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ABSTRACT

We provide quantitative analyses of two striking historical episodes, the timing of the Industrial Revolution in England, and the sources of U.S. economic fluctuations between 1889-1929. Applying data from 1245-1845 within the "Malthus to Solow" framework shows that the timing of the Industrial Revolution reflects a subtle interplay between large changes in TFP and deaths from plagues. We find that U.S. economic fluctuations, including the Panics of 1893 and 1907, were driven primarily by volatile TFP, and that growth during the "Roaring Twenties" should have been even stronger, reflecting a large labor wedge that emerged around World War I.

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1 Introduction

Macroeconomists have increasingly been studying historical events using quantitative general equilibrium tools, with a focus on important historical episodes that previously had been studied using traditional historical methods (see for example Ohanian (1997), Cole and Ohanian (1999, 2004), Kehoe and Prescott (2007), McGrattan (2012)). The application of general equilibrium analysis is shedding new light on important historical episodes by using diagnostic methods that help identify potential classes of models for evaluating these events, and by quantifying the impact of different shocks on macroeconomic activity during historical periods within fully articulated general equilibrium models.

The recent integration of macroeconomics with economic history involves the practice of combining general equilibrium analytical methods and historical narratives with existing and recently constructed historical datasets. This is creating new insights about long-run growth and cyclical fluctuations.

This chapter advances the use of quantitative general equilibrium tools within the field of historical economics to study two important and very different historical episodes that have received little attention using general equilibrium macroeconomic growth models. The first is the Industrial Revolution, which captures the transition of Western economies from the Malthusian era, in which there was little, if any growth in per-capita income, to that of the era of Modern Economic Growth, which has featured persistent, long-run per capita growth and rising living standards, all of which took place around the middle of the 18th century. This analysis uses Hansen and Prescott (2002) model of the Industrial Revolution to analyze newly constructed data from Britain that dates back to 1245 (Clark (2010)).

Clark's data include total factor productivity (TFP), real output, population, factor prices, and capital stocks, among other variables, which allow us to provide the first quantitative-theoretic analysis of the transition from the Malthusian era to the modern growth era. Our main finding advances our quantitative understanding of the timing of the transition to modern economic growth that occurred in the 1700s.

We find that this transition realistically could never have occurred much before that time, as the productivity of the the Malthusian sector peaked around 15th century, virtually guaranteeing that the nascent capital-intensive technologies of that time would not be close to being competitive. Instead, a 300 year stagnation of the Malthusian sector implicitly allowed the newer capital-intensive production methods to catch up, become viable alternatives to the Malthusian technology, and ultimately dominate the labor and land-intensive Malthusian technologies. Moreover, we find that the timing of this catchup is robust to plausible amounts of historical TFP mismeasurement.

The second episode studied is the U.S. economy from 1889-1929. This is a particularly striking period in the history of the U.S., involving World War I, two major financial panics, the diffusion of several important new technologies, including electricity and the internal combustion engine, and the "Roaring Twenties", one of the most rapid growth decades in U.S. history, and the period which immediately preceded the Great Depression. This section uses variants of Business Cycle Accounting (Cole and Ohanian (2002), Chari et al. (2007), and Brinca et al. (2016)), a general equilibrium diagnostic tool, to study this period in its entirety, and well as analyze individual events, including World War I and the Panics of 1893 and 1907, and the "Roaring Twenties".

One main finding is that technology shocks are remarkably important drivers of economic activity between 1889 and 1916, including the Panics of 1893 and 1907. This finding stands in sharp contrast to the perception that technology shocks today are quantitatively unimportant. Our second main finding is that labor is substantially depressed during World War I, and this labor depression continues through the 1920s, one of the highest growth decades in U.S. history. We find that a large labor wedge is the key factor depressing growth during the 1920s, and that output per capita should have been about 15 percent higher by 1929 in the absence of the increased labor wedge. We find that standard factors, such as tax rates, do not account for the post-1916 labor wedge, and that future research should study this decade to gain a better understanding of the specific factors that created this wedge.

The chapter is organized as follows. Section 2 presents the analysis of the Industrial Revolution. Section 3 presents the analysis of the U.S. economy between 1889-1929. Section 4 concludes.

2 Growth in the Very Long Run

In this section, we use the model studied in Hansen and Prescott (2002) to interpret data from Clark (2010). In particular, this model features an endogenous transition from Malthusian stagnation to sustained growth. Malthusian stagnation is the result of firms choosing to use a production process where land's share of income is positive, and hence there are decreasing returns to capital and labor. Another important feature required for Malthusian stagnation is that the population growth rate is an increasing function of living standards. Sustained growth begins when a production process is employed that exhibits constant returns to capital and labor.

Perhaps the most important feature of this model is that both production process are available throughout history and the choice to employ one or both processes is made by firms in response to the total factor productivity associated with each of these processes. In the early stages of development, when TFP for the second production process is low, only the land intensive technology is used. Eventually, if TFP associated with the second production process grows over time, that process will inevitably begin to be employed. At this point an "industrial revolution" occurs and the economy converges to a standard Solow type balanced growth path.

The approach followed by Hansen and Prescott (2002) differs from other contributions to the literature using dynamic general equilibrium models to understand the industrial revolution in two respects. First, Hansen and Prescott (2002) study the consequences of technological progress while papers such as Galor and Weil (2000) or Lucas (2018) aim to explain technological progress itself. Second, the transition to sustained growth happens in the Malthus to Solow model when a production process with a lower land share becomes profitable and is adopted. In the other two papers, sustained growth results from an increase in the rate of return to human capital that leads to a demographic transition resulting from endogenous fertility decisions of the sort modeled in Becker and Barro (1988). Doepke (2004) develops a model that aims to unify these two approaches.

2.1 The "Malthus to Solow" Model

The model of Hansen and Prescott (2002) is a version of the Diamond (1965) overlapping generations growth model. Households live for two periods. They earn labor income when young which is used to finance consumption, investment in physical capital and land. In the second period of life, households are the owners of capital and land and finance consumption from renting these assets to firms, who use them along with labor as inputs in production. At the end of the period, old households sell their land to the young, which also helps finance their consumption. An additional important feature of the model is that population growth is a function of living standards as is generally assumed in a Malthusian growth model.

2.1.1 Technology

This is a one-good economy in which the single consumption good can be produced from two available production processes that are assumed to be accessible throughout time. The first is called the Malthus process and requires capital, labor and land ($K_M, N_M, \text{and} L$) to produce output according to the following Cobb-Douglas technology:

$$Y_{Mt} = A_{Mt} K_{Mt}^{\phi} N_{Mt}^{\mu} L_M^{1-\phi-\mu} \tag{1}$$

The second production process uses only capital and labor (K_S and N_S):

$$Y_{St} = A_{St} K_{St}^{\theta} N_{St}^{1-\theta} \tag{2}$$

Given that these two processes are always available and that Y_M and Y_S are the same good, the aggregate production function can be described as follows:

$$Y = F(K, N, L) = \max_{K_M, K_S, N_M, N_S} \left\{ A_M K_M^{\phi} N_M^{\mu} L^{1-\phi-\mu} + A_S K_S^{\theta} N_S^{1-\theta} \right\} \tag{3}$$

$$\begin{aligned} \text{subject to } K_M + K_S &\leq K \\ N_M + N_S &\leq N \end{aligned}$$

Here, A_M is total factor productivity specific to the Malthus production process and A_S is total factor productivity specific to the Solow process.

Land is in fixed supply, it can't be produced and does not depreciate. Its only use is for production employing the Malthus process. Hence we normalize this to be one ($L_M = L = 1$).

Total output, $Y_t = Y_{Mt} + Y_{St}$, can be consumed or invested to produce capital productive the following period. Capital depreciates fully in the period it is used in production. Hence, the resource constraint is

$$C_t + K_{t+1} = Y_{Mt} + Y_{St} \tag{4}$$

One way of decentralizing this economy is to assume that one firm, called the Malthus firm, operates the Malthus production process (1) and another operates the Solow process (2).[1] Let w be the wage rate, r_K be the capital rental rate and $r_L$be the rental rate for land. Given these factor rental prices and values for A_M and A_S, each firm maximizes profit,

$$\max_{N_j, K_j, L_J} \{Y_j - wN_j - r_K K_j - r_L L_j\}, \ j = M, S \tag{5}$$

2.1.2 Households

We assume that N_t households are born in period t live for two periods. A household born in period t consumes c_{1t} units of consumption in the first period of his life and $c_{2,t+1}$ units in the second. His utility is given by

$$U(c_{1t}, c_{2,t+1}) = \log c_{1t} + \beta \log c_{2,t+1} \tag{6}$$

The number of new households born in a given period is assumed to grow at rate that is a function of living standards. Living standards at date t are assumed to be given by c_{1t} and N_t evolves as follows:

$$N_{t+1} = g(c_{1t})N_t \tag{7}$$

The initial old at date t_0 are assumed to be endowed equally with land ($\frac{1}{N_{t_0-1}}$ units) and capital ($\frac{K_{t_0}}{N_{t_0-1}}$ units). In addition, each young household is endowed with one unit of labor that is supplied inelastically. Old households are assumed to rent land and capital to firms and then sell their land to the young at the end of the period. This finances consumption in the second period of life, c_2. The young supply labor and earn labor income which is used to finance c_1, investment (k_{t+1}), and the purchase of land from the old. The price of land is denoted by q. Hence, a household born in period t will choose consumption, investment and land purchase to maximize (6) subject to the following budget constraints:

$$c_{1t} + k_{t+1} + q_t l_{t+1} = w_t \tag{8}$$

$$c_{2,t+1} = r_{K,t+1} k_{t+1} + (r_{L,t+1} + q_{t+1}) l_{t+1} \tag{9}$$

[1] Given constant returns to scale, the number of firms does not matter.

2.1.3 Competitive Equilibrium

Given N_{t_0}, N_{t_0-1} and K_{t_0}, as well as a sequence of sector specific total factor productivities $\{A_{Mt}, A_{St}\}_{t=t_0}^{\infty}$, a competitive equilibrium consists of sequences of prices $\{q_t, w_t, r_{Kt}, r_{Lt}\}_{t=t_0}^{\infty}$, firm allocations $\{K_{Mt}, K_{St}, N_{Mt}, N_{St}, Y_{Mt}, Y_{St}\}_{t=t_0}^{\infty}$, and household allocations $\{c_{1t}, c_{2t}, k_{t+1}, l_{t+1}\}_{t=t_0}^{\infty}$ such that

- Given the sequence of prices, the firm allocations solve the problems specified in equation (5).
- Given the sequence of prices, the household allocation maximizes (6) subject to (8) and (9). Recall that the old in period t_0 are endowed with $\frac{1}{N_{t_0-1}}$ units of land and $\frac{K_{t_0}}{N_{t_0-1}}$ units of capital.
- Markets clear:
  - $K_{Mt} + K_{St} = N_{t-1}k_t$
  - $N_{Mt} + N_{St} = N_t$
  - $N_{t-1}l_t = 1$
  - $Y_{Mt} + Y_{St} = N_t c_{1t} + N_{t-1}c_{2t} + N_t k_{t+1}$
- $N_{t+1} = g(c_{1t})N_t$

2.1.4 Characterizing the Equilibrium

Here we briefly summarize how we solve for an equilibrium sequence of prices and quantities. More details are provided in Hansen and Prescott (2002) and Greenwood (2020). The key results show that the Malthus sector will always operate, but the Solow sector will only operate if A_S is sufficiently large. In particular, the papers cited establish the following results:

1. For any w_t and r_{Kt}, the Malthus sector will operate. That is, $Y_{Mt} > 0$ for all t.
2. Given values for w_t and r_{Kt}, maximized profit per unit of output in the Solow sector is positive if and only if
$$A_{St} > \left(\frac{r_{Kt}}{\theta}\right)^{\theta}\left(\frac{w_t}{1-\theta}\right)^{1-\theta} \tag{10}$$
Profits are zero if equation (10) holds with equality. Hence, the Solow firm will only produce output ($Y_{St} > 0$) if A_{St} is greater than or equal to the right hand side of (10).

