TECHNOLOGICAL INNOVATIONS: Slumps and Booms*

Leonardo Felli
(London School of Economics)

François Ortalo-Magné
(London School of Economics, CEPR)

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Abstract. This paper documents the delayed adoption of a major technological innovation: the adoption of the diesel locomotive in the US railway industry. Contrary to other instances of major technological innovations, the delay in the adoption of the diesel locomotive was not associated with an initial slump in output. We provide a theoretical model which is consistent with both an increase and a decrease in output following the invention of a new technology. Within this model we identify the key factors that make a slump in output unlikely.

Address for correspondence: Leonardo Felli, University of Pennsylvania, Department of Economics, 434 McNeil Building, 3718 Locust Walk, Philadelphia PA 19104-6297. E-mail: felli@ssc.upenn.edu.

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1. Introduction

1.1. Overview

New technologies are adopted on a large scale and have a sizable productivity effect only after a prolonged period of time following their invention (Mansfield 1968). A recent study by David (1990) argues that this delayed adoption is associated with an initial slump in output, as observed in the case of the dynamo in the US. This paper documents an example of a major technological innovation: the adoption of the diesel locomotive in the US. In spite of an overall decrease in the number of locomotives, the quantity of transportation services provided by the US railroad industry did not decrease.

The natural question to ask then, is why does the adoption of the dynamo generate an output decrease while the adoption of diesel locomotives generate an output increase? This paper proposes a theoretical model that is compatible with both of these outcomes and identifies the economic factors that may prevent an output slump following the invention.

A technological discovery may lead to an output slowdown because firms need to divert resources to develop the inputs needed by the new technology (Helpman and Trajtenberg 1994) or to learn how to implement the new technology (Aghion and Howitt 1996). When a new technology is embedded in capital, however, as in the case of locomotives, a simpler model can explain a slowdown in investment and output.

Consider an industry whose production technology is embedded in machines which depreciate over time. Adopting a new technology therefore, means discarding current machines in favour of new ones. Suppose that at some date, machine manufacturers announce that a new and better type of machine will be available in the future and everyone knows that this new type of machine will eventually take over the whole industry. As a consequence, optimizing agents decrease their investments in current machines because they foresee their forthcoming obsolescence. The stock of machines therefore declines before the new machines are adopted. Although existing machines may be used more intensively before being scrapped, their reduced number implies a decline in output before the adoption of their better successors generates a boom.

This provides an explanation for a slump in investment and in output following a technological discovery. It is not, however, compatible with stylised facts on technological innovation: investment tends to continue in the old technology during the early period of adoption of the new technology, and diffusion curves in the new technology tend to be S-shaped (Mansfield 1968, Chari and Hopenhayn 1991, Helpman and Trajtenberg 1996). We therefore extend the simple model above in order to match these facts. This allows us to identify economic factors that make a slump in output unlikely, even if the innovation in not immediately widely adopted and the stock of capital decreases.

The key ingredients of the extended model are learning-by-doing in the machine producing sector and productivity heterogeneity in the sector which uses the machines as an input. When a new technology is invented, the firm for which the new machines yield the highest productivity gain adopts them first. This adoption sparks the learning-by-doing process in machine production, making new machines progressively more competitive relative to the old machines. The other firms, foreseeing that new machines will eventually take over the industry, reduce their investment in old machines before selling them on the used market or scrapping them. In other words, each one of these firms behaves as the single firm of our initial model. Overall output is therefore subject to two countervailing effects. On the one hand, the immediate adoption of the new technology by the relatively most efficient firm increases output. On the other hand, the reduction of investment in the old technology by the lagging firms reduces output. The resulting path of aggregate output depends on the relative size of these two effects.

Two other factors counteract an initial output decline. First, firms using the old machines use them more intensively since they foresee their forthcoming obsolescence. This is compatible with the diesel locomotive evidence. Secondly, whenever a firm adopts the new technology, it sells the old machines on the used market where they are bought by the lagging firms who benefit from the implied price decrease. The result is an increase in the production capacity of the lagging firms. This also explains why investment in both new and old machines can be observed at the same time.

Learning-by-doing introduces an externality in the production of new machines. This externality induces lower than optimal investment in the new machinery. In addition, the sequence and timing of individual firms' switching decisions may be sub-optimal. A social planner would care not only about the relative productivity of the two technologies within each firm, but also about the size of each firm, as this affects the size of its investments and hence, the pace of the learning-by-doing in machine production.

The paper is organised as follows. In Section 2, we discuss the data concerning the adoption of the diesel locomotive in the US railroad industry. We then develop our basic model for the transmission of technological shocks in Section 3. Section 4 extends the basic model by introducing learning-by-doing and firms' heterogeneity in the new technology. Section 5 concludes. In the remainder of this section, we provide a brief description of the related literature.

1.2. Related Literature

The papers most closely related to the present one are Helpman and Trajtenberg (1994 and 1996) and Aghion and Howitt (1996).[1] They explain why the discovery of a general purpose technology may generate an initial slump in output before an eventual progressive increase as reported in David (1990).

Helpman and Trajtenberg (1994 and 1996) rely on a cost of adoption mechanism. In their economic environment, agents must develop a new range of intermediary inputs before adopting the new technology, represented by a new production function. This research and development activity diverts workers away from output production,

[1] There is a wide body of literature concerned with technological innovation. See for example Chari and Hopenhayn (1991), Jovanovic and MacDonald (1994) and Jovanovic and Nyarko (1997) among many others. However, except for the work of Helpman and Trajtenberg and that of Aghion and Howitt, this literature is not concerned with the potential negative effect of innovations on output.

generating an immediate slump in output. As soon as suitable intermediary inputs are available, the new technology is adopted and output rises.

Aghion and Howitt (1996) argue that fluctuations in research and development and in employment of resources are not large and gradual enough to explain significant and progressive fluctuations in output. Their model is build around a social learning assumption. Once the new technology is available, firms experiment with it. Only once a big enough mass of firms has experimented can the new technology be successfully adopted. The expenditure of resources incurred for the experimentation implies the slump in output and the delay before widespread adoption.

Our analysis differs from both these papers in the mechanism that characterises the transition from the old technology to the new one, and in the implications of the model on aggregate output. As argued above, our mechanism does not rely on the complementarity of inputs or a learning externality in final output production, but rather on the optimal investment policy of an agent. A key difference in the empirical implications of our analysis is that the reduction in intermediate input may be associated with an increase, as well as a decrease, in output following the invention. Therefore, our model is compatible with both the observed slump which followed the invention of the dynamo as well as the steady increase of transportation services following the production of the first diesel locomotive.

2. Empirical Evidence

Locomotives are an essential and costly input in the railroad transport industry. They depreciate over time. Adopting a new technology such as the diesel locomotive entails replacing the existing steam locomotives. In the early Twenties, a few countries had diesel locomotives where coal was lacking. In the U.S., the first diesel locomotive was used for commercial demonstration in 1924 (Mansfield 1968). Before that, most locomotives where built around steam engines. Figure 1 plots the number of locomotive of each type from 1911 to 1967. Very few diesel engines were used between 1924 and 1933 while this new technology was being further developed and made more cost effective. Following the construction of the first lightweight diesel engine in 1933, Burlington railroads introduced the first diesel powered train for main line service in 1934 (Overton 1940). Other companies followed, especially when the demand for transport services increased due to World War II. During the war, three quarters of new orders were for diesel locomotives.

