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Productivity and Technological Change in the Railroad Sector, 1840–1910

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Schumpeter once expressed the opinion that the economic history of the United States in the second half of the nineteenth century could be written solely in terms of the railroad sector. Clearly an exaggeration, the observation still has the merit of focusing upon one of the dynamic forces in American economic development. Yet our measure of that force is severely restricted. Our only continuous railway series is mileage operated, and such relevant magnitudes as ton and passenger mileage, employment, and capital stock are not available, even in imperfect form, until the 1880's, well after the phase of most rapid growth.

The first and principal part of this paper seeks to repair these omissions by setting out a continuous quantitative record of development for the railroad sector from its beginnings in the 1830's to its peak just before the First World War. The detailed statistics compiled by the Interstate Commerce Commission carry the record forward more than adequately from that time on.

Four series are constructed: output, employment, capital stock, and fuel consumption. Despite their obvious diversity, as well as the differences in the quality of the underlying information, there is a unity in the approach that should be noted. In the great majority of instances, the estimates have been reached by two alternative routes. The first is by direct manipulation of physical units—ton- and passenger-miles, tons of coal, track mileage, and so forth—whereas the second starts from the financial accounts reflecting these magnitudes—traffic receipts, fuel expenditures, book value of road and equipment—but has the same goal. The obvious

NOTE: I gratefully acknowledge the painstaking care with which the original draft of this paper was read by Richard A. Easterlin. His comments and suggestions have contributed much to the final form the paper has taken, although he must be absolved of any responsibility for the shortcomings that remain.

virtue of this duality is an internal check upon the final estimates. However, there are further gains as well. It is the inconsistency between movements in the trackage and equipment index and Ulmer's investment series that calls attention to the inadequacies in our existing dollar measures of investment. This is an instance where the check is not internal, but relates to other previous estimates. A second advantage of the physical approach to the capital stock—spelled out in greater detail below—is its avoidance of some particularly nasty deflation problems. Cumulative railroad investment can be interpreted unequivocally as the reproduction cost of the current-year stock with base-year prices and technology, but current-year quality. Ordinary price indexes, built up of quotations on an ever-changing unit, when applied to current expenditures, do not produce the same straightforward result.

The second part of the paper goes on from these estimates to consider the record of productivity change implied by them. It both corrects Kendrick's post-1869 measures of productivity in the railroad sector, and extends those measures considerably backward in time. Then, in an effort to explain the observed pattern of increasing productivity, we take up the contribution of certain key innovations of the latter nineteenth century: steel rails, automatic couplers, power brakes, improved rolling stock. Of more general interest in this section is the use of a simple technique for integrating the up-to-now distinct approaches from the side of sectoral productivity measures, and from the side of specific technological developments.

Quantitative Measures of Railroad Development, 1840–1910: Output

Table 1 sets out estimates of passenger- and ton-miles, and the rates that make possible their combination into a single output index. This index is of the link-relative form, one familiar to users and producers of statistics covering relatively long spans of years.[1] The virtue of the method is the comparability it affords between adjacent observations when structural change is quite rapid—in this instance, the relative importance of freight and passenger service, and their rates. Laspeyres or Paasche indexes freeze the price structure or the output mix at that of a given year, with the consequence that they are very sensitive to the choice of the base.[2]

[1] See, for example, John W. Kendrick, *Productivity Trends in the United States*, Princeton for NBER, 1961, p. 55, for a discussion of the link-relative approach and its use in that study.

[2] Although the Paasche index is currently weighted in the sense that prices of the current year are used to evaluate output of the current and the base year, there are different results when alternative bases, i.e., output mixes, are used.

TABLE 1

PHYSICAL OUTPUT ESTIMATES, 1839-1910

Fiscal Year[a]	Passenger-Miles	Ton-Miles	Passenger Rate	Freight Rate	Output Index
	(billions)		(cents)		(1910=100)
	(1)	(2)	(3)	(4)	(5)
1839	0.09	0.03	5.0	7.5	0.04
1849	0.47	0.35	2.9	4.05	0.31
1859	1.9	2.6	2.44	2.58	1.74
1870	4.1	11.7	2.8	2.18	6.03
1880	5.7	32.3	2.51	1.29	13.78
1890	12.1[b]	80.0[b]	2.20	.92	32.79
1900	16.2	144.0	2.00	.73	54.79
1910	32.5	255.0	1.94	.75	100.00

Source

Cols. 1-4
1839-59: Albert Fishlow, *American Railroads and the Transformation of the Ante Bellum Economy* (in press), Cambridge, Mass., Appendix A.
1870: Interpolated on sample series between 1859 and 1880; see text.
1880: U.S. Bureau of the Census, *Tenth Census, 1880*, Vol. IV, *Agencies of Transportation*, p. 11.
1890: U.S. Bureau of the Census, *Eleventh Census, 1890*, Vol. XI, *Agencies of Transportation*, p. 593.
1900, 1910: Harold Barger, *Output in the Transportation Industries*, Princeton for NBER, 1951, Appendix B.
Col. 5: The formula for the link-relative index is:

$$\frac{O_t}{O_{1910}} = \frac{P_t\left(\frac{p_t+p_{t+1}}{2}\right) + T_t\left(\frac{f_t+f_{t+1}}{2}\right)}{P_{t+1}\left(\frac{p_t+p_{t+1}}{2}\right)+T_{t+1}\left(\frac{f_t+f_{t+1}}{2}\right)} \cdot \frac{P_{t+1}\left(\frac{p_{t+1}+p_{t+2}}{2}\right) + T_{t+1}\left(\frac{f_{t+1}+f_{t+2}}{2}\right)}{P_{t+2}\left(\frac{p_{t+1}+p_{t+2}}{2}\right) + T_{t+2}\left(\frac{f_{t+1}+f_{t+2}}{2}\right)} \cdot$$

$$\ldots \cdot \frac{P_{1900}\left(\frac{p_{1900}+p_{1910}}{2}\right) + T_{1900}\left(\frac{f_{1900}+f_{1910}}{2}\right)}{P_{1910}\left(\frac{p_{1900}+p_{1910}}{2}\right) + T_{1910}\left(\frac{f_{1900}+f_{1910}}{2}\right)},$$

where P are passenger-miles from col. 1, p the passenger rates of col. 3, T the ton-miles of col. 2, and f the freight rates of col. 4.

[a] Fiscal year for 1880-1910 ends June 30. For previous years the typical practice of individual roads was to report either on September 30 or at year's end, which would make the covered year correspond to a fiscal year ending in the autumn (cf. Edwin Frickey, *Production in the United States, 1860-1914*, Cambridge, Mass.,1947, p. 115).

[b] Coverage was extended by means of the ratios of mileage of roads reporting tonnage and passengers to mileage of roads reporting ton-miles and passenger-miles. It was assumed that the average haul per ton was half the national average for roads not reporting ton-mileage, while passenger trips were assumed to be of equivalent length. This adjustment is preferable to one based upon mileage coverage of receipts relative to output since the latter leads to average rates much smaller than those reported elsewhere. The mileage disparity between receipts and output is probably as large as it is because of incorrect tabulating of subsidiary roads rather than of actual differences in coverage.

Thus an 1839 Laspeyres (or a 1910 Paasche) yields an 1839 output of .03 (1910 = 100), whereas the 1910 Laspeyres (or 1839 Paasche) gives a result almost three times as large. The link-relative index presented functions like a weighted average of these two extremes, with weights changing over the course of the period.

As the source notes to Table 1 indicate, 1880 marks the start of official tabulation of passenger- and ton-miles. Rapidly thereafter, there was a proliferation of sources so that 1890 affords the option of three alternative estimates from *Poor's Manual*, the report of the Interstate Commerce Commission, and the Census volume, *Agencies of Transportation*. The latter was used because its coverage is more complete than that of the other two. By 1900 the ICC's official status and continuous collection of data led to the cessation of further Census inquiry, and it is these data, as adjusted by Barger, that are entered here.

For roughly half the period, therefore, no official tallies exist.[3] One survey was taken by the Secretary of the Treasury in 1856, it is true, but that effort is marred by considerable error.[4] The apparent total of 3.4 billion ton-miles for fiscal 1856 must be scaled down by about 1 billion ton-miles, the output incorrectly reported for a single New York railroad of insignificant size and a financial failure to boot. That adjustment is insufficient. For the residual is now too small because many railroads failed to return ton-miles, even when responding to other parts of the questionnaire. Stated passenger-miles, although free of gross errors, are unreliable for the same reason.

Since passenger- and ton-miles were rarely reported by individual railroads before the Civil War, and tabulated by less than a handful of states, it is necessary to proceed from receipts. The reduction to physical quantities is accomplished by dividing through by the average charge for transport services. This further information on rates is required in any event to combine passenger- and ton-miles into a single output measure.

Elsewhere I have described in some detail the derivation of the receipts and rate information for the antebellum period;[5] only a brief summary

[3] There is also a nonofficial, continuous series on ton-miles going back to 1852 developed by Carl Snyder in his *Business Cycles and Business Measurements*, New York, 1927. This has had a reasonably wide circulation as a consequence of its appearance in Joseph A. Schumpeter's *Business Cycles*, New York, 1939. Snyder extrapolated back from the 1880's on a sample series of ton-miles for the large systems. At its maximum the coverage is substantial, but for the antebellum period it is limited to four railroads at most and to only a single road for part of the 1850's. The series is sometimes useful for cyclical analysis, but the absolute levels are not always reliable, as one would anticipate from the method of derivation.

[4] It is published in the *Report on Finances for 1855-56*, S. Ex. Doc. 2, 34th Cong., 2d Sess.

[5] In Appendix A of Albert Fishlow, *American Railroads and the Transformation of the Ante Bellum Economy* (forthcoming), Cambridge, Mass.

noting the relative reliability of these estimates is presented here. The receipts data are of good quality. Less than 10 per cent of the 1839 total could not be obtained directly, and a still smaller 2 per cent in 1849 and 1859 had to be estimated. The allocation of receipts to their passenger and freight origins is slightly more inexact, but that is still of small consequence. The caliber of the passenger and freight rates is subject to more concern, especially because small absolute errors in these are transformed into large percentage deviations in the output aggregates. For 1839, a small sample of roads and the considered judgment of Franz Anton von Gerstner, a visiting Belgian engineer who chronicled early American railroad development in a very thorough fashion, must suffice.[6] By 1849 information on rates had become more abundant and a survey of charges by almost all operating railroads in 1848 forms the basis of the estimates.[7] So detailed is the source that regional, and even state, disaggregation is possible, and this contributes to greater confidence in the final output entry for that year. The 1859 rates rest upon an elaboration of the 1855-56 Treasury survey mentioned above. Exact 1855-56 rates were calculated from simultaneous output and receipts information for roads carrying 60 per cent of aggregate ton- and passenger-miles. Only the extension of these rates to 1859 affords a cause for concern, and this not a serious one. The time span is so short, and rates so stable—as sample data of individual roads and the state reports of New York and Massachusetts testify—that the potential error is minimal. Freight rates were extrapolated on a small sample of roads, chosen for their geographic representativeness, and passenger rates left unaltered except for a slight reduction in the initially above-average charges of southern railroads. All in all, the resultant 1859 output estimates are the best of the antebellum period and subject to relatively small deviations.

This elaborate procedure for the pre-Civil War years could be avoided for the 1870 estimate because it was straddled by firm benchmarks in 1880 and 1859 and a suitable interpolating series was available. By that time the five trunk lines reporting ton-miles at all three dates not only represented one-fourth of the national aggregate, but a stable proportion as well.[8] Hence interpolation is a quite satisfactory procedure here. And

[6] Gerstner visited almost every railroad in the country in the late 1830's and collected a storehouse of information, published (much of it posthumously) as a series of articles in 1839–41 in the *American Railroad Journal* and *Journal of the Franklin Institute* and as a two-volume book in German, *Die Innern Communicationen der Vereinigten Staaten von Nord Amerika*, Vienna, 1842-43. There is no question of his knowledgeability.

[7] See *American Railroad Journal*, Vol. XXI, 1848, pp. 467 ff.

[8] The sample consists of the Boston and Albany, the New York Central, the New York and Erie, the Pennsylvania, and the Pittsburgh, Fort Wayne, and Chicago railroads (see *Wholesale Prices, Wages and Transportation*, S. Rept. 1394, 52d Cong., 2d Sess., 1, pp. 618–620).

although there is no equivalent set of observations for passenger-miles, the results of extrapolating on Frickey's two sample series—one forward from 1859, the other backward from 1880—are so close that large errors are doubtful.[9] The average of the respective projections of 4.2 and 4.0 billion passenger-miles is used in Table 1. The same technique applied to ton-miles yields an estimate almost identical to that obtained by interpolation, a finding which supports the extrapolation approach and also the ton-mile estimate itself.

Logarithmic interpolation was also used for 1870 rates. Two alternative series produced quite similar estimates for the freight rate: the average New York State rate derived from the state reports for the three years, and the average rate of a sample of large railroads roughly comparable to those used in the derivation of 1870 ton-miles.[10] The absolute level was further corroborated by comparison with the average freight charge reported for thirteen trunk lines in 1870.[11] Information on passenger rates is less abundant and more confusing. The passenger-mile rate on all New York railroads shows an increase from 1859 to 1870—but only a moderate one—and a national rate derived from it stands substantially below the rate reported on the thirteen trunk lines. Since the 1880 rate of the trunk lines is comparable with the known 1880 national average, there is a disparity in 1870 between these two methods. With the trend of the New York State rate also at variance with the movement in the national rate from 1859 to 1880, the interpolated estimate is further suspect. In its stead, an average rate somewhat lower than that prevailing on the thirteen trunk lines, but higher than that indicated by the New York results, was selected.[12]

The greater uncertainties of the 1870 rate estimates have less effect on the accuracy of the final output index than might appear at first blush.

[9] Edwin Frickey, *Production in the United States, 1860–1914*, Cambridge, Mass., 1947, pp. 87 ff. John W. Kendrick also uses Frickey's sample to extrapolate 1880 passenger and ton-miles to an earlier date, 1869. But he does not make an adjustment for the increasing coverage of Frickey's sample over time, and hence underestimates both passenger- and ton-miles (Kendrick, *Productivity Trends*, pp. 509–510).

[10] New York Board of Railroad Commissioners, *Annual Report on the New York Railroads*, 1859, 1870, and 1880 (title varies); S. Rept. 1394, 1, pp. 615–617. The sample this time included eight railroads rather than five as before.

[11] The information on the thirteen lines was gathered by *Poor's Manual of Railroads*, and presented in various issues; see, for example, the volume for 1900, p. xlix. The average of these trunk railroads is some .12 cents less than the 2.11 actually used, a deviation whose direction is correct and whose magnitude seems to be of the right order.

[12] This procedure obtains support from a pattern of passenger-rate increase in Massachusetts during the same interval that is closer to the national trend estimated in Table 1.

In the first instance, the gross receipts conjointly implied by the output and rate estimates appear quite consistent with other information in this sphere. Thus the $388.4 million total for 1870 (including allowance for additional revenues from mail, express, etc.) compares with Poor's estimates for 1867 and 1871 of $334.0 and $403.3 million.[13] Furthermore, extrapolation of 1859 and 1880 national receipts upon Frickey's two sample receipts series yields totals of $386 and $360 million, which at worst fall within about a 5 per cent margin of our implied figure. In the second instance, since it is the relative weight of passenger charges to freight charges averaged over two decadal observations that determines the level of the output index, small changes in a single year are of small matter. As a case in point, if the passenger rate implied by the New York State series were in fact used, the index for 1859 and 1870 would be smaller by scarcely more than 1 per cent than the entries in Table 1.

In general, with the availability of official information after 1880 and the low levels of the index before that date, the advance it portrays—while subject to the usual disclaimers of perfect representation—is probably one of our more adequate long-term measures of industrial growth.

Quantitative Measures of Railroad Development, 1840–1910: Capital

The same cannot be said for existing capital estimates. For no part of the period in question are there official statistics of gross investment in current dollars, let alone the desired magnitude of the net value of road and equipment in constant dollars. Capital expenditure was first recorded by the ICC in 1912 and, although book value was collected from 1890 on, this is subject to the vagaries of financial manipulation as well as being limited by its original cost form. This lack led Melville Ulmer to estimate annual gross and net investment in constant and current dollars, as well as the capital stock, as far back as the beginning of 1870.[14] Close examination suggests serious defects in these series that make them unacceptable for use here, or in many other contexts. Since the data have already gained a wide audience, it is important to set forth in some detail the grounds for such a judgment.

The most telling objection is the inconsistency of Ulmer's constant-dollar estimates with physical series corresponding to various parts of the

[13] These figures are reprinted from their original source, *Poor's Manual*, in *Historical Statistics of the United States, Colonial Times to 1957*, Bureau of the Census, Washington, 1960, p. 428, Ser. Q-38.

[14] Melville J. Ulmer, *Capital in Transportation, Communications, and Public Utilities: Its Formation and Financing*, Princeton for NBER, 1960, Appendixes A and C.

capital stock. Thus while Ulmer's value of the capital stock in 1929 dollars increases by 167 per cent over the period 1870–1910, mileage grows by some 400 per cent (trackage even faster), and equipment goes up by a larger factor.[15] Within certain decades—the 1900's are a prominent example—the divergence is more striking. To be sure, Ulmer's series is net whereas trackage and equipment are gross (undepreciated), and this explains part of the difference. But if Ulmer's stock estimates are reconstructed gross on the most favorable terms by adding the flow of constant-dollar gross investment to the original net value of the capital stock for 1870, the growth rate is increased only to 321 per cent and continues to be significantly below that of the physical series. Since we would expect the "true" gross investment series to capture the increasingly important expenditures on stations, realignment, electrification, etc., not included in the mileage and equipment series, the shortfall would be still greater if the two series were of comparable scope.

To appreciate the defects in Ulmer's estimates that contribute to this inconsistency necessitates a brief description of his method. Ulmer starts from current-dollar additions to capital account reported by railroads in certain sample states and sample years. National investment for the sample years is equal to the sample total scaled up by the ratio of national book value of road and equipment to book value of the reporting roads; interpolation on a trackage series fills in the missing years. The total investment in current dollars during the interval 1870–1915 is then checked by comparing this sum with the change in original cost of road and equipment over the period. The two magnitudes are almost identical, a finding which Ulmer takes as confirmation both of a low level of retirements—cumulative gross investment should include expenditures for equipment replacement whereas original cost will not be affected—and of the correctness of his investment flows. The resultant annual series is converted to 1929 dollars by applying a weighted price index of input components, namely, labor, building materials, metals, and implements. A depreciation rate applicable to current-dollar investment is derived from unpublished ICC calculations and some skillful manipulation. The capital stock estimates in constant dollars follow from an adjusted ICC 1936 benchmark; values for later years are the 1936 value plus cumulative net constant-dollar investment; values for earlier years, the 1936 value less cumulative net investment.