Given values for A_{Mt}, A_{St}, K_t and N_t for some t, define w_t^M and r_{Kt}^M as follows:

$$w_t^M \equiv \mu A_{Mt} K_t^{\phi} N_t^{\mu-1} \tag{11}$$

$$r_{Kt}^M \equiv \phi A_{Mt} K_t^{\phi-1} N_t^{\mu} \tag{12}$$

Our solution procedure involves first evaluating the right hand side of equation (10) at w_t^M and r_{Kt}^M each period. If A_{St} is less than or equal to this value, only the Malthus sector will operate. In this case, in equilibrium $w_t = w_t^M$, $r_{Kt} = r_{Kt}^M$ and $r_{Lt} = (1-\phi-\mu)A_{Mt}K_t^{\phi}N_t^{u}$. If A_{St} is greater than this value, both sectors will operate and the marginal product of labor and capital will be equated across sectors (see problem (3)). Hence, the equilibrium rental rates are as follows:

$$w_t = \begin{cases} w_t^M & \text{if } A_{st} \leq \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta}\left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \\ \mu A_{Mt}K_{Mt}^{\theta}N_{Mt}^{\mu-1} = (1-\theta)A_{St}K_{St}^{\theta}N_{St}^{-\theta} & \text{if } A_{St} > \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta}\left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \end{cases} \tag{13}$$

$$r_{Kt} = \begin{cases} r_{Kt}^M & \text{if } A_{st} \leq \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta}\left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \\ \phi A_{Mt}K_{Mt}^{\phi-1}N_{Mt}^{\mu} = \theta A_{St}K_{St}^{\theta-1}N_{St}^{1-\theta} & \text{if } A_{St} > \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta}\left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \end{cases} \tag{14}$$

$$r_{Lt} = (1-\phi-\mu)A_{Mt}K_{Mt}^{\phi}N_{Mt}^{u} \tag{15}$$

The first order conditions for choosing k_{t+1} and l_{t+1} in the household's problem can be written

$$c_{1t} = \frac{w_t}{1+\beta} \tag{16}$$

$$q_{t+1} = q_t r_{K,t+1} - r_{L,t+1} \tag{17}$$

Finally, the budget constraints and market clearing conditions imply that

$$K_{t+1} = N_t(w_t - c_{1t}) - q_t \tag{18}$$

Given a value for q_{t_0}, $\{A_{Mt}, A_{St}\}_{t=t_0}^{\infty}$, K_{t_0} and N_{t_0}, the equations (3), (7) and (13) - (18) determine the equilibrium sequence of prices and quantities,

$$\{Y_t, w_t, r_{Kt}, r_{Lt}, c_{1t}, q_{t+1}, K_{t+1}, N_{t+1}\}_{t=t_0}^{\infty} \ .$$

The initial price of land, q_{t_0}, is not given but is also determined by the equilibrium conditions of the model. In particular, q_{t_0} turns out be uniquely determined by the requirement that iterations on equation (17) do not cause q_t to eventually become negative or K_{t+1} (determined by equation 18) to become negative. We use a numerical shooting algorithm to find this value of q_{t_0}.

2.1.5 Calibration of Population Growth Function

In the application carried out here, we interpret one model time period to be 25 years. We use the same population growth function, $g(c_{1t})$, as in Hansen and Prescott (2002). This function, which was based on data from Lucas (1988) on population growth rates and per capita income, has the following properties: (1) the population growth rate increases linearly in living standards until population doubles every 35 years or 1.64 periods; (2) at the point where population doubles every 35 years, living standards are twice the Malthusian level; (3) the population growth rate decreases linearly from this point until living standards are 18 times the Malthusian level at which point the growth rate of population is zero; and (4) population is constant as living standards continue to rise. Here, c_{1M} is the Malthusian steady state level of c_{1t} and γ_M is the growth factor of A_{Mt} in a Malthusian steady state. This will be characterized fully in the next subsection.

$$g(c_{1t}) = \begin{cases} \gamma_M^{1/(1-\mu-\phi)}\left(2 - \frac{c_{1t}}{c_{1M}}\right) + 1.64\left(\frac{c_{1t}}{c_{1M}} - 1\right) & \text{for } c_{1t} < 2c_{1M} \\ 1.64 - 0.64\frac{c_{1t}-2c_{1M}}{16c_{1M}} & \text{for } 2c_{1M} \leq c_{1t} \leq 18c_{1M} \\ 1 & \text{for } c_{1t} > 18c_{1M} \end{cases} \tag{19}$$

2.1.6 The Malthusian Steady State

As in Hansen and Prescott (2002), we will assume that this economy begins in a Malthusian steady state, which is the asymptotic growth path for a version of the model with only the Malthus production process available or where A_S is sufficiently low for all t that equation (10) is never satisfied. Also, prior to period t_0, A_M is assumed to grow at a constant rate equal to $\gamma_M - 1$, $c_{1t} < 2c_{1M}$, and the population growth rate is determined according to the first segment of the function g in equation (19). In this case, the Malthusian steady state growth rate of population will be $g_N = \gamma_M^{1/(1-\mu-\phi)}$. Both the price of land and the stock of capital will also grow at this same rate on this steady state growth path.

It will be useful for our empirical exercise if we choose a value for steady state income per capita, call it y_M, and compute the rest of the steady state to be consistent with that value. From steady state versions of equations (11) and (16), we can compute c_{1M} as

$$c_{1M} = \frac{w_M}{1+\beta} = \frac{\mu}{1+\beta} y_M \ . \tag{20}$$

Next, the following three equations, which are steady state versions of equations (14), (17) and (18), can be solved to obtain the rental rate of capital, $r_{K,M}$, the steady state capital to labor ratio, $\hat{k}_M$, and the steady state land price to labor ratio, $\hat{q}_M$:

$$r_{K,M} = \phi\frac{\hat{y}}{\hat{k}} \tag{21}$$

$$\left(\frac{r_{K,M}}{g_N} - 1\right)\hat{q} = (1-\mu-\phi)\hat{y} \tag{22}$$

$$g_N\hat{k} = \left(\mu - \frac{\mu}{1+\beta}\right)\hat{y} - \hat{q} \tag{23}$$

2.2 Quantitative Exercise: England from 1245 to 1845

The model presented in the last subsection is now used to interpret time series taken from Clark (2010).[2] Clark uses a variety of sources to construct data that can be used in a quantitative general equilibrium model, including TFP, national income, the capital stock, and payments to capital and labor. This allows us to study the Industrial Revolution in much more quantitative detail than previously possible.

Given that one model time period is interpreted to be 25 years, we use 25 year averages of annual data on total factor productivity, output per capita, and population constructed by Clark using the methodology described in Clark (2010). In particular, data for a given year, say 1845, is actually an average constructed from annual data from 1845 to 1870.[3]

Figure 1 shows Clark's total factor productivity series from 1245 to 1845. The series is extended to 2020 by allowing it to grow from 1845 according to the value we assign to the parameter γ_M. Twenty five year averages of Clark's estimate of England's population from 1245 to 1845 is shown in Figure 2 and his estimate for real per capita income is in Figure 3.

2.2.1 Model Calibration

The model parameter values we used were $\mu = 0.65$ and $\phi = 0.1$ for the Malthus production process and $\theta = .35$ for the Solow process. These values imply that labor's share of income is the same (0.65) for both production processes, following Hansen and Prescott (2002). Land's share in the Malthus process is 0.25. The growth factor for Malthus total factor productivity prior to 1245 and after 1845, when our measured data series ends, is given by $\gamma_M = 1.0074$. This was set to match the average population growth rate from 1245 to 1745 and characterizes our Malthusian steady state. Similarly, the growth factor for Solow total factor productivity beginning in 1895 is $\gamma_S = 1.27$. This implies an asymptotic growth rate of real output per capita equal to 1.5 percent per year. The value of the discount factor, β, was set equal to one following Hansen and Prescott.

The value of y_M used is equal to 55. The movements in per capita income exhibited by our model economy are both the direct result of TFP movements and the Malthusian dynamics associated with the economy converging back to steady state following a given change in TFP. We chose y_M by simply trying different values above and below the mean of per capita income from 1245 to 1745 and taking the one that allowed our model to best fit the time series on per capita income during that period.

The final calibration issue to be resolved, other than initial conditions K_{t_0} and N_{t_o}, is a time series for A_S prior to 1895. Recall that the Solow production process will be employed only when A_S satisfies equation (10). We construct our A_S time series so that this happens

[2] Clark (2010) provides data at ten year intervals on a variety of macroeconomic aggregates. The data we actually use was received from the author and includes annual data that enabled us to compute 25 year averages.

[3] Specifically, total factor productivity is from the third column of Table 33 in Clark (2010), which was constructed using a price index of domestic expenditures. An alternative measure is provided using the price of net domestic output. Similarly, we chose to measure per capita output using real national income that was also constructed using domestic expenditure prices. This series is contained in Table 28 of Clark (2010). The population series we use is from Table 7 of that paper.

for the first time in the year 1745. Prior to that, the value of A_S is perhaps growing at a slow rate, but is irrelevant to the computation of an equilibrium. We set $A_{S,1745}$ equal to 25, which is the smallest integer value that satisfies equation (10). Following that, A_S grows 10 percent each period until 1870. This value was chosen so that a demographic transition would not occur until at least this date given that the rate of population in our data sample continues to raise with living standards. That is, we chose this value so that the population growth rate would continue to be determined by the first branch of equation (19). Figure 4 is a plot of our assumed A_S series from 1745 to 1845.

2.2.2 Benchmark Simulation

We assume that the economy was in a Malthusian steady state at date $t_0 - 1 = 1220$. Given $y_M = 55$ and $N_{t_0-1} = 5$, we obtain $K_{t_0-1} = \hat{k}N_{t_0-1}$. Also, so that $y_{1220} = y_M$, we set $A_{M,1220} = A_{M,1245}$ and normalize the A_M sequence so that $y_{t_0-1} = Y_M = A_{M,t_0-1}K_{t_0-1}^{\phi}N_{t_0-1}^{\mu-1}$. In this case, our initial conditions for 1245 are $N_{t_0} = g_N N_{t_0-1}$ and $K_{t_0} = \hat{k}N_{t_0}$.

We also add an additional element in our benchmark simulation that is not part of the model described so far. In particular, England suffered from a series of plagues that decimated its population for three centuries from 1345 (the Black Death) to 1645 (the Great Plague of London). In particular, there is a downward sloping portion in Figure 2 that shows that population was declining from 1320 to 1470.[4] We capture this by replacing equation (7) with

$$N_{t+1} = P_t g(c_{1t}) N_t \, , \tag{24}$$

where P_t, which we interpret as a "plague shock", is equal to one for all t except for $t = 1295 - 1445$. For these dates, we set $P_t = 0.8$.

Figure 5 shows that our benchmark simulation successfully captures the decline in population from 1295 to 1445. After that, England's actual population increased more rapidly than in the model economy. This is particularly true after 1750. Figure 6 shows that the model economy captures the fluctuations in per capita income quite well.

The transition from employing all inputs in the Malthus production process to having almost all of the capital and labor assigned to the Solow process is shown in Figure 7. In particular, in the first period of the industrial revolution, 1745, 31 percent of capital and 12 percent of labor is employed in the Solow process. The fraction of inputs employed in Solow production increases over time and exceeds 95 percent in 1895 for labor and in 1870 for capital. At this point, the economy has come close to converging to a standard neoclassical steady state growth path where real output per capita is growing by 1.5 percent per year.

2.2.3 No Plagues

As a counterfactual experiment, we recompute the benchmark under the assumption that $P_t = 1$ for all t. In this case, as shown in Figure 8, model population is as much as three times larger

[4]We will discuss how the model would respond to the plagues beyond 1470 in subsequent experiment.

than in the actual data during the period of plagues from 1345 to1645. Similarly, Figure 9 shows that per capita income in our model is significantly lower than in the actual data during this period due to population in the model economy being so high.

2.2.4 More Plagues

As mentioned previously, England suffered plagues pretty continuously from 1245 to 1645. In this experiment, we set $P_t = 0.8$ for $t = 1295 - 1620$. As shown in Figure 10, this leads to model population being as much as a third of what is observed in the actual data from 1550 to 1750. This result is simply a more extreme version of what is observed with population in the benchmark simulation. Model and data series for per capita income look fairly similar in this experiment as shown in Figure 11. Clearly there is something happening with population during the period 1550-1750 that is not captured solely by plagues and Malthusian dynamics.