By the mid to late Fifties, diesel locomotives had taken over the entire industry. The number of steam engines decreased sharply for several years before the number of diesel locomotives started increasing, as is apparent from Figure 1. Interestingly, the decrease in the number of steam locomotives starts the *same* year the diesel locomotive appears in demonstration in the U.S., 1924. One possibility for such a decrease could be a coincidental sharp improvement of the power of steam locomotives. Figure 2 addresses this concern by plotting the aggregate tractive power of steam locomotives. It shows that the decrease in number of locomotives was accompanied by a decrease in aggregate horse power with a marked change in its trend, again in 1924. One last possibility we check is that the decrease in number of steam locomotives is due to a decrease in demand for rail transport. Figure 3 shows this is not the case. This graph contests the argument that major technological changes generate slumps in output, unless one is prepared to argue that the switch from steam to diesel locomotives is the cause of the 1929 depression! Unfortunately, the U.S. recession of the Thirties does affect our series, as well as the Second World War and later progress in road transport. The explanation seems to be that railroad companies started running larger trains on average. The number of car-miles per locomotive-mile indeed jumped above trend for the 1924-33 period as shown in Figure 4.[2]

The model we put forward in this paper does seem to fit the introduction of the diesel locomotive. Of course, we are convinced that other mechanisms also played a role. For example, railroad firms waited to get more information about the performance and cost of running diesel locomotives before investing in them (as in Aghion and Howitt (1996)). Furthermore, they had to develop refuelling and maintenance

[2]The data for Figures 1 through 4 are from the Bureau of Railway Economics which reports data for Class I railways. Around 1924, Class I railways were defined as all the carriers with annual operating revenues above $1,000,000. They operated 90 per cent of the total railway mileage in the U.S., and earned about 96 per cent of the total revenues.

facilities before being able to use them (as in Helpman and Trajtenberg (1994)). We simply argue that part of the explanation is an optimal decline in investment in view of better opportunities in the future. Our argument is confirmed by the observed decline in steam equipment investment around 1924, as shown on Figure 5. This decline occurred several years before investment in the alternative diesel equipment took off.[3]

3. The Basic Model

In this section, we present the basic model that affords the key effects described above. In particular, the discovery of a more productive technology is initially followed by a delayed output slump, and then by a progressive increase in output. Output does not rise until a few periods after the discovery, due to the delayed adoption of this new technology. Furthermore, even after the technology has been adopted, output continues to increase for a while before reaching the new steady state. As argued above, these effects are the result of the interplay of the announcement of the new technology embedded in a new type of intermediate inputs (machines), and the optimal investment policy of the representative agent. The downward pressure on output generated by the depreciation of old machines is partly compensated by a progressive increase in the intensity of use of these machines, followed by a progressive decrease in the intensity of use of new machines, until steady state is reached.

3.1. Economic Environment

Consider an open economy with a measure one of infinitely lived agents and three commodities: output y with fixed price of 1, machines of type 1, k_1, machines of type 2, k_2, with prices q_1 and q_2, respectively. Agents maximise the discounted sum of profits with discount factor $\beta = 1/(1+r)$, where r is the exogenous interest rate, $r \geq 0$. Every period, agents use the technology $y = \theta_i k_i^\alpha \iota_i^\gamma$ to produce units of the consumption good. The inputs of this technology are the agent's indivisible endowment of management activity, normalised to 1, and an intermediate input:

[3]The data in Figure 5 are from the Bureau of Transport Economics and Statistics.

a quantity k_i of machines of two distinct types $i \in \{1, 2\}$. The choice variable ι_i denotes how intensively the machines of type i are used. Increasing the intensity of use of the machines increases output less than an increase in the amount of machines: $\alpha > \gamma$. Machines of type 2 are more productive than the machines of type 1: $\theta_2 > \theta_1 > 0$. An entrepreneur cannot use both types of machine at once.[4] Both types of machines require some maintenance. This cost is proportional to the number of machines an entrepreneur uses and the intensity with which she uses them: $m\, k_{i,t}\, \iota_{i,t}$, where m is a positive parameter denoting the cost of maintenance. In addition, a proportion δ of machines breaks down every period. This last form of depreciation is independent of the use of the machines and corresponds to the usually assumed form of depreciation. In this context, we consider output to be final goods production minus the maintenance expenditures.

Agents may freely borrow and lend at the interest rate r. The timing of the model is such that markets for machines open at the beginning of each period, then production takes place, and finally, the output market opens. We assume that the machines of type 1 are supplied according to an exogenous supply function $\kappa_1(q_1)$ with $\kappa_1(q) = 0$, for all $q \leq q_1^{\min}$, and $\kappa_1'(q) \geq 0$ for any price q above $q_1^{\min}$.[5] Furthermore, we assume that machines of type 1 have a scrap value q_1^s such that $0 < q_1^s < q_1^{\min}$. The positive scrap value corresponds to the market value of the raw material embedded in the machines.

Machines of type 2 are discovered and appear in the economy at some previously unknown time period t_d. To simplify the analysis we take this discovery to be a complete surprise for the agents in the economy. When the discovery occurs, a sequence of prices for machines of type 2, $\{q_{2,t}\}_{t=t_d}^{\infty}$ is announced. This sequence is strictly decreasing until some later date $t_s > t_d$: $q_{2,t} \geq q_{2,t+1}$, for every $t \geq t_d$, and

[4]The fact that the output production technology displays some kind of indivisibility is key to our results, although any production function with finite marginal product at zero would have also been adequate.

[5]This supply function could obviously be rationalised by a production process involving a fixed cost.

$q_{2,t} = q_{2,t_s}$, for every $t > t_s$.[6] It is also such that the user cost of type 2 machines $u_{2,t} = q_{2,t} - \beta(1-\delta)q_{2,t+1}$ is decreasing between t_d and t_s.

Since this section focuses on the basic mechanism at play in our model, we treat the sequence of prices of type 2 machines as exogenous. The key purpose of the following section will be to identify the effects at play here which carry through when production of type 2 machines is endogenized. Throughout, we assume an exogenously fixed output price. Endogenizing it would only reinforce our results.

3.2. Representative Agent's Problem

An agent in our economy chooses levels of machine holdings, $k_{1,t}, k_{2,t}$, intensity of use $\iota_{1,t}, \iota_{2,t}$, and activity (type 1 machines or type 2 machines), so as to maximize the present value of her earnings:

$$\max_{k_{i,t},\iota_{i,t}} \quad \sum_{t=0}^{\infty} \beta^t \ \max\left\{\Pi_{1,t}, \Pi_{2,t}\right\} \tag{1}$$

where $\Pi_{i,t}$ denotes the period t profit accruing from using technology i, $i \in \{1,2\}$:

$$\Pi_{i,t} = \theta_i \ k_{i,t}^{\alpha} \ \iota_{i,t}^{\gamma} - u_{i,t} k_{i,t} - m \ k_{i,t} \ \iota_{i,t} \tag{2}$$

As mentioned above, the variable $u_{i,t}$ denotes the per-unit user cost of holding machine $k_{i,t}$:

$$u_{i,t} = q_{i,t} - \beta \left(1-\delta\right) q_{i,t+1} \tag{3}$$

[6] Notice that for the output to decrease progressively following the discovery, it is sufficient to assume that at date t_d it is announced that at a future date t_s a new technology will be available at a given invariant price q_2.

From the solution of program (1), we obtain the following demand and intensity of use for machines of type i at time t if the agent chooses activity $i \in \{1,2\}$:

$$k_{i,t} = \left(\frac{\gamma}{m}\right)^{\frac{\gamma}{1-\gamma}} \left[\frac{(\alpha-\gamma)\theta_i^{\frac{1}{1-\gamma}}}{u_{i,t}}\right]^{\frac{1-\gamma}{1-\alpha}}, \quad \iota_{i,t} = \frac{\gamma u_{i,t}}{m\,(\alpha-\gamma)}. \tag{4}$$

Since $\alpha > \gamma$, it follows immediately from (4) that when the user cost of machines increases, the entrepreneurs use fewer machines more intensively. The activity choice is determined by comparing $\Pi_{1,t}$ and $\Pi_{2,t}$. Therefore, type $i \in \{1,2\}$ machines will be adopted if and only if $\Pi_{i,t} > \Pi_{j,t}$ for $i \neq j$, or:

$$\frac{u_{i,t}}{u_{j,t}} \leq \left(\frac{\theta_i}{\theta_j}\right)^{\frac{1}{(\alpha-\gamma)}}. \tag{5}$$

3.3. Equilibrium

An equilibrium of this basic model is fully characterised by a sequence $\{q_{1,t}\}_{t=0}^{\infty}$ of prices for the machines of type 1 and an allocation $\{k_{1,t}, k_{2,t}, \iota_{1,t}, \iota_{2,t}\}_{t=0}^{\infty}$ such that the allocation solves program (1) and the market for the machines of type 1 clears in every period t:

$$k_{1,t} = \kappa(q_{1,t}) + (1-\delta)k_{1,t-1}. \tag{6}$$

Before the discovery, the economy is in a steady state equilibrium where newly produced machines replace the irreparable ones: $\kappa\left(q_1^*\right) = \delta\ k_1^*$, where the $*$ denotes steady state values. For all $t \geq t_s$, the economy is again in steady state. Given the objective of the paper, we are only interested in the case where machines of type 2 take over the industry in the new steady state. We assume, therefore, that type 2 machines represent a sufficient innovation to be preferred to type 1 machines even when the latter are priced at their scrap value:

$$\frac{q_{2,t_s}}{q_1^s} \leq \left(\frac{\theta_2}{\theta_1}\right)^{\frac{1}{(\alpha-\gamma)}}. \tag{7}$$

The transition from the type 1 to type 2 machines will be delayed if type 2 machines are too expensive at first, which we also assume:

$$\frac{u_{2,t_d}}{u_{1,t_d}} > \left(\frac{\theta_2}{\theta_1}\right)^{\frac{1}{(\alpha-\gamma)}}. \tag{8}$$

Under these assumptions, we prove that following the discovery of type 2 machines, *output progressively decreases before rising, after the delayed adoption of the type 2 machines.*

We present our argument in two steps. First, we show that the sequence of prices $\{q_{1,t}\}_{t=t_d}^{\infty}$ is non-increasing and the sequence of user costs $\{u_{1,t}\}_{t=t_d}^{\infty}$ is non-decreasing. Secondly, we demonstrate that such properties of $\{q_{1,t}\}_{t=t_d}^{\infty}$ imply a declining sequence of equilibrium quantities of machines of type 1, and consequently, a declining output before agents adopt the machines of type 2 and output eventually rises.

