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STEAM AS A GENERAL PURPOSE TECHNOLOGY: A GROWTH ACCOUNTING PERSPECTIVE*

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The contribution of steam to British economic growth in the nineteenth century is estimated using growth accounting methods similar to those recently employed to examine the role of ICT. The results indicate that steam contributed little to growth before 1830 and had its peak impact about a hundred years after Watt's famous invention. Only with the advent of high-pressure steam after 1850 did the technology realise its potential. Compared with ICT, steam's impact on the annual rate of growth was modest. It is unlikely that these conclusions are vulnerable to quantification of hitherto unmeasured TFP spillovers.

In recent years there has been an upsurge of interest among growth economists in General Purpose Technologies (GPTs). A GPT can be defined as 'a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many Hicksian and technological complementarities' (Lipsey *et al.*, 1998*a*, p. 43). Electricity, steam and information and communications technologies (ICT) are generally regarded as being among the most important examples.

An interesting aspect of the occasional arrival of new GPTs that dominate macroeconomic outcomes is that they imply that the growth process may be subject to episodes of sharp acceleration and deceleration. The initial impact of a GPT on overall productivity growth is typically minimal and the realisation of its eventual potential may take several decades such that the largest growth effects are quite long-delayed, as with electricity in the early twentieth century (David, 1991). Subsequently, as the scope of the technology is finally exhausted, its impact on growth will fade away. If, at that point, a new GPT is yet to be discovered or only in its infancy, a growth slowdown might be observed. A good example of this is taken by the GPT literature to be the hiatus between steam and electricity in the later nineteenth century (Lipsey *et al.*, 1998*b*), echoing the famous hypothesis first advanced by Phelps-Brown and Handfield-Jones (1952) to explain the climacteric in British economic growth.

Although there exists pioneering cliometric research on the social savings of both steam engines (von Tunzelmann, 1978) and railways (Hawke, 1970), there has never been an attempt to examine the long-run impact of steam technology on British economic growth during the late eighteenth and nineteenth centuries. This paper uses growth-accounting to fill this gap and, in so doing, both to assess

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the validity of a GPT-based account of British economic growth and also to place the impact of steam in a comparative perspective.

In particular, three questions are addressed:

1. When did steam have its greatest impact on productivity growth?
2. How does steam measure up to the contribution of ICT in the late twentieth century?
3. Was steam's contribution to productivity growth responsible for the chronology of trend growth in the economy overall?

The answers will provide a way of contextualising the modest growth now perceived to have characterised the first industrial revolution, which is summarised in Table 1. Whereas earlier estimates had seen TFP growth surging from 0.2% per year before 1800 to 1.3% per year in 1800–30 before falling back to 0.8% per year in the mid 19th century (Feinstein, 1981), it now appears that there was a modest acceleration rather than a surge in TFP growth in the early 19th century followed by a long period of steady but unspectacular productivity growth. The apparent TFP growth climacteric suggested by the endpoint calculations reported in Table 1 is deceptive – when subjected to time series analysis there is at most a slight weakening of trend growth (Crafts *et al.*, 1989).

The paper proceeds as follows. The growth accounting methodology used in the paper is set out in Section 1 which also contains a benchmark calculation of the impact of ICT on recent American productivity growth. Section 2 describes and quantifies the diffusion of steam power in Britain between 1760 and 1910. Section 3 builds on these data to provide growth accounting estimates of the contribution of steam to labour productivity growth, uses these to address the questions posed in this introduction and offers some reflections on the elusive issue of TFP spillovers. Section 4 concludes.

