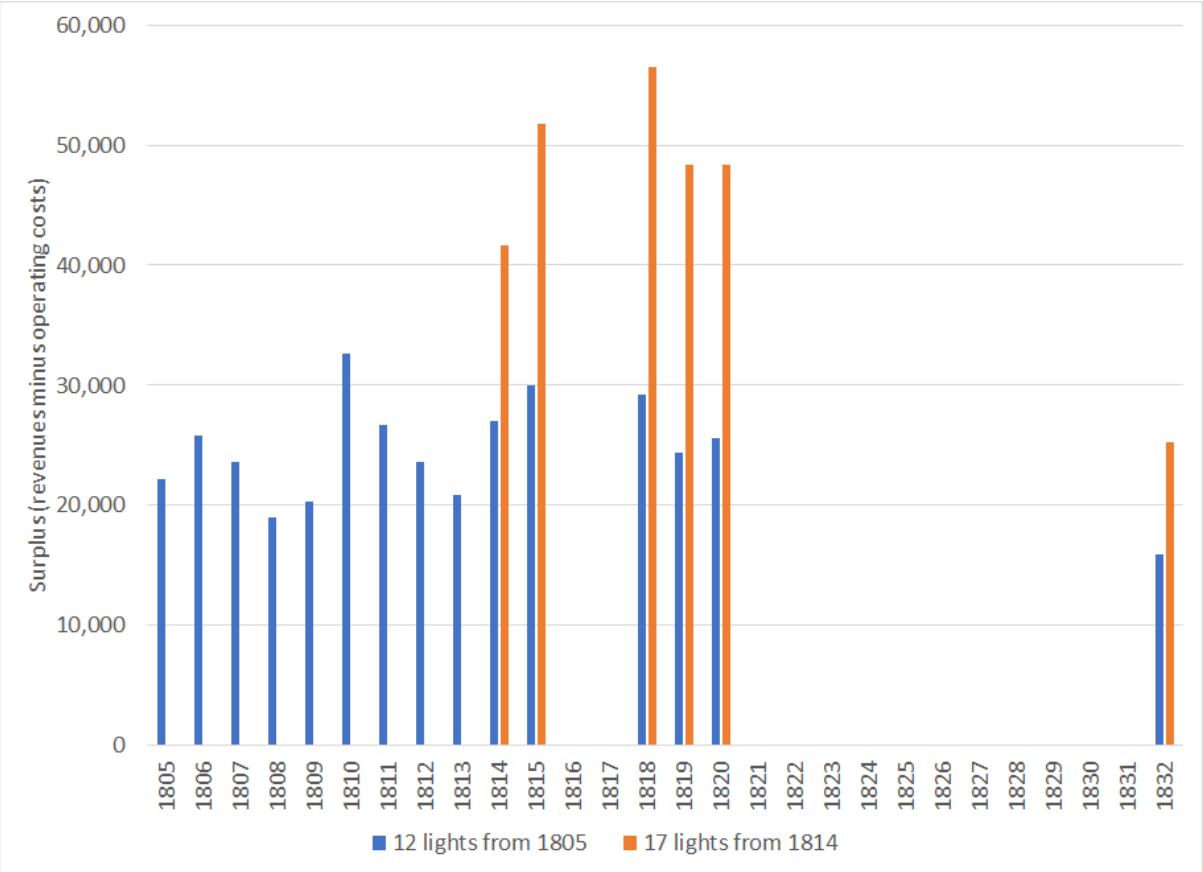
Trinity's low operating margins and light due rates in 1831 were a key factor in their efficiency advantage over privates. When did these two advantages come about? In this section, we argue that key pricing changes occurred in the 1820s and they were prompted by government intervention, and specifically, pressure on Trinity. The selection committee report from 1822 gives financial data like above for all 20 lights operated by Trinity in 1818, 1819, and 1820. The average operating margin was 0.545. For these same lights, the average operating margin was 0.481 in 1832, indicating a decline in margins over time. Moreover, Trinity lights with the highest revenues in 1820 also tended to have the highest margins. The top five out of twenty lights in terms of gross revenues had an average margin of 0.658 from 1818 to 1820. The average operating margin for those same lights in 1832 was 0.425, indicating an even greater decline.

