ISSN 2042-2695

CENTRE *for* ECONOMIC PERFORMANCE

CEP Discussion Paper No 1050

May 2011

Spinning Welfare: the Gains from Process Innovation in Cotton and Car Production

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THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL

Abstract
Economists and economic historians want to know how much better life is today than in the past. Fifty years ago economic historians found surprisingly small gains from 19th century US railroads, while more recently economists have found relatively large gains from electricity, computers and cell phones. In each case the implicit or explicit assumption is that researchers were measuring the value of a new good to society. In this paper we use the same techniques to find the value to society of making existing goods cheaper. Henry Ford did not invent the car, and the inventors of mechanised cotton spinning in the industrial revolution invented no new product. But both made existing products dramatically cheaper, bringing them into the reach of many more consumers. That in turn has potentially large welfare effects. We find that the consumer surplus of Henry Ford's production line was around 2% by 1923, 15 years after Ford began to implement the moving assembly line, while the mechanisation of cotton spinning was worth around 6% by 1820, 34 years after its initial invention. Both are large: of the same order of magnitude as consumer expenditure on these items, and as large or larger than the value of the internet to consumers. On the social savings measure traditionally used by economic historians, these process innovations were worth 15% and 18% respectively, making them more important than railroads. Our results remind us that process innovations can be at least as important for welfare and productivity as the invention of new products.

Keywords: Process innovations, new goods, welfare, consumer surplus, mechanisation, mass production, automobiles, cotton, industrial revolution, second industrial revolution
JEL Classifications: N22, N24, O31, O40

This paper was produced as part of the Centre's Globalisation Programme. The Centre for Economic Performance is financed by the Economic and Social Research Council.

Acknowledgements
We thank Stephen Broadberry, Bruce Campbell, Alexander Klein, Mark Overton and Bas van Leeuwen for making available the data underlying their working paper "British Economic Growth and the Business Cycle, 1700-1870", and Paul Rhode for help in identifying data sources. Jonathan Hersh generously helped in implementing the Matlab code for the Greenwood-Kopecky-calculations.

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Published by
Centre for Economic Performance
London School of Economics and Political Science
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London WC2A 2AE

1. Introduction

How much better is life today than in the past? And how much better have production technologies become? These questions are intimately connected, and central to economics and economic history. Economic historians pioneered the social savings methodology, which found surprisingly modest gains from 19th century US railroads, primarily because alternative production techniques were relatively effective (Fogel 1964, Fishlow 1965). Economists have found relatively large welfare gains to consumers, as measured by the rise in consumer surplus, from goods as diverse as electricity, computers, cell phones, Apple-Cinnamon Cheerio cereal, the internet, and sugar and tea.

Studies of consumer surplus and social savings typically assume that utility-maximizing consumers will rapidly adopt new goods after invention. In this paper, we try to open the 'black box' of the interactions between price decline and adoption. In many cases, "new" goods were already available, but not widely consumed because of price. Rose sugar, for example, was found at the court of Henry II (1154-89), but it is only with the arrival of sugar derived from sugar cane from the 17th century onwards that adoption became widespread. Motor cars were in use before Henry Ford introduced assembly-line production, but were limited to the affluent. In this paper, we investigate the extent to which social savings and consumer surplus are driven not by product inventions – like the railway or the cell phone – but by process innovations that made these goods cheap enough for mass consumption.

We focus on two process innovations that rank amongst the most important advances in manufacturing techniques during the last 200 years – mechanical cotton spinning and the motor car assembly line. Both led to sensational price declines and both transformed what had been luxury items for upper class consumption – Indian calicoes and motor cars for the rich and famous – into items of everyday consumption for a significant part of the population. Workers on Ford's Model-T assembly line could afford the cars they made; cotton spinners would wear cotton shirts.

Process innovations create consumer surplus not through the availability of a new good, but by making existing ones cheaper. The key difficulty in estimating consumer surplus with new goods is the value of the first units available. These tend to be hard to measure in quantity and difficult to assess in value. With process innovations, the good produced is typically already established. If the declining cost did not translate into a lower selling price the gain to society would be equal to the rise in profits. Not so if the price declines: in this case, consumers receive a windfall.

Our paper is related to the literature on the value of new goods and increasing variety. Hausman (1996, cf Bresnahan , 1997) found that the introduction of Apple-Cinnamon Cheerios raised consumer welfare in the US by 0.002% of 1992 consumer expenditure. Other scholars have investigated gains from online booksellers (Brynjolfsson et al. 2003), the internet (Goolsbee and Klenow 2006), the introduction of the minivan (Petrin 2002), and satellite TV (Goolsbee and Petrin 2004). Broda and Weinstein (2006), using a method pioneered by Feenstra (1994), argued that international trade had increased US consumer welfare substantially by increasing the range of goods available. Papers in the tradition of Berry, Levinsohn and Pakes (1995) use data at the household level, and are almost impossible to replicate with historical data. Greenwood and Kopecky (2010) have recently used a modified model of consumer demand to calculate the gains from the introduction of personal computers. They estimate gains of up to 4% of consumption expenditure.

Our work also connects with research on efficiency gains from product innovation in historical perspective. The pioneering work was by Fogel (1964) and Fishlow (1965) with critiques from Davis (1966), Lebergott (1966) David (1969) and others. Research using the same methods for other countries only partly confirmed their conclusions (Hawke 1970, Herranz-Locan 2006, Summerhill 2005, Huenemann 1983). Recently, Leunig (2006) showed that the railway's time savings were substantial. Work on the history of cotton spinning has focused strongly on the appropriateness of technology choice (in particular, the adoption of mule vs. ring spinning - Sandberg 1969, Lazonick 1981, Saxonhouse and Wright 1984, Leunig 2001, Ciliberto 2010.) Research on the assembly line has examined the importance of complementary managerial skills and organizational capacity (Chandler 1990), and the challenges of adapting the system to changing demand and taste heterogeneity (Wilson and McKinlay 2010). More recently, historians of technology have argued that the introduction of all-steel bodies may have been as important for economies of scale (Nieuwenhuis and Peter 2007).

We proceed as follows. The next section discusses the historical context and background. We then discuss and implement methods for assessing welfare gains and productivity advances for each of our two innovations, before discussing the implications and concluding.

2. Historical background and data

In this section, we briefly summarize the rise of assembly line production, as pioneered by Henry Ford, and the development of mechanized cotton spinning in the Industrial Revolution.

