*The Diffusion of Newcomen Engines, 1706-73: A Reassessment**

By Harry Kitsikopoulos

Abstract

The present paper attempts to quantify the diffusion of Newcomen engines in the British economy prior to the commercial application of the first Watt engine. It begins by pointing out omissions and discrepancies between the original Kanefsky database and the secondary literature leading to a number of revisions of the former. The diffusion path is subsequently drawn in terms of adopted horsepower and adjusted for the proportion of the latter being in use throughout the period. This methodology differs from previous studies which quantify diffusion based on the number of steam engines and do not take into account those falling out of use. The results are presented in terms of aggregate, sectoral, and regional patterns of diffusion. Finally, following a long held methodology of the literature on technological diffusion, the paper weighs the number of engines installed by the end of the period in relation to the potential range of adopters. In the end, this method generates a less celebratory assessment regarding the pace of diffusion of Newcomen engines.

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The prevailing view among economic historians is that steam power, as a general purpose technology, played a pivotal role in shaping the *long-run* trajectory of the British Industrial Revolution although its role was fairly limited in boosting productivity and aggregate economic growth until well into the nineteenth century. To appreciate the temporal impact of steam power, one needs to focus on its diffusion process by calibrating the analysis to take into account regional and sectoral patterns of diffusion since the dynamic sectors of the British Industrial Revolution tended to exhibit a strong regional concentration.[1]

The first comprehensive effort to quantify the number of steam engines erected during the eighteenth century, by Harris, concluded that their diffusion exhibited a "remarkably dispersed geographical distribution" in light of the fact they were very expensive at the time of their appearance. This assessment carried weight among other experts such as Allen who also characterized their rate of adoption as "nothing short of remarkable" when contrasted with other technological innovations of the period. This impression became even stronger when Kanefsky and Robey revised the figure of the total number of engines adopted during the eighteenth century nearly doubling Harris' figure leading experts like Flinn to point out the "remarkably rapid" spread of steam power. The choice of superlatives is virtually identical in the latest assessment by Nuvolari, Verspagen and von Tunzelmann (henceforward NVT): "the spread of steam power technology appears to have been, from the very outset, remarkably wide."[2]

The present paper focuses exclusively on the diffusion of Newcomen engines from their first commercial application (1706) to the year prior to the first commercial application of the Watt engine (1773). The author does not wish to argue with the previous assessments when the *absolute* number of adopted steam engines is taken into account; that was indeed remarkable by any standards. But it does wish to argue that the latest and most sophisticated attempt by NVT adopts a methodology which obscures the *relative* success rate of the diffusion process.

The NVT study counts the number of years it took to get to the midpoint of the diffusion process and the number of years needed to get from ten to ninety percent of the "saturation level," the latter being defined as "the number of steam engines that will be installed at the end of the diffusion process" the

[1] Nuvolari et. al., "Early Diffusion," pp. 292-3.
[2] Ibid., p. 296. See also Harris, "The employment of steam power," p. 138; Allen, "The introduction of the Newcomen engine," p. 170; Kanefsky and Robey, "Steam engines," p. 185; Flinn, *British coal industry,* p. 119.

authors examine, i.e., 1800.[3] In other words, the extent of diffusion is taken as given and the question becomes one of how fast is the rate which culminates to that extent. I wish to address a different question: what was the extent of the gap by the end of the period between the actual adoption rate and the ideal one assuming the Newcomen engine was utilized by every potential user. Phrasing the question this way is in sync with a methodology prevalent in the literature of technological diffusion and it is more illuminating in appreciating the delay of steam power in having a radical impact on the rates of productivity and aggregate economic growth. The ideal rate of adoption is shaped by two types of factors. First, the extent to which the engine could prove suitable to production needs across different sectors given its technical features. Once such suitability was ensured, economic considerations such as its purchase price and operating cost, particularly in relation to other energy sources and taking into account the size of firms, and constraints on the supply side such as the availability of engineering skills were of paramount importance. The present paper will consider only the former factor due to space limitations.

The paper is divided into two main sections. The first one will point out several discrepancies that were discovered between the Kanefsky database and the secondary literature in terms of the precise number of steam engines installed, the year of their erection, and their technical characteristics; these discrepancies necessitated a fair amount of revisions.[4] It will discuss different methodologies in deriving and utilizing the data used to draw the diffusion trajectory and it will provide estimates regarding the horsepower installed over time in contrast to the NVT method of counting the number of steam engines. The section concludes by summarizing the statistics, particularly from an aggregate, sectoral, and regional perspective. The second section weighs the rate of diffusion relative to the potential range of adoption by focusing on two sectors for which this assessment can be done, mining and the use of steam engines in the operation of blast furnaces.

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[3] Nuvolari et. al., “Early Diffusion,” pp. 300-8, 316-7; quote from p. 300.

[4] The database revised by the author (henceforward Database K) along with three accompanying appendixes can be found in the “supporting information” feature of the journal.

Considerable doubts were raised about the accuracy of the Kanefsky database while doing a fairly meticulous comparison with information found in the secondary literature.[5] Three areas of discrepancies were identified:

First, there were discrepancies regarding the erection year of particular engines but no changes were made in this regard if they fell within four years from each other since they did not have a noticeable effect on the diffusion trajectory.[6]

Second, there is a failure in some of the secondary sources to record engines cited in the database. But the reverse also holds true. For instance, the Kanefsky database cites only three engines as being erected in Derbyshire by 1730 but according to Barton this figure was “nine or more” by that year. The latter author, referring to Cornish engines during the period 1739-75, relies on a statement by Pryce who claimed that “above three score [above 60] have been erected”; by 1777-8, according to Barton, there were “probably about 75 Newcomen engines.” In contrast, the database’s figures for Cornwall are 56 and 66 respectively.[7] In the end, 31 additional engines were added by the author, all listed in Database K, Appendix 1.[8]

Third, the database was revised and supplemented in terms of the technical characteristics of individual steam engines which, in some cases, allowed the calculation of their hp. These revisions are enumerated in Database K, Appendix 3.

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[5] The data gathering method of the database and the gaps in the evidence are described in Kanefsky and Robey, “Steam engines,” pp. 163-82 and in Kanefsky, *Diffusion of power technology*, pp. 260-2, 268, 270-1, 273, 434-5, 437-9, 442. One particularly useful source of the secondary literature was the so-called Brown list. William Brown, viewer of Throckley colliery and erector of engines, compiled a list of 99 engines erected in collieries by 1769 (57 of which were still in operation); his list was also utilized by Smeaton. It is not clear whether he intended this list to be inclusive of all engines erected in collieries until that year (well over 300 by then) or just in the Newcastle coalfield. The fact of the matter is that the list focuses mainly on the coalfields of Northumberland and Durham with few outliers in Scotland. See Duckham, *Scottish coal industry,* p. 83; Flinn, *British coal industry,* pp. 122-3; Rolt, *Thomas Newcomen*, pp. 120-1.

[6] These discrepancies are pointed out in Database K, Appendix 2.

[7] *Cornish beam engine*, pp. 18, 22. Granted these problems, it should be stressed that some claims found in the secondary literature should be treated with caution. For instance, Pryce was a resident of Cornwall, and thus presumably an authority on local matters, leading Rogers (*The Newcomen engine*, p. 17), for instance, to the conclusion that his claims were “perfectly plausible.” And Pole (*Cornish pumping engine*, p. 12) conveys uncritically Pryce’s claim that in the 36 years prior to the time he wrote (1740) there was only one engine erected in Cornwall, while the database cites six of them.

[8] The author has made an effort, whenever possible, to document the existence of these engines by finding more than one reference to them in the secondary literature. But revisions cannot be precluded based on further research.

The database incorporating the aforementioned revisions was then used to calculate the diffusion path by focusing on cumulative hp figures; this methodology comprises a radical departure from previous ones tracing diffusion based on the number of engines installed. The author finds the latter methodology problematic in light of the nearly fivefold increase scored in the hp of a typical engine from the beginning to the end of the period (see Appendix I); the numbers used in the latter are reproduced in Figure 1.[9] A cursory look at the trend clearly indicates a fairly narrow range through the 1730s and a growing one thereafter. Ignoring the substantial increase in energy output and counting engines as if each unit had the same economic impact amounts to a flawed methodology.