1. Growth Accounting and Innovation

Traditional growth accounting captures the contribution of technological change to growth through total factor productivity (TFP) growth, i.e., the Solow residual. With the standard Cobb-Douglas production function and competitive assumptions

$$Y = AK^{\alpha}L^{1-\alpha} \tag{1}$$

Table 1
Growth Accounts for Britain, 1760–1913 (% per year)

	Due to capital	Due to labour	TFP growth	GDP growth
1760–80	0.25	0.35	0.00	0.6
1780–1831	0.60	0.80	0.30	1.7
1831–73	0.90	0.75	0.75	2.4
1873–99	0.80	0.55	0.75	2.1
1899–1913	0.80	0.55	0.05	1.4

Source: Crafts (1995). The estimates are based on a conventional neoclassical growth accounting equation where $\Delta Y/Y = 0.4\Delta K/K + 0.6\Delta L/L + \Delta A/A$.

the Solow residual is computed as

$$\Delta A/A = \Delta Y/Y - s_K \Delta K/K - s_L \Delta L/L \tag{2}$$

where s_K and s_L are the factor income shares of capital and labour respectively.

A straightforward generalisation of this has been used in the growth accounting literature on ICT. This allows for different types of capital and distinguishes separate components of TFP growth. In the variant proposed in the well-known paper by Oliner and Sichel (2000), capital is divided into three types of ICT capital (computer hardware, computer software and telecom equipment) and other capital each of which is weighted by its own factor income share. TFP growth is decomposed into a component based on the production of ICT capital and other TFP growth. In turn, the latter is based on production of the rest of GDP deriving both from unrelated advances in technology and from (unremunerated) TFP spillovers from ICT. These might result, for example, from re-organisation effects similar to those accruing when factories were re-designed after electricity had replaced steam (David and Wright, 1999).

Thus the growth accounting equation is written as

$$\Delta Y/Y = s_{KO}\Delta K_O/K_O + s_{Ki}\Delta K_i/K_i + s_L\Delta L/L + \gamma(\Delta A/A)_{ICTM} + \phi(\Delta A/A)_{NICTM} \tag{3}$$

where the subscript O indicates other capital, the subscript Ki indicates ICT capital of type i, the subscript $ICTM$ and $NICTM$ indicate manufacture of ICT equipment and the rest of the economy, respectively, and γ and ϕ are the gross outputs of these sectors as a share of GDP.[1] Modifying (3) to accounting for labour productivity rather than output growth we have

$$\Delta(Y/L)/(Y/L) = s_{KO}\Delta(K_O/L)/(K_O/L) + s_{Ki}\Delta(K_i/L)/(K_i/L) + \gamma(\Delta A/A)_{ICTM} + \phi(\Delta A/A)_{NICTM}. \tag{4}$$

Thus the innovation of ICT is allowed to have impacts on growth both through an embodied, capital-deepening effect and through disembodied TFP growth. This equation can readily be modified to include a term for ICT TFP spillovers if desired.

Table 2 displays the estimates made by Oliner and Sichel (2000), as revised by them in an update on their research, where I have combined the contributions of the three types of ICT into a consolidated aggregate. Oliner and Sichel do not report an estimate for TFP spillovers from ICT nor do they attempt to identify cyclical effects on the utilisation of factors of production.

It should be noted that this approach seeks only to benchmark the *ex post* ICT component of productivity growth. It does not answer the (much harder) question 'how much faster was productivity growth as a result of ICT ?' This turns on the counterfactual rates of growth of other capital in the absence of ICT, estimation of which would require a complex modelling exercise taking account of both 'crowding out' and 'crowding in' effects. One answer to the harder question was, however, provided by Fogel (1964). He maintained that the additional growth

[1] These are so-called Domar weights which sum to greater than 1. For an algebraic justification of this procedure, see Hulten (1978).