2.1 Henry Ford's production line

Henry Ford is an icon of twentieth century business. His most famous car, the Model-T, is best remembered for his quip that "Any customer can have a car painted any colour he wants so long as it is black" (Ford and Crowther, 1922, p. 72). Black was chosen because it dried faster. Speed mattered because the Model-T's success was not that it was a particularly good car – it wasn't – but because it was remarkably cheap. That in turn came from it being mass produced: it was built on a moving assembly line using interchangeable parts. In *Cannery Row,* John Steinbeck pointed out the importance of standardized components: "There was one nice thing about Model-T's. The parts were not only interchangeable, they were unidentifiable." (1990 Mandarin edition, p. 62). He had just stolen a Model-T carburettor to replace a broken one in a car he had borrowed. The phrase "mass production" was first used in an article that appeared in the entry on Henry Ford in the 1925 Encyclopaedia Britannica. (Lewchuk 'Mass production', in Mokyr *Encyclopaedia*, vol 3, p. 466)

The concept of a moving assembly line was not new. Oliver Evans, for example, used assembly lines to produce flour as early as the late eighteenth century, while the Cincinnati slaughter houses used a moving production line in the 1870s (Hounshell, pp. 242-3). But Ford's production line was far and away the most complex production line in existence. In all probability, Ford's staff, not Ford himself, were responsible for the breakthrough, but Ford at least deserves credit for allowing them to experiment and innovate, and for backing their ideas. The story is well-told in Hounshell's *From the American System to Mass Production, 1800-1932.*

The effects were impressive: the time taken to assemble a Ford chassis fell from just under 12.5 hours in spring 1913 to 93 minutes a year later (Hounshell, pp. 254-5). Greater efficiency led to big falls in price: the Model-T cost $950 in 1909, and $360 in 1916, a fall in real terms of more than two-thirds (Hounshell, p. 224), which in turn enlarged the market. That was Ford's aim – "I will build a car for the great multitude. It will be large enough for the family, but small enough for the individual to run and care for. It will be constructed of the best materials, by the best men to be hired, after the simplest designs that modern engineering can devise. But it will be so low in price that no man making a good salary will be unable to own one – and enjoy with his family the blessing of hours of pleasure in God's great open spaces." (Ford and Crowther, 1922, p. 73) Between 1908 and 1927 Ford sold a total of 15 million Model-Ts, a production run that would not be surpassed until the Beetle in the 1970s, and by the outbreak of war more than half the cars in the United States were Fords. The "Tin Lizzie" became so popular that Steinbeck wrote that "Most of the babies of the period were conceived in Model-T Fords and not a few were born in them." (*Cannery Row* pp. 55-6)

Ford's production line was gradually copied by his rivals, transforming the industry. The average price of a car sold in the US fell dramatically, from $2,126 in 1908 – the year in which the Model-T was introduced – to $642 in 1915, or $588 in real terms. Prices continued to fall in real terms, reaching $317 in 1923, at which point the price had declined by 85% in real terms (HSC series Df345/Df344). The number of cars sold in the US rose from 64,000 in 1908 to 3.6 million in 1923 (Df344). By 1923 automobile sales represented 2.6% of GDP. (A full set of price and quantity data are given in the appendix). Ford's invention of the moving assembly line, or at very least the application of the moving assembly line to the production of motor cars by the Ford Motor Company clearly had big welfare effects, yet economic historians have never sought to place a value on this.

2.2 Cotton spinning

Hobsbawm famously remarked, "Whoever says Industrial Revolution says cotton". The British cotton industry stood at the heart of Britain's transformation from an agricultural nation to an industrial one. From almost nothing in the mid-eighteenth century, cotton became Britain's leading industry by 1815, a position it retained until the end of the century (Sandberg, 1981, p. 114). At its peak it was to employ half a million people directly, and at least the same again indirectly. The effect on consumers was also profound. As the great English political historian, A.J.P. Taylor – himself from a cotton merchant family – remarked "Every piece of cotton cloth is going to make someone warmer of cleaner or more comfortable" (1976).

Britain had no natural advantage in the cotton industry: cotton does not grow in Britain, with wool and flax being the locally produced fibres. But cotton is a good for clothing: easy to print, wash and easier on the skin for the wearer. As a naturally "straight" fibre, the cotton production was much easier to mechanise than wool production. The spinning jenny and flying shuttle, the mule and power loom, the ring and automatic loom are known to generations of students. Of these, the first to have major economic significance was Crompton's 1779 mule. The first mules were relatively primitive, and in was only in 1790 that power, first animal, later water and steam were applied, and only with the invention of the "self-acting" mule in 1825 that it become the dominant form of spinning. Blaug (1961) argued that the period 1834-60 saw the introduction of a series of labour-saving refinements, and gradually, extra spindles were added to each mule allowing labour productivity to rise from 0.4 pounds per spinner per hour in 1830 to 2.3 in 1892. Although Cliometricians have studied the mule extensively, no-one has valued the welfare gains from the fall in price of cotton goods.

Mitchell gives the quantity of cotton processed in Britain. Prior to 1811 the figures do not adjust for changes in stocks, and so are best seen as accurate taking one year with the next, but not necessarily for any given year. After 1811 the figures include changes in stocks. We know the price of yarn thanks to the painstaking archival work of Harley (1998). Here we concentrate on the price of medium yarn (40s), and in order to abstract from any improvements in cotton growing, or transatlantic shipping, which would affect the cost of raw cotton and so in turn yarn prices, we subtract the price of raw cotton from the price of yarn. The price of "Bowed Georgia" cotton is given in Mitchell for 1793 onwards (p. 759), which we project backwards using data for Philadelphia (Bezanson et al). Although the price level would have been different in Philadelphia and Liverpool, the changes in prices would have closely matched, given that shippers could send cotton freely to either place. Both Mitchell and Bezanson et al give maximum and minimum prices. We use the minimum prices, because the maximum price may have been a short-lived spike, and was often higher than the average value of the yarn that it could have produced at that time. Cotton can be stored, so no-one would have been forced to purchase large amounts of cotton at temporarily high prices.

Given that cotton firms were well-known for using all of the raw cotton, we simply subtract the cost of a pound of raw cotton from the selling price of a pound of yarn to find the cost of manufacturing a pound of cotton yarn. That fell from 107d/lb in 1784 to 47d/lb within a decade, to 21d/lb by 1810 and to a low of just over 10d/lb by 1819, all in 1784 real terms. This 90% fall in the cost of manufacturing yarn clearly had important welfare implications. Interestingly, the total revenue did not rise dramatically, with values of between £5.0m and £8.4m in the first five years of this period, and between £5.2m and £6.5m in the last five years. As a result the value of cotton processing fell rather than rose as a share of GDP over time. Notice that these figures include cotton yarn that would later be exported, either directly as yarn, or having been made into thread.

3. Methods and Results

In this section we list, explain and apply various methods of assessing the value of the two process innovations outlined above. When we look at mass production of cars, we define 1908 as the pre-mass production reference point (the Model-T was introduced only at the end of 1908, and sold in limited numbers initially), and 1923 as the end point. This is the year in which the price of the Model-T was lowest in real terms. In the case of cotton, we define 1784 as the pre-improvement year and take 1820 as the end point. Clearly further improvements occurred after this, but this date is a reasonably approximation for the end of the initial improvements to the mule spindle.

3.1 Social Savings

The first formal oral exposition of the social savings concept was given by Fogel at the 1960 Purdue Cliometrics meeting, and first appeared in print in his 1962 Journal of Economic History article. With the benefit of hindsight that article does not explain the concept well, as Fogel admitted in his 1978 EHA Presidential Address (Fogel, 1979, p. 3). There he was much clearer: “I defined the social saving of railroads in any given year as the difference between the actual cost of shipping goods in that year and the alternative cost of shipping exactly the same bundle of goods between exactly the same points without the railroad” (Fogel 1979, pp. 2-3). The concept is simple: social savings are the fall in the cost of doing exactly what was done with a new technology, without it. Algebraically, therefore:

$$SS = (P_1 - P_0).Q_1 \qquad (1)$$

Where P_0 and P_1 are the pre- and post- technological improvement prices, and Q_1 the quantity consumed at price P_1.

Clearly the comparison can never be perfectly like for like: without the railways goods and people cannot travel as quickly, for example. Foreman-Peck (1991) showed that social savings are identical to total factor productivity growth under standard neo-classical conditions. Social savings records the fall in inputs required to produce a certain level of output when technology improves while TFP studies record the rise in output that an improvement in technology makes possible from a certain level of inputs. Analytically these are identical.