[15] For mileage changes and the terminal stock of trackage and equipment, see *Historical Statistics*, 1960, pp. 427 ff. Trackage and equipment estimates have been made for 1870 and are presented as part of this paper.

Despite its frequent ingenuity and a welcome reliance upon the rich resources of railroad reports, Ulmer's technique is seriously marred by inadequate execution. Specifically, the cumulative gross investment flow in current dollars is both understated and subject to important distortions in its annual distribution. A dubious price deflator compounds these difficulties, and thereby contributes to the further underestimate of the growth of the capital stock from 1870 to 1910.

Current-dollar gross investment is not large enough, principally because Ulmer misinterprets nineteenth century railroad accounting categories. Until the ICC regulations of 1907 instituted depreciation accounting, the practice of replacement accounting was almost universal.[16] With the latter, equipment replacements—that is, retirements—were charged to current operating expenses at the time expenditures were made, and no entry ever appeared in the capital account. Hence Ulmer's exclusive focus on the capital account excludes one component of gross investment.

Were retirements as modest as the $239 million Ulmer finds during the period 1870–1914, this objection, however valid, would not be vital. The point is that this estimate of retirements and the simultaneous check upon the magnitude of cumulative gross investment are both far off the mark. The basic identity involved, which can be written $\sum_{0}^{T}$ gross investment$_t$ $\equiv$ book value of road and equipment$_T$ minus book value of road and equipment$_0$ minus $\sum_{0}^{T}$ write-ups$_t$ plus $\sum_{0}^{T}$ retirements$_t$, is obviously not at fault. But the estimate of 1870 book value, $3.4 billion, is. This figure is the result of linear interpolation between 1860 and 1876 book values, a procedure justifiable only if approximately equal absolute increments to the capital account occurred in each of the intervening years. In fact, the average annual increment in mileage (a reasonable proxy for investment despite changing price levels) was about 1,500 miles during the period 1860–69, against more than 4,000 miles from 1870 to 1876. We expect, therefore, that the true book value at the beginning of 1870 should be smaller than $3.4 billion. And so it is. The *American Railroad Journal* tabulation of construction accounts of individual roads yields a more

[16] For rapid confirmation of this point one need only examine the very state reports Ulmer used in making up his sample investment series. In Massachusetts in 1873, for example, all roads clearly charged such replacement purchases of new equipment to current account. Also see the reports of individual companies like the Baltimore and Ohio, Lake Shore and Michigan Southern, and others, where clear distinction is made between replacements and additions to the capital stock in reckoning changes in construction account.

appropriate $2.2 billion.[17] Substitution of this value in the above formula suggests a deficiency of cumulative current-dollar gross investment of well over $1 billion, and thus over 10 per cent of Ulmer's sum.

Indeed, if we apply this method rigorously, and substitute an independent estimate of retirements derived from a model to be described presently, it suggests possible additional understatement from sources other than exclusion of retirements. Thus the correct difference in book value from 1870 to 1910 is $12.4 billion which, with the addition of estimated retirements of $1 billion, brings gross investment to $13.4 billion less write-ups over the period. The ICC estimate of original cost in 1915, when its series began, is only 8.8 per cent less than the corresponding book value, and if this is accepted as a measure of write-up included in the latter, the cumulative investment is reduced to $12.3 billion or $1.6 billion more than Ulmer's series during the same interval. On the other hand, it may well be that the ICC original cost estimates, composed as they were largely of reproduction costs in 1914 prices, understate the write-up inherent in the book value statement.[18] Certainly *Poor's Manual*, a competent contemporary authority, suggests a higher margin, as does the qualitative evidence of the era.[19] A more ample allowance still supports my basic contention that retirements are excluded from Ulmer's estimates, and that they represented a sizable proportion of gross investment.

Not only is the total flow from 1870 to 1910 too small, but also its distribution through time is irregular. Ulmer does nothing to ensure that the level of investment in his various sample years is consistent with the level of the expenditure index used to interpolate changes between such years. That is, if in a given year x miles of trackage is built and sample investment is y, in a subsequent year trackage can well be $2x$ and sample

[17] *American Railroad Journal*, Vol. XLIII, 1870, p. 2. Had Ulmer even consulted *Historical Statistics* (1949, p. 201, Ser. K-18 and K-19), the excess of his estimate would have become apparent.

[18] The original cost series can be found in W. H. S. Stevens, *Analysis of Steam Railway Dividends*, Interstate Commerce Commission, Washington, 1943, Table H. Ulmer reprints it in his Table C-12.

Stevens (*ibid.*, p. 43, n. 3) describes the method of its derivation. There can be little doubt that much of the original cost at that early date was estimated by taking reproduction costs in 1910–14 prices. In the valuation cases before the Commission at the time, actual original costs were a rarity. Moreover, an original cost figure even from company records easily might embody the implicit exaggeration associated with payment to contractors in securities accepted at par but actually selling at less than the market price.

[19] *Poor's Manual* for 1900 (pp. liv ff.) asserts that some 40 per cent of the capital stock outstanding in that year was fictitious. Even if all bonds were sold at par, total cost would be overstated by about 20 per cent, and correspondingly more dependent upon the actual discount on bonds. The implication of the ICC estimate that there was no write-up by 1914 is doubtful at best.

investment $\frac{1}{2}y$, after price changes are taken into account. So, although the expenditure index in the early 1900's stands at levels as great as those of the early 1870's, investment comes to just half as much. Since the ratio of equipment to trackage increased rapidly in the later decades, along with other capital expenditures, the difference is not due to the limitations of the index, which is biased in exactly the opposite direction. The failure to gear the value estimates properly to the underlying physical series is the fundamental flaw. It leads not only to cumulative and decadal distortion but also to annual misrepresentation. In no fewer than six pairs of years do changes in Ulmer's expenditures and expenditure index diverge in *direction*: 1876-77, 1888-89, 1891-92, 1895-96, 1905-06, and 1908-09. A particularly striking case is 1891-92. The 1891 sample yields expenditures of $234 million, that of 1892, $251 million, but trackage opened in the latter year is less than half that in the former. Poor methods of interpolation and of sampling are responsible for these incongruities. Allowance for the lead of outlays over track emplacement and incorporation of equipment changes in the index would improve the annual distribution. Stratification of the sample roads into those in the process of extension and those building *de novo* would tie the levels of the value estimates more closely to the interpolating index than simple escalation by the ratio of assets does.

As mentioned earlier, the conversion of these imperfect current-dollar investment flows to real terms makes matters still worse. As is often done for construction investment, a price index of inputs is used to deflate current expenditures. But since labor bulks large as an input, the part of increased wages that reflects productivity change in the building trades results in substantial exaggeration of the increased price of final output. Labor productivity had an upward trend over the period, and thus the measured change in the real capital stock is biased downward. Adding to this defect, which is admittedly difficult to circumvent, is the selection of a bad index. In particular, the price of metal inputs is an unweighted conglomeration of prices of door knobs, butcher knives, and files, among others, but not of steel rails.[20] At the end of the century, rails were perhaps the largest single metallic input in value, and subject to a sharp downward trend in price. From 1880 to 1889, their price plummeted from $67.52 a ton to $29.25, a decline of almost 60 per cent, but the Ulmer index declines only 25 per cent. In addition, the weights of the index allot less

[20] This is the Aldrich Committee unweighted index of prices of metal implements (excluding pocket knives) contained in S. Rept. 1394. The composition would be irrelevant as long as the series moved approximately like a rail-price series. The point made here, however, is that it does not.

importance to metal inputs than is appropriate and more to other materials with a lesser rate of price decline.[21] The combination of these two factors is sufficient to transform a correctly weighted aggregate price reduction perhaps as great as 30 per cent into price stability during the decade. As a consequence, real capital formation at the beginning of the 1880's is overstated relative to that at the end, and it is toward the end that the large spurt of current-dollar outlay occurred. The use of a skilled-wage series rather than one for laborers and of a materials index comparable in its misrepresentation to the metals index distorts the real series as well, but the effects are not as obvious.

This rejection of Ulmer's post-1870 estimates made it impossible to link my own pre-Civil War investment series to his in 1870, as had been originally intended. Complete correction of his series was not feasible because of the incomplete detail of the published materials; nor in any event would it represent the most efficient method of deriving continuous and consistent capital-stock estimates of the sort required here. For this limited objective, an approach from the physical rather than the value side seems especially promising. Few industries possess such extensive records of physical components of the capital stock, namely, trackage and equipment, which retain reasonable homogeneity over time and which encompass such a large proportion of total investment. On the other hand, the resultant estimates are only a partial replacement for Ulmer's comprehensive coverage of the sector. The task of reworking his investment series, both current and constant, to correct for the error in trend and the annual aberrations still awaits attention.

The construction of capital-stock estimates from physical components is not without its difficulties. Despite the notable extent to which capital expenditures consisted of additions to trackage and rolling stock, over time there was some substitution of other outlays, for stations, realignment of way, electrification, and so forth. But these introduce only a small bias, if any, during the period of our interest, a period of initial extension of the system. As late as 1914–18, equipment alone accounted for more than 40 per cent of total investment, and such direct outlays associated with construction of road—like grading, track laying, rails, and ties, etc.—make up more than half the residual. In total, therefore, the activities to which the index is most obviously sensitive represent almost three-fourths of capital expenditure, and if an allowance were made for the "usual" amount of station and shop construction associated with

[21] Ulmer's weights of 4.8 for other materials—4 for labor and 1.2 for metals—are derived from maintenance outlays of class 1 roads in 1925 and 1935 and are singularly inappropriate to initial construction of road in the late nineteenth century.

mileage extension, an even higher proportion. Very much earlier a similar ratio was not very different—85 per cent in the 1850's—and the maintenance of such a continuing high level so late leaves little scope for trend distortion in a combined trackage and equipment index.[22] Accordingly, in the absence of firm indications of the temporal incidence and magnitude of changing coverage, no adjustment is made here.

Another and more serious problem arises from the changing nature of the physical units over time. On the one hand, there is technological change. An index of equipment designed to measure changes in this segment of the capital stock cannot treat the primitive 10-ton locomotives of the 1830's the same as the later behemoths; nor can a trackage index fail to differentiate between mileage laid with strap iron and later with steel rails. On the other hand, there were geographic shifts in construction that were associated with altered real costs: a mile on the prairies of the Middle West was not as expensive as one scaling the Rocky Mountains.

The principle involved is clear. Each physical unit, whether of track or equipment, should be weighted by its cost of reproduction in the prices and technology of a given year before being compared. In this way, one gets a consistent measure of the capital stock over time, where real investment is measured, as is conventional, by its cost, not its capacity.[23] In the subsequent calculations we apply this rule, as far as the data permit, to deal both with technological change and the aggregation of different types of track—main, second, yard, etc.—and equipment at a moment of time.

No geographic weights are used, however. The shift in the regional concentration of construction is dramatic—almost one-third of total 1890 mileage was located in states west of the Missouri compared with one-tenth in 1870—but its significance depends upon the interregional variance of costs of road construction, and these are surprisingly limited. Total cost per mile of track in the eight regions distinguished in *Poor's Manual* ranges from \$35,000 to \$73,000, with six of the observations clustered from \$35,000 to \$45,000.[24] The differences here are exaggerated

[22] ICC, *Statistics of Railways in the United States for 1918*, p. 87; for comparable distribution in the 1850's (after subtraction for excess interest and discount charged to construction account), see my *American Railroads*, Table B-4.

[23] It is well to point out two characteristics of this technique. First, the choice of a technology base is effectively limited to later years, since the type of construction before that date could be duplicated, whereas the same condition does not hold for early years. Second, there may well be different results corresponding to different technology bases, since the range of products that must be reproduced may be relatively cheaper to duplicate at different later dates.

[24] *Poor's Manual for 1891*, pp. ii, iii, and xviii. The slightly different Census regions would not alter the terms of the comparison.

TABLE 2

NET TRACK IN EQUIVALENT MAIN-TRACK MILES OF 1909

End of Year[a]	Miles of Main Track (1)	Miles of Other Track (2)	Total Track in Equivalent Miles, Specified Date (3)	Rail Weight, Gross (tons per mile) (4)	Index of Resource Content (1909=100) (5)	Total Track in Equivalent Main-Track Miles of 1909 (6)	Cumulative Depreciation Since 1828 in 1909 Equivalent Main-Track Miles (7)	Net (Surviving) Track in Equivalent Main-Track Miles of 1909 (8)
1838	2,633	132	2,699	41	78.6	2,121	135	1,986
1848	6,279	936	6,747	80	89.9	6,065	607	5,458
1858	27,621	4,598	29,920	85	91.3	27,317	2,440	24,877
1869	46,844	9,369	51,528	85	91.3	47,045	6,512	40,533
1879	86,566	18,200	95,666	90	92.8	88,778	13,872	74,906
1889	161,276	40,812	181,682	100	95.6	173,688	27,739	145,949
1899	190,046	64,418	222,255	107.5	97.8	217,574	47,936	169,429
1909	238,116	108,916	292,574	115	100.0	292,574	73,677	218,897

Source

Main track

1838: Gerstner total of 3,172 miles at end of 1839 shifted to 1838 by relative change between two dates in 1880 Census mileage-added series (reprinted in *Historical Statistics*, 1960, Ser. Q-43). For Gerstner mileage total, see *Journal of Franklin Institute*, N.S. XXVI, 1840, pp. 89-102, 227-230, and 301-307; also my *American Railroads*, Appendix B.

1848, 1858: 1860 Census figures for 1850 and 1860 extrapolated as above. *Preliminary Report of the Eighth Census*, Washington, 1862, p. 238.

1869-89: *Poor's Manual* for 1900.

1899-1909: Average of ICC *Statistics of Railways* totals for adjacent fiscal years.

Other trackage

1838: 0.05 times mileage. (For justification of this and other antebellum figures, see my *American Railroads*, Appendix B.)

1848: 0.10 times change in mileage between 1838 and 1848 plus 600 miles of double track in 1850 interpolated to 1848 on 1880 Census mileage series.

NOTES TO TABLE 2 (concluded)

1858: 0.10 times change in mileage between 1848 and 1858 plus 1,700 miles of 1860 double track interpolated to 1858, as above.
1869: Average of 1858 and 1879 ratios of other track to mileage times 1869 mileage.
1879–1909: Same as main track, 1899–09.
Col. 3: Col. 1 + .5 col. 2.
Col. 4: See text.
Col. 5: Col. 4, converted to an index with 1909 base, weighted one-third. Thus the 1838 value, 78.6, is equal to $\frac{41}{115}$ + 200.0/300.0.
Col. 6: Col. 3 x col. 5.
Col. 7: Cumulative depreciation$_t$ = cumulative depreciation$_{t-10}$ + 10 x .01 x (col. 3_{t-10}) + 5 x .01 x (col. 3_{t-10}).
Col. 8: Col. 6 - col. 7.

[a]These years have been selected to conform as nearly as possible to the midpoints of the years for which output has been estimated. From 1880 on, the calendar-year basis of the stocks and the fiscal-year basis of the output flows result in perfect agreement. Beforehand, because of a later fiscal year, the stock may be centered slightly before the midpoint.

owing to variations in rolling stock per mile; roads in the Middle Atlantic group, with the highest cost, operated less than one-sixth of the mileage but one-third of the equipment. Total cost divided only by trackage thus distorts the extent of regional differences in construction of road. Nonetheless, even these imperfect weights applied to the mileage increase from 1870 to 1890 produce a rate of change of only 215 per cent, as opposed to 200 per cent for the unadjusted totals. Accordingly, the price paid for the neglect of this complication is small.

Table 2 presents the calculations translating the initial mileage series into an index of real capital invested in road and structures according to the principle of equivalent costs. First, the mileage of main-line and other track have been aggregated into the single, uniform trackage series in column 3 by assigning weights of 1 and ½, respectively. This approximate relative cost of other track has been derived from both financial and engineering considerations. We start from the general observation that, despite large changes in relative prices over the period, direct superstructure costs do not deviate much from 30 per cent of the total expense of construction. To this outlay for track must be added the investment in the permanent way, grading, masonry, and so on. For double, third, and fourth track, this did not escalate proportionally, but by a much smaller factor. Two engineers, arguing from technical considerations, claim the incremental investment in this other construction to be less than 50 per cent of that required for first track. A weight of one-half for double and other main-line track is therefore suggested.[25] The same value is used for sidings, although the possible substitution of lighter rails could reduce the proportion somewhat; however, one railroad commission valuation in the opening years of the twentieth century indicates a relative cost of .55, so the one-half weight cannot be too far off the mark.[26] Yard track is assigned the same weight also. Although newly constructed from the start, because the selection of the site was determined by advantageous physical circumstances—and hence less excavation, grading, etc.—and because multiple tracks were always involved, the per unit cost of the trackage inevitably was less than that for first main track. In the most unfavorable circumstances, where only two tracks were built upon a substructure as expensive as the average for main line, the per mile relative cost for yard trackage would be .75. For parallel trackage many times greater, built under favorable conditions, the previous one-half weight therefore retains its applicability. This is fortunate, since the distinction among the various types of other track is never very clear in the mileage statistics until very late in the period.

The second step in the process is to convert the equivalent main track miles of the various dates to equivalent mileage of a specific date. This requires temporal relative cost weights to supplement the previous cross-sectional ones. That is, we must determine what it would have cost to construct the mileage at the specified dates, with 1909 prices and technology, but as it actually was; this cost relative to 1909 costs can then be used to derive a new mileage series homogeneous through time.

The most apparent way in which mileage differed over time is the increase in rail weights. A network laid in the 1830's principally with strap iron of 25 gross tons to the mile gave way to one in the first decade of the twentieth century with steel rails weighing something like 115 gross tons to the mile. At a minimum, therefore, the rail component of total investment in road must be reduced in earlier years relative to 1909 if temporal uniformity is to prevail. At a maximum, all investment could

[25] See W. M. Camp, *Notes on Track*, Chicago, 1904, p. 623; and Arthur Wellington, *The Economic Theory of the Location of Railways*, 6th ed., New York, 1887, p. 765. Wellington frames his judgment directly in terms of the increment to total cost associated with the additional grading and masonry. His 10 to 15 per cent increment to total cost is roughly equivalent to Camp's evaluation of a 50 per cent increase in substructure outlays, since grading and masonry made up about 40 per cent of the total.

The addition of the 10 to 20 per cent required for the substructure of a double track to direct superstructure outlays of about 30 per cent leads to the total incremental cost of one-half used here. (Wellington's 10 to 15 per cent range is probably too low because it excludes some other variable costs like interest, station facilities, etc., and that is the reason for a one-half weight rather than something smaller.)

