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Agglomeration Externalities and Productivity Growth: U.S. Cities in the Railroad Era, 1880-1930

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Abstract

We investigate the role of industrial structure in labor productivity growth in U.S. cities during the 'second industrial revolution'. We find that greater specialization was associated with faster productivity growth but that diversity only had positive effects in large cities. We interpret our results as demonstrating the existence of dynamic Marshallian externalities. Industrial specialization increased considerably in U.S. cities at this time, partly because of improved transportation which brought additional gains in labor productivity. Although this would augment the social savings from railroads, the magnitude is too small to undermine Robert Fogel's claim that his estimate is an upper bound.

Keywords: agglomeration externalities; industrial structure; manufacturing productivity; social savings

JEL Classification: N91; N92; O18; R12

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1. Introduction

In the last 20 years or so there has been a great revival of interest in the nature and extent of agglomeration economies that cities generate. The study of agglomeration externalities has developed so rapidly under the auspices of the new economic geography that major survey articles are frequently written (Rosenthal and Strange, 2004; Combes and Gobillon, 2014). Yet, remarkably little is known about the extent or nature of such externalities in U.S. cities during American industrialization (Kim and Margo, 2004).

Filling in this gap becomes all the more important when it is recognized that American cities were growing fast and the urban system was evolving rapidly around the time at which the United States overtook the United Kingdom to become the world's leading economy during the so-called 'second industrial revolution'. Between 1880 and 1920, the percentage of urban population rose from 28.2 to 51.2. Cities became larger; in 1880 there were 41 cities with population of 50,000 or more accounting for 14.3 per cent of the population but by 1920 this had risen to 144 cities with 31.0 per cent of the population. This became the era of large industrial cities (Kim, 2000). Cities also became more specialized as is epitomized by the examples of Akron, Ohio and Detroit.

In this paper, we examine the role of dynamic agglomeration externalities as a source of productivity growth in urban manufacturing. The idea is that the initial industrial structure of a city has impacts on subsequent productivity performance. This hypothesis has been supported in analyses of late-20th century American experience (Glaeser et al., 1992; Henderson et al., 1995). Two aspects of industrial structure are highlighted in this literature, namely specialization and diversity. A specialized industrial structure may promote intra-industry sources of increased productivity as envisaged by Alfred Marshall (1890) while a diversified structure could be conducive to productivity improvement arising from interactions between industries as proposed by Jane Jacobs (1969).

The size and industrial structure of cities is influenced by the costs of transporting goods and people. So, improvements in the railroad network could have the potential to generate additional agglomeration externalities. Such gains would be additional to those resulting directly from lower transport costs which are captured by the social savings of railroads in the tradition of Robert Fogel (1964). Fogel estimated the social savings on the basis of assuming that the demand for transport was perfectly price-inelastic which he claimed would deliver an upper-bound estimate. However, this is not necessarily true if there are external economies of scale in the transport-using sector depending, of course, on their magnitude.

The specific questions that we address through a detailed analysis of data in the Census of Manufactures are the following:

1) Did dynamic Marshallian and/or Jacobian agglomeration externalities raise labor productivity growth in American cities in the period between 1880 and 1930?
2) Were such externalities large enough to imply that conventional estimates of the social savings from railroads are possibly not an upper bound?

Our empirical strategy is to run regressions that relate labor productivity growth in manufacturing at the city-industry level during periods of between 20 and 50 years between 1880 and 1930 to measures of the degree of industrial specialization and diversity of urban economic activity while controlling for a wide range of variables relating to geography and state-level factor endowments. We have constructed a unique dataset derived from the Census of Manufactures for this purpose.

The main contributions of the paper are to establish the connection between specialization and diversity of industrial structure in early-20th century American cities and labor productivity growth and also to clarify and quantify the contribution that dynamic agglomeration externalities made to the social savings of American railroads. In particular, we report four main findings. First, we show that greater specialization was correlated with faster labor productivity growth in a city's industrial sectors. This effect is both economically and statistically significant. Second, we find that greater diversity of a city's industrial structure has a non-linear effect on productivity growth. For small cities, the effect is negative but at larger city size (bigger than Cleveland) the effect is positive. Third, we note that specialization in our sample of cities increased on average by about 25 per cent on our measure and that our regressions indicate that this would have had raised manufacturing labor productivity growth in our cities by 0.13

to 0.26 percentage points per year between 1890 and 1920. Fourth, we show that improvements in the connectivity of the railroad network which markedly reduced travel time and transport costs in the late nineteenth century facilitated increased specialization of cities. The productivity gains from this source that can be attributed to railroads are, however, very small at about 0.1 per cent of U.S. GNP in 1920. Such a small addition to the traditional social savings leaves intact Fogel's claim that his estimate is an upper bound.

The paper proceeds as follows. Section 2 presents a detailed account of the literatures on agglomeration externalities and social savings of railroads as it relates to our research. Our approach to estimation is set out in Section 3. Section 4 describes and summarizes the data. In Section 5, we present detailed econometric estimates. We discuss the economic significance of the results in Section 6. Section 7 concludes.

2. Agglomeration Externalties

The sources of agglomeration externalities can be categorized as sharing, matching and learning mechanisms (Duranton and Puga, 2004). Sharing mechanisms include sharing indivisible facilities, sharing the gains from a wider variety of input suppliers, sharing the gains from a finer division of labor, or sharing risks. Matching mechanisms include better expected quality and/or higher probability of matches especially between employers and workers in a larger labor market. Learning mechanisms relate to the diffusion and accumulation of knowledge including tacit knowledge which is enhanced by the proximity of other producers. These benefits of agglomeration may occur within industries or across sectors. The former can be thought of as localization externalities which accrue from specialization and the latter as urbanization externalities which stem from diversity of production. Conventionally, external economies from specialization are described as Marshallian (Marshall, 1890) while those from diversity are termed Jacobian (Jacobs, 1969).

Dynamic agglomeration economies result when initial conditions have a persistent impact on productivity growth, for example as technological spillovers or learning effects accrue. The general idea can be stated formally along the lines proposed by Combes and Gobillon (2014). Consider the case where log labor productivity ($y_{s,c,t}$) in a sector in a city at time t is a function of a fixed effect (α) and a static externality ($\beta_{s,c,t}$). Then

$$y_{s.c.t} - y_{s,c,t-1} = \beta_{s,c,t} - \beta_{s,c,t-1} \quad (1)$$

Dynamic externalities are introduced by assuming that for $t \geq 1$

$$y_{s,c,t} - y_{s,c,t-1} = \beta_{s,c,t} - \beta_{s,c,t-1} + \mu_{c,s,t-1} \quad (2)$$

where μ represents the impact of initial conditions on productivity growth between time t – 1 and time t. It can then be hypothesized that initial conditions are located in industrial structure such that μ is a function of specialization and diversity where the former is measured by the sectoral share of city employment and the latter is captured by a Hirschman-Herfindahl index of sectoral employment shares.

Empirical investigation of dynamic externalities in the new economic geography literature was pioneered by Glaeser et al. (1992) and Henderson et al. (1995). Both papers investigated the relationship between initial industrial structure and subsequent employment growth in U.S. cities in the later 20th century. Under reasonable assumptions, employment growth at the city-industry level will be correlated with productivity growth. The former paper found that diversity of employment but not specialization promoted industrial employment growth while the latter found that past employment concentration generated employment growth in mature capital goods industries but for new high-tech industries both diversity and specialization had positive effects. So there was some evidence in favour of both dynamic Jacobian and Marshallian externalities. A later paper by Cingano and Schivardi (2004) investigated a dataset for Italian firms in the 1980s and 1990s using an estimating equation derived from (2) in which the dependent variable was total factor productivity (TFP) growth rather than employment and found strong evidence in favour of a positive impact from specialization but could not reject the null hypothesis for diversity.

When we turn to the era of the late 19th and the early 20th century, evidence about agglomeration economies is thin on the ground, as is evident from the survey article by Kim and Margo (2004) which suggested that Marshallian externalities may have been important in the rise of American cities but noted that quantitative evidence on these externalities was not available. Kim (2006) showed that urban manufacturing firms had substantially higher wages, labor productivity and TFP than rural firms and that the wage premium increased considerably between 1850 and 1880. Simon and Nardinelli (2002) found that cities with occupational structures intensive in the use of human capital at the start of the 20th century experienced stronger employment growth in the decades through to the 1980s and suggested that this may have reflected knowledge spillover effects but did not provide evidence of externalities. On the other hand, Bostic et al. (1997) found no evidence that variables designed to capture 'urbanization', 'specialization' or 'localization' had a positive effect on labor productivity growth in American cities in the 1880s.

While cities can generate agglomeration economies, at the same time, increasing city size tends to raise congestion costs. Thus efficient city size decreases as commuting costs increase. If diversity does not offer agglomeration economies but specialization does, then diversity will undermine the realization of total agglomeration externalities by raising commuting costs for workers. Then, if final goods can be traded costlessly between cities, we would expect to see completely specialized cities whose size would depend on the extent of Marshallian externalities in their industry (Henderson, 1974). More generally, as transport costs decline and more final goods can be imported into a city, additional gains from increased specialization are possible (Abdel-Rahman, 1996). So, improvements in transportation which reduce the costs of commuting and trading tend to facilitate Marshallian externalities by permitting larger and more specialized cities.

One of the most famous episodes in cliometrics concerned the contribution of the railroads to nineteenth century American economic growth. The best-known study was by Fogel (1964) who pioneered the technique of social savings as a methodology. This is based on estimating the cost-savings of the new technology compared with the next best alternative. The saving in transport costs was also taken to be equal to the gain in real national income (Fogel, 1979, p. 3). The natural interpretation of the gain in real income obtained from reducing the resource costs of transportation is as an increase in TFP. However, equating the transport benefits to the users with total economic benefits to the economy is valid only if the rest of the economy is perfectly competitive with constant returns to scale (Jara-Diaz, 1986). Benefits from internal or external economies of scale in the transport-using sector mean that the economic benefits exceed the transport benefits, for example, as would be the case if the advent of railroads led to agglomeration externalities. David (1969) made essentially this point in a discussion of learning-by-doing and its possible implications for cost reductions in the transport-using sector.