2.2.5 Timing of the Industrial Revolution

In the experiments done so far, we constructed the A_S sequence so that the Solow production process is initially adopted in 1745. Note that in Figure 12, A_M (the solid line) reaches a peak in 1445 and then drops significantly. In this counterfactual experiment, we assume this drop never occurred and that A_M simply grew at rate $\gamma_M - 1$ after 1445 (see dotted line in Figure 12). Will this relative success of the Malthusian production process, given the same sequence for A_S as in the benchmark, cause the Industrial Revolution to happen at a later date? Turns out that the adoption of the Solow process begins at exactly the same date as in the benchmark (1745). Figure 13 shows the right hand side of equation (10) for both the benchmark and this counterfactual case from 1245 to 1745. We see that while this threshold is very high when A_M reached its peak in 1450 in both cases, the threshold falls very quickly in the benchmark due to declines in A_M. In the counterfactual, however, Malthusian dynamics dominate. As A_M continues to grow, population also grows (see Figure 14). This causes income per capita to decline as it converges to the Malthusian steady state of $y_M = 55$ (see Figure 15). These same dynamics cause the Solow threshold to decline and, as it turns out, it is still profitable to adopt the Solow process in 1745 when A_S is equal to 25.

The key here is that in the Malthusian steady state, the right hand side of equation (10) is a constant. This threshold might deviate from this steady state due to short run fluctuations in A_M, but over time will converge back to this constant. Hence, while we chose the A_S sequence in the benchmark so that the Solow production process would be adopted in 1745, this result turns out to be robust in the absence of significant upward movements in the A_M process in the period near 1745.

3 Business Cycle Accounting of the 1889-1929 U.S. Economy

To apply Business Cycle Accounting (BCA) for this period, we use data constructed by John Kendrick (1961). Kendrick constructed data from 1869-1957 for the U.S. economy using NIPA principles. These data include real measures of consumption, private and government fixed investment, inventories, government consumption, and exports and imports. The data also have consistent measures of labor and capital input that are aggregated from sectoral measures of these variables. These data are considered to be high quality and the best available for this time period. The data are decennial from 1869-1889, and are annual from 1889 onwards, which leads us to begin in 1889.

The period from 1889-1929 is striking from a macroeconomic perspective because of a number of short-run events and also because of it its importance in the long-run evolution of the American economy. This period includes the "Roaring Twenties", well-known for its high economic growth rate and as the runup to the Great Depression. It also includes World War I, in which government consumption rose enormously, taking away resources from the private sector. There were also two very famous financial panics, the Panic of 1893 and the Panic of 1907.

More broadly, 1889-1929 is a period of enormous technological change, including the diffusion of electrification and the expansion of the internal combustion engine, which transformed production methods (electrification) and transportation (internal combustion engine). 1889-1929 also includes the heyday of American monopolies, including the famous Standard Oil trust and John D. Rockefeller, and Andrew Carnegie's U.S. Steel trust, both of which motivated the passage of the country's major antitrust acts, the Sherman Act in 1890 and the Clayton Act in 1914.

To our knowledge, neither this period in its totality, nor any of the individuals events within the period, have been analyzed using quantitative general equilibrium tools. This chapter thus provides the first such evaluation of this remarkable period. BCA, first used in Cole and Ohanian (2002), and Chari et al. (2002), and then developed further in Chari et al. (2007), and Brinca et al. (2016), henceforth BCKM, is ideally suited for investigating this period, because it is the leading diagnostic general equilibrium framework for identifying a set of possible factors affecting macroeconomic performance and for measuring the quantitative importance of these factors for output, consumption, investment, and hours worked. Moreover, we show that BCA is not only useful for analyzing fluctuations at the business cycle frequency (e.g. four years), but also is useful for studying lower frequency phenomena that evolve over a decade or more.

1889-1929 represents a period of unique long-run economic evolutions that are overlayered with several large short-run fluctuations that are of interest in their own right. As we show below, BCA highlights a number of key factors that are striking and surprising relative to the literature, and surprising relative to findings from postwar business cycles and the Great Recession. They also will suggest specific theoretical classes of models for understanding this important episode.

We summarize BCA and its application protocol here, and refer the reader to BCKM for details. BCA begins with a standard optimal growth model. Each period t, a random event s_t is realized. Let $s^t = (s_0, \ldots, s_t)$ denote the history of events up through and including period t and $\pi_t(s^t)$ be the probability of history s^t being realized at period t. Preferences are defined over expected sequences of consumption and leisure. There is a standard Cobb-Douglas constant returns to scale production function with labor-augmenting technological change. Output is divided between consumption, investment, and government consumption. There is a standard law of motion for capital, and the household time endowment is normalized to unity:

$$\max E_0 \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) U(C_t(s^t)/N_t, 1 - l_t(s^t))$$

subject to:

$$F(K_t(s^{t-1}), (1+\gamma)^t N_t l_t(s^t)) \geq C_t(s^t) + X_t(s^t) + G_t(s^t)$$

and the capital accumulation law:

$$K_{t+1}(s^t) = X_t(s^t) + (1-\delta) K_t(s^{t-1})$$

All variables except for time allocated to market production are then divided by technological progress $(1+\gamma)^t$ and population $N_t = (1+\gamma_n)^t$ to induce stationarity, and the transformed variables are denoted by lower case letters. The optimality conditions for this problem (assuming that transversality is satisfied) are given by[5]:

$$U_{lt}(s^t) = U_{ct}(s^t) f_{lt}$$

$$U_{ct}(s^t)(1+\gamma) = \beta^* \sum_{s^{t+1}} \pi_t(s^{t+1}|s^t) U_{ct+1}(s^{t+1}) \{f_{kt+1} + 1 - \delta\}$$

$$f(k_t(s^{t-1}), l_t(s^t)) \geq c_t(s^t) + k_{t+1}(s^t)(1+\gamma)(1+\gamma_n) - (1-\delta) k_t(s^{t-1}) + g_t(s^t)$$

To use this model for diagnostic purposes, we first augment these optimality conditions with multiplicative terms known as "wedges", that are functions of state s^t. The wedges will allow this model to completely account for the data. As you will see below, several of the wedges appear to be tax rates, though we do not give the wedges structural interpretations at this stage of analysis. The augmented first order conditions are below:

$$U_{lt}(s^t) = U_{ct}(s^t)[1 - \tau_{lt}(s^t)] A_t(s^t) f_{lt}$$

[5]We will be using log utility, therefore β^* denotes $\beta(1+\gamma_n)$.

$$A_t(s^t)f(k_t(s^{t-1}), l_t(s^t)) \geq c_t(s^t) + k_{t+1}(s^t)(1+\gamma)(1+\gamma_n) - (1-\delta)k_t(s^{t-1}) + g_t(s^t)$$

$$U_{ct}(s^t)(1+\gamma)[1+\tau_{xt}(s^t)] = \beta^* \sum_{s^{t+1}} \pi_t(s^{t+1}|s^t)U_{ct+1}(s^{t+1})\{A_{t+1}(s^{t+1})f_{kt+1} + (1-\delta)[1+\tau_{xt+1}(s^{t+1})]\}$$

We begin with the wedge $A_t(s^t)$, which multiplies the production function. This wedge is observationally equivalent to the Solow Residual, and thus accounts for movements in output not due to movements in capital and labor. This is called an *efficiency wedge*. Next, consider the first order condition for allocating time between market work and leisure. The wedge here is denoted as $1 - \tau_{lt}(s^t)$, and is written in this way because it is observationally equivalent to a tax on labor income. This is called the *labor wedge*, and as noted above, is not given a structural interpretation at this stage. The economy's intertemporal condition is augmented with a wedge denoted as $1/[1 + \tau_{xt}(s^t)]$, and is written in this way because it is similar to a tax on investment. It is called the *investment wedge*. The last wedge is called the *government consumption wedge*, which accounts for the sum of government consumption and net exports. With a Markovian implementation there is one to one and onto mapping from the event s_t to the wedges $(A_t, \tau_{lt}, \tau_{xt}, g_t)$.

The stochastic process for the event $s_t = (A_t(s^t), \tau_{lt}(s^t), \tau_{xt}(s^t), g_t(s^t))$ is governed by a first-order VAR:

$$s_{t+1} = P_0 + Ps_t + \varepsilon_{t+1}, \ E(\varepsilon\varepsilon') = V$$

in which P_0 and P are matrices of autoregressive coefficients to be estimated, ε is a vector of innovations, and V is the variance-covariance matrix of the innovations. As BCKM show, it is straightforward to estimate the coefficients and the elements of the variance-covariance matrix using maximum likelihood after log-linearizing the model, setting it up in state space form, and using the Kalman Filter.

With these wedges, which equal the number of endogenous variables, the augmented model fits the data perfectly, and therefore the model is used as an *accounting device*. To do this, we first measure the wedges as realizations from their stochastic process, and we then use the wedges within the linearized model to conduct various experiments, including quantifying the contribution of one or more wedges in accounting for the endogenous variables. We then use the results from these experiments to evaluate different classes of structural models. Below, we report some very surprising findings from this analysis in comparison from findings from postwar analyses, and from the perspective of narrative historical studies about this period.

3.1 Business Cycle Accounting Findings

Real GNP and its components, and labor input, measured as hours worked, are from Kendrick (1961). Following standard practice, all variables are first divided by the population, 16 years old and over[6]. As is standard practice, we divide all growing variables by a common trend,

[6]The data are available from 1900 to 1929. Linear interpolation is used to construct the data from 1889 to 1899 using the data on the population 15 years old and over. Details are available upon request.

in which we use 1.6 percent annually. We divide government spending into government consumption and government investment, in which the latter is put in the investment category, and following BCKM and Hansen and Ohanian (2016), we add net exports to government consumption.

Figure 16 shows these data. There are several noteworthy features. One is the very large increase in government consumption during World War I, which suggests potentially large effects of the war on the economy. Ohanian (1997) and McGrattan and Ohanian (2010) quantitatively analyze how well a neoclassical model can account for the World War II economy, and how much government fiscal policy affected output, labor input, investment and consumption. Applying BCA to this period will provide an assessment of the neoclassical model for the World War I economy which will be a natural complement to the existing World War II studies.

Another notable feature is the behavior of the economy around the two major financial panics, the Panic of 1893 and the Panic of 1907. Both episodes feature above-normal economic growth for some years prior to the panic, followed by a drop in real GDP and hours worked, then followed by a rapid rebound in economic activity.

But perhaps the most striking feature of these data is the pattern of hours worked. These average around 1/3 of the households time endowment from the mid-1890s up to the mid-teens, but then hours drop around the end of World War I and remain at that low level through the booming 1920s. This raises an important question: Why do hours worked remain so low during an economic boom with sharply rising investment and productivity? Standard theory indicates that hours should be higher than average during the 1920s, not lower than average.

To quantitatively evaluate these three issues, we log-linearize the model, set it up in state space form, and estimate the parameters of the wedge stochastic process using maximum likelihood via the Kalman Filter. To model the stochastic process for the wedges, we use a VAR. We use one lag for the VAR because the data are annual.

Figure 17 reports the four wedges between 1889-1929. Panel A shows the efficiency wedge over time. This shows large and stationary movements until World War I, then it rises substantially through the 1920s, likely reflecting the rapid diffusion of electricity and the internal combustion engine. Given the large literature on 1920s productivity growth and innovation diffusions, we refer to the efficiency wedge during this period as productivity growth.

The investment wedge shows a large trend decline, which is observationally equivalent to a continuously declining tax on investment goods. It also features temporary increases around the times of the Panics of 1893 and 1907. The World War I spending increases dwarfs all other movements in the government wedge, as government spending rises by about a factor of four during the war. The labor wedge declines in the early teens, which is equivalent to a higher labor income tax. This higher labor wedge continues through World War I and the 1920s.

3.1.1 Contribution of the Wedges

Figure 18 shows the contribution of the efficiency wedge to output, hours worked, and investment. This is the model prediction for these variables over time with only the efficiency wedge included, and the other wedges set to their steady state values. We have split the graph between the period 1889-1916 and 1917-1929. We do this because the findings are so remarkably different between these two periods, and these large differences are economically very interesting.