We prove that $\{q_{1,t}\}_{t=t_d}^{\infty}$ is non-increasing and that $\{u_{1,t}\}_{t=t_d}^{\infty}$ is non-decreasing by induction. Denote by $\bar{t}$ the date at which all agents adopt the machines of type 2. This date $\bar{t} \in [t_d, t_s]$ does exist by condition (7). Since all agents in the economy are identical at date $\bar{t}$, all agents want to sell their type 1 machines. Hence, there is no demand for type 1 machines. So the only equilibrium price for these machines from that date onward is their scrap value q_1^s. Furthermore, in the steady state preceding t_d, the steady state price exceeds the scrap value of type 1 machines since their per period supply is positive: $q_1^* > q_1^s$.

We first prove that at the announcement date, the price of type 1 machines decreases, $q_{1,t_d} < q_1^*$, and their user cost increases, $u_{1,t_d} > u_1^*$. We proceed by contradiction. Assume that $q_{1,t_d} > q_1^*$. This implies $\kappa(q_{1,t_d}) > \kappa(q_1^*)$. Since the quantity of machines to be replaced out of depreciation is the same at date t_d and at date $t_d - 1$

by the market clearing condition (6), we conclude $k_{1,t_d} > k_1^*$. This implies that the marginal productivities of capital in both periods are such that:

$$\alpha\, \theta_1^{\frac{1}{1-\gamma}} \left(k_1^*\right)^{\frac{\alpha-1}{1-\gamma}} \left(\frac{\gamma}{m}\right)^{\frac{\gamma}{1-\gamma}} > \alpha\, \theta_1^{\frac{1}{1-\gamma}} k_{1,t_d}^{\frac{\alpha-1}{1-\gamma}} \left(\frac{\gamma}{m}\right)^{\frac{\gamma}{1-\gamma}}. \tag{9}$$

Condition (9) implies that $u_1^* > u_{1,t_d}$. The definition of user cost (3) yields:

$$q_{1,t+1} = \frac{1}{\beta(1-\delta)} \left(q_{1,t} - u_{1,t}\right). \tag{10}$$

This equation (10), together with $q_{1,t_d} > q_1^*$ and $u_{1,t_d} < u_1^*$, implies $q_{1,t_d+1} > q_1^*$. Repeating the same construction for every period $t = t_d + 1, \ldots, \bar{t}$, we conclude that $q_{1,\bar{t}} > q_1^*$ which contradicts the fact, stated above, that $q_{1,\bar{t}} = q_1^s < q_1^*$.

Assume now that $q_{1,t} < q_{1,t-1}$ and $u_{1,t} > u_{1,t-1}$ for a given $t \in [t_d, t_s - 1]$. We prove that $q_{1,t+1} < q_{1,t}$ and $u_{1,t+1} > u_{1,t}$. We proceed, once again, by contradiction. Assume that $q_{1,t+1} > q_{1,t}$. Then by equation (10) we obtain that:

$$\left(q_{1,t} - u_{1,t}\right) > \left(q_{1,t-1} - u_{1,t-1}\right). \tag{11}$$

Inequality (11) contradicts both induction assumptions $q_{1,t} < q_{1,t-1}$ and $u_{1,t} > u_{1,t-1}$.

The dynamics of the type 1 machine prices imply that output decreases following the discovery of the new technology. Since the equilibrium supply $\kappa(q_{1,t})$ is upward sloping and the stock of existing machines is depreciating through time, the sequence $\{q_{1,t}\}_{t=t_d}^{\infty}$ is associated in equilibrium with a non-increasing sequence of quantities of machines of type 1 $\{k_{1,t}\}_{t=t_d}^{\infty}$, converging to zero. Given that for every $t \in [t_d, \bar{t} - 1]$, no agent adopts machines of type 2, then the decreasing set of quantities of machines used in equilibrium $\{k_{1,t}\}_{t=t_d}^{\bar{t}-1}$ generates a set of equilibrium levels of output decreasing over time.

¿From the firm's problem, we have that the intensity of use of machines increases while their stock declines. This implies that output does not decline as fast as the stock of machines. It declines nonetheless, given that $\alpha > \gamma$. By definition, at time $\bar{t}$ all agents adopt the machines of type 2 which generates a sudden increase in the level of output produced. This increase continues until date t_s, while the user cost of the machines of type 2 continues to decrease as agents increase their stock. As the user cost decreases, the intensity of use also decreases until it reaches its steady state level.

The simulations reported on Figures 6 and 7 illustrate our argument.[7] Following the discovery of the better machines at $t = 4$, the representative firm cuts down on investment of machines of type 1. Its stock declines while the intensity with which it uses this type of machines rises; output declines. At $t = 9$, the firm scraps the type 1 machines and starts buying type 2 machines. As the firm's stock of new machines increases, output rises and the firm uses the machines less intensively.

We conclude this section with a comment on the efficiency of the dynamic equilibrium described above. The transition path we derive in this section is socially efficient. Indeed, the equilibrium path of the allocation of old machines and output coincides with the solution to the central planner's problem. Even if our model yields an initial decline in output, welfare cannot decrease because of the innovation, as there are no externalities and agents are free not to adopt the new technology. We obtain a decrease in output thanks to an intertemporal substitution mechanism as opposed to a labour reallocation mechanism, as in the literature cited earlier.

4. Endogenous Production of New Machines

In this section we specify the technology for the production of the type 2 machines. We assume that this technology benefits from learning-by-doing. This extension of our basic model affords three additional effects with respect to the basic model described in Section 3 above. First, the decrease in the price of the type 2 machines is the result of learning-by-doing in the production of these machines and the endogenous decision

[7] The parameters for this simulation are as follows: $\alpha = .6$, $\beta = .95$, $\gamma = .3$, $\delta = .25$, $\theta_1 = 1$, $\theta_2 = 2$, $m = 1.25$. In addition, the supply function for machines type 1 is such that their steady state price is 0.193 and no production of new machines takes place at or below the price 0.179. The announced sequence of type 2 machine prices is the one that will be generated in equilibrium in the simulations of the next section. It is approximately. $\{5.583, 4.482, 3.862, 3.422, 3.085, 2.828, 2.568, 2.299, 2.019, 1.730, 1.441, 1.181, 1.021,$ 1.000, 1.000, 1.000, $\}$.

of the heterogeneous firms to adopt the new machines. Second, firms heterogeneity allows for the possibility of continuing investment in the old technology while the new one starts being adopted. Third, the heterogeneity of the firms creates the potential for an externality exerted by the firms that adopt the new technology on the remaining firms that have not yet adopted it.

The result of these effects is an economy in which, following the introduction of the new technology, the stock of capital initially decreases and only later progressively increases. At the same time, aggregate output may immediately increase (as in the adoption of the diesel locomotive documented in Section 2) or may initially decrease and only later increase, following the adoption of the new technology (as in David (1990), Helpman and Trajtenberg (1994) and Aghion and Howitt (1996)). Finally, as highlighted in Chari and Hopenhayn (1991) and Helpman and Trajtenberg (1996), we observe continuing investment in the old technology while the new technology is available and adopted by some firms in the industry.

To keep the treatment as simple as possible, we assume that the technology that produces machines of type 2, after the innovation occurs, takes the following form:

$$\ell_t(\psi + \mu e^{-K_{2,t-1}}) \tag{12}$$

where ψ and μ are positive constants, ℓ_t the labour input, and $K_{2,t-1}$ the aggregate stock of type 2 machines in period $t-1$.

This specification is different from the standard experience curve,[8] in which productivity is an increasing function of cumulative output of type 2 machines, but has the same flavour: the more machines produced, the higher the output of machines per worker.[9] Assuming the machine production industry is competitive and faces a

[8] Cfr. for example Arrow (1962).