Table 2

Contributions to Labour Productivity Growth in US Non-Farm Business Sector, 1974-2001 (% per year)

	1974–90	1991–5	1996–2001
Capital deepening	0.77	0.52	1.19
ICT Capital	0.41	0.46	1.02
Other	0.36	0.06	0.17
Total Factor Productivity	0.59	1.02	1.24
ICT sector	0.27	0.41	0.77
Other	0.32	0.61	0.47
Labor productivity growth	1.36	1.54	2.43
Memorandum Items			
ICT capital income share (%)	3.3	5.3	6.3
ICT sector output share (%)	1.4	1.9	2.5

Source: Derived from growth accounting estimates of (4) by Oliner and Sichel (2002); labour quality is included in other TFP.

attributable to a new technology should not include any capital-deepening component since in its absence the same normal rate of return would have been earned on alternative investments. In this case only the TFP component needs to be considered.[2]

2. The Diffusion of Steam Power in Britain in the 18th and 19th Centuries

Steam technology had major implications for the supply of power to industry, and for both domestic and international transportation. As with ICT, there were three major types of steam capital-deepening in the form of stationary steam engines, railways and steamships.

Kanefsky (1979*a*) provides the most complete reckoning of the growth of steam power in the British economy. Although the data are incomplete, notably in the period between the expiration of James Watt's patent in 1800 and the first returns under the Factory Acts in 1838 and again after 1870 when these returns ceased, the picture established by Kanefsky, which is summarised in Table 3, is accepted as broadly accurate.

The striking feature of Table 3 is that accumulation of capital in the form of steam engines was rather slow. James Watt's improved steam engine was patented in 1769. Yet, it was only in 1830 that steam reached parity with water as a source of power in the economy at which point only 165,000 steam horsepower had been installed representing about 1.5% of the total capital stock. For a very long time, water power remained cost effective in many activities. Even in 1870 almost half of all steam power was used in mining and in cotton textiles while important sectors in the economy including agriculture and services (apart from transport) were

[2] Readers who take this position can easily see its implications in Tables 5 to 8. None of the main conclusions about steam as a GPT would be affected. Fogel expressed the contribution of railways to nineteenth century American growth in terms of a concept of 'social savings'. It is easy to show that this is equivalent to the TFP contribution in growth accounting, see Foreman-Peck (1991, p. 77). So Fogel's social saving is a subset of the growth accounting estimate of the contribution of a new technology.

Table 3
Sources of Power, 1760–1907 (Horsepower)

	1760	1800	1830	1870	1907
Steam	5,000	35,000	165,000	2,060,000	9,659,000
Water	70,000	120,000	165,000	230,000	178,000
Wind	10,000	15,000	20,000	10,000	5,000
Total	85,000	170,000	350,000	2,300,000	9,842,000

Source: Kanefsky (1979*a*, p. 338); not including internal combustion engines.

virtually untouched by steam. Similarly, in the US the steam engine took a long time to gain the ascendancy over water power and it was not until the 1860s that it supplied more horsepower. Detailed calculations in Atack (1979) show rapid declines in American steam and waterpower costs during the 19th century. Although these occurred more rapidly in steam than in water technology, only in the 1850s did steam become a cheaper source of power for manufacturers in most locations.

Steam technology took a long time to perfect. The original Watt engines were a low pressure design whereas it was later realised that much lower coal consumption could be achieved with high pressure. In turn, reliable high pressure steam engines required big improvements in the design and manufacture of boilers. Although these engines were pioneered by Woolf in the early nineteenth century in Cornwall, where coal prices were very high and they were used in tin mining, only after the invention of the Lancashire boiler in the early 1840s were they an economic proposition in textile mills (von Tunzelmann, 1978). Much greater effort was then put into developing higher pressure steam power, especially after 1850 when progress in the theory of heat finally explained the rationale (Hills, 1989).

The upshot of improvements in steam engine design was that coal consumption (per hp per hour) improved from about 30 lb. with the Newcomen engines prior to James Watt, to 12.5 lb. with the Watt engine, 5 lb. with the move to high pressure in the mid 19th century and 2 lb with very high pressure in the early 20th century (Kanefsky, 1979*a*; Winterbottom, 1907). In the meantime, maximum steam pressure in textile mills had risen from 60 in 1850 to 200 p.s.i in 1900 (Hills, 1989). These improvements in steam technology were reflected in the declining costs of steam power reported in Table 4. These estimates are for a benchmark case, namely a textile mill in Lancashire, and would not necessarily apply in other sectors or locations. Nevertheless, they match very closely the estimated modal experience in the US where the annual costs of a horsepower of steam fell by just over 80% between the 1820s and the 1890s (Atack, 1979, p. 423).

