8. The diffusion of the steam engine in eighteenth-century Britain

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INTRODUCTION

Whilst economic historians have long discussed the nature and the determinants of technical change in the early phases of industrialization (see Habakkuk, 1962; Landes, 1969; Mathias, 1983; just to mention a few classical contributions), comparatively less attention has been devoted to the diffusion of new technologies in this historical period. Reviewing the state of the art more than thirty years ago, Rosenberg noted:

> [I]f we focus upon the most critical events of the industrial revolution, such as the introduction of new techniques of power generation and the climactic events in metallurgy, our ignorance of the rate at which new techniques were adopted, and the factors accounting for these rates is, if not total, certainly no cause for professional self-congratulation. . . . Our knowledge of the sequence of events at the purely technical level remains far greater than our knowledge of the translation of technical events into events of economic significance. (Rosenberg, 1976: 189–90, note that the original paper was published in 1972)

At the time, Rosenberg was undoubtedly right in indicating the existence of a fundamental and largely unexplored research issue. Since then, some considerable progress has been made, so that today we have a number of studies which portray with some accuracy the patterns of diffusion for a number of key technologies of the industrial revolution. To name just a few major contributions, Hyde (1977) has analysed the diffusion of iron production techniques, David (1975, chs. 4, 5) has studied the diffusion of the reaper in the USA and in Britain, and von Tunzelmann (1978) and Kanefsky (1979) have examined the diffusion of power technologies. These studies have also ventured some way towards interpreting the factors driving the process of diffusion (sometimes igniting interesting controversies such as in the case of Alan Olmstead's (1975) critique of David's study of the reaping machine). Furthermore, in certain cases, the analysis of the diffusion process has also induced some overall reassessment of the role played by specific technologies in the process of economic growth.

This chapter serves a twofold purpose. The first is to provide a thorough reconstruction of the early diffusion of steam power technology (in the form of Watt and Newcomen engines) by providing new estimates for the timing, the pace and the geographical extent of steam engine usage during the eighteenth century. The second goal is to assess the factors influencing the adoption of steam engine technology in this period. In particular, the chapter will pay attention to the process of *spatial spread* of steam technology during the eighteenth century. The focus on the geographical aspects of the diffusion process is motivated by the fact that a growing number of contributions have argued (in our view rather compellingly) that a proper understanding of the processes of economic change taking place during the British industrial revolution needs to be based on a regional perspective (Pollard, 1981; Langton, 1984; Hudson, 1989; Berg and Hudson, 1992). In particular, these authors claim that industries exhibiting fast rates of output growth and extensive technical and organizational changes displayed a strong tendency towards regional concentrations. From these considerations, it is clear that, when accounting for the diffusion of new technologies in this period, due attention must be paid to spatial aspects.

The rest of the chapter is organized as follows. In the next section we present a brief overview of the development of steam power technology in the course of the eighteenth century. Clearly the aim of this section is to provide the necessary background (from the history of technology) to our diffusion study. In the third section, we provide a broad outline of the geographical diffusion patterns of Newcomen and Watt engines. In the fourth section, by estimating 'adoption equations' of various types of steam engines by county, we assess the relative role of a number of specific location factors. In the same section, we also attempt to interpret the results of our econometric analysis against the background of the existing historical accounts of the emergence of steam power technology. The final section draws conclusions.

THE DEVELOPMENT OF STEAM POWER TECHNOLOGY DURING THE EIGHTEENTH CENTURY

In the late seventeenth century mining activities began to be severely hampered by flooding problems. Following the scientific investigations of Torricelli and Pascal, there were several attempts to use atmospheric pressure to lift water out of mines. The Savery engine, clearly inspired by the scientific investigations of the time, can be considered as the first successful effort in this direction. The engine was developed in the period 1695–1702. In the Savery engine, steam was first admitted and then condensed inside a 'receiving' vessel by pouring cold water over its outside. Following steam condensation, atmospheric pressure drove the water to be pumped up into the vessel. The engine suffered from two major shortcomings, which severely limited its practical utilization. The first defect was the restricted height of operation: the suction lift could raise water only to a height of 20 feet (about 6 metres). The second was the high fuel consumption due to the need to re-create steam inside the vessel at each stroke. Undoubtedly, the historical importance of the Savery engine lies more in its showing the general potentialities of the use of steam power rather than in its practical applications, although a number of such engines continued in practical use for many years.

The Newcomen engine, developed in 1712, resolved the problem of the limited height of operation. The engine consisted of a piston-cylinder arrangement connected to one arm of a working beam. The opposite end of the working beam was connected to the mine pump-rod. Steam was admitted from the boiler into the cylinder by means of a valve. Then a cold jet of water was sprayed into the cylinder, condensing the steam. This created a partial vacuum inside the cylinder, so that the piston was pushed down by atmospheric pressure[1] (the top of the cylinder was open), lifting the pump-rod at the other end of the beam. The use of the cylinder-piston arrangement together with the beam made possible the use of the engine for effective mine drainage, as pump-rods could easily be extended to reach the necessary depth. Furthermore, the Newcomen engine was robust, highly reliable and based on a fairly simple working principle.

Given these merits, it is not surprising that Newcomen engines soon came into widespread use in mining activities. However, the Newcomen engine had two main technical shortcomings. As with the Savery engine, one deficiency was the high fuel consumption due to the need for cooling and heating the cylinder at each stroke. The second limitation was the irregularity of its movement, which prevented the use of this kind of engine for directly delivering rotary motion.[2] Savery and Newcomen formed a partnership to exploit the patent rights of their inventions (Savery had been granted a patent for his invention in 1699). The patent expired in 1733.

The problem of the high fuel consumption of the Newcomen engine was successfully tackled by James Watt in the late 1760s. In the Watt engine condensation was carried out in a separate vessel and not in the cylinder, so there was no need to re-heat the cylinder at each stroke. The Watt engine, like the Newcomen engine, consisted of a piston-cylinder arrangement connected with a working beam, but the piston was pushed down by the action of steam and not by atmospheric pressure (the cylinder had a closed top). After having pushed down the piston, the steam was admitted by means of a system of valves into a separate vessel where it was condensed. This allowed for a much higher fuel economy compared with the Newcomen engine.

In the second half of the eighteenth century, there were also a number of attempts to introduce modifications to the Newcomen engine so that it could deliver a steady rotary motion. The most convenient solution was patented in 1780 by James Pickard. It involved the combined use of the crank and a flywheel (Hills, 1989: 60). At more or less the same time, Watt, at the insistence of his business partner Matthew Boulton, was also working on the transformation of reciprocating into rotary motion. Pre-empted by Pickard in the use of the crank, Watt was forced to contrive an alternative mechanical device, the 'sun and planet' gear. However, after the expiration of Pickard's patent, in 1794, Boulton and Watt resorted to the use of the simpler and more effective crank (von Tunzelmann, 1978: 20). The conversion of reciprocating into rotary motion was also facilitated by the development of the double-acting engine, another invention by Watt, which was patented in 1782. In the double-acting engine steam is alternatively admitted into the cylinder on both sides of the piston. This resulted in a more powerful action, but also in a much more uniform movement of the piston, making the Boulton and Watt double-acting design state-of-the-art for applications requiring rotary motion.

Finally, in the second half of the 1790s, Richard Trevithick developed the first high-pressure engine (Watt engines used steam at a little more than atmospheric pressure). This type of engine did not use the separate condenser, but discharged exhaust steam directly into the atmosphere. For this reason, they were called 'puffers'. The main advantage of this type of engine was the compactness and the cheaper cost of installation due to elimination of the condenser, the air pump and the beam (von Tunzelmann, 1978: 23). The nineteenth-century development of steam power technology was to be increasingly characterized by the use of higher and higher steam pressures, though usually in combination with condensing.

DIFFUSION PATTERNS IN EARLY STEAM POWER TECHNOLOGY

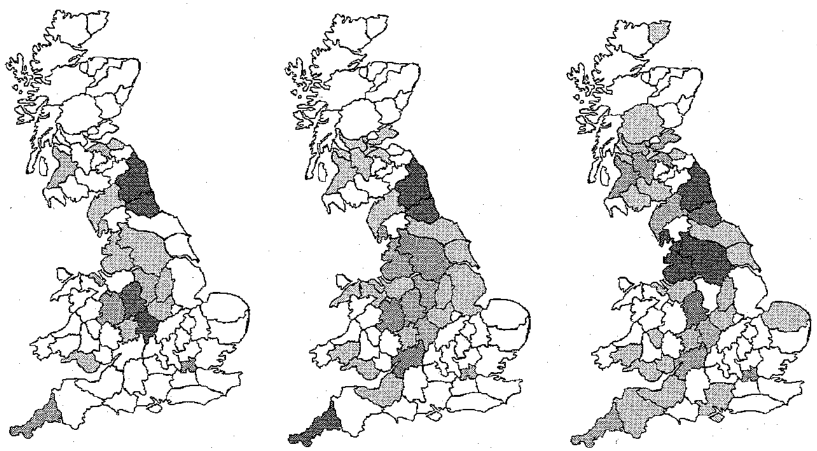
Kanefsky and Robey (1980) compiled a survey of all the steam engines erected in Great Britain in the course of the eighteenth century.[3] For each (known) steam engine erected during the period 1700–1800, Kanefsky and Robey recorded the year of construction, the type or design of the engine (that is Newcomen, Watt, and so on), the county, and the sector of application.[4] It is worth remarking that this dataset intends to cover engine construction and not engine utilization. This means that besides the year of erection there is no other information on the time period over which the engine was actually used, and there is no information on the date at which the engine was scrapped or replaced.