[9] Although it is irrelevant here, a bad feature of this specification of the learning-by-doing process is that the price of a machine would increase if the stock were to decline. Notice that this problem is easily solved by replacing current stock by the maximum of previous stocks. This would not affect in any way our results given that in our context, the stock of new machines is non-decreasing over time.

constant cost of labour, w, the equilibrium price of machines of type 2 is:

$$q_{2,t} = \frac{w}{\psi + \mu e^{-K_{2,t-1}}} \tag{13}$$

We do not want labour reallocation between production of output and machines to affect our model. Obviously, we know from Helpman and Trajtenberg (1994) that it could only reinforce our mechanism. This is why we assume a perfectly elastic supply of labour.

For learning-by-doing to generate a decreasing sequence of prices for type 2 machines, at least one firm must adopt them on the date of discovery. This instantaneous adoption is required in order to spark the learning-by-doing process. If all firms adopt at once, the mechanism of the previous section does not apply. Therefore, we introduce a form of heterogeneity in the productivity of type 2 machines in the final good technology. In particular, we assume $\bar{J}$ firms can produce the consumption good using the same intermediate input $k_{2,t}$. We take the type 2 machines to have different productivities across firms, $\theta_2^j \neq \theta_2^i$ for $j \neq i$, $j, i \in \{1, \ldots, \bar{J}\}$, and to be more productive than type 1 machines: $\theta_2^j > \theta_1$ for every $j = 1, \ldots, \bar{J}$. Without loss of generality, let $\theta_2^1 > \theta_2^2 > \ldots > \theta_2^{\bar{J}}$.

Let J_t denote the set of the indexes of firms that have adopted the new technology at time t. The aggregate demand and equilibrium quantity of type 2 machines at time t is then:

$$K_{2,t} = \left(\frac{\gamma}{m}\right)^{\frac{\gamma}{1-\gamma}} \sum_{j \in J_t} \left(\frac{(\alpha - \gamma)\ \left(\theta_2^j\right)^{\frac{1}{1-\gamma}}}{u_{2,t}} \right)^{\frac{1-\gamma}{1-\alpha}}. \tag{14}$$

The definition of equilibrium here is similar to that of the previous section except that we account for the heterogeneity of the firms, keeping track of J_t, and that we have an extra market and price for the type 2 machines.

The equilibrium transition from one steady state to the other — following the technological innovation — can be described as follows. At the announcement date, the price of the new machines is $q_{2,t_d} = (w/\psi)$. Assume parameters are such that only firm one adopts the new machine right away. This is true if the following conditions are satisfied:[10]

$$\frac{u_{2,t_d}}{u_{1,t_d}} < \left(\frac{\theta_2^1}{\theta_1}\right)^{\frac{1}{\alpha-\gamma}} \tag{15}$$

$$\frac{u_{2,t_d}}{u_{1,t_d}} > \left(\frac{\theta_2^j}{\theta_1}\right)^{\frac{1}{\alpha-\gamma}} \quad \forall j \neq 1 \tag{16}$$

We then have:

$$q_{2,t_d+1} = \frac{w}{\left(\psi + \mu e^{-k_{2,t_d}^1}\right)} < q_{2,t_d}$$

and $J_{t_d} = \{1\}$. This will in turn decrease the user cost $u_{2,t_d} > u_{2,t_d+1}$ of type 2 machines and increase the demanded quantity of these machines in period $t_d + 1$: $k_{2,t_d}^1 < k_{2,t_d+1}^1$. The result will be an even further decrease of the equilibrium price for type 2 machines.

Consider now firms $j > 1$. These firm are facing a declining user cost and price of new machines. Therefore, the analysis presented in Section 3 above applies: the user cost of the type 1 machines $u_{1,t}$ and the intensity of use of these machines $\iota_{1,t}$ increase. This increase together with the decrease in the price of type 2 machines $u_{2,t}$ implies that at some future date $\hat{t} > t_d$ at least firm two (the second relatively most

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[10] Notice that these conditions are more complex that it might seem at first sight. In particular, in this new model, the user cost u_{2,t_d} is only implicitly defined by (3). Indeed, u_{2,t_d} is a function of the price q_{2,t_d+1}. Learning-by-doing renders this price a function of the stock of type 2 machines firm one has adopted at t_d, k_{2,t_d}^1, as in (13). In equilibrium, the stock k_{2,t_d}^1 is in turn a function of the user cost u_{2,t_d}:

$$k_{2,t}^j = \left(\frac{\gamma}{m}\right)^{\frac{\gamma}{1-\gamma}} \left(\frac{(\alpha-\gamma)\ \left(\theta_2^j\right)^{\frac{1}{1-\gamma}}}{u_{2,t}}\right)^{\frac{1-\gamma}{1-\alpha}}.$$

productive firm) will be in a situation to adopt the type 2 machines: $J_{\hat{t}} = \{1, 2\}$ and

$$\frac{u_{2,\hat{t}}}{u_{1,\hat{t}}} < \left(\frac{\theta_2^2}{\theta_1}\right)^{\frac{1}{\alpha-\gamma}}. \tag{17}$$

The situation evolves in a similar fashion until all the firms that use type 2 machines in the new steady state have adopted the new technology.

Notice that in this equilibrium we observe a sequential pattern of adoption of the new technology. This implies that the output produced by each firm decreases following the innovation and then eventually increase when adoption occurs, with the exception of the most efficient firm which adopts at the announcement date and hence faces no slump in output. In addition, when a firm adopts the new technology, it releases old machines on the used market. If the amount the firm sells is larger than the aggregate quantity of machines lost by depreciation, then the output of the firms still using the old machines rises in the period of the adoption.

In the aggregate, two distinct scenarios are possible. The first scenario is characterized by a situation in which the increase in output generated by firm one's immediate adoption is more than compensated by the decrease in output of all the other firms. This is most likely if the first firm to adopt is relatively small and it takes several periods before any other firm adopts the new technology. The result is an aggregate output which first decreases and then increases as a result of enough firms switching to type 2 machines. The behaviour of aggregate output then replicates the type of findings of Helpman and Trajtenberg (1994 and 1996) and Aghion and Howitt (1996) without relying on a labour reallocation mechanism. The second scenario, instead, is characterized by a situation in which the decline in aggregate investment in old machines is fully compensated by the increase in productivity of the firm that adopted the new technology, the increase in intensity of use of the old machines, and the increase in the investment in old machines by the firms that still use them.

This alternative behaviour is compatible with the empirical evidence on the adoption of the diesel locomotive as described in Section 2 above. In particular, it is possible to envisage parameter values of the model such that the overall number of locomotives decreases before increasing, while the transportation services (output) do not decrease.

Figure 8 provides an example by illustrating the result of a simulation of our model in the case of two firms.[11] Firm one immediately adopts the new technology at the period of discovery $t = 4$; firm two keeps the old technology. Although the production of type 1 machines stops at the date of discovery, the output of firm two increases at this date because firm two invests in the old machines of firm one. Hence, firm two's output rises slightly. From then on, firm two is subject to the mechanism described in the previous section by which its stock of capital and output declines until it eventually joins firm one in the use of the new technology at $t = 9$. Despite the increase in investment in the new technology, the aggregate output growth is slowed down during the initial part of the transition by the declining output of firm two. As firm two adopts the new technology, output is boosted by the increased efficiency of this firm. Furthermore, the adoption by firm two implies an increased demand of type two machines which accelerates the learning-by-doing process in their production. Notice that in Figure 9, the investment in new machines is progressive. It actually displays the S-shaped pattern often noted in the empirical literature (Mansfield 1968). Furthermore, as shown in Figure 10, the model predicts investment in old machines at the individual firm level while the new machine is already being adopted. This matches the other stylised fact concerning the adoption of new technologies mentioned in the introduction (Chari and Hopenhayn 1991, Helpman and Trajtenberg 1996).[12]

Conditions (15), (16) and (17) do not include any measure of the benefit to other firms of the reduction in the price of type 2 machines generated by their adoption. The competitive equilibrium is therefore characterised by a slower adoption path with respect to the socially efficient one. This occurs for three reasons. First, the central planner would require each firm to invest more in type 2 machines for the

[11]This simulation uses the parameters of the previous one with, in addition, $\mu = 4.5, \psi = 1, w = 1$. The firm of the previous simulation is now firm two. Firm one has the productivity coefficients $\theta_1^1 = 1$, $\theta_2^1 = 4$.

[12]In our simulation, this only happens for one period because we only have two firms.

purpose of better exploiting the learning-by-doing externality (the "usual" learning-by-doing externality effect). Secondly, the central planner would require firms $j > 1$ to adopt the new technology earlier than in a competitive equilibrium. Thirdly, the central planner might not necessarily require firms to switch only according to their relative efficiency parameter $\left(\theta_2^j/\theta_1^j\right)$ which is what matters in equilibrium. Instead, the central planner would also take into account the amount of type 2 machines which each firm will use when switching. Hence, the firm size, determined by the absolute productivity of the firm with type 2 machines, θ_2^j, matters for efficiency whereas it is irrelevant in equilibrium. The result is that not only the levels of investment of each firm are socially suboptimal, but also the pattern of adoption may be. This implies that output growth possibly observed in the transition from one steady state to the other is socially inefficient, in the sense that a central planner would generate a higher increase in output, and hence, a higher growth with respect to the perfectly competitive equilibrium.