The switch from sailing ships to steamships also depended on moves to high pressure steam which increased fuel efficiency. Here though the steam technology was based on compound engines and the eventual triumph of steam was based on the availability by the 1880s of cheap, high-quality steel which reduced hull weights. Until these developments the economic viability of steam voyages was undermined by the proportion of capacity that had to be devoted to coal storage as opposed to cargo and this increased sharply with distance.

Table 4

Capital Cost and Annual Cost per Steam Horsepower per Year (£ current)

	Capital cost	Annual cost
1760	42	33.5
1800	56	20.4
1830	60	20.4
1850	37	13.4
1870	25	8.0
1910	15	4.0

Note: The estimates are for a benchmark textile mill in a low coal cost region like Manchester, annual costs include depreciation and interest costs, and running costs including coal and labour. In 1760 steam engines were not yet employed in this way and the estimate is for a typical Newcomen (pre-Watt engine) used in mining.
Sources: Capital cost: 1760, 1800 and 1830 from von Tunzelmann (1978, pp. 49, 72, 75); 1850 and 1870 from Kanefsky (1979*a*, pp. 158–9); 1910: Winterbottom (1907, p. 238). Running cost: 1760 from Kanefsky (1979*a*, pp. 172–3); 1800, 1830 and 1850 from von Tunzelmann (1978, pp. 74, 150); 1870 from Kanefsky (1979*a*, p. 175); 1910 from Winterbottom (1907, p. 238).

The first continuous steam crossing of the Atlantic was achieved in 1838 but early nineteenth century steamships operated at 6–7 p.s.i. and consumed 10 lb of coal per hp per hour. By the early 1850s working with higher pressure had reduced coal consumption to 5 lb per hour and the era of commercial steamships began. Coal consumption had halved again by 1870 and again to 1.25 lb per hp per hour by 1914 by which time boiler pressures of 200 p.s.i. were possible in quadruple-expansion engines (Pollard and Robertson, 1979, p. 15). The economic limit of a steam voyage was about 3,500 miles in 1870 but by the 1890s journeys from the UK to the Far East and California were viable as much less coal was required on board. The improvements in fuel efficiency and metallurgy also made possible reductions in crews and larger ships which economised on handling charges. In other words, rapid TFP growth after 1850 ushered in the heyday of steamships which, however, arrived only in the late nineteenth/early twentieth centuries (Harley, 1988).

The history of railways is much better known and needs only brief description. This form of transport was initially wholly dependent on steam engines and can be seen as a manifestation of a developing GPT at work. The first major scheme was the Liverpool and Manchester railway opened in 1830. By the early 1850s the core trunk routes of the network were in place and about 7,000 miles of track were open. Eventually the network grew to about 20,000 miles. Railways were a massive investment by the British economy which was undertaken rapidly such that by 1855 their capital stock was equal to 30% of GDP. Total train miles grew from about 60 million per year in the early 1850s to 200 million by the mid-1870s and a little over 400 million by 1910 (Mitchell, 1988, pp. 541–7). As with the stationary steam engine, railway technology evolved greatly from the early days. Developments in engine and track design, braking, and signalling facilitated denser use of the rail network, faster trains, greater loads etc. The technology was still improving rapidly in the US in the early 20th century (Fishlow, 1966).

3. The Contribution of Steam to Productivity Growth, 1760–1910

This Section develops growth accounting estimates of the contribution of steam technology to British productivity growth based on implementing a formula equivalent to (4). Estimates which identify contributions from capital-deepening and own TFP growth are developed separately for stationary steam engines, railways and steamships but, as with the estimates for ICT in Table 2, no attempt is made explicitly to quantify TFP spillovers.