Following this reasoning, a list of 45 engines with known hp was compiled based on figures provided by Kanefsky (but ignoring experimental engines since they had no economic impact), supplemented by information found in the secondary literature, and deriving some other figures based on the technical characteristics of engines.[10] Subsequently, three methods of imputing the unobserved hp data were tested, including two Monte Carlo simulations using static and rolling bins (see Appendix III). The last one proved to be the most sophisticated producing the most statistically robust results and was adopted in constructing the aggregate hp curve (Figure 2). This estimate shows a figure of 13,172.7 hp installed by 1773.[11]

Horsepower diffusion figures derived through this method are substantially higher than the useful power generated by these engines because part of it was wasted due to friction. No effort was made to account for this factor for two reasons: sources which state the hp of engines are often not explicit on this point and that precludes knowing whether they refer to indicated or effective hp, though most likely they refer to the former; and also because of the wildly different estimates on how to account for friction.[12] Burn, for instance, argues that the right method is to deduct 1.5 lbs from the load when applying a formula to calculate hp. Other experts opted to deduct a certain percentage from the

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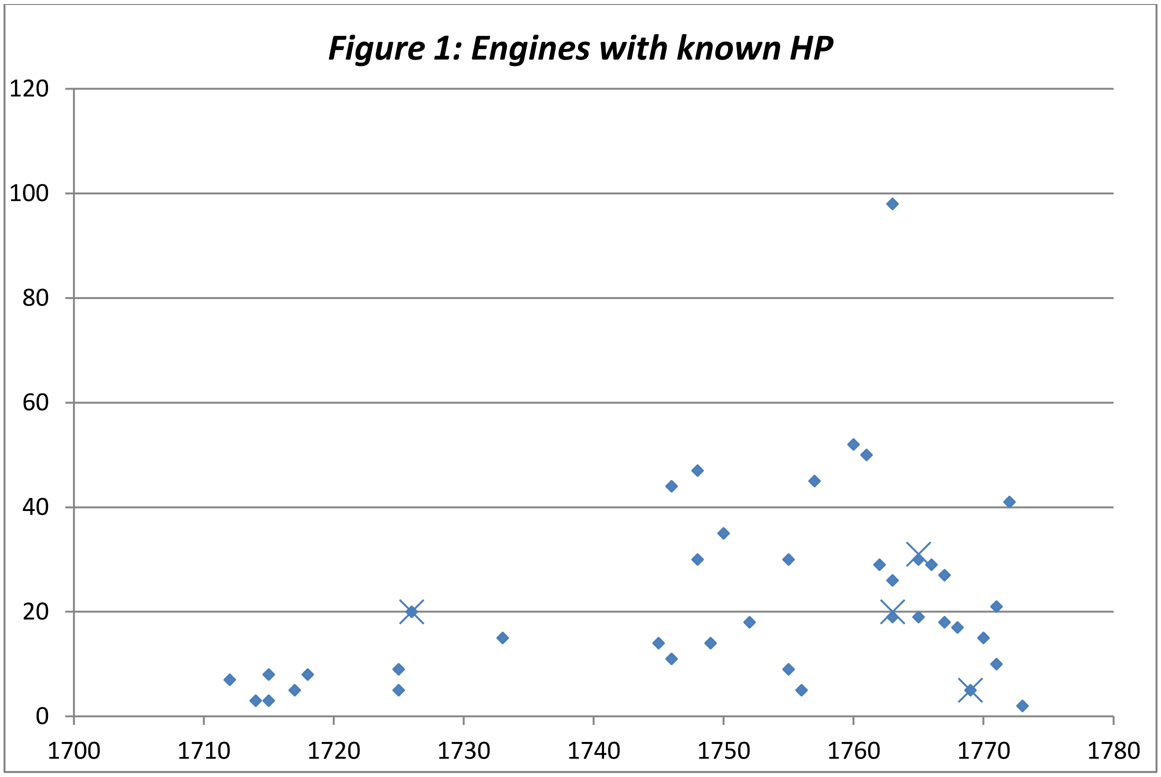
[9] See next paragraph regarding the derivation of the data.

[10] The methods used in the last type of derivations are described in Appendix II. The harvest of information they provided was not bountiful but they comprise a promising venue for expanding the list of engines with known hp, particularly to researchers with stronger knowledge of engineering principles than the author.

[11] This figure is the mean of 1,000 iterations on the Monte Carlo/rolling bins simulation.

[12] There are three definitions of hp. First, *nominal hp* which is a function of two technical features of an engine: the diameter of its cylinder and length of the stroke. Second, *the indicated hp* which takes into account two additional features, the number of strokes per minute or feet traveled by the piston per minute (also known as velocity), and the pressure or load on the piston expressed in lbs per square inch. Indicated hp is closely related to the duty of an engine. Finally, *effective hp* (also called *actual* or *net hp*) deducts the amount of friction lost from the indicated hp



due to its moving parts. See Hawkins, *Hand book of calculations*, p. 101; Perry, *An elementary treatise*, p. 62; Roper, *Hand-book of land and marine engines*, p. 61.

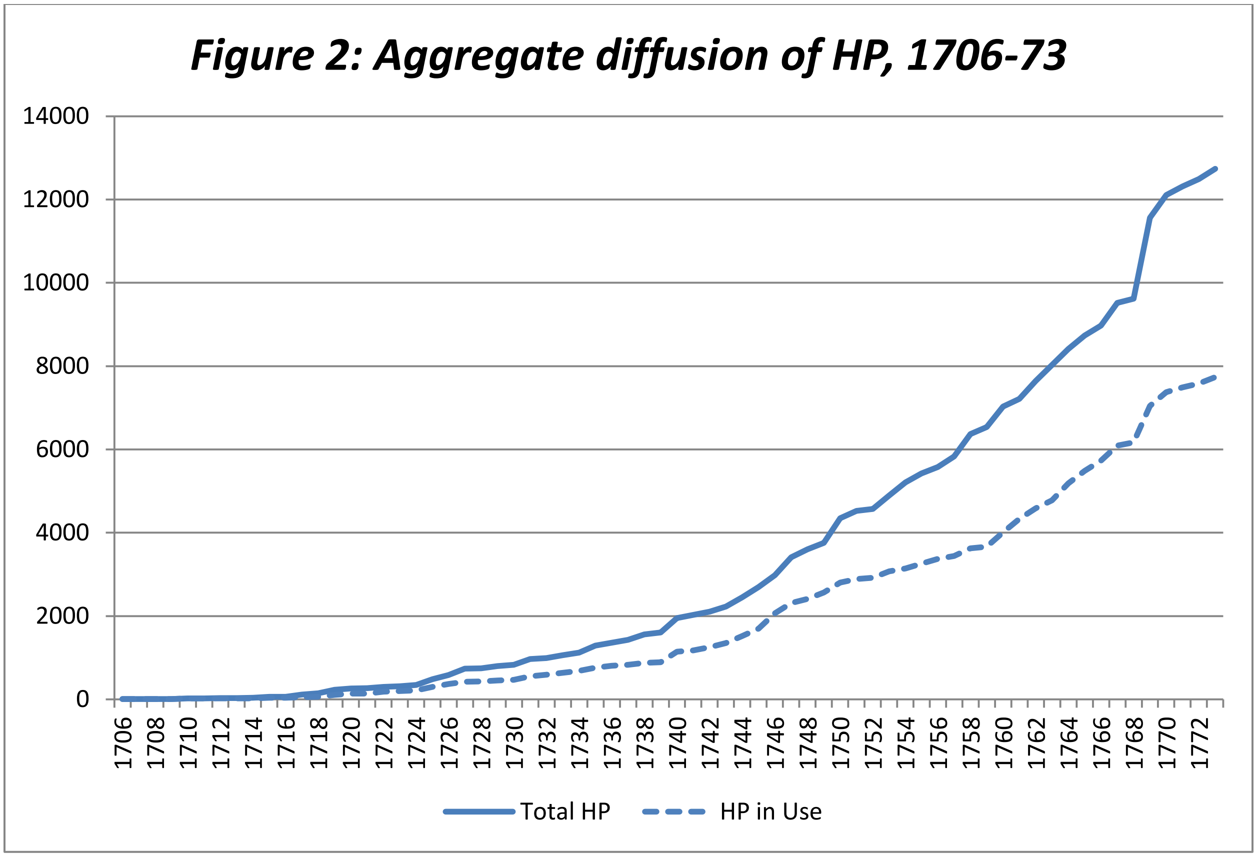


Figure 2: Aggregate diffusion of HP, 1706-73
14000
12000
10000
8000
6000
4000
2000
0
1706
1708
1710
1712
1714
1716
1718
1720
1722
1724
1726
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1738
1740
1742
1744
1746
1748
1750
1752
1754
1756
1758
1760
1762
1764
1766
1768
1770
1772
Total HP
HP in Use

indicated hp. Roper suggested that friction deducted 15%, Hawkins' figure was 30%, while others went as far as deducting half of the generated power. It should be noted that the proportion of lost power actually depended on the size of the engine, being higher in engines of smaller size.[13]

However, adjustment of the diffusion figures was made to account for the fact that, at any given time, some engines were out of use.[14] But, once again, the evidence in this regard is not ideal. Kanefsky ventured the estimate that by 1760, out of a possible total of 350 engines, at least 200 (57%), perhaps as many as 250 (71%), were at work.[15] There is a fair amount of evidence referring to the very end of the period, in line with Kanefsky's date, which supports the lower-bound figure of his range. Specifically, the database cites 34 engines erected at the Shropshire ironworks and coal and iron mines through the end of 1775 but, according to an account cited by Trinder, there were "about" 20 of them working at the time (c. 59%).[16] Most importantly, out of the 99 engines compiled in the Brown list, only 57 of them were still working in 1769 (58%).[17] The evidence is compelling since it encompasses a substantial number of engines and refers to the two most important sectors in terms of their adoption (see below). Unfortunately, the evidence is very weak regarding pre-1760 years. The author is aware of only one estimate by Rogers referring to Cornwall according to which there were only three engines still at work by 1741 out of seven installed by that time based on figures of the database revised by the author (42%).[18] In light of this evidence, it has been decided to adopt Kanefsky's lower-bound figure and reduce the cumulative diffusion figures for each year down to 57% despite the prospect the proportion of engines at work may have been lower for the pre-1760 decades. The adjustment of the figures commences with the year 1714 when the first known engine went out of commission, that is, the Wheal Vor engine in Cornwall which is the third commercial engine in the database (erected in 1710).[19] The aggregate hp in use is also depicted in Figure 2. By the end of 1773 it reached a figure of 7,508.42, once again, being the mean of 1,000 iterations.