As the authors would admit, the data collected by Kanefsky and Robey are probably affected by some biases in both upward and downward directions. The principal source of overestimation is the double counting of engines that were moved from one place to another, whereas underestimation is mainly due to small engines that have left no trace in the records. Notwithstanding these problems (which might result in some revisions in the future), the survey constitutes the most accurate attempt to trace the growth of steam power in Britain over the eighteenth century. In this work, we employ an up-to-date version of this dataset compiled by Kanefsky.[5]

On the basis of the historical outline presented on pp. 167–9, the development of steam power technology in the eighteenth century can be divided rather naturally into three distinct 'epochs'. The first epoch (1700–33) goes from the invention of the Savery engine to the expiration of the Savery-Newcomen patent. This phase represents the early introduction of the new technology. The second epoch covers the period 1734–74. The final period goes from 1775 (the year of the first successful erection of a Watt engine) to 1800 (the year in which Watt's patent for the separate condenser expired).

The maps presented in Figure 8.1 provide a preliminary 'impressionistic' view of the geographical (county) distribution of the engines erected in these three periods. Darker (lighter) areas indicate a higher (lower) number of engines. White areas indicate that no engines were erected in that particular county. In addition, map 5 represents the geographical distribution of water-wheels (the 'predominant' power technology of the period) and map 6 illustrates the prevailing level of coal prices in the various counties in (*circa*) 1800 (again, darker areas indicate higher prices, lighter areas represent lower prices, and in this case white areas correspond to missing values).[6]

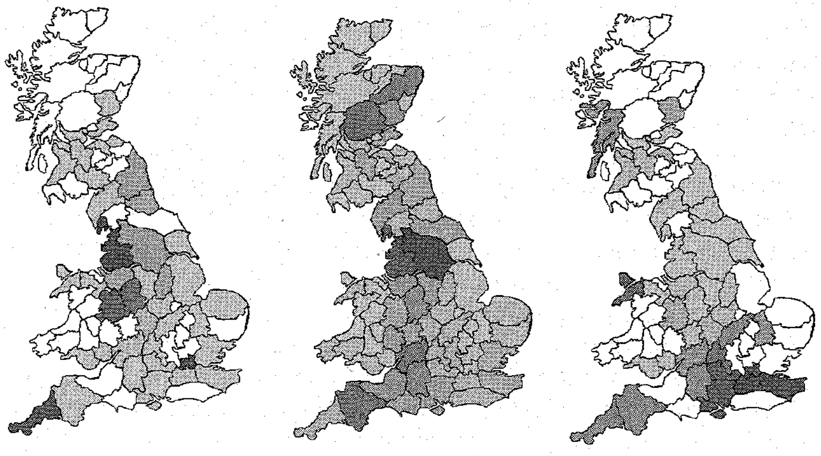
The spread of steam power technology appears to have been, from the very outset, remarkably wide.[7] Available evidence indicates that it is highly likely that the first Newcomen engine was erected in Cornwall at the Wheal Vor tin mine in 1710. However, because of the high price of coal, Cornwall did not represent the most fertile soil for the diffusion of the new technology. The erection of the Wheal Vor engine remained a sporadic event and the introduction of Newcomen engines in Cornish mines actually took place only from the 1720s (Rolt and Allen, 1997: 45).



1: Newcomen engines 1700–1733

2: Newcomen engines 1734–1774

3: Newcomen engines 1775–1800



4: Boulton & Watt engines 1775–1800

5: Water-wheels, *c.* 1800

6: Coal prices, *c.*1800

Figure 8.1 *Geographical diffusion of steam technology during the eighteenth century*

Coal mining represented of course a much more receptive environment for the new technology, since the coal would be relatively cheap. The Midlands coalfields (Stafford and Warwickshire) were the first location where Newcomen engines could take firm root. The commercialization of the engine was at first controlled by the Newcomen and Savery partnership. After Savery's death in 1715, a syndicate for the exploitation of the patent rights, the 'Committee of Proprietors of the Invention for Raising Water by Fire' was constituted. The Committee, under the direction of its secretary John Meres, promoted rather successfully the use of Newcomen engines for drainage in various mining areas by means of a network of agents and licensees.[8] Apart from the Midlands, as the map of Figure 8.1 indicates, by 1733, Newcomen engines had been adopted in some numbers in Cornwall and in the coalfields in the North East (Northumberland and Durham).

Overall, during the period of the monopoly of the 'Proprietors' about one hundred Newcomen engines were constructed. As Smith (1978: 12) has aptly remarked, for the time, this must be considered 'by any standards a colossal business achievement'. On the other hand, it should also be noted that historians (see for example, Flinn, 1984: 117) have generally contended that the high level of royalties claimed by the 'Proprietors' (up to £350 a year) hampered the diffusion process in this initial phase.[9] Be this as it may, one has to acknowledge that, under the 'Proprietors', a group of skilled engine-builders emerged, and although (as we have mentioned in the previous section) one of the main merits of Newcomen's invention was its relative easiness of construction and maintenance, in this initial phase, the engine still represented a rather sophisticated piece of equipment and its erection probably called for more than ordinary engineering skills. Thus, the formation and consolidation of this base of engine-building skills presumably represented a critical factor for the successful introduction of the engine in various locations. Among these engineers we may mention Henry Beighton, who worked for the Parrot-Sparrow partnership and compiled a table containing some rules of thumb for the proportions of the various components of the engine; Joseph Hornblower, who supervised the erection of various engines first in the Midlands and then in Cornwall;[10] Samuel Calley, the son of John Calley (the partner of Thomas Newcomen in the invention of the engine); and Marten Triewald, a Swedish engineer who installed various Newcomen engines in the North East and who would erect a (not very successful) Newcomen engine in Sweden at the Dannemora mine.

In the period 1734–74 Newcomen engines continued to be built in mining areas. However as can we see from map 2, in this phase, steam power also penetrated new locations. This wider spread of the engine was mainly due to its adoption by the iron sector (Shropshire) where it was used to assist water-wheels in blowing coke blast furnaces during drought periods (Hyde, 1977: 69–75). Newcomen engines also began to be constructed in some numbers in Scotland in the counties of the Clyde Valley.[11]

In this second phase, the 'Proprietors' had completely ceased to control the installation of the engines and Newcomen engines were typically erected by local craftsmen, leaving the cylinder, the cylinder bottom and a small number of other critical components to be manufactured by 'specialist' firms and then shipped to the location of the engine. In this respect, it is worth noting that, up to the 1780s, in Britain there existed only four ironworks that could supply cast iron cylinders for steam engines, namely Coalbrookdale and New Willey (in Shropshire), Bersham (in Denbigh) and Carron (Stirling).

The period 1775–1800 is characterized by competition between Watt and Newcomen engines. In this phase, typically textile counties such as Lancashire and Renfrew (cotton) and West Riding (wool) began to resort to some use of steam to power machinery. The main difference in the spread of the two types of engines is that Watt engines appeared capable of achieving some penetration (although in low numbers) in the counties of the South East, an area which appears, by and large, to exclude Newcomen engines.

Table 8.1 reports Moran I statistics for the three periods we are considering. Moran I statistics assess whether a variable displays a tendency to be systematically clustered in space, or, on the contrary, it is randomly spread. Higher values of Moran I statistics indicate stronger degrees of (positive) spatial autocorrelation. In other words, higher values of the statistics mean that counties with relatively high numbers of engines tend to be neighbouring (see Cliff and Ord, 1981: 42–6 for more details on the calculation of the Moran I statistic). Here the statistic was computed using a spatial contiguity matrix indicating whether two counties have borders in common or not. Significance levels have been computed under two different hypotheses: the first one holds that the observations of our variable (number of engines

Table 8.1 Spatial autocorrelation between engines

Type of engine	Period	Number of engines	Moran I statistic	Significance (normal)	Significance (randomized)
Newcomen	1700–33	97	0.167	**	***
Newcomen	1734–74	442	0.124	*	**
Newcomen	1775–1800	616	0.192	***	***
Boulton & Watt	1775–1800	479	0.074		

Notes: *,**,*** indicate significance levels of 10 per cent, 5 per cent and 1 per cent respectively.

installed in each county) are normally distributed, whereas the second one assumes that the realizations of the variable were extracted from one of the possible $n!$ permutations of the n values of the variable over the n locations (counties).

Table 8.1 shows that the Moran I statistic is higher for Newcomen engines than for Watt engines. Notably, in the case of Newcomen engines the coffiecient appears to be significantly different from zero, both when the original variable is assumed to be characterized by a normal distribution and when it is supposed to be generated by an unspecified one (randomized).