5. Concluding Comments

In this paper we document the adoption of the diesel locomotive in the US railway industry in the first half of the century. We highlight a potential puzzle. Indeed, while the invention of the dynamo, as documented by David (1990), leads to an initial decrease in output, the invention of the diesel locomotive does not reduce the supply of transportation services. We provide a model which is compatible with both situations.

In particular, the paper identifies two key factors that may prevent a technological innovation from generating an initial slump in output. First, whenever a firm adopts a new technology, the extent to which its discarded factors of production are available on the used market is critical. If they are available for other firms to use, then only when the productivity of these factors is very heterogeneous across firms will the model generate a slump in output. Second, in many lot of industries, the intensity of capital use is a choice variable. When the discovery of a new technology announces an obsolescence of existing capital faster than expected, it provides incentives for a more intensive use of this capital, hence, generating a decline in output less than proportional to the decline in the capital stock.

Finally, the paper highlights a learning-by-doing externality which yields inefficiently slow diffusion of new technologies, independent of whether the effect on aggregate output is positive or negative.

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Figure 1: The Locomotive Revolution in the U.S.

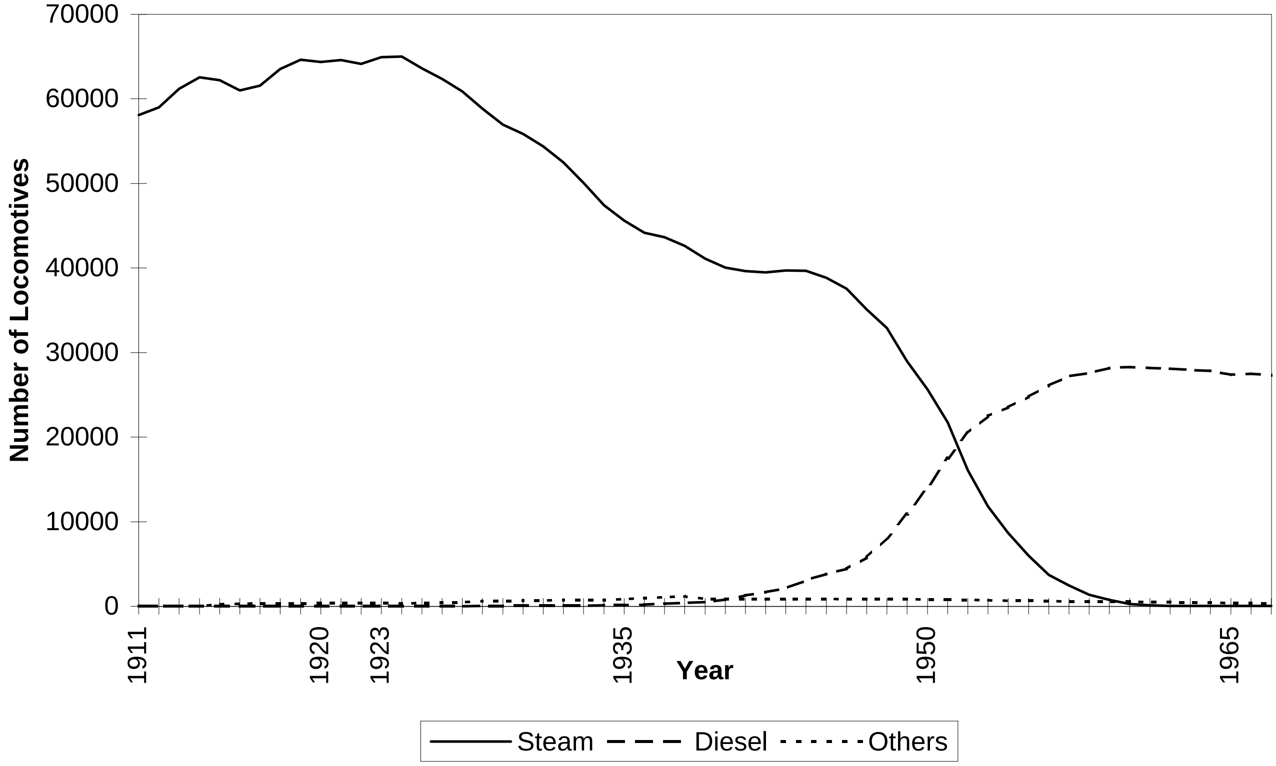
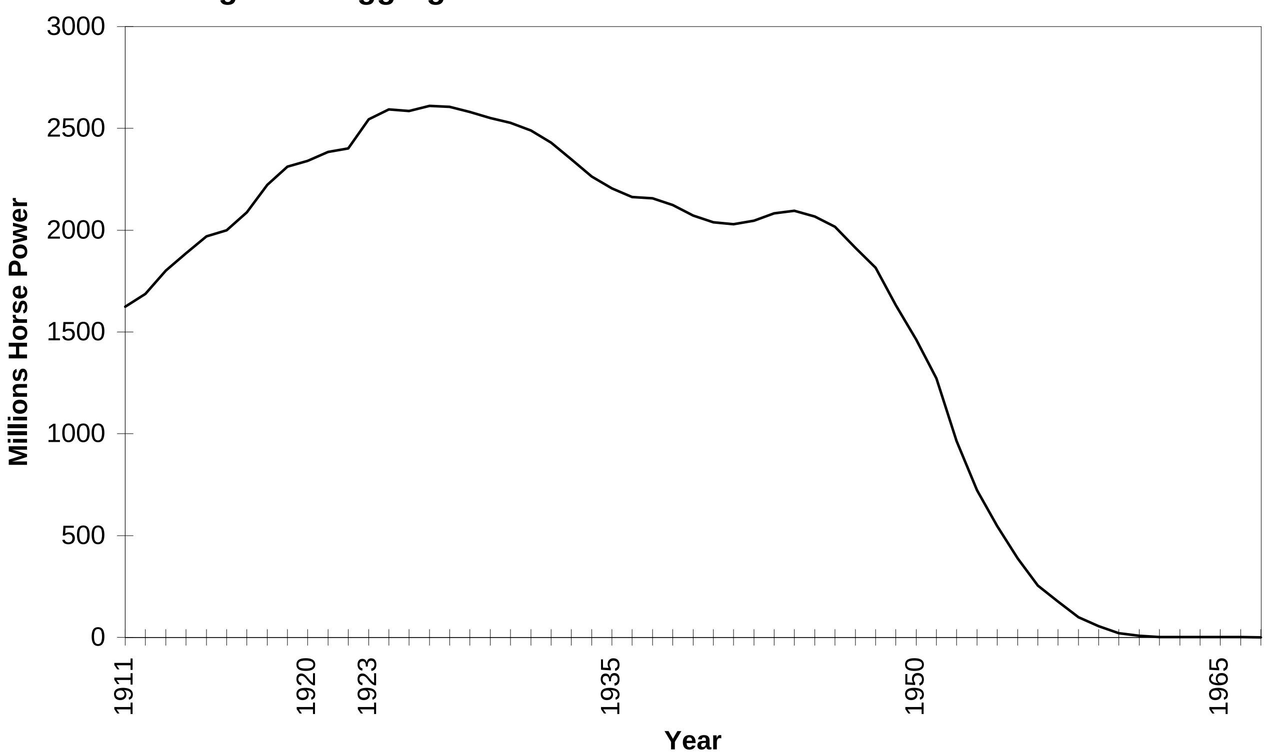