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[13] Hawkins, *Aids to engineers' examinations*, p. 79; Burn, *The steam-engine*, p. 99; Roper, *Hand-book of land and marine engines*, p. 61; Allen, *The science of mechanics*, pp. 337-8.
[14] Such adjustment is not made by NVT, constituting a major difference with the methodology of the present paper.
[15] *Diffusion of power technology*, p. 260.
[16] *The industrial revolution in Shropshire*, p. 48.
[17] Dunn, *The coal trade*, pp. 23-4; Rolt, *Thomas Newcomen*, pp. 120-1; Galloway, *Annals*, pp. 261-2; Galloway, *The steam engine*, pp. 127, 129; Farey, *Treatise on the steam engine*, pp. 233-4. It should be noted that, contrary to every other authority the author is aware of, Flinn claims that every engine in the Brown list was at work in 1769; see Flinn, *British coal industry,* p. 122.
[18] *The Newcomen engine*, p. 16.
[19] Rolt, *Thomas Newcomen*, pp. 58-9.

The data can be analyzed from several perspectives. First, the diffusion of Savery engines, either in its original or modified forms, was virtually non-existent during this period, not taking into account experimental engines. There were only four Savery engines adopted (1706, 1714, 1739, 1766), two of which were used to drain mines.[20] The remaining 562 non-experimental engines installed were of the Newcomen type.[21]

Second, the aggregate diffusion data (Figure 2) reveal three distinct phases.[22] The first one, characterized by a slow pace of diffusion, runs during the period 1706-18 with only 9.1hp adopted per annum. During the period 1719-42 the pace accelerates to 87hp and becomes impressive thereafter (1743-73) with 347.7hp per annum. The peak of the trend is witnessed during the 1760s when the figure reaches the level of 533.5hp. It should be noted that this trend is different from the one pointed out by previous authors who discern a two-phase pattern with the break point being the expiry of the patent in 1733; my method, on the contrary, reveals that the patent's expiration did not have a discernible effect on the trend.[23] Lastly, the data were subjected to testing to discern whether a logistic growth or Gompertz curve fits them better; the latter was deemed a better model for both the aggregate HP curve and the aggregate HP in use (see Appendix III).

[20] Arago, *Life of James Watt*, p. 54 falsely claims there was only one Savery engine erected in the mining sector. See database K and Jenkins, "The early history of the steam engine," pp. 115-6. There was some debate as to whether the first Cornish engine at Wheal Vor was a Savery model but most certainly it was one by Newcomen since Savery ceased his efforts to introduce his engines in mines by 1705; see Rolt, *Thomas Newcomen*, p. 59.

[21] Newcomen himself had a keen interest in having his engine adopted in Cornwall and, in fact, two of the earliest engines were erected there but the failure of the Wheal Vor engine focused his attention to the Midlands through his connections with the local Baptist community. An engine was erected in the property of William Bache of Wolverhampton but Bache died shortly thereafter and the engine was re-erected at Tipton in the estate of Lord Dudley; see Allen, "The 1712 and other Newcomen engines," p. 8. For the location and supporting evidence regarding some of the early Newcomen engines see Galloway, *Annals, vol. 1*, pp. 240-4; Flinn, *British coal industry*, pp. 119-20.

[22] The presence of structural breaks was tested using two methods: running a linear regression on the logarithm of the hp data with dummy variables representing break-points, and the Chow test. Both tests confirmed the break for 1718 but the results were a bit more ambiguous for 1742. There was also another structural break in the late 1760s but the author decided to ignore it because of a bias of undetermined size in recording the installation of engines; specifically, data is drawn from the Brown list which records engines as being installed in 1769 despite the fact than an unknown number of them was erected in earlier years.

[23] Kanefsky and Robey were the first ones to view 1733 as a critical date and the endpoint of the first phase of diffusion followed by a second phase running through the period 1734-80. Flinn used the same dividing line reasoning, that the "expiry of the patent in 1733 removed a major inhibition." Nuvolari et al followed suit based on a historical outline they provide emphasizing the expiration of the patent as a critical event (their second phase is 1734-74). None of these authors, however, subject aggregate data to some kind of testing procedure hence the contrast with my dates regarding structural break points. See Nuvolari et al, "Early Diffusion," p. 296; *British coal industry*, pp. 120-1 (quote from former page); Kanefsky and Robey, "Steam engines," p. 174.

Third, there is a distinct bias from a sectoral point of view. Of the engines with known sectors of adoption, comprising the vast majority in the database, 87% of the total hp was installed in the mining industry.[24] The contribution of other sectors was minimal: ironworks trail far behind mining with 6% of total hp; the first one was adopted in 1731 but the bulk of them in the 1750s. Waterworks come next (3%), the first engine installed in 1714 and the rest of them spread fairly evenly through the entire period. Brassworks, canals, chemical works, oil/mustard, chocolate, paper, edge, and sugar mills complete the list each accounting for c. 1% or less.

Table1: Regional concentration ratios in the diffusion of Newcomen engines, top four counties at the end of three distinct periods, hp and % of aggregate hp adopted

1718		1742		1773	
Durham	24.9 (21%)	Northumberland	297.8 (13.5%)	Northumberland	2,254.5 (17.3%)
Staffordshire	18.2 (15.3%)	Warwickshire	289.6 (13.1%)	Durham	1,542.3 (11.8%)
Cornwall	16.9 (14.2%)	Durham	256.1 (11.6%)	Cornwall	1,473.5 (11.3%)
Northumberland	11.3 (9.5%)	Staffordshire	204.2 (9.2%)	Shropshire	843.1 (6.5%)
Total	71.3 (60.1%)	Total	1,047.7 (47.4%)	Total	6,113.4 (47.0%)

Source: Database K.

Fourth, analyzing the data from a regional perspective reveals a striking concentration of hp in a very limited number of counties.[25] Following my three-phase chronology, the top four counties accounted for sixty percent of aggegate hp by 1718 and despite the decline of the figure to 47 percent in the following two phases the concentration ratio remained fairly substantial (see table 1). During the first phase the northeastern coalfield (Durham and Northumberland) clearly played the leading role (30.5%), followed by Staffordshire and Cornwall;[26] even when Warwickshire's hp is added to that of Staffordshire the combined share is distant second (22.6%). Cornwall drops from the top four list in the second phase but the northeast still retains its leading spot with a quarter of the total hp followed by Staffordshire and

[24] Several collieries erected multiple engines, often moved around from pit to pit as one got exhausted and others opened up. A contemporary technical report referring to Heaton colliery recommended the use of three engines over the extent of 20 acres from depths of 70 fathoms. See Flinn, *British coal industry*, pp. 120-2; Raistrick, "The steam engine on Tyneside," p. 140.

[25] It is difficult to make comparisons between my regional assessment and those of other authors since our analyses are broken down into different sub-periods and, in some cases, use different regional units of assessment (counties vs. wider regions). But, notwithstanding differences in tone, the assessments are in sync and they certainly confirm NVT's findings of high spatial clustering through the 1730s and a wider dispersion afterwards. See Nuvolari et al, "Early Diffusion," pp. 297-300, 315; Kanefsky and Robey, "Steam engines," pp. 176-9; Flinn, *British coal industry*, pp. 120-2.