Table 5 sets out the growth accounting estimates for stationary steam engines. The rate of growth of the capital stock is based on the rate of growth of horsepower. This is obviously not quite the equivalent of estimating the growth of computer power using hedonic prices to deflate ICT expenditure but it does capture the key characteristic as seen by contemporaries. Moreover, with the move in the mid-19th century to measuring this in terms of 'indicated' rather than nominal horsepower this did reflect the real capabilities of this investment (Kanefsky, 1979*a*, pp. 23–8).

The contribution of TFP growth in the provision of steam power to the economy is estimated using the concept of social savings popularised in the cliometric literature on railways following Fogel (1964). This is simply the difference in resource cost of supplying a given volume of output using old and

Table 5

Contributions to British Labour Productivity Growth from Stationary Steam Engines, 1760–1910 (% per year)

	1760–1800	1800–30	1830–50	1850–70	1870–1910
Rates of growth					
Steam HP per worker	4.3	3.9	4.2	5.2	3.9
TFP in steam power	2.8	0.06	1.2	3.5	1.7
Contributions					
Capital deepening	0.004	0.02	0.02	0.06	0.09
TFP	0.005	0.001	0.02	0.06	0.05
Total	0.01	0.02	0.04	0.12	0.14
Memoranda (%GDP)					
Steam Income Share	0.1	0.4	0.5	1.2	2.2
Social Saving	0.2	0.02	0.3	1.2	1.8

Source: Derived using growth accounting methods equivalent to Table 2.

Capital stock growth based on Kanefsky (1979*a*, p. 338) for growth of horsepower. From 1850, the figures are for indicated horsepower. The estimate of horsepower in 1870 (1,668,000) is based on corrections for horsepower actually in use reported in Kanefsky (1979*b*, p. 373) and the horsepower estimate for 1850 (487,500) is derived from Musson (1976, p. 435) adjusted in accordance with Kanefsky's suggestions to account for omissions and divergence between indicated and nominal horsepower.

TFP growth in steam power based on the annual costs of steam to the user reported in Table 2 adjusted for inflation using the implicit GDP deflators in Mitchell (1988, pp. 831–9) and for 1760–1800 in Crafts (1985, p. 41). For 1800–30 it is assumed that TFP growth was only achieved in Cornish steam engines, see text.

Steam engine income share derived using capital costs reported in Table 4 to derive share of total capital stock using the estimates in Feinstein (1988, pp. 437–8).

The social savings of steam engines, which are derived using the period reductions in annual costs per horsepower in Table 4 multiplied by the estimates for horsepower is use, are used to estimate the TFP growth contribution, as described in the text.

new versions of the technology. For constant input prices, the price dual measure of TFP growth is just equal to the rate of output price decline, i.e., TFP growth can be interpreted as the rate of real cost reduction (Harberger, 1998). Social savings from reductions in the cost of steam power as a proportion of GDP can therefore be used to estimate the rate of TFP growth. Indeed, this seems to be the only practical way to proceed.

Thus, the estimates of TFP growth in Table 5 are based on the changes in the annual cost of steam horsepower reported in Table 4, converted into real terms using the GDP deflator. For example, the social saving in 1910 relative to 1870 is obtained as follows. The annual cost of a horsepower in 1870 in 1900 prices was £8.0/101.5 = £7.9 while in 1910 it was £4.0/100.2 = £4.0. The real cost decrease implies a rate of TFP growth of 1.7% per year. The resource saving to the economy is calculated as (7.9 − 4.0) = 3.9 × 9.659 mn hp = £37.67 mn = 1.84% of GDP which implies a growth contribution of 0.05% per year during 1870–1910.