On the contrary, the Moran I statistic for Boulton and Watt engines does not turn out to be significant. This seems to indicate that the adoption of Boulton and Watt engines was less susceptible of being conditioned by specific locational factors. This finding may be accounted for by two possible sets of factors acting respectively on the demand and the supply side. On the demand side, given its superior fuel efficiency, it is likely that the adoption of Watt engines was less conditioned by the proximity to cheap coal (this is indeed consistent with the penetration of the Watt engine in the South East of England). Concerning the possible existence of spatial constraints from the supply side, it is worth noting that, apart from the early period of the 'Proprietors', the installation of Newcomen engines was typically in the hands of local millwrights and for this reason, the geographical adoption of the engine could have been limited to areas endowed with the necessary amount of engineering skills. On the contrary, as we shall see, Boulton and Watt instead adopted immediately a much wider horizon in their marketing of steam engines, aiming to serve the entire national market for power.

To compare the speed of the diffusion between counties, we have fitted logistic curves to our data.[12] In particular, we have fixed the saturation level at 100 per cent (which amounts to assuming that all the potential adopters at the end of the diffusion process will have adopted the technology). This allows us to make use of the following log-linear transformation, which can then be easily estimated using ordinary least squares.

$$\log_e\left(\frac{P_t}{1-P_t}\right)=a+b\cdot t \qquad (1)$$

In Equation (1), P_t is equal to the percentage of adopters that, at time (year) t, have erected a steam engine, a is the intercept that defines the position of the logistic curve and the slope parameter b indicates the rate of diffusion (higher values of b indicate a faster diffusion process).

We have calculated the values for P_t from the last observation (cumulative number of engines erected) in our possession (1800), assuming that this final observation corresponds to levels of saturation going from 5 to 99 per cent, adopting steps of 1 per cent. Within this set of estimations we have chosen the one with the best fit (highest R^2). Tables 8.2 and 8.3 give the results, for Newcomen and Watt engines (note that we have performed this exercise only for counties with more than four engines). The table also reports the growth time (Δt) in terms of the time interval needed for moving from 10 per cent to 90 per cent of the final saturation level and the estimated midpoint of the logistic curve. Finally, we have also calculated average compound growth rates for the number of engines constructed in each county (which represents the 'limit' case of a growth rate invariant over time).

Table 8.2 reveals some interesting aspects of the spread of Newcomen engines. Looking at the midpoint values there appears to exist a relatively ordered sequence in the penetration of the engine in various locations. The technology is first adopted in the coal mining areas of the Midlands (Stafford and Warwick), of the North East (Northumberland, Durham) and in Cornwall (copper and tin mining). In a second phase, Newcomen engines are adopted in ironworks (Shropshire). Finally, we have the penetration in typically 'textile' counties, such as West Riding (wool) and Lancashire, where the adoption appears to be characterized by slower diffusion rates. It is interesting to note that Scottish counties (Lanark, Fife and Stirling) display the highest rates of diffusion. This is probably to be explained by the initially delayed penetration of the engine in these counties. Presumably, the establishment of the Carron ironworks (which made use of the cylinder boring machine designed by John Smeaton) in Stirling in 1760 spurred the rapid adoption of steam power in Scottish counties from the early 1760s, triggering a 'catching-up' type of process.[13] Figure 8.2 charts the estimated diffusion paths for a number counties which were particularly intensive users of Newcomen engines.

If we compare Table 8.2 with Table 8.3, the much higher values of the rates of diffusion for Boulton and Watt engines are immediately evident. The average rate of diffusion (b) for Newcomen engines is equal to 0.07, whereas for Watt engines it is equal to 0.26, indicating that the diffusion process of the latter was indeed much faster.[14]

Considering midpoint values, as in the case of Newcomen engines, the adoption of the Watt engine in various locations also seems to have been characterized by a sequential order. First we have Cornwall and Shropshire (where steam engines were mainly used in ironworks), followed by the textile districts of Nottingham and later on of Lancashire and the West Riding. The table also indicates a comparatively slow rate of diffusion of the Watt engine in Northumberland (coal mining), where the cheap price of coal presumably

Table 8.2 Rates of diffusion of atmospheric engines

County	Number of engines	First erected	Growth rate	Saturation point reached in 1800 (%)	R^2	Intercept (a)	Rate of adoption (b)	Growth time (Δt)	Midpoint
Cornwall	75	1710	0.048	91	0.968	−4.150 (0.1589)	0.0761 (0.0033)	57.7	1765
Cumberland	23	1717	0.038	5	0.965	−5.946 (0.1975)	0.0367 (0.0028)	119.8	1879
Derby	62	1717	0.050	68	0.989	−4.078 (0.1133)	0.0564 (0.0018)	78.0	1789
Durham	103	1717	0.056	88	0.953	−3.437 (0.1568)	0.0606 (0.0033)	72.5	1774
Gloucester	49	1735	0.060	96	0.977	−3.297 (0.1434)	0.1008 (0.0035)	43.6	1768
Lancashire	85	1719	0.055	5	0.993	−7.725 (0.0977)	0.0579 (0.0015)	76.0	1853
Leicester	10	1724	0.030	78	0.996	−2.601 (0.0917)	0.0510 (0.0015)	86.1	1775
Middlesex	44	1698	0.037	48	0.975	−3.936 (0.1178)	0.0373 (0.0015)	117.7	1803
Northumberland	163	1718	0.063	83	0.965	−3.745 (0.1240)	0.0605 (0.0027)	72.7	1780
Nottingham	16	1728	0.038	41	0.942	−3.262 (0.2261)	0.0390 (0.0041)	112.7	1812
Shropshire	74	1715	0.051	79	0.976	−3.963 (0.1068)	0.0563 (0.0018)	78.1	1785
Somerset	8	1745	0.037	70	0.983	−1.582 (0.0908)	0.0427 (0.0018)	102.8	1782
Stafford	59	1706	0.043	72	0.952	−3.615 (0.1648)	0.0452 (0.0023)	97.2	1786
Warwick	39	1714	0.043	96	0.834	−1.877 (0.3225)	0.0468 (0.0054)	93.9	1754
Worcester	13	1725	0.034	66	0.892	−2.338 (0.2310)	0.0340 (0.0048)	129.1	1794
West Riding	100	1715	0.054	26	0.986	−5.852 (0.0949)	0.0550 (0.0014)	80.0	1821
North Riding	4	1754	0.029	85	0.894	−1.034 (0.4393)	0.0846 (0.0198)	51.9	1766
Carmarthen	5	1750	0.031	5	0.931	−4.580 (0.0946)	0.0292 (0.0050)	150.7	1907
Flint	19	1715	0.034	96	0.916	−2.079 (0.2237)	0.0554 (0.0051)	79.4	1753
Glamorgan	13	1717	0.031	83	0.939	−2.961 (0.2020)	0.0575 (0.0034)	76.4	1769
Ayr	32	1720	0.043	5	0.937	−6.002 (0.2022)	0.0361 (0.0030)	121.8	1886
Clackmannan	5	1764	0.043	5	0.968	−4.573 (0.1154)	0.0416 (0.0039)	105.7	1874
Dumfries	6	1787	0.127	99	0.993	−1.811 (0.1672)	0.4645 (0.0237)	9.5	1791
East Lothian	6	1720	0.022	5	0.702	−4.845 (0.7303)	0.0171 (0.0105)	257.0	2003
Fife	21	1764	0.083	74	0.850	−2.616 (0.3205)	0.0959 (0.0146)	45.8	1791

Table 8.2 (continued)

County	Number of engines	First erected	Growth rate	Saturation point reached in 1800 (%)	R^2	Intercept (a)	Rate of adoption (b)	Growth time (Δt)	Midpoint
Lanark	26	1760	0.081	24	0.976	−4.467 (0.1438)	0.0883 (0.0048)	49.8	1811
Midlothian	26	1720	0.041	5	0.858	−6.004 (0.2566)	0.0329 (0.0039)	133.4	1902
Renfrew	8	1767	0.061	5	0.969	−5.179 (0.2966)	0.0669 (0.0107)	65.6	1844
Stirling	18	1760	0.071	78	0.926	−2.517 (0.2366)	0.0896 (0.0080)	49.1	1788
West Lothian	9	1764	0.060	7	0.949	−3.693 (0.0792)	0.0274 (0.0027)	160.5	1899

Notes: The growth rate is the average compound growth rate. The logistic trend is estimated using the formula $\log_e[P_t/(1-P_t)] = a + b \cdot t$. Standard errors are reported in parentheses. Growth time ($\Delta t = \ln 81/b$) is the time interval (in years) for moving from 10 per cent to 90 per cent of the diffusion path. Midpoint $= -(a/b) +$ year in which the first engine was installed in the county.