Fogel (1964) calculated social savings of railroads were calculated as equal to $(P_{T0} - P_{T1})*T_1$ where P_{T0} is the price of the alternative transport mode, water, P_{T1} is the price of rail transport and T_1 is the quantity transported by rail. These were directly estimated for agricultural goods at 2.8 per cent of GNP in 1890 extrapolated to 4.7 per cent of GNP from freight transport overall.[1] Fogel deliberately intended this to be an upper-bound measure, constructed as if demand for transport was perfectly price inelastic, to compensate for omitted gains in the transport-using sector. Fogel accepted that his approach did not capture benefits arising from changes in the spatial location of economic activity or the scale effects discussed by David but, basing his analysis on the agricultural sector, he argued that the latter were smaller than the upward bias in his social saving estimate resulting from the assumption of a vertical demand curve for transport services and were at most equal to 11 per cent of the social saving compared with an upward bias of around 30 per cent (Fogel, 1979, p. 12, 44). Fogel did not, however, address similar issues relating to manufacturing or urbanization which is where agglomeration externalities may have been important.

This was unfortunate because important historical accounts of economic development in the railroad era have stressed these implications of the railroad network. Pred (1966) provided an interpretation of urban growth in the period as strongly influenced by declining transport costs which facilitated increased city specialization and likewise Chandler (1977) memorably saw the late 19th century as the point at which integration of the domestic market underpinned the beginnings of mass production

[1] Transport of passengers would raise the social saving estimate by a further 2.6% of GNP to a total of 7.3% according to estimates by Boyd and Walton (1972).

together with mass distribution. Recent advances in quantitative economic history have added to the plausibility of such claims. Atack et al. (2010) have estimated that more than half of mid-western urbanization in the 1850s can be attributed to the causal impact of railroad diffusion and Atack et al. (2011) found that the coming of the railroad was a causal factor in the rise of factories in 19th century American manufacturing.

No-one, however, has provided a serious quantification of the extent and nature of agglomeration economies or, indeed, the wider economic benefits of improvements in the transport system.[2]

3. Estimation Framework

The empirical literature on agglomeration economies has grown considerably over the past two decades, creating a pool of estimation techniques, regression specifications, and variables capturing the effects of agglomeration externalities.[3] We take advantage of this literature and choose an empirical specification which best suits our data. Specifically, we choose an estimation strategy linking labor productivity to measures of industrial specialization and industrial diversity used on numerous occasions to investigate the effect of dynamic Marshallian and Jacobian externalities on productivity growth; see, for example, Glaeser et al. (1992), Henderson et al. (1995), and Cingano et al. (2004). A simple model motivating our estimation strategy and offering guidance for our reduced-form regression analysis is discussed in detail in Appendix I. In a nutshell, it is a model of city-industry growth which incorporates dynamic local spillovers within and across industries. Specifically, dynamic agglomeration spillovers introduced by Glaeser et al. (1992) are incorporated into a simple model of city-industry labor productivity growth due to Combes et al. (2008) which matches our data best since it operates with value-added per worker.[4]

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[2] Donaldson and Hornbeck (2016) have recently revisited Fogel's agricultural social saving using a clever method to estimate the impact of railroads on the value of agricultural land which produces an implied agricultural social saving of 3.2 per cent of GNP in 1890 but, as they stress, this approach does not encompass impacts on the manufacturing sector.

[3] It is beyond the scope of this paper to provide a comprehensive review but one can be found in Combes and Gobillon (2014).

[4] We do not use total factor productivity as our dependent variable because (i) US Census of Manufactures in 1930 did not report estimates of city-industry capital stock, and (ii) city-industry capital stock figures in 1880and 1920 are of very low quality.

We specify the regression equation as follows:

$$ln(y_{c,s,t+m}) - ln(y_{c,s,t}) = \alpha + \beta_1 SPEC_{cst} + \beta_2 DIV_{cst} + \beta_3 X_{cst} + \theta_c + \lambda_s + \epsilon_{cs} \quad (3)$$

where $y_{c,s,t}$ and $y_{c,s,t+m}$ is value-added per worker in industry *s*, city *c*, and time *t* and *t+m* respectively, $SPEC_{cst}$ and DIV_{cst} are variables capturing specialization and diversity in industrial structure, X_{cst} is a vector of controls, λ_s is a vector of industry dummies to control for unobserved industry-effect, and θ_c is a vector of city dummies to control for any unobserved city-effect to avoid omitted variable bias.[5] The error term is expressed as $\epsilon_{cs} = \epsilon_{cst+m} - \epsilon_{cst}$. This regression specification thus expresses the growth rate of value-added per worker in an industry *s* in a city *c* in a period from *t* to *t+m* (for example between 1890 and 1920) as a function of specialization and diversity obtaining in industry *s* and city *c* in the initial period *t*, capturing thus the dynamic effect of *initial* industrial specialization (conducive to Marshallian externalities) and diversification (conducive to Jacobian externalities) in city *c* on subsequent productivity growth.[6]

Before discussing how we estimate equation (3) and estimation issues which arise, we define the variables to measure specialization and diversity. In so doing, we are guided by Combes (2000) and Cingano and Schivardi (2004). The degree of specialization is defined as:

$$SPECR_{cs} \equiv (L_{cs}/L_c) \qquad (4)$$

where $L_{c,s}$ is employment in sector *s* and city *c*, and L_c is the total employment in city *c*. Diversity is captured by the degree of industrial sector variety outside sector *s* in the city which is expressed using a Hirschman-Herfindahl index and defined as:

$$DIV_{CS} \equiv \Sigma_{j \neq s} \left(\frac{L_{cj}}{L_c - L_{cs}}\right)^2 \qquad (5)$$

[5] The vector of controls includes initial period value added per worker of industry *s* in city *c*, and share of manufacturing employment in the state where the city is located.
[6] We would like to stress that this is a reduced-form rather than a structural analysis.

The value of the index is 1 if employment outside industry s is concentrated in a single sector, and $1/DIVc$ if employment outside industry s is uniformly distributed across other sectors.[7]

Equation (3) will be estimated for the periods 1880-1920, 1880-1930, 1890-1920, 1890-1930, and 1900-1920, 1900-1930.[8] In the first instance, we estimate regression equation (3) by OLS but there are econometric issues to be addressed. First, the errors, $\epsilon_{cs} = \epsilon_{cst+m} - \epsilon_{cst}$, could be correlated within cities as well as industries. Therefore, we use the two-way clustering method of Cameron et al. (2011). Second, unobserved factors contained in the error term, $\epsilon_{cs} = \epsilon_{cst+m} - \epsilon_{cst}$, may bias the estimates of Marshallian and Jacobian externalities. Two sorts of biases can be imagined. First, there might be other factors which influence Marshallian and Jacobian externalities, and are correlated with the value-added growth rates but which are not controlled for by X_{cst}. We believe that we control adequately for unobserved effects using industry and city dummies. Second, firms might partially predict $\epsilon_{cs} = \epsilon_{cst+m} - \epsilon_{cst}$ and relocate in anticipation. For example, if $\epsilon_{cs} = \epsilon_{cst+m} - \epsilon_{cst}$ includes specific long-run changes in technology, then a city that has an initial industrial structure which is more conducive to technological change might *systematically* attract firms. This would, as a result, make the initial industrial composition of cities – and our Marshallian and Jacobian externalities – potentially endogenous. While, the historical circumstances of the decades 1880-1930, the so-called 'second industrial revolution', make us believe that this was not the case, nevertheless, as a robustness check, we also estimate (3) using instrumental-variables methods.

4. Data

We created a unique data set of SIC 3-digit city-industry real value added per worker, sectoral specialization, industrial variety, and U.S. state-level employment at SIC 2-digit level in the period 1880-1930. The data come from several sources. City-industry nominal value-added, number of

[7] In the regression analysis, we use a logarithmic transformation of *DIV* which allows us a very useful measure of the percentage change in diversity. The literature sometimes uses the log of the diversity index (Combes, 2000) and sometimes an index without logarithmic transformation (Henderson et al., 1995; Cingano and Schivardi, 2004). As a robustness check, we performed the regression analysis without the logarithmic transformation of the diversity index and the results (available from the authors upon request) were qualitatively similar.

[8] We do not use the data from the Census of Manufactures in 1910 because its quality is inadequate for the reconstruction of reliable SIC 3-digit level industrial groups.

workers, sectoral specialization, and industrial variety are drawn from the U.S. Census of Manufactures and the aggregation of individual industries at the three-digit level follows the standard industrial classification.[9] U.S. state-level employment at SIC 2-digit level in 1880-1920 comes from Klein and Crafts (2012), supplemented by data from the 1930 U.S. Census of Manufactures. The aggregation of individual industries at two-digit level again follows the standard industrial classification. We use the wholesale price index offered by the U.S. Historical Statistics Millennial Edition, series Cc-126 to calculate city-industry real value-added.[10]

The U.S. Census of Manufactures, while an excellent and unique source of city-industry level data, is not without its challenges. First, the 1880 census reports the number of workers and not the number of employees which begins only in 1890. Therefore, we use the number of workers to be consistent over the entire period 1880-1930. Second, value added, as reported by the census in 1900, 1920, and 1930, does not exclude some of the costs.[11] Therefore, we calculated value added by subtracting all the costs from the reported gross value of output. Third, the number of cities included in the censuses changes over time.

Table 1 shows the distribution of the cities in our sample across time and U.S. regions. We see that the 1900 Census of Manufactures contains the most comprehensive information on U.S. cities. Most of the cities come from the New England, Middle Atlantic and East North Central regions, reflecting the dominant position of those regions in American economic development at the turn of the twentieth century. Table 2 presents the number of matched cities across the periods of our interest. Two points are worth mentioning. First, we see that the number of cities which can be consistently followed over time increased between 1880 and 1900. Second, there is a drop in the number of cities reported in the

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[9] The assignment of individual industries into each SIC 3-digit level category is available from the authors upon request.

[10] We have also used the wholesale price indices at SIC 2-digit level offered by Cain and Paterson (1981). Their indices, however, run only up to 1919, and so we use them as a robustness check for the regressions of 1880-1920, 1890-1920, and 1900-1920.

[11] Rents for offices are excluded in 1900 and 1920, value of fuel in 1930.

1920 and 1930 Census of Manufactures resulting in fewer cities which can be followed up to 1920 and 1930, respectively.

There are two ways to deal with the changing number of cities. We can create a sample of only those cities for which the census consistently provides data in every period we analyze. This would give us a dataset with the same cities throughout. Alternatively, we can use all the cities provided by the census and have a different number of cities in each period we analyze. We do both. Analyzing the latter data set, however, brings up the issue of how to compare the results across different periods. For example, the results for the period 1890-1920 can be different from 1880-1920 because, in addition to the cities which were in the 1880-1920 sample, we have 'new' cities entering the sample of 1890-1920 as well as cities exiting from the 1880-1920 sample.