Note that between 1889 and 1916, the efficiency wedge accounts very closely for output fluctuations which is just before the U.S. entered World War I in 1917. The figure shows this very close relationship between data and the model, in which the detrended model economy is driven just by stationary productivity shocks. Table 1 provides complementary information on goodness of fit by presenting what is analogous to an R^2 statistic for this procedure. Known as the "ϕ-statistic" within the literature, this R^2-type measure is given by:

$$\phi_i^Y = \frac{1/\sum_t (y_t - y_{it})^2}{\sum_j (1/\sum_t (y_t - y_{jt})^2)},$$

where ϕ_i^Y is the percentage of variable y accounted for by wedge $i = (A, \tau_l, \tau_x, g)$. In the numerator, y is the individual variable, i is the wedge individually driving the system, and y_{it} is the model prediction of variable y at date t using wedge i. In the denominator, the summation over j indicates that all wedges are included, which delivers a perfect fit of the model net of approximation error. The statistic lies between 0 and 1, in which a perfect fit is 1.

The efficiency wedge accounts for 83 percent of the squared model deviations from trend (see Table 1). This is high when compared to similar calculations made for different episodes and across countries. BCKM calculate this statistic for the Great Recession across 25 countries, including the U.S., and find an average of 64 percent. For the U.S, it was just 16 percent during the Great Recession.

After that, however, there is a significant disconnect between efficiency variations and output variations, as the efficiency wedge accounts for much less of output. Throughout the 1920s, the efficiency wedge is rising (see Figure 18), and by 1929, these large increases in the efficiency wedge alone drive output about 19 percent above its trend growth path within the model. This stands in sharp contrast to actual output, which is about 4 percent above its trend growth path in 1929.

These findings are striking when viewed within the context of the literature on twentieth century economic growth and the context of BCA. There is a broad consensus that the 1920s was one of the most striking decades of U.S. economic growth in its history, and that this growth was fostered by an unusual wave of technological advances, including the diffusion of electrification, which transformed production methods, and the internal combustion engine, which revolutionized transportation. The BCA efficiency wedge only economy result presented here indicates that the famous 1920s economic boom is much weaker than it should have been relative to the technological improvements that took place.

As a related point, we are unaware of any other period, in the U.S. or in other countries, in which the efficiency wedge accounts for so much of output (83 percent), and is then followed by an immediate and large change in this accuracy, in which the efficiency wedge accounts for so little of output. Note that the efficiency wedge accounts for only about 10 percent of output following 1916.

The post-1916 figure and the associated ϕ-statistic indicate that some other factor changed substantially around this time, and it persistently depressed the economy relative to what it could have achieved with the measured, positive efficiency wedge realizations. The figure also shows the accounting of labor and investment using just the efficiency wedge, and these patterns reveal more about the pre and post-1916 economy.

Note that the efficiency wedge's accuracy in accounting for hours is also very different between these two sub-periods. Table 1 shows that the efficiency wedge accounts for about 46 percent of hours worked between 1889 and 1916, which is very high relative to similar calculations in the real business cycle literature. In particular, much of the criticism of real business cycle models is that productivity shocks account for very little of hours worked in post-1983 data (Kehoe et al. (2018)).

The fraction of hours worked that the model accounts for declines from 46 percent to about two percent, in which the large positive efficiency wedge changes of the 1920s generate much higher labor than what actually occurs. This predicted large rise in labor reflects increases in both labor demand and in labor supply, both of which are driven by higher efficiency which raises worker productivity.

The pattern for investment (bottom Figure 18 panels) is qualitatively similar to that of hours, in that the model with just the efficiency wedge generates much higher investment than observed. Quantitatively, the deviation between model and data is much larger. By 1929, the model driven just by the efficiency wedge predicts investment that is about 70 percent above trend, compared to the actual value which is modestly above trend.

Figure 19 provides complementary information about the impact of the efficiency wedge by plotting the model predictions including all wedges *except* the efficiency wedge. Note that the prediction of the model with all other wedges is far from the data for output, and surprisingly, also for labor through the 1916 period. This latter finding is particularly noteworthy given that the labor wedge is included in making this prediction.

The post-1916 deviations present a consistent pathology about the 1920s. Rapidly growing efficiency should have led to higher labor input, which in turn should have led to much higher investment, given the complementarity between capital and labor in production. The fact that the post-1916 prediction errors are so large and of a consistent pattern suggests that a quantitatively important factor emerged around this time to simultaneously depress labor, investment, and output, and that was sufficiently large to negatively offset much of the expansionary effect of higher efficiency.

Simulating the model in response to just the labor wedge provides important information about this factor. Figure 20 shows that the labor wedge captures nearly all of the movement in labor after 1916. Recall that Figure 17 Panel B showed that the labor wedge, which is observationally equivalent to a labor income tax, becomes larger (more negative) around the time of World War I through the 1920s. Driven by just the labor wedge alone, the model predicts that the 1920s would have been one of the *worst* growth decades for the U.S. economy, with output remaining about six percent below trend through the decade, and with labor averaging about seven percent below trend through the decade.

This indicates the key reason why output was low was because labor was low, and while the labor wedge alone doesn't account for the fluctuations in investment, it does accurately predict that investment was depressed below its normal level during the 1920s. Since the labor wedge creates a wedge between the marginal rate of substitution between consumption and leisure, and high productivity, this suggests that the economic factor(s) behind the rising importance of the labor wedge during this period depressed either the incentives and/or the opportunities for individuals and firms to trade labor services.

Figure 21 and Figure 22 show the model's ability to account for output, labor, and investment from the investment wedge individually, and the government wedge individually. The figures suggest that neither of these wedges are broadly important for understanding output, labor, or investment over the full period. The ϕ-statistics indicate that government accounts for more than 50 percent of output and investment after 1916, but that largely reflects the very large increase in government spending in 1917-19. Ohanian (1997) and McGrattan and Ohanian (2010) show that neoclassical models driven by large fiscal shocks closely account for the World War II economy. The World War I fiscal shock generates higher hours worked, higher output, and lower investment, all of which are qualitatively similar to the actual World War I economy. The model is not as quantitatively accurate for World War I as World War II, which likely reflects the fact that the World War I shock is not nearly as large as the World War II shock.

3.2 Business Cycle Accounting and the Panics of 1893 and 1907

The years 1889-1912 occurred under the The National Banking Era, a monetary and financial system created by the National Banking Act of 1863. As a precursor to the Federal Reserve system, the National Banking Era featured nationally chartered banks that were under the oversight of the Comptroller of the currency. The goal was to create a de facto national currency in which national chartered banks would accept each other's currency. The system had flaws, however, and panics occurred frequently.

The Panics of 1893 and 1907 were two of the most severe panics in the history of the U.S. Previous research by Jalil (2015) as well as earlier studies of these panics, dates them consistently, with the Panic of 1893 occurring around the middle of the year, and the Panic of 1907 beginning around October of 1907. This section uses BCA to study these episodes and compares them to the most recent findings within the historical literature. BCA findings show that these two episodes differ regarding the importance of wedges, particularly regarding the labor market, and we find very different contributions of the panics on economic activity relative to the literature.

3.2.1 The Panic of 1893

The Panic of 1893 features large declines in output, hours worked, and investment, which began declining before the panic. Other authors have noted in higher frequency data that the economic decline began before the run on banks, and this makes it in principle difficult to evaluate how much of the panic was a symptom of economic weakness compared to its potential depressing effect on the economy by disrupting the financial system.

A recent assessment of the National Banking era panics by Jalil finds very large and persistent effects. He fits a VAR to Davis's (2004) constructed industrial production series, along with indicator variables that are based on how the financial press of that time viewed the panic. By reading the financial newspapers at that time, he grades a panic on a 1-3 scale as to the extent that the panic was an independent event, or whether it was more a symptom of the downturn. He constructs another indicator variable regarding the state of the economy at the time of the panic, also on a 1-3 scale, depending on its underlying strength. He finds that a panic has very large and persistent effects on industrial production during this period, with a one-unit change in the financial indicator variable leading to a 10 percent change in industrial production, and that the impact of the shock persists roughly unchanged for at least 3 years.

BCA provides a different, and complementary analysis to Jalil's VAR study. We find the efficiency wedge plays a very important role in the 1893 panic. The left panel of Figure 23 shows the predicted movements from the efficiency wedge alone from 1889 to 1905. The figure shows a close correspondence between predicted and actual changes, particularly for output, which fits nearly perfectly.

The efficiency wedge also captures the qualitative features of labor and investment movements. For labor, it predicts a somewhat smaller increase before the panic, but predicts an overall decline in labor over the downturn in percentage terms that is very close to the actual decline. Table 2 shows the ϕ-statistics for the efficiency wedge, which accounts for 92%, 51%, and 66% of the movements, respectively. This episode looks like it was generated largely by a classic real business cycle model, as the efficiency wedge substantially accounts for changes in output, labor, and investment.

This real business cycle interpretation of the Panic of 1893 is consistent with some earlier research. Sprague (1910) presents evidence of declining economic activity prior to the panic, including slowing investment in railroad expansion and building construction, and in silver production (see Figure 24). Davis (2004) shows that a broader-based index of industrial production declined in 1893 (see Figure 25). Moreover, the real investment to output ratio did not drop in 1893, which stands in contrast to what should have occurred if an impaired financial system was substantially impacting the economy. These data support the view that the Panic of 1893 was more of a symptom of the downturn, rather than a primary contributing factor, and that the downturn partially reflects a natural slowing of business following a boom.

3.2.2 The Panic of 1907

The Panic of 1907 is similar in that the efficiency wedge accounts largely for output, but differs in that it doesn't account as closely for labor or investment. The right panel of Figure 23 shows the predicted movements from the efficiency wedge alone from 1903 to 1909. Table 3 shows the ϕ-statistics for the Panic of 1907. It shows that the labor wedge plays a central role in the Panic of 1907 (see also Figure 26). The labor wedge accounts for 73% and 82% of the movements in labor and investment, respectively, while the efficiency wedge accounts for 73% of the movements in output.

A hint about the factors that generated the rising labor wedge during the Panic of 1907 may lie in the labor market and a failure for wages to adjust to slowing economic conditions at this time. Figure 27 shows an index of composite wages from 1889 to 1909. The figure shows that wages decline considerably around the 1893 downturn, but decline much less around the time of the 1907 downturn. This suggests that labor market imperfections around that time that slowed nominal wage adjustment may have significantly depressed employment during 1907.

The fact that we find a significant labor wedge in the Panic of 1907 is intriguing because this makes it similar to the Great Recession, in which a large labor wedge is also quantitatively important (see Ohanian (2010) and Brinca et al. (2016)). This comparison also emerges among economic historians comparing the two periods, including Bernanke (2013) and Tallman (2013). They argue that the Panic of 1907 is similar to the Great Recession from the perspective of lightly regulated financial intermediaries. For example, one can think of trust companies in 1907, which were relatively less regulated, and not part of the New York Clearinghouse, like shadow banks during the Great Recession, which were also less regulated and did not have immediate access to the Federal Reserve System.

3.3 Potential Interpretations of the 1920s BCA Findings

The BCA results after 1916 indicate very large changes in either the shocks hitting the economy relative to the pre-1916 period, and/or how these shocks affected the economy. The findings stand in sharp contrast to the literature, which focuses on relatively rapid 1920s economic growth that was driven by the increased diffusion of new technologies, specifically electricity and the internal combustion engine. The BCA findings show that technology did rise rapidly during this period, but that its large and positive contribution was substantially attenuated by some factor(s) creating a labor wedge that is observationally equivalent to a rising labor income tax distortion. This section considers some possibilities that may have created the large increase in the labor wedge.

The post-1916 findings regarding rapidly rising productivity in conjunction with a sizable labor market imperfection are similar to findings from studies that have analyzed why the recovery from the Great Depression was not stronger. Cole and Ohanian (1999) showed that the efficiency wedge rose rapidly after 1933, which should have promoted strong growth and returned hours worked back to normal after a few years. However, similar to 1917-1929, hours worked remained depressed as productivity increased. Cole and Ohanian analyzed a number of possible factors that could have depressed hours worked, including labor and capital income taxes, and financial market stability and monetary policy. They concluded that neither monetary policy, which eliminated deflation, nor financial markets, which were stabilized by new legislation, were at fault. They found that modestly higher labor and capital income taxes were minor factors. This led them (Cole and Ohanian (2004)) in subsequent research to study how much industry-labor cartel policies depressed hours worked, and found that it accounted for most of continuation of low hours worked. Chari et al. (2007) found that a very large labor wedge was responsible for the continuation of depressed hours, and also cited industry-labor cartels.