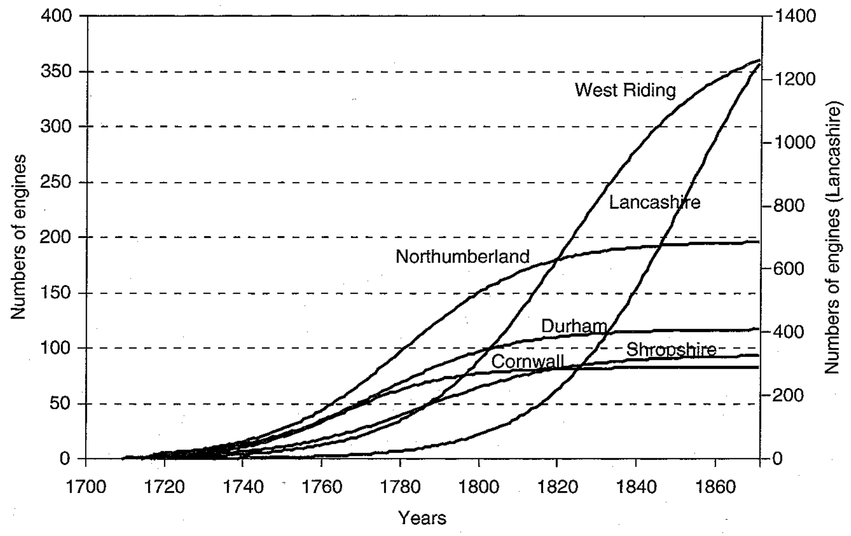


Figure 8.2 Estimated diffusion paths for Newcomen engines

gave some advantage to Newcomen engines with respect to Watt. The estimated diffusion curves for Watt engines in a number of steam-using counties are displayed in Figure 8.3.

The rank correlation coefficient between the total number of Newcomen and Watt engines erected in each county (Spearman's rho) is equal to 0.7, whereas that between the rates of diffusion is equal to 0.53. They are both significant at the 1 per cent level. This finding can be interpreted as indicating that the rates of diffusion and the extent of usage of the two types of engines were affected by a number of common factors.

Our inquiry on the patterns of diffusion reveals that steam engine technology was, from a very early stage, integrated rather successfully into several of the different 'regional production systems' which comprised the British economy during the eighteenth century (see Pollard (1981) for an overview of the distinguishing features of each regional economy). In other words, by the end of the eighteenth century steam technology had already become source of power capable of being used in a wide variety of production processes and in different local contexts.

As mentioned in the previous section, the distinctive feature of the Boulton and Watt engine was its superior fuel economy with respect to the Newcomen. Watt engines, however were normally more expensive, because of their additional components (separate condenser, air pump, and so on) and because their erection required higher engineering standards.

Table 8.3 *Rates of diffusion of Boulton and Watt engines*

County	Number of engines	First erected	Growth rate	Saturation point reached in 1800 (%)	R^2	Intercept (a)	Rate of adoption (b)	Growth time (Δt)	Midpoint
Cheshire	17	1778	0.125	49	0.983	−3.875 (0.1756)	0.1699 (0.0096)	25.9	1801
Cornwall	56	1777	0.175	99	0.907	−2.798 (0.3673)	0.2848 (0.0285)	15.4	1787
Cumberland	5	1789	0.132	81	0.985	−0.890 (0.1257)	0.2299 (0.0161)	19.1	1793
Durham	18	1791	0.301	91	0.959	−4.088 (0.6223)	0.6387 (0.0776)	6.9	1797
Gloucester	7	1787	0.139	87	0.972	−2.399 (0.1495)	0.3323 (0.0137)	13.2	1794
Lancashire	74	1777	0.188	5	0.984	−7.749 (0.1534)	0.1967 (0.0088)	22.3	1816
Middlesex	77	1776	0.182	85	0.975	−3.930 (0.1106)	0.2125 (0.0067)	20.7	1794
Northumberland	20	1778	0.133	5	0.950	−6.446 (0.3905)	0.1468 (0.0203)	29.9	1822
Nottingham	18	1786	0.198	99	0.940	−1.958 (0.3065)	0.4402 (0.0373)	10.0	1790
Shropshire	44	1776	0.157	99	0.966	−3.196 (0.2332)	0.2999 (0.0168)	14.7	1787
Stafford	38	1775	0.144	95	0.975	−3.123 (0.2104)	0.2146 (0.0116)	20.5	1790
Warwick	11	1777	0.101	8	0.965	−4.866 (0.1694)	0.1026 (0.0093)	42.8	1824
West Riding	22	1782	0.167	27	0.968	−4.283 (0.1929)	0.1851 (0.0141)	23.7	1805
East Riding	6	1779	0.081	81	0.957	−1.933 (0.1530)	0.1784 (0.0192)	24.6	1790

Notes: See Table 8.2.

On the basis of the available data on the fuel consumption of the two types of engines and of their capital costs, von Tunzelmann (1978, ch. 4) calculated the threshold levels of the price of coal at which it would have been convenient for a fully rational entrepreneur to adopt a Boulton and Watt engine. Figures 8.4 and 8.5 contain scatter diagrams showing the relation between price of coal and the share of Watt engines in the total number of engines erected in the county during the period 1775–1800. We have also plotted the threshold levels as calculated by von Tunzelmann (1978). Note that there are two threshold levels in each diagram: the first (and lower) one (I) indicates the threshold for a new engine, the second one (II), the threshold for the replacement of an existing Newcomen engine with a new Boulton and Watt one.[15] Figure 8.4 considers the case of reciprocating engines (where the gap in fuel efficiency between the Newcomen and Watt engines was larger), whereas Figure 8.5 displays the scatter diagram for rotary engines. It is important to remark that these threshold levels are computed for best-practice techniques.

Figures 8.4 and 8.5 suggest that the price of coal was indeed one of the major determinants (acting on the demand side) dictating the adoption of a Watt *vis-à-vis* a Newcomen engine. In other words, an interpretation of the patterns of adoption of steam engine in terms of the threshold model is surely consistent with some broad features of the diffusion process. However, considering that most counties are situated in what seems to be a 'transitional' state, it is clear that non-economic factors, possibly in combination with information delays and 'entrepreneurial failures', also affected the geographical spread of steam power technology.[16] In this respect, it must be recognized that the adoption of a new technology involves much more than the assessment of the direct costs and benefits between different pieces of equipment as is assumed in threshold view of the diffusion process, but is