We turn now to estimating the social savings from improvements in car assembly and cotton spinning. All we need to know to assess the social savings are the prices before and after, and the final level of consumption. We know that the cost of the average car sold declined in the United States between 1908 and 1923 from $2,126 to $317, in 1908 dollars, and that 3.6m cars were sold in 1923. It follows arithmetically that the social saving from the application of the production line to automobiles between 1908 and 1923 is therefore $(2126-317) x 3.6m. This is $6.6bn in 1908 terms, or $12.6bn in 1923 terms. That in turn represents a staggering 14.7% of GDP. This is a quite remarkable result: automobiles valued at 2.6% of GDP created social savings of 14.7% of GDP. The power of a process innovation to improve the productivity of American industry appears to be truly remarkable.

The cost of producing cotton fell from 107.2d/lb in 1784 to 12.6d/lb in 1820 in 1784 pence. By 1820 Britain was producing 120m lbs of cotton. It follows, therefore, that the social savings of improvements in cotton processing were £47m in 1784 terms, or £64m in 1820 terms. This is equivalent to 17.6% of GDP. The benefit to British consumers was equal to 7.5% of GDP, with the remainder accruing to those who bought Britain's cotton exports.

Many of the critiques levied at Fogel and Fishlow do not apply here. It is not the case that the previous technology was not scalable – with enough labour, 3.6m cars could have been produced in 1923 using 1908 production methods, for example. It is doubtful that the long run cost curve for that technology sloped either up or down to any significant extent. Pre-mass production and post-mass production techniques for both car assembly and cotton production are much closer substitutes than canals and railways, for example.

The social savings estimates for these process innovations are very large indeed, and suggest that process innovations should be seen as just as important as product innovations to those who wish to understand the rise in material living standards over time. Nevertheless, the sheer scale of the result should give us pause for thought: we need to ask ourselves whether social savings estimates 5 or 7 times the market value of the products are plausible estimates of the benefits of the technology used to produce them. There is, of course, no a priori reason why the social saving cannot exceed the cost of production many times over. But what warrants caution here is that when the price was high, people did not buy many cars or as much cotton. To claim, for example, that every person who bought a car for $317 in 1923 made a welfare gain of $1809 is not supported by revealed preference.

3.2 Consumer surplus

Simple approximation

We know that the social savings methodology is an absolute upper bound on the welfare gain to consumers, correctly defined as the increase in the area under the demand curve. There are many ways to assess this area, all with different data requirements. The connection between consumer welfare and social savings is portrayed effectively by Crafts in figure 1 of his 2004 paper on social savings. This is reproduced (and relabelled) below as figure 1. In this diagram, P_0, Q_0 and P_1, Q_1 represents the pre- and post- technology improvement price and quantity equilibria respectively. Social savings is defined as $(P_0 – P_1).Q_1$ and therefore equals the areas a + b + c + d + e in figure 1.

Crafts notes that connecting the initial and final equilibria creates the line "D" in figure 1. Insofar as the demand for the good at any given price level is identical before and after the invention of the new technology these two points lie on a single demand curve (which is shown as being a straight line for simplicity – with only two observations it could clearly take any functional form provided that it passes through the initial and final equilibria). In that case the rise in consumer surplus equals areas a + b + c, and the social savings methodology overestimates this by the amount d + e. If, therefore, in addition to knowing the initial and final prices, and final consumption level, we also know the initial consumption level, we are able to calculate the consumer surplus as defined in figure 1 as a + b + c. It is defined algebraically as $(P_0 – P_1).(Q_0 + Q_1)/2$.

We know that 64,000 cars were sold in the United States in 1908. It follows arithmetically that area a + b + c is equal to $3.3bn (in 1908 terms), $6.4bn in 1923 terms, and 7.5% of GDP. This is still a large number, but it is only a fraction over half the original social savings estimate.

The case of cotton is not quite so straightforward, since some of the cotton produced in 1820 was exported, and replaced cotton that would have been produced locally abroad in

1784.[1] For that reason we restrict ourselves here to cotton yarn produced and consumed in Britain. We have good quantity data for the proportion of cotton goods that were exported from 1800 onwards, and good value data prior to this date (Edwards, p. 243). It is therefore straightforward to estimate that Britain processed and retained 9.9 m lbs of cotton in 1784 and 51.3 m lbs in 1820. Taken with the 1784 and 1820 costs of processing cotton given earlier, this implies that the consumer surplus, as measured by a + b + c is equal to £12.1m in 1784 terms, or 4.5% of GDP. As with the case of cars, this is considerably smaller than the 7.5% of GDP estimated by the social savings methodology. The difference in this case is a little less marked, because the initial level of consumption was higher. By inspection of figure 1, we can see that when area a is larger relative to b + c + d + e, the difference between the consumer surplus and social savings estimates is smaller. In the limit, if demand does not rise when the cost falls (b + c + d +e = 0), consumer surplus and social savings will be equivalent, whereas if demand was zero prior to costs falling (a=0), then consumer surplus (as measured by schedule D and assuming linearity) will be half the value of social savings. The Ford example is close to the second limit case.

Taking into account the change in demand

Insofar as demand rises in the period in which the new technology is invented and adopted, then the initial and final equilibria do not lie on the same demand schedule, and the line marked D should not be seen as a valid demand curve. Crafts labels these as D_0 and D_1, representing demand before and after the invention of the new technology. Final demand will be higher by the rise in income multiplied by the income elasticity of demand, and by the rise in population. Insofar as we have only one observation for each demand curve, we cannot say much about the shape of D_0 and D_1, save only that the price elasticity of demand must be lower than for schedule D. The consumer welfare estimate of the benefit of the new technology is given by the area under the D_1 schedule, that is, by areas a + b + c + d.

In order to estimate the consumer surplus under D_1, we need to be able to estimate consumption when price is P_0. Here we proxy this by the actual consumption multiplied by

[1] In his 1999 response to Cuenca Estaban, Harley presents estimates of the linear approximation to consumer surplus from the development of the cotton industry 1770-1841, termed here a + b + c. However, he defines consumer surplus incorrectly. In the case of linear demand, he defines it as the area vertically below the demand curve between the pre- and post- innovation quantities, rather than the area horizontally to the left of the demand curve between the pre- and post- innovation prices. This leads him to overestimate the linear approximation consumer surplus. The correct value, for his exercise, is 13.8%, rather than 17.6% of GDP.

the rise in GDP, that is, we are assuming a linear relationship between income and consumption of cotton and cars. Insofar as much of the rise in income comes about from the rise in population this assumption is likely to be reasonably accurate. This is particularly true for cotton, where 85% of the rise in GDP occurred because of population growth.

US GDP rose by 50% in real terms between 1908 and 1923. It is plausible to imagine that demand for automobiles would have risen 50% over this period were automobile prices to have remained at their 1908 level. This implies that 94,000 cars would have been bought at a price of $2126 in 1908, under schedule D_1. Although this quantity is 50% greater than the quantity actually bought, this growth is trivial compared with the expansion to 3.6 million that would occur in the following 15 years. D_1 and D turn out to be virtually indistinguishable, and arithmetically we find that a + b + c + d exceeds a + b + c by under 1%, so that the ratio of consumer surplus to social savings remains at 51%, when expressed to the nearest integer.

Broadberry et al find that GDP increased in Britain by 73% between 1784 and 1820. This implies that demand for cotton would have been 17.1m lbs in 1784 under 1820 demand conditions, but with price at its 1784 level. One sixth of the overall rise in actual demand between 1784 and 1820 can be accounted for not by the fall in prices, but by the rise in national income. Under this scenario the rise in consumer surplus becomes £13.5m in 1784 terms, or 5% of GDP. Including area d increases the estimate of consumer surplus by about 10%. The effect is larger in the case of cotton than cars because rising incomes account for a greater proportion of the rise in overall demand.