We do not think that the changing number of cities across periods is the result of sample selection. It is highly unlikely that the changing number of cities had anything to do with unobserved factors which might be correlated with labor productivity growth since decisions to include new cities in the census were driven by the capabilities and financial resources of the Census Bureau. However, it will be useful to see what kind of cities were entering and exiting the sample in the period of 1880-1900 and stayed there until 1920 and 1930, respectively. There was only one town which was present in 1880 but not after, namely, Saint Louise, Maine and two towns were present in 1880 but not in 1900, namely, Saint Louise, Maine, and Washington DC. As for 1890, there are only two towns present in 1890 but not in the 1900 census: Lincoln, Long Island, and Long Island City. The cities which entered the sample in 1890 and 1900, and stayed there until 1920 and/or 1930 were mostly small and medium size towns except for St. Louis, Akron (Ohio), Portland (Oregon), Seattle, and Los Angeles which entered the sample in 1890. As for the degree of industrial specialization and industrial diversity, cities entering the sample in 1890 are not, on average, different from the cities already in the sample. Cities entering the sample in 1900 are slightly more specialized and slightly less diversified. We believe, however, that this will not bias our results since there are only 9 new cities entering the sample for 1900-1920. Nevertheless, we conduct a series of robustness checks in the next section.

As we have seen in Table 2, it is a feature of the Census of Manufactures in 1930 that fewer cities were included in the census relative to the earlier censuses. As a result, our sample of cities in the period ending in 1930 drops relative to the one ending in 1920. Again, this was due to the resources of the US Census Bureau so that it is very unlikely that there would be any kind of systematic relationship between the change in the sample size and the growth of labor productivity of cities and we do not need to worry about sample-selection bias. The towns which dropped out of the sample (but were present until 1920) were mostly smaller towns with an average population of about 40,000, together with two large cities: Omaha and Milwaukee. As for the degree of industrial specialization and diversity, these towns are, on average, more specialized and less diversified than those which remained in the sample. Again, we believe that this will not materially affect the overall results; nevertheless, we conduct a series of robustness checks in the next section.

The period 1880 to 1930 witnessed the 'second industrial revolution' and our data set reflects that. Table 3 presents the average share of employment in selected SIC 3-digit level traditional and modern industries in 1880 and 1930, respectively. We see a clear trend: traditional industries such as textiles (SIC 223 and 225) or leather (SIC 313 and 319) are declining while modern industries such as chemicals (SIC 291 and 287), electrical industries (SIC 362 and 364) and car manufacturers (SIC 371) are rising.[12] Table 4, which shows the fastest- and the slowest-growing industries in U.S. cities, corroborates these results. We see that chemicals, steel, and industries producing instruments and devices were among the fastest growing while food processing, leather, or printing were among the slowest. Of course, Tables 3 and 4 present unconditional averages, and the year 1930 reflects the beginnings of the Great Depression which might bias the productivity growth figures downward. Nevertheless, they provide a clear picture of the increasing dominance of modern industries.

Since this paper focuses on dynamic Marshallian and Jacobian agglomeration economies, it is interesting to see which industries were found in the most specialized and the most diversified industrial

[12] US Census of Manufactures contains an industrial category called 'All other industries' which contains all industries which were not reported separately to prevent the disclosure of individual firms. We coded that as SIC 399 – Miscellaneous industries. We performed a robustness check and conducted the entire analysis with and without those industries. The results are qualitatively unchanged.

environments. We take the index of specialization for each city to be the average *SPEC* score for its industries and likewise the index of diversity to be the average *DIV* score for its industries. Table 5 presents the top five and the bottom five industries according to the average specialization and variety indices that they faced across all cities in 1880, 1900, and 1930.

We see in Panel A that traditional industries, such as textiles, were in cities of high specialization, though by 1930, this was also true of modern industries such as petroleum refining and motor vehicles, reflecting increased concentration of those industries in cities (e.g. motor vehicles in Detroit). On the other hand, modern industries such as chemicals and household appliances were located in cities with a diversified industrial structure. This is confirmed when looking at Panel B which shows that modern industries such as plastic materials or household appliances were in cities with the highest variety index while traditional industries such as textiles, food, or the leather industry were in locations with the lowest variety index. It is interesting to see, however, that by 1930, some of the modern industries such as aircraft were located in the cities with a low variety index, indicating that they had become highly specialized.

Figure 1 graphs city populations against their specialization index and to a first approximation this shows that the smallest cities were the most specialized. On a closer look, the relationship, however, is a bit more complex. Indeed, at the lower end of the spectrum, with population up to about 50,000, there were both quite specialized as well as quite diversified towns. For example, in Hamilton, Ohio, population 23,914 in 1900, almost 50 percent of all workers worked in iron and steel foundries; or in South Omaha, Nebraska, population 26,001 in 1900, 89 percent of all workers worked in the slaughtering and meat packing industry. On the other hand, there are towns such as Racine, Wisconsin, population 29,102 in 1900, in which no industry was dominant (21 percent in agricultural implements, 19 percent in the production of carriages, wagons, and bicycles, 12 percent in leather, 8 in metal products, and 8 percent in primary metal production). Then, as city population increases, the degree of industrial specialization declines rather rapidly in a curvilinear fashion, until specialization does not vary with the size of the cities.

Figure 2 shows that there seems to be a positive relationship between the city size and industrial diversity. However, that relationship is, again, not linear, but this time seems to be concave. As with Figure 1, up to a population of about 50,000 there were both highly diversified towns as well as more specialized towns. Then, as population increases, cities become more and more diversified.[13] Even so, a clear outlier is Pittsburgh, where, even though it was one of the largest cities with population of 451,512 in 1900, the dominant industry was iron and steel with about 35% of city's employment. Cleveland can also be considered as an outlier with the iron and steel industry being the largest in the city.

Figure 3 offers a comparative perspective on the relationships between city size and specialization, and between city size and variety over the years 1890 through 1920. In the former case, the fitted curve shifts out appreciably after 1900 so that the degree of specialization for a given population was increasing over time. Not surprisingly, in the latter case, the fitted curve shifts in quite considerably so the degree of diversification for a given population was decreasing over time. Detroit is a well-known example of this process, having been a city of diversified industrial composition before becoming a highly specialized city with a dominant car industry by 1920.

A first look at the relationship between labor productivity of manufacturing industries and the specialization and variety indices is provided in Figures 4 and 5, respectively. These figures show that, while the average labor productivity in a city was positively related to the level of industrial specialization of the city, there seems to have been a convex relationship between the index of variety of manufacturing industries and their productivity. This is indeed an interesting relationship and, to our knowledge, it has not previously been observed in the literature. The convexity in Figure 4 implies that to enjoy Jacobian externalities required location in a large city and that the benefits of agglomeration were lower than their costs in the cities in the middle of the diversity spectrum. We shall see in the next section whether this convex relationship also emerges in a regression framework.

[13] For presentation purposes, Chicago, Philadelphia, and New York City were excluded from Figures 1-2 because their population is more than three times larger than the population of the fourth largest city – St. Louise. Similarly, the city of Spokane was excluded from Figures 4-5. The qualitative features of these figures, however, are not changed. Figures including all cities are available from the authors upon request.

5. Empirical Results

The results of the OLS estimation of equation (3) are presented in Tables 6, 7, and 8. In addition to the main variables of interest — *SPEC* and *DIV* which capture aspects of industrial structure conducive to Marshallian and Jacobian externalities, respectively — the regression controls for city and industry fixed effects, beginning-of-period value-added per worker, and beginning-of-period share of state-level employment in the U.S. total for the corresponding SIC-2 digit level. This last is used to control for the presence of spatially correlated omitted variables operating at the state-level and also at the higher level of industrial aggregation. For example, there might be state-specific effects influencing city-industry productivity not controlled by city-industry dummies, for example, from state-specific factor endowments. Controlling for industry-specific effects at the higher-level industrial classification is important because there might be spillovers operating within industry groups. For example, labor productivity of industries producing transportation equipment could be influenced by unobserved industry effects specific to the transportation industry; hence our decision to control for industry employment at SIC 2-digit level. We have also estimated equation (3) with city latitude and longitude, access to waterways, lakes, and oceans, distance to New York City, temperature, share of state-level employment in mining, state-level prices, and share of state-level skilled occupations.[14] The results for the main variables of interest were unchanged, reassuring us that our estimates of Marshallian and Jacobian externalities are not affected by geography and state-level factor endowments.

Table 6 shows that average annual labor productivity growth is positively related to *SPEC* and negatively to *DIV*. The positive Marshallian relationship is statistically significant in all periods but 1890-1930 while the negative Jacobian relationship is significant in all periods but 1880-1930 and 1890-1930. A test of joint significance of *SPEC* and *DIV* is significant in every period but 1880-1930. As for the remaining regressors, the share of state-level SIC 2-digit level employment is not significant whereas value-added per worker at the beginning of the period is significant and negative, indicating a β-type convergence among SIC 3-digit level industries.

[14] The results are available from the authors upon request.

Table 7 adds DIV^2 to the estimating equation to investigate the possibility of a quadratic relationship between average annual labor productivity growth and diversity. The results show that the relationship is convex and that a positive effect is only found for large cities, as suggested by Figure 5. For example, in the estimation for 1890-1920, the city at the lower turning point is Detroit and those to the right of this include Boston, Chicago, New York City, Philadelphia, and San Francisco while those not big enough to enjoy positive dynamic Jacobian externalities include Baltimore, Denver, Minneapolis, and Washington DC. These results also have implications for the well-known analysis of American economic growth in Lucas (1988) which emphasized the importance of Jacobian externalities as an engine of growth. To an extent, our findings provide support for this hypothesis during the period of the second industrial revolution. The key point that stands out, however, is that these externalities from diversity were not generated by urbanization generally but accrued in the really large cities of the United States. If Lucas's vision is correct, the basis for it would be the economic activity of Chicago and New York rather than Denver and Minneapolis.

This relationship is not significant in the periods 1880-1930 and 1890-1930, although all industrial structure variables are jointly significant (in the period 1880-1930 marginally at 13%). We should be cautious about this insignificance since it may reflect failure of the Census to collect information on small and medium-sized towns so that there is insufficient variation in the data capturing the left part of the convex curve. Further investigation of this relationship using a semi-parametric technique which gives some support to positive Jacobian externalities for industrial diversity indices greater than 2, which are generally found in relatively large cities, is reported in Appendix II.

As we discussed in the previous section, the number of cities changes across periods under consideration. Even though the cities which enter our sample in 1890 and 1900 are not very different from the cities already in the sample, and the results are robust across all six periods, their inclusion might raise an issue of the comparability of the results between 1880, 1890, and 1900. Therefore, Table 8 presents the estimation results when we keep the number of cities constant over time. The first four columns show the results for the periods starting in 1890 and 1900 and only for the cities of the 1880 Census of Manufactures; the last two columns for the periods starting in 1900 and only for the cities of the 1890 Census of Manufactures. We see that the results are consistent with the results in Table 6 and 7, and the only difference is for the period 1890-1920 in which DIV^2 loses conventional statistical significance, although the joint significance of the linear and quadratic terms is highly statistically significant.