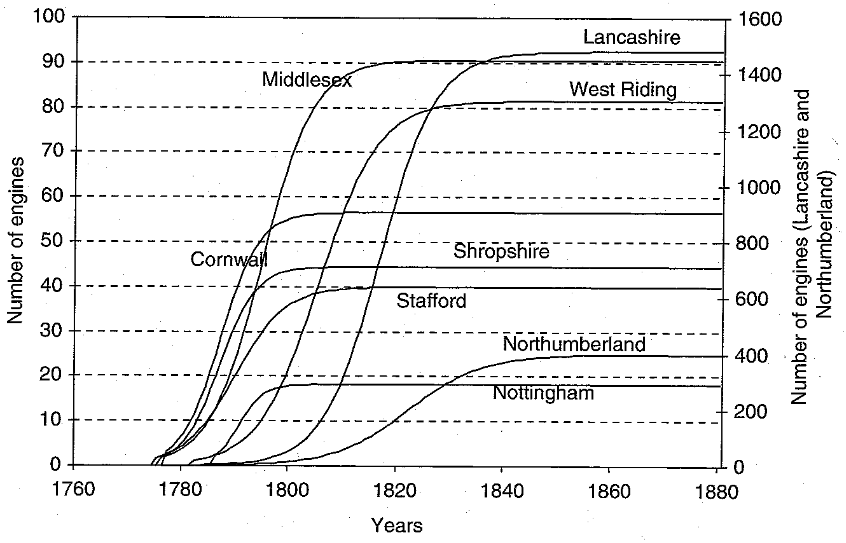


Figure 8.3 Estimated diffusion paths for Watt engines

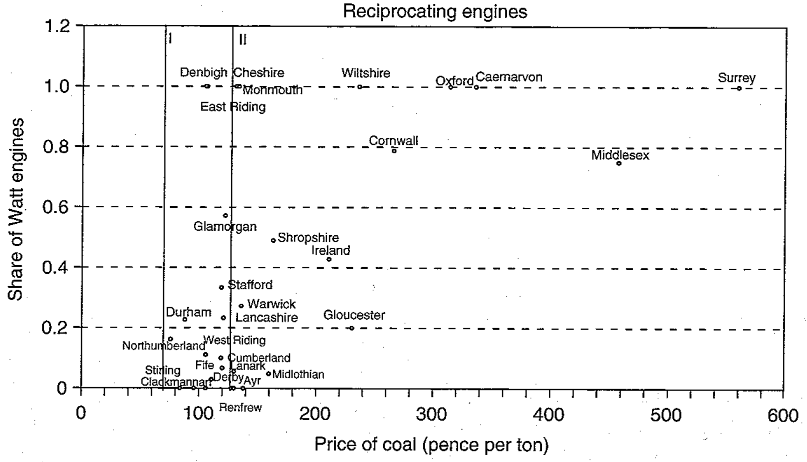


Figure 8.4 Price of coal and share of Watt reciprocating engines

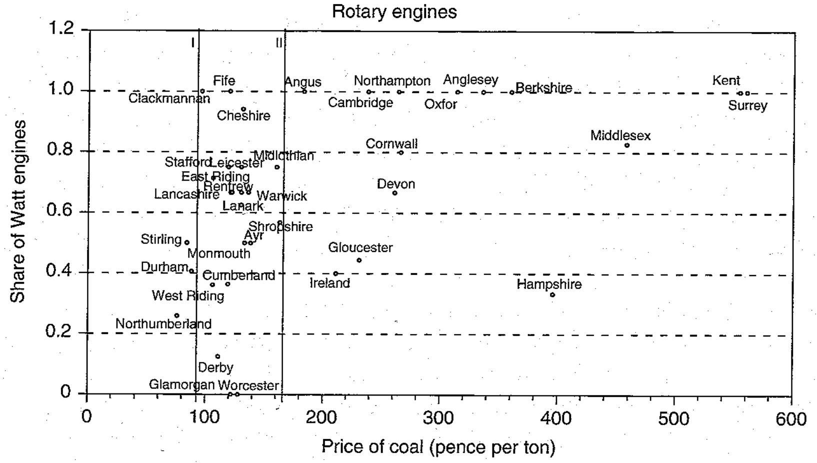


Figure 8.5 Price of coal and share of Watt rotary engines

likely to reflect a host of other factors, such as the development of skills in operating the various technologies, the expectations concerning possible future technological developments and the fit of the new technology with complementary pieces of equipment and other contingent production activities. All this makes the adoption of new technologies the outcome of a particularly complex decision process, which goes well beyond the relatively straightforward profitability calculation based on current factor prices (Gold, 1980).

AN ECONOMETRIC MODEL OF ENGINE ADOPTION

In order to shed some additional light on the factors driving the spread of steam power technology we estimate 'adoption' equations for eighteenth century steam engines. We focus on the late eighteenth century (1775–1800) and estimate two distinct models for Newcomen and Watt engines. Clearly, the aim is to check whether there were noteworthy differences in the factors driving the diffusion processes of the two types of engines. Our dependent variable is the number of steam engines (Newcomen or Watt) erected in each county in the period 1775–1800. In both cases, the distribution of the variables is skewed, with a non-negligible number of counties having no (that is, zero) engines. Accordingly, we will make use of negative binomial regressions for estimating the two models (Greene, 2000: 880–93; for a thorough treatment of regression analysis techniques with count data, see Cameron and Trivedi, 1998). Our explanatory variables are:

1. the price of coal prevailing in the county;
2. a dummy indicating the level of coal prices in a dichotomous way (that is low/high, with low being approximately less than 14 s.). This characterization of the price of coal variable allows us to use in the estimation of the regression equation all the counties and not just the 41 for which coal prices are directly available. Furthermore, one could argue that the dummy specification is a more appropriate representation of 'threshold' behaviour. The dummy variable has been constructed considering the studies of the coal mining industry of Flinn (1984), von Tunzelmann (1986) and Turnbull (1987);
3. the number of water-wheels, which can be considered as a proxy for the demand for power (note that in some applications such as ironworks and textiles, steam engines were initially used to assist the operation of water-wheels during drought periods);
4. the number of steam engines erected in the previous period (that is 1734–74) which captures, admittedly in a rough way, both the familiarity of potential users with steam technology and the (possibly related) level of 'mechanical skills' in the county in question;
5. the number of blast furnaces in operation existing in the county *c.* 1800;
6. the number of cotton mills existing in the county *c.* 1800;
7. the number of woollen mills existing in the county *c.* 1800.

The last three variables are included in order to assess the influence of industries (ironworks and textiles) that were among the most intensive users of steam power. A complete description of the sources and the construction of the variables used is given in the Appendix.

Admittedly, our set of explanatory variables is far from covering all the potential factors affecting the diffusion of steam technology in the period in question. In particular, our variables consider mainly factors acting on the demand side. Coal prices reflect the cost of a unit of power for the adopter of a steam engine. However this coefficient can also reflect the use of the steam engine in coal mines (as in coal mining areas coal was cheap). Similarly, the number of water-wheels is a proxy for the overall demand of power existing in the county, but, at the same time, the variable can also capture some 'substitution' or 'complementarity' effects between steam and water power. The sectoral variables (number of blast furnaces, number of cotton mills, number of woollen mills), indicating the size of different branches of economic activities in various counties, are obviously aimed at accounting for the different (steam) power requirements of a number of application sectors. Note that our coverage of application sectors cannot by any means considered as exhaustive. Lack of suitable data has prevented us from estimating for a sufficient number of counties the size of a number of sectors which were very intensive users of steam power, such as mining, food and drink (breweries) and waterworks and canals. As already mentioned, the variable 'engines erected in the previous period (1734–74)' aims at capturing the degree of familiarity (of both adopters and suppliers) with steam technology extant in each county. In this sense the variable controls for a mix of effects operating both on the supply and on the demand side.

It is fair to say that our model neglects the possible 'proactive' role played by the suppliers of the technology in the diffusion process. As we have already mentioned, the high rates of diffusion for Watt engines estimated in Table 8.3 were plausibly not only determined by the superior fuel efficiency of the Watt engines, but also by the effectiveness of Boulton and Watt's organization of steam engine production and marketing techniques. From the very outset, Boulton and Watt wanted to establish themselves as a leading 'national' producer of steam engines.[17] Instead, the construction of Newcomen engines was mainly undertaken by local manufactures with narrower and less ambitious business horizons.[18]

In this respect, Roll (1930) and Dickinson (1936) stressed the critical role played by Boulton's entrepreneurial and marketing abilities for the success of the partnership.[19] Boulton's efforts ensured that Watt engines were quickly adopted in a wide range of industrial applications, which before had not made much use of steam power (breweries, textiles, and so on). For example, the erection of the famous Albion Mills in London is frequently pointed out as an example of a successful marketing strategy which succeeded in triggering the interest in steam power of many industrialists (in particular, breweries) in the London area.[20] Another initiative aimed at broadening the use of steam technology was the publication by Boulton and Watt of small technical booklets (of course only reserved for their customers) providing detailed descriptions of the procedures for erecting and operating their engines. In this way, 'distant' customers could hopefully be able to cope with minor technical difficulties without the assistance of Boulton and Watt's men.

Furthermore, Boulton and Watt successfully established standard units of measure for both the fuel efficiency (duty) and the power (horsepower) of steam engines. Note that the establishment of a standardized unit of power was an event not only of technically, but especially of economic significance (perhaps one of the main determinants of the successful adoption of the engine in various manufacturing applications). The horsepower unit permitted industrialists to have a rather reliable assessment of their power requirements and it also permitted a rough, but rather effective, cost-benefit analysis of the adoption of various power sources. Rules of thumb soon came into common usage for expressing the power requirements of a number of industrial processes (for example in cotton spinning 1 horsepower was typically supposed to drive 100 spindles).

From these considerations it is clear that our econometric exercise can hope to provide just a partial appraisal of the determinants of the usage of steam technology in the late eighteenth century. Hence, the results ought to be regarded with care, taking into account the possible influence of factors not included in our set of explanatory variables.

Tables 8.4 and 8.5 give the results of the estimates for Newcomen engines. Table 8.4 includes all the specifications with the coal dummy variable (these regressions include all observations in our sample), whereas Table 8.5 covers the specifications employing the price of coal variable (these regressions refers to a more restricted sample of 41 counties). We have estimated the coefficients considering two different forms of the negative binomial density function. In the first case we have assumed that the negative binomial density function has mean equal to μ and variance

Table 8.4 'Adoption' equations for Newcomen engines, 1775–1800

Model	(I)		(II)		(III)		(IV)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	84	84	84	84	84	84	84	84
Constant	1.122***	1.328***	0.270	0.633**	1.497***	1.855***	1.390**	1.647***
	(0.334)	(0.261)	(0.363)	(0.273)	(0.463)	(0.273)	(0.285)	(0.218)
Dummy coal	−1.919***	−1.740***			−2.021***	−1.901***	−1.900***	−1.613***
	(0.359)	(0.333)			(0.436)	(0.346)	(0.369)	(0.335)
Water-wheels	0.003	0.004**	0.003	0.002	0.008**	0.004**		
	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)		
Engines	0.079***	0.035***	0.078***	0.046***			0.087***	0.037***
	(0.021)	(0.004)	(0.028)	(0.005)			(0.022)	(0.004)
Blast furnaces	−0.005	0.032*	0.063	0.068***	0.008	0.035	0.011	0.045***
	(0.043)	(0.016)	(0.059)	(0.017)	(0.046)	(0.023)	(0.045)	(0.015)
Cotton mills	0.003	0.004*	0.015	0.010***	−0.002	0.005	0.008	0.009***
	(0.008)	(0.003)	(0.014)	(0.003)	(0.010)	(0.003)	(0.008)	(0.002)
Wool mills	−0.008	−0.015*	−0.014	−0.008	−0.018	−0.011	−0.001	0.002
	(0.012)	(0.009)	(0.013)	(0.009)	(0.015)	(0.009)	(0.011)	(0.004)
α	1.474***		2.586***		2.795***		1.572***	
	(0.391)		(0.603)		(0.630)		(0.403)	
δ		6.268***		9.828***		13.744***		7.331***
		(1.8)		(2.748)		(3.946)		(2.051)
Log likelihood	−172.122	−159.629	−184.825	−173.546	−186.199	−173.969	−173.160	−162.241
Pseudo R^2	0.154	0.215	0.091	0.147	0.084	0.144	0.148	0.202

Notes: Negative binomial estimations. Standard errors in brackets. *,**,*** indicate significance levels of 10, 5 and 1 per cent. The α and δ statistic verify the existence of 'overdispersion' (χ^2 test).