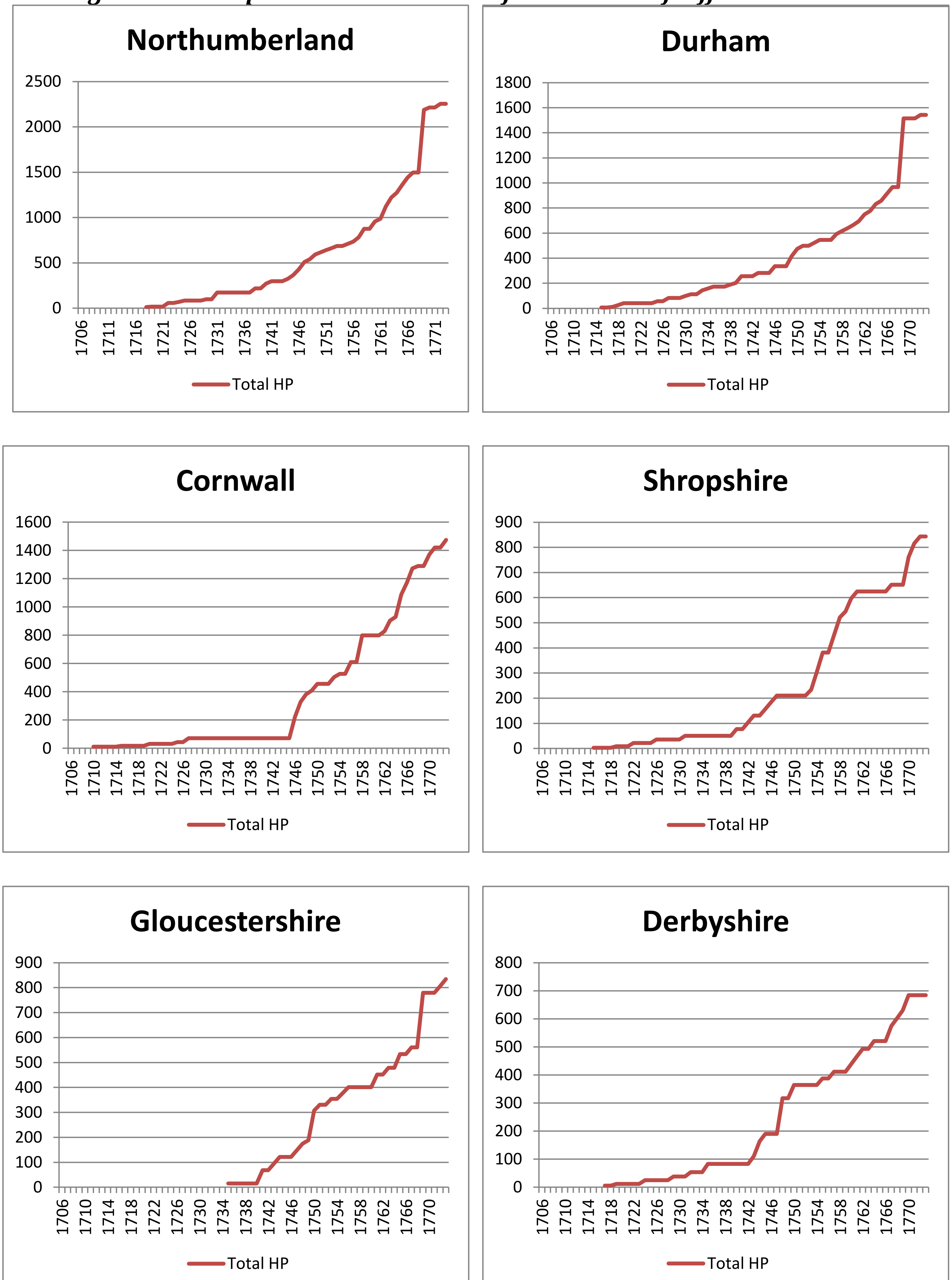
[26] For the earliest (and subsequent) engines in Cornwall see Barton, *Cornish beam* engine, pp. 15-6, 19-20.

Warwickshire with a combined 22.3%. But the gap between the northeast and other regions widens again in the third phase with the former accounting for 29.1% of the total, followed by Cornwall and Shropshire; even when bringing in Gloucestershire and Derbyshire to consider the top six counties (see figure 3), the top three Midland counties are still far distant from the leading region (with a combined 18.1% of the total).[27] Another interesting characteristic of the diffusion data is the very limited inroads the Newcomen engine made in Wales and Scotland throughout this period, with the former accounting for 4.6% and the latter for 7.2% of the total by 1773. In some cases the engine was adopted by a particular colliery but failed to find other imitators in the immediate vicinity as, for instance, in the case of Stevenson colliery which adopted all five of the pre-1750 engines erected at the Ayrshire coalfield. In some other cases an entire county failed to adopt it until very late during this period, as was the case in Lanarkshire which erected its first engine in 1760.[28]

A substantial portion of the literature on technological diffusion has long established that the proper method of assessing the adoption rate of a technique is to measure the gap that remains between the level of adoption at any given point in time with the potential range of adoption at that moment.[29] Two often suggested methods are to contrast the number of firms that have adopted the technology with the total potential pool of users at the firm level; or, to measure the portion of total output produced by the technology. Neither of these methods, however, is straightforward. When counting firms, defining the denominator may be problematic because economic factors such as firm size may prevent adoption by all firms; and the productive capacity of a potential user has to be taken into account since a single firm may be capable of adopting multiple units of the technology in question. Most importantly, simply counting firms that may have adopted a single unit may provide a skewed picture of the rate of diffusion: if a couple of large firms have adopted it but the sector is comprised of several other smaller firms, the rate of adoption may appear falsely limited. When it comes to counting output, this method becomes problematic too if the technology can be used in only some aspects of an integrated production process but not in others or when the new technology is complementary to an old one in the

[27] Figure 3 is drawn based on figures of the cumulative hp installed without taking into account engines falling out of use because the latter information is impossible to estimate in the case of individual counties. Incidentally, the results of testing reported in Appendix III indicate that the logistic growth curve fits better the data at the county level.
[28] Hamilton, *Economic history of Scotland*, p. 207; Whatley, "The introduction of the Newcomen engine to Ayrshire," p. 69. For references to some Scottish engines, see Duckham, *Scottish coal industry*, pp. 82-3.
[29] For instance, see Atack et al, "The regional diffusion of the steam engine," p. 284.

Figure 3: The top six counties with the fastest rates of diffusion



context of the same production process.[30] Another important element to be taken into account is that the upper ceiling of adopters may be shifting due to technological improvements which expand the respective range; the latter is neither fixed nor homogenous. In this case, the range of potential adoption is depicted as a step-like line superimposed above the diffusion curve.[31] Despite the list of issues to be tackled with this method, particularly with defining the potential range of adopters, things are a bit easier in the context of the present study for two reasons: no economic considerations are taken into account in defining the upper limit of adoption, instead concerning ourselves only with the productive applicability of Newcomen engines; and technological improvements were not substantial enough to change dramatically the range of potential diffusion.

While we have some reasonably good estimates on the actual extent of the adoption of steam power, we tread on a riskier territory when it comes to the potential range of adopters, particularly when it comes to the top two sectors utilizing energy sources of any sort, i.e., mining (especially collieries) and iron. Nevertheless, some reasonable generalizations can be made starting with the mining sector.[32] There were two tasks power sources were necessary for: draining water from mines and winding coal or ore. Prior to the steam engine era winding and drainage machinery were often the same. One of the most common methods was the use of a pulley and rope tied to a horse, the latter moving on the surface a distance that was equal to the one separating the bottom of the pit from the surface. When it comes to the drainage of collieries in particular, Galloway noted that "so long as the demand for coal was small, and supplies were attainable from shallow mines above the level of free drainage, the mining of coal had been comparatively easy. But about the beginning of the seventeenth century, this happy state of matters was coming to an end." By the beginning of the eighteenth century "in the great majority of cases water continued to harass or even altogether baffle the mines."[33] When the quantities of water to be drained were small, man-operated windlasses or horse-gins would be adequate. Whenever possible, water-powered pumps were less expensive to devices powered by humans or horses and capable of draining larger quantities, hence especially sought after in larger collieries. Water

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[30] Nabseth and Ray, eds., *Diffusion of new industrial processes*, p. 8; Radnor et al, *Diffusion of innovations*, pp. 46-7; Metcalfe, "Impulse and diffusion", pp. 349-50; Metcalfe, "Diffusion of innovation", pp. 148-9; Karshenas and Stoneman, "Technological diffusion," p. 267.

[31] Hurter and Rubenstein, "Market penetration," pp. 205-6; Gold, "On the adoption of technological innovations," p. 107; Rosegger, *Economics of production and innovation*, p. 210; Radnor, et al, *Diffusion of innovations*, pp. 46-7; Metcalfe, "Impulse and diffusion," pp. 349-50; Nabseth and Ray, eds., *Diffusion of new industrial* processes, p. 297.

[32] Hatcher, *British coal industry,* pp. 217-33; Flinn, *British coal industry*, p. 113; Galloway, *History of coal mining*, p. 78.

[33] *History of coal mining*, pp. 52, 76-7.

streams, however, were not always readily available and the specter of drought was always present. Wind-powered mechanisms were the least common method of drainage. Based on contemporary accounts from experts like J. C. and assessments of modern historians, there seems to be no doubt that horses provided the bulk of power, water-draining methods playing a secondary role whereas human and wind power a very minor one.

The Newcomen engine was introduced at the very beginning of the eighteenth century but the winding process kept relying on non-steam power sources due to technological impediments. Even the most prominent engineer of his era, Smeaton, was very resistant to the idea of turning the Newcomen engine into rotative by the simple addition of a connecting rod and crank, insisting that the only feasible arrangement was to act as a power auxiliary to water wheels. Smeaton's reservations were shared by many engineers at the time who thought that the variable stroke could cause the destruction of the engine, failing to appreciate that the crank would be able to control its variability. There were some isolated efforts towards a solution such as the ratchet device by Joseph Oxley and a similar one by John Stewart in 1766 but they both proved failures.[34]

There were three methods used in winding during the eighteenth century. First, the use of horse-gins; however, this method created the potential of a bottleneck in the mining industry. A single horse-gin could not raise more than 100 tons/day, hence restricting output to 25,000 annually. This figure was fairly high given the size of mines during the first half of the eighteenth century but the scale of operations gradually increased as the century progressed. In some isolated regions, such as the Scottish coalfield of Fife, wind power was utilized but obviously wind could not function as a universal solution. Water-power could also be used but given its spatial and seasonal limitations, considerable efforts were made to use the Newcomen engine as an auxiliary force to it. In a very poorly documented case, Long Benton colliery seems to have attempted to use two engines pumping water over a water-wheel for winding purposes in 1749.[35] According to Galloway, the first documented case refers to Chesterhaugh colliery where, in 1753, a basket of coals was raised while a basket of water descended and the water was pumped up to the surface by a steam engine. Another engine was presumably used to operate a winding-gin at Walker colliery in 1758. And in 1762 Joseph Oxley attempted to use steam power at Hartley colliery to pump water over a water-wheel but the effort proved unsuccessful. The full extent these efforts materialized is not clear but there is a consensus that the technical problems were finally