Overall, it is clear that there is strong evidence that *SPEC* has a positive impact on labor productivity growth in manufacturing in our sample of cities during the early 20th century. This result which indicates that dynamic Marshallian agglomeration externalities were obtained is consistent with the findings of the literature on the late 20th century reviewed above. For the 1890-1920 sample, the difference in predicted labor productivity growth from these Marshallian externalities between the 25th and the 75th percentile city is 0.09 per cent per year. The evidence on dynamic Jacobian externalities is, however, altogether more mixed, as one might also expect. On balance, we believe that there is some support for a positive impact of industrial diversity at high values of *DIV* but that this was most likely to be found in large cities whereas in smaller cities it is likely that diversity had a negative impact on productivity growth. For the 1890-1920 sample, the difference in predicted labor productivity growth from Jacobian externalities between the 25th and 75th percentile city is 0.119 per cent per year (from -0.086 to + 0.033).

For OLS to be consistent there must be no link between factors which affect initial industrial structure and general improvements that affect future industrial productivity. We believe that the history of technological progress makes this a plausible assumption. Technological progress accelerated at this time but its progress was quite erratic and the development of new technologies and industrial locations was unpredictable. This is epitomized by the history of the automobile. Automobile registrations rose from 8000 in 1900 to 23 million in 1930 but at the start of the 20th century the future had appeared to be steam-powered cars rather than the internal combustion engine. Detroit would become the center of car-making industry and was home to more than 50 per cent of producers by the mid-1930s but, in the early years of the industry, none of 69 car manufacturers entering the market between 1895 and 1900 located in Detroit (Klepper 2010).

The process of technological change was characterized by creative destruction in an economy where barriers to entry and exit were relatively low. There were many clusters and multiple sources of technological progress but advance was quite uneven. Estimates of TFP growth in Kendrick (1961) are 2.0 per cent per year in the 1880s, 1.1 per cent in the 1890s, 0.7 per cent in the 1900s, 0.3 per cent per year in the 1910s, and 5.3 per cent in the 1920s. It took 40 years after the commercial generation of electricity to work out how to transform many American factories through electrification in the 1920s (David, 1991). New industries (entertainment, electric utilities, and transport equipment) averaged the highest TFP growth rates over these decades but, at the industry level, rank correlation coefficients between decadal rates of TFP growth were very low – 0.4 between the 1900s and 1910s, 0.0 between the 1910s and the 1920s, and 0.2 between the 1920s and 1930s and there were spectacular jumps in sectoral rankings; for example, chemicals rose from 33rd to 4th and petroleum & coal products from 35th to 1st between the 1910s and the 1920s (Bakker et al., 2015).

Our first instrumental variable estimation strategy is based on a widely-used shift-share instrument introduced by Bartik (1991). The Bartik-type instrument constructs an exogenous source of variation of employment in a local geographical area based on national employment growth at the industry level to create an instrument for the industrial composition of cities. In so doing, it isolates the exogenous variation in local labor demand coming only from national shock in each manufacturing sector, thereby removing potentially endogenous local labor demand shocks that might be driving local employment levels (in our case city employment levels). We construct this instrument in two steps. In the first step, we predict city-industry level of employment by interacting city industrial composition at time *t* with national industry-level employment growth over the period from *t* to *t+m*. Specifically, we calculate the level of employment for industry *s* in city *c* in period *t+m* as

$$l_{cst+m}^{predict} = l_{cst}\left(\frac{l_{st+m}}{l_{st}}\right) \qquad (6)$$

where the employment in city *c* and industry *s* at time *t* – l_{cst} – is multiplied by the employment growth of that industry at the *national* level between time *t* and *t+m*. In the second step, we then use the predicted values of employment to calculate the instruments $IVSPEC_{cs}$ for initial specialization and $IVDIV_{cs}$ for initial diversity:

$$IVSPEC_{cs} \equiv (L_{cs}^{predicted}/L_{c}^{predicted}) \qquad (7)$$

$$IVDIV_{CS} \equiv \sum_{j \neq s} \left(\frac{L_{cj}^{predicted}}{L_{c}^{predicted} - L_{cs}^{predicted}} \right)^2 \qquad (8)$$

As a result, we have instruments for the periods 1890-1920, 1890-1930, 1900-1920, and 1900-1930. Unfortunately, the census does not provide city-industry employment in 1870 so we are unable to use this method for sample periods beginning in 1880.

Fortunately, our second strategy does not require these 1870 data. This allows us to conduct instrumental-variables estimation for periods starting 1880 and also permits us to examine the robustness of Bartik-type instruments. This method is based on an approach suggested originally by Durbin (1954). Here the city-industry values of *SPEC* and *DIV* are ranked nationally. The rank-based instrument is constructed using a rank function which takes the value of the rank of variable *x*. In our case, we order the values of city-industry $SPEC_{cs}$ and DIV_{cs} variables and assign their respective *national* rank values:

$$IV\_RANK\_SPEC \equiv RANK(SPEC_{cs}) \qquad (9)$$

$$IV\_RANK\_DIV \equiv RANK(DIV_{cs}) \qquad (10)$$

where $RANK(SPEC_{cs})$ and $RANK(DIV_{cs})$ are rank functions assigning the values of 1, …, *N* with *N* being the total number of city-industry pairs in the US. This creates a national ranking of the values of potential Marshallian and Jacobian externalities which then serve as instruments in 2SLS estimation of equation (3). The rank-based instrument will be acceptable provided it is correlated with a city's initial levels of *SPEC* and *DIV* but not with technological trends unfolding in the following decades.

Tables 9 and 10 report the results of estimating equation (3) with instruments discussed in details in Section 3. Table 9 provides the results of estimation with the Bartik-type instrument for the periods beginning with 1890 and 1900 and a rank-based instrument for the decades beginning with 1880 since, as discussed earlier, we are unable to use the Bartik instrument for the sample period beginning in 1880 due to data unavailability. We can take advantage of being able to construct a rank-based instrument for all time periods and so Table 10 presents the results of estimating equation (3) with the rank-based instrument only. The instruments pass the weak instrument test in all cases. Endogeneity tests for *SPEC* and *DIV* variables indicate that, given the exogeneity of the instruments, *SPEC* and *DIV* are in most cases unlikely to be endogenous.

Generally speaking, the pattern of statistical significance of the industrial structure variables in Tables 9 and 10 is similar to that for the OLS estimation in Table 7. In other words, the estimates in that table survive these robustness checks. An exception to this is the loss of statistical significance of DIV^2 with the Bartik-instrument. The absolute magnitude of the estimated coefficients on the industrial structure variables is typically larger so that predicted agglomeration externalities would, if anything, be greater. As for the estimated relationships between labor productivity and Marshallian and Jacobian externalities reported in Table 8, the robustness of that pattern is also confirmed.

6. Economic Significance of the Results

Table 11 reports estimates of the impact of dynamic Marshallian externalities for labor productivity growth in American cities obtained by multiplying the value of *SPEC* at the start of each decade by its estimated coefficient in the OLS equation for 1890-1920 reported in Table 7, column 3.[15] The result is these externalities are estimated to have generated labor productivity growth at an average annual rate of 0.131 per cent per year during 1890-1920 which raised the level of labor productivity in this sample of cities by 3.93 per cent in 1920 compared with 1890. Estimates based on instrumental-variables estimation using Table 11, column 3 are also reported in Table 11; in this case the impact on labor productivity is bigger at 0.262 per cent per year adding up to 7.86 per cent in 1920. Most of these productivity gains (about 80 per cent) would have been accrued with the degree of specialization

[15] We disregard the contribution of diversity externalities which net out to approximately zero.

existing already in 1890 but the remaining 20 per cent or so resulted from increased specialization during the period, as the counterfactual calculations in Table 11 reveal.

These productivity gains are rather small relative to the aggregate American economy. Total manufacturing output in our sample of cities was $16.272 billion in 1920 while U.S. GDP in that year was $91.5 billion. In the absence of the productivity boost from estimated dynamic agglomeration externalities, American GDP would have been reduced by 0.67 per cent (OLS) or 1.30 per cent (2SLS). Of this, the contribution from post-1890 increases in specialization would have been 0.12 per cent or 0.23 per cent, respectively.

We find that increases in specialization in cities allowed a labor productivity gain in manufacturing in the period 1890-1920. What led cities to become more specialized? This is an important topic for future quantitative research but the traditional history literature provides a strong hypothesis. Pred (1966) stressed the role of falling railroad rates which he argued increased the practicability of serving national demands from a limited number of cities. In the late-nineteenth and early-twentieth century, there were indeed major improvements to the American railroad system. Mileage tripled between 1880 and 1920, total factor productivity almost doubled between 1880 and 1910, while average costs per ton-mile of freight fell from 2.2 cents in 1870 to 0.75 cents in 1910 (Fishlow, 2000). Maps show a huge increase in the density of the railroad network between the Civil War and the First World War (Atack, 2013). All this was highly conducive to increased integration of the market.

It is not possible to quantify the change in trade costs delivered by these railroad investments but it is possible to show that better connectivity of the railroad network was correlated with increased specialization of American cities using the dataset underpinning Pérez-Cervantes (2014). This provides estimates of the impact of the expansion of the railroad network on travel times between 3109 U.S. counties between 1840 and 1900. There were large changes in travel times for the average pair of cities in the 1880s and 1890s, namely, 38.2 per cent (52.9 days) between 1870 and 1880 and 48.9 per cent (45.5 days) between 1880 and 1890.

We have created a pairwise data set of travel times among all cities in our sample and average city-level degree of specialization of those cities and examined a relationship between the changes in travel times and percentage-point change in the degree of specialization of a city using the following regression equation

$$\Delta SPEC^{c}_{1890-1920} = \alpha + \beta \Delta Travel\,Times^{c}_{1880-1890} + \theta_c + \varepsilon_c \qquad (11)$$

where θ_c are city-dummies, and ε_c is an error term. We estimated this regression equation with OLS and used clustered-robust standard errors at city-level. This regression analysis is meant to be illustrative of a possible relationship between changes in travel times and changes in specialization of cities without any strong claims on causal interpretation of the estimated coefficients. The estimated coefficient is $\beta = 0.0474$ and is significant at the 1 per cent level. The estimate implies that improved railroad services accounted for about 25 per cent of the increase in the average value of *SPEC* between 1890 and 1920. We performed a similar analysis of the relationship between the change in travel times between 1870 and 1880 and the change in specialization between 1880 and 1890. Again, β was significant at the 1 per cent level and the implication of the estimate is that the average value of *SPEC* in 1890 would have been 7 per cent lower.