We now apply a similar approach as used in Cole and Ohanian (1999) to evaluate potential factors that could have kept labor depressed after 1917. Regarding tax rates, statutory tax rates declined substantially after World War I, which would motivate higher hours worked, ceteris paribus. Average tax rates were low, and did not change much over the period. Barro and Sahasakul (1983) construct average tax rates and find an average tax rate of about 0.5 percent in 1916, which rises to about two percent during the war, and then declines to about one to 1.5 percent during the 1920s. These data indicate that changes in taxes were quantitatively unimportant in accounting for the 1920s labor wedge.

Immigration slowed in the 1920s, as the population rose about 15 percent in the decade compared to about 21 percent in the two decades before that. This is frequently discussed in the literature on the 1920s as an important factor (Smiley (1994)). However, a relative decline in the labor force should motivate *higher* hours per worker, because hours per worker are a substitute for workers. A relative decline in labor should also lead to higher wages, ceteris paribus. Smiley notes that manufacturing wages for men rose 5.3 percent for semi-skilled males to 8.7 percent for unskilled males, but manufacturing output per hour worked rose 29 percent this same period. These data indicate that reduced immigration is not a promising candidate in accounting for the labor wedge.

The data on real manufacturing wages, and real manufacturing output per hour, suggest another issue within the labor market, and one that may be related to the 1920s labor wedge. The standard model of labor supply and demand predicts that the real wage will move closely with worker productivity. This is not the case in the 1920s, with manufacturing output per hour rising 29 percent, but real wages rising only between 5.3 and 8.7 percent. Why didn't competitive pressure increase wages? Why didn't comparatively low wages stimulate more hiring?

These observations about the 1920s labor market reveal dysfunction that is more difficult to identify than that of the Great Depression. During the 1930s, wages were far above trend, while labor was far below trend. This naturally suggested excess supply, in which labor market policies prevented the wage from falling and clearing the labor market. In this case, both the relative price of labor and the quantity of labor hired are below trend, despite the fact that productivity was high. Given these findings, future research should consider addressing these important questions about the 1920s.

4 Conclusion

This chapter provides quantitative general equilibrium analyses of the Industrial Revolution and the period of 1889-1929 in the United States. These episodes were selected because of their importance and interest, the lack of existing quantitative general equilibrium studies of these episodes, and the simplicity of applying quantitative general equilibrium models and methods.

Previous discussions about the Industrial Revolution have focused on inventions such as the steam engine and the Spinning Jenny. But this analysis shows that these developments are only half of the story. These new, capital intensive technologies were substitutes for the older, less capital-intensive technologies. The new technologies, which improved over time, would only be implemented if they were competitive with the alternatives. Given TFP data from that time, there was no chance that the Industrial Revolution could have taken place in the 1500s, or before, as the productivity of the Malthusian technologies were temporarily high around that time. After that, the Malthusian productivity stagnated, which meant that it was only a matter of time before the Solow technologies ultimately caught up and became profitable to adopt over the alternative, land-intensive Malthusian technologies.

In addition, our analysis of the period from 1245 to 1845 reveals some puzzling issues concerning population movements during this period that deserve additional study.

Moving from the very long-run to a shorter horizon, we studied the remarkable 1889-1929 period in the U.S., one of the most important episodes in American economic history. In particular, the decade of the 1920s is known as perhaps the greatest peacetime growth decade. The research presented here shows that growth could easily have been much higher, given the remarkable productivity growth of the decade.

Instead, puzzlingly low labor input depressed the economy by a cumulative 15 percent relative to predicted model output driven by just productivity shocks. The decade reveals a large labor wedge, and we find that the labor wedge does not have an obvious interpretation. The coincidence of a large labor wedge, low labor input, and low wages suggest a labor market puzzle more challenging to identify that the labor market dysfunction that occurred just a decade later. What factor depressed employment in such a booming economy? Why didn't wages grow at nearly the same rate as productivity? Why didn't firms hire more labor, given its low relative price? These are open and important questions for future research.

References

R. J. Barro and C. Sahasakul. Measuring the average marginal tax rate from the individual income tax. *The Journal of Business*, 56(4):419–452, 1983.

G. S. Becker and R. J. Barro. A reformulation of the economic theory of fertility. *The Quarterly Journal of Economics*, 103(1):1–25, 1988.

B. S. Bernanke. The crisis as a classic financial panic, 11 2013. Remarks by Ben S. Bernanke Chairman Board of Governors of the Federal Reserve System at Fourteenth Jacques Polak Annual Research Conference Sponsored by the International Monetary Fund, Washington, D.C. [Accessed: 2020 10 15].

P. Brinca, V. V. Chari, P. J. Kehoe, and E. McGrattan. Accounting for business cycles. In *Handbook of Macroeconomics*, volume 2, pages 1013–1063. Elsevier, 2016.

V. V. Chari, P. J. Kehoe, and E. R. McGrattan. Accounting for the great depression. *American Economic Review*, 92(2):22–27, 2002.

V. V. Chari, P. J. Kehoe, and E. R. McGrattan. Business cycle accounting. *Econometrica*, 75 (3):781–836, 2007.

G. Clark. The macroeconomic aggregates for England, 1209–2008. volume 27 of *Research in Economic History*, pages 51–140. Emerald Group Publishing Limited, 2010.

H. L. Cole and L. E. Ohanian. The great depression in the United States from a neoclassical perspective. *Quarterly Review*, 23:2–24, 1999.

H. L. Cole and L. E. Ohanian. The U.S. and U.K. great depressions through the lens of neoclassical growth theory. *American Economic Review*, 92(2):28–32, 2002.

H. L. Cole and L. E. Ohanian. New deal policies and the persistence of the great depression: A general equilibrium analysis. *Journal of Political Economy*, 112(4):779–816, 2004.

J. H. Davis. An annual index of U. S. industrial production, 1790–1915. *The Quarterly Journal of Economics*, 119(4):1177–1215, 2004.

P. A. Diamond. National debt in a neoclassical growth model. *The American Economic Review*, 55(5):1126–1150, 1965.

M. Doepke. Accounting for fertility decline during the transition to growth. *Journal of Economic Growth*, 9(3):347–383, 2004.

O. Galor and D. N. Weil. Population, technology, and growth: From malthusian stagnation to the demographic transition and beyond. *American Economic Review*, 90(4):806–828, 2000.

J. Greenwood. Numerical methods for macroeconomists. Manuscript, Department of Economics, University of Pennsylvania, 2020.

G. Hansen and L. Ohanian. Neoclassical models in macroeconomics. In J. B. Taylor and H. Uhlig, editors, *Handbook of Macroeconomics*, volume 2, pages 2043–2130. Elsevier, 2016.

G. D. Hansen and E. C. Prescott. Malthus to solow. *The American Economic Review*, 92(4): 1205–1217, 2002.

A. J. Jalil. A new history of banking panics in the United States, 1825-1929: Construction and implications. *American Economic Journal: Macroeconomics*, 7(3):295–330, 2015.

P. J. Kehoe, V. Midrigan, and E. Pastorino. Evolution of modern business cycle models: Accounting for the great recession. *Journal of Economic Perspectives*, 32(3):141–66, 2018.

T. Kehoe and E. Prescott. *Great Depressions of the Twentieth Century.* Research Department, Federal Reserve Bank of Minneapolis, 2007.

J. W. Kendrick. *Productivity Trends in the United States.* National Bureau of Economic Research, Inc, 1961.

R. E. Lucas. On the mechanics of economic development. *Journal of Monetary Economics*, 22 (1):3–42, 1988.

R. E. Lucas. What was the industrial revolution? *Journal of Human Capital*, 12(2):182–203, 2018.

E. R. McGrattan. Capital taxation during the U.S. great depression. *The Quarterly Journal of Economics*, 127(3):1515–1550, 2012.

E. R. McGrattan and L. E. Ohanian. Does neoclassical theory account for the effects of big fiscal shocks? Evidence from World War II. *International Economic Review*, 51(2):509–532, 2010.

L. E. Ohanian. The macroeconomic effects of war finance in the United States: World War II and the Korean War. *The American Economic Review*, 87(1):23–40, 1997.

L. E. Ohanian. The economic crisis from a neoclassical perspective. *Journal of Economic Perspectives*, 24(4):45–66, 2010.

G. Smiley. *The American Economy in the Twentieth Century.* College Division, South-Western Publishing Company, 1994.

O. Sprague. *History of Crises Under the National Banking System.* History of Crises Under the National Banking System. U.S. Government Printing Office, 1910.

E. Tallman. The panic of 1907. In E. P. Randall and R. Whaples, editors, *Routledge Handbook of Major Events in Economic History.* Routledge, 2013.

Tables and Figures

Table 1: ϕ-Statistics for output, labor, and investment

	Output				Labor				Investment			
Samples:	ϕ_A^Y	$\phi_{\tau_l}^Y$	$\phi_{\tau_x}^Y$	$\phi_{\tau_g}^Y$	ϕ_A^L	$\phi_{\tau_l}^L$	$\phi_{\tau_x}^L$	$\phi_{\tau_g}^L$	ϕ_A^X	$\phi_{\tau_l}^X$	$\phi_{\tau_x}^X$	$\phi_{\tau_g}^X$
1889-1916	0.83	0.07	0.04	0.06	0.46	0.22	0.05	0.27	0.26	0.27	0.10	0.37
1917-1929	0.09	0.19	0.18	0.54	0.02	0.75	0.16	0.07	0.02	0.29	0.13	0.56
1889-1929	0.29	0.25	0.16	0.30	0.01	0.56	0.12	0.31	0.07	0.32	0.12	0.49

Table 2: ϕ-Statistics for the Panic of 1893

	Output			Labor			Investment		
Samples:	ϕ_A^Y	$\phi_{\tau_l}^Y$	$\phi_{\tau_x}^Y$	ϕ_A^L	$\phi_{\tau_l}^L$	$\phi_{\tau_x}^L$	ϕ_A^X	$\phi_{\tau_l}^X$	$\phi_{\tau_x}^X$
1889-1890	0.65	0.01	0.30	0.42	0.03	0.25	0.47	0.03	0.46
1989-1891	0.86	0.01	0.09	0.47	0.03	0.31	0.57	0.03	0.36
1889-1892	0.95	0.01	0.02	0.22	0.04	0.52	0.83	0.03	0.10
1889-1893	0.88	0.02	0.05	0.41	0.06	0.14	0.72	0.05	0.14
1989-1894	0.92	0.02	0.02	0.61	0.10	0.03	0.65	0.11	0.06
1889-1895	0.92	0.02	0.02	0.51	0.11	0.04	0.66	0.10	0.06

Table 3: ϕ-Statistics for the Panic of 1907

	Output			Labor			Investment		
Samples:	ϕ_A^Y	$\phi_{\tau_l}^Y$	$\phi_{\tau_x}^Y$	ϕ_A^L	$\phi_{\tau_l}^L$	$\phi_{\tau_x}^L$	ϕ_A^X	$\phi_{\tau_l}^X$	$\phi_{\tau_x}^X$
1903-1904	0.73	0.14	0.05	0.65	0.31	0.01	0.05	0.78	0.03
1903-1905	0.73	0.14	0.05	0.71	0.27	0.01	0.04	0.83	0.02
1903-1906	0.87	0.06	0.02	0.18	0.75	0.01	0.02	0.90	0.01
1903-1907	0.88	0.06	0.02	0.24	0.69	0.01	0.01	0.92	0.01
1903-1908	0.85	0.08	0.02	0.25	0.69	0.01	0.03	0.83	0.02
1903-1909	0.86	0.07	0.02	0.18	0.73	0.01	0.03	0.82	0.02

Figure 1: Malthusian TFP (A_M)

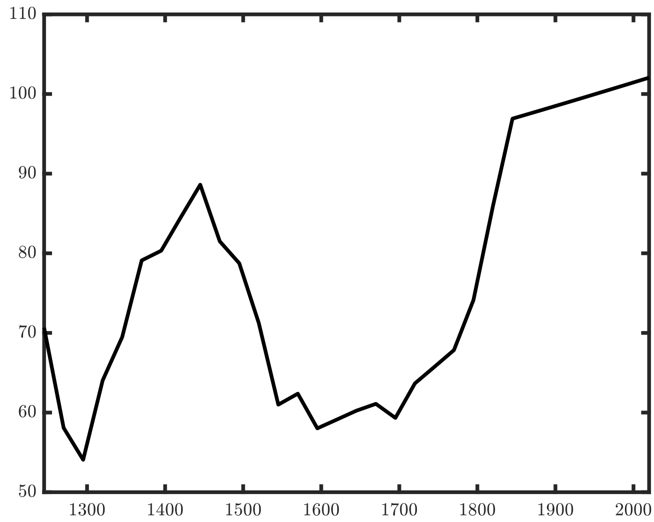


Figure 2: Population of England, 1245-1845

(millions of people)