Higher light due rates were one reason for higher operating margins in 1820. The selection committee report from 1822 reports that for the 20 Trinity lights, the average light duty rate charged to British vessels was 0.534 pence per ton in 1818 to 1820.The average rate for the same 20 lights was 0.372 in 1832, indicating a significant decline over time. For the top 5 highest grossing lights, the average rate fell from 0.8 to 0.3 pence per ton from 1820 to 1832.

The high rates and operating margins for Trinity's lights caught the attention of government officials. In 1816, the House of Commons published an account of the 'profits of lighthouses,' distinguishing each from the total from 1805 to 1815. Upon inspection, the profits listed are what later reports would call the surpluses, or gross revenues minus operating costs. We have linked surpluses for Trinity lights in the 1816 printed paper to the 1822 and 1834 select committee reports In figure 7, we chart the total surplus for 12 Trinity lights from 1805 to 1832. Five lights were added to this group to chart surpluses for 17 Trinity lights from 1814 to 1832. The 12 Trinity lights had the highest surpluses from 1810 to 1820, and the end of the War in 1815 seems to have put them at a consistently higher level.

The 17 lights may have also had higher surpluses after the War, although there are fewer observations to confirm that. Overall, the trends give some hints as to why governments began to investigate Trinity's affairs in the late 1810s and eventually intervene in this market. Note that the literature has highlighted government intervention in the 1830s and in the other private providers, so this is all the more enlightening as it shows that trinity was not beyond reproach when it came to its finances.

Figure 7: Financial surpluses from Trinity lights, 1805 to 1832



The text of the 1822 SC report gives a more direct insight into the government's concerns. The 1822 select committee report states at its outset that commerce and shipping should be free of taxation and regulation as far as possible, following contemporary influential laissez-faire economic philosophy. Shippers were reported as having grown especially unhappy about the mixed and decentralised system of lighthouse provision, and especially the way

light dues were calculated and collected at ports. 400 pages of evidence were gathered from witnesses to work out what was going on in this complex system of mixed ownership.

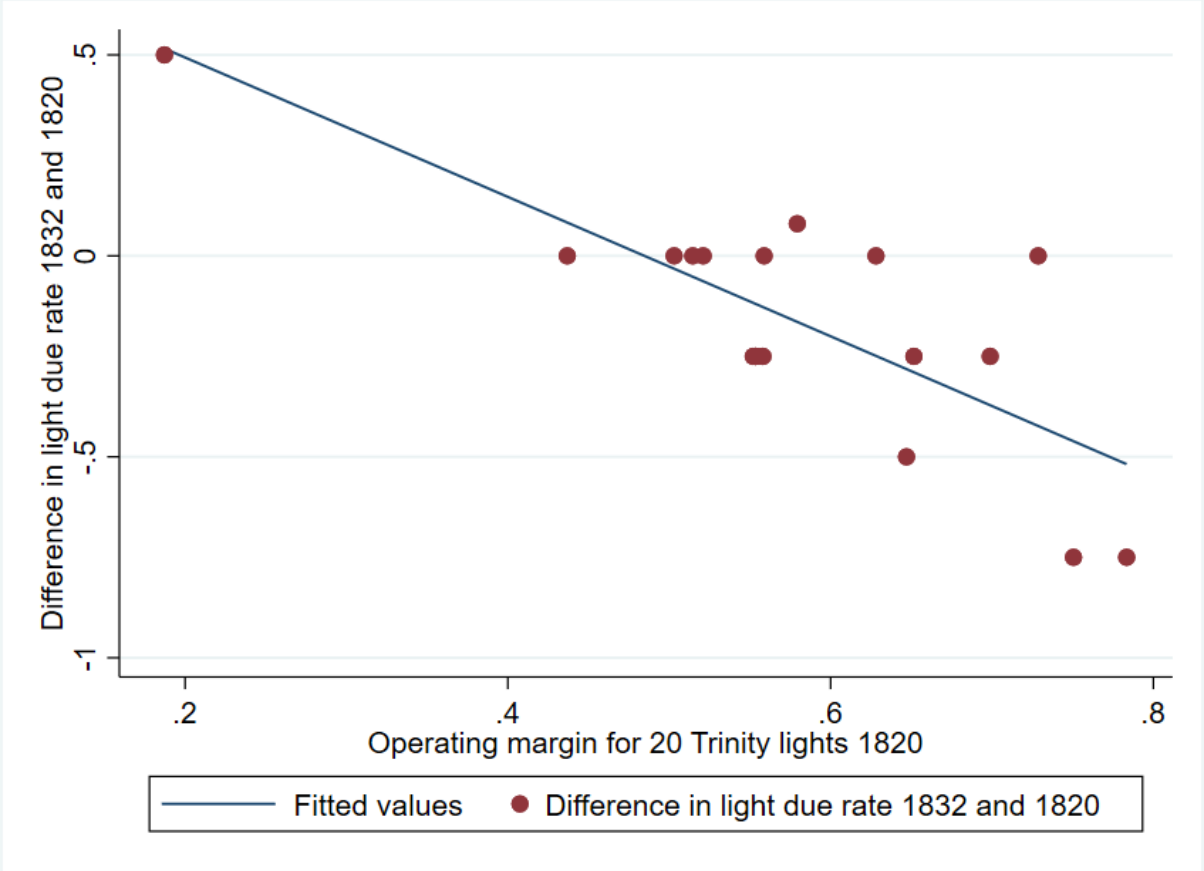
Trinity attracted the strong ‘disapprobation’ of the 1822 SC because of its high charges - mixed but primarily from its light duties - encompassing duties for a bundle of maritime services it charged tolls for, including: Trinity dues, ballastage, pilotage, and the light duties. Surpluses from all these duties should by law have been spent on charitable purposes or on management costs, not taken as profit, according to the SC. Light duties, by contrast, were stated as intended specifically to pay for building and upkeep of lights.