Lowering specialization in 1890 by 7 per cent, removing 25 per cent of the increase in specialization between 1890 and 1920, and subtracting the implied reduction in agglomeration externalities from our earlier calculation has only a small impact on GNP in 1920 – 0.07 per cent if the OLS estimates are used and 0.13 per cent if the 2SLS estimates are chosen. In other words, in so far as we have been able to identify railroad-induced productivity gains in the transport-using sector they would raise the estimated social saving of railroads by only a modest amount which is much smaller than the upward bias in Fogel's method of calculation.

Obviously, the method that we have used to infer the contribution of railroads to increase in specialization may not capture their impact very accurately. So, in the spirit of Fogel himself, suppose that the whole addition to GNP in 1920 of 1.3 per cent in our largest estimate of the contribution of dynamic agglomeration externalities was attributed to railroads – surely an extreme upper bound.

Would this be enough to undermine Fogel's claim that the social saving estimated delivered by his method is an upper bound? The answer is a clear 'no' as the following calculation reveals.

As Fogel pointed out, the extent of upward bias introduced by his assumption of perfectly price-inelastic demand depends on the ratio of alternative-mode to rail transport costs and the price elasticity of demand for freight transport. The formula that he derived (Fogel, 1979, p.11) is the following:

$$B = \left[\frac{\{(1-\varepsilon)(\varphi-1)\}}{\varphi^{1-\varepsilon}-1} - 1\right] 100 \qquad (12)$$

where φ is the transport cost ratio and ε is the price elasticity of demand. Following Fogel, we assume that ε = 0.8 and that φ = 1.87 in 1890. Extrapolating Fogel's social saving to 1920 can be achieved by assuming railroad transport costs fall at the rate implied by railroad TFP growth (Kendrick, 1961, pp. 543-544) and multiplying Fogel's social saving by the ratio of TFP in 1920 to TFP in 1890 (=2.27) and by the ratio of freight revenues in 1920 to those in 1890 (=5.64). This gives a social saving for railroad freight of $7.94 billion = 8.7 per cent of 1920 GNP. The implied value for φ in 1920 is 4.25 so that on the basis of equation (12) the upward bias is now 93 per cent and the true social saving would be lower by 4.2 per cent of GNP.

In sum, we have found that dynamic Marshallian externalities generated a useful addition to urban manufacturing productivity and that some of this gain is probably due to improvements in the railroad network and would therefore comprise an addition to traditional social savings estimates. However, the magnitude of this addition is not large and is undoubtedly a good deal smaller than the upward bias in the traditional measure of social savings.

7. Conclusions

Our analysis of productivity growth in early 20th-century U.S. cities has produced some interesting new results which not only provide some quantification of the role of agglomeration externalities in raising labor productivity in manufacturing but also have implications for evaluating the social savings of railroads. The main conclusions are the following.

First, we find that, on average, more specialized cities enjoyed higher labor productivity growth in manufacturing. This suggests that dynamic Marshallian externalities were an aspect of urbanization during the second industrial revolution. The impact of specialization within cities on labor productivity was both economically and statistically significant. An important task for future research will be to explore the sources of these agglomeration economies. In contrast, it seems likely that dynamic Jacobian externalities were only realized in large cities such as Chicago, Philadelphia, and New York and played only a minor part in raising productivity. In smaller cities, increased diversity tended to reduce productivity growth. The nonlinearity of dynamic Jacobian externalities has not been found in the literature before, which offers an opportunity to investigate its causes in future research.

Second, the degree of industrial specialization in American cities increased appreciably in the early 20th century. This had a positive impact on labor productivity, small but not trivial. We estimate, if specialization had remained at the 1890 level, the contribution of agglomeration externalities to labor productivity growth in manufacturing in our sample of cities between 1890 and 1920 would have been about 20 per cent lower and that the level of manufacturing labor productivity in the United States would have been about 0.75 to 1.5 per cent lower in 1920.

Third, we found evidence to suggest that increases in specialization in U.S. cities and the agglomeration economies that ensued were at partly a result of the expansion of the railroads network and the greater degree of market integration that this promoted. This would imply an addition to the direct user benefits which comprise the traditional measure of the social savings of railroads. The magnitude of this extra component is, however, very small both absolutely and relative to the upwards bias built into a Fogel-type calculation of the social savings.

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Appendix I

We use a simple model of city-industry growth which incorporates local spillovers within and across industries to motivate the empirical framework discussed toward the end of this section. Specifically, we put the framework of dynamic agglomeration spillovers introduced by Glaeser et al (1992) into the simple model of Combes et al (2008) which we have chosen because it matches our data best as it operates with value-added per worker. We consider an industry of sector *s*, in a city *c*, at time *t* with a Cobb-Douglas production function

$$y_{cst} = A_{cst} l_{cst}^{\mu} k_{cst}^{1-\mu} \qquad \text{(A1)}$$

where A_{cst} is the Hicks-neutral factor-augmenting technology level, l_{cst} is labor and k_{cst} is the quantity of other inputs. The profit is given by

$$\Pi_{cst} = \sum_{c} p_{cst} y_{cst} - w_{st} l_{cst} - r_{st} k_{cst} \qquad (A2)$$

where y_{cst} is the quantity exported to city c, p_{cst} is the mill price in city *c* net of marginal costs of the intermediate inputs, w_{st} is the wage rate and r_{st} is the price of intermediate inputs other than labor. The profit function can be rewritten as

$$\Pi_{cst} = p_{st} y_{st} - w_{st} l_{cst} - r_{st} k_{cst} \qquad (A3)$$

where

$$p_{st} = \sum_{c} p_{cst} \frac{y_{cst}}{y_{st}} \qquad \text{(A4)}$$

is the average unit value of the produced goods net of the cost of intermediate inputs. As a result, $p_{st}\, y_{st}$ is sector's *s* value added. The standard first order conditions plugged into the equation A1 yield the average labor productivity defined as value-added per worker

$$\frac{p_{st} y_{st}}{l_{cst}} = (1-\mu)^{(1-\mu/\mu)} \left(\frac{p_{st}^{1-\mu} A_{cst}}{r_{st}^{1-\mu}} \right)^{1/\mu} \qquad (A5).$$

Following the dynamic externalities framework of Glaeser et al (1992), the growth rate of technology is given by

$$ln\left(\frac{A_{cst+m}}{A_{cst}}\right) \equiv E_{cst} \qquad \text{(A6)}$$

where E_{cst} is the amount of localized spillovers in industry s in a city c. Theory does not offer us any concrete functional form linking the growth rate of technology with agglomeration externalities, hence, at this stage, we postulate that E_{cst} is a linear function of Marshallian (Marshall-Arrow-Romer) externalities MAR_{cst} and Jacobian externalities $JACOBS_{cst}$. We can use equation A6 to derive the growth rate of city-industry value-added per worker as a function of the growth of technology. Specifically, we transform equation A5 in logs, express it for period $t+m$, plug both log-equations for t and $t+m$ into equation A6 to obtain

$$ln\frac{y_{cst+m}}{y_{cst}} = \frac{1}{\mu}E_{cst} + \left(\frac{1-\mu}{\mu}\right)\left[\left(ln\frac{p_{st+m}}{p_{st}}\right) - \left(ln\frac{r_{st+m}}{r_{st}}\right)\right] \qquad \text{(A7)}$$

where, for the sake of clarity in equation (A7), we abbreviate value-added per worker as y. This equation expresses the growth rate of value-added per worker in terms of (i) localized externalities which depends of MAR and Jacobian externalities, and (ii) the difference between the output prices and the prices of inputs. It motivates the regression equation.

Appendix II

The results in Table 8 show a quadratic relationship between average annual labor productivity and Jacobian externalities. To explore the robustness of that relationship, we dispose of the quadratic specification of Jacobian externalities, make no assumption about that relationship and estimate a semi-parametric specification of equation (A8)

$$ln(y_{c,s,t+m}) - ln(y_{c,s,t}) = \alpha + \beta_1 SPEC_{cst} + f(DIV_{cst}) + \beta_2 X_{cst} + \theta_c + \lambda_s + \epsilon_{cs} \quad (A8).$$

We estimate equation (A8) with Robinson's (1988) semi-parametric estimator which uses a double-residual methodology. We present the results of that non-parametric function only in Figure 6 since the results for the specialization index and the other controls are qualitatively unchanged. The results reveal interesting patterns. The non-parametric estimates show broadly a curvilinear pattern for the periods 1890-1920 and 1900-1930 though the pattern in 1900-1930 exhibits two local u-shaped patterns for relatively less diversified towns. This, however, is driven by small number of observations in the left part of the distribution with towns having a diversity index around 1.8 and 2.3, respectively, which, with different non-parametric bandwidth might yield a smoother curvilinear pattern. The patterns in those time periods are confirmed by the parametric estimates. The period 1880-1920 also shows a curvilinear pattern, though not as pronounced as in 1890-1920 or 1900-1930. The period 1880-1930 shows no relationship between industrial diversity and average annual labor productivity growth, similar to the parametric estimates, while 1900-1920 exhibits a declining pattern which peters out for highly diversified cities. All this is consistent with the parametric estimates. The period 1890-1930 is the only period exhibiting a clear U-shaped relationship for which statistical significance is not confirmed by the parametric regression.[16] Overall, the graphs show that in four out of six cases, Jacobian externalities exhibit a non-linear U-shaped pattern in which the average annual labor productivity begins to increase for rather diversified cities with industrial variety indices between 2 and 2.5, similar to those reported in Table 10.

[16] The graphs of nonparametric estimates in Figure 6 were trimmed from below for the period 1890-1930 and 1900-1930 respectively due to a handful of observations being clear outliers. The graphs including the outliers are available from the authors upon request.

Table 1: Number of Cities by US Regions as Reported in the US Census of Manufactures 1880-1930.

Region/Number of Cities	1880	1890	1900	1920	1930
East North Central	18	33	44	26	8
East South Central	6	11	11	8	1
Middle Atlantic	26	40	53	35	15
Mountain	2	3	4	1	1
New England	21	32	40	22	10
Pacific	3	7	9	11	8
South Atlantic	10	12	16	14	3
West North Central	8	18	23	14	6
West South Central	3	7	9	9	7
DC	1	1	0	0	0
US	*98*	*164*	*209*	*140*	*59*

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930

Table 2: Number of Matched Cities 1880-1930.

Number of Cities/Time Period	1880-1920	1880-1930	1890-1920	1890-1930	1900-1920	1900-1930
Matched cities	81	41	118	53	127	54
Cities entering sample in 1890 and 1900			37	12	9	1
Cities exiting the sample in 1930		40		65		73

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930

Table 3: Average share of employment in selected industries in US Cities 1880, 1930 (%).