Taking into account the shape of the demand curve

Until now we have assumed that demand curve for cotton and cars are linear. This is computationally easy, but has no theoretical or empirical underpinnings. Even were we to know only the pre- and post- innovation equilibria we could estimate consumer surplus using alternative functional forms. In this case, however, we observe annual price and quantity equilibria, which we can use to ascertain the shape of the demand curve. In each case the curve that we estimate will be equivalent to D in Craft's diagram, and we make a subsequent adjustment to D_1.

The markers in figure 2 represent the actual price/quantity equilibria that we observe in the data. All except two are joined by a line which we take to be the correct representation of the schedule D in the stylised figure presented by Crafts. Where the line does not directly join up two equilibria it is shown as a dashed line. Below the dashed line lies the observation for 1921, when fewer cars were sold than we would expect given the price prevailing in that year. 1921 was of course a year of severe depression, and it is reasonable to imagine that this observation will lie below the overall equilibrium demand schedule. In addition, the observation for 1916 lies above the expected line – more cars were sold than expected, given the price. The error is not large, however, as is best treated as a deviation of the sort that social scientists encounter from time to time.

Figure 2 shows that the demand curve for cars in the US was not linear, but instead highly convex. It is possible to calculate the consumer surplus from the line given in figure 2, including the dashed section, arithmetically, simply by assuming that the demand curve is a straight line between the individual points on the graph, and calculating the area accordingly. When we do this, we find that the consumer surplus amounts to $798m in 1908 terms, which is $1.5bn in 1923 terms, or 1.8% of 1923 GDP. This is approximately one-eighth the size of the social savings estimate, and much smaller than the stylised representation of consumer surplus given in figure 1. Figure 2 estimates D rather than D_1, but we have shown that D and D_1 differ only trivially.

Figure 3 shows that the price and quantity observations for cotton do not naturally form as smooth a line as in the equilibrium points for the US car market. We therefore estimate the relationship, using a simple 1/x function. The estimated equation is clearly a reasonable fit, and takes the form Q = 10.2 + 1209/margin, with t-statistics of 2.2 and 11.4 on the constant and margin terms respectively. The adjusted R^2 is 0.78.

We can calculate consumer surplus by integrating the demand curve with respect to the cost of processing cotton and evaluating it between the margin values for 1784 (107.2d) and 1820 (12.6d) respectively. The result is that the consumer surplus caused by the fall in prices is estimated to be £14.8m in 1784 terms, which is 5.5% of GDP. This is an estimate for the area under the curve D in Crafts' diagram, and since we found earlier that the area under D_1 is around 10% larger, the best estimate of the consumer surplus benefits of the fall in cotton prices as estimated by this method is around 6% of UK GDP, including benefits to foreigners. The benefit to UK consumers would be 2.6% of GDP.[2]

Hausman methodology

There are two analytically distinct measures of welfare gains: compensating variation and equivalent variation. Both rely on comparing two imaginary situations: In the first situation, people cannot buy a particular good; in the other, they can. Effectively, we assume a price of infinity in the state of the world where the good is not accessible. Compensating variation (CV) measures the decline in income (λ) a consumer is willing to accept just to keep access to a new good. We write:

$$W((1-l_{CV})y_2, p_2) = W(y_2, \infty) \tag{2}$$

where $W(y_t, p_t)$ maps incomes and prices into utility.

Equivalent variation (EV) measures the increase in income required to give a consumer who does not have access to a particular good the same utility as a consumer with access:

$$W((1+l_{EV})y_2, \infty) = W(y_2, p_2) \tag{3}$$

For consumers with quasi-linear preferences, the results for EV and CV are identical. Compensating and equivalent variation cannot be estimated simply by knowing initial and final prices and quantities. A useful short-cut for obtaining values of CV was proposed by Hausman (1999). He suggests triangulating the area under the demand curve, with a simple tangent (hyperplane in the multivariate case) through the point of current consumption. This implies that the compensating variation, expressed as a proportion of consumers' expenditure can be approximated as follows:

$$CV \approx \frac{1}{2} Sh^{-1} \tag{4}$$

where S is the budget share of spending on the new good, and η is the price elasticity of demand.

[2] Again, Harley does likewise but makes the same analytical error as outlined earlier. In this case his estimate of the constant elasticity consumer surplus should be 2.9% rather than 8.7%.

To apply the Hausman short-cut, we need estimates of the price elasticity of demand η for the budget share of the new good. Typically, estimating η is complicated by the fact that we only observe the intersection of demand and supply curves – we cannot identify the effect of price changes on consumption without a good instrument. In this case, however, we have already demonstrated in figures 2 and 3 that we can calculate the effect of a fall in price on consumption.

In the case of cars we can estimate η by OLS, which gives a coefficient of -1.67 (estimated on a log-log basis). Table 1 sets out the calculation of consumer surplus in this case.

The convexity of the demand curve implies that the consumer surplus from introducing cars was relatively small for any given budget share. Since budget shares were also relatively low, the overall increase in consumer welfare was also relatively limited, at around 1% of GDP. The price elasticity of demand was not sufficiently low to create windfalls that are large relative to the budget shares of the automobile industry. However, the greater the convexity of the demand curve, the less accurate the triangulation method by Hausman becomes, and this means that we have to be careful in using this method in this case.

Results for cotton spinning show a similar pattern. We again estimate the price elasticity of demand from a double-log specification. This gives a figure of -0.94, which implies that cotton goods were more "essential" to the British in the 18th and 19th century than cars were to Americans in the 20th. The lower elasticity is plausible.

Again, since aggregate demand even in the absence of price changes would have grown over this period, we need to add around 10% to cover the difference between D_0 and D_1 in Crafts' diagram. It is best to see the Hausman method as suggesting that cotton goods generated consumer surplus equivalent to around 2-3% of GDP in this era.

A different way of estimating the consumer surplus for new goods was pioneered by Greenwood and Kopecky (2010). They effectively use a combination of estimation and calibration to derive a precise measure of the gain in consumer surplus, estimating the shape of the demand curve. In particular, it takes full account of the fact that demand curve will shift as incomes change. They employ a shifted utility function so that the marginal value of the first unit of a new good is bounded. This allows the calculation of welfare gains. The utility function for old goods is CRRA:

$$U(c) = \frac{c^{1-r}}{1-r}, \text{ with } \rho \geq 0 \tag{5}$$

and for new goods, it is identical except for a shift factor ν.

$$V(n) = \frac{(n+n)^{1-r}}{1-r}, \text{ with } V(0) = \frac{n^{1-r}}{1-r} > -\infty \text{ and } V_1(0) = n^{-r} \tag{6}$$

Here, 1/ρ is intertemporal elasticity of substitution. For the new good, the first unit yields utility $\nu^{-\rho}$. This maps into a threshold price $\hat{p}$ when utility is low enough for the new good to be just adopted by one unit. Greenwood and Kopecky assume that the consumer maximizes overall utility:

$$W(y, p) = \max_{c,n} \left[qU(c) + (1-q)V(n) \right] \tag{7}$$

with $0 < \theta < 1$; $c, n \geq 0$; and subject to the budget constraint $c+pn=y$

This implies a demand function for new goods of the form:

$$\hat{n} = \frac{y + p}{p + [(1-q)/q]^{-1/r} \, p^{1/r}} - n \tag{8}$$

q gives the weight in terms of utility for the old good, and *(1-q)* the utility weight of the new good, *c* serves as a numeraire, *p* is the relative price of new goods, and *y* is income.