[34] Rolt, *Thomas Newcomen*, pp. 131-2; Farey, *Treatise on the steam engine*, p. 275.
[35] The database records only one engine for that purpose, the only such returning engine in any type of mine.

resolved in the 1770s, Smeaton playing a critical role in this regard, and the method of using steam power to pump water to a cistern above a wheel became generalized. The important point to stress is that until then steam power failed to replace or even to aid to a substantial extent alternative sources of power when it comes to winding.[36]

It follows that the process of drainage was the exclusive beneficiary of the adoption of steam power in the mining sector. The main question then to be addressed is how the c. 6,500 hp adopted in the draining of mines contrasts to the hp offered by other power sources, something that will tell us the gap between actual and potential diffusion.[37] There were two types of mines, collieries and metal mines. It seems that in collieries the bulk of power in drainage was provided by steam engines supplemented to an undetermined degree by the use of adits; the latter were used in parts of the northeast, especially south and southwest of the High Main seam of Newcastle, all of the collieries in north Staffordshire, the lower half of Wales, Cumberland, Derbyshire, and Somerset. According to Kanefsky, the lack of water resources was so acute that they failed to play a significant role in both drainage and winding.[38]

The situation was substantially different in metal mines with regional particularities regarding the availability of water, with the morphology of the terrain, and the size (and thus power needs) of mines producing a more diversified picture. In the Pennines (500-1,000 hp), the Lake Counties, and upland Wales (up to 500 hp in the country as a whole) water power was both readily available and sufficient. The use of steam power was widespread in Cornwall, Denbigh/Flint, and Shropshire either because water resources were scarce or they were inadequate given the size of mines. All in all, water power contributed 5,000 hp in 1760, a figure that remained unchanged through the end of the period this study covers.[39] If Kanefsky's judgment is valid, virtually all of it was utilized in metal mines.

But, presumably, part of this figure was utilized in the winding process to an extent that can only be guessed through circumstantial evidence. Deriving his evidence from Cornwall, Kanefsky pointed out

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[36] Farey, *Treatise on the steam engine*, p. 297; Musson and Robinson, *Science and technology,* pp. 398-9; Flinn, *British coal industry,* pp. 100—2, 112; Galloway, *History of coal mining*, pp. 113-5. Contemporary publications, such as Leupold's *Theatrum Machinarum* (1727), often depicted the use of water-power in driving machinery; see Musson and Robinson, *Science and technology*, p. 398.
[37] The figure is derived by multiplying the total hp in use by 1773 (7,508.42) by the share of the mining sector (86.88%); see previous section.
[38] *Diffusion of power technology*, pp. 148, 201; Flinn, *British coal industry,* pp. 100, 110-1; Hatcher, *British coal industry,* p. 214. Water power made some inroads in winding after 1770, until then horse gins being the predominant form of power.
[39] But even in Cornwall there were 50 water wheels used in drainage averaging 20 hp and thus producing 1,000 hp; see Kanefsky, *Diffusion of power technology*, pp. 148, 200-2, 231. In contrast, the cumulative hp by steam in 1773 was 1,473 but, given the 57% rule, only 840 hp was in use; see Database K.

that the power capacity of water wheels used for drainage was clearly larger than those used for winding.[40] In light of the absence of other evidence I would venture the estimate that the ratio stood at 2:1, that is, of the 5,000 hp provided by water in metal mines, 3,350 hp was utilized in drainage and thus was part of the potential range of diffusion of steam power, with the remaining 1,650 hp being used in winding and thus not part of this range since technological impediments prevented the use of steam in this process.

The contribution of other power sources is not clear. Horse gins were virtually eliminated from the effort to drain mines. Wind power, found mainly in East Anglia, made a minimal contribution.[41] The role of soughs and adits, however, was not negligible. According to Flinn, their contribution was "extremely limited since they required the existence, within a reasonable distance, of naturally drained land the surface of which was lower than that of the pit sump. Only mining in hilly districts could possibly meet these requirements, and it is clear that even in hilly areas not many hundreds of feet of depth would put a pit sump below the point at which it could be run out by driving a sough horizontally to an adjacent valley." However, he even admits that "at lesser depths this method was possible … and some coalfields … were in sufficiently hilly country."[42] I would venture the guess that the residual role of these power sources, particularly adits, amounted to c. 2,500 hp, accounting for 20% of the total power required for drainage purposes (12, 350 hp), behind steam (6,500 hp, 53%) and water (3,350 hp, 27%).[43] The figure may not be based on hard data but it is certainly plausible since every authority seems to agree that these three power sources played collectively a minor, albeit not trivial, role. In the end, it is fairly safe to assume that steam power accounted for a little over half, to a maximum of c. 60%, covering the needs of drainage in the mining sector.[44] It made "remarkable" progress in collieries, to use the favorite characterization of other authors, but had a considerable way to go in metal mines.

Another sector in which the supply of a constant flow of power was of vital importance was ironworks which traditionally utilized water power to blow the blast furnaces. Given the insufficient supply of water during summer months, steam engines were first used to return water to wheels. There was some confusion as to when the first returning engine was installed in blast furnaces. Farey placed the

[40] *Diffusion of power technology*, p. 200.
[41] Ibid., pp. 221, 225-7.
[42] Flinn, *British coal industry,* pp. 110-1.
[43] The proportion counted by steam would change only by a percentage point or so when the standard deviation of hp in use in 1773 is taken into account.
[44] The figure of 60% is derived by reducing the proportion of non-steam/water power sources down to 1,000 hp which seems to be the lowest we should be willing to go in this regard.

timing in the early 1760s citing Coalbrookdale or Carron as the pioneering adopters. But, according to Hyde, the first such use was in the former firm in 1742. However, the database includes one returning engine, installed in Warwickshire, as early as 1731. The subsequent use of such engines reveals a strong clustering pattern towards the iron industry of Shropshire.[45] Finally, during the late 1760s, blowing cylinders attached directly to an engine came to replace the leather bellows and supersede the use of water power.[46] It follows that for virtually the entire period examined here steam and water were complementary sources of power, unlike the mining industry were it was a matter of "either-or" in the use of these two energy sources.

There is also a lack of unanimity among economic historians when it comes to the degree to which water power was adequate in itself powering blast furnaces. Hyde takes an optimistic stance by stating that "water power was often sufficient to operate a single coke blast furnace [coming into being for the first time in the early 1750s] and that steam engines were purchased only when a second or third furnace was added".[47] The crucial question boils down to how long a blast furnace could go with no, or inadequate, power before putting at risk its economic viability. The minimum amount of time furnaces had to close down for repairs was for 4-5 weeks, spread intermittently throughout the year. But Hyde also adds that water could provide power for eight months of the year [c. 34 weeks] which he considered the minimum amount of time for the operation of the bellows as long as it was consistent during the working period.[48] Richard Pegg a "master workman" in Bradford (Yorkshire) stated in 1593 that, in order to generate a profit with a furnace, there had to be sufficient water to operate it for 20-30 weeks/year. By the eighteenth century an operating period of thirty weeks was considered satisfactory. It seems, however, that the norm, when utilizing water power, was falling below these figures. Data from South Yorkshire indicate that the average operating span of furnaces during the period 1698-1756 was 26-30 weeks. Even more so, in regions such as the Black Country (south Staffordshire), rich in coal and iron deposits, exploitation of the latter could not have been feasible without steam power in light of its limited water resources. The fact that water power was endemically inadequate is also indicated by the fact that at any given point in time there were a number of furnaces in stock but not operating;

[45] Farey, *Treatise on the steam engine*, pp. 296-7; Hyde, *Technological change*, p. 70; Trinder, *The industrial revolution in Shropshire,* p. 48.
[46] Of the 23 steam engines cited in the database in relation to this sector installed by 1773 all but two are designated as "returning engines." The first engine used to blow a cylinder was installed in 1767 at the Bradley Ironworks (Staffordshire) followed by one in Coalbrookdale in 1772.
[47] In supporting his statement, he adds that as late as 1790, 12 out of 83 coke blast furnaces did not utilize any steam power while all 25 charcoal furnaces were water-powered; Hyde, *Technological change*, p. 71.
[48] *Technological change*, pp. 11, 71.