SIC 3	Industry SIC 3	1880	1930
		Traditional Industries	
203	Preserved Fruits & Vegetables	7.94	2.45
208	Beverages	2.63	0.49
223	Broadwoven Fabric Mills, Wool	12.68	5.32
225	Knitting Mills	1.78	0.43
242	Sawmills & Planing Mills	6.75	1.79
273	Books	5.28	2.55
313	Footwear Cut Stock	4.41	2.57
319	Leather Goods, nec	1.23	0.19
325	Structural Clay Products	3.55	1.24
332	Iron Foundries	13.81	6.27
		Industries of 'Second Industrial Revolution'	
287	Agricultural Chemicals	0.65	1.10
291	Petroleum Refining	0.00	20.02
331	Blast Furnace & Basic Steel Products	0.53	6.00
345	Screw Machine Products, Bolts, Etc.	0.62	2.13
355	Special Industry Machinery	0.63	2.63
356	General Industry Machinery	0.18	0.26
362	Electrical Industrial Apparatus	0.32	3.68
364	Electric Lighting & Wiring Equipment	0.27	0.48
371	Motor Vehicles & Equipment	1.41	8.77
382	Measuring & Controlling Devices	0.18	0.89

Sources: US Census of Manufactures 1880, 1930.

Note: The employment shares are calculate relative to city total employment.

Table 4: Average Annual Growth of Value-Added per Worker of SIC 3 Industries in US Cities: 1880-1920.

US State	US City	SIC 3	Industry Name SIC 3	Growth Rate 1880-1920
			Fastest Growing Industries	
NEW YORK	BUFFALO	242	Sawmills & Planing Mills	0.077
PENNSYLVANIA	PHILADELPHIA	339	Misc Primary Metal Industries	0.061
KENTUCKY	LOUISVILLE	289	Miscellaneous Chemical Products	0.056
GEORGIA	ATLANTA	399	Miscellaneous Manufacturers	0.055
OHIO	CLEVELAND	342	Cutlery, Handtools & Hardware	0.054
NEW YORK	BUFFALO	331	Blast Furnace & Basic Steel Products	0.053
NEW JERSEY	NEWARK	284	Soap, Cleaners & Toilet Goods	0.053
NEW JERSEY	Hoboken	332	Iron & Steel Foundries	0.051
NEW YORK	BUFFALO	283	Drugs	0.051
PENNSYLVANIA	SCRANTON	332	Iron & Steel Foundries	0.050
MICHIGAN	DETROIT	399	Miscellaneous Manufacturers	0.050
NEW YORK	UTICA	344	Fabricated Structural Metal Products	0.050
PENNSYLVANIA	PHILADELPHIA	286	Industrial Organic Chemicals	0.049
MICHIGAN	DETROIT	382	Measuring & Controlling Devices	0.048
			Slowest Growing Industries	
NEW YORK	NEW YORK CITY	207	Fats & Oils	-0.021
MASSACHUSETTS	NEW BEDFORD	201	Meat Products	-0.023
MASSACHUSETTS	WORCESTER	319	Leather Goods, nec	-0.023
RHODE ISLAND	Providence	209	Misc Food & Kindred Products	-0.023
INDIANA	INDIANAPOLIS	201	Meat Products	-0.023
NEW YORK	ROCHESTER	209	Misc Food & Kindred Products	-0.023
NEW JERSEY	NEWARK	201	Meat Products	-0.023
NEW YORK	BUFFALO	275	Commercial Printing	-0.023
MISSOURI	Kansas city	242	Sawmills & Planing Mills	-0.026
MASSACHUSETTS	Lawrence	251	Household Furniture	-0.026
CALIFORNIA	SAN FRANCISCO	289	Miscellaneous Chemical Products	-0.027
MINNESOTA	Saint Paul	278	Blankbooks & Bookbinding	-0.029
OHIO	CINCINNATI	259	Miscellaneous Furniture & Fixtures	-0.029
CALIFORNIA	SAN FRANCISCO	201	Meat Products	-0.029

Sources: US Census of Manufactures 1880, 1920.

Table 5: Top five and bottom five industries by specialization and variety index.

1880	1900	1930
	Panel A:	
	SIC 3 industries with the highest specialization index	
Miscellaneous Manufacturers	Miscellaneous Manufacturers	Miscellaneous Manufacturers
Broadwoven Fabric Mills, Cotton	Broadwoven Fabric Mills, Cotton	Petroleum Refining
Iron & Steel Foundries	Petroleum Refining	Motor Vehicles & Equipment
Broadwoven Fabric Mills, Wool	Broadwoven Fabric Mills, Wool	Iron & Steel Foundries
Chewing & Smoking Tobacco	Iron & Steel Foundries	Blast Furnace & Basic Steel Products
	SIC 3 industries with the lowest specialization index	
Greeting Cards	Handbags & Personal Leather Goods	Miscellaneous Primary Metal Industries
Industrial Machinery, nec	Secondary Nonferrous Metals	Industrial Machinery, nec
Nonferrous Foundries (Castings)	Industrial Organic Chemicals	Refrigeration & Service Industry
Photographic Equipment & Supplies	General Industry Machinery	Watches, Clocks, Watchcases & Parts
Plastics Materials & Synthetics	Household Audio & Video Equipment	Miscellaneous Transportation Equipment
	Panel B:	
	SIC 3 industries with the highest variety index	
Plastics Materials & Synthetics	Handbags & Personal Leather Goods	Industrial Machinery, nec
Fabricated Rubber Products, nec	Office Furniture	Miscellaneous Primary Metal Industries
Toys & Sporting Goods	Photographic Equipment & Supplies	Miscellaneous Textile Goods
Leather Gloves & Mittens	Household Appliances	Knitting Mills
Special Industry Machinery	Nonferrous Foundries (Castings)	Carpets & Rugs
	SIC 3 industries with the lowest variety index	
Metal Forgings & Stampings	Leather Goods, nec	Aircraft & Parts
Broadwoven Fabric Mills, Wool	Newspapers	Special Industry Machinery
Iron & Steel Foundries	Metal Forgings & Stampings	Books
Paper Mills	Bakery Products	Bakery Products
Tobacco Stemming & Redrying	Men's & Boys' Furnishings	Iron & Steel Foundries

Sources: US Census of Manufactures 1880, 1900, 1930.

Note: Specialization and variety indices are calculated as the average across all cities in the data set.

Table 6: Agglomeration and Productivity Growth: OLS Regression

	1880-1920	1880-1930	1890-1920	1890-1930	1900-1920	1900-1930
DIV	-0.00315**	0.00001	-0.00798***	0.00215	-0.02139***	-0.00499
	[0.001]	[0.001]	[0.002]	[0.003]	[0.005]	[0.005]
SPEC	0.01440***	0.00881*	0.02626***	0.01149	0.05343***	0.02723***
	[0.005]	[0.005]	[0.007]	[0.009]	[0.012]	[0.007]
Initial Value-Added per Worker	-0.00002***	-0.00001***	-0.00001***	-0.00001***	-0.00001*	-0.00000**
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Initial State Manuf Empl (% from US)	0.00001	-0.00007	0.00001	-0.00001	-0.00007	0.00003
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Constant	0.03385***	0.03537***	0.01528***	0.01356***	0.03614***	0.02197***
	[0.003]	[0.004]	[0.006]	[0.004]	[0.008]	[0.007]
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
Joint significance						
DIV & *SPEC* $\neq 0$	8.93**	3.38	15.99***	4.16^	19.82***	17.41***
R^2	0.609	0.635	0.525	0.677	0.432	0.508
N	1,254	727	1,954	1,046	2,192	1,157

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930.

Notes: ^ significant at 12%, * significant at 10%; ** significant at 5%; *** significant at 1%

standard errors are clustered at city and industry level

Table 7: Agglomeration and Productivity Growth: OLS Regression with Nonlinearities.

	1880-1920	1880-1930	1890-1920	1890-1930	1900-1920	1900-1930
DIV	-0.01744**	-0.01266	-0.02331***	-0.00883	-0.02541***	-0.03045***
	[0.008]	[0.013]	[0.007]	[0.009]	[0.007]	[0.009]
DIV^2	0.00444*	0.00356	0.00453**	0.00297	0.00127	0.00689**
	[0.003]	[0.004]	[0.002]	[0.002]	[0.002]	[0.003]
SPEC	0.01633***	0.01021*	0.03088***	0.0129^	0.05421***	0.02967***
	[0.005]	[0.006]	[0.008]	[0.009]	[0.012]	[0.008]
Initial Value-Added per Worker	-0.00002***	-0.00001***	-0.00001***	-0.00001***	-0.00001*	-0.00000**
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Initial State Manuf Empl (% from US)	0.00002	-0.00007	0	-0.00001	-0.00007	0.00001
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Constant	0.04503***	0.04405***	0.02685***	0.02240***	0.03910***	0.04297***
	[0.007]	[0.010]	[0.008]	[0.007]	[0.009]	[0.008]
Joint significance						
DIV & $DIV^2 \neq 0$	8.92**	1.09	23.54***	2.43	21.78***	10.77***
DIV & DIV^2 & $SPEC \neq 0$		5.51^		6.27*		
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
R^2	0.611	0.636	0.526	0.678	0.432	0.51
N	1,254	727	1954	1,046	2,192	1,157

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930.