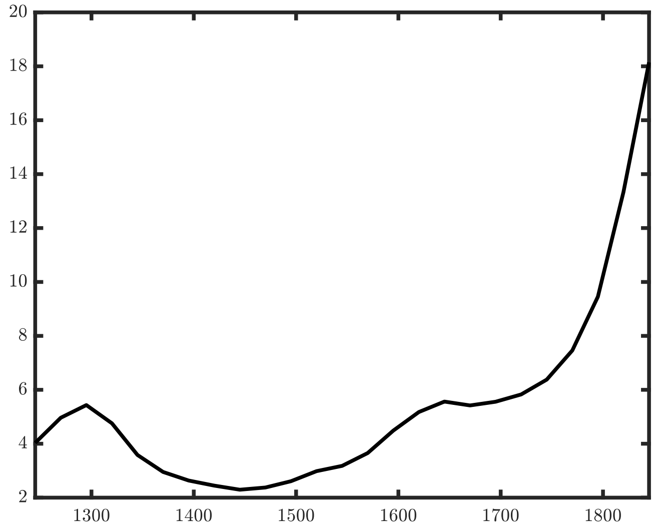


Figure 3: Real national income per capita of England, 1245-1845

(average from 1860-69 = 100)

Figure 4: Solow TFP (A_S)

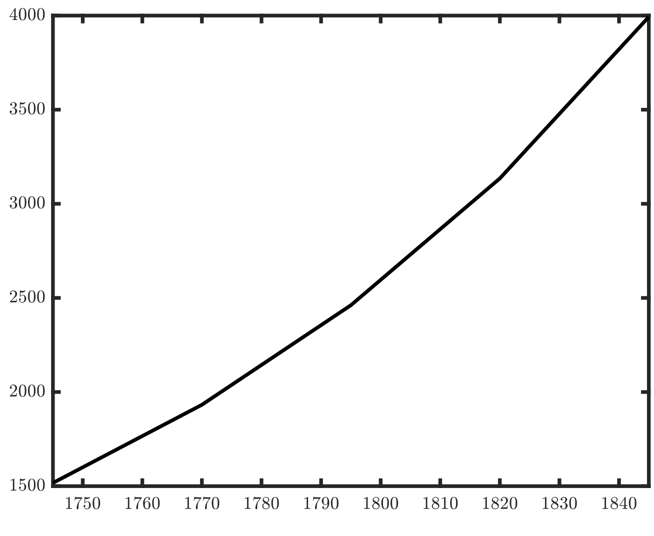


Figure 5: Population from Benchmark experiment

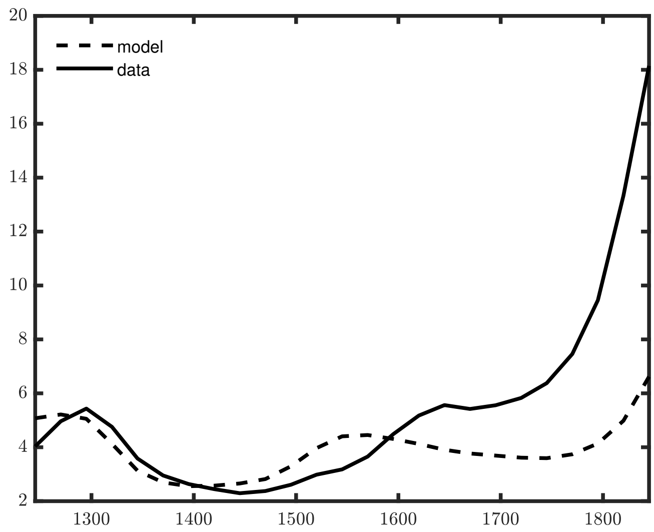


Figure 6: Output per capita from Benchmark experiment

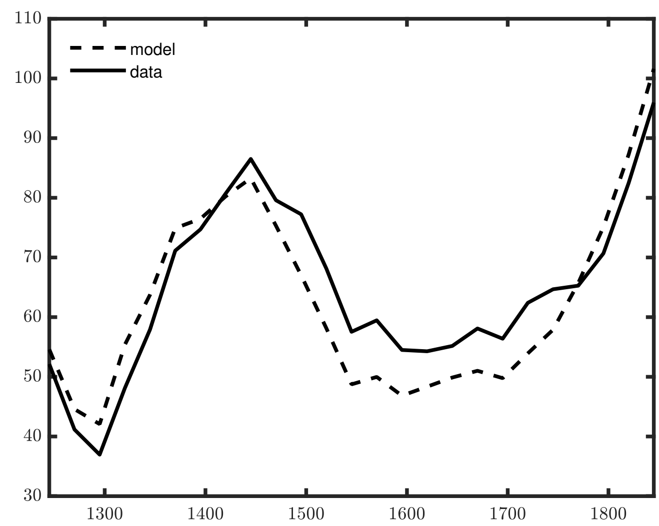


Figure 7: Fraction of inputs employed in Solow

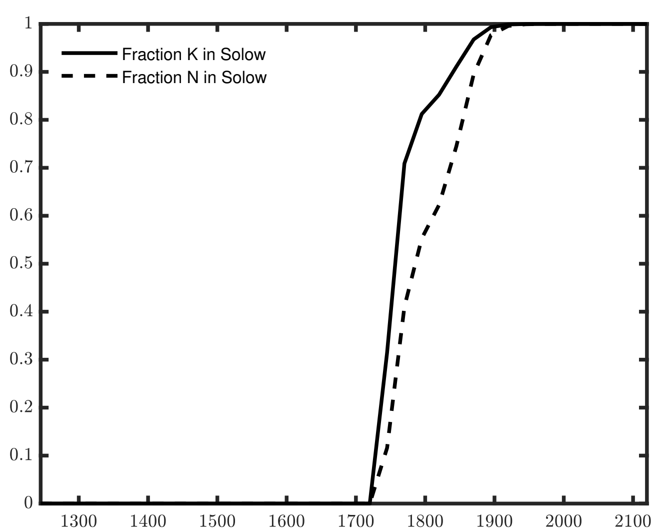


Figure 8: Population from “No Plagues” experiment

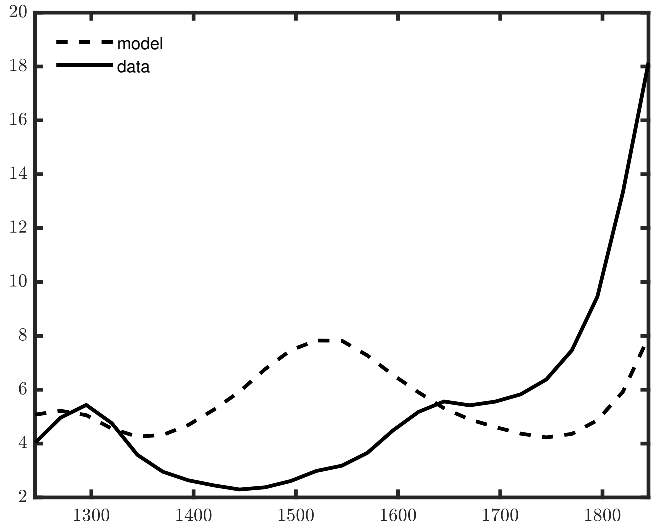


Figure 9: Output per capita from “No Plagues” experiment

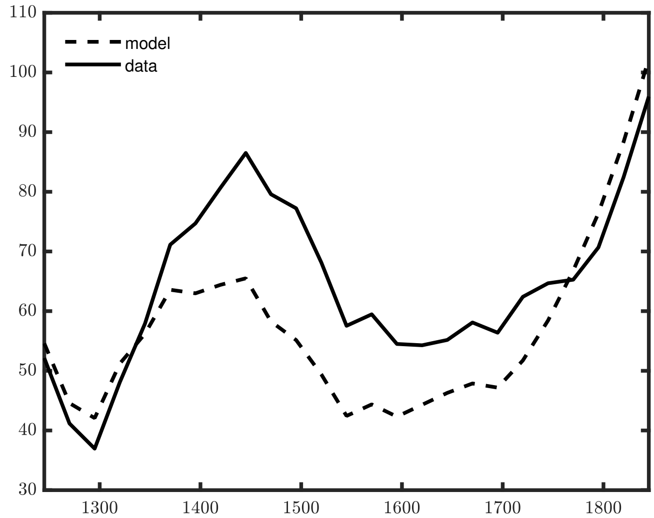


Figure 10: Population from “More Plagues” experiment

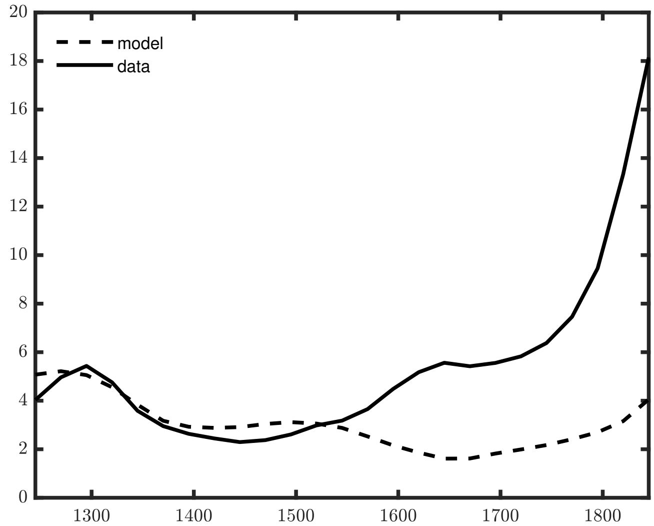


Figure 11: Output per capita from “More Plagues” experiment

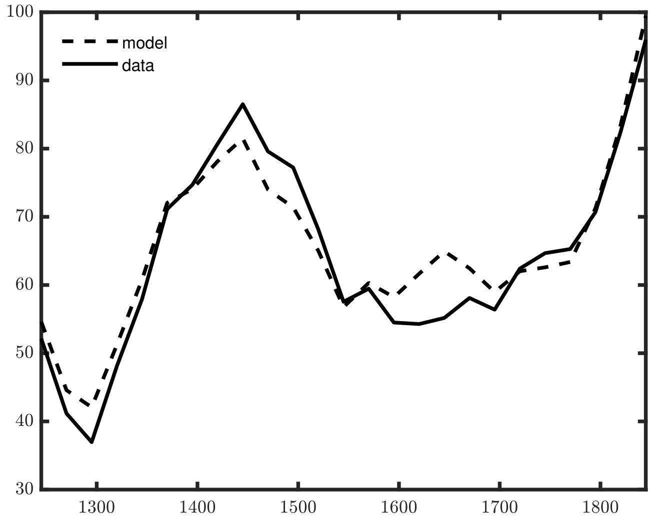


Figure 12: A_M for “Timing of Industrial Revolution” and Benchmark experiments

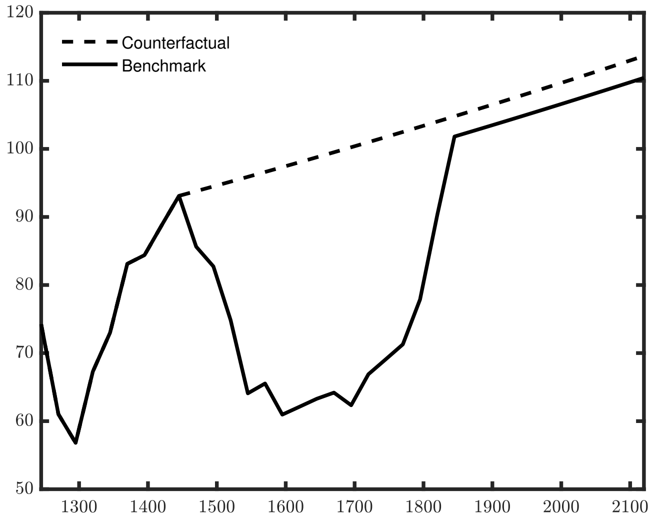


Figure 13: Solow threshold from “Timing of Industrial Revolution” and Benchmark experiments