Figure 2: Aggregate Tractive Power of Steam Locomotives



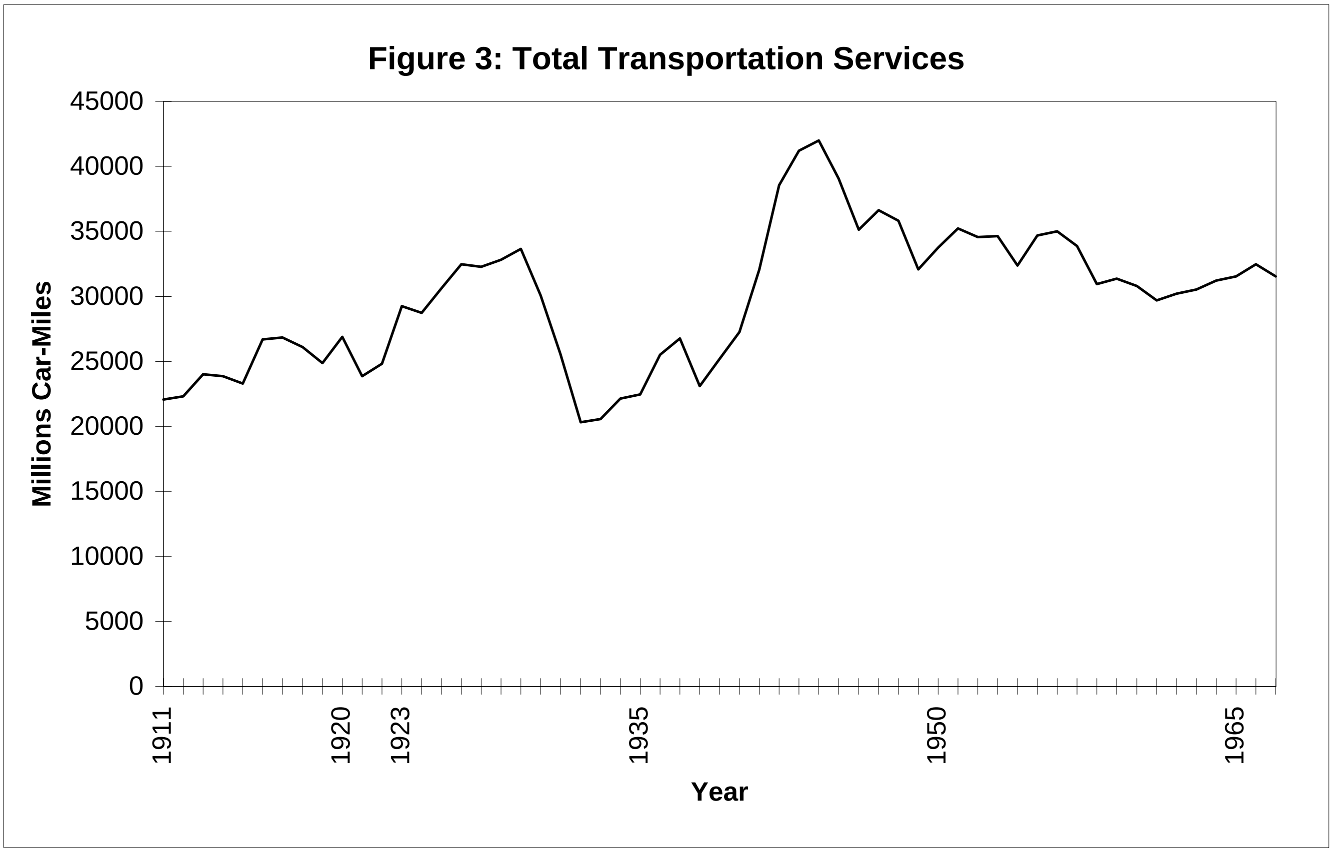


Figure 3: Total Transportation Services
Millions Car-Miles
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1911
1920
1923
1935
1950
1965
Year

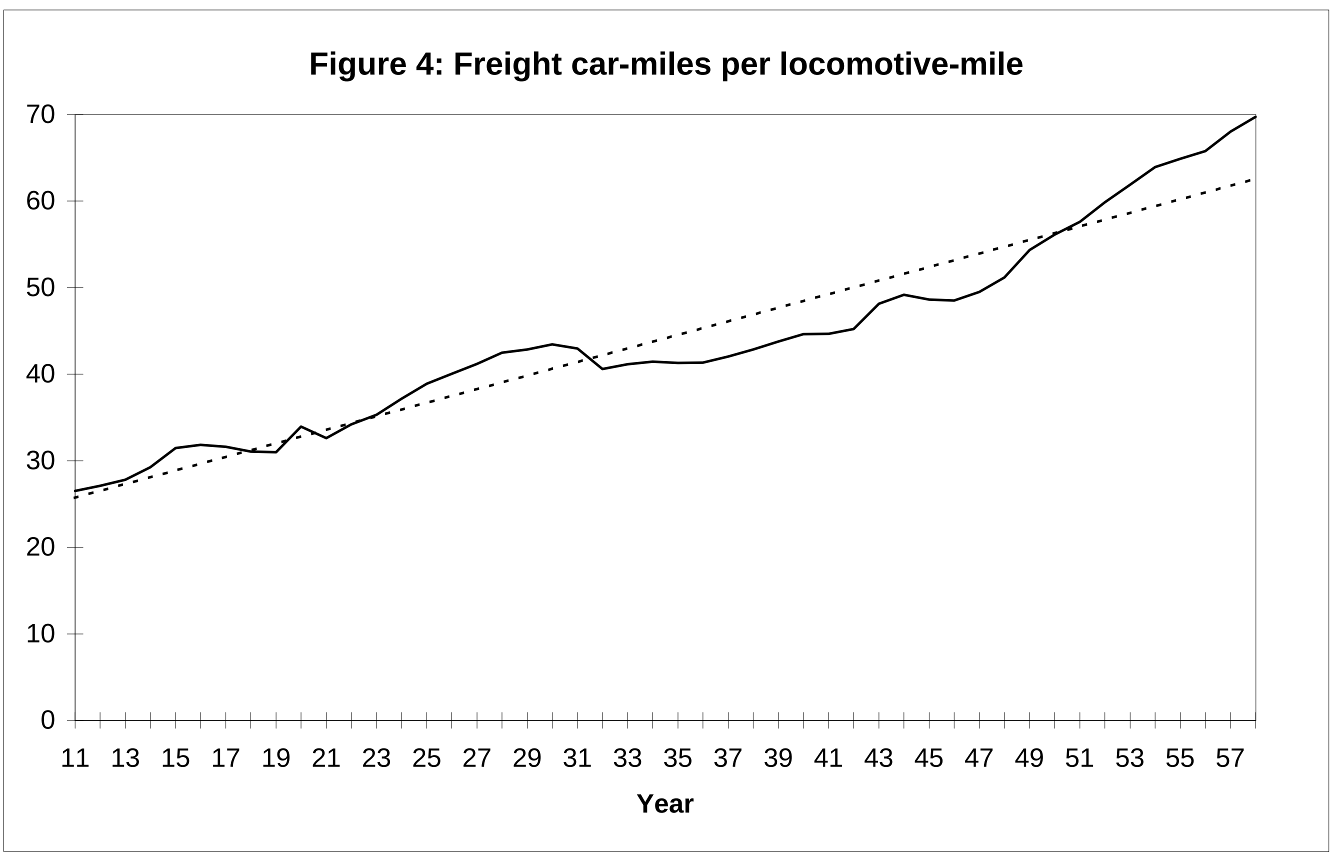


Figure 4: Freight car-miles per locomotive-mile
70
60
50
40
30
20
10
0
11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57
Year