Next, the Greenwood and Kopecky method performs a calibration of n, q, and r to minimize the sum of squares of differences between observed new goods, *n*, and the predicted new goods, $\hat{n}$.[3] To this end, we require data on income *y*, prices *p* and new good consumption *n*.

[3] As in Greenwood and Kopecky, we constrain consumption in the beginning of the period to zero. Due to the nonconvex nature of the equation 8, a Nelder-Mead nonlinear optimization algorithm is used for the sum of squares minimization.

To apply the Hausman short-cut, we need estimates of the price elasticity of demand η for the budget share of the new good. Typically, estimating η is complicated by the fact that we only observe the intersection of demand and supply curves – we cannot identify the effect of price changes on consumption without a good instrument. In this case, however, we have already demonstrated in figures 2 and 3 that we can calculate the effect of a fall in price on consumption.

In the case of cars we can estimate η by OLS, which gives a coefficient of -1.67 (estimated on a log-log basis). Table 1 sets out the calculation of consumer surplus in this case.

The convexity of the demand curve implies that the consumer surplus from introducing cars was relatively small for any given budget share. Since budget shares were also relatively low, the overall increase in consumer welfare was also relatively limited, at around 1% of GDP. The price elasticity of demand was not sufficiently low to create windfalls that are large relative to the budget shares of the automobile industry. However, the greater the convexity of the demand curve, the less accurate the triangulation method by Hausman becomes, and this means that we have to be careful in using this method in this case.

Results for cotton spinning show a similar pattern. We again estimate the price elasticity of demand from a double-log specification. This gives a figure of -0.94, which implies that cotton goods were more "essential" to the British in the 18th and 19th century than cars were to Americans in the 20th. The lower elasticity is plausible.

Again, since aggregate demand even in the absence of price changes would have grown over this period, we need to add around 10% to cover the difference between D_0 and D_1 in Crafts' diagram. It is best to see the Hausman method as suggesting that cotton goods generated consumer surplus equivalent to around 2-3% of GDP in this era.

Greenwood and Kopecky method

We obtain a reasonable fit, as indicated by an R2 of 0.72 overall. The shift parameter of ν=2.05 implies that the first units of cotton goods in our series have a value of 84 (in unit-free utility), twice as high as the value for cars. Our estimate of the budget share is clearly off, since the θ returned by our calibration/estimation exercise suggests that there are virtually no purchases of cotton goods, while the actual budget share was anything but small. As a result, the Greenwood-Kopecky method suggests relatively small gains in consumer welfare, of 1.3-1.7% of consumer expenditure. This figure is somewhat lower – but not categorically different from – the estimates obtained by the Hausman method.

4. Discussion:

4.1 What were these process innovations worth to society?

This paper has constructed social saving and consumer surplus estimates for two of the most important process innovations in the last two centuries. The results are given in table 5.

We find very considerable social savings for both cotton and car production – far greater in magnitude than found by Fogel or Fishlow for the railways. At the same time, the consumer surplus created by the introduction of process innovations is an order of magnitude smaller. Furthermore, there are considerable differences between the different methods of assessing consumer surplus. What is clear is that, as we would expect, linear approximations are very poor methods to estimate consumer surplus: knowing the elasticity of demand is critical in accurately assessing consumer surplus.

Of the remaining methods, all are of the same order of magnitude, supporting their use in each case. The Greenwood-Kopecky method is more ‘precise’ than the Hausman method, in the sense that it allows us to approximate the area under the demand curve even if it is non-linear. The Hausman method, by comparison, is more crude, and uses a linear approximation that will almost always result in a lower bound of the true effect. The Greenwood-Kopecky method struggled somewhat with predicting consumer expenditure, particularly for cotton. It is probably best to see the invention of the production line for cars as having generated consumer surplus of a little under 2%, and the invention of better methods to spin raw cotton as having generated consumer surplus for British consumers of a little over 2%, with an additional gain of the same order of magnitude for foreign consumers of British cotton goods.

4.2 The relationship between consumer surplus and social savings

Theory pins down a precise relationship between these two concepts. As Leunig (2010) shows, the following mapping should hold:

$$\Delta CS/SS= [(P_0/P_1)^{e+1}-1]/[(e+1)((P_0/P_1)-1] \quad (9)$$

Where e is the price elasticity of demand, and other notation as above

The difference between social savings and consumer surplus therefore depends on two factors – the extent of the price fall, and the price elasticity of demand. To see the intuition for this, it helps to think of the post-introduction decline in price as a “bribe” to get consumers to take up the good. If a large bribe is necessary to induce consumption then the product was not worth its original price to many people. The extent to which extra consumption of the new good was ‘bought’ by lower prices is measured by the price elasticity of demand.

Following Leunig (2010) we can plot the ratio of the change in consumer surplus and social savings given in equation nine graphically, to give that ratio as a function of the fall in price and elasticity of demand. We do this in figure 6, which shows the ratio between these two measures when the elasticity is 1.67 and 0.94, the elasticities for cars and cotton respectively.

The ratios of old to new prices were 6.7 and 8.5 for cars and cotton respectively, which, given the estimated elasticities, implies that the rises in consumer surpluses caused by the process innovations will be 0.30 and 0.19 respectively. These points are marked on figure 6. Our estimates for social savings are 14.7% and 17.6% respectively, implying gains in consumer surplus of 2.8% and 5.4% for cars and cotton (2.3% for cotton consumed in the United Kingdom). All of these figures are in line with direct estimates for consumer surplus, again, giving us considerable confidence in the validity of our estimates.

5. Conclusion

In this paper we attempt to stand on the shoulders of two of the giants of Cliometrics: Robert Fogel and Albert Fishlow. Until now the social savings method has almost exclusively been applied to railways. At the same time, many other big improvements in technology took place in the past. In this paper, we shift the emphasis from product innovations and look instead at process innovations. This is an important contribution to the social savings literature. We argue that the social savings methodology is better suited to evaluating process innovations than product innovations, for two reasons. First, the product produced is often pretty much identical before and after the process innovation. Cotton yarn spun on a ring, a mule, a water frame or a jenny was much the same product. We can therefore escape much of the debate about the extent to which, for example, a canal is a good substitute for a railway. Second, process innovations are (sometimes) adopted rapidly. Henry Ford was not able to introduce mass production overnight, but it took only a year for the moving assembly line to be fully introduced for the main chassis, and mass production covered the bulk of the total assembly process within less than a decade. When the time frame is compressed like this, the external before and after conditions are much more aligned, allowing for a cleaner comparison.

We find that the process innovations that made cotton and cars cheaper generated very large social savings estimates. We can get a sense of this by comparing them with a range of railway social savings estimates in different places and times. These are given in table 6.

In the context of table 6 the social saving estimates for improvements in producing cars (14.7% of GDP) and cotton (17.6% of GDP) are large. Only railways in Argentina and Mexico had noticeably bigger social savings results. Process innovations can be hugely important.

Social savings and consumer surplus are, as we argued in the introduction, closely related concepts. Our findings suggest that in the cases studied here, social savings were at least one order of magnitude larger than consumer surpluses created by them. That said, the consumer surplus estimates that we have presented here are not negligible, and stand comparison with the consumer surplus estimates for many of the new goods that have been studied. The details are given in table 7.