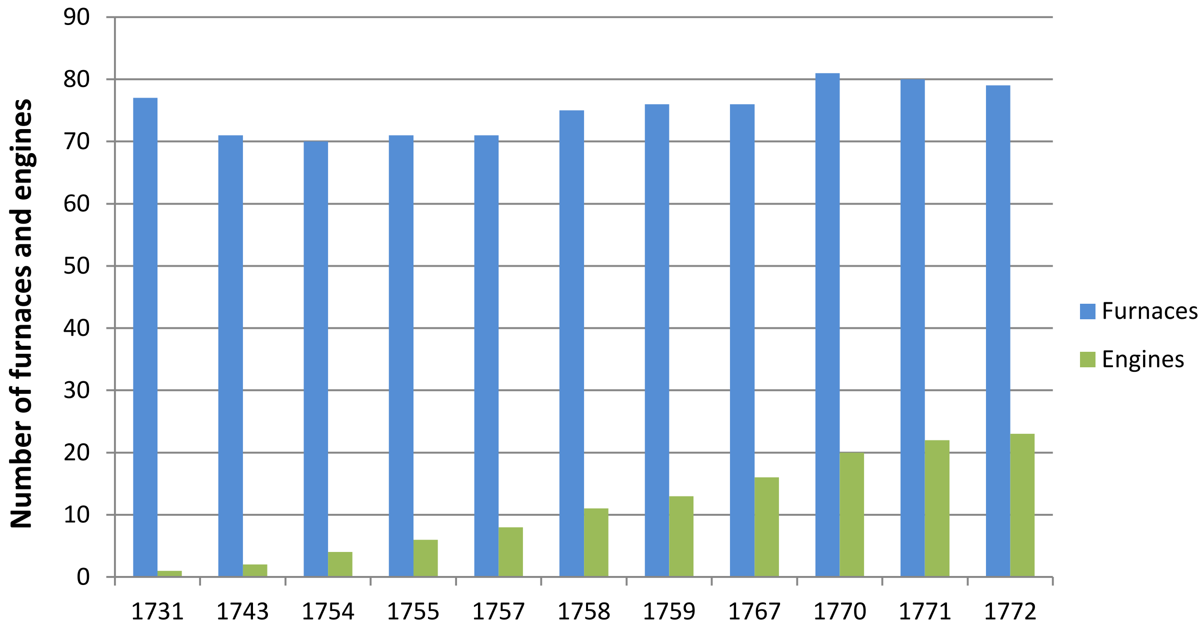
weak demand may have been a contributory factor but mostly because of the unreliability of water power in providing the blast.[49] In light of these facts, Kanefsky's assessment that the lack of adequate water power created a "serious bottleneck" seems justified; "in many works the need was sufficiently great to justify this expensive innovation."[50]

The gap between actual and potential diffusion in the mining industry was quantified in terms of hp but this is not feasible in the iron industry. To define the latter we would need to know the water flows in every location of blast furnaces in order to determine the power of steam engines these locations required, something that is well beyond the documentary evidence. And to define the former we need to know the hp of every single one of the 23 engines installed to aid blast furnaces. But this is not an intractable problem. There is strong circumstantial evidence which points to the fact that the installed engines were of sufficient power. We have figures for only two engines (both installed in the 1750s) which were of 30 and 45 hp, well above the decadal mean (c. 24 hp) and some steam engines designed for this purpose by Smeaton shortly after the end of my period; the two figures are also well above the typical hp of water wheels at the time used to power blast furnaces (10-12 hp).[51] Moreover, it is not unreasonable to presume that since steam engines were introduced in this sector after a few decades of experience, engineers must have had enough sense to erect engines of adequate power in each blast furnace location. If that was the case, it is perfectly fine to contrast the number of engines installed with the number of blast furnaces, as Figure 4 does, since the gap would be the same compared to the method of using hp.

There are considerable discrepancies in the literature regarding the number of furnaces, particularly for the first half of the century, though this is not a serious problem since the bulk of engine installations took place afterwards. The author consulted the figures cited by Riden, and Davies and Pollard, considered to be amongst the most authoritative. It should be noted that the former cites figures for furnaces in use whereas Davies and Pollard for the total number in stock (i.e., including those being

[49] The records of Coalbrookdale are spotty but when they begin in 1755, several years after steam came to replace horse-driven pumps, they show two major changes through 1761: output more than doubled (rising to 1,200-1,600 tons/year); and the seasonal fluctuations of output, with troughs in the summer and peaks in the winter, came to a halt; see Raistrick, *Dynasty of ironfounders*, pp. 107-13, 115-8, 144. Also, Hyde, *Technological change*, p. 72; Schumbert, *British iron and steel industry*, p. 243; Davies and Pollard, "The iron industry", p. 79; Rolt and Allen, *The steam engine of Thomas Newcomen*, p. 122.
[50] *Diffusion of power technology*, pp. 139-40.
[51] Farey cites two engines erected in Yorkshire and Wales in 1779-80 whose power were c. 12 and 18 hp respectively; see his *Treatise on the steam engine*, pp. 279-81. See also Kanefsky, *Diffusion of power technology*, p. 200.

Figure 4: Number of furnaces and cumulative number of engines installed, 1731-72



Source: see text

idle). Interestingly enough, the expectation that the latter figures ought to have being higher than the former is not always met. But the differences between the two sets of figures are not overly wide with the exception of the early 1770s when Davies and Pollard's figures rise consistently above those of Riden and thus result in depicting a slower rate of diffusion.[52] In the end, the Davies-Pollard figures were utilized for the construction of the graph with the exception of the first two years since they begin in the 1750s; this choice was made because counting furnaces in stock is preferable since they include idle furnaces which, most likely, were such because of the absence of adequate water power. The rate of adoption comes to 29% of the ideal but it should be stressed that the data overstate the rate of diffusion because, presumably, an undetermined number of engines may have been out of use by the end of the period. If the previously adopted assumption of 57 percent engines in use applies in this case, then the proportion of blast furnaces having a steam engine is reduced from 29 down to 16.5 percent by 1772.[53] On the other hand, there is also a reverse bias in that in some undetermined number of blast furnaces the use of steam engines may not have been imperative. In the end, the two biases may roughly cancel each other out.

Space limitations preclude extending the discussion to other sectors of the economy.[54] It is safe to argue that the diffusion process was certainly inadequate in waterworks which adopted 17 engines starting from early on (1714) replacing the use of horses. All but three of them were found in London, the three other installations being in the very small towns of York, Kingston-upon-Hall, and Hull while skipping the towns that trailed London, though by far, in the urban hierarchy of the period (Bristol, Birmingham, Liverpool, Manchester, Leeds, Sheffield). In other sectors, such as paper mills (350-400 by the end of the period) and brassworks, where steam could be used as an auxiliary power pumping water over wheels the diffusion process seems to have been weak with only one and six engines respectively being installed during the entire period.[55]

The purpose of this paper was twofold. The first aim was to take a fresh look at the Kanefsky database which has proven an invaluable tool in tracing the utilization of steam power in the British economy of the eighteenth century. However, it is clear that it is not the definitive record of this process. The

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[52] Davies and Pollard, "The iron industry", pp. 77-8; Riden, "The output of the British iron industry," p. 448.
[53] The 57% figure is fairly accurate in light of the evidence cited in ft. 16 above.
[54] Farey, *Treatise on the steam engine*, pp. 212, 296; Kanefsky, *Diffusion of power technology*, pp. 201-2.
[55] More detailed analysis, however, is needed for these sectors. Paper mills, for instance, had very low power requirements (7-8 hp/mill) and thus water power may have been largely adequate in many, if not most, mills.

discrepancies that were identified in relation to the erection year of engines, when not very much apart, are not a serious flaw. But Kanefsky seems to have missed a fair amount of engines in light of the addition of 31 engines by the author bringing the total to the figure he speculated was the true extent of diffusion; one wonders whether the erection of more engines awaits discovery. Another potential goldmine of information is the enrichment of the database with crucial technical characteristics of the engines installed, particularly the pressure on the piston and the velocity, which could allow us to derive their horsepower by utilizing the formulas mentioned in Appendix II.

But the main motivation to engage in this study stems from the author's perception of what is the appropriate methodology in counting and assessing the diffusion path of Newcomen engines. To take the number of engines installed at a point in time and consider this the "saturation level" implies the impossibility of extending the diffusion process beyond this point, stimulated by whatever factors determined it; in other words, it implies a state of perfection. Furthermore, all this method allows us to do is to fit a curve between points A and B and test the nature of this curve. Instead, in my view, the right approach is to place the diffusion of any technology in a sectoral context and count the gap between actual and potential diffusion in order to gain hindsight on the extent this technology contributed to productivity and aggregate growth.[56] And, in the context of this methodology, it makes little sense to pursue calculations on the basis of engines installed just because the latter offers a greater level of convenience but ignoring the fact that the typical engine scored a fivefold increase in its power by the end of the period; nor does it make sense to ignore the amount of steam power falling out of use. There are admittedly gaps in the evidence in both respects but they are not grave enough to preclude plausible generalizations with the use of sophisticated econometric techniques.

In the end, this new methodology does not overturn the long-held belief that the absolute number of Newcomen engines installed by the time Watt comes into the scene was indeed remarkable, particularly in light of the fact that the engine relied on an entirely novel working principle and was fairly complex. But it does create a more subdued assessment when we focus on the relative pace of diffusion. Steam power came to dominate the process of draining in collieries but had a long way to go in metal mines; it is worth repeating that in Cornwall, the county with the third highest figure of installed steam hp by 1773, the latter was barely on an equal footing with water power. In the mining sector as a whole, steam accounted by 1773 for a little over half of total power and even less in the iron industry.

[56] That is not to say that Newcomen engines made a significant contribution to such growth or that they had the potential to do so for the economy as a whole, given their technological limitations. I wish to thank the anonymous referee for bringing this point to my attention.

Appendix I: The increasing power of Newcomen engines

Table 1: Mean hp per engine

Period	1706-1719	1720s	1730s	1740s	1750s	1760-73
Mean	5.66	13.5	15	26.66	23.66	27.36

Source: Database K.

Notes and comments: Decadal averages of hp per engine were compiled beginning with the 1710s the average figure of which was projected back to the only commercial engine prior to that decade, specifically to an engine erected in 1706. At the other end of the chronology the average hp per engine for the 1760s was calculated by incorporating data through 1773.