Figure 5: U.S. Railroads Investments in Locomotives
Net changes during the year

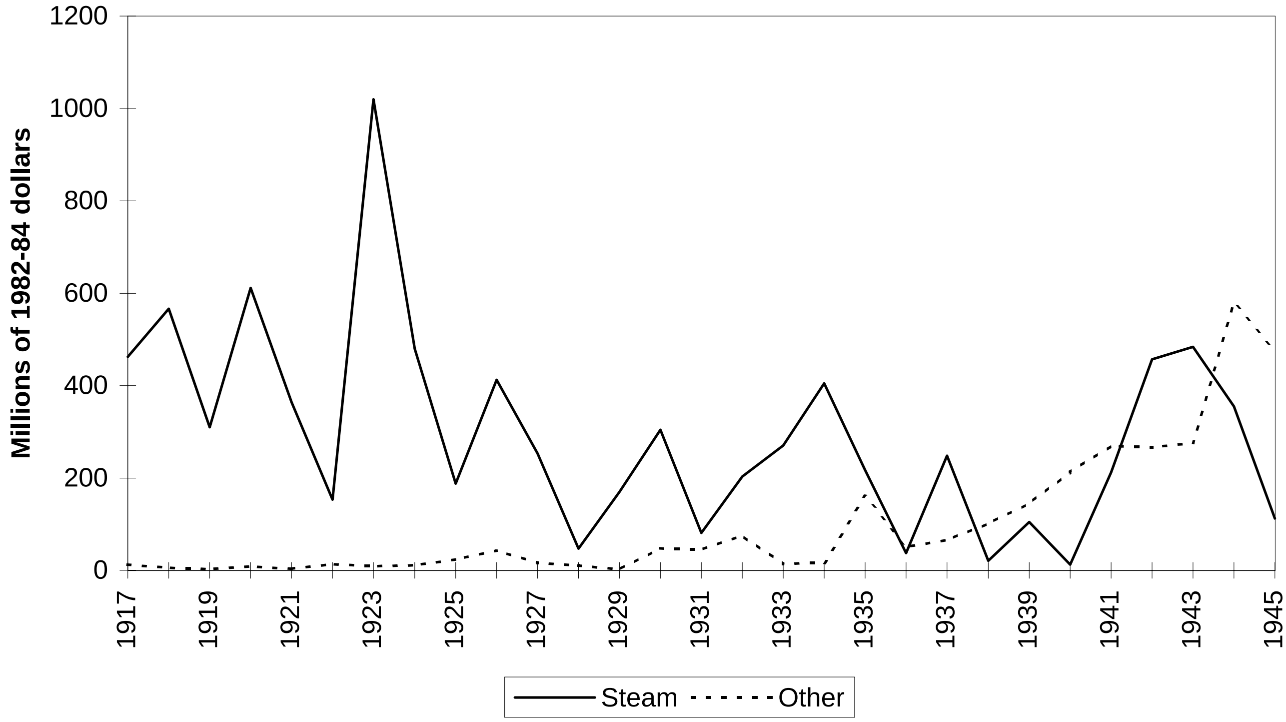


Figure 6: Basic Model
Output

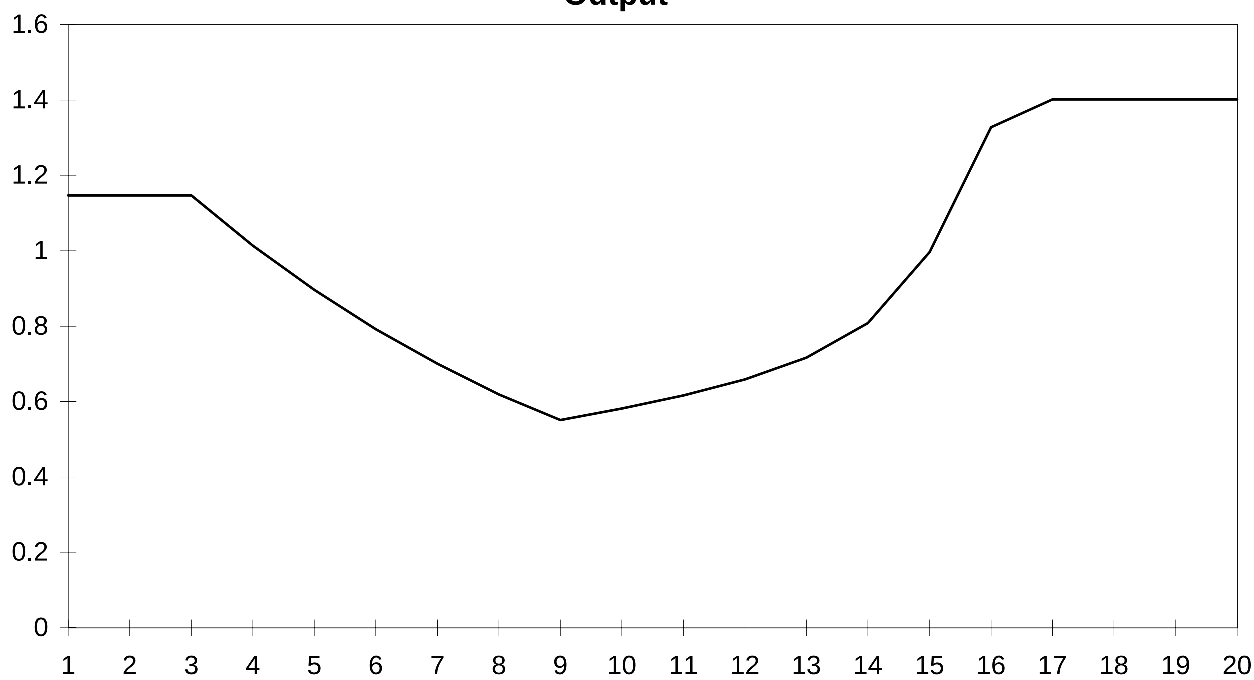


Figure 7: Basic Model
Stock of machines and intensity of use

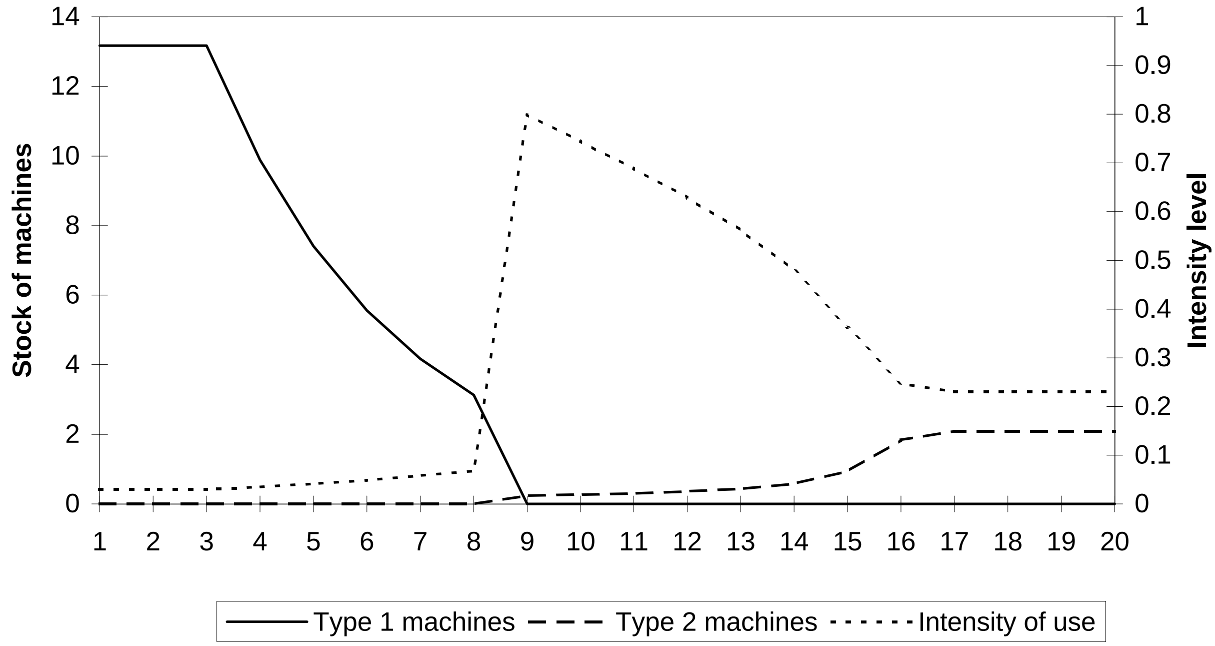
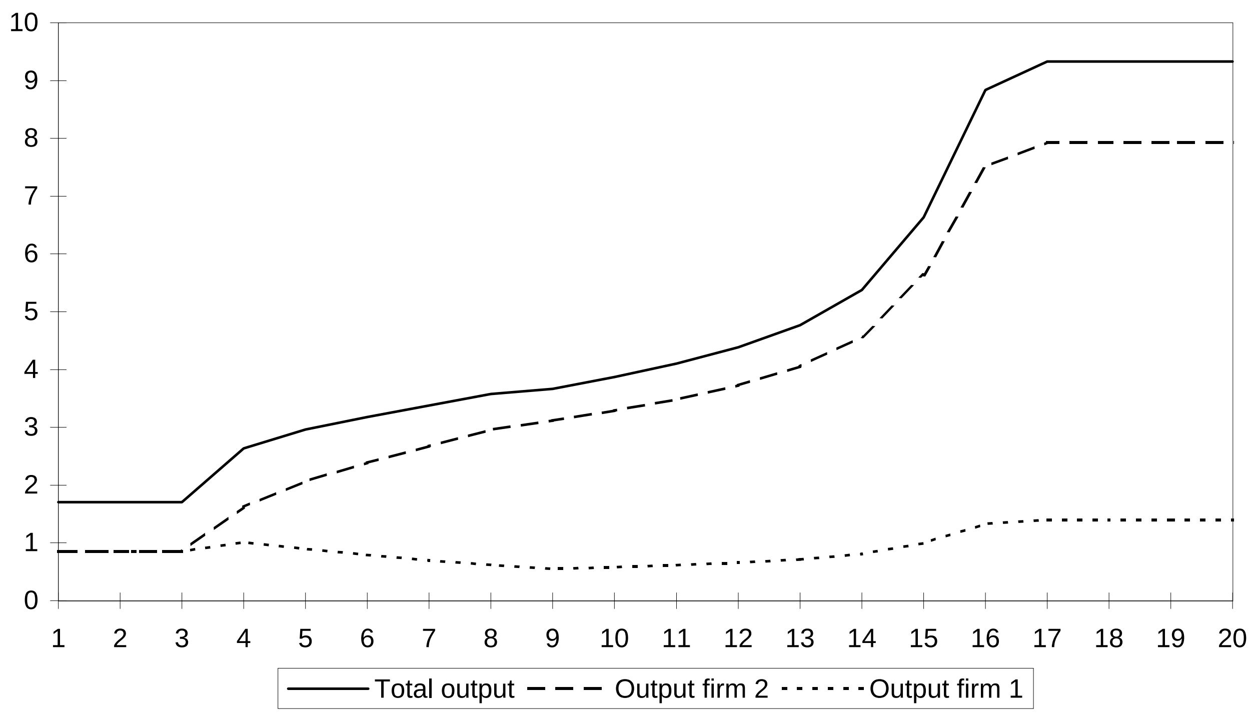