[26] Cited in F. Lavis, *Railway Estimates*, New York, 1917, pp. 35–36.

be scaled in this manner if the increase in rail weights represented parallel improvements in the substructure, bridges, shops, and so on. We follow an intermediate course here, and allocate to the variation in rail weights shown in column 4 an influence of one-third the approximate relative importance of the entire superstructure in order to derive the index of resource content in column 5. The rationale for such a weight is the constancy of quality of much of railroad investment over time. Excavation and grading, masonry work, and the like were probably as well done in the antebellum period as at the end of the nineteenth century, quite independently of the continuous improvement in superstructure. All expenditure on the superstructure is considered, because not only did rail weights increase, but the number of ties per mile, the depth of ballast, the type of rail chairs, and other costs of the superstructure also changed as the rails did. Two cross-section observations are relevant here. The first is the evidence that the investment in the substructure at a moment in time is determined by the circumstances of terrain, etc., and not by rail weight. The second is the almost proportional movement of rail weights and costs per mile for the entire superstructure (of which direct purchases of rails constitute less than half); as rail weights increase from 50 to 60 to 80 to 100 pounds per yard, estimated costs climb from $7,600 to $8,800 to $10,600 to $12,300 a mile.[27] Although neither piece of evidence relates exactly to the problem at hand—and could not since our difficulties lie with reconstructing the unobserved—they do afford some support for our decision to weight the increased size of rails only by the superstructure component of road investment and not to apply it either more or less universally. That costs perhaps did not increase quite as rapidly as rail weight did provides a small additional, and warranted, allowance for the better bridges and other structures along the line.

Since the index in column 5 is central to the final results, it may be well to emphasize its insensitivity to errors in the average rail weights specified in column 4. These last are only approximations, based upon scattered contemporary reports on the subject, except for the terminal observations. The 1838 weight is firmly established from Gerstner's researches into the type and weight of rail on almost all railroads then in operation. Similarly the 1909 observation is sufficiently close to the first ICC report on the subject in 1920 so that its order of magnitude is well founded. The

[27] *Ibid.*, pp. 34, 240. Different relative prices of superstructure inputs will influence the results, of course. At this date, the first decade of the twentieth century, rails were relatively cheap. The more expensive rail costs are, the more nearly proportional is the movement. Over much of the period, therefore, the relationship was presumably better than that described here.

gradations from decade to decade are limited in importance because of the minor weight attached to the series;[28] from 1848 to 1909, while rail weight goes up almost by 50 per cent, the index goes up by 9 per cent. The crucial assumption, therefore, is the one-third weight to be assigned to the rail index rather than the precision of that index itself.

The series of 1909 equivalent main track miles must be further adjusted to reflect depreciation if it is to measure the capital stock at various dates. Wear of rails and ties can be excluded because their lives are short, and their replacement is implicit in the trackage figures. (Of course, to the extent that renewals are not exactly uniform, the proportion of track requiring replacement may differ slightly in each of the terminal years of Table 2, and may thereby distort short-term comparisons.) For the inevitable obsolescence of the more permanent components of the road, such as earthworks, culverts, etc., and for shorter-lived structures inadequately maintained, a 1 per cent charge per annum is levied. This corresponds to the ICC finding of 0.86 per cent in 1917 and 0.82 per cent in 1949, and is set slightly higher to reflect the small increase in longevity of the permanent way over time.[29] In addition, because the depreciation allowance is deliberately applied to the mileage series unadjusted for resource content (column 3), the effective rate is tapered downward from 1.28 per cent in the 1830's to 1 per cent in the early twentieth century. Subtracting the cumulative depreciation so calculated in column 7 from the gross series of column 6 yields the final net series in column 8.

Tables 3 to 5 present a transformation of equipment to 1909 equivalent freight cars through application of the same real cost principle. The procedure in this instance is slightly more complicated because the shorter life of equipment necessitates the derivation of production statistics rather than simple manipulation of the stocks as before. The stock of locomotives, passenger cars, and freight cars is already reduced to a quasi-net basis owing to prior retirements, but it also contains an element of depreciation which can be determined only by exact knowledge of its vintage. Hence the need for production statistics.

[28] The allocation to intervening years is intended to convey a consensus of comment on the trend to heavier rails. For the antebellum years, see my *American Railroads*. Subsequently, cf. *Railway Gazette*, Vol. IV, 1872, p. 107; XII, 1880, p. 334; Wellington, *Economic Theory*, p. 119; Lavis, *Railway Estimates*, p. 242.

Note that there is no distinction here between iron and steel rails since in 1909 their prices had converged to the point where no significant difference between the two existed. Since 1909 technology is the basis of the reduction, it is conditions at the latter date that are relevant.

[29] These are cited by Ulmer, *Capital in Transportation*, p. 225. For evidence of pre-Civil War rates of similar (but slightly higher) magnitude, see my *American Railroads*, Appendix B.

Table 3 presents their determination from prior information on the stocks and the retirement rates. The stock at any date is equal to the stock a decade earlier plus intervening purchases, less intervening retirements. Once the retirement rates are specified, retirements are determined, and purchases then follow directly. The equipment lives used in Table 3 are twenty years for both locomotives and freight cars, and twenty-five years for passenger cars (with the exception that twenty years has been applied to the production of the 1830's). These are a fair consensus of informed engineering opinion, and they incorporate a longer service life over time, since the average mileage run each year showed an upward tendency.[30] Fortunately, the validity of the assumptions can be checked from 1879 on by comparing the implied production estimates against actual production statistics. The results are quite favorable as the figures below reveal:[31]

	1880–89	*1890–99*	*1900–09*
Locomotives			
Predicted	18,957	18,326	40,893
Produced	17,200	17,060	44,234
Passenger cars			
Predicted	16,771	13,022	25,015
Produced	12,857	11,393	25,113
Freight cars			
Predicted	686,701	643,819	1,473,837
Produced	532,400	723,900	1,455,300

The large overstatement of the 1880's is as much due to the inadequate coverage of the production series as to the inaccuracy of the retirement model. The production series excludes rather extensive production by railroad repair shops. As late as 1900, railroads themselves produced an addition of 20–25 per cent to commercial output of cars and the trend, if any, would make the earlier proportion even larger. Self-manufacture of locomotives was less widespread. The inclusion of exports in the production tabulation only partially offsets the understatement, since these amounted but to 5 per cent of output.[32] For the same reason, the closer correspondence after the 1880's exaggerates the adequacy of fit.

[30] For retirement ages, see Wellington, *Economic Theory*, p. 419; J. L. Ringwalt, *Development of Transportation Systems in the United States*, Philadelphia, 1888, p. 320; *Railroad Gazette*, Vol. XVIII, 1886, pp. 201, 869; Emory Edwards, *Modern American Locomotive Engines*, Philadelphia, 1883, p. 119.

[31] These production statistics come from *Historical Statistics*, 1960, p. 416, Ser. P-213-215.

[32] *Twelfth Census, 1900*, Vol. X, *Special Reports on Selected Industries*, pp. 273 and 279, gives production of cars in railroad repair shops. For the importance of exports, see William Howard Shaw, *Value of Commodity Output Since 1869*, New York, NBER, 1947, pp. 56–57.

TABLE 3

DERIVATION OF EQUIPMENT PRODUCTION ESTIMATES

End of Year	Locomotives	Passenger Cars[a]	Freight Cars[b]	Locomotives	Passenger Cars[a]	Freight Cars[b]
		STOCK				
1838	375	417	1,250			
1848	1,168	1,238	14,415			
1858	5,158	4,703	80,402			
1869[c]	10,000	10,000	185,000			
1879	17,084	16,528	480,190			
1889	30,566	28,524	1,051,141			
1999	37,183	34,282	1,330,520			
1909	59,119	46,422	2,117,656			
		RETIREMENTS			PURCHASES	
1829-38				375	417	1,250
1839-48				793	821	13,165
1849-58	375	417	1,250	4,365	3,882	67,237
1859-69	950	533	16,000	5,792	5,830	120,598
1870-79	4,525	2,450	69,250	11,609	8,978	364,440
1880-89	5,475	4,775	115,750	18,957	16,771	686,701
1890-99	11,609	7,264	364,440	18,226	13,022	643,819
1900-09	18,957	12,875	686,701	40,893	25,015	1,473,837

Source

Stock

1838-58: See my *American Railroads*, Appendix D, for estimates of equipment stocks at end of 1839, 1849, and 1859. These were extended to the stated years (after allowance for replacements in the instance of 1858) by an annual series of locomotive production to be found in *ibid.*, Appendix B, Table B-8.

1869: These are approximated to the nearest thousand and are derived by interpolating the aggregate ratio of each type of equipment to earnings on the sample ratios derived from twenty-five railroads reporting at the three dates, 1859, 1869, 1880. The sample was representative at the terminal dates of 1859 and 1880; that is, the sample ratios corresponded to the national ratios, so interpolation is a satisfactory procedure. The sample data came from the share lists of the *American Railroad Journal* in 1860 and 1870, and the 1880 Census. The aggregate fiscal 1870 receipts needed to convert the ratios to absolute stocks are estimated from the physical outputs and are discussed above.

The final estimates are consistent with the contemporary report of 10,000 locomotives and 214,000 cars in the early 1870's (*Railway Gazette*, Vol. III, 1873, p. 287).

1879-1909: Same as trackage; see Table 2.

Retirements: $P_{t-9—t} = P_{t-29—t-20}$ for locomotives and freight cars; $= P_{t-34—t-25}$ for passenger cars, after 1829-38. A linear distribution of production was assumed to obtain $P_{t-34—t-25}$. (Since there is one eleven-year interval from 1859 to 1869, the formula had to be adjusted for the estimated output in the overlapping year; this is the reason for the lack of exact correspondence between retirements and production entries two decades previously for some of the figures.)

Purchases: Equals change in stocks plus retirements.

[a]Includes baggage and mail cars in passenger service. For 1838-58, the number of cars is given in terms of eight-wheel equivalents. Thereafter, most cars took this form, with the exception of some twelve-wheel cars.

[b]For 1838-58, noncoal cars in eight-wheel equivalents. Thereafter, most box cars were of this variety. Coal cars are reported as units, and no attempt has been made to render the gradual change from four-wheel to eight-wheel cars.

[c]For 1869, since an earnings estimate was essential to the method, the equipment stock corresponds more closely to the end of the output year rather than its midpoint.

But only in the instance of freight car output in the 1890's is the divergence —including an allowance for understatement in the production series— troublesome. Even here, the apparent understatement of retirements only lends authority to our expressed view of the seriousness of their neglect by Ulmer. From 1870 through 1909, we estimate retirements at 40,666 locomotives, 27,364 passenger cars, and 1,236,141 freight cars. At prices of $8,000 per locomotive, $2,500 per passenger car, and $400 per freight car—prices that are among the lowest of the period—retirements are seen to amount to $900 million, or far more than the Ulmer results yield.[33]

Just as adjustment for changes in the weight of rails increased the comparability of the trackage series over time, so the weight of equipment provides initial guidelines for a similar transformation to a consistent real cost standard. The average weight of engines rose from something like 10 tons in the 1830's to exactly 72 tons in 1909 as measured by an ICC count. The increase in weight seems to have been fairly regular, and modest, until the 1870's. Then the introduction of the Mogul and Consolidation types to replace the standard American 4-4-0 led to more rapid change. Accompanying this acceleration, and interdependent with it, was the development of more capacious freight cars. Not only did the use of steel in trucks and underframes make possible an increase in size with far less than proportional investment, but also newer designs using conventional materials came forth as soon as driving power was available.[34] Therefore the virtual doubling of capacity between the 1870's and 1880's was accomplished with little increase in dead weight (and resource cost).

[33] For prices twice as large as these in the 1870's, see *Railway Gazette*, Vol. III, 1873, p. 34, and Vol. I, 1871, p. 516. These prices are representative of the 1880's (cf. Wellington, *Economic Theory*, pp. 163, 411, and 565). In 1889 the average price of locomotives was $8,200, and in 1899, $9,500; in the latter year, passenger cars were sold at $7,500 and freight cars at $530. By 1909 the three types of equipment were priced at $12,065, $8,638, and $843. All these prices, except that for locomotives in 1909, come directly from Census reports. The 1909 locomotive price was calculated by multiplying the 1899 price by the ratio of the prices of locomotives manufactured in railroad repair shops at the two dates, i.e., $P_{1909} = P_{1899} \times p^1{}_{1909}/p^1{}_{1899}$, where p^1 is the price of locomotives built in repair shops and is given in the Census. This technique is necessary because the average locomotive built by railroads themselves was undoubtedly larger than average since such railroads had heavier traffic than average.

[34] Credit for the rapid increase in the ratio of payload to dead weight before 1900 must be sought elsewhere than in the use of steel. As late as June 30, 1915, out of some 55,000 passenger cars only 10,884 were steel and 5,197 had steel underframes. Freight cars took part in this materials revolution to a greater degree: of more than 2,300,000 freight cars, 515,000 were steel (almost all for the transportation of coal) and another 681,000 had steel underframes (ICC, *Statistics of Railways in the United States for 1915*, pp. 22–23).

In light of this record, it is difficult to attribute the early decline in the dead-weight ratio to the substitution of steel. That transformation, with its significant productivity effects, discussed later, is one that will repay much more careful study.

TABLE 4

REAL COST OF EQUIPMENT

	Locomotive Weight (tons) (1)	Index of Real Cost, Locomotives (1909=100) (2)	Passenger-Car Weight (tons) (3)	Index of Real Cost, Passenger Cars (1909=100) (4)	Freight-Car Weight (tons) (5)	Index of Real Costs, Freight Cars (1909=100) (6)
1830-38	10	42.6	14	48.7	8.0	56.6
1839-48	20	51.8	14	48.7	8.0	56.6
1849-58	25	56.5	14	48.7	8.0	56.6
1858-69	30	61.1	16	52.8	10.0	65.7
1870-79	35	65.7	20	61.0	11.0	70.3
1880-89	45	75.0	27	75.4	12.5	77.1
1890-99	58	87.0	35	91.8	15.7	91.8
1900-09	78	105.6	45	112.3	18.3	103.7
1909	72	100.0	39	100.0	17.5	100.0

Source

Col. 1, 1830-1858: *Railway and Locomotive Historical Society Bulletin*, No. 35, 1934, pp. 10-37.

Col. 1, 1858-1909: *Ibid.*; Wellington, *Economic Theory*, pp. 407, 499, 544. *Twelfth Census, 1900*, Vol. X, *Manufacturing*, p. 245. ICC, *Statistics of Railways* for 1902 and 1909, giving average weights at those dates.

Col. 2: $2/3 \left(\frac{\text{weight}_t}{\text{weight}_{1900-09}}\right) + \frac{1}{3}\,100.0.$

Col. 3: J. L. Ringwalt, *Development of Transportation Systems in the United States*, Philadelphia, 1888, p. 337; Wellington, *Economic Theory*, p. 524; Edwin Pratt, *American Railways*, London, 1903, p. 89; Lavis, *Railway Estimates*, New York, 1917, p. 424.

Col. 4: $4/5 \left(\frac{\text{weight}_t}{\text{weight}_{1900-09}}\right) + \frac{1}{5}\,100.0.$

Col. 5: Ringwalt, *Development of Transportation*, p. 336; Wellington, *Economic Theory*, pp. 114, 135; *National Car Builder*, Vol. VIII, 1877, p. 9; Pratt, *American Railways*, p. 51; Master Car Builder's Association, *Car Builder's Dictionary for 1906*, New York, 1906, pp. 166 ff. *Twelfth Census, 1880*, Vol. X, *Special Reports on Manufactures*, p. 264. ICC, *Statistics of Railways* for 1902 and 1909, giving average capacities at those dates. For the fares associated with those capacities, see *Car Builder's Dictionary*.

Col. 6: $4/5 \left(\frac{\text{weight}_t}{\text{weight}_{1900-09}}\right) + \frac{1}{5}\,100.0.$

From the 1880's to the first part of the twentieth century another doubling in capacity occurred, again with less than equivalent increases in weight. Precise information is lacking on the development of passenger cars, but it seems a substantial upgrading of passenger comfort occurred during the latter part of the nineteenth century. Giant palace and sleeping cars, as well as the enlargement of the more prosaic coaches, contributed to perhaps a tripling in the average size of units between the antebellum decades and 1910. Moreover, increased relative prices of passenger cars versus freight cars testify to this greater change in real costs in the former.

Table 4 summarizes this history. Associated with the weight changes are real cost changes but, as before, not in exact proportion. Fortunately, there is more to go on here than the indirect methods used to convert variations in rail weight to variations in unit resource consumption. Actual prices of locomotives per unit weight at a moment of time afford a measure of the relationship we are after. What data have been found tend to indicate a decline in cost per ton as size increases, that is, a change in real cost substantially smaller than the simple increase in weight. Thus, in 1876, as locomotives increased in weight from 20 to 40 tons, the price went up from $7,000 to $9,200. In another instance ten years later, Baldwin locomotives varied from a 24-ton American to a 59-ton Consolidation, with selling prices rising from only $5,750 to $9,750. The marginal cost was only $110 per ton against an average cost of almost $250 per ton for the smaller unit. Later, in 1906, the same circumstances prevailed: a 40-ton freight engine was quoted at $8,000; an 80-ton engine, at $12,800; and a 140-ton engine, at $20,160. Over a somewhat narrower range, from 46 to 60 tons, a final observation dating from the late 1880's reveals constant unit costs.[35] All four bodies of information diverge from the findings of Dorothy S. Brady which assert increasing unit prices over the size range.[36]

Despite this unsatisfactory current state of knowledge about price-size relationships for locomotives, I have accepted the evidence pointing to a declining cost pattern. Materials inputs made up only slightly more than half the expense of locomotive production, so doubling of size would yield increased costs of only 50 per cent on this account. For such a specialized industry as locomotive production in which engineering salaries and wages of skilled workmen loom large, and with machine tools capable

[35] Wellington, *Economic Theory*, pp. 411 and 565; Lavis, *Railway Estimates*, p. 418; *The American Railway*, New York, 1889, p. 126.

[36] See her "Relative Prices in the Nineteenth Century," *Journal of Economic History*, June 1964, especially Table 2. The evidence presented here also seems to contradict her generalization of price-size relationships to either increasing or U-shaped forms.

TABLE 5

STOCK OF EQUIPMENT IN 1909 EQUIVALENTS

End of Year	Gross Stock, Loco-motives (1)	Net Stock, Loco-motives (2)	Gross Stock, Passenger Cars (3)	Net Stock, Passenger Cars (4)	Gross Stock, Freight Cars (5)	Net Stock, Freight Cars (6)
1838	160	114	203	152	708	531
1848	571	348	603	371	8,159	5,765
1858	2,877	1,952	2,290	1,672	45,507	30,405
1869[a]	5,924	3,102	5,108	3,130	115,684	65,645
1879[a]	10,994	6,562	9,391	5,617	332,689	211,273
1889[a]	21,867	12,570	19,585	12,453	786,087	461,135
1899	30,097	15,447	27,336	14,895	1,120,912	575,631
1909[b]	59,062	36,352	46,367	27,888	2,119,865	1,294,033

Source

Gross stock of all types of equipment:

Cols. 1, 3, 6: (production$_t$ times index of real cost$_t$) minus (retirements$_t$ times index of real cost$_t$), where the inputs are taken from Table 3 and 4.