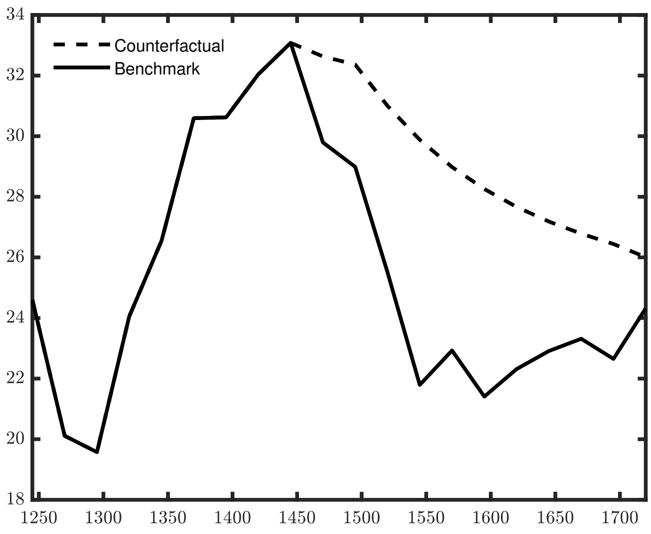


Figure 14: Population from "Timing of Industrial Revolution" experiment

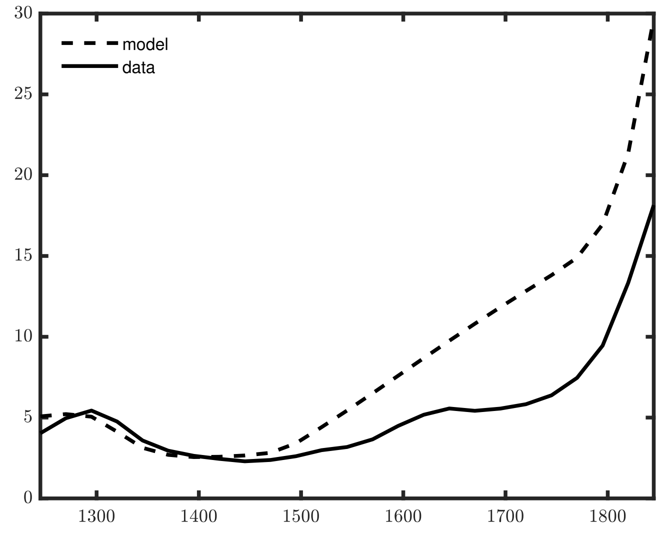


Figure 15: Output per capita from "Timing of Industrial Revolution" experiment

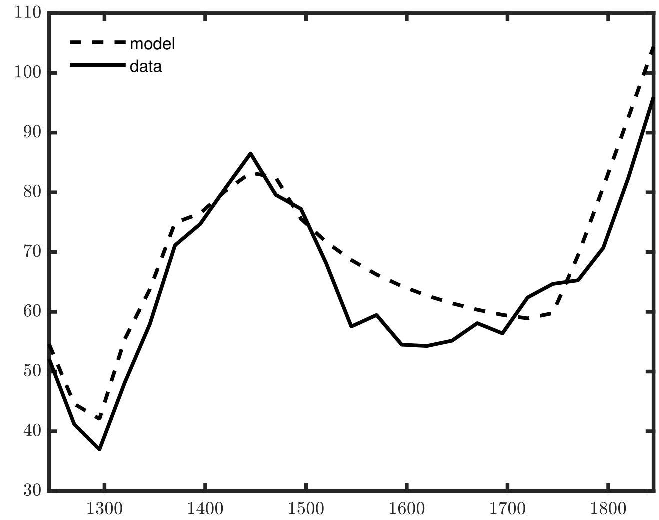


Figure 16: Detrended macro aggregates

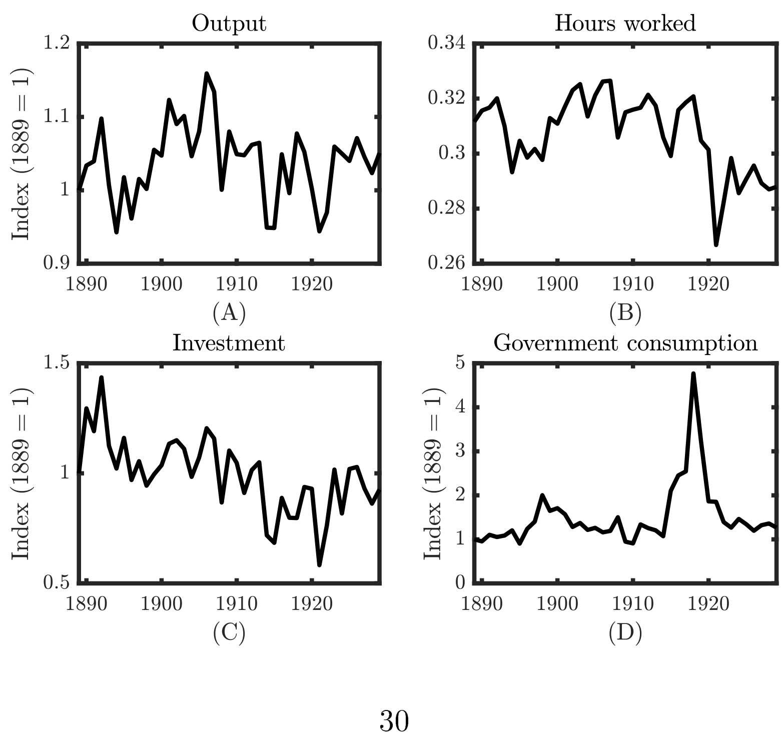


Figure 17: Estimated wedges

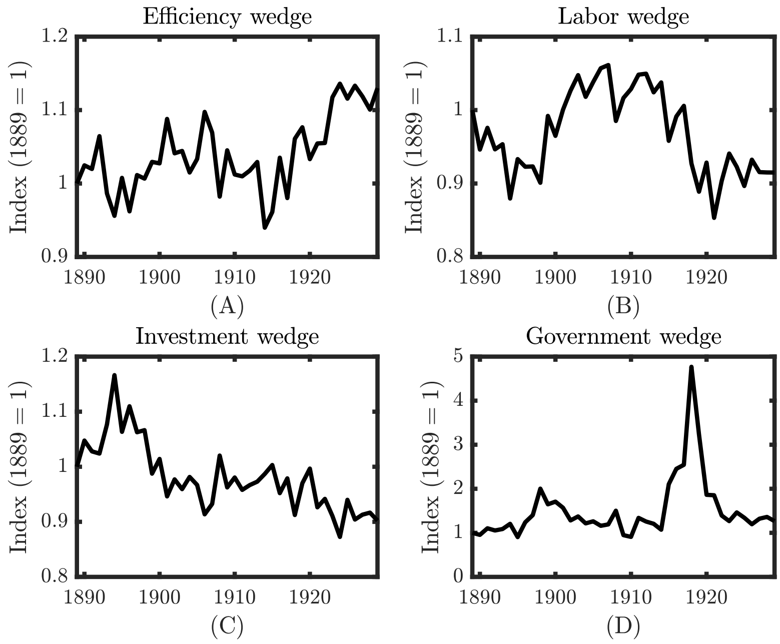


Figure 18: Efficiency wedge only economy

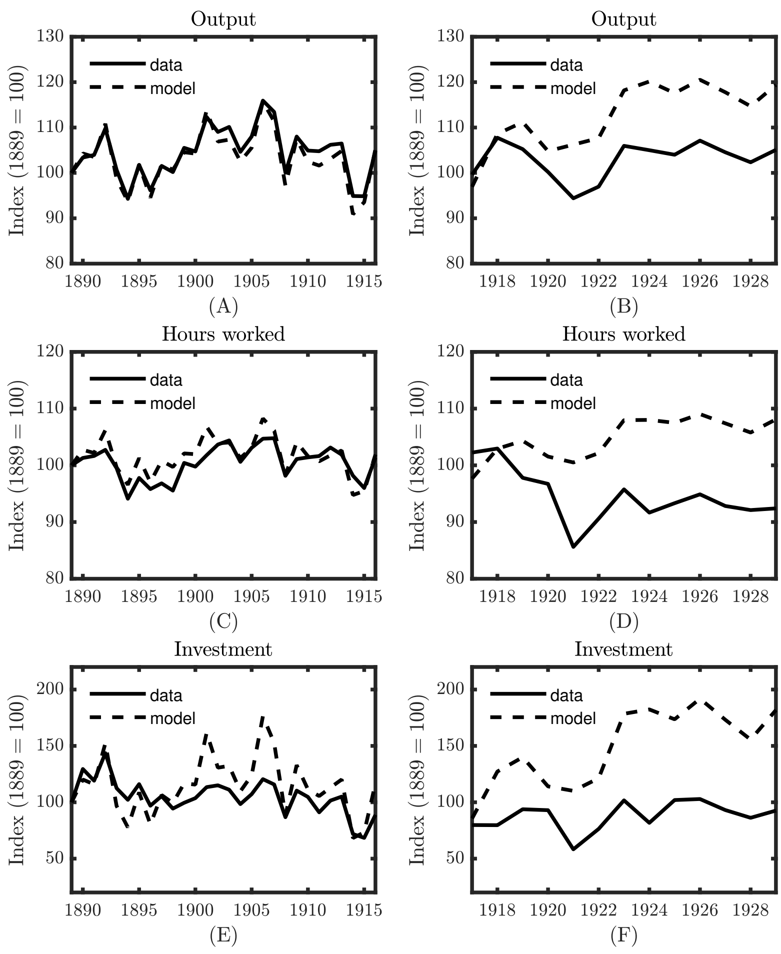
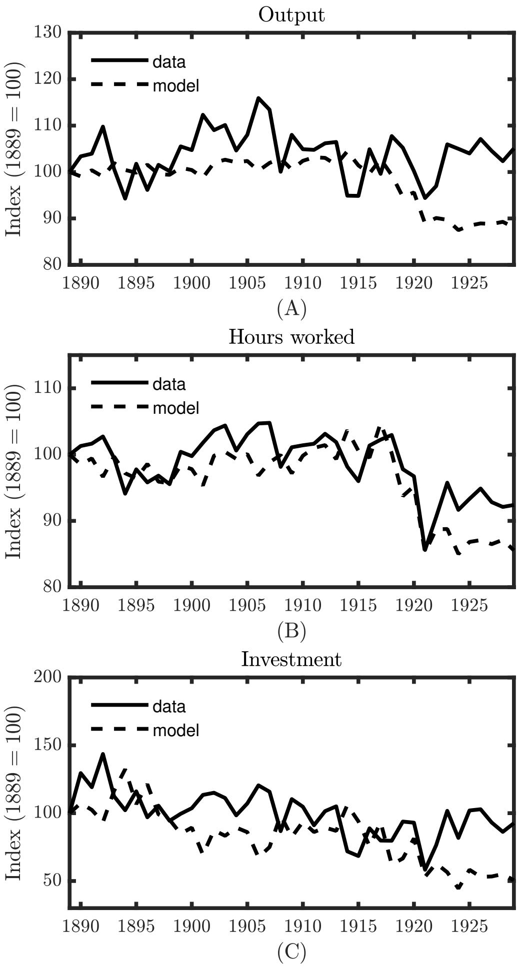


Figure 19: All wedges except efficiency wedge economy



(A)
(B)
(C)