It is important to compare my figures with others in the literature. First, the decadal means derived through this method are consistently somewhat above figures cited in Kanefsky and Robey ("Steam engines," p. 185, table 9; see also Kanefsky, *Diffusion of power technology*, pp. 261-2, 442). However, the author's sample relies on figures from 45 (non-experimental) engines, as opposed to only 35 taken into account by Kanefsky and Robey.

Another discrepancy emerges based on a statement made by Stuart according to whom the 57 engines in the Brown list still working in 1769 had an average hp of 20.84. A sample of 15 engines drawn from the Brown list by Farey presents an average of 25.1hp; see Stuart, *Historical and descriptive anecdotes*, p. 292, and Farey, *Treatise on the steam engine*, p. 234. Both figures are below mine referring to the period 1760-73 (27.36). Most of the engines in the Brown list, and presumably in Farey's sample, were erected in the 1760s but few come from earlier decades when the typical steam engine was of lesser hp, presumably lowering unjustifiably their figures.

Finally, Stuart ((*Historical and descriptive anecdotes*, p. 628) refers to a sample of 18 *large* Cornish engines working in 1770; according to Lord's speculation (*Capital and steam-power* p. 149), they had cylinder diameters in the range of 60-70 inches. The average hp of these 18 engines was 27.22, i.e., virtually identical with the average of my method regarding the period 1760-73. But since these were large engines and the nine installed Cornish engines included in my sample for the period 1760-73 had somewhat lower hp compared to the overall mean of the sample, seems to suggest the possibility of upward bias. But it is a discrepancy that refers to only one county and thus does not warrant placing excessive weight on it.

Appendix II: Alternative methods of calculating hp

A really rough but very easy method to calculate nominal hp is to adopt a rule suggested by Farey according to which 90 square inches of cylinder diameter = 1hp.[57] Mott reflects a similar view by arguing that "the potential power of an engine was proportional to the square of the diameter these engines were capable of developing."[58] If this rule was accurate we could use a fairly large amount of data on cylinder diameters provided by Kanefsky and supplement it by the approximately four dozen engines

[57] *Treatise on the steam engine*, p. 237.
[58] "The Newcomen engine", p. 70.

that can be positively identified in the Brown/Smeaton list whose diameters are also stated.[59] However, when this method was tested on engines for which both the hp and the cylinder diameter are known the results were very unsatisfactory. Simply put, an increase of cylinder diameters does not increase proportionally the amount of hp and that is evident even by a cursory examination of the two respective columns in the database.[60] In fact, it is puzzling that Farey even suggested such a method in light of his statement that Smeaton's observations on 15 engines erected in the Newcastle region (1769) proved "that the powers of the engines bore no settled proportion to the dimensions of the cylinder."[61]

The formal method of calculating nominal hp is to multiply the square of the diameter of the cylinder in inches by the cube root of the stroke in ft and divide by 47. This formula is based on assumptions regarding the load on the piston and its velocity, such assumptions differing from author to author. Once again, it does not provide a reliable method because contrary to the belief that nominal and indicated hp were very similar in the eighteenth century, that is not borne out when we apply this formula to engines whose indicated hp is known.[62]

"The elements really entering into the number of horses-power which any engine will develop are, the average effective steam pressure, and the velocity of the piston."[63] There are a number of formulas which allow for the incorporation of either or both of these, most crucial, variables permitting us to calculate the indicated hp of an engine:

F1: $P \times L \times A \times N/42{,}017$, where P= the pressure on the piston in lbs per square inch, A=the square of the diameter of the cylinder in circular inches, L=the length of the stroke in ft, N=the number of strokes per minute. The numerator of the fraction gives the duty whereas the figure in the denominator is used

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[59] It should be borne in mind, however, that there are discrepancies on the figures quoted in the Brown list and other sources. See Kanefsky and Robey, "Steam engines," p. 183; Kanefsky, *Diffusion of power technology*, p. 442; Galloway, *The steam engine*, pp. 128-30; Galloway, *Annals of coal-mining, vol. 1*, pp. 261-2; Rolt, *Thomas Newcomen*, pp. 120-1; Farey, *Treatise on the steam engine*, p. 234; Rogers, *The Newcomen engine*, pp. 51-2; Dunn, *An historical, geological, and descriptive view of the coal trade*, pp. 23-4.

[60] Rolt, *Thomas Newcomen*, pp. 126-7. As cylinder diameters increased, along with the amount of steam generated, it prompted the use of multiple boilers beginning in the middle of the century. According to a sample put together by Kanefsky and Robey ("Steam engines," pp. 183-4) diameters increased from 21 inches in the 1710s, to 32 inches by the 1730s, 42 inches by the 1740s, peaking at 49 inches in the 1760s. The diameter of 67 engines from the Brown list was 45.8 inches; Galloway, *The steam engine*, p. 129. On this trend as well as large lists of cylinder sizes, see Barton, *Cornish beam engine*, pp. 20, 270; Briggs, *The power of steam*, p. 51; Flinn, *British coal industry*, p. 123; Rogers, *The Newcomen engine*, pp. 51-2.

[61] *Treatise on the steam engine*, p. 234.

[62] Kanefsky argues that, by driving hard an engine, nominal and indicated hp could deviate from each other but not by much; *Diffusion of power technology*, pp. 23, 28. See also Bourne, *Handbook of the steam-engine*, pp. 208-10.

[63] Rigg, *Practical treatise on the steam engine*, p. 14.

when *A* is expressed in circular inches as is the case in Kanefsky's database. If the diameter of the cylinder is expressed in square inches then the figure used in the denominator ought to be 33,000. To convert circular to square inches we multiply the square of the diameter by 0.7854.[64]

F2: *A x L x N/6,000*.[65]

F3: *(d-1)² x L x N/5,640*, where *d* is the diameter of the cylinder.[66]

The problem we have here, however, is that while we have *average* figures for a large number of engines regarding the pressure and the number of strokes, we have very few figures on these two variables referring to particular engines that would allow us to calculate their hp. An alternative method contemplated was to use mean figures and impute them on engines for which this information was missing to supplement data on cylinder diameters and length of stroke.

Regarding pressure, that of the atmosphere is 15 lbs/square inch but the vacuum in atmospheric engines was so imperfect that the effective pressure was bound to be lower. Watt believed that the typical figure before he came to the scene was 6.8 lbs/square inch for small engines and 6.94 for large ones (e.g., 100 hp); subsequent writers rounded up the figure to 7 lbs. On the other hand, Kanefsky has argued that the true figure was more like 9-10 lbs. Watt, however, seems to have been right on. The average pressure of 15 engines from the Brown list was 6.72 lbs and when supplemented by data on six other individual engines the range is 5-c.11 lbs whereas the mean is 7 lbs.[67]

Regarding the number of strokes, we have data only from a handful of engines, the range being 6-15. Watt believed that the typical velocity of engines prior to his arrival on the scene was 128 ft; Kanefsky challenges this figure too, raising it to 200-250 ft and Rigg's estimate backs him up. However, to the author's surprise, these figures are way off the mark. Taking into account the average of 15 engines from the Brown list supplemented by figures on ten additional engines, provides a range of 50-105 ft

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[64] Bourne, *Catechism of the steam engine*, p. 103; Hodge, *The steam engine*, pp. 43, 161; Farey, *Treatise on the steam engine*, p. 440; Benjamin, *The steam engine,* p. 2; Perry, *Elementary treatise on steam*, pp. 61-2; Burn, *The steam-engine*, p. 99.

[65] Farey, *Treatise on the steam engine*, p. 165.

[66] Bourne, *Treatise on the steam engine*, p. 247. For other formulas utilized, some less straightforward, see Allen, *The science of mechanics*, pp. 337-40; Farey, *Treatise on the steam engine, vol. II*, p. 230.

[67] Kanefsky, *Diffusion of power technology*, pp. 22-3; Galloway, *Annals*, pp. 261-2; Galloway, *The steam engine*, pp. 129-30; Rolt, *Thomas Newcomen*, p. 126; Bourne, *Handbook of the steam-engine*, p. 211; Rigg, *Practical treatise on the steam engine*, p. 14; Allen, *The science of mechanics*, pp. 337-8; Scott, *The engineer's and machinist's assistant*, p. 48; Farey, *Treatise on the steam engine*, p. 234; Stuart, *Historical and descriptive anecdotes,* p. 292; Hawkins, *Hand book of calculations*, p. 79. Additional data were utilized from the revised database.

and a mean of either 61.54 or 91.66 ft, well below any of the aforementioned estimates, including Watt's very conservative one.[68]

Attempts were made to compute the hp of individual engines by using the aforementioned means of pressure and velocity and applying F1, F2, and F3 but the results were not encouraging when testing these formulas on engines whose hp is already known. Given the wide range of deviations from both means, knowing the latter was not a good substitute for the lack of precise information on the pressure and velocity of specific engines.

Appendix III: Data augmentation and logistic vs. Gompertz model testing

By Lawrence Costa and Michel D. Dilmanian

This appendix discusses the paper's testing methodology and presents statistical results. We cover the procedure used to impute unobserved horsepower figures and that used for testing whether a Gompertz or logistic model best tracks Newcomen engine diffusion.