Improvements in the ability to manufacture cars and to convert raw cotton into cotton yarn generated additional consumer surplus greater than that from mobile phones, and of a similar order of magnitude to the creation of the internet, or the expansion of foreign trade. Only the arrival of sugar, tea and coffee, goods that must have been unbelievably novel, had materially larger welfare effects.

This paper has shown that, whether measured by social savings or consumer surplus, process innovations can have large effects for welfare and productivity, comparable in size with those of “big inventions” – the railway, the mobile phone and the internet. History has seen important welfare gains from improvements in how we produce goods, as well as from new products themselves.

Table 1: Hausman method of assessing consumer surplus: cars

Year	Expenditure on cars	total expenditure	budget share	elasticity	CV
1908	0.14	20	0.5%	-1.67	0.2%
1923	2.2	56.9	3.9%	-1.67	1.15%
1929	2.79	69.1	4.0%	-1.67	1.2%

Consumer expenditure is set to two thirds of GDP. Figures are in current $ billion.

Table 2: Hausman method of assessing consumer surplus: cotton.

	expenditure on cotton	total expenditure	share	elasticity	CV
1784	5	103	4.9%	-0.94	2.6%
1820	6.3	178	3.5%	-0.94	1.9%

Figures are in 1784 £m.

Table 3: Welfare results for Cars, Greenwood-Kopecky method, 1909-1929

Sumerr	0.78
EV	0.036
CV	0.035
n	0.002
r	0.56
q	0.89
R2	0.95

Table 4: Greenwood-Kopecky results for cotton, 1769-1810

Sumerr	10.28
EV	0.013
CV	0.017
n	2.05
r	-6.36
q	1
R2	0.72

Table 5: The benefits of process innovation as a % of GDP

	Cars	Cotton	(Cotton: domestic only)
Social Savings	14.7	17.6	7.5
Consumer surplus:			
linear a+b+c	7.5		4.5
linear a+b+c+d	7.5		5.0
area under plotted line	1.8	6.1	2.6
Hausman	1.2		2.5
Greenwood-Kopecky	3.5		1.5

Notes: G-K applies to different dates, see text for more details

Table 6: Railway social saving estimates

	Freight	Passengers
Argentina 1913	26.0	
England and Wales 1865	4.1	2.5
England and Wales 1890	10.2	6.4
USA 1859	3.7	
USA 1890	4.7	2.6
Spain 1878	6.5	
Spain 1912	18.5	
Russia 1907	4.6	1.0
India 1900	9.0	
Brazil 1913	18.0	1.6
Mexico 1895	14.6	
Mexico 1910	31.5	0.6

Sources: Freight: Argentina and Brazil: Summerhill (2003); England and Wales: 1865: Hawke (1970), 1890: Foreman-Peck (1991); USA: 1859: Fishlow (1965), 1890: Fogel (1964); Russia: Metzer (1976); India: Hurd (1983); Spain: Gomez-Mendoza (1983); Mexico: Coatsworth (1981). *Passengers:* England and Wales: Leunig (2006); USA: Boyd and Walton (1972); Russia: Metzer (1976); Brazil: Summerhill (2003); Mexico: Coatsworth (1981)

Table 7: Welfare gains from new goods and processes

	Good	Consumer Surplus	Study
This study	Assembly line/cars	1.2-3.5%	
	Cotton spinning	5.4-6.1% (1.5%-2.6% for UK consumed cotton)	
Other studies	Sugar, Tea, Coffee	8-17%	Hersh and Voth 2010
	Internet	2-3%	Goulsbee and Klenow 2006
	Mobile phones	0.5-0.9%	Hausman 2006
	Foreign varieties	2.2-2.6%	Broda and Weinstein 2006