The period 1800–30 where Table 5 reports TFP growth of 0.02% per year deserves a closer look. For Manchester, von Tunzelmann concluded that 'there was little decline in the money costs of steam power from the turn of the century until the late 1830s' (1978, p. 73) and it is clear that there was little if any improvement in the design of mill engines (Hills, 1989, p. 113–5). There was technological progress primarily in the Cornish steam engine which accounted for between 5 and 10% of total horsepower. This was centred on experiments with higher pressure steam which were designed to reduce coal costs in an area where coal was very expensive. The Cornish-type engine was not, however, adopted in Lancashire where it was uneconomic in the context of the textile industry's requirements for a reliable source of power, the much lower cost of coal, and the additional fixed costs that would have been incurred (von Tunzelmann, 1978, p. 84). Cornish engineers improved the steam engine to the extent of making savings of coal inputs worth £84,300 per year by the early 1830s (Hills, 1989, p. 112). If we assume that these represent the full extent of TFP growth in the provision of steam power in the period 1800–30, then the results reported in Table 5 are obtained.[3]

The picture that emerges from Table 5 is fairly predictable given the discussion of Section 3 but may well be rather surprising to economists brought up on the dramatic accounts of the industrial revolution of the Rostowian era. The contribution to growth made by the stationary steam engine was very small prior to 1830, was considerably bigger in the second half of the 19th century than during the industrial revolution but was always quite modest. The slow diffusion of steam power accounts for this result and this is in turn explained by its lack of cost effectiveness in the era of low pressure steam. At no time did steam engines represent anything other than a small proportion of the total capital stock. TFP growth was relatively rapid at the point where the Watt engine appeared and again

[3] The unchanged nominal costs of steam power reported in Table 4 would imply an increase in its real cost and thus a decrease in TFP given that prices were falling. This seems unlikely and the assumption of no TFP growth in Lancashire steam is preferred.

when it became possible generally to switch to much higher pressure steam engines in the mid-19th century.

Table 6 reports growth accounting estimates for the contribution of railways to productivity growth. Here the well-known studies by Foreman-Peck (1991) and Hawke (1970), which quantified the social savings of railways, have been re-worked into the growth accounting format of this paper. As the latter study showed, the impact of railways in the mid 19th century was appreciable but did not transform the overall growth rate because the sector was still quite small relative to GDP. By 1870, when railways were much larger, investment had subsided and TFP growth had ebbed. In this case, the maximal contribution to economic growth arrived relatively quickly but even so was not immediate.

Table 7 reports growth accounting estimates for the contribution of steamships to British labour productivity growth. No attempt has been made to quantify a contribution prior to 1850 but it was entirely trivial since the net stock of capital in steamships was only £2.4 mn in 1850 (Feinstein, 1988, p. 351). Prior to that time steamships were generally uneconomic because they used far too much coal to permit an adequate payload. The results show that steamships added significantly to productivity growth after 1870. They reinforce the point that the main impetus to growth from steam came in the era of high pressure working in the second half of the nineteenth century.

Table 8 combines the results from the previous two tables to give an estimate of the total contribution of steam to British labour productivity growth. This confirms that the impact of steam was very small during the industrial revolution, peaked in the third quarter of the 19th century and was well-sustained through till World War I. Comparison of these estimates with those in Table 2 indicates that steam had a much smaller impact on annual productivity growth than did ICT in the US even before the mid-1990s – at no time does steam's contribution match the 0.68%

Table 6

Contributions to British Labour Productivity Growth from Railways, 1830–1910

(% per year)

	1830–50	1850–70	1870–1910
Rates of growth			
Railway capital per worker	22.8	5.9	0.4
TFP in railways	1.9	3.5	1.0
Contributions			
Capital deepening	0.14	0.12	0.01
TFP	0.02	0.14	0.06
Total	0.16	0.26	0.07
Memoranda (%GDP)			
Railway profits share	0.6	2.1	2.7
Railway output share	1.0	4.0	6.0

Source: Derived using growth accounting methods equivalent to Table 2.
Capital stock growth from Feinstein (1988, p. 452).
TFP growth pre-1870 from Hawke (1970, p. 302) and post-1870 from Foreman-Peck (1991, p. 81).
Railway profits and output shares based, respectively on net and gross receipts derived from Foreman-Peck (1991, p. 76), Hawke (1970, p. 406) and Mitchell (1988, pp. 545–6).