Cols. 2, 6: .75 production$_{t-9—t}$ plus .25 production$_{t-19—t-10}$.

Col. 4: .8 production$_{t-9—t}$, plus .4 production$_{t-19—t-10}$ plus .1 (.5) production$_{t-29—t-20}$.

[a]There is some small modification in these years of the formulae for the derivation of the net stock due to the eleven-year interval from 1858 to 1869, and hence a slightly different average age of equipment.

[b]The 1909 entries deviate from the comparable gross stocks of Table 3 only because of rounding.

TABLE 6

REAL NET CAPITAL STOCK, 1838-1909
(million 1909 dollars)

End of Year	Equipment (1)	Track (2)	Total[a] (3)	Index (1909=100) (4)	Index, Variant II (5)
1838	2.9	79.8	82.7	0.8	0.8
1848	11.4	219.4	230.8	2.2	2.3
1858	59.2	1,000.1	1,059.2	10.1	10.6
1869	111.7	1,629.4	1,741.1	16.6	17.3
1879	286.1	3,011.2	3,297.4	31.5	32.5
1889	606.8	5,867.2	6,474.0	61.9	63.7
1899	749.6	6,811.0	7,560.6	72.3	74.2
1909	1,658.2	8,799.7	10,457.9	100.0	100.0

Source

Col. 1: Net stock of locomotives times $11,000; net stock of passenger cars times $8,000; net stock of freight cars times $800.
Col. 2: Net surviving mileage times $40,200.
Col. 3: Col. 1 plus col. 2.
Col. 4: Total divided by 10,457.9.
Col. 5: Index of col. 1 times .1 plus index of col. 2 times .9.

[a]May not add to total because of rounding.

of turning out a variety of shapes and sizes, the variable costs of other inputs well might decline per unit, and it is difficult to imagine their increase. In the subsequent calculations, therefore, I have allowed all materials inputs to increase proportionally with the increase of weight, but only about three-tenths the other costs. This is equivalent to assuming that two-thirds of total cost is influenced by the increase in weight, and roughly accords with the weight-price data cited earlier.[37] Column 2 of Table 4 presents the index of resource content for locomotives based upon this weighting scheme. The ratio of materials purchases to value of final product is not the same for the manufacture of passenger and freight cars, and so this relationship between weight and resource content will not hold there. But the same general method can be used, in which all materials inputs and one-third of other inputs vary with weight, inasmuch as scattered data affirm declining unit costs for cars as well.[38] Since materials were more important in car manufacture, the more nearly proportional indexes of columns 4 and 6 result.[39]

To estimate the net stock of equipment in consistent equivalents first requires conversion of all production flows to the common 1909 denominator; that is why the indexes of real cost have been put in decadal terms rather than in those of a single date. This done, the gross stock at each date is easily reconstructed in 1909 equivalents from the information in Table 3. To these are applied depreciation rates of 5 per cent for locomotives and freight cars, and 4 per cent for passenger cars, following the useful lives of the various types of equipment developed earlier. The results are presented in Table 5.

Two additional pieces of information are required to transform the materials already developed into a measure of the net capital stock. The first is a set of weights to combine the various types of rolling stock; the second, the weights to aggregate equipment and mileage units. For both, 1909 prices are used in order to maintain a consistent technology and price base, but as we shall show, the results are not especially sensitive to this specification. Let us begin, however, with the capital data in 1909 dollars and technology presented in Table 6.

[37] In both 1890 and 1900, materials outlays absorbed slightly more than one-half the total costs of locomotive construction, with labor inputs about 40 per cent (*Twelfth Census, 1900*, Vol. X, p. 243).

[38] See Lavis, *Railway Estimates*, pp. 423 and 428–429.

[39] Materials were about two-thirds of the value of cars in 1889, 1899, and 1909. So variable costs of .67 + .3(.33) yields variable costs of .77 (or four-fifths) the change in weight. The larger fraction (rather than three-fourths) was used, since the very large range encompassed here would tend to cause convergence to proportionality. For the materials ratios, see the *Twelfth Census, 1900, Special Reports on Manufactures*, Vol. X, p. 267, and *Thirteenth Census, 1910*, Vol. VIII, p. 474.

The equipment stock in Table 5 has been valued at prices of $11,000 per locomotive, $8,000 per passenger vehicle, and $800 per freight car. These are derived from corresponding Census valuations of $12,045, $8,638, and $843 for the year 1909-10, after adjustment for the greater size of equipment produced in that year than the average for the stock as a whole. The prices are slightly higher than direct application of the earlier formulas would indicate in order to allow for delivery and set-up costs met by the railroads and included in capital outlays.[40]

This equipment total for 1909 is an input in the determination of the 1909 price for construction of an average mile of main track.[41] This latter is not observable since in a year of limited construction, concentrated geographically, the cost per mile of road actually built is not a good proxy for the national average reproduction cost. What has been done, therefore, is to subtract this equipment estimate of $1.7 billion from Ulmer's 1909 total net capital stock estimate and thereby obtain a corresponding aggregate for net road investment alone. This is convertible into a per mile statistic by division by the earlier series of net 1909 equivalent main trackage. The resultant unit price of $40,200 is applied to the quantities in all previous years.

Following so soon after my severe criticism of Ulmer's pre-1909 figures, this ready acceptance of his 1909 net capital stock estimate may give the impression of a double standard. There is none. Ulmer's investment flows beginning with 1912 are derived from the ICC reports, not the sampling method under attack earlier. Likewise, his post-1914 price index is also entirely of ICC origin. Finally, his capital stock estimates throughout are developed by adding his net investment figures to an ICC benchmark of January 1, 1937. This means that, as long as the constant dollar investment flows between a given date and January 1, 1937, are

[40] To determine the prices for the average equipment stock as of 1909, the prices of the average increment to the stock in 1909 were divided by the relevant indexes of real cost. The average weight of the additions to locomotives and freight cars was calculated by using the ICC information on purchases and retirements, and the weights of the stock in 1908 and 1909. These gave rise to indexes of 114.8 and 109.1, respectively; the index of real cost in Table 4 was used for passenger cars in the absence of exact information. These divided into prices of $12,271 for locomotives, $8,313 for passenger cars, and $843 for freight cars yield 1909 prices applicable to the 1909 stock of $10,689, $7,402, and $772. (Note that the 1909 prices used here differ slightly from the Census values of footnote 32 because they are adjusted for manufacture in railroad repair shops.) These prices in turn were rounded to the values cited in the text.

[41] The exclusion of cars in company service (information on which is not available continuously) leads to a very small and insignificant bias here because it overstates the investment in road relative to equipment and these two do not grow in parallel fashion. How limited this distortion is may be seen from the later comparison between columns 4 and 5 of Table 6, which are the results of applying two different sets of weights for road and equipment.

accurate, so is the capital stock estimate. The date 1909 satisfies this condition; earlier dates do not because the flows are subject to the flaws detailed before. Beyond this, there is further corroboration from various attempts by state railroad commissions around 1909 to estimate current reproduction costs less depreciation of railroads lying within their borders. In the instance of Nebraska, the 1909 valuation, less cost of right-of-way and station grounds, was $34,000 per mile. Since the book value of railroads in that state was some 30 per cent below that for the country as a whole, the implied national valuation of $47,000 per mile of roadway corresponds quite well with the $44,000 implied by Ulmer's net capital stock estimate.[42] Accordingly, the 1909 Ulmer total can be equated with mine, a procedure which has the added virtue of allowing a smooth linkage with Ulmer's subsequent, and reliable, capital stock totals.[43]

In light of the successive layers of assumption which underlie these final estimates of the net capital stock, it is essential that there be some independent checks upon their validity. The cause of the most easily allayed doubt is the influence of alternative relative prices upon the movements of the capital stock series. Column 5 of Table 6 presents an alternative index of total capital based upon a share of equipment in total investment of 10 per cent, and a 90 per cent share of road.[44] The 1909 prices actually used imply constant shares of 16 per cent and 84 per cent, which, although representative of the situation at the terminal date, overstate the role of equipment during much of the period—hence the relevance of the weighting scheme of Variant II. Note how little difference the substitution makes. A similar test on the equipment total was performed by substituting relative prices for locomotives, passenger cars, and freight cars that were more typical of nineteenth century conditions than

[42] *Fourth Annual Report*, Nebraska State Railway Commission, 1910-11, pp. 328, 330, and 498. The book value of road and equipment was $42,000 per mile for Nebraska railroads versus $58,000 for all United States railroads, as calculated from ICC statistics for 1909.

[43] His constant-dollar estimates can be converted to 1909 dollars by multiplying by .568, the ratio of the value of his price index in 1909 to that in 1929. Since the ICC index is based upon 1910–14 weights, the earlier constant dollars are probably more appropriate in any event.

[44] This ratio is probably more indicative of the situation during most of the nineteenth century. See my *American Railroads*, Table B-4, for the antebellum period, and Ulmer, *Capital in Transportation*, p. 225, citing the ICC, for the latter part of the period.

The use of shares as weights for the index is identical with the use of prices for the original quantities:

$$\frac{R_t}{R_0}\cdot\frac{P_{R_0}R_0}{P_{R_0}R_0+P_{E_0}E_0}+\frac{E_t}{E_0}\cdot\frac{P_{E_0}E_0}{P_{R_0}R_0+P_{E_0}E_0}=\frac{P_{R_0}R_t+P_{E_0}E_t}{P_{R_0}R_0+P_{E_0}E_0}$$

where R is the quantity of road, P_R its price, E the quantity of equipment, and P_E its price.

those in 1909 were; the principal difference is the increase in the relative price of passenger cars by the latter date. Although not shown here, the two alternatives move in virtually identical fashion. The further force of these results is the independent validity of the rates of growth of the capital stock estimates even if the absolute values based on Ulmer's 1909 total are in error.

Beyond this reassurance of relative inconsistency, there are some measures of absolute reliability as well. Table 7 brings together the relevant information. The first test compares the antebellum flow and stock estimates with a set derived by deflating current dollar expenditures developed from railroad accounts.[45] The almost perfect agreement in the decades of the 1830's and 1840's is heartening. At their worst in the 1850's, moreover, gross capital formation obtained from the present model is within 20 per cent of the other series, with the corresponding terminal stocks still closer. In terms of deviation from a long-term trend, the error is negligible, in sharp contrast to the break in 1869 when the Ulmer series begins.

A second check involves extension of the method to the decade beyond 1909 when Ulmer's data assume the authority of an official basis. The last line in Table 7 presents the results. My capital stock projection of $11,277 million in 1909 dollars falls short of the Ulmer $12,053 million because of a corresponding underestimate of gross investment.[46] That

[45] The conversion from prices of 1860 to those of 1909 was accomplished by substituting the corresponding 1909 prices of rails, daily wages of unskilled labor, materials, and locomotives for the 1860 ones. The 1909 locomotive price first was converted to a 1909 price for an 1860-size locomotive. Actual 1909 and 1860 prices are: rails, $29.40 and $49.98 per ton; labor, $1.38 and $1.04 per diem; locomotives, $6,710 and $9,250. The relative materials price of 1.493 was calculated from the Warren and Pearson and BLS index of wholesale prices of building materials. Sources for the 1909 prices are: rails, *Historical Statistics*, 1960, p. 123, Ser. E-108, with an allowance of 5 per cent for delivery; labor, ICC *Statistics of Railways for 1909*, daily wages of "other trackmen"; locomotives, see above; materials, *Historical Statistics*, 1960, pp. 115, 117, Ser. E-8 and E-21.

The use of a daily-wage relative avoids overstating the increase in costs between the two dates, since some of the productivity advance was absorbed in a shorter working day. This, and a large weight for materials, helps explain the very different index found by Ulmer (based after 1890 on hourly wage rates). His 1909-1860 relative is 1.75 and would place the pre-Civil War estimates in sharp contradiction. (But the rate of change within the antebellum period would still agree; at issue only would be the change from 1858 to 1869, and even with Ulmer's cost index, his 1869 estimate is out of line.)

[46] As further evidence of the satisfactory fit of the retirements model in this period, there are the ratios of predicted to actual equipment purchases during the decade 1910–19: locomotives, 1.056; passenger cars, .953; freight cars, .863. Information on actual purchases and retirements during the decade may be found in ICC *Statistics of Railways for 1919*, p. 15.

TABLE 7

ALTERNATIVE INVESTMENT AND STOCK ESTIMATES
(million 1909 dollars)

	Gross Capital Formation		Capital Consumption Allowance		Net Capital Stock (terminal dates)	
	Variant I (1)	Variant II (2)	Variant I (3)	Variant II (4)	Variant I (5)	Variant II (6)
1828-38	89.3	88.8	6.6	4.6	82.7	84.2
1839-48	172.2	172.5	24.1	30.0	230.8	226.7
1849-58	926.9	761.2	98.5	114.5	1,059.2	873.4
1859-69	919.9		238.0		1,741.1	3,911.0
1870-79	2,010.4	2,458.0	454.1	843.0	3,297.4	5,526.0
1880-89	4,094.6	3,478.0	918.0	1,271.0	6,474.0	7,733.0
1890-99	2,498.6	2,659.0	1,412.0	1,767.0	7,560.6	8,625.0
1900-09	4,945.8	3,967.0	2,048.5	2,133.0	10,457.9	10,459.0
1910-19	3,554.1	4,414.0	2,784.5	2,820.0	11,227.5	12,053.0

Source

Col. 1: Purchases of equipment in 1909 equivalents and change in undepreciated 1909 equivalent main trackage times 1909 prices.
Cols. 2, 6, 1828-58: Gross investment in 1860 dollars from Table B-10 (of my *American Railroads*) times 108.23.
Cols. 2, 6, 1870-1919: Gross investment in 1929 dollars from Ulmer, *Capital in Transportation,* times 56.8.
Cols. 3, 4: Gross capital formation minus changes in net capital stock.
Col. 5: Table 6, col. 3.

the procedure should yield such favorable results in that decade with the smallest increase in mileage of road since the 1860's, and consequently a much larger expenditure upon betterments than additions, is confirmation of its merit. The shortfall is significant not only because it represents the anticipated deviation, but also because it reinforces the criticism earlier made that Ulmer's gross investment estimates before 1910 are too small. It would require a sharp reversal indeed, and within a single decade, in the coverage of the road and equipment index to explain the exactly opposite divergence between Ulmer's investment flow of 1900–09 and my own.

A final test consists of the very magnitude of that divergence over the longer span 1870–1909. Ulmer's total gross investment is about $1 billion (1909) smaller than mine. Earlier I have contended that the principal cause of understatement in Ulmer's investment estimates was his neglect of retirements. Accordingly, total retirements in 1909 equivalents valued in 1909 prices should approximate this sum. In fact, they do, aggregating $1.16 billion. Thus the flows in column 1 are at least reasonably correct.

The same judgment applies to the stocks. Although the above difference in gross investment explains but half the difference in 1869 stock estimates, with the remainder due to Ulmer's much higher capital consumption allowances, the latter are also easily shown to be in error by the appropriate amount. What is responsible for Ulmer's excess is not higher depreciation rates, but rather the understatement of flows in conjunction with the erroneous 1869 original cost estimate to which attention was drawn earlier. In the decade 1910–19 when the depreciation base is identical, the two estimates of capital consumption virtually coincide, and draw progressively apart only as one moves back in time. That is because Ulmer calculates his allowances as a percentage of an exaggerated total; his 1869 original cost is more than one-third too large, and his estimates for the intervening years to 1909 are likewise too great because they are interpolated backwards by the inadequate gross flows. If we reduce his capital consumption allowances by the ratio of the two different estimates of the capital stock at the beginning of the decade, i.e., substitute a smaller depreciation base, his total is almost at parity with mine.

The positive fruits of this extended discussion of railroad capital formation in the nineteenth and early twentieth centuries are a new series of constant-dollar gross and net investment, by decades, and a corresponding set of net stocks. At the same time there is a negative product. No longer can we safely rely upon the pre-1910 Ulmer estimates. Thus there remains the task of providing new annual series, both current and constant dollar, to fill the gap. Reworking the sample results obtained by Ulmer from railroad accounts to include retirements represents one approach, to which must be tied revision of the method of annualization to make the year-to-year changes consistent with the levels. For trend analysis, however, the capital stock estimates presented here should suffice in the interim.

Quantitative Measures of Railroad Development, 1840-1910: Labor

The estimation of labor inputs poses less difficulty than the reconstruction of the capital stock series. First, employment is a much more straightforward magnitude that was measured reasonably accurately at the time. Thus from 1880 on, there are counts of employment for the whole industry, and, even from 1850 on, national tallies of an occupational group termed "railroad men." Secondly, employment is a good measure of labor inputs because the standard number of hours per week remained constant over the entire period under investigation. Not until 1917 did the length of the workweek decline from sixty to forty-eight hours.[47] Finally, close relationships between labor inputs and measures of output like receipts, ton-miles,

TABLE 8

LABOR INPUTS, 1840-1910

End of Fiscal Year[a]	Employment (thousands)
1839	5
1849	18
1859	85
1870	230
1880	416
1890	750
1900	1,018
1910	1,699

Source

1839-59: *American Railroads*, Appendix C.
1870: .592 (the sample regression coefficient) times $388.4 million, the estimated total receipts in that year derived in developing Table 1.
1880: *Tenth Census, 1880*, Vol. IV, *Agencies of Transportation*, adjusted to reflect corrected Atchison, Topeka, and Santa Fe report presented in the note (*ibid.*, p. 13).
1890-1910: Same as Table 1.

[a]In principle, the employment figures should be annual averages to represent accurately labor inputs corresponding to the flow of output. But until the appearance of the ICC data averaging counts, these are estimates of end-of-year totals.

etc., afford the possibility of estimating industry-wide employment in the earlier part of the period when it was not directly reported.

Such an approach is preferable to working with the Census of Occupation totals. These are badly understated because the category "railroad men" excludes a considerable number of maintenance and shop workers listed under other titles. In 1880 when industrial and occupational classifications are presented together for the first time, the ratio of the occupation to the industry total is .56, and increases to .64 by 1910.[48] An upward trend in coverage extends back still further, but is not sufficiently stable to permit the effective use of the occupation statistics. According to our independently derived industry estimates, the ratio is as low as .27 in 1850, rising thereafter to .42 in 1860, and .67 in 1870.