The SC noted how Trinity’s income varied by light, but that in the main, its duties had grown out of proportion to the amount required to manage each lighthouse and build new ones. They noted the problem of growing shipping tonnage that had raised fixed rates of income far beyond this originally defined purpose, and how this was particularly problematic for older lights, whose rates were set at a time when fewer ships paid light duties. Importantly, the SC recommended that rates should be reduced. And the committee recommended that Trinity end its spending on its pensions to provide savings to enable reduction in its tolls.

Some small proportion of Trinity’s surplus was spent on pensions to needy mariners and their dependents, which was used to justify its income. However, the SC noted how ‘impartial’ the distribution of pensions were said to be by witnesses who provided it with evidence. High internal payments to Trinity management were also identified, yet found to be justified in the round. Trinity’s commission payments for the collection of the light duty by local customs were heavily criticised. In London, it was noted with dissatisfaction how in 1818, £5200 was paid to Trinity’s agent in the capital, with £15,000 paid to agents in the outports (outside London). The agency fees were described as being unnecessary, excessive, and burdensome to the public, and contributing to unwelcome high levels of light duties (1822, p10).

The recommendations of the Select Committee seem to have led to a change in Trinity's internal policies in the 1820s. As noted above, Trinity's average light due rates fell from 1820 to 1832. Upon closer inspection, we find some lights had their light dues maintained between 1820 and 1832, and two even had them increased. We don't have direct evidence on why decisions differed across lights, but it appears related to high operating margins in 1820. Figure 8 graph plots the operating margin for 20 lights in 1820 against the difference in the light due rate between 1832 and 1820. There is a clear negative relationship, suggesting Trinity responded to the government's criticism by reducing rates on lights with the highest margins, and maintained dues on lights that had moderate margins. In the one case, rates were substantially increased; this light had the lowest operating margin in 1820 around 0.2.