Figure 20: Labor wedge only economy

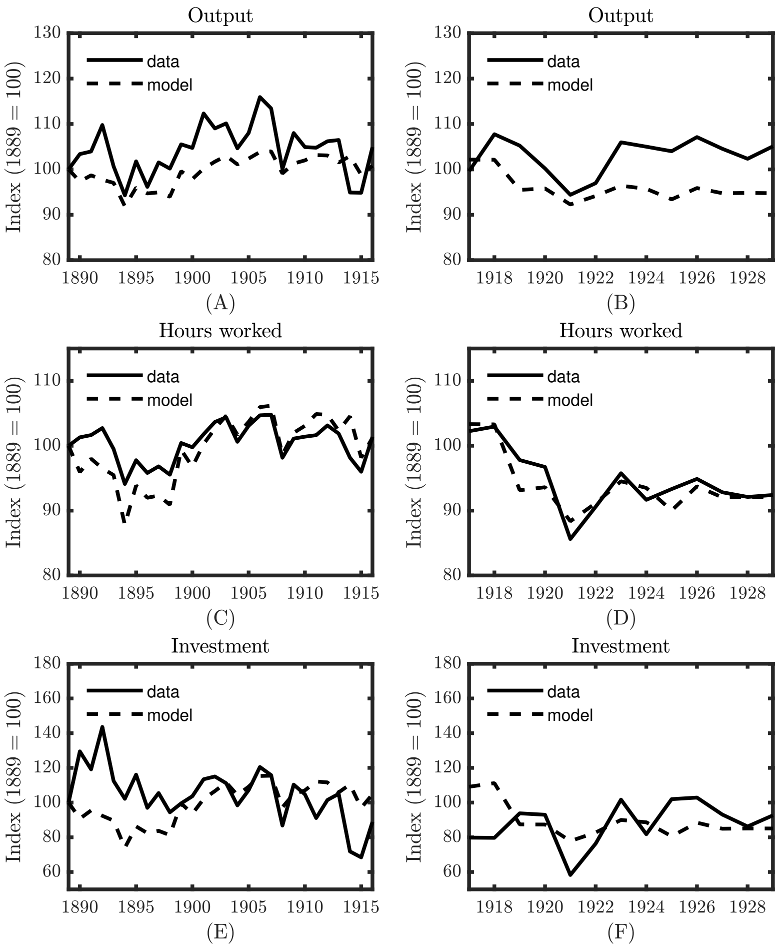


Figure 21: Investment wedge only economy

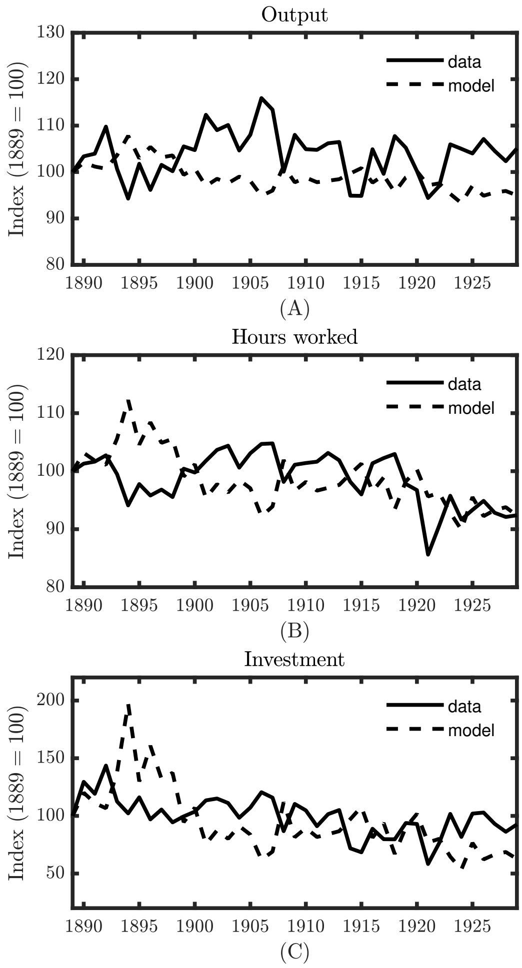


Figure 22: Government wedge only economy

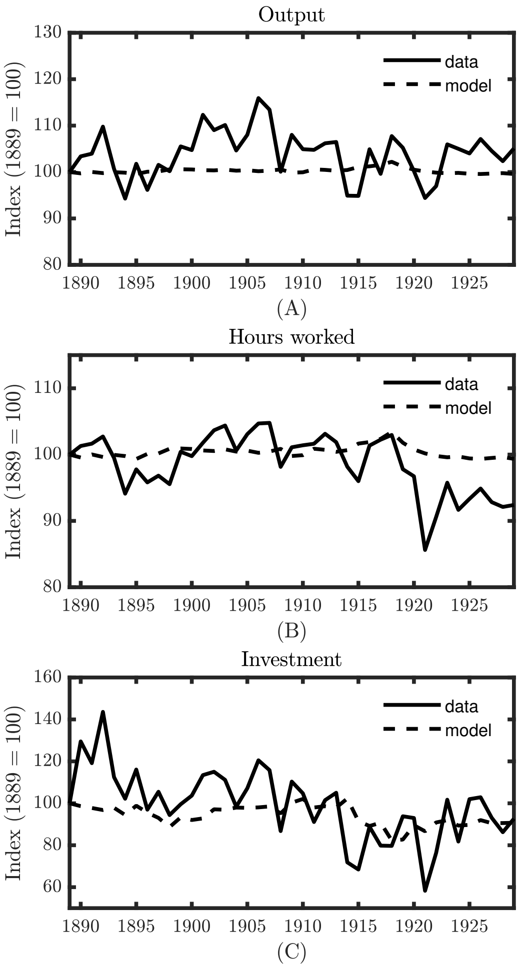


Figure 23: Efficiency wedge only economy in the Panics of 1893 and 1907

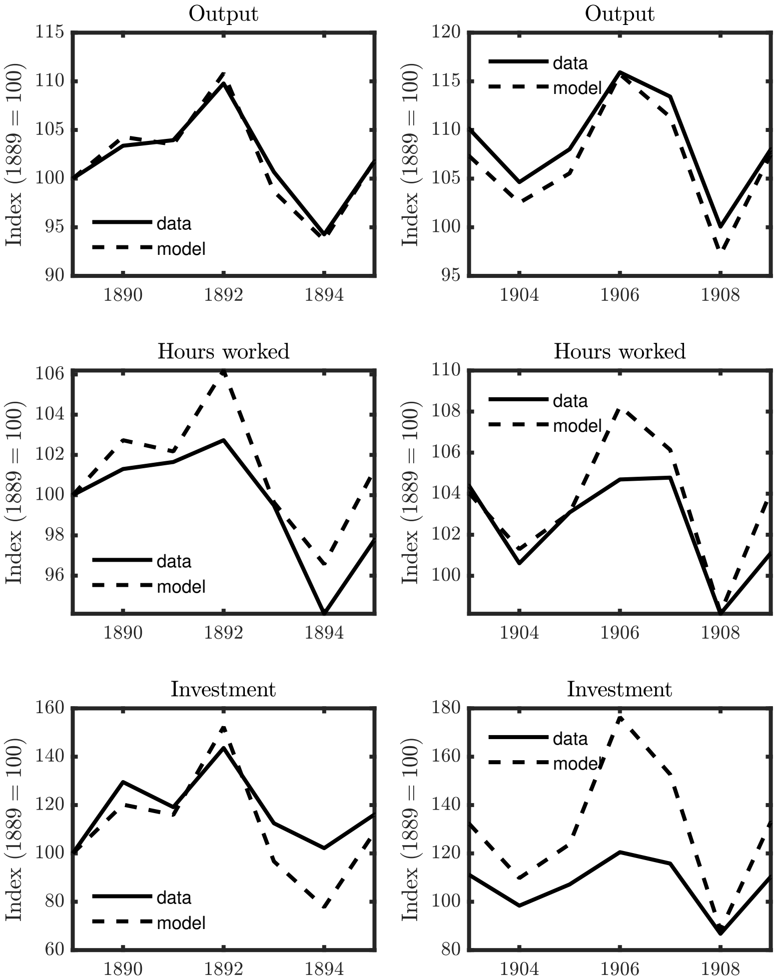


Figure 24: Industrial production of metals and machinery for United States, 1889-1909

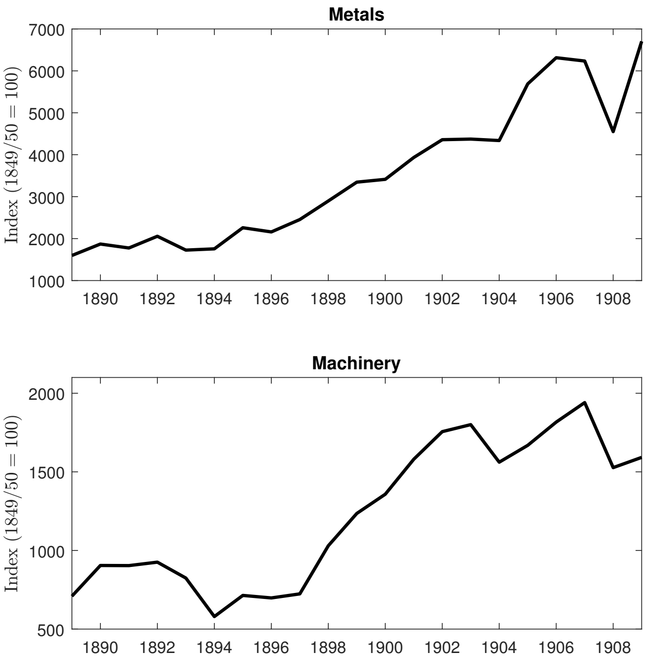


Figure 25: Index of industrial production for United States, 1889-1909

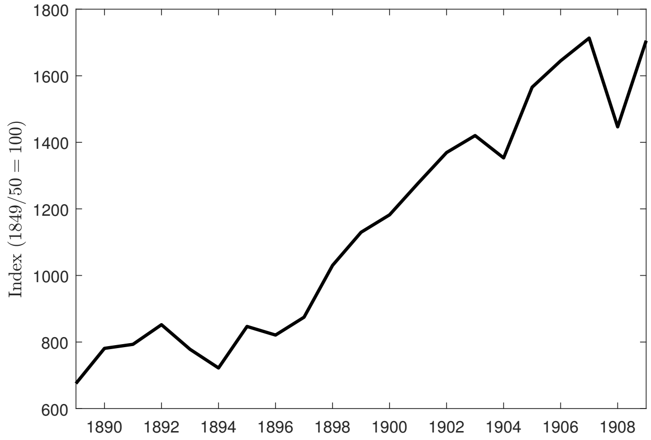


Figure 26: Labor wedge only economy in the Panics of 1893 and 1907

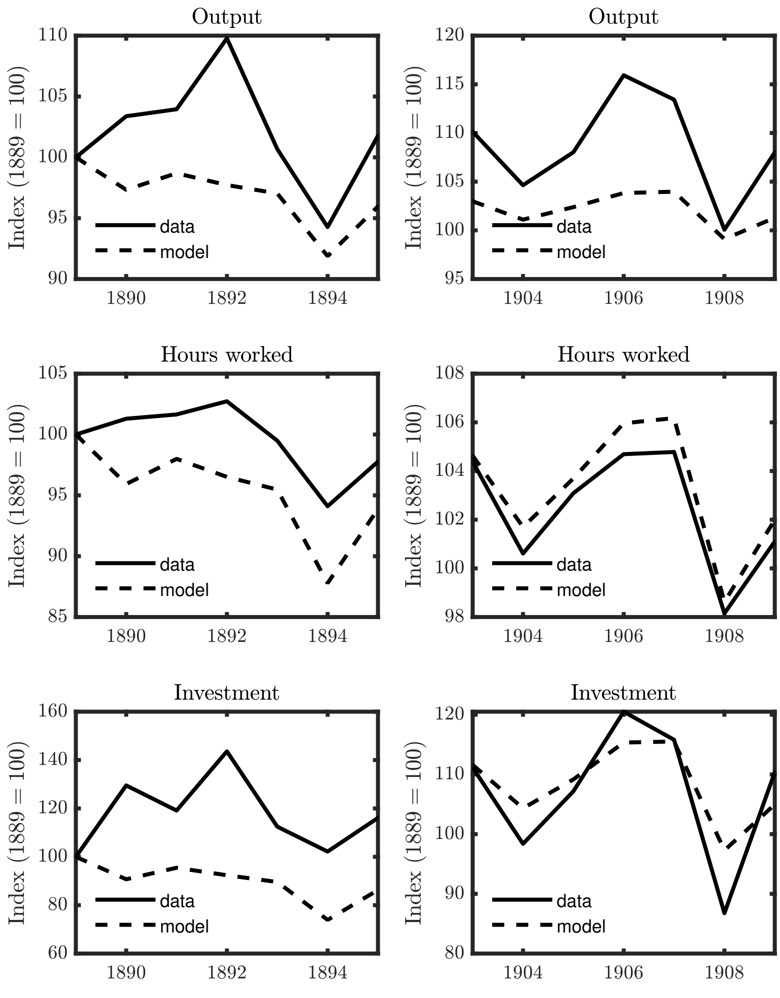


Figure 27: Index of composite wages for United States, 1889-1909