These pre-1880 industry estimates, arrayed in Table 8 along with the

[47] See the Aldrich Report, S. Rep. 1394, pp. 1365 ff., and Leo Wolman, *Hours of Work in American Industry*, NBER Bulletin 71, New York, 1938. As a consequence, Kendrick's man-hour and employment series show an almost exactly parallel change over the period.

[48] These are computed in Daniel Carson, "Changes in the Industrial Composition of Manpower since the Civil War," *Studies in Income and Wealth, 11*, New York, NBER, 1949, p. 127.

later and more reliable Census and ICC reports, have been developed by extending cross-section relationships between employment and receipts fit to sample observations in each of the years except 1839. For 1839, because of the limited information available, application of the 1849 parameter was the only feasible procedure.

We first evaluate the strengths and weaknesses of this method, and then compare its results with alternative estimates. A minimum criterion that there should be a significant relationship between employment and receipts for the sample observations is certainly satisfied by this approach. In 1849, with thirty-six reporting railroads in Massachusetts and New York, the share of the variance in employment explained by a single pooled regression is 89 per cent. In 1859, with a total of sixty-three observations, and three different regressions for each of the three states represented, R^2 varies from .82 to .99. Finally in 1870, a single pooled function relating employment to receipts on thirty-six railroads in Ohio and Massachusetts yields an R^2 of .98.[49]

This internal consistency of the relationships is not conclusive evidence in favor of the technique, however. An equally important requirement is that the sample relationships derived from these two or three states be appropriate to all regions of the country. If all railroads in Massachusetts in 1849, say, conform closely to the practice of having one employee per $1,500 of receipts, but southern and western railroads have two for

[49] Receipts are in thousand dollars, employment in units. Thus the coefficients are to be read as 64 men per $100,000 of receipts, 71 men, etc. The regressions are homogeneous in each case, that is, without a constant term, to facilitate aggregation. If $E = a + bR$, $\Sigma E = \text{Na} + b\Sigma R$, whereas if $E = bR$, $\Sigma E = b\Sigma R$ without the necessity of specifying the number of railroads in the country. In all instances the constant a was determined not to be significantly different from zero before the homogeneous form was fitted.

Only in 1859 were the regressions so distinct that an analysis of covariance test rejected the hypothesis of a single population. The reason is the extremely large weight of the New York observations in the total and the very close fit achieved in that state. As is pointed out, the coefficients are sufficiently close that the failure of a single regression to hold does not invalidate either the method or the results.

For 1870 two adjustments were made. The Massachusetts State report covered only ten months of operation, requiring multiplication of earnings by 6/5 to convert them to an annual basis. Three Ohio railroads were excluded from the sample, the Central Ohio, the Sandusky, Mansfield and Newark, and the Marietta and Cincinnati, because they deviated obviously and radically from their counterparts in the direction of an excess of employment. This is almost certainly due to part-time employment, for in the next year, all three railroads exhibited decreases in employment with increases in receipts.

Exact references to antebellum state reports are to be found in Appendix C of my *American Railroads;* for 1870 they are Massachusetts Board of Railroad Commissioners, *Second Annual Report*, 1870, and Ohio Commissioner of Railroads and Telegraphs, *Annual Report*, 1870 and 1871.

the same volume of earnings, the Massachusetts statistic will do rather poorly as a projection device. No direct demonstration of the satisfaction of this condition can be made since it is the lack of complete information that necessitates estimation in the first place. Nonetheless a blend of a priori analysis and indirect checks supports the approach.

The selection of receipts as the independent variable for the regressions carries the promise of greater regional stability than alternative choices like physical output or operating expenses. By rewriting the equation $E = bR$ in the following form, $E = \left(\frac{O}{R} \cdot \frac{W}{O} \cdot \frac{1}{w}\right) R$, where E is employment, O operating expenses, W the total wage bill, and w the annual wage per worker, it is easy to see why. The same parameter b may obtain in all regions even when there are differences in labor productivity (w), or profit margins (O/R), or income shares of capital and labor (W/O) as long as they all move in such a way as to produce a constant or near constant product. Since greater labor productivity will yield larger shares in income when substitution possibilities are limited (as in railroad technology), there are reasons to expect a positive correlation between w and W/O; at the empirical level, it also seems to be true that high profit margins coincide with relatively low wages, as in the South, where lack of railroad competition not only maintained rates but also kept wages low. Supporting this line of argument is the considerable stability of b over time, while all three components in its determination varied widely. Its value is .64 in 1849, .71 in 1859, .59 in 1870.[50] The ability to pool observations, except in 1859, also confirms geographic stability, although admittedly within a narrow compass; note too that in 1859 the range of variation in b is limited to the difference between .63 in Ohio and .73 in New York. Finally, the sample states represent the regions with the greatest employment so that errors in extrapolation to others are less crucial. Thus in 1859 the Middle Atlantic and New England regions plus Ohio account for 60 per cent of national railroad receipts. Suppose that the coefficient used to determine employment in other regions is as much as 20 per cent too small, total employment is in error by only 8 per cent. In earlier years the sample coverage is greater, and it is probably not much smaller in 1870.

Three less conjectural checks buttress the case. First, there is the 1880 distribution of receipts and employment. Although the very extensive difference between the lowest and highest ratios of employment to receipts —.48 in the Far West and .88 in the South Atlantic states—seems to belie

[50] For simplicity here, we have pooled the 1859 Massachusetts, Ohio, and New York observations, despite the circumstances elaborated in footnote 49.

the logic developed above, initial appearances are somewhat misleading. For the three regions with 80 per cent of total employment, the simple ratios range only from .67 to .76.[51] Moreover, because our 1870 sample states are drawn from two of these regions, a second check that consists of comparison of 1880 total employment projections using sample Ohio and Massachusetts relationships with the known total also comes out well. An 1880 Ohio sample as small as the 1870 one yields an almost exact estimate of the true 1880 figure, falling short by less than 1,500 from the observed 416,300. The Massachusetts coefficient in 1880, however, is smaller relative to the Ohio one—.63 vs. .71—and so leads to an underestimate of about 12 per cent. This is still a creditable performance; and since the disparity in coefficients did not prevail in 1870, it does not necessarily imply an equivalently large error earlier.

The last test draws upon new employment and receipts information in a southern state (Virginia) in 1859 and contrasts the calculated coefficient there with the statistic estimated from Massachusetts, New York, and Ohio data. A close relationship holds in Virginia between employment and receipts, but with a larger coefficient (.82) than the .63 to .73 recorded in the others.[52] A maximum error of about 25 per cent is involved if one uses the Ohio value to predict Virginia employment, and less than 15 per cent for the pooled .71. If this result holds for the South generally, the implied total 1859 error is well within the 8 per cent limit discussed above. But this is the worst possible representation of the comparison. If a single Virginia observation is eliminated from the sample, the coefficient for that state is altered to a much more consistent .70, and virtually without reduction in R^2. To the extent that this single road is indeed atypical, there apparently need be no concern at all for the application of the sample regressions to other regions, at least in the early years.

For these reasons, therefore, we can expect the pre-1880 employment estimates in Table 8 to be accurate measures of railroad employment.[53] Stanley Lebergott's estimates in this volume derived by an entirely different technique—extrapolation of 1880 regional employment-mileage ratios based on sample ratios—confirm these expectations for the three antebellum years.[54] His 7,000, 21,000, and 82,000 totals are quite comparable to our 5,000, 18,000, and 85,000, and leave little to choose between.

[51] This information is drawn from the *Tenth Census, 1880*, Vol. IV, pp. 25 and 257.

[52] The source is the *Annual Report* of the Virginia Board of Public Works for 1858/59. There are ten observations and the R^2 of .82 is significant at the 1 per cent level.

[53] This applies even to the 1839 estimate obtained by using the 1849 parameter without change. The relative constancy of the coefficient over time is the reason for confidence in this procedure.

[54] See pp. 117–204.

But his 1870 estimate of 159,000, even allowing for a slight difference in timing in our measures, is so far short of our 230,000 to compel comment. Lebergott's shortfall can be traced to a single region, the Middle Atlantic; his data indicate a rise of more than 85 per cent in employers per mile between 1870 and 1880 in that region, while the ratio increases in the rest of the country only by 13 per cent. This inconsistency suggests that the 1870 Middle Atlantic value may be too low, but not necessarily: the rate of increase in the same regional ratio between 1860 and 1870 (if my 1870 estimated employment is correct) considerably exceeds that of others due to much greater increases in output per mile of line. To document this allegation further, therefore, it has been necessary to examine the employee-mileage ratio in Ohio both in 1868 and in 1880; at the former date, it stands at 6.10, well above Lebergott's regional value of 3.95, and actually declines to 6.07 in 1880.[55] Both the earlier absolute level as well as the direction of change are inconsistent with Lebergott's analysis, and this for a state with 20 per cent of the mileage in the area. The other states would have to have a much smaller number of employees per mile (3.5) for the results to be consistent, and this would imply a difference between Ohio and other Middle Atlantic railroads much greater than that observed in either earlier or later years.

These technical details are sufficient reason to cast extreme doubt on Lebergott's 1870 alternative. Another, more general argument is the inconsistency of the lower employment estimate with the pattern of output growth. Ton-miles per mile of road increased from about 100,000 in 1859 to more than 270,000 in 1870 and to 370,000 in 1880.[56] Yet Lebergott's employment per mile climbs more rapidly from 1870 to 1880 than from 1860 to 1870. Unless one can explain the almost unparalleled productivity growth of the decade 1860–70 and the negative movement in the next ten years, it is best not to rely on the 1870 Lebergott magnitude.

The only other possible comparison also relates to the disputed 1870 figure. But in this instance, our 230,000 is substantially *below* Daniel Carson's 270,000, which was obtained by scaling up the Census of Occupations count by the undercoverage observed in later years.[57] It is tempting to invoke the virtue of being at neither extreme as further justification for our 1870 value; but a little reflection should establish

[55] The Ohio data are to be found in the *Annual Reports of the Commissioner of Railroads and Telegraphs* for 1867/68 and 1879/80. One reason why Lebergott—who also used Ohio in his tabulations—may have gone awry is that employment is listed for the Ohio portion of the line only, not the total. If total mileage is then used in the denominator, the number of employees per mile is incorrectly depressed.

[56] According to the estimates presented in Tables 1 and 2.

[57] See Carson's paper in *Studies in Income and Wealth, 11.*

that a middle-of-the-road position has no intrinsic merit in statistics, whatever its advantages in politics. Rather, the ground for preferring our 1870 estimate to Carson's is its basis in contemporary sample data, while Carson's depends upon extrapolation of later nonbehavioral relationships. There would seem to be little reason why the undercount of the Census of Occupations in 1870 (a rather questionable Census in many respects) should be the same as in 1880, whereas there is good and obvious reason for employment to be related to receipts, and also for a cross-section extrapolation to yield a close approximation to the correct national total.

The 1880 and subsequent entries require no comment beyond that already presented in Table 8 itself.

Quantitative Measures of Railroad Development, 1840-1910: Fuel

In principle, an analysis of productivity changes ought to be concerned with inputs of materials as well as of capital and labor. For reasons of convenience, however, materials are usually neglected in favor of working directly with value added. This simplification overstates productivity change in the typical case and also obscures one important source of increased output per unit of labor and capital.[58] Although this criticism

[58] When technological change is positive, a value-added index (geometric or arithmetic) will exaggerate the rate of change for a given industry. See Evsey D. Domar, "On the Measurement of Technological Change," *Economic Journal*, December 1961, p. 716, and "On Total Productivity and All That," *Journal of Political Economy*, December 1962, p. 603.

But frequently *gross* output and *net* inputs are used. This formulation actually may eliminate the value-added bias, depending upon changes in the relative importance of materials. I will illustrate with the arithmetic, or total factor productivity, index, although the argument can also be extended to the geometric index. Let Y be value of real output in base-period prices; L, K, and R physical inputs of labor, capital, and raw materials; and w, i, and r their respective prices. Then there are three alternative indexes corresponding to (1) all inputs, (2) value added, and (3) gross output, net inputs:

$$C_1 = \frac{Y}{w_0L + i_0K + r_0R}$$

$$C_2 = \frac{Y - r_0R}{w_0L + i_0K}$$

$$C_3 = \frac{Y}{w_0L + i_0K} \cdot \frac{w_0L_0 + i_0K_0}{Y}$$

$$C_2 > C_1 \text{ when } C_1 > 1, \text{ but } C_3 = C_1 \text{ when } \frac{w_0L_0 + i_0K_0}{V} = \frac{w_0L + i_0K}{w_0L + i_0K + r_0R},$$

that is, when the share of materials in total inputs valued at base-year prices is constant. If the share declines, C_3 will understate C_1, and if it increases, $C_3 > C_1$, but for certain ranges $C_1 < C_3 < C_2$, making C_3 a better measure than the value-added index.

applies with less force to the railroad sector, because of its high value-added ratio, nevertheless, I have undertaken to include fuel inputs explicitly among the series. Although not exhaustive of the complete range of materials necessary to railway operation, fuel does account for the largest part of current material inputs.[59]

The inclusion of fuel inputs has the further virtue of highlighting a significant nineteenth century technological change. Before the Civil War, despite some preliminary experimentation that began to yield tangible progress by the 1850's, American locomotives were fired almost exclusively by wood. Within a score of years thereafter, a transformation so rapid had occurred that twenty times more coal than wood was being consumed annually, and more than a fourth of bituminous coal output was regularly absorbed by the railway sector. The underlying mechanism is almost a text book illustration of substitution in response to changing relative prices. To begin with, eastern railroads with large coal deposits along their lines, and hence both low coal prices and elastic supply, invested in research necessary to eliminate the troublesome technical problems that had limited the development of coal-burning locomotives. Once successful, the eastern railroads penalized by high wood prices and the western railroads favored by low coal prices led the parade to mineral fuel. Note that it was not so much the initially high price of cordwood that motivated the first research as the prospect of much higher future cordwood prices due to rapidly growing demand and inelastic supply. But once the break-through had come, the New England railroads that paid high prices found it profitable to switch. The last holdouts, naturally enough, were southern railroads whose scant demands and favorable environment meant continued low prices for wood.[60]

Unfortunately, the pace of this transition, as well as the quantities of fuel consumed at various dates, is largely unrecorded at the national level. A single observation on the 1880 volume of cordwood consumption must suffice until ICC tabulations of coal purchases begin in 1917. All we can glean from railroad records are accurate reports of total fuel expenditures (and not before 1880).

[59] The other large material inputs are those of rails and ties to compensate for depreciation of capital. To ignore these is to measure outputs gross but inputs net, or, in terms of footnote 58, to use C_3 as our index. Since depreciation actually declined due to technological changes, C_3 will then understate the observed increase in productivity, but the magnitude of the effect is limited. In 1880 the neglected nonlabor costs and purchases of all additional services amount to about 20 per cent of output, in 1910 to 18 per cent.

[60] For further discussion of the shift before the Civil War, see my *American Railroads*, Chapter III. Appendix D of the *1880 Census of Transportation* confirms the concentration of wood consumption on southern railroads.

TABLE 9

MATERIALS INPUTS, 1840-1910

Fiscal Year	Expenditures on Fuel (mill. dollars) (1)	Locomotive Mileage (mill. miles) (2)	Cordwood Consumption (mill. cords) (3)	Coal Consumption (mill. net tons) (4)
1839	.4	5.4	.12	--
1849	1.5	15.9	.35	--
1859	8.1	81.0	2.0	.3
1870	25.2	233.0	3.3	4.3
1880	32.8	465.3	2.0	13.4[a]
1890	64.0	919.7	--	36.8[a]
1900	90.6	1,170.6	--	58.8[a]
1910	217.8	1,714.4	--	128.1[a]

Source

Col. 1, 1839-1859: Estimated operating expenses times 10 per cent in 1839 and 1849 and 12 per cent in 1859. See my *American Railroads*, Appendix A and Chapter 3. The proportion of expenses accounted for by fuel was estimated by a sampling technique for 1859.

Col. 1, 1870: Estimated operating expenses times 10 per cent. Expenses were derived from receipts by applying 1871 operating ratio reported in *Poor's Manual*. The fuel account proportion for this period is given in Wellington, *Economic Theory*, pp. 176, 180.

Col. 1, 1880, 1890: *Tenth Census, 1880*, Vol. IV, and *Eleventh Census, 1890*, Vol. XI.

Col. 1, 1900, 1910: ICC, *Statistics of Railways* for 1900, 1910.

Col. 2, 1839, 1849: Terminal locomotive stock[b] multiplied by 12,000 miles. The 1849 average service is determined by extrapolating the 1859 average on the New York average train-miles per locomotive in both years. (The New York average train-miles per locomotive was the same as the national average locomotive mileage in 1859.)

Col. 2, 1859: Terminal locomotive stock[b] times 15,000 miles, the average service of 1,571 locomotives on twenty-five railroads in 1858. See *American Railroad Journal*, Vol. XXXI, 1858, p. 297.

Col. 2, 1870: .6 times $388.4 million; the coefficient was determined from a random cross-section sample of fifteen roads in 1870 with $R^2 = .82$, and the earnings total is the one discussed in connection with Table 1.

Col. 2, 1880, 1890: *Tenth Census, 1880*, Vol. IV, and *Eleventh Census, 1890*, Vol. XI. Total train mileage in these years includes switching and non-revenue service and is therefore equivalent to locomotive mileage.

Col. 2, 1900: ICC, *Statistics of Railways*. Revenue train mileage adjusted to locomotive mileage by interpolating between the ratios of locomotive mileage to train mileage in 1890 and 1910; the interpolating series is the ratio of other track to total mileage, on the grounds that switching mileage is dependent thereon.

Col. 2, 1910: *Statistics of Railways*.

Cols. 3, 4: See text.

[a]Contains some wood and oil consumption, to a maximum extent of 5 per cent in fuel equivalents.

[b]These terminal stocks differ slightly from the 1838, 1848, and 1858 totals of Table 3. The 1839, 1849, and 1859 values are 450, 1325, and 5400, respectively.

There are two alternative approaches to take full advantage of what few data are available. For the period beginning with 1880 when solid information on expenditures exists, coal was used almost exclusively. This means that division of the financial aggregate by an average unit coal price will yield the relevant physical volume. And, fortunately, for the one year in which wood loomed largest, 1880, we can separate out expenditures for it with the help of the Census tabulation of cordwood consumed by railroads in that year. Earlier, our most reliable knowledge is of the number of locomotives and the approximate consumption of wood and coal per mile run. It is not too difficult to convert the locomotive stock to an annual flow of service performed based on sample data from railroad reports. Nor is it perilous in the antebellum period to specify the division between mileage logged by wood and coal burners since, even in 1859, the latter accounted for a meager proportion of the total. This method does encounter difficulty with the 1870 estimate due to the uncertain division between wood and coal in that year. With the further use of state reports, and some variation upon the technique just described, we treat that problem in a fashion described below.