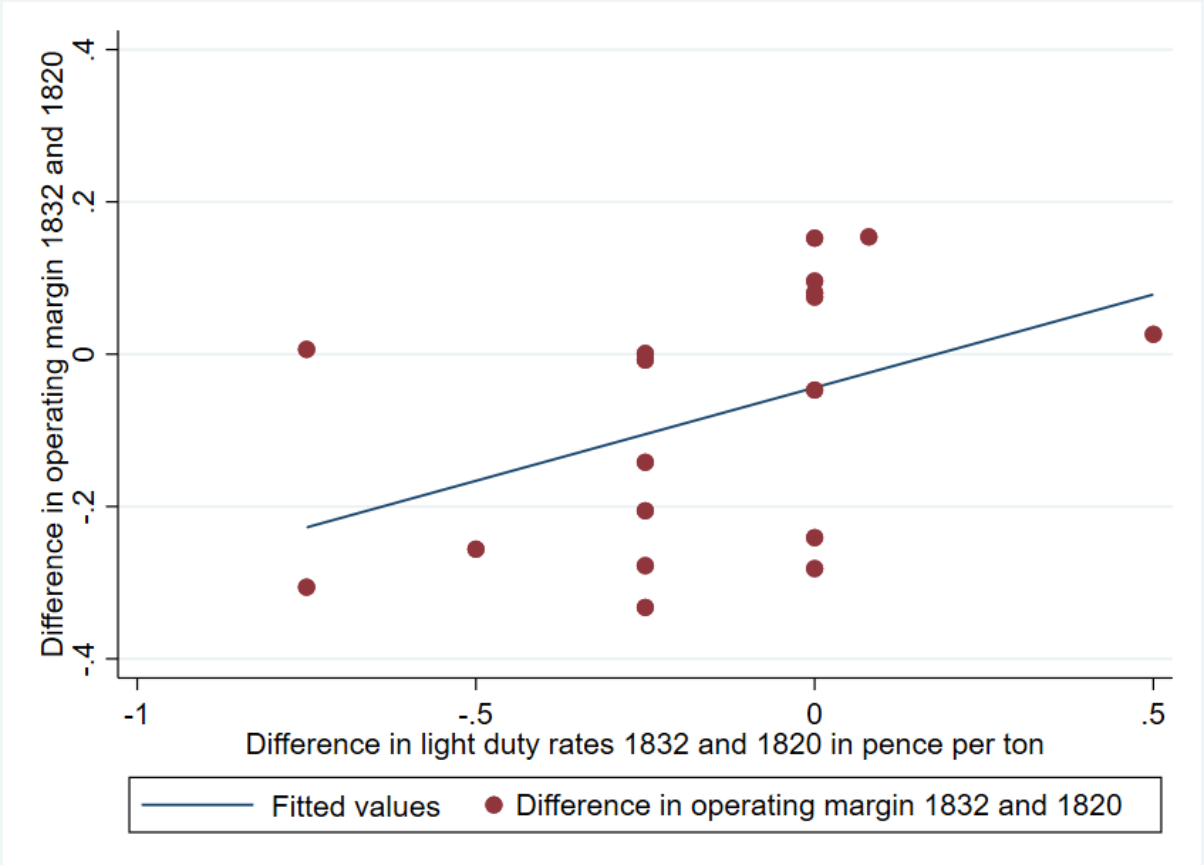
Figure 8: The relationship between operating margins and light due rate changes for 20 Trinity lights from 1820 to 1832



What was the impact of the changing rates on operating margins after 1820? Figure 9 shows that lights which had their rates decrease the most between 1820 and 1832 generally had greater declines in operating margins between 1820 and 1832. The statistical relationship is noisy, but on the whole the correlation suggests Trinity achieved lower operating margins by 1832 in part because of a policy change designed to lower its light dues.

The progress made by Trinity in reducing its light dues was noted by later governments. The 1834 SC report recommended more centralisation of ownership in Trinity. Private lights were seen as too costly to shipping and that these lights should also be put into Trinity's hands. Greater centralization was achieved by the mid 1830s after decades of earlier fragmentation.

Figure 9: The relationship between light due rate changes and operating margin changes for 20 Trinity lights from 1820 to 1832