Figure 1: The stylised relationship between consumer surplus and social savings

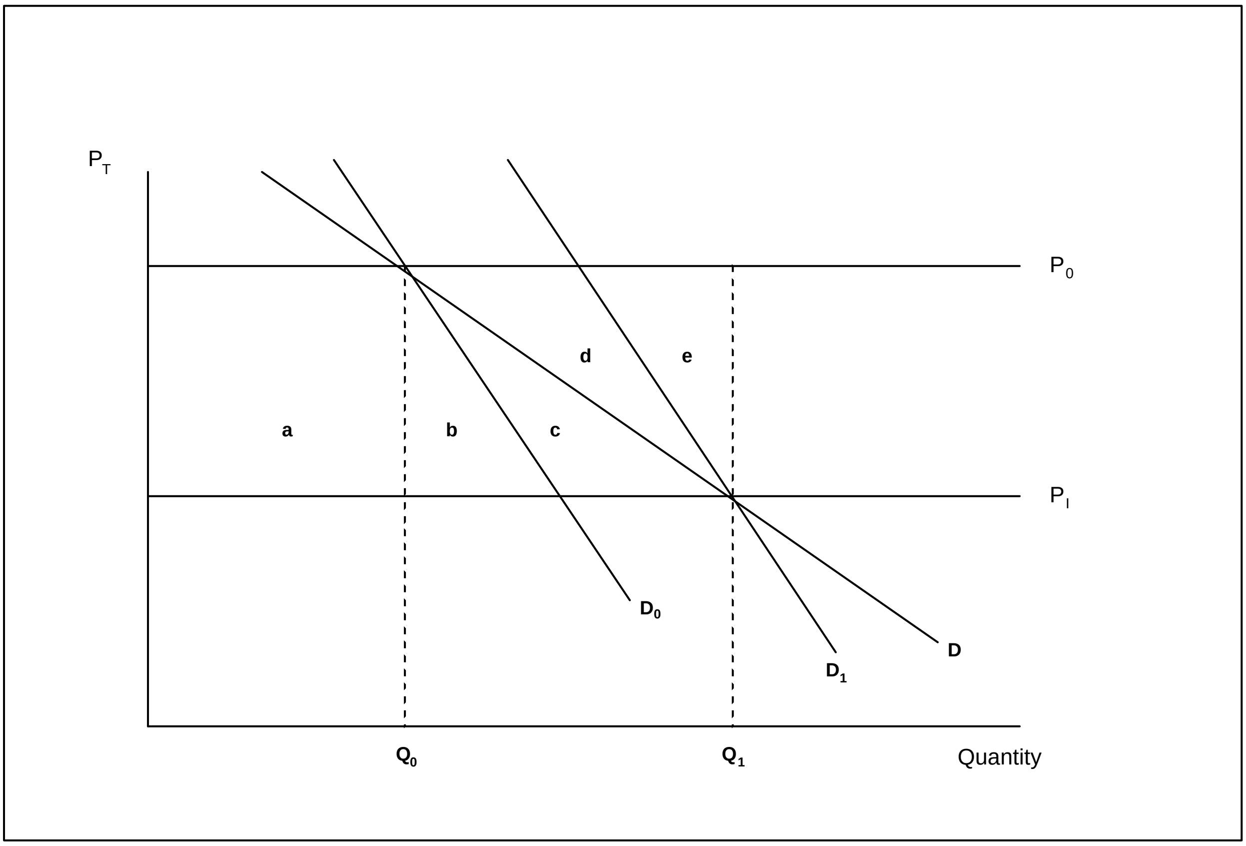


Figure 2: The price and sales of cars in the US, 1908-1923

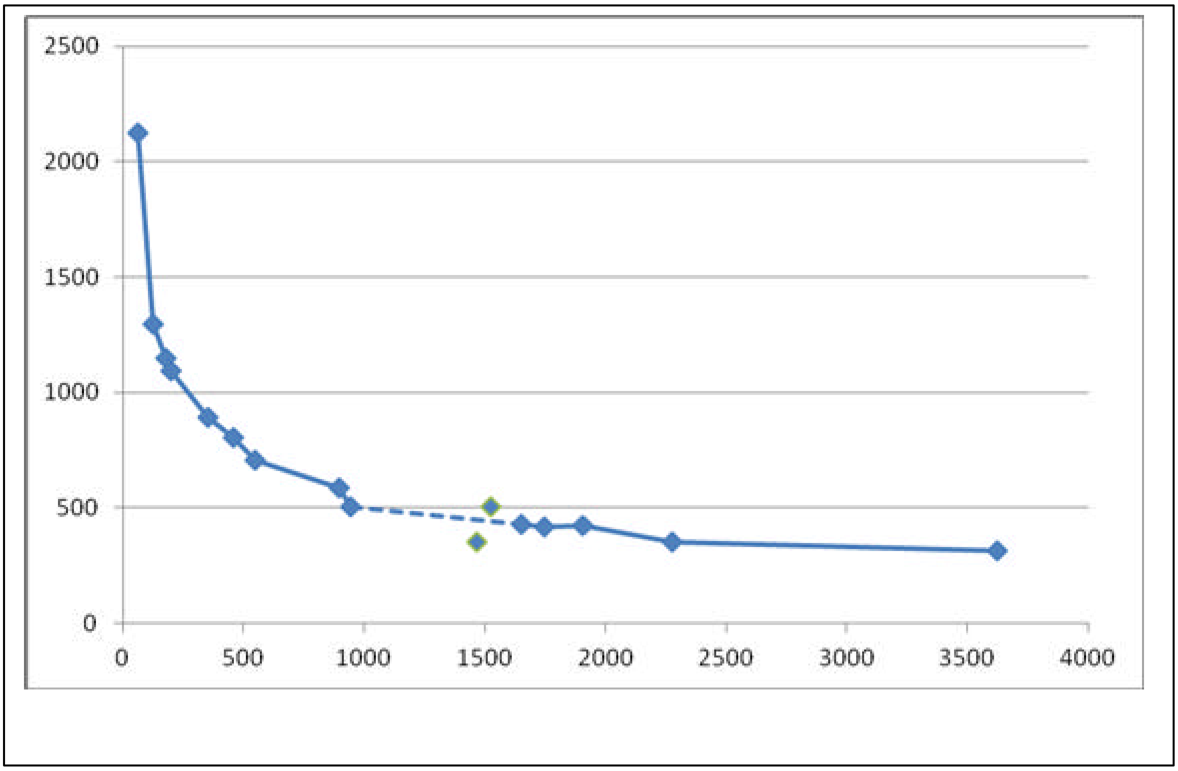


Figure 3: Cotton processing costs and sales, 1784-1820

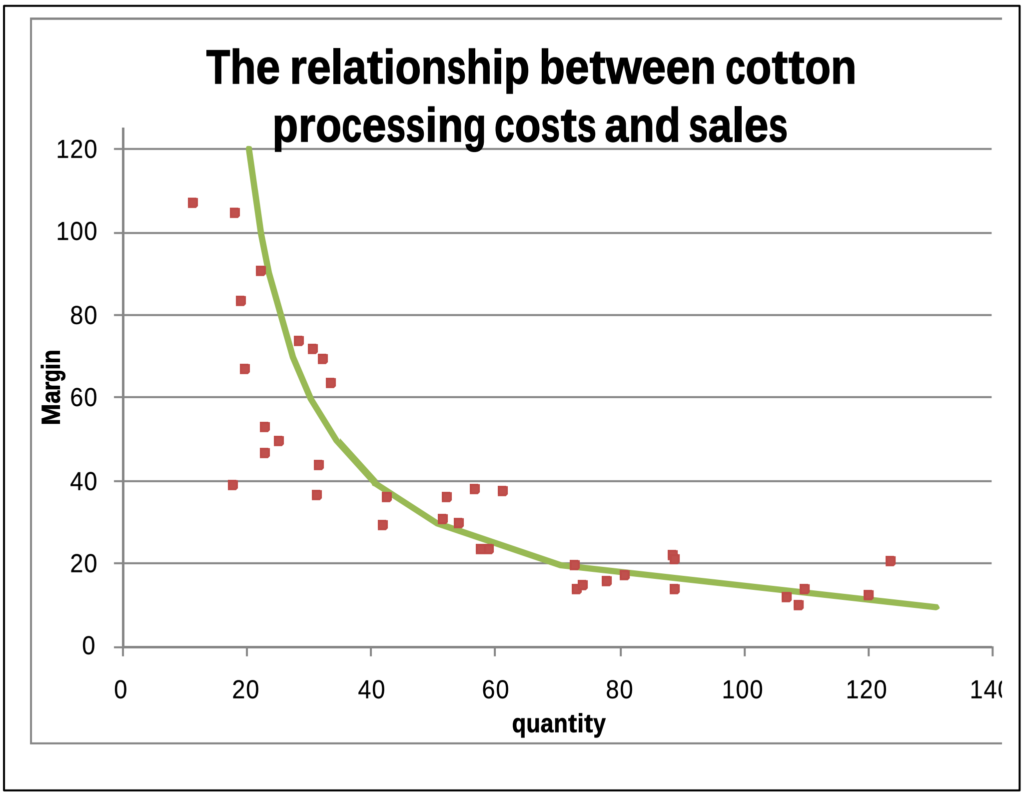


Figure 4: Greenwood-Kopecky estimation of car sales

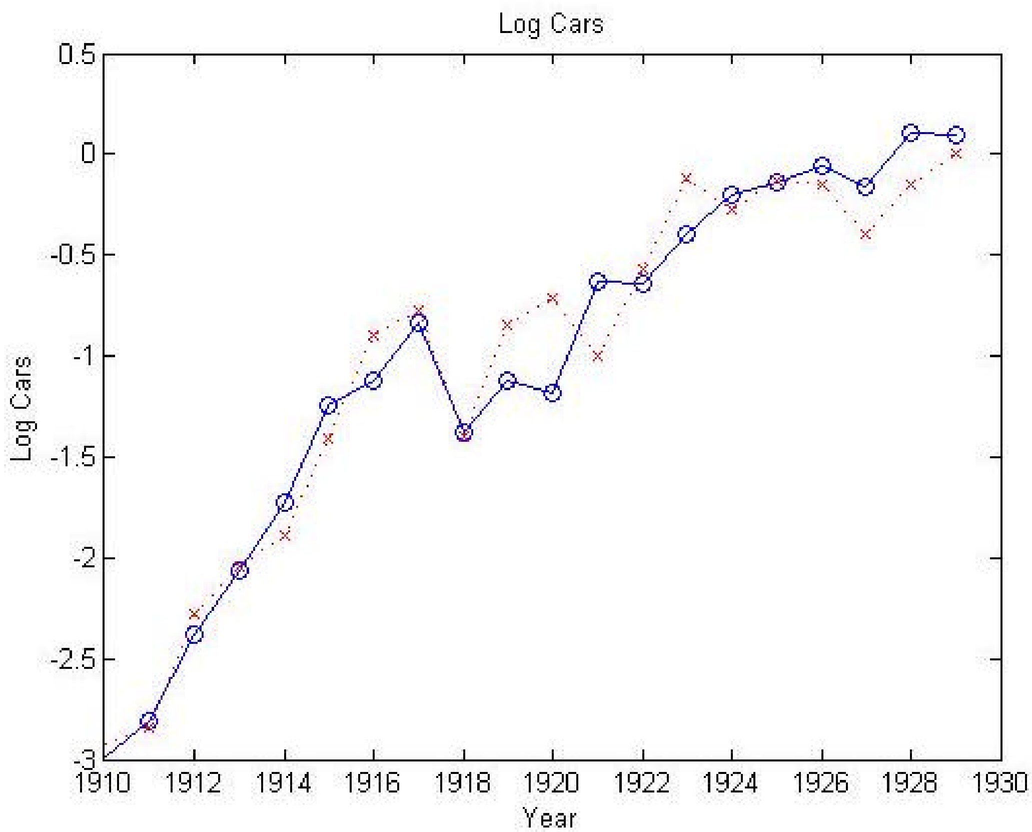


Figure 5: Greenwood-Kopecky estimation of cotton consumption

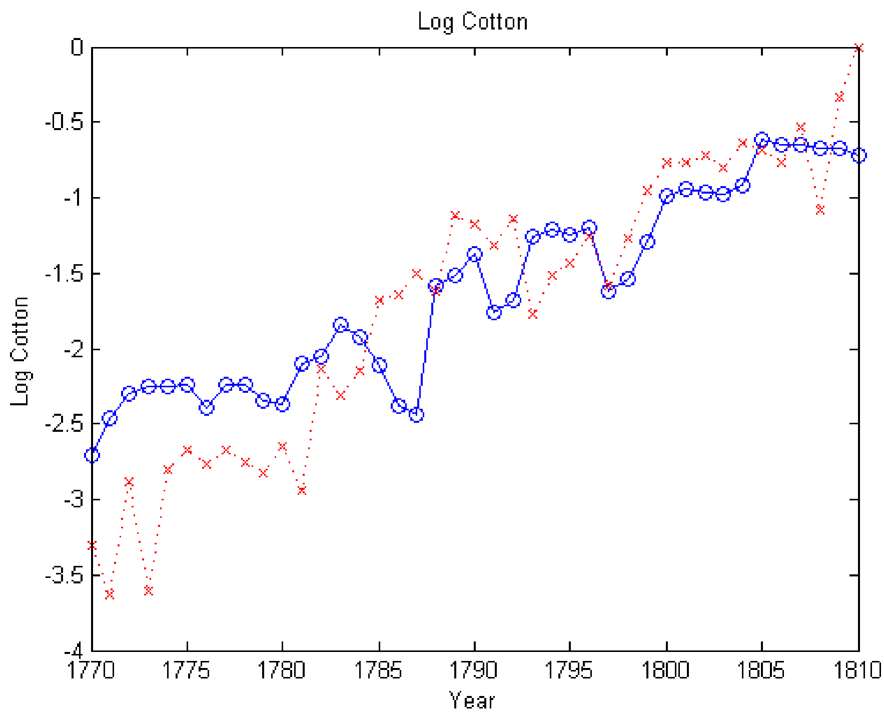
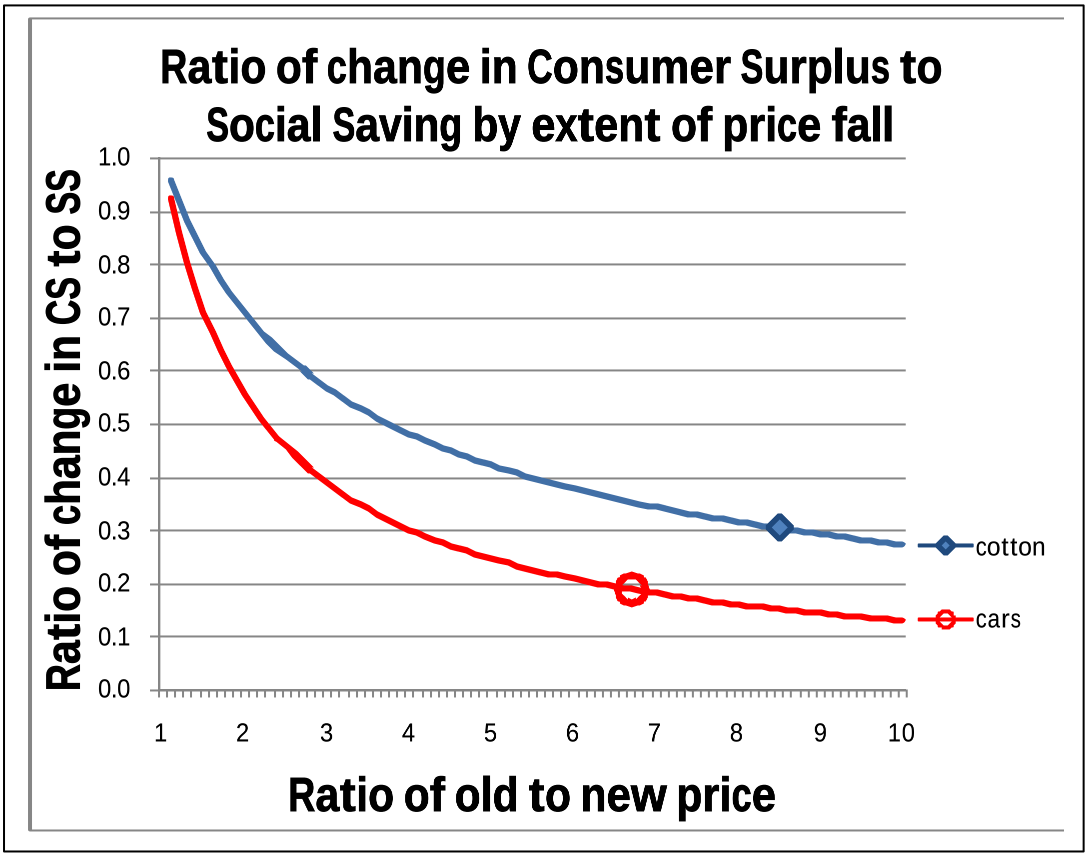


Figure 6: The ratio of the change in consumer surplus to social savings when the elasticity of demand is 0.94 and 1.67.



Appendix: Prices and consumption of cars and cotton

Cars				Cotton				Cotton		
	Q	P real			Q	P real			Q	P real
1908	63.5	2126		1784	11.3	107.2		1803	52.3	36.5