Neither of these two methods is mutually exclusive, and although each has reason to be favored in particular periods, the other is also employed as a check. Accordingly Table 9 presents in column 1 a complete series of fuel outlays to serve as the basis of the expenditure approach, and in column 2 a full complement of locomotive mileages. Generally, the figures for 1880 on are official, or comparable in quality thereto. Earlier, they are the product of indirect calculations. For example, the fuel outlays are estimated as a proportion of operating expenses, which are themselves obtained from an array of contemporary sources in the same fashion as the total receipts discussed in connection with Table 1. Similarly, locomotive mileage in 1870 is tabulated from earnings, and at earlier dates from sample accounts of annual services.[61]

It is easiest to explain the derivation of the cordwood and coal consumption totals of columns 3 and 4 in chronological order. The antebellum estimates do not pose great problems despite the lack of any official benchmarks. Abundant contemporary evidence confirms an average run of 30 to 40 miles per cord in the later 1850's, a distance that must have been greater in earlier years as a result of shorter and less frequent freight

[61] Although 1870 locomotive mileage was determined by a regression technique utilizing earnings as the independent variable, other data on annual mileage per locomotive also support the aggregate reached. The Pennsylvania average in 1870 is 23,000 miles per engine, as calculated from Wellington, *Economic Theory*, p. 141 (after allowance for switching mileage). Since the Pennsylvania experience was close to the national average both in 1858 and 1880, this is relevant evidence.

trains and greater concentration upon passenger accommodation. Fuel requirements for both 1839 and 1849 are, therefore, pegged at the lower level of 45 miles per cord. This may be immediately divided into the stated locomotive mileage to obtain cordwood consumption for 1839 and 1849 since coal was, for all practical purposes, not used. For 1859, the intermediate step is necessary of allocating the locomotive mileage between wood and coal burners due to the first appearance of the latter in any number. Contemporary discussions suggest that at most 500 coal-burning locomotives were in use in 1859, and that their total mileage could not have exceeded 10 million miles with aggregate consumption of 300,000 tons. The residual 71 million miles gives rise to the cordwood entry.[62]

These inputs, in combination with the corresponding financial magnitudes, yield prices of $3.33, $4.29, and $3.60 per cord of wood. Towne and Rasmussen's prices for comparable years are far lower at $0.84, $1.10, and $1.60 and imply consumption levels at least twice as high as our estimates.[63] I am not inclined to give this disparity much weight, however. Towne and Rasmussen's prices are based upon extrapolation of a single 1880 observation on a single series of prices received by Vermont farmers. In 1880 this average price is itself 20 per cent below a comparable Census price of wood purchased by railroads, and earlier the divergence seems to be greater. At the end of the 1850's, all indications point to a price of over $2.00 per cord for even the most favorably situated railroads, and the average price for Massachusetts railroads as a whole was $4.46.[64] The implied prices, therefore, seem quite reasonable and consistent with recorded prices, far more so than Towne and Rasmussen's which embody the dubious assumption that the trends of national scarcity and demand replicated the Vermont experience.

Cordwood and coal requirements in 1870 are more difficult to gauge. The distribution between the fuels at this time is quite uncertain although there are clear indications both of the absolute superiority of coal and a rapid, continuing tendency in that direction. In Ohio in 1868, wood burning was still more than twice as prevalent as coal consumption; by 1870 equality prevailed; and by 1872 the proportions had been almost reversed. Massachusetts railroads in 1871, too, were using more than twice as much coal, and Illinois roads, due to the accessible bituminous

[62] My *American Railroads*, Chapter III, gives detailed sources and elaborates the procedure summarized here.

[63] *Trends in the American Economy in the Nineteenth Century*, Studies in Income and Wealth 24, Princeton for NBER, 1960, p. 311.

[64] The average national price in 1880 reported by the *Tenth Census* (Vol. IX, p. 479) is $2.21; the corresponding railroad price is $2.60. Also in 1876 the *Railroad Gazette* (Vol. III, 1872, p. 114) indicates prices of $3.50 a cord; Towne and Rasmussen, only $2.44.

deposits in that state, even more.[65] If we accept a 2-to-1 ratio in favor of coal in the East in 1870 (as suggested by the Massachusetts experience), parity in the West (as indicated by the Ohio transition), and zero coal consumption in the South, we can reach a national ratio by weighting each region by its relative importance in traffic operations. Such a procedure points to a 30 per cent disparity in favor of coal consumption in 1870.[66]

To obtain aggregates of cords of wood and tons of coal, it is necessary to add information on fuel requirements per locomotive-mile. Here varied evidence suggests the equivalent of some 60 pounds of coal a mile. Ohio locomotives in 1861 were apparently using an even greater amount, 69 pounds, and Illinois railroads are found to have used over 80 pounds in 1872, but these seem to be exaggerated in the light of later observations in these states and simultaneous Massachusetts use of less than 50 pounds and consumption of 64 pounds on the Pennsylvania Railroad.[67] The small Massachusetts requirements are natural in view of a passenger predominance in that state, and the significantly smaller fuel requirements associated with passenger trains—half as much—whereas it is doubtful that the national average exceeded the experience of the heavily freight-oriented Pennsylvania Railroad.

At an input of 60 pounds a mile, aggregate coal-equivalent consumption in 1870 reached a level of 7 million tons. With a national ratio of coal to cordwood consumption of 1.3 tons to 1 cord, this is translated into estimates of 4.3 million tons of coal and 3.3 million cords of wood.[68] The financial ledgers are quite consistent with this allocation. At prices

[65] These accounts of consumption are derived from the relevant state reports, except for the 1870 Ohio observation which is reprinted in *Railway Gazette*, Vol. II, 1872, p. 377. For Massachusetts, the average expenditures on wood and coal were converted to physical units by dividing by prices of $5.50 per cord and $8.00 a ton, prices determined from prices paid by individual railroads within the state.

[66] That is, with ratios of coal to wood of 2, 1, and 0 and weights of .434, .432, and .132, we derive the national relationship of $x = 2(.434) + 1(.432) + 0(.132) = 1.3$. The weights are 1871 regional gross earnings relative to the national total as reported in *Poor's Manual* for 1872-73, p. xxviii. (The Pacific region is included in the West.)

[67] These data are derived from the state reports mentioned earlier. The observation relating to the Pennsylvania Railroad is found in Wellington, *Economic Theory*, p. 141. One reason for the overstatement both in Illinois and Ohio is the tendency of railroads to err in returning locomotive mileage; gross errors such as substitution of car mileage are easy to detect and eliminate, but more subtle distortions cannot be rectified.

For the purposes of a coal equivalent consumption total, cordwood is converted to coal at the rate of 1 cord of wood = .8 ton of coal. This is the same factor used in Sam H. Schurr, Bruce C. Netschert *et al.*, *Energy in the American Economy*, Baltimore, 1960, p. 499.

[68] Algebraically, this converts to the solution of two simultaneous equations. Let x be million tons of coal consumed, and y million cords of wood. Then

$$x + .8y = \frac{60 \times 233}{2000} = 7.0$$

and

$$x = 1.3y.$$

of \$4.00 a cord for wood, and \$3.00 a ton for coal, drawn from quotations in the railroad literature, total expenditure is \$26.1 million or within \$.9 million of the entry obtained from railroad operating expenses. As further evidence, one may adduce the vintage of the 1870 locomotive stock. Almost 60 per cent of the locomotives extent at the beginning of that year were built during the decade 1859–69. If most were coal burners, as they probably were, the postulated distribution of coal and wood consumption in 1870 is to be expected.[69] Whatever its shortcomings, such a picture is undoubtedly closer to reality than the exaggerated claim of 6 million cords of wood consumed by railroads at the end of the 1860's.[70]

The publication of accurate fuel expenditures beginning with 1880 signals a corresponding change in estimating technique. Now the task becomes one of determining accurate coal prices paid by railroads. In preference to simple extrapolation of the prices actually paid by railroads—which first became available in 1917—a somewhat more complicated procedure has been substituted. To the minehead price, we add a variable transport charge equal to 100 miles of transportation at .8 the average ton-mile rate in the given year. This formulation has been determined from the data of the period 1917–25.[71] How well it does as far back as 1880 depends upon changes in the average haul for coal and the structure of rates. Since railroads on the average were closer to coal deposits in 1880 than thereafter, I have altered the specification to assume only 80 miles of transport in that year. Some notion of the maximum error is given by the largest difference between predicted and actual level of fuel purchases during the 1917–25 period; it occurred in 1917 when it amounted

[69] Systematic tabulation of the locomotive rosters published in the *Bulletin of the Railway and Locomotive Historical Society* would be necessary to establish firmly the contention that most new locomotives were coal burners. But this is the impression I have gained from scanning the records. In addition, conversions increased the ranks of the coal business. Thus the Michigan Central, which increased its locomotive stock only by two between 1859 and 1869, and retired a few additional units, therefore lagged in conversion to coal, whereas the Burlington, whose locomotive stock doubled, was entirely dependent upon coal (*ibid.*, No. 19, pp. 24–25, and No. 91, 127).

[70] Cited by Schurr *et al.*, *Energy in the American Economy*, p. 52.

[71] Let Q be tons of fuel consumed, p the price of bituminous per ton at the mine, f average freight rates per ton-mile, and X fuel expenditures. I have solved the equation $\sum_{1917}^{1925} Q_t(p_t + mf_t) = \sum_{1917}^{1925} X_t$ for m, the number of miles coal was transported at the average rate. This turns out to be 83.8. Since rates for coal lay below the average rate, I have interpreted this as 100 miles of transportation at .8 the average rate, an equivalent formulation.

Extrapolation can be expressed as $\frac{X}{Q} = \frac{X_0}{Q_0} \cdot \frac{p}{p_0}$

Q and X (1917–25) came from the ICC, *Statistics of Railways; p* and f from *Historical Statistics*, 1960, Series M-91 and Q-86, respectively. The same p and f series are used for the 1880–1910 estimates, except that 1880 freight rates are given in Table 1.

to 19 per cent; the average absolute deviation is a much lower 5.4 per cent, however. This is a good deal better than that obtained by extrapolation of the 1925 price over the same period, when it underestimates aggregate consumption by more than a tenth and is too small by 28 per cent in 1917. The reason for the bias is the upward tendency in rates during 1917–25. Since the opposite tendency in rates is observed between 1917 and the 1880–1910 period, simple extrapolation necessarily leads to substantial overestimates of consumption if applied earlier.

An equally error-prone method is that adopted by H. S. Fleming in order to derive his estimates of bituminous coal consumption by railroads, a series which the volume *Energy in the American Economy* seems to sanction.[72] What he has done is to multiply ton- and passenger-miles by fuel factors for each. These are roughly constant, and hence make no allowance for the increasing efficiency of longer trains and less deadweight, and in addition are set at levels that far exceed what the later data of the ICC affirm. Not surprisingly then, Fleming's estimates are pegged higher than those in Table 9 for 1890 and diverge increasingly, to the point where the 1900 upper bound set by price extrapolation actually falls below Fleming's figure. Indeed, because he also assumes that railroads not only used coal exclusively, but also used only bituminous coal, his estimated consumption of bituminous in 1905 is almost equal to the ICC 1919 bituminous total, despite a doubling of output between the two dates.

Although the disparity with Fleming's series can easily be dismissed, it nonetheless is useful to check the estimates for 1880 and thereafter against independent information on coal consumption per locomotive-mile. The coal equivalent consumption per mile implied by columns 2 and 4 of Table 9 rises from 65 pounds in 1880 to 150 pounds in 1910, a trend determined by the shift to heavier trains. The early levels are consistent with Wellington's 1885 fuel requirements of 25–50 pounds for passenger trains and 75–125 pounds for freight trains, as well as with the 1870 value of 60 pounds used earlier. The later observations accord with the ICC measured consumption of 166 pounds in 1917 and an informed 1906 estimate of "not less than 90 million tons," which when translated into requirements per mile comes to 120 pounds.[73] Finally, extrapolation to earlier dates of the 1917 national consumption per mile by the use of state reports from Kansas, Iowa, and Illinois, encompassing as much as 20 per cent of locomotive mileage, lends additional confirmation to the

[72] See the approving citation on p. 73. Fleming's estimates are found in *A Report to the Bituminous Coal Trade Association on the Present and Future of the Bituminous Coal Trade*, New York, 1908.

[73] Wellington, *Economic Theory*, pp. 132 ff; ICC, *Statistics of Railways for 1917*, pp. 32, 61; W. F. M. Goss, "The Utilization of Fuel in Locomotive Practice," *U.S. Geological Survey Bulletin* No. 402, 1909, p. 17.

estimates. The average of the three projections in 1910 is 3 per cent smaller than the entry in Table 9, within 1 per cent in 1900, and at worst in 1890—when extrapolation becomes a more dubious tool and only two states are reporting—8 per cent smaller. If anything, the suggestion is a slight underestimate, but it is so small as to require no revision.

Output, Input, and Productivity Change

The pattern described by the first eight decades of railway operation, as we have just derived it, is summarized in Table 10 and Chart 1. The

TABLE 10

SUMMARY OF RAILROAD OUTPUT, INPUT, AND PRODUCTIVITY (1910 = 100)

Fiscal Years	Output (1)	Persons Engaged (2)	Capital: Road (3)	Capital: Equip. (4)	Capital: Total (5)	Fuel (6)	Total Input (7)	Total Factor Productivity (8)
1839	.04	.3	.9	.2	.8	.07	.5	8.7
1849	.31	1.1	2.5	.7	2.2	.2	1.4	22.1
1859	1.7	5.0	11.4	3.6	10.1	1.5	6.6	26.4
1870	6.0	13.5	18.5	6.7	16.6	5.4	13.9	43.4
1880	13.8	24.5	34.2	17.3	31.5	11.7	25.9	53.2
1890	32.8	44.1	66.7	36.6	61.9	28.7	49.3	66.5
1900	54.8	59.9	77.4	45.2	72.3	45.9	63.2	86.7
1910	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source

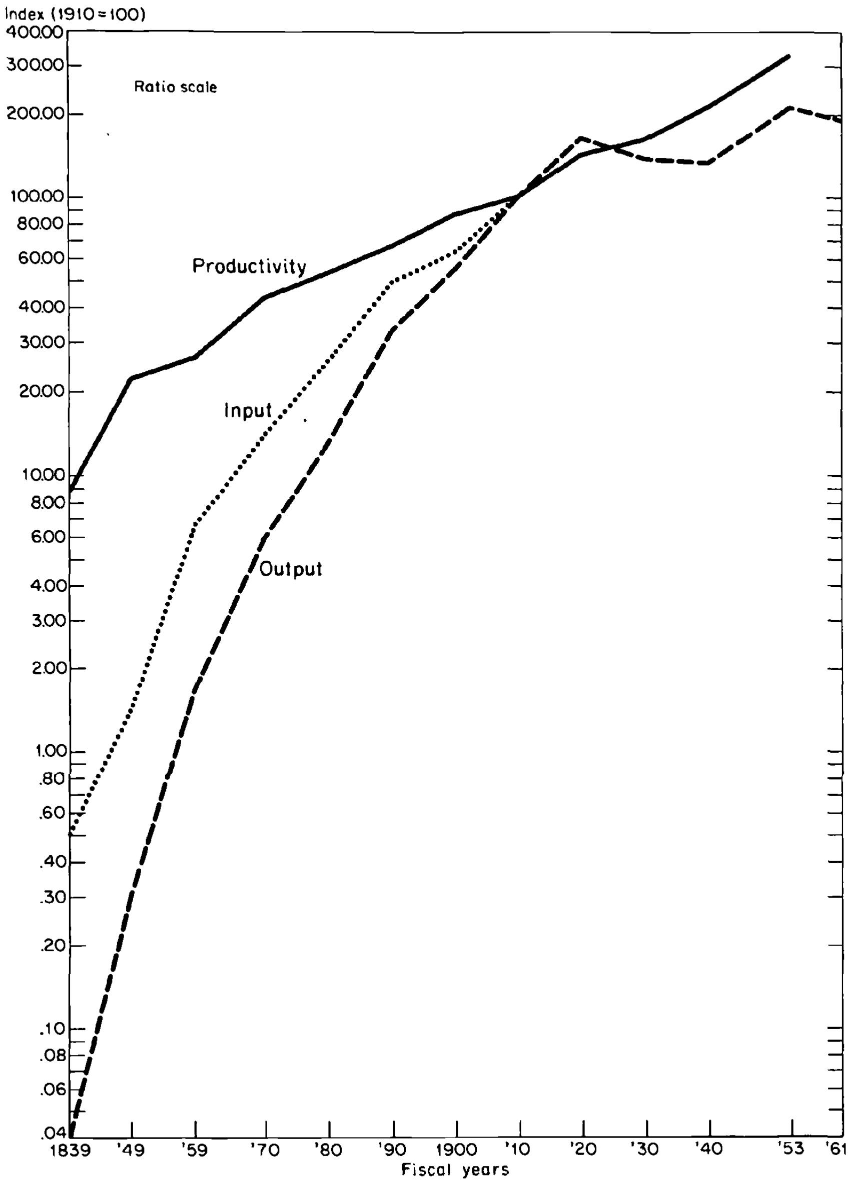
Cols. 1-6: Tables 1-9.
Col. 7: Weights for employment, capital, and fuel are .52, .38, and .10, which are the proportional 1910 shares of the factors as determined from ICC, *Statistics of Railways for the United States for 1910*, pp. 45, 57, 74, and 76.
Col. 8: Output divided by total input.

growth of output is no different from that exhibited by many industries in their initial phases. An extraordinary advance from the small pre-Civil War base yielded to a still impressive, but much lower, stable rate of 7.3 per cent per annum from 1870 through 1910. This record far exceeded that of such aggregates as national income or total commodity production. Over the entire interval 1839–1910, railroad services grew at an annual rate of 11.6 per cent, with income and commodity output proceeding at a pace only one-third as rapid. Indeed, no single major sector grew as rapidly. With an 1870 benchmark, these same observations obtain, albeit with a somewhat narrowed margin of superiority. Nonetheless, every single decade saw the railroads as a pace setter.[74] There is little reason,

[74] The income and commodity output estimates are the earlier cited ones of Robert E. Gallman. The sector breakdown of commodity output includes agriculture, manufactures, mining, and construction; and services can be approximated as the difference between income and the comomdity flow.

CHART 1

Output, Input, and Productivity Change, 1839–1961



then, to wonder at the prominent position railroads won in the hearts and minds of contemporaries.