INVESTMENT AND TECHNOLOGY ADOPTION

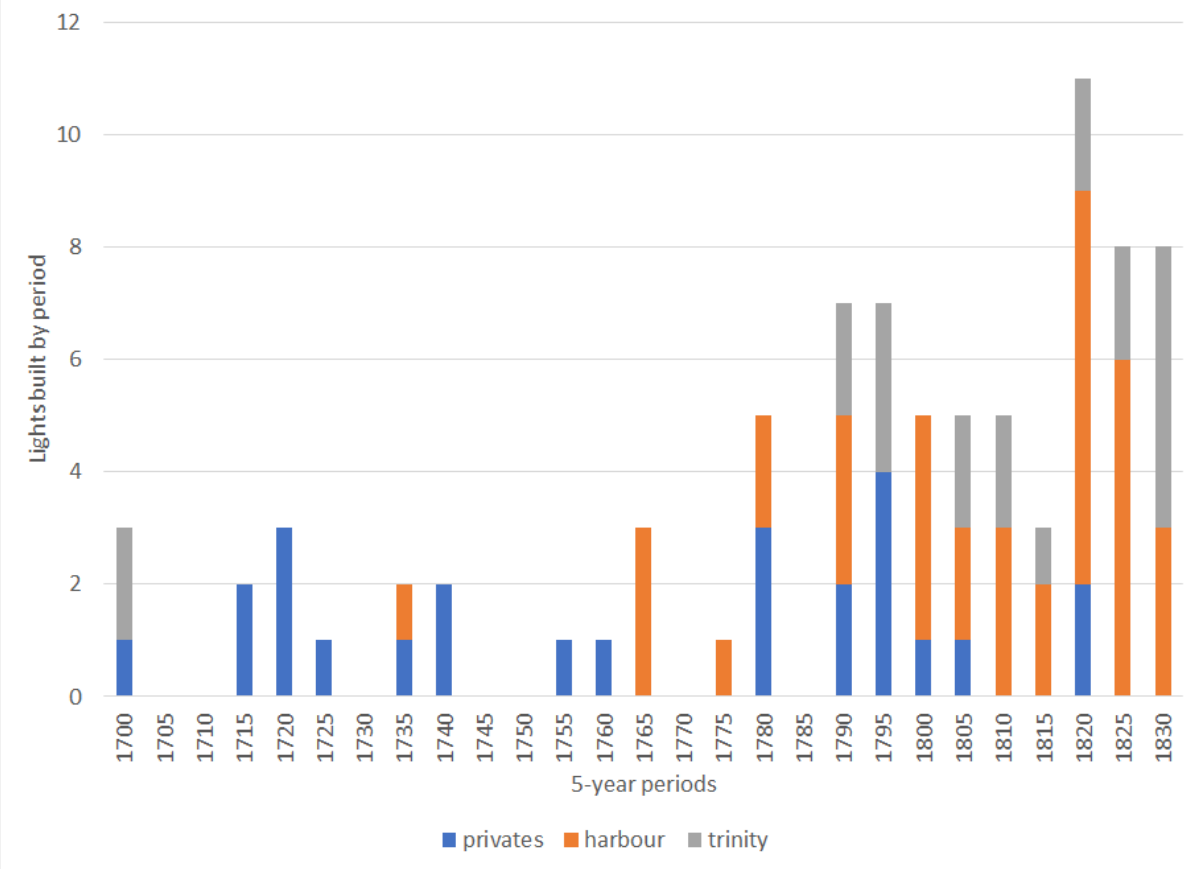
Thus far we have compared organizations using concepts of static efficiency, namely whether light dues exceeded the amount needed to cover the cost of capital and maintenance. But dynamic efficiency requires one to consider investment. This raises questions about what role Trinity and privates played in building and financing the lights that operated in 1831. Lights were challenging investment projects. At a cost of 5,000 to 10,000 they were expensive to build compared to most capital goods in the economy. Such amounts go well beyond the cost of new machinery in cotton textile firms around the same time (Allen 2009).[22] Perhaps a more difficult challenge was collecting light dues from ships. It was possible that upon building a lighthouse, an organization would be unable to collect enough revenues to pay for the capital and maintenance costs. Changing technology was another consideration. The introduction of Argand lamps in the 1780s increased the potential visibility of lights, but the capital and maintenance costs of lights also increased. Organizations had to consider whether they could collect enough revenues to pay for the installation of Argand lamps.

In this section, we evaluate to what degree Trinity or privates led in the building of lights and in the adoption of new technologies, especially Argand lamps. The first striking fact is that among the 50 lights managed by Trinity in 1832, half were not originally built and financed by Trinity. The 50 lights managed by Trinity were matched with detailed histories provided by Stevenson. From this we learn that 19 were built and financed by private investors and later taken over by Trinity as their leases expired. Moreover, 6 light vessels were built and financed by the Admiralty and then transferred to Trinity.

[22] That said, the capital and maintenance costs of lights were comparable to many ships involved in the coastal trade and were not especially large in transport. Canals for example, often required more than 100,000 in investment (Ward 1979).

Using data from the Admiralty list and the 1834 SC report we also date when lights were built in all locations with lights in 1831. Lights at a location in 1831 were sometimes rebuilt, so here the date of building applies to the 1831 structure, not necessarily the original light. The yearly data is divided into 5-year periods starting in 1700-1704 and continuing up to 1825-1829 and we count the number of lights built at locations by Trinity, privates, and harbour authorities. The time series are shown in figure 10. Trinity shown in grey built few lights during most of the eighteenth century. Its role in building was only prominent in the nineteenth century. Privates in blue built more lights in the eighteenth century, but less in the nineteenth. Harbour authorities in orange built from the 1760s, but they really picked up in the nineteenth century.