Notes: ^ significant at 13%, * significant at 10%; ** significant at 5%; *** significant at 1%
standard errors are clustered at city and industry level

Table 8: Agglomeration and Productivity Growth: OLS Regression. Robustness Check

	1890-1920	1890-1930	1900-1920	1900-1930	1900-1920	1900-1930
	Sample of Cities in 1880		Sample of Cities in 1880		Sample of Cities in 1890	
	Basic specification					
DIV	-0.00943***	0.00255	-0.01575***	-0.00302	-0.01505***	-0.00193
	[0.002]	[0.004]	[0.005]	[0.004]	[0.005]	[0.004]
SPEC	0.03406***	0.01756**	0.04331***	0.01966***	0.03842***	0.01372**
	[0.008]	[0.009]	[0.013]	[0.006]	[0.011]	[0.006]
Value-added/Worker	-0.00001***	-0.00001***	-0.00002***	-0.00001***	-0.00002***	-0.00001***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
State Manf. Empt. (% US)	0	-0.00003	-0.00003	0.00001	-0.00004	0.00003
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Constant	0.02552***	0.02003***	0.05971***	0.04893***	0.05131***	0.03944***
	[0.004]	[0.005]	[0.007]	[0.008]	[0.006]	[0.005]
Joint significance						
DIV & *SPEC* ≠ 0	24.89***	5.63*	11.97**	9.57**	12.12***	6.45**
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
R^2	0.528	0.663	0.56	0.642	0.553	0.634
N	1,581	876	1,693	935	2,138	1,148
	Nonlinearities					
DIV	-0.02282***	-0.00263	-0.01462*	-0.02660**	-0.01977***	-0.02642***
	[0.009]	[0.010]	[0.008]	[0.013]	[0.007]	[0.008]
DIV^2	0.00394	0.0014	-0.00034	0.00616**	0.00144	0.00663***
	[0.003]	[0.003]	[0.002]	[0.003]	[0.002]	[0.002]
SPEC	0.03651***	0.01756**	0.04319***	0.01823***	0.03946***	0.01617**
	[0.008]	[0.009]	[0.013]	[0.006]	[0.011]	[0.006]
Value-added/Worker	-0.00001***	-0.00001***	-0.00002***	-0.00001***	-0.00002***	-0.00001***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
State Manf. Empt. (% US)			-0.00003	0.00001	-0.00004	0.00002
			[0.000]	[0.000]	[0.000]	[0.000]
Constant	0.03574***	0.02374***	0.05878***	0.07085***	0.05486***	0.05964***
	[0.008]	[0.007]	[0.009]	[0.015]	[0.007]	[0.007]
Joint significance						
DIV & DIV^2 ≠ 0	33.25***	0.73	11.75***	4.21^	10.89**	9.85*
DIV, DIV^2 & *SPEC* ≠ 0		6.27*				
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
R^2	0.529	0.663	0.56	0.643	0.553	0.635
N	1,581	876	1,693	935	2,138	1,148

Sources: US Census of Manufactures 1890, 1900, 1920, 1930.

Notes: ^ significant at 12%, * significant at 10%; ** significant at 5%; *** significant at 1%
standard errors are clustered at city and industry level

Table 9: Agglomeration and Productivity Growth: 2SLS Instrumental Variable Regressions.

	1880-1920	1880-1930	1890-1920	1890-1930	1900-1920	1900-1930
DIV	-0.02187*	-0.02038	-0.04106**	-0.00165	-0.02491**	-0.01747*
	[0.012]	[0.012]	[0.018]	[0.024]	[0.012]	[0.010]
DIV^2	0.00465	0.00429	0.0071^	0.0007	0.00239	0.00517**
	[0.003]	[0.003]	[0.005]	[0.006]	[0.003]	[0.003]
SPEC	0.02624**	0.02737**	0.04601***	0.01819*	0.03910***	0.01679**
	[0.011]	[0.011]	[0.011]	[0.009]	[0.012]	[0.008]
Beginning of Period Value-Added per Worker	-0.00002***	-0.00001***	-0.00001***	-0.00001***	-0.00002***	-0.00001***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Beginning of Period State Manuf Empl (% from US)	-0.00002	-0.00011*	-0.00002	-0.00001	-0.00003	0.00002
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
<u>*Weak Instrument Tests*</u>						
DIV (F-stat from first-stage)	231.8	278.09	43.07	9.86	32.51	33.29
DIV^2 (F-stat from first-stage)	220.56	166.17	67.23	10.28	35.44	30.04
SPEC (F-stat from first-stage)	77.77	122.15	22.2	112.81	152.44	300.64
Anderson-Rubin chi-square test	7.397	12.05	26.25	27.78	16.55	9.528
Anderson-Rubin chi-square test p-values	0.0603	0.0072	8.45E-06	4.03E-06	0.000873	0.023
<u>*Endogeneity Test*</u>						
Endogeneity test chi-square	3.087	3.44	2.104	0.114	2.513	3.097
Endogeneity test chi-square t-test	0.3784	0.3287	0.551	0.9901	0.4729	0.3768
R^2	0.418	0.37	0.295	0.273	0.357	0.387
N	1,254	727	1,190	695	1,840	1,003

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930

Note: ^ significant at 12%; * significant at 10%; ** significant at 5%; *** significant at 1%

Standard errors are clustered at city and industry level; in 1880-1920 and 1880-1930, 2SLS is based on rank instruments.

Weak IV test is Sanderson and Windmeijer (2016) F-test.

Table 10: Agglomeration and Productivity Growth: 2SLS Instrumental Variable Regressions (Rank-Based Instruments).

	1880-1920	1880-1930	1890-1920	1890-1930	1900-1920	1900-1930
DIV	-0.02187*	-0.02038	-0.04507***	-0.02757**	-0.07734***	-0.05191***
	[0.012]	[0.012]	[0.011]	[0.013]	[0.015]	[0.012]
DIV^2	0.00465	0.00429	0.00814***	0.00508**	0.00987***	0.00922***
	[0.003]	[0.003]	[0.002]	[0.002]	[0.003]	[0.003]
SPEC	0.02624**	0.02737**	0.06172***	0.04846**	0.13399***	0.07403***
	[0.011]	[0.011]	[0.016]	[0.019]	[0.025]	[0.020]
Beginning of Period Value-Added per Worker	-0.00002***	-0.00001***	-0.00005	-0.00008	-0.00023**	-0.00005
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Beginning of Period State Manuf Empl (% from US)	-0.00002	-0.00011*	-0.00001***	-0.00001***	-0.00001**	-0.00000**
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
City Dummies	YES	YES	YES	YES	YES	YES
Industry Dummies	YES	YES	YES	YES	YES	YES
<u>*Weak Instrument Tests*</u>						
DIV (F-stat from first-stage)	231.8	278.09	215.79	190.59	177.42	188.85
DIV^2 (F-stat from first-stage)	220.56	166.17	399.42	331.18	501.03	435.85
SPEC (F-stat from first-stage)	77.77	122.15	84.72	79.12	90.6	63.08
Anderson-Rubin chi-square test	7.397	12.05	17.1	7.769	38.16	21.4
Anderson-Rubin chi-square test p-values	0.0603	0.0072	0.000193	0.0206	5.16E-09	2.26E-05
<u>*Endogeneity Test*</u>						
Endogeneity test chi-square	3.087	3.44	4.605	5.696	12.673	7.464
Endogeneity test chi-square t-test	0.3784	0.3287	0.2031	0.1474	0.005	0.058
R^2	0.418	0.37	0.294	0.321	0.174	0.186
N	1,254	727	1,190	695	1,840	1,003

Sources: US Census of Manufactures 1880, 1890, 1900, 1920, 1930

Note: ^ significant at 12%; * significant at 10%; ** significant at 5%; *** significant at 1%

Standard errors are clustered at city and industry level.

Weak IV test is Sanderson and Windmeijer (2016) F-test.

Table 11. Predicted Labor Productivity Growth from Dynamic Marshallian Externalities, 1890- 1920.

	OLS	***2SLS***
Average Labor Productivity Growth (% per year)	0.131	0.262
Counterfactual Labor Productivity Growth (% per year)	0.106	0.212
Cumulative Increase in Labor Productivity (%)	3.93	7.86
Counterfactual Cumulative Increase in Labor Productivity (%)	3.18	6.36

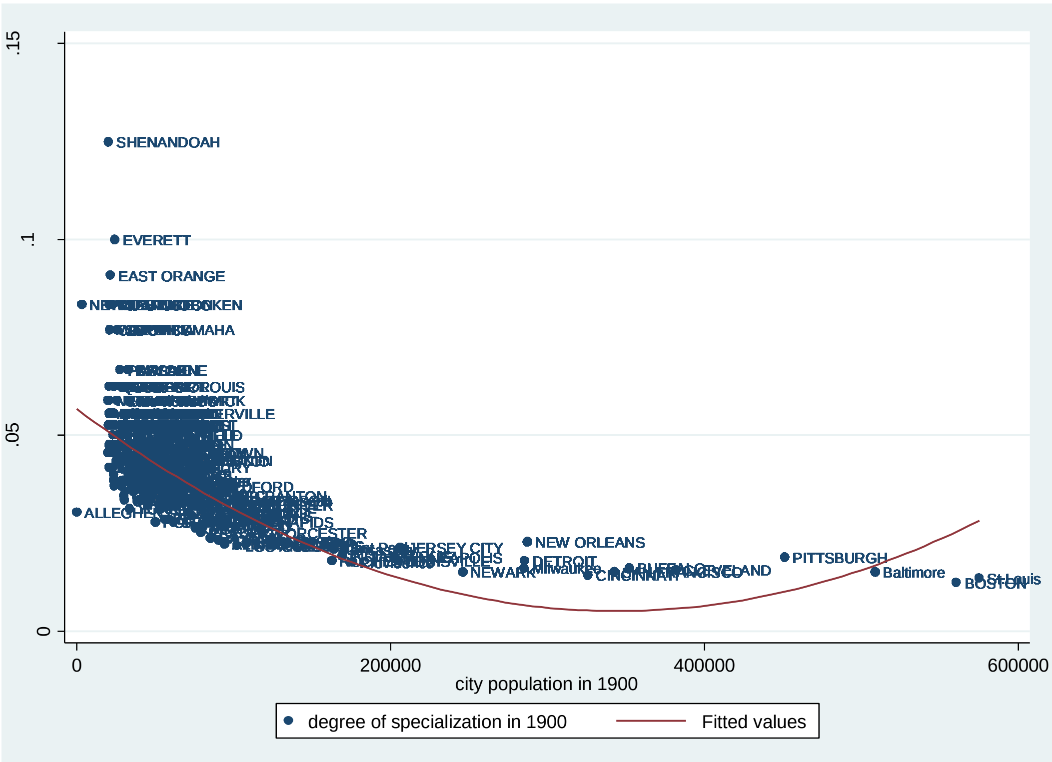
Notes:

OLS predictions based on Table 7, column 3; 2SLS predictions based on Table 11, column 3.

Counterfactual assumes specialization constant at 1890 level.