After World War I, the forces of retardation increased in strength. Chart 1 tells a tale of continuing deceleration, broken only by episodes of wartime prosperity. Indeed, the final stage of absolute decline is already here or very close upon us. The reason is not hard to find. Output growth before World War I derived considerable impetus from a substantial geographic extension of the system; it suffices to recall that the 1910 mileage was almost eight times the 1860 level; as a consequence, from 1859 to 1910, geographic extension bears the largest share of the explanation of output growth. Mileage in use increased just about twice as rapidly as traffic density, and if we credit the lengthening of average haul to the influence of extension as well, the role of geographic widening in output growth is 2.2 times that of intensified demand.[75]

Because the system reached its peak in 1916, this dominant source of previous expansion gave out by World War I. At the same time railroads were faced with mounting competition from new forms of transport, revitalized waterways, and, especially, motor vehicles. Finally, unit transport requirements may well have declined as the industrial composition of national income in the twentieth century altered. From virtually all sides, therefore, railroads have been subject to retarding tendencies, against which diversified regional development with a concomitant longer average haul has stood as a lone and inadequate defense.

This pattern of output changes was duplicated by input trends, with one crucial exception. Both the stock of capital and employment grew

[75] Railroad output can be decomposed into three factors, tons (and passengers) originating per mile, number of miles of road, and average distance carried:

$$O = T/M \times M \times d.$$

Therefore, $$O_{1910}/O_{1859} = \frac{T/M_{1910}}{T/M_{1859}} \times \frac{M_{1910}}{M_{1859}} \times \frac{d_{1910}}{d_{1859}} = 4.51 \times 8.62 \times 1.16 = 45.1.$$

The relative size of the ratios of the components is the basis for the assessment of the importance of each. Note that the output index of Table 1 gives a slightly larger ratio of output between the two dates because 1910 weights have been used for this comparison; this probably leads to understatement of the change in average haul, and the role of extension since it was calculated as a residual. Offsetting this is the use of total tonnage and passengers carried rather than those originating. Consolidation probably meant that tonnage originating was a higher proportion of total tonnage at the later date, and so T/M_{1910} divided by T/M_{1859} may underestimate the change in intensity of demand.

Tonnage and passengers carried are taken from Frickey, *Production in U.S.*, p. 100; mileage from Table 2; and ton-miles and passenger-miles from Table 1; average distance was calculated as the residual. 1910 average revenues per passenger and per ton were used to weight those quantities and 1910 rates for passenger- and ton-miles.

much less rapidly, and it is this divergence which gives rise to the impressive productivity advance recorded by the railroad sector. As with output, the accomplishment in this sphere outstrips that of the economy as a whole. Between 1839 and 1910, railway output per employee expanded 2.8 per cent annually; Gallman's aggregate product estimates divided by Lebergott's labor force totals yields a rate of 1.3 per cent, or less than half as great.[76] A productivity index including capital services enhances the margin in favor of railroads. In that sector, unlike the economy as a whole, labor productivity increased in the face of a *declining* capital-output ratio, and a total factor productivity comparison therefore pits a higher railroad rate of growth of 3.5 per cent against an aggregate rate indeterminately lower than 1.3 per cent.

This disparity is reflected, although inexactly, in a dramatic relative decline in the price of railroad services. In terms of the bundle of commodities making up Warren and Pearson's wholesale price index, it cost little more than one-tenth as much to purchase a ton-mile of transportation in 1910 as in 1839, and about two-fifths as much for a far more comfortable passenger-mile. Even excluding the very large decline in rates (and increase in productivity) between 1839 and 1849, real freight rates fell more than 80 per cent from their 1849 level, and real passenger charges 50 per cent.[77]

The continuation of the data beyond 1910 in Chart 1 reveals a striking difference between the trends of output and productivity that had so much in common earlier. Kendrick's data affirm a continuing upward movement in productivity from 1909 through 1953 at the creditable rate of 2.7 per cent each year, while output, as we have seen, manages hardly to expand after 1920. This pace, although below the 3.5 per cent rate maintained through the nineteenth century, actually exceeds the 1870–1910 rate of 2.2 per cent. Not only is there scant evidence of retardation, therefore, but there are possible signs of accelerated advance. One distinction between the earlier and later period is relevant, however. After 1919 the gains in railway productivity relative to those achieved throughout the

[76] These are found in this volume, and in Stanley Lebergott, *Manpower in Economic Growth*, New York, 1964, p. 512. Gallman's 1840 and 1909 outputs were divided by Lebergott's labor force estimates for the same years.

[77] The BLS all-commodity price index stands at 101 in 1909-10, and the Warren-Pearson continuation of the same at 112 in 1839 (1910–14 = 100). Thus the decline of rates in current prices only slightly overstates its real descent. The indexes are found in *Historical Statistics*, 1960, pp. 115–117.

The failure of the real price decline to equal precisely the ratio of sectoral to aggregate productivity is due to inappropriate index number construction and to a more rapid decline in the price of inputs in the railway sector than in the whole economy. (See last few pages of this paper, where we show that the dual of Kendrick's productivity index is a price index of inputs and output.)

economy drop off sharply. To this extent, the productivity series mirrors the same decline in importance of the sector as do the output statistics.

With these trends in mind, we may now turn to the final task before us—explanation of that impressive nineteenth century productivity advance. The fundamental factors operating then (and later) may be grouped into two major categories: improved quality of inputs and economies of scale. The latter rubric is used to shelter a number of different positive effects all associated with size, and it will be taken up first.

To begin with, it is useful to make allowance for an effect that is peculiar to railroads and other related industries. For capital-intensive and capital durable sectors faced with indivisibilities, the size of the capital stock is not a good proxy for the annual flow of services it delivers. At their inception, firms will typically be burdened with higher capital-output ratios than current demand seems to dictate, due both to technical considerations and to positive expectations. Only over time will capital services attain a stable relationship with the magnitude of the stock. As can be seen in Table 11, the railway industry during its period of geographic extension is a prime example of what has just been described. From a capital-output ratio of over 70 in 1839, it descends to less than 4 in 1910. The pace of descent varies over time. Periods of rapid extension of the rail network like the 1850's and the 1880's exhibit much smaller declines than adjacent decades when increased output is accommodated by existing road and equipment. Conversely, a period of curtailed construction, coupled with greater demand such as that of the Civil War, saw dramatic declines. After 1910, as could be expected, the capital-product ratio moves within relatively narrow limits.

Because the capital stock has been used as an input, part of the measured productivity gain of railroads recorded in Table 10 derives from this phenomenon of increasing utilization. Two very crude adjustments assist in isolating the effect of this special factor. On the one hand, we may assume that the true production relationship involved capital inputs exactly proportional to the employment of labor; that is, over time each worker used no less capital, as the capital stock and employment data of Table 10 tell us, but actually the same amount. On the other, we may suppose that the capital-labor ratio actually increased—as it did for the economy as a whole—and postulate a constant ratio of capital services to output. In the former case, total factor productivity converges to the lesser growth of labor productivity, while in the latter it is further reduced because the implied increase in capital per worker partially explains the greater output.

Table 11 computes each of these alternatives. Series I for total factor productivity results when the capital-output ratio is held constant at its 1910 level, while series II reflects a 1910 capital-labor relationship. The rate of growth of series I is 2.3 per cent annually, while that of II is a higher 2.9 per cent. Contrasted with the initial 3.5 per cent, it seems that secular variation in capital utilization may explain between one-sixth and one-third of the recorded rate of productivity gain. A constant capital-output ratio undoubtedly removes too much of the gain. Such capital saving innovations as increased motive power per unit of weight, the higher ratio of load to dead weight in freight cars, and the greater durability

TABLE 11

PRODUCTIVITY EFFECT OF INCREASING UTILIZATION

Fiscal Years	Capital-Output Ratio (1910 dollars) (1)	Capital-Labor Ratio (1910 dollars) (2)	Total Factor Productivity (1910 = 100) (3)	Total Factor Productivity Variant I (1910 = 100) (4)	Total Factor Productivity Variant II (1910 = 100) (5)
1839	73.5	16.6	8.7	20.0	13.3
1849	26.4	12.8	22.1	44.3	31.0
1859	22.2	12.5	26.4	50.0	37.0
1870	10.3	7.6	43.4	61.2	47.2
1880	8.5	7.9	53.2	71.9	59.5
1890	7.0	8.6	66.5	85.6	77.0
1900	4.9	7.4	86.7	96.8	93.7
1910	3.7	6.2	100.0	100.0	100.0

Source

Col. 1: ICC fiscal 1910 receipts of $2,812 million extended back upon output index of Table 1, and divided by capital estimates of Table 7.

Col. 2: Capital estimates of Table 7 divided by employment estimates of Table 8.

Col. 3: Table 10.

Col. 4: Output divided by new input index calculated by weighting employment index of Table 10 by .52, materials of Table 10 index by .10, and new capital index (equated to output index) by .38.

Col. 5: Derived like col. 4, except new capital index is equated to employment index.

of rails probably superimposed an exogenous downward trend. Disaggregation to the firm level could help in extracting the appropriate utilization correction. But note that even after a maximum allowance for this factor, in the shape of series I, the railway sector continues to exceed the performance of the economy as a whole.

In explaining this still quite large residual, we may invoke more conventional economies of scale. First, there are the familiar increasing returns at the level of the firm production functions, that is, nonproportionalities associated with higher levels of labor and capital inputs (correctly measured). Another possibility is the traditional Marshallian external economies of specialization enjoyed as the industry approaches an optimal size; separate supplying firms may absorb tasks formerly carried out in the industry less efficiently, for example. A third mechanism ties firm size to productivity increases via technological progress. Edwin Mansfield's important research has suggested that large firms typically have been the most aggressive innovators and also the most rapid followers (the latter point is less well established).[78] There is a corresponding industry analogue in technological and production effects, as has been demonstrated by Jacob Schmookler's results relating inventive activity to the size and growth of industries.[79]

Historically, all four of these linkages probably operated at various times in the nineteenth century evolution of the railway sector. Firm size certainly increased quite significantly. Between 1860 and 1880, as output rose more than sevenfold, the number of firms increased by a modest 50 per cent. As a result, the average output of an 1880 firm was five times that of an 1860 firm. From 1880 to 1910, further intensification of demand and, more significant, financial consolidation led to another quadrupling.[80] Any nonproportionalities inherent in railroad production conditions—and their size is a subject for further research—thus had abundant scope for exploitation. So did the technological effects, but here there is positive evidence of their existence. Of five important innovations (as measured by frequent citation in discussions of railroad technological change)—the use of the telegraph to control train movements (1851), the substitution of steel rails for iron (1862), the development of block signaling (1863), the adoption of air brakes (1869), and the employment of automatic couplers (1873)—four can be traced unequivocally to major roads, and one is uncertain.[81] A larger sample of innovations that

[78] See Mansfield's paper, "Innovation and Technical Change in the Railroad Industry," in *Transportation Economics*, Special Conference 17, New York, NBER, 1965.

[79] Jacob Schmookler, "Economic Sources of Inventive Activity," *Journal of Economic History*, March 1962, pp. 1–20, and other sources cited there.

[80] I estimate the number of railroads in 1860 at between 400 and 500, based upon the partial count made by the Treasury Department in 1856. The 1880 Census enumerates 631 corporations, and ICC *Statistics of Railways* gives 926, 1224, and 1306 for 1890, 1900, and 1910, respectively.

[81] I am indebted to Jacob Schmookler for making available a chronology of inventions in the railroad industry. This facilitated the identification of specific innovators. The Erie Railroad introduced telegraphic communication; the Pennsylvania, steel rails, after Edgar Thomson had viewed them abroad, and also the automatic coupler; the Camden and Amboy pioneered with block signaling, again an original English innovation. There is some mystery surrounding the air brake. An *American Railroad Journal* reprint credits the Boston and Providence and Eastern with first use, but other indications point to the Baltimore and Ohio as the earliest.

The following sources (in the order of the innovations) were accepted: *Railway Age*, Vol. 141, 1956, p. 285; *Twentieth Annual Report of the Pennsylvania Railroad*, 1867, p. 25; *Railway Gazette*, Vol. XXXII, 1900, p. 506; Stewart H. Holbrook, *The Story of American Railroads*, New York, 1947, p. 290; *Railway Age*, Vol. 141, 1956, p. 259; *American Railroad Journal*, Vol. XLVI, 1873, p. 776.

include less dramatic but perhaps equally significant changes probably would show as much concentration on large lines increasingly staffed with skilled personnel.[82]

Expansion of demand naturally contributed to increased firm size. It also led to external economies and induced technical progress on its own. Thus, as railroads grew in importance, production of rolling stock was more and more consigned to specialty firms that had evolved from a previous general machinery orientation. Similarly, a class of rail mills emerged from what had been manufacturers of the whole gamut of rolled products. Other examples, including all the special commodities used in railway operation, could be cited. As to the potential feedback to technology associated with increased levels of output, no one who has even casually studied the industry can fail to be impressed by the volume of literature that disseminated and critically evaluated new ideas. Formal industry-wide associations and committees also blossomed. Standardization was one result. In the instance of rails, there were 119 patterns of twenty-seven different weights produced in 1881; within a few years after an 1893 report by a special committee of the American Society of Civil Engineers, three-fourths of the rails were of the standard ASCE sections.[83] If efficient flow of information is essential to technological progress, the conditions in the large railway industry of the late nineteenth century tended toward the optimal.

The exact contribution and timing of these effects require much additional study. What may well be the most promising approach is a limited assault upon specifics. For example, how much more would it have cost to produce car wheels directly in railroad repair shops rather than in specialized firms? At what size industry were maximum economies reaped? Or, how much more slowly or rapidly would an industry of smaller or larger firms have introduced steel rails than was actually done? 1880 Ohio cross-section data show a significant positive correlation between firm size and adoption of steel rails, with unitary elasticity of response.[84] Given the very much greater increase in adoption of steel rails than

[82] Greater technical sophistication also occasionally has its costs. Charles B. Dudley, Ph.D., chemist for the Pennsylvania Railroad, and hence commanding wide respect, persuasively advocated low-carbon, or soft, steel rails in the 1870's. The error was not corrected until ten years later when breakage soared under the ever heavier motive power. William H. Sellew, *Steel Rails*, New York, 1912, p. 13; *Railway Gazette*, Vol. XXII, 1890, pp. 702 ff.

[83] See the discussion of the development of rails in the United States by Robert W. Hunt in *Railway Gazette*, Vol. XXXII, 1900, pp. 505–507 and 522–523.

[84] The data for this regression come from the 1880 Census. $R^2 = .56$ with twenty-six observations so the relationship is significant. Size is measured here by total receipts, not assets, it should be noted.

indicated by changes in size, this hardly casts size in a crucial role. The subject awaits fuller treatment, however. The typical analysis of industry production functions cannot supply answers to such questions; and most of the answers it can provide actually confound the individual mechanisms distinguished here.

It is precisely in this modest spirit that I wish to go on to examine the impact of quality changes in capital—or technological progress—upon recorded productivity advance.[85] The object is to measure the absolute and relative importance of four significant innovations introduced in the latter half of the nineteenth century, namely, steel rails, increased equipment capacity, air brakes, and automatic couplers. Typically their contribution is assumed to be both large and uniform: "The ... increases in efficiency brought by ... a host of other technical advances permitted lower railroad rates. The use of steel rails, the adoption of standard gauge, the utilization of faster and more powerful locomotives pulling longer and heavier trains, the introduction of standard time, better brakes, and improved couplers all helped to create a truly national rail network." [86] Yet preliminary study suggests that these innovations varied substantially in significance and also only partially explain the total productivity gains achieved at the end of the nineteenth century.

As evidence of the extent of variation among the innovations, there is first the differential rapidity of their diffusion. Neither air brakes nor couplers were greeted with much enthusiasm. Although first used in 1869 and 1873, respectively, and despite the designation of a standard form of coupler by 1887 and the definitive proof of the Westinghouse brake in the third Burlington trial in the same year, it finally required national legislation to secure their adoption. In 1890, although almost all passenger locomotives and cars had been fitted with brakes, not many more than half of the freight locomotives and less than one-tenth of the cars used the appliance. Couplers had attained still lesser acceptance: only 3 per cent of locomotives and 10 per cent of cars (but almost all passenger cars) were so equipped. The low marginal rate of adoption at that time quite justifies the conclusion of the statistician of the Interstate Commerce Commission that the railroad "claim that the adoption of uniform safety

[85] We do not examine quality changes of labor in this paper. This is not because they did not apply. On the contrary, the railroads were quite interested in industrial education. The Baltimore and Ohio Railroad even set up a special comprehensive training program for employees in 1885 (W. T. Barnard, *Report on Technical Education*, Baltimore, 1887). To deal adequately with the subject here would overburden the already sorely taxed patience of the reader. I hope to publish some findings on this subject elsewhere in the near future.

[86] John F. Stover, *American Railroads*, Chicago, 1961, pp. 143–144.

devices is progressing with satisfactory rapidity is not supported by the facts." [87] Congress acted in 1893, requiring both appliances to be installed on equipment used in interstate commerce before January 1, 1898, a deadline later extended to August 1900. Compliance followed, and the beginning of the twentieth century saw air brakes and automatic couplers as standard equipment, although it took almost another decade for them to become universal.

This diffidence can be contrasted with the reception afforded steel rails. Although steel rails commanded a substantial premium in price over the iron variety, by 1880, less than twenty years after their first use on the Pennsylvania Railroad, almost 30 per cent of the nation's trackage was so equipped. By 1890, 80 per cent of track mileage consisted of steel rails.[88] In the single decade 1871 to 1880, the investment in steel rails—measured as the price differential multiplied by consumption—totaled more than $80 million. Not only was such a sum commensurate with the extra absolute cost of the safety appliances installed twenty years later, but it was much larger relative to the smaller railroad assets of the time.

The assimilation of successive improved designs of locomotives and freight cars likewise proceeded without external pressures. Its cumulative character and the lack of a single impressive innovation should not obscure its rapidity. Within the space of some forty years—from 1870 to 1910—freight-car capacity more than trebled. The remarkable feature of the transition was its apparent small cost; capacity increased with only a very modest increase in dead weight, the ratio changing from 1:1 to 2:1. Over the same interval, locomotive force more than doubled as powerful engine types, such as the Mogul, the Consolidation, etc., replaced the familiar and faithful American 4-4-0.

Either railway decision-makers were irrational in their apparent hesitancy to adopt air brakes and automatic couplers, or their economic value relative to steel rails and improved equipment was markedly smaller. Both qualitative evidence and some crude calculations support the latter inference. In the first place, the properties of the innovations were well known, which rules out ignorance as a factor in the delay. Nor can undue weight be given to the claim that lack of uniformity of design

[87] ICC, *Statistics of Railways for 1891*, p. 45. The railroad opposition to legislation was contradictory. One group argued that the new techniques were unproven; another that railroads were moving ahead as rapidly as possible. Cf. U.S. Senate Interstate Commerce Committee, *Hearings in Relation to Safety Couplers and Power Brakes in Freight Cars*, 51st Congress, 1st Sess., 1890.