Table 7

Contributions to British Labour Productivity Growth from Steamships, 1850–1910 (% per year)

	1850–70	1870–1910
Rates of growth		
Steamship capital per worker	9.7	4.5
TFP in steamship services	1.6	1.6
Contributions		
Capital deepening	0.02	0.05
TFP	0.01	0.05
Total	0.03	0.10
Memoranda (% GDP)		
Steamship income share	0.2	1.1
Steamshipping output share	0.7	3.4

Source: Derived using growth accounting methods equivalent to Table 2.
Capital stock growth from Feinstein (1988, p. 351).
TFP growth in steamship services for 1850–70 based on data underlying the estimates presented for different periods in Harley (1988) and for 1870–1910 based on the average of four routes in Mohammed and Williamson (2003, Table 4) in each case augmented for TFP growth in steamship construction derived from the rate of decrease of hull weight per ton in Feinstein (1988, pp. 338–9) weighted by capital's share in steam ship output.
Steamship income share based on share of capital stock (Feinstein, 1988, pp. 437–8) multiplied by profits share of national income.
Steamshipping output share based on net shipping credits in the balance of payments from Imlah (1958, Table 4) adjusted for steam's share of shipping tonnage according to the formula in Lewis (1978, p. 259).

per year of ICT in 1974–90.[4] Of course, it remains to be seen how long-lasting is the impact of ICT and it would be premature to argue that the total effect of ICT will be the larger.[5] What is apparent is that there was no equivalent to Moore's Law in the age of steam.

None of these estimates quantifies the extent of TFP spillovers. With regard to steam it is important to distinguish between the pre- and post-1850 periods. The literature on the social savings of steam engines and railways addressed this issue directly and argued strongly that TFP spillovers were negligible for the former period. The main point with regard to railways is that they seem to have very little impact on location decisions in an economy that had already been able to assemble the agglomerations of Birmingham and Manchester based on canals

[4] If a comparison with ICT in the UK is preferred, the same result emerges in that at no time does steam's contribution match that of ICT in the 1990s. Estimates in van Ark *et al.* (2003) show ICT contributing 0.57 and 0.97 percentage points to labour productivity growth in 1990–5 and 1995–2000, respectively.

[5] It should be noted that the ICT contribution is based on hedonic prices for ICT equipment. This exaggerates the difference between ICT and steam though the point should not be overstated. A crude estimate can be obtained by comparing the rates of price decrease for computers and software according to the national accounts of the US and the UK, a country which continued to use traditional methods to estimate price declines for these items. The data presented in Oulton (2001) show that price decreases for computers (software) were greater by 7.3 (0.6)% per year for 1979–89 and 8.8 (3.4)% per year for 1989–94. This suggests that the use of hedonic prices in Table 2 raises the capital-deepening contribution by a little less than 0.1 percentage points per year and the own TFP contribution by a similar amount.

Table 8
Total Contribution to British Labour Productivity Growth from Steam Technology, 1760–1910
(% per year)

1760–1800	0.01
1800–30	0.02
1830–50	0.20
1850–70	0.41
1870–1910	0.31

Source: The combined impact of capital deepening and own TFP growth of steam engines, railways and steamships derived by summing the contributions from Tables 5, 6 and 7.

(Hawke, 1970, pp. 381–400; Turnbull, 1987). As far as steam engines are concerned, the main impact might be expected through technological change in textile production but von Tunzelmann (1978) pointed out that all the major advances were originally developed for other forms of power.

In the second half of the nineteenth century TFP spillovers from steam may well have been much more important. Rosenberg and Trajtenberg (2001) have argued that the improvements embodied in the Corliss steam engine, notably more sophisticated valves which allowed a continuous uniform flow of power as well as much greater energy efficiency, facilitated increased agglomeration and the realisation of both internal and external economies of scale in nineteenth century manufacturing. The first Corliss steam engine was installed in Britain in 1861. Also, more indirect stimuli to agglomeration benefits may have arisen from the reductions in international transport costs and enhanced specialisation along lines of comparative advantage associated with the steamship.