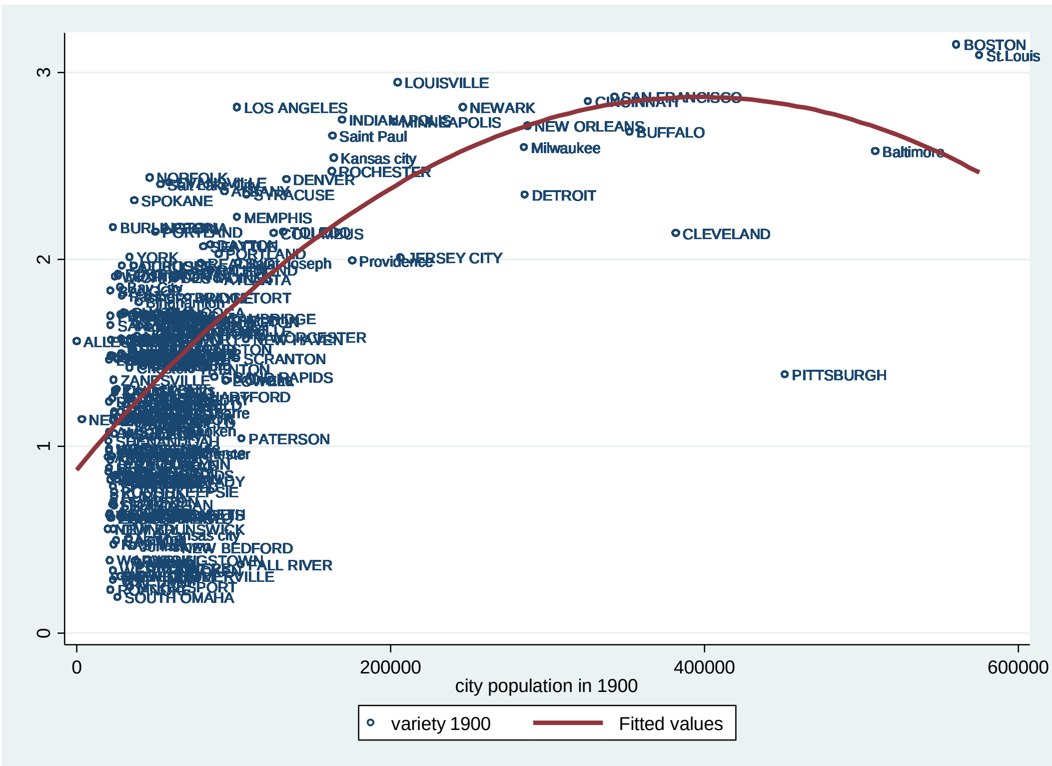
Source: own calculations

Figure 1: City Population vs Specialization in 1900.



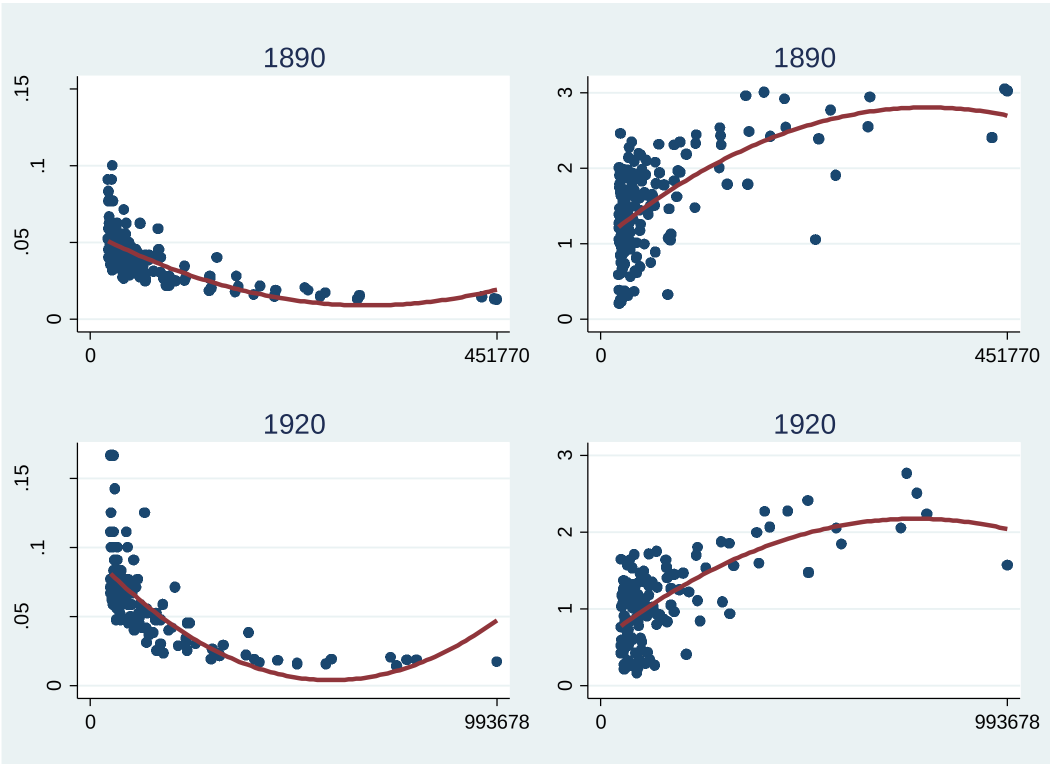
Source: derived from U. S. Census of Manufactures 1900.

Figure 2: City Population vs Variety in 1900.



Source: derived from U. S. Census of Manufactures 1900.

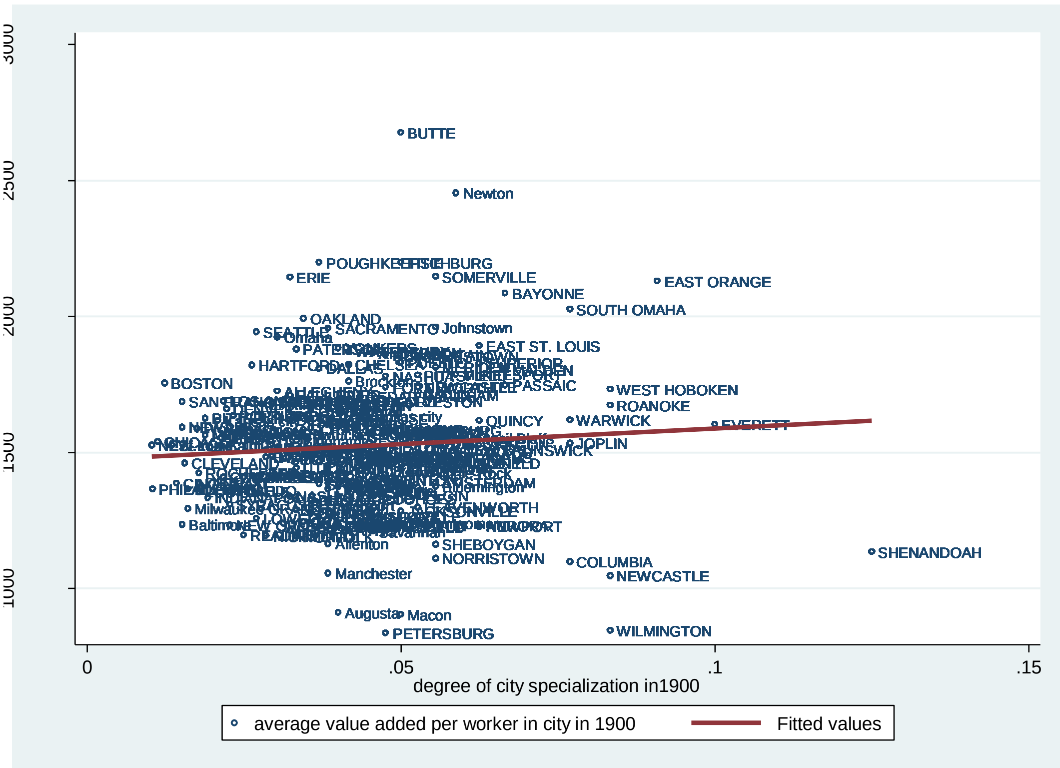
Figure 3. City Size, Specialization and Variety: 1890 vs. 1920.



Notes: left panels: population vs. specialization; right panels: population vs. variety

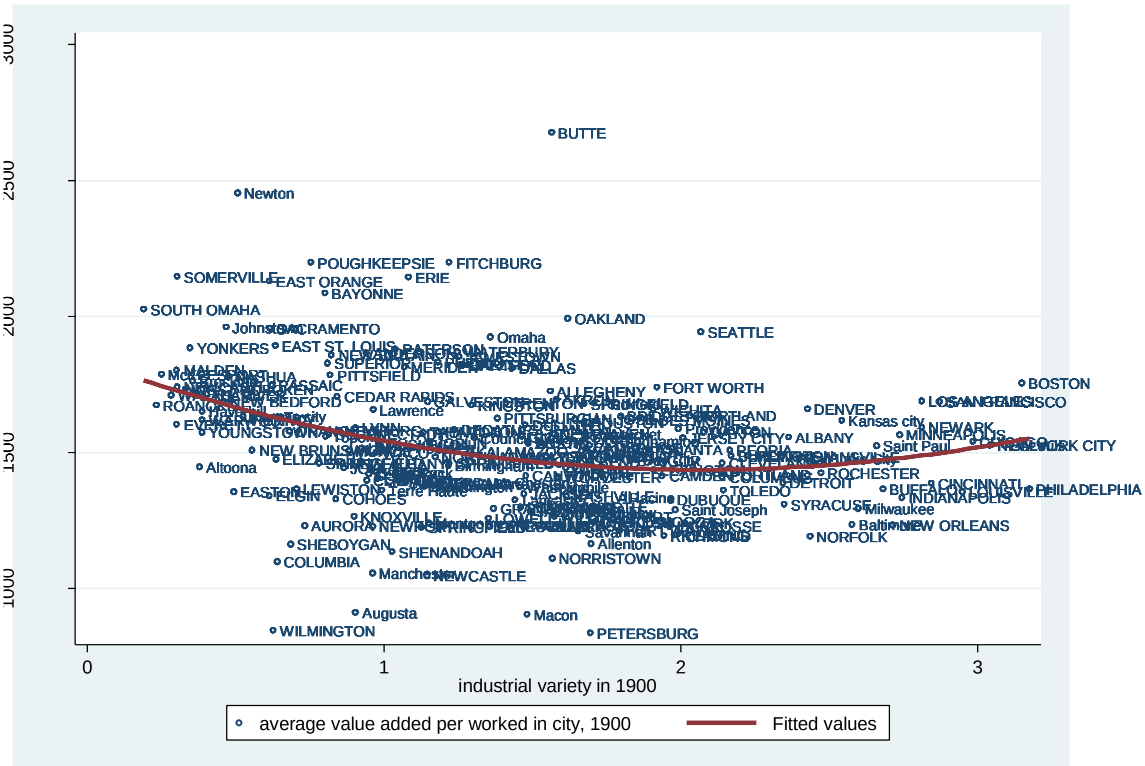
Source: derived from U. S. Census of Manufactures 1890 and 1920.

Figure 4: City Labor productivity vs Specialization in 1900.



Source: derived from U. S. Census of Manufactures 1900.

Figure 5: City Labor productivity vs Variety in 1900.



Source: derived from U. S. Census of Manufactures 1900.

Figure 6: Nonparametric estimates of Jacobian externalities