Figure 10: Series on lighthouses built by different organizational types



Why was Trinity reluctant to build lights for most of the eighteenth century? Stevenson points out that Trinity did not respond to several proposals for new lighthouses, especially in the seventeenth and early eighteenth centuries. Petition for new lights regularly came from shippers, especially in locations which suffered serious wrecks. Trinity often argued that lighthouses were not really needed or they were not practical in many locations. In one case, there is a mention that better lights undermined the value of pilotage, which was Trinity's monopoly.

Private groups on the other hand seemed willing to take risks, and some were successful in getting the Crown to authorize their projects over Trinity's objections. Crucially private groups were given the right to charge light dues, which allowed them the ability to force passing ships to pay. Many of the early lights in England were built by private operators, often under unfavorable financial conditions. Eventually Trinity seems to have decided to work with rather than against them. The system that came about in the early eighteenth century, was one in which Trinity obtained a patent authorizing the collection of light dues and then leased the rights to private parties, who would then build the lights, collect the dues, and pay Trinity a rent. Eddystone light provided an example of this system.

Stevenson remarks that Trinity's role began to change after the invention of Argand lamps in the 1780s. Along with parabolic reflectors, Argand lamps increased the usefulness of lights, especially by extending their visibility. They allowed more passing ships to benefit and enhanced the value of using light dues. While privates used light dues too, Trinity's scale advantages would have favored a single organization in this period and perhaps for that underlying reason it decided to take on a greater role in building.

The data on the timing of building provides more support that Argand stimulated Trinity and led them to replace private operators. Argand's lamp was patented in England in 1784, and a

London firm manufactured the lamp from that date. Thus the year 1785 is a good demarcation point for the beginning of the Argand period. Our data on the building dates of lights shows that between 1700 and 1785 Trinity did not build a single light at any location. Over that same period lights were built at 15 locations by private persons. After 1785 Trinity took the lead, changing its long history of an activity relative to private providers. Trinity built lights at 30 locations from 1785 to 1830, while privates built lights at 10 locations. Even more telling is that Trinity built its first eighteenth century lighthouse in 1786 just two years after the patent. Trinity built two lightships in 1788 and 1791 and another lighthouse in 1791. All of them were equipped with Argand lamps.

The shift in Trinity's leadership around 1785 can be confirmed statistically. We run a regression of new light counts in each 5-year period by Trinity and privates. The explanatory variables are a Trinity dummy variable, a post 1785 dummy, and an interaction between a post 1785 dummy and Trinity dummy. The results show that the interaction variable is positive and significant, implying Trinity built more lights after 1785 than privates.

While Trinity was quick to adopt Argand lamps after 1784, it should be noted that private groups did the same. Lighthouses were built at seven different locations by private groups between 1790 and 1798 and all appear to have been equipped with Argands. Thus it appears that Trinity was not the sole leader in adopting Argand lamps. Privates deserve credit for advancing the scale and quality of lighting services by adopting technologies.

The driving forces behind harbour authorities building lights is not as well documented in the literature. Like Trinity, their role in building increased after 1785, yet this doesn't relate to Argand technology, although other and presumably cheaper non-patented lamps were used (Stevenson). Harbour authorities constructed lights at 19 locations between 1785 and 1830, which is almost three times their building before 1785. Harbour authorities were not as likely

to adopt Argand lamps based on the descriptions of their technologies in the 1834 SC report. The growing demand for lighting services in harbours was perhaps a more important factor. Our data show a more prominent increase in harbour authority light building after 1815. We know from various sources that there was a large growth in shipping volumes after 1815. Harbour authorities were probably most sensitive to revenues from shipping volumes and broader demand for harbour facilities since they bundled these services.

CONCLUSION

Complex policy challenges in the infrastructure sector are seen in a fresh light when studying one of the most celebrated historical examples: lighthouses in England. We show that in 1832, the largest actor in the market, Trinity, provided services more efficiently than numerous private operators. Trinity's advantages partly came from lower revenue collection costs. Moreover, Trinity was pressured into charging lower prices, which proved illuminating to policy makers. While much of analysis shows the advantages of Trinity, we document that privates built many more lighthouses. Trinity became active only after a technological shock which increased the utility of lights. Finally, our analysis sheds light on a largely ignored provider: harbour authorities. They relied on alternative pricing and bundling strategies, achieved low operating costs, and served in markets largely ignored by Trinity and privates.

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