It seems very probable that if TFP spillovers could be added into the estimates summarised in Table 8 they would reinforce the main result, namely, that the strongest impact of steam power on British productivity growth was felt in the second half of the 19th century rather than earlier. It is, however, much less clear what might be implied for a comparison with ICT since TFP spillovers for that technology also remain to be convincingly quantified although some microeconomic evidence suggests they may be substantial (Brynjolfsson and Hitt, 2000).

What are the wider implications for the GPT literature of the results obtained in this paper? The first and most obvious message is that the major impact of a GPT on productivity in the world's leading economy of the day may be very long-delayed. While electricity delivered its major boost to American economic growth about 40 years after the first commercial generating stations came on stream (David, 1991), the lag following James Watt's steam engine was about 80 years. In a proximate sense, this long delay resulted from the time taken to understand the true potential of steam in an era when science and technology were relatively primitive. In turn, this implied that steam power accounted for a very small share of the capital stock; only in the third quarter of the 19th century did the combined share of stationary steam engines, railways and steamships match that of ICT in the United States in the 1980s. In this context, the well-known Solow paradox – that you could see computers everywhere but in the productivity statistics – appears less puzzling and in fact the impact of ICT on labour productivity growth has appeared quite fast. Perhaps the true paradox is that so much was expected of ICT.

The second point to note is that these results help to explain the modest rate of productivity growth during the British industrial revolution which has now been established by quantitative research. Table 1 reported that TFP growth in the British economy during 1780–1830 averaged only 0.3% per year. This can now be seen to be associated with the relatively weak initial impact of steam as a GPT. This should not really be a big surprise given the modest social savings from steam power in von Tunzelmann (1978) but this connection has not previously been made explicitly.

The third important aspect of the results is that, while they help explain a delay in the acceleration of productivity growth as Britain industrialised, they suggest that the claim that an ending of the massive application of steam power led to a late 19th century climacteric is implausible. In fact, the revisionist notion of a late 19th century climacteric in TFP growth at the level of the aggregate economy does not survive serious econometric investigation (Crafts *et al.*, 1989). Moreover, it is clear from Table 5, 6 and 7 that any reduction in TFP growth from steam was very small – well below 0.1 percentage points per year.

If, a more traditional view of the climacteric is taken, namely, that it is to be interpreted in terms of the growth of industrial output per worker, then the suggestion that there was a post-1870 slowdown based on a weakening of the application of steam power can be rejected by reworking the data underlying Table 4 in terms of industry rather than GDP.[6] This is easy since the stationary steam engine was used in industry rather than the rest of the economy. The capital deepening contribution to industrial labour productivity growth is found to rise steadily over time from 0.09 in 1800–30 to 0.18 in 1830–70 and 0.39 percentage points per year in 1870–1910. The objection made by Musson (1963) that the hypothesis is invalid because steam-powered mechanisation was still proceeding rapidly is sustained.

4. Conclusions

In the introduction three specific questions were posed. The answers that have been obtained in the paper can be summarised as follows.

First, steam had its greatest impact on productivity growth in the second half of the 19th century not during the industrial revolution.

Second, in terms of its impact on the annual rate of productivity growth through capital-deepening and own TFP growth steam always had a much smaller impact than ICT even before the mid-1990s.

Third, slow productivity growth during the industrial revolution followed by acceleration in the mid-19th century is at least partly explained by steam's contribution; on the other hand, the idea of a late 19th century climacteric resulting from a weakening in the application of steam power is not persuasive.

[6] Industrial output per worker growth was 1.5% per year in 1831–71 but fell to 0.8% per year in 1871–1911 (Crafts and Mills, 2004).

In sum, seeking to base an account of 19th-century British economic growth primarily on the implications of steam is surely misconceived. At no time is its impact large enough to dominate. Perhaps in this respect there is a real difference from the world of ICT – but only time will tell.

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