1909	123.9	1298		1785	18.0	104.7		1804	61.4	38.0
1910	181	1150		1786	19.2	83.6		1805	58.9	23.7
1911	199.3	1093		1787	22.2	90.8		1806	57.5	23.6
1912	356	893		1788	19.6	67.4		1807	72.7	20.0
1913	461.5	803		1789	32.3	69.6		1808	42.0	29.6
1914	548.1	705		1790	30.6	71.8		1809	88.5	22.5
1915	895.9	588		1791	28.3	73.7		1810	123.7	21.1
1916	1525.5	506		1792	33.4	63.9		1811	89.0	21.4
1917	1745.7	420		1793	17.9	39.0		1812	73.0	14.0
1918	943.4	503		1794	23.0	47.0		1813	78.0	16.1
1919	1651.6	426		1795	25.2	49.7		1814	74.0	15.0
1920	1905.5	423		1796	31.4	44.0		1815	81.0	17.5
1921	1468	352		1797	22.7	53.3		1816	89.0	13.9
1922	2274.1	349		1798	31.3	37.0		1817	107.0	12.1
1923	3624.7	317		1799	42.5	36.2		1818	110.0	14.1
				1800	51.6	30.9		1819	109.0	10.3
				1801	54.1	30.1		1820	120.0	12.6
				1802	56.6	38.5				

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