Table 8.5 *'Adoption' equations for Newcomen engines, 1775–1800*

Model	(I)		(II)		(III)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	41	41	41	41	41	41
Constant	1.817***	2.442***	1.962***	2.509***	2.933***	3.423
	(0.463)	(0.427)	(0.405)	(0.422)	(0.455)	(0.464)
Coal price	−0.003**	−0.007***	−0.003**	−0.006***	−0.004**	−0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Water-wheels	0.002	0.003*				
	(0.003)	(0.002)				
Engines	0.047***	0.028***	0.049***	0.031***		
	(0.016)	(0.005)	(0.016)	(0.005)		
Blast furnaces	0.047	0.039**	0.059	0.050***	0.065	0.049**
	(0.042)	(0.017)	(0.040)	(0.015)	(0.048)	(0.020)
Cotton mills	0.010	0.006**	0.012*	0.010***	0.011	0.010**
	(0.008)	(0.003)	(0.007)	(0.002)	(0.008)	(0.002)
Wool mills	−0.015	−0.013	−0.011	−0.001	−0.009	−0.001
	(0.011)	(0.008)	(0.009)	(0.004)	(0.013)	(0.006)
Log likelihood	−126.331	−113.44	−126.515	−115.116	−134.141	−125.594
α	1.190***		1.214***		2.019***	
	(0.359)		(0.362)		(0.520)	
δ		6.970***		8.124***		17.812***
		(2.301)		(2.626)		(5.853)
Pseudo R^2	0.096	0.188	0.095	0.176	0.040	0.101

Notes: See Table 8.4.

equal to $\mu(1+\alpha\mu)$. Cameron and Trivedi (1998: 62) refer to this model as 'NB 2'. In the second case we have assumed a density function with mean equal to μ and variance equal to $\mu(1+\delta)$. This case is termed 'NB 1' by Cameron and Trivedi (1998: 62). It is possible to test for the actual existence of 'overdispersion' (that is, that the variance is larger than the mean) by verifying that α or δ are different from zero. In our case this was done by means of a likelihood ratio test (Cameron and Trivedi, 1998: 77–8).

In all specifications, α and δ are significantly different from zero, confirming the existence of overdispersion and supporting our choice of negative binomial estimations. In this respect, one can note that the existence of overdispersion points to the fact that the data exhibit a higher degree of cross-sectional heterogeneity (that is clustering in counties with 'high' or 'low' number of engines), than in the case of a spatially homogeneous Poisson process.[21] In other words, the existence of overdispersion points to a pattern of spatial clustering among counties in terms of their extent of steam usage that goes beyond what can be accounted for by our set of explanatory variables. Furthermore, one could actually suggest that this cross-sectional heterogeneity reveals the existence of county-specific 'absorptive capabilities' affecting the spread of steam technology.

The coefficient for the coal dummy variable is significant with a negative sign in all the specifications in which it is included. Similarly, the price of coal (whose inclusion restricts the sample to 41 counties) is also negative and significant. These results confirm rather clearly that high coal prices deterred the adoption of Newcomen engines.

The coefficient for the variable 'engines erected in the previous period' is positive and significant in all specifications, showing the positive influence of a certain degree of 'previous' familiarity with steam technology.

The coefficient for water-wheels is significant (with a positive sign), only in the NB1 type of model. Similarly, also the sectoral variables turn out to be significant only in NB1 type of models. In this respect, one may note that NB1 models seems to display consistently a better 'fit' to the data, at least, so far as this is reflected in the 'pseudo R^2'.

The coefficient for the blast furnaces appears to be higher than the one for cotton mills, indicating a stronger relationship between iron manufacturing and the adoption of Newcomen engines. Unfortunately, lack of suitable data has prevented us from assessing the impact of the main sector of application of the Newcomen engine, coal mining.

This result probably reflects the different degree of familiarity that these user sectors had with the Newcomen engine. Newcomen engines were successfully adopted in ironworks from the early 1740s. Instead they had begun to be used to drive cotton machinery only from the 1780s. In general, the motion they delivered was rather unsteady and it was not particularly suited for powering textile machinery (Hills, 1970: 141–3). Some ingenious technical solutions that could mitigate this problem were introduced in the early 1790s by Francis Thompson and Bateman and Sherrat for the Newcomen engines installed in cotton mills in Lancashire and Nottinghamshire (Hills, 1970: 147–8; see also Frenken and Nuvolari, 2004). Finally, it is worth noting that the adoption of Newcomen engines in ironworks and in cotton mills in the period we are considering was limited by the competition of Watt engines.

The coefficient of the wool mills variable is not significant (with the only exception of regression I (NB1) in Table 8.4 where it has a negative sign). This can be accounted for by the fact that the transition to steam power mechanization in the wool textile industry (which was concentrated in Yorkshire (West Riding) and in the West of England) was much slower than in cotton. Furthermore, in this industry, the diffusion of steam technology proceeded at two very different paces in the two areas. In the West Riding, atmospheric returning engines were rapidly and rather successfully adopted for power carding and spinning machines (jennies). Table 8.2 indicates that about 100 engines were installed in the West Riding by 1800. Instead in the other wool regions of the West of England (Gloucester, Wiltshire) and of Scotland, steam power technology was introduced very slowly (Jenkins and Ponting, 1982: 50–6). The combined effect of these two contrasting patterns of adoption can help explain why the coefficient for wool mills is not significant in the majority of the specifications.

Tables 8.6 and 8.7 contain the results of the set of regressions having the number of Watt engines as dependent variable. As in the case of Newcomen engines, the tests on α and δ confirm the presence of overdispersion, upholding our choice of negative binomial estimations.

The coal dummy is significant with a negative sign in three specifications (Model I (NB 2), Model III (NB 1) and Model IV (NB 2)). It is worth noting that the (negative) coefficient is lower than in the Newcomen case. In our interpretation, rather than reflecting a direct impact of coal price on the adoption of Watt engines, this result is due to the fact that a number of counties with high levels of coal prices were also 'peripheral' or 'rural' counties with low demand for steam power. In particular, this is true for the 'northern' Scottish counties. In fact, when the model is specified in terms of coal prices (as we have said, this reduces the sample to 41 counties, centred essentially on 'industrial' counties (North of England, Wales, South of Scotland), see Appendix), the coal price coefficient appears to be generally positive and significant, providing support for the idea that high coal prices tend to enhance the adoption of Boulton and Watt engine, on account of their superior fuel efficiency.

Table 8.6 'Adoption' equations for Watt engines, 1775–1800

Model	(I)		(II)		(III)		(IV)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	84	84	84	84	84	84	84	84
Constant	0.524	0.970***	0.036	0.616**	1.082*	1.420***	0.608	1.162***
	(0.469)	(0.366)	(0.399)	(0.296)	(0.628)	(0.337)	(0.388)	(0.318)
Dummy coal	−0.831*	−0.555			−0.341	−0.934***	−0.821*	−0.541
	(0.466)	(0.355)			(0.555)	(0.328)	(0.463)	(0.357)
Water-wheels	0.001	0.002	0.001	0.002	0.004	0.003		
	(0.003)	(0.002)	(0.003)	(0.002)	(0.004)	(0.002)		
Engines	0.113***	0.033***	0.101***	0.038***			0.113***	0.034***
	(0.028)	(0.007)	(0.027)	(0.005)			(0.028)	(0.006)
Blast furnaces	0.0002	0.061***	0.044	0.076***	0.054	0.060**	0.006	0.066***
	(0.055)	(0.022)	(0.052)	(0.019)	(0.057)	(0.026)	(0.052)	(0.021)
Cotton mills	0.008	0.011***	0.015	0.013***	0.008	0.010***	0.009	0.013***
	(0.010)	(0.003)	(0.011)	(0.003)	(0.012)	(0.004)	(0.009)	(0.002)
Wool mills	0.002	−0.016	0.009	−0.016	−0.011	−0.014	0.003	−0.006
	(0.014)	(0.011)	(0.014)	(0.011)	(0.016)	(0.011)	(0.014)	(0.006)
α	2.351***		2.452***		4.165***		2.346***	
	(0.516)		(0.542)		(0.821)		(0.515)	
δ		10.805***		10.457***		14.941***		10.916***
		(3.076)		(2.956)		(4.350)		(3.095)
Log likelihood	−166.275	−164.164	−167.919	−165.364	−181.911	−170.660	−166.329	−164.754
Pseudo R^2	0.114	0.125	0.105	0.119	0.031	0.090	0.114	0.122

Notes: See Table 8.4.