Figure 8: Endogenous machine production
Output



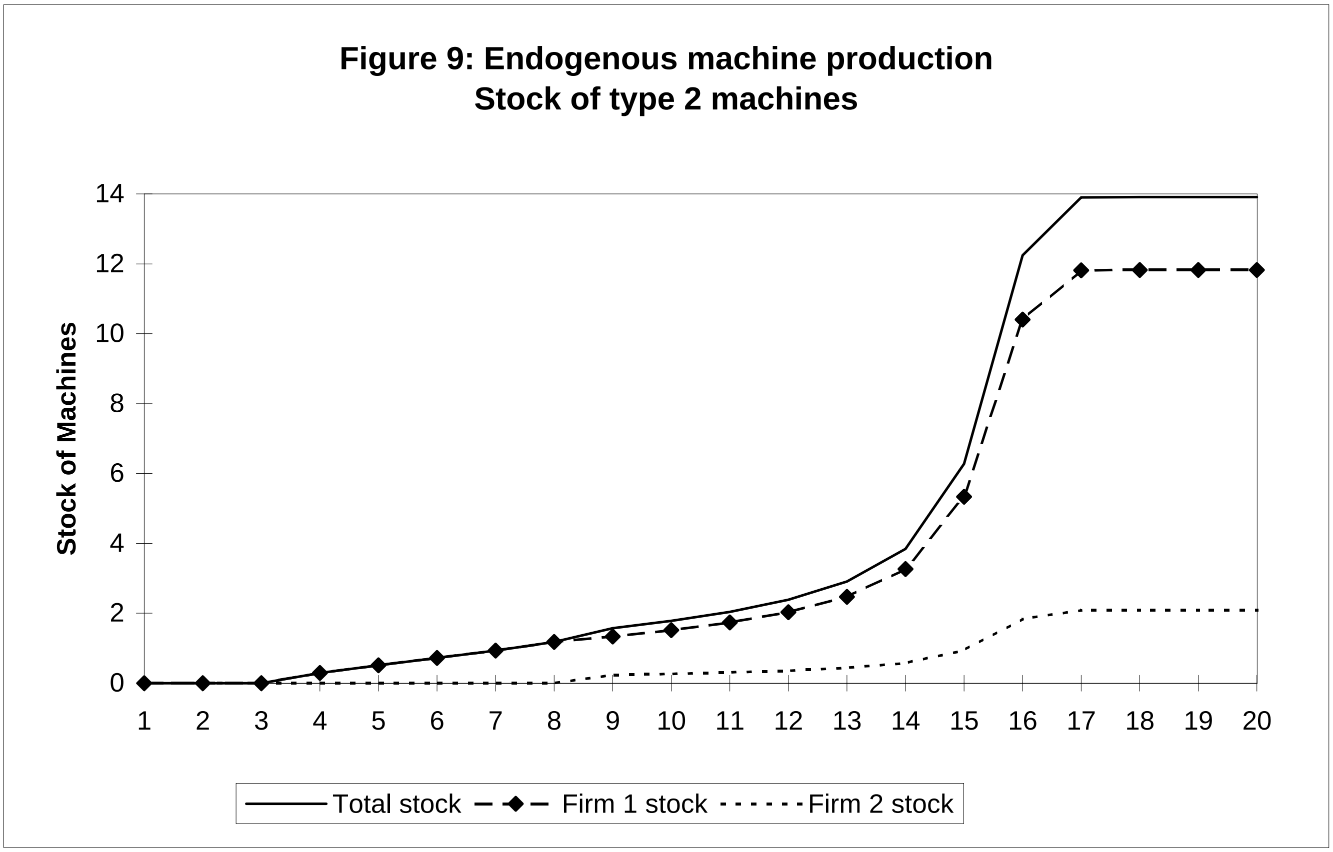


Figure 9: Endogenous machine production
Stock of type 2 machines
Stock of Machines
0
2
4
6
8
10
12
14
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Total stock
Firm 1 stock
Firm 2 stock

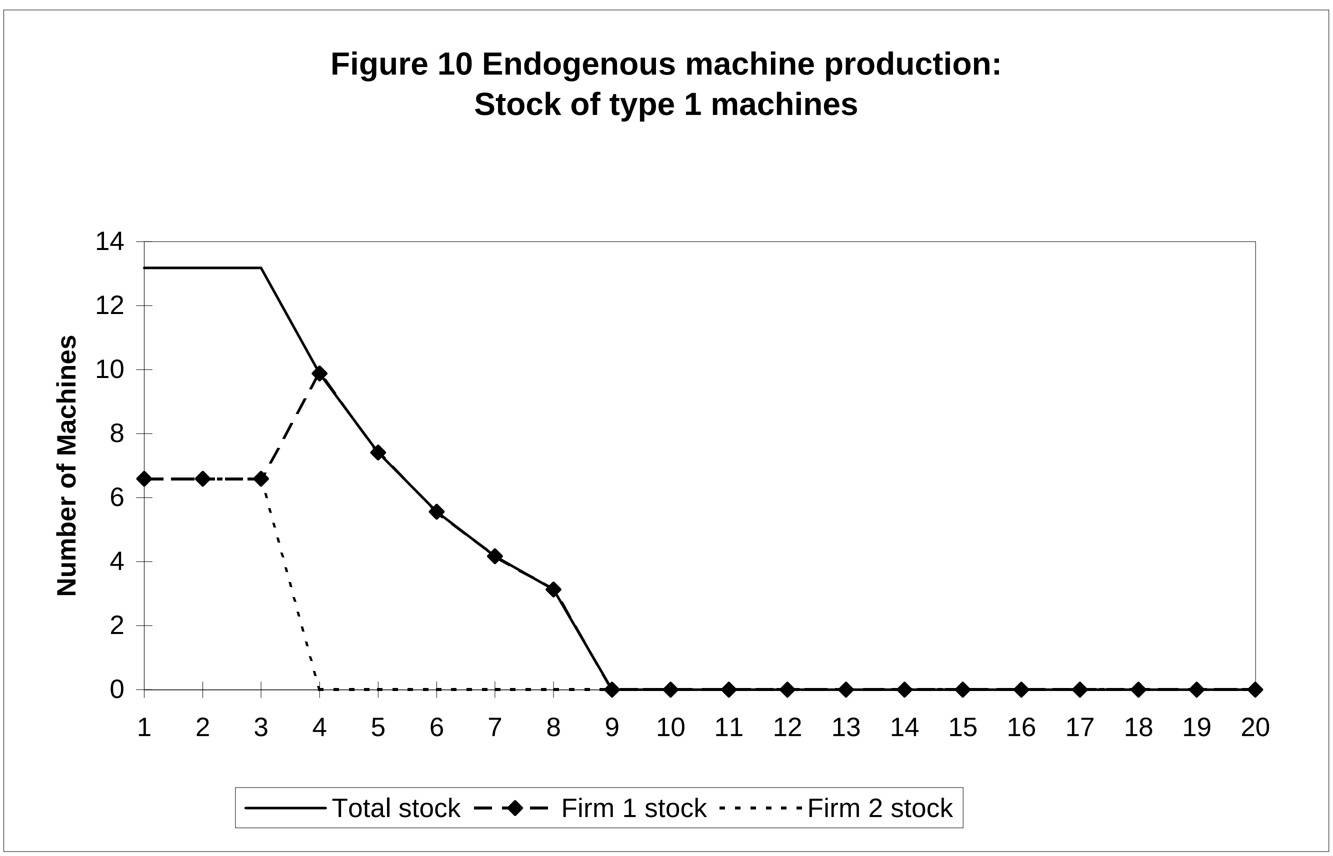


Figure 10 Endogenous machine production:
Stock of type 1 machines
Number of Machines
0
2
4
6
8
10
12
14
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Total stock
Firm 1 stock
Firm 2 stock