[88] *Poor's Manual for 1891*, p. xxi. The 1880 Census records a slightly higher percentage in that year, namely 35 per cent, but its result may be based upon an unrepresentative sample.

compelled caution on the part of individual railroads in outfitting themselves. Many systems were large enough that interchange of equipment was not an overriding concern. Moreover, the ultimate Congressional legislation specified no single type, but allowed the choice to emerge from within the industry. Finally, there is the unmistakable emphasis on safety considerations in the debate about brakes and couplers. Proponents before Congress spoke of savings in terms of human lives, not operating expenses. On at least two occasions when the question was directly put, there were no assurances of reduced personnel requirements attendant upon the innovations; otherwise, the various railroad labor organizations might have been less whole-hearted in their support.[89] Twenty years later an air-brake engineer commented upon the same tendency of railroad men to emphasize the safety features of the appliances.[90] Perhaps they were justified: in Europe, where adoption was not compulsory, diffusion was notably slow; and in the United States, prior to compulsion, only the western lines with steep grades felt that the potential economies of train brakes outweighed their cost.[91]

Calculation of the cost savings realized in 1910 from these four innovations seems to support the minor economic contribution of the air brake and automatic coupler. The principal advantage afforded by these devices was increased speed. Although longer trains were also claimed to depend upon them, there seems to be little direct relationship. Automatic couplers were not notably stronger, and it was possible without great hazard to extend the number of cars in the absence of air brakes simply by adding more trainmen. That a trend toward heavier freight trains was under way well before these appliances were installed is proof of the virtual independence of these developments.[92] Greater speed in itself is not an unmixed blessing, however. Unless engine capacity is not being fully utilized, higher speeds can be attained only by the sacrifice of load. What the air brake and coupler really did, therefore, was to allow a greater element of choice in train operation, permitting higher speed when it was more desirable than larger loads. But exactly because its

[89] U.S. Senate ICC, *Hearings*, 1890, p. 53, and *ibid.*, 1892, p. 55.

[90] W. V. Turner and S. W. Dudley, *Development of Air Brakes for Railroads*, Pittsburgh, 1909, p. 6.

[91] For the concentration of brake installation upon the four major western railroads—the Union Pacific, the Southern Pacific, the Atchison, Topeka, and Santa Fe, and the Northern Pacific—see ICC, *Annual Report for 1889*, Appendix 10.

[92] It is, of course, probable that the great increase in train size and load after 1910 may have required prior advance in the design of couplers and brakes. A longer time horizon, therefore, might alter the relative economic significance of the innovations. (Note, however, that the absolute importance of other changes also increased at the same time.)

influence manifested itself in this literally marginal fashion, the size of the economies was limited.

The two positive features of greater speed are reduced capital costs, through increased utilization of the rolling stock, and smaller train wages, through fewer hours of travel time. On the other side are increased repairs to equipment and roadway at higher speeds of operation, as well as larger fuel expenses. Quantitatively, the economies are circumscribed because so much rolling stock time in transit is spent off the road—in loading, redirection in yards, repair, etc.—and because train wages are relatively small. If later experience is any guide, and scattered late nineteenth century evidence affirms that it is, a 100 per cent increase in speed could have made possible a less than 10 per cent reduction in the number of freight cars.[93] Likewise, with train wages accounting for some 12 per cent of operating expenses, the same radical change in speed could have led to a saving in total outlay of only 6 per cent. Against these must be reckoned the diseconomies of speed, moreover. Fuel outlays were widely regarded as increasing more than proportionally with speed, and the fuel account is almost 10 per cent of expenses. Rail replacement and equipment repair also may have been adversely affected. Indeed the principal discussions of speed in the technical literature relate to its disadvantages rather than its virtues.[94]

To ascertain the absolute sum saved in 1910 by the more nearly optimal speed made possible by the air brake and automatic coupler, we have to specify how far from the actual circumstances a hand brake and link-and-pin-coupler regime would have been. Evidence on this point suggests a very small divergence. Freight and passenger train speeds in 1910 hardly differ from those recorded twenty years before.[95] But because trains were much heavier at the later date, let us suppose that attained speed, both freight and passenger, would have been one-third smaller

[93] A report by the Federal Coordinator of Transportation in 1935 reveals that freight-car time in trains was responsible for only 16 per cent of total time (cited in James C. Nelson, *Railroad Transportation and Public Policy*, Washington, 1959, p. 266). A discussion of car utilization in *Railroad Gazette* (Vol. XLII, 1907, p. 200) affirms the same low proportion at that earlier date.

[94] Cf. the extended comments running through *Railroad Gazette*, Vol. XXXII, 1900. The most favorable report was an increase in speed of 30 per cent with only a 20–25 per cent *increase* in costs (*ibid.*, p. 215).

[95] The Pennsylvania State Railroad Report for 1888 lists average freight-train speeds, including stops, as ranging from 12 to 18 miles per hour. The New York 1885 report records similar responses. The average speed in 1920 was 10.3 miles per hour (Julius H. Parmalee, *The Modern Railway*, New York, 1940, p. 210). Since the latter is based on actual performance, it is not surprising to find it somewhat smaller than the earlier cited speeds. We can safely infer rough equality at the two dates. The same approximate parity holds for speed of passenger trains.

without the benefit of the safety appliances. On this generous basis, the rolling stock required would have been about 3 per cent larger than it was; since equipment was roughly equal to 20 per cent of the total capital stock, and returns to capital were $821.9 million, the added expense would have come to $4.9 million. Increased train wages of $113.7 million augment this, from which we deduct fuel savings of $42 million, to reach a final tally of $77 million.[96] In sum, railroad rates would have been about 3 per cent greater in 1910 to compensate for the inefficiencies of the older technology.

An additional contribution of speed is a reduction in transit time and hence smaller inventories. Also there are the direct safety gains to be dealt with. Neither factor influences the previous total greatly. Delivery time is reduced only 3 per cent because freight-car train time is such a small proportion of elapsed time. The average reduction in working capital involved is an insignificant $40 million, even if the railroads are assumed to have transported the entire value of gross national product.[97] At an interest rate of 6 per cent, this is a negligible gain of $2.4 million. As far as safety is concerned, the 1910 losses were a higher proportion of operating expenses than in either 1880 or 1890. It is conceivable that the absence of safety appliances could have forced the percentage up even higher, but it is equally possible that a reduced pace of operations, such as we have necessarily hypothesized, may have reduced it to its previous level. In any event, the 1910 total loss is only $50 million, so an increment on either side is safely neglected.

Granting the crudeness of these calculations, it is still difficult to see how the state of affairs envisaged by a railroad spokesman in 1912 could have prevailed: "It may safely be said . . . that if we were dependent,

[96] Increased train wages are one-half of actual 1910 train wages of $227.4 million, or $113.7 million (since the hypothetical hours worked are 50 per cent greater than the actual ones). Reduced fuel outlays are less than one-third of actual expenses of $189.0 million, however, to compensate for fixed consumption independent of running speed. It is assumed that two-thirds of consumption is related to speed, and hence the figure in the text is $2/9 \times$ $189.0 million (since speed and associated fuel outlays are assumed to vary proportionally).

[97] GNP in 1910 was approximately $30 billion. Even if the value of railroad freight was this large, this is equivalent to a daily transport of about $90 million. The average length of trip was fifteen days, tying up $1350 million of capital. A speed one-third greater could have reduced delivery time to a little more than fourteen and a half days, or reduced required working capital by $40 million.

Later indications (1936) are that the aggregate value of goods transported by rail is something like twelve times the freight payment. This would make the actual value of freight in 1910 less than $25 billion, and reduce the saving even more.

See L. F. Loree, *Railroad Freight Transportation*, New York, 1926, pp. 264 ff., for an analysis of 1910 freight-car trip time, and Parmalee, *Modern Railway*, p. 236, for the 1936 ICC valuation of railroad freight.

for one day, on the brakes of 20 years ago, the business of the country would be practically paralyzed, and the loss of both life and property very great." [98] The fact of technological advance is not synonomous with its indispensability.

In contrast to these results stand the estimates of the saving attributable to a steel-railed 1910 track in place of one of iron. Steel rails influenced railway operations in two respects: first, and most obviously, they wore much longer; second, and perhaps more important, they bore much heavier loads without breakage. Both technical advantages were of economic significance.

The durability of iron rails in the 1870's was variously placed between 4 and 15 million tons of traffic, although the Lehigh Valley reported tonnages as small as 1.5 and 2.3 million on two different stretches of road.[99] The total traffic in 1910, including the weight of rolling stock, amounted to some 830 billion ton-miles; the average total tonnage passing over each mile is estimated by dividing this sum by the number of miles of track in the system—351,767. The resultant figure, 2.4 million tons, divided into a modal durability of iron rails of 8 million tons, say, means an average life under 1910 conditions of 3.3 years. To put it another way, 30 per cent of the track mileage in 1910, or 105,530 miles, would have required replacement in that year. Expense for the 12.1 million tons of rails, allowing for the scrap of the worn-out rails, then would have come to almost $200 million.[100] Actual 1910 outlays for rails were less than $17 million. Steel rails, therefore, wore more than ten times as well as iron would have. Such a ratio agrees with independent engineering assessments placing the life of steel rails at from 100 to 250 million tons, against the earlier cited range of 4 to 15 million tons for iron rails.[101]

From this aspect alone, steel rails were almost three times as important as the air brake and automatic coupler. To the differential materials

[98] *Journal of the Franklin Institute*, Vol. 173, 1912, p. 35. Appropriately enough, the author was also arguing against the virtue of scientific management à la Taylor.

[99] See *Transactions of the American Society of Civil Engineers*, Vol. III, 1870, p. 104; C. P. Sandberg, "The Manufacture and Wear of Rails," in *Minutes of Proceedings of the Institution of Civil Engineers*, Vol. 27, 1867/68, p. 325; *Railroad Gazette*, Vol. II, 1870, p. 243; *ibid.*, Vol. III, 1871, p. 510.

[100] The average weight of rails per mile in 1910 as cited in Table 2 is 115 gross tons. The wholesale price of rails in that year, as in other years after the formation of U.S. Steel, was $28. With the addition of delivery charges to make the retail price close to $30 and a $14 or 50 per cent scrap allowance, the net charge becomes equal to $16 per ton.

[101] Camp, *Notes on Track*, pp. 97–98. The variety of experimental evidence cited there points to an average of 140 million tons; the implied 1910 average is just about 100 million tons, which is of the same general magnitude.

cost, moreover, must be added the increased labor inputs associated with more frequent replacement. Although accurate information on the labor cost of rail renewal is difficult to obtain, various technical sources point to a coefficient of between 50 and 100 man-days per mile of replacement. At 1910 daily wage rates of $1.50 for trackmen, the aggregate cost of relaying 105,000 miles of track is $11.8 million, and the differential $10.8 million.[102]

The second-order effect of greater strength considerably extends the economic consequences of greater durability. Nonhomogeneous iron rails were limited in the locomotive weight they could bear. Under heavy loads they were subject to lamination and crushing. Steel sections, on the other hand, wore evenly. Consequently it is impossible to maintain that 1910 engines could have been accommodated by iron rails: the maximum engine weight capable of being borne by eighty-pound track would have been closer to fifty tons, and quite below the seventy-ton average locomotives actually upon the scene.[103] Smaller engines, in turn, would have meant more frequent trains. The simplest case is one in which we assume that total tonnage, load factors, direction of traffic, etc., were unchanged. Then required freight-train mileage—passenger trains would have remained almost unaffected—would have been 40 per cent greater, i.e., the ratio of the seventy-ton average weight in 1910 to the fifty-ton maximum (and average) that would have prevailed. Under these conditions, and accepting Wellington's computations indicating a .5 ratio of marginal cost per train-mile to average cost, the incremental outlay in 1910 comes to $279 million.[104]

[102] The practical literature gives a rather varied set of figures that extends from less than 30 man-days per mile of replacement to more than 100. The 75 man-days actually used is not likely to introduce a very great absolute error. For discussions of labor requirements, see *ibid.*, pp. 563–565; E. E. Tratman, *Railway Track and Track Work*, New York, 1901, pp. 335–340.

[103] *Description of Sandberg's Standard Rail Sections*, London, 1872, Table 1; *Transactions of the American Society of Civil Engineers*, Vol. III, 1870, p. 113; Sellew, *Steel Rails*, p. 13.

[104] Wellington, *Economic Theory*, p. 571. An allowance for interest on the increased stock of required locomotives is included in the determination of the ratio.

Freight expenses are not broken down separately in 1910, and they have been estimated using the 1916 proportion, when the ratio between ton- and passenger-miles is virtually identical to that in 1910. The imputed freight expenses on this basis are almost $1.4 billion, of a total of $1.8 billion.

There are two offsetting biases in this simplified calculation that should be mentioned. More frequent, but smaller, trains might have permitted more efficient loading and reduced the proportion of empty to full cars per train; on the other hand, the comparison of the 1910 *average* weight of locomotives with the hypothetical maximum makes no allowance for the fact that the 1910 hypothetical average would have been somewhat smaller, and so increased the divergence under the two alternative technologies.

In all, therefore, steel rails directly and indirectly saved something like $479 million in 1910. How much do the increase in freight-car capacity and the autonomous increase in locomotive tractive power from 1870 to 1910—which grew by more than the difference between iron and steel rails can explain—add to this total? With the same kind of simplification just resorted to, we can approximate the answers. The total increase of average locomotive tractive power between 1870 and 1910 was more than 100 per cent. The calculation of savings due to steel rails has subsumed less than half of this change. At least double the actual number of 1910 trains would have been required under conditions of 1870 motive power. Beyond the $279 million reckoned above, therefore, there is another $420 million in outlay that improved locomotive design obviated.

Had the powerful twentieth century engines been developed without that simultaneous remarkable advance in freight-car construction, much more of the increased power would have been dissipated in the non-productive task of hauling dead weight. A higher ratio of dead weight requires either more or heavier trains to deliver the same payload, both involving additional expense. If 1910 tonnage had to be moved in 1870 freight cars, it would have required about 3.3 of them to equal one 1910 car, and at twice the weight. With identical load factors under both technologies, the same loads would have been carried in four trains of identical weight (but with 3.3 times as many cars) as were actually transported in three. Making the simplifying, and savings minimizing, assumption that trains of so many more cars but equal weight could be operated at the same cost, we still reach the substantial additional expense of $329 million.[105] These important savings credited here to modern equipment reflect the observed secular association of increased loads per train and railroad productivity growth.

To recapitulate, our computations indicate that the incremental expenses incident upon meeting 1910 railroad demands with an 1870 technology of iron rails, light engines, low-capacity freight cars, hand brakes, and manual couplers would have amounted to about $1.3 billion. This is not likely to be much of an exaggeration. The estimate does not suffer from

[105] Operating expenses for the one-third increase in train mileage, using the same .5 relationship between marginal and average train-mile costs as before, total $233 million; interest in catpital outlays for the tripled number of smaller freight cars comes to a further $96 million since each smaller freight car would have cost about two-thirds of the actual 1910 price. The aggregate capital outlay required is, therefore, equal to twice the valuation of the 1910 freight-car stock, or $3.2 billion. Interest on the differential $1.6 billion, at 6 per cent, is $96 million.

Once more, there is a possibility that smaller cars, more efficiently loaded, could have compensated. But the explicit American choice of large, capacious cars, with an attendant lower load factor seems to suggest that such economies were limited.

the usual substantial upward bias associated with requiring an older technology to meet later demands, because in this instance exactly the same bill of goods was not imposed. Trains were not required to go as fast as they did in 1910; only the direct costs of a slower pace were reckoned. Equally heavy trains with a tremendous toll upon iron rail wear were eschewed in favor of the feasible alternative of lighter ones. Thus, one element of substitution enters the calculations, although not the response of demand for railroad output to its inevitably higher price. At every stage, moreover, assumptions that mildly understated savings were introduced.

This $1.3 billion is an impressive total against the backdrop of 1910 railway operations. To compensate, revenues in that year would have had to be more than 40 per cent greater. The question remains, however, as to the importance of this saving in the continual cost reduction—i.e., productivity advance—that railroads had been enjoying. These innovations, after all, were not the product of a single decade, or even two. Their effects were transmitted over some forty years, and by 1910 they had fully worked themselves out. It is misleading to limit the comparison to a single year; the entire range of years from 1870 to 1910 must be included.

In embarking upon such a task, it is useful first to reinterpret our previous total factor productivity measurements and to show how they relate to the foregoing analysis of technological change. An index of total factor productivity, *TFP*, is the ratio of an index of output to a weighted index of inputs, where the weights are the base-period income shares of the factors:

$$TFP_{t/0} = \frac{\frac{X_t}{X_0}}{\Sigma a_j \frac{I_{jt}}{I_{j0}}} = \frac{\frac{X_t}{X_0}}{\frac{W_0 L_0}{P_0 X_0} \cdot \frac{L_t}{L_0} + \frac{i_0 K_0}{P_0 X_0} \cdot \frac{K_t}{K_0} + \frac{r_0 R_0}{P_0 X_0} \cdot \frac{R_t}{R_0}} . \qquad (1)$$

X represents output; L, K, and R stand for inputs of labor, capital, and raw materials; P is the unit price of output, and w, i, and r are factor prices; the subscripts 0 and t refer to the base period and the period of comparison, respectively.

Now, eq. (1) can be rewritten simply as the ratio of the value of output in base-period prices to the value of inputs in base-period prices:

$$TFP_{t/0} = \frac{P_0 X_t}{W_0 L_t + i_0 K_t + r_0 R} . \qquad (2)$$

It follows from (2) that Kendrick's measure of technological change is nothing more than the ratio of an index of input prices to one of output prices. When output prices fall relative to input prices, technological change has occurred, and vice versa. For eq. (2) divided by P_tX_t numerator and denominator (remembering that $P_tX_t = W_tL_t + i_tK_t + r_tR_t$) is the same as

$$TFP_{t/0} = \frac{\dfrac{P_0X_t}{P_tX_t}}{\dfrac{W_0L_t + i_0K_t + r_0R_t}{W_tL_t + i_tK_t + r_tR_t}} = \frac{\dfrac{W_tL_t + i_tK_t + r_tR_t}{W_0L_t + i_0K_t + r_0R_t}}{\dfrac{P_tX_t}{P_0X_t}} \tag{3}$$

when the final numerator and denominator are seen to be indexes of input and output prices, respectively.[106]

This result recasts productivity analysis in a value frame of reference similar to one that has been used here to evaluate the specific innovations. Explicitly, we have computed C_0^t, the cost of producing output in the base year (1910) using the technology of another year t (1870). This can be expressed as

$$C_0^t = P_0^tX_0 = X_0\left(w_0\frac{L_t}{X_t} + i_0\frac{K_t}{X_t} + r_0\frac{R_t}{X_t}\right); \tag{4}$$

that is, the hypothetical cost is equal to the volume of 1910 output, X_0, multiplied by 1870 unit input requirements, $\frac{L_t}{X_t}$, etc., valued in 1910 prices, w_0, etc. Dividing both