Table 8.7 'Adoption' equation for Boulton and Watt engines, 1775–1800

Model	(I)		(II)		(III)	
Type	NB 2	NB 1	NB 2	NB 1	NB 2	NB 1
Number of counties	41	41	41	41	41	41
Constant	0.794*	1.111***	0.554	1.053**	1.502***	1.918***
	(0.426)	(0.426)	(0.391)	(0.415)	(0.436)	(0.378)
Coal price	0.003**	0.002*	0.003**	0.002*	0.002	0.0004
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Water-wheels	−0.003	−0.001				
	(0.002)	(0.002)				
Engines	0.046***	0.033***	0.044***	0.032***		
	(0.011)	(0.006)	(0.011)	(0.006)		
Blast furnaces	0.076**	0.060***	0.058**	0.058***	0.064*	0.057**
	(0.034)	(0.018)	(0.030)	(0.018)	(0.034)	(0.022)
Cotton mills	0.017***	0.014***	0.014***	0.013***	0.013**	0.012***
	(0.006)	(0.003)	(0.005)	(0.002)	(0.006)	(0.003)
Wool mills	0.005	−0.003	0.0004	−0.007	−0.006	−0.004
	(0.010)	(0.009)	(0.009)	(0.006)	(0.010)	(0.006)
α	0.854***		0.891***		1.479***	
	(0.221)		(0.227)		(0.329)	
δ		7.847***		7.948***		13.339***
		(2.338)		(2.363)		(3.937)
Log likelihood	−121.9162	−123.5604	−122.6542	−123.6762	−132.7414	−131.1648
Pseudo R^2	0.1154	0.1035	0.1101	0.1027	0.0369	0.0483

Notes: See Table 8.4.

The coefficient for the variable 'engines erected during the previous period' is positive and significant in all specifications (as it was for Newcomen engines). The coefficient for the number of water-wheels, instead, is never significant.

Turning our attention to the role of application sectors, Tables 8.6 and 8.7, in a number of specifications, report a positive and significant sign for the number of cotton mills and the number of blast furnaces. (In Table 8.6 the sectoral variables are significant only in NB1 regressions, as in the case of Newcomen engines, the NB1 model is characterized by a better fit as measured by the 'pseudo R^2'). Notably, the size of these coefficients is similar to the ones reported for Newcomen engines. This finding is indeed fully in line with historical accounts which pointed out that ironworks and cotton mills were among the first intensive users of the Watt engines. However, it should be noted that in the case of Watt engines as well, our adoption equations do not include a number of application sectors which were intensive users of these engines such as (non-coal) mining ventures, breweries, and so on, and that, for this reason, the estimates of the impact of application sectors should be considered with care. Finally, as in the case of the Newcomen engines, the coefficient for wool mills is not significant.

CONCLUDING REMARKS

In this chapter we have provided a reconstruction of the patterns of diffusion and adoption of steam engine technology during the eighteenth century. Our findings indicate that the level of coal prices was indeed one of the major determinants of the distinctive patterns of adoption of Newcomen and Watt engines, giving further support to the previous studies of von Tunzelmann (1978) and Kanefsky (1979). However, it is also clear that, together with the level of coal prices, a number of other factors were also at work. In this respect, it must be also acknowledged that the design of the engine did not only determine its fuel efficiency, but also the quality of the power delivered (smoothness and regularity of motion, susceptibility to breakages, and so on). Hence, particular types of engines turned out to better suited for particular applications (in some cases, despite their level of fuel efficiency). This issue is examined more in detail in Frenken and Nuvolari (2004).

Our diffusion study has also revealed that steam engine technology was, from a very early stage, integrated rather successfully into different regional production systems of the eighteenth-century British economy. However, our econometric analysis has also indicated that the regional patterns of adoption displayed considerable diversity reflecting the influence of location factors such as the price of coal and the productive structure of the various counties, but, also of more complex and idiosyncratic factors impinging on the absorptive capabilities of individual counties. In a more general perspective, this finding confirms the need of taking regional differences properly into account when examining the diffusion of new technologies during the British industrial revolution (Hudson, 1989).

These considerations also provide some indications for further research. As noted by Dosi:

> [T]he 'logistic curves' approaches to technological diffusion . . . show the same descriptive usefulness as well the same limitations of the epidemic curves (or, for that matter, probability models) to which they are formally similar: they show the pattern of diffusion of, say cholera, and they can also relate it to some broad environmental factors, such as the conditions of hygiene of a town, the reproduction time of bacteria, etc. but they cannot explain *why* some people get it and other do not, which relates to the immunological mechanisms of human bodies, the precise ways bacteria are transmitted, and so on. (Dosi, 1984: 286, italics in the text)

Thus, the reconstruction of the patterns of technological diffusion needs to be supplemented by further research on the 'microbiology' of the adoption process. In this respect, it would be wrong to assume that the diffusion of Newcomen and Watt engines proceeded neatly along 'equilibrium' paths. The available evidence on individual adoption decisions reveals that at the county level, the process of diffusion was driven by an 'epidemic' information spread. For example, Boulton and Watt frequently asked their 'first' customers in different counties to let potential buyers inspect the engines they had just installed (Hills, 1970: 156 and 158). Furthermore, one should also consider the 'proactive' role played by the suppliers of the new technology. As a consequence, the high rates of diffusion of Watt engines estimated in Table 8.3 are not simply determined by the superior fuel efficiency of the Watt engine, but they also reflect the effectiveness of Boulton and Watt's organization of steam engine production and marketing techniques. Boulton and Watt aimed immediately at establishing themselves as a 'national' producer of steam engines. Instead, in the period 1775–1800, the construction of atmospheric engines was mainly in the hands of local manufacturers with 'narrower' horizons. The wider spread of Watt engines should be also considered in this light. In this respect, Dickinson (1936) and Roll (1930) emphasized Boulton's entrepreneurial and marketing abilities, which ensured that steam power, in the form of the Watt engine, was quickly adopted in a wide range of industrial applications (for example the food industry especially breweries, textiles, and so on). Overall, the early diffusion process of steam technology in each county appears to have been driven by a complex interplay of factors (resource prices and availability, information delays, entrepreneurial failures) acting contextually both on the user's and the supplier's side. On theoretical grounds, one could consider this proposed interpretation (which, of course, needs to be corroborated by further research) as broadly consistent with 'evolutionary' types of diffusion models, where patterns of technological diffusion are seen as the emerging outcome of micro-processes of technological learning and market selection among boundedly rational agents (Silverberg *et al.*, 1988).

APPENDIX: SOURCES AND CONSTRUCTION OF THE DATA

Number of Steam Engines (Newcomen ('atmospheric') and Boulton & Watt) Installed During the Period 1775–1800 and Number of Engines Installed in the Period 1734–74

Data taken from the updated version of the Kanefsky and Robey (1980) list.

Price of Coal, *c.* 1800

Data taken from von Tunzelmann (1978: 148). The 41 counties for which coal prices were available are:

Cornwall, Devon, Wiltshire, Hampshire, Berkshire, Surrey, Middlesex (London), Kent, Cambridge, Northampton, Oxford, Leicester, Warwick, Worcester, Gloucester, Monmouth, Glamorgan, Shropshire, Stafford, Anglesey, Caernarvon, Denbigh, Cheshire, Derby, Nottingham, Lancashire, East Riding, West Riding, North Riding, Durham, Northumberland, Cumberland, Ayr, Renfrew, Lanark, Stirling, Argyll, Clackmannan, Midlothian, Fife, Angus.

Coal Dummy, *c.* 1800

The variable distinguishes between 'cheap' and 'dear' coal counties. Counties with coal prices higher than 14 s. per ton are considered as having a 'high' price of coal. The counties have assigned on the basis of the price list in von Tunzelmann (1978: 148) and of the maps and discussion of Flinn (1984), von Tunzelmann (1986) and Turnbull (1987).

Low coal price counties
Cheshire, Cumberland, Derby, Durham, Lancashire, Leicester, Monmouth, Northumberland, Nottingham, Shropshire, Stafford, Warwick, Worcester,

West Riding, East Riding, Carmarthen, Denbigh, Flint, Glamorgan, Pembroke, Angus, Ayr, Berwick. Clackmannan, Dunbarton, East Lothian, Fife, Kinross, Lanark, Midlothian, Renfrew, Stirling, West Lothian.

High coal price counties

Bedford, Berkshire, Buckingham, Cambridge, Cornwall, Devon, Dorset, Essex, Gloucester, Hampshire, Hereford, Hertford, Huntingdon, Kent, Lincoln, Middlesex (London), Norfolk, Northampton, Oxford, Rutland, Somerset, Suffolk, Surrey, Sussex, Westmorland, Wiltshire, North Riding, Anglesey, Brecknock, Caernarvon, Cardigan, Merioneth, Montgomery, Radnor, Aberdeen, Argyll, Banff, Caithness, Dumfries, Inverness, Kincardine, Kirkcudbright, Moray, Nairn, Peebles, Perth, Ross and Cromarty, Roxburgh, Selkirk, Sutherland, Wigtown.