Determining the Appropriate Diffusion Model

We estimate both logistic and Gompertz models using the data for aggregate horsepower installed, aggregate horsepower in use, and horsepower installed in relation to the top six counties adopting steam power by 1773. We then compare the relative goodness of fit using a Vuong test. The methodology is described below.

Logistic Model

Following Verhulst's model as exemplified by Pearl and Reed, the logistic curves are estimated using the form $y = \frac{L}{1+ae^{-bt}}$ where *y* represents the predicted horsepower figures, *b* and *a* are positive

[68] The discrepancy in the mean figures stems from the fact that Farey states the velocity of the 15 Brown engines as 50.1 whereas Stuart as 100.2 ft and that affects the weighted mean figure. Kanefsky, *Diffusion of power technology*, pp. 22-3; Bourne, *Handbook of the steam-engine*, p. 211; Rigg, *Practical treatise on the steam engine*, p. 14; Farey, *Treatise on the steam engine*, p. 234; Stuart, *Historical and descriptive anecdotes*, p. 292. Additional data were utilized from the revised database.

parameters, *t* represents the period/observation, and *L* is a scaling parameter.[69] We then define $Y = \ln(\frac{L}{y} - 1)$, $\alpha = \ln(a)$, and $\beta = -b$. Thus the logistic function is transformed to the linear form $Y = \alpha + \beta t$, which is estimated by least squares. The model is fit by choosing an *L* that minimizes the squared difference between the predicted *y* and the observed value. In our case, this optimization is performed using Microsoft Excel's Solver add-in.

Gompertz Model

The Gompertz model is approximated according to the method outlined by Franses.[70] We begin with the standard Gompertz form: $y_t = \alpha e^{-\beta e^{-\gamma t}}$ where *y* is the predicted horsepower figure; α, β, and γ are positive parameters; and *t* denotes the period. Taking the natural logarithm, we arrive at the equation $\ln(y_t) = \ln(\alpha) - \beta e^{-\gamma t}$. Finally, we take first differences: $\ln(\Delta\ln(y_t)) = -\gamma t + \ln(\beta e^{\gamma} - \beta)$ where Δ represents the first difference operator, and estimate the equation using nonlinear least squares. Again, we make use of Excel's Solver for this estimation.

Testing

We apply two tests to determine which model best fits the data. The first of these, derived by Franses, appears biased toward the logistic model and, unsurprisingly, indicates that it is a better fit across the board.[71] Essentially, the Franses test rewrites both the logistic and Gompertz models in a similar fashion and then tests whether some auxiliary terms in the logistic form are statistically different from zero. The problem lies in an asymmetry. The terms must be statistically zero for a Gompertz result; anything else indicates a logistic fit.

A more satisfying approach follows from Lien and Vuong who specify a likelihood test based on the theory developed by Vuong.[72] In this case we compare the error terms from the predicted *y*-values of each model and use them to derive the Vuong statistic, denoted by *LR*:

$$LR = \frac{\ln\left(\sum_{t=1}^{T} e_{G,t}^2 / \sum_{t=1}^{T} e_{L,t}^2\right)}{\sqrt{\sum_{t=1}^{T}\left(\frac{e_{G,t}^2}{\sum_{s=1}^{T} e_{G,s}^2} - \frac{e_{L,t}^2}{\sum_{s=1}^{T} e_{L,s}^2}\right)^2}}$$

[69] "On the Rate of Growth."
[70] "Fitting a Gompertz Curve."
[71] "A Method to Select Between Gompertz and Logistic Trend Curves."
[72] Lien and Vuong, "Selecting the best linear regression model"; Vuong, "Likelihood Ratio Tests."

where *e* denotes the error terms corresponding to either of the two models, the subscript *G* denotes the Gompertz model, and the subscript *L* denotes the logistic.

The Vuong statistic is reported on a *t*-scale and tests whether the two models' errors are significantly different. A significant negative result indicates that the Gompertz curve is a better fit—note that it is the first term in the numerator—and a significant positive result points toward the logistic model.

Data Augmentation Procedures and Test Results

Only 44 of 566 relevant engines in Database K have an indicated horsepower.[73] In order to mitigate this problem, we apply three methods of increasing sophistication to both the aggregate and the aggregate in-use horsepower figures.

Method 1 (Decadal Means): We fill in the gaps using the average horsepower for a given decade (e.g., missing values in the year 1725 would be filled in with the average value from 1720-1729).

Method 2 (Static Bins): We use a Monte Carlo simulation of an Approximate Bayesian Bootstrap (ABB) technique to impute unobserved horsepower values.[74] In each iteration of the test, engines are grouped into decade long bins. The ABB technique follows a two-stage process. In the first step, we take a random sample with replacement of the available horsepower values for each bin; in the second, we choose an imputed value (again, with replacement) from the first stage sample. The bins ensure that an engine without an existing horsepower receives an imputed value from a contemporary engine, rather than one separated in time by as much as half a century.[75]

Let us restate the preceding method mathematically. For each bin we consider a sample $y_1, \dots, y_n$, where the first i values are observed and the following $n - i$ values are missing, and where $i < n$. In the first stage, we sample and replace i values from $Y_{observed} = (y_1, \dots, y_i)$ to create the set $Y^*_{observed}$. In the second stage, we choose the imputed values from $Y^*_{observed}$. This creates the imputed set $Y^*_{missing} = (y_{i+1}, \dots, y_n)$.

Method 3 (Dynamic Bins): We repeat the Monte Carlo simulation using 20-year rolling bands instead of static bins. Thus, an engine without an associated horsepower datum receives an imputed value from an

[73] A 45th engine, installed in the 1760s, could not be assigned a specific year.
[74] The ABB is described in Schafer, "Multiple imputation."
[75] Using linear regression, we first confirm that the data reflects an increasing trend in horsepower over time.

engine erected within plus or minus ten years. By drawing imputed values from equally wide bands on both ends of the unobserved value, this approach seems most effective in mitigating the problem of increasing horsepower over time.

Both of the Monte Carlo simulations (*Methods 2* and *3*) are repeated 1000 times. Excel's Analysis add-in is used for random sampling, Excel's Solver add-in performs the Gompertz and logistic optimizations, and the repeated iterations are automated using an Excel VBA macro. The results from our tests are reported in the tables below.

Table A3.1: Vuong statistics for aggregate horsepower installed by testing procedure

	Decadal Means	Static Bins	Dynamic Bins
Vuong Statistic	-3.11766	-3.38231	-4.09967
Standard Deviation	N/A	0.969031	0.694526
Model Indicated	Gompertz	Gompertz	Gompertz
HP Observations	44	44	44
Years	68	68	68
Imputed Values	522	522	522
Simulations	1	1000	1000

Table A3.2: Vuong statistics for horsepower in use by testing procedure

	Decadal Means	Static Bins	Dynamic Bins
Vuong Statistic	-2.76371	-3.1405	-3.80655
Standard Deviation	N/A	1.067384	0.712661
Model Indicated	Gompertz	Gompertz	Gompertz
HP Observations	44	44	44
Years	68	68	68
Imputed Values	522	522	522
Simulations	1	1000	1000

Note: Regarding the in-use figures, we assume that all installed capacity is in use until 1714, when the first engine is taken out of service. From then on, we assume that 57% of installed capacity is in use.

Note that, in both tables above, the method using dynamic bins is the most statistically robust—it yields the largest Vuong statistic (in absolute value) and a smaller standard deviation compared to the static bins approach. Therefore, we use imputed data from this method as the basis for the aggregate and in-use diffusion graph in the paper (Figure 2).

Last, we find Vuong statistics by county. ABB data imputation in this case is untenable given the sparseness of observations. Instead, we use decadal means to fill in unobserved horsepower values (*Method 1* above). To avoid large breaks resulting from gaps in the data, we also use linear interpolation to account for years when no engines are recorded as installed. Given that our Gompertz estimation makes use of the natural logarithm of first differences, it is unfeasible to simply repeat values. However, when approximating repeated values by making slight adjustments to the figures (e.g., by adding .1 HP per year over the span of the gap in the data), the results are not significantly different from those using linear interpolation.

Table A3.3: *Results for the Vuong-statistic for horsepower by county (top 6)*

	Cornwall	Derbyshire	Durham	Gloucestershire	Northumberland	Shropshire
Vuong Statistic	2.25	-1.18	1.80	3.28	4.06	3.75
Model	logistic	N/A	N/A	logistic	logistic	logistic
Years	64	57	60	39	56	59

Concluding Remarks

Our results indicate that while most of the county-specific diffusion rates may be better approximated by a logistic model, the figures for aggregate installed horsepower and in use horsepower more closely fit the Gompertz equation.

We postulate that, given more horsepower observations, the county results may be different. The sparse data typically leads county diffusion tests to start with years after 1706. Since the early stages of a Gompertz diffusion are characterized by a slow initial period followed by a pronounced uptick, this truncation of the observed date range favors a logistic result. What would normally be the Gompertz upturn ends up occurring at the start of the observation range. Thus, it looks more akin to the very early stages of a logistic diffusion. Either way, we note that the county level results should be interpreted with care. While the aggregate diffusion tests are based on a significant number of observations, the county level data sets are smaller; furthermore, some years in those cases are interpolated rather than observed.

Moreover, our analysis supported concerns about the applicability of the Franses test. It indicated a logistic curve in every case, even when the sum of squared errors was lower with the Gompertz model.

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