Water-wheels, *c.*1800

Data taken from Kanefsky (1979: 215–16). The data have been constructed on the basis of contemporary maps (that is they are presumably likely to underestimate the actual figures). For more details, see Kanefsky (1979).

Blast Furnaces, *c.*1800

Data taken from Scrivenor (1854). The original source is government survey after the proposal of a tax on coal. The data refer to the year 1796.

Cotton Mills, *c.* 1800

Data taken from Chapman (1970: 257–66). Chapman's figures are based on insurance records and they mostly refer to the year 1795. For Lancashire we have estimated a figure of 204 mills, which is based on the assumption that the county had 50 per cent of large mills (types B and C) and 50 per cent of type A (that is small) mills. This is in line with the considerations contained in Chapman's paper.

Wool Mills, *c.* 1800

Data taken from Jenkins and Ponting (1982, pp. 34–38). The data refer to the year 1800. When more detailed information was lacking, an equal share of wool mills was assigned to the counties in the wool regions for which Jenkins and Ponting provide figures for the number of wool mills.

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NOTES

1. For this reason, Newcomen and Savery engines were also commonly termed 'atmospheric' engines.
2. A number of Newcomen engines were successfully used to raise water over a water-wheel which, in turn, delivered rotary motion for factory machinery. This type of engine was usually called a 'returning engine'. One major limitation of this engine was that the inefficiency of the water-wheel was combined with the inefficiency of the engine. See Hills (1989: 49).
3. See Kanefsky (1979) for a detailed account of the construction of the database.
4. Other information available for some of the engines are the maker, the cylinder size and the horsepower.
5. The list originally compiled by Kanefsky and Robey contained a total of 2191 steam engines, the new updated dataset contains 2279 engines. The updated version of the list has been kindly provided to us by John Kanefsky. Concerning Watt engines, the updated list by Kanefsky contains 479 engines. Tann (1988) on the basis of a careful examination of the Boulton and Watt papers considers this total too high. Her estimation of the engines constructed by Boulton and Watt by 1800 is 449. In this work, mainly for sake of convenience, we have utilized Kanefsky's list without attempting corrections.
6. The source for the number of water-wheels is Kanefsky (1979: 215–16) and for coal prices von Tunzelmann (1978: 148). For more details on the sources of the data used in this chapter, see Appendix.
7. Note that maps 1, 2 and 3 show the distribution of Newcomen and Savery engines considered together. As a consequence, a more precise definition would be 'atmospheric engines'. Given the relatively small number of Savery engines installed, the results of our study are not affected by ignoring this distinction.
8. The most active licensee of the 'Proprietors' was the partnership formed by Stonier Parrot and George Sparrow who were engaged in the erection of more than 15 Newcomen engines. According to Flinn (1984: 120), the high number of engines erected in Warwick and Stafford (far in excess of the two counties' share in British coal production) is to be accounted for by the fact this was the 'home stronghold' of the Parrot–Sparrow partnership. For an account of the activities of Stonier Parrot, see Rowlands (1969).
9. Kanefsky's data provide some quantitative support for this view. From 1710 to 1733, 95 Savery-Newcomen engines were constructed. This is approximately equal to four engines erected per year. In the period 1734–1774, instead, 442 engines were built, corresponding to 11 engines per year.
10. Joseph Hornblower would decide to settle definitely in Cornwall. He was the grandfather of Jonathan, the inventor of the compound engine.
11. For an account of these cases of early installation of Newcomen engines in Scotland, see Hills (2002: 297).
12. Note that here we are not interested primarily in the relative virtues of various types of S curves for the estimation of diffusion process (as one would be when engaged in a forecasting type of exercise). Following Griliches (1957), we estimate logistic trends as

'summary devices' for comparing the rate of diffusion across counties. In other words, we are more willing to accept some loss of fit in order to get results that are easily comparable.

13. In the late 1760s and 1770s, Watt himself was involved in the installation of several Newcomen engines in Scotland. The erection of these engines provided Watt, who was until then acquainted only with experimental models, with a good deal of practical experience with the problems related with the installation and operation of full scale engines (Hills, 2002: 358).
14. As a term of comparison the rate of diffusion of the high pressure expansive engine in Cornwall estimated by von Tunzelmann (1978: 258) in the early nineteenth century is equal to 0.25. Von Tunzelmann considers this as a case of a relatively fast diffusion process.
15. The threshold prices calculated by von Tunzelmann are, in case of rotary engines, 7s. 10d. for installation of a new engine and 14s. for replacement, in case of reciprocating engines 5s. 10d. for installation and 11s. 3d. for replacement, see von Tunzelmann (1978: 76–7).
16. This was also the speculative conclusion reached by von Tunzelmann (1978, ch. 4).
17. In a famous letter to Watt (7 February 1769), Boulton, declining the offer of Watt and Roebuck (the first partner of Watt) of becoming the licensee of the Watt engine in three counties, wrote: '. . . I was excited by two motives to offer you my assistance which were love of you and love of a money-getting ingenious project. I presumed that your engine would require money, very accurate workmanship and extensive correspondence to make it turn to best advantage, and that the best means of keeping up the reputation and doing the invention justice would be to keep the executive part out of the hands of the multitude of empirical engineers, who from ignorance, want of experience and want of necessary convenience would be very liable to produce bad and inaccurate workmanship; all of which deficiencies would affect the reputation of the invention. To remedy which and produce the most profit, my idea was to settle a manufactory near to my own by the side of our canal where I would erect all the conveniences necessary for the completion of engines and from which manufactory we would serve all the world with engines of all sizes. By these means and your assistance we could engage and instruct some excellent workmen (with more excellent tools that would be worth any man's while to procure for one single engine) could execute the invention 20 per cent cheaper than it would be otherwise executed, and with a great difference of accuracy as there is between the blacksmith and the mathematical instrument maker. *It would not be worth my while to make for three counties only, but I find it very well worth my while to make for all the world*' (quoted in Dickinson and Jenkins, 1927: 30–1, italics added).
18. For an account of the activities of local producers of atmospheric engines in Lancashire in the second half of the eighteenth century, see Musson and Robinson (1969: 393–426).
19. In his *Memoir* of Matthew Boulton written in 1809, Watt stressed the role played by Boulton's entrepreneurial abilities (and by his extensive network of acquaintances) for the successful development of the engine partnership: 'Boulton . . . possessed in a high degree the faculty of rendering any new invention of his own or others useful to the publick, by organizing and arranging the processes by which it could be carried on, as well as promoting the sale by his own exertions and by his numerous friends and correspondents' (cited in Dickinson, 1936: 195–6).
20. The engines constructed for the Albion Mills were among the first rotary double acting engines constructed by Boulton and Watt. The choice of a plant of the almost unprecedented size of the Albion Mills was meant to attract the maximum of attention towards the new engine. From a strictly economic point of view the undertaking was not successful, however, according to many contemporaries, following the 'mechanical' success of the mill, double-acting rotary engines were adopted in a variety of industrial mills where direct rotary motion was needed (Westworth, 1933). The engine erected at the Albion Mill also convinced some textile manufacturers in the North to install Boulton and Watt engines for powering their mills, see Hills (1970: 156).
21. Silverberg and Verspagen (2003) have originally proposed this intuitive interpretation of the overdispersion test in the context of the temporal clustering of basic innovations.

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9. Knowledge diffusion with complex cognition

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BACKGROUND

Modern economy has been described as knowledge-based, or a learning economy, due to the central role that knowledge and learning play for economic development (OECD, 1996). None the less, the processes of learning and knowledge diffusion are still largely undiscovered and require substantial theoretical and empirical efforts to be properly understood.

From the premise that learning is a complex and interactive process which can take place at all times (we learn at school, we learn at work, we learn reading a book, we learn watching TV, we learn talking with people, we learn while using ICT), we operate a logical simplification to understand this phenomenon. Following the theoretical structure defined in previous work (Morone, 2001; Morone and Taylor, 2001), we divide learning into two categories: *formal learning* and *informal learning*. We define *formal learning* as the kind of learning that occurs in certain environments which are meant for learning such as schools, workplaces, and training groups. On the other hand we call *informal* those learning processes that occur 'spontaneously', simply by interacting with peers. Following the more traditional approach, we could define the knowledge acquired by formal learning as a standard economic good (for which I'm paying a price; that is tuition fees, forgone earnings); and the knowledge acquired by informal learning as an unconventional public good. Some authors have defined the latter kind of knowledge as a *club* good (Cornes and Sandler, 1996; Breschi and Lissoni, 2003) which is non rival and non excludible only for restricted groups of people (that is the *members of the club*).

Formal learning has been extensively investigated both theoretically and empirically (Becker, 1964; Mincer, 1974; Psacharopoulos, 1994), whereas the second learning process has only recently captured the attention of scholars. Mechanisms of innovation diffusion (Clark, 1984; Rogers, 1995) are often viewed as good examples of informal learning processes because they tend to occur through interaction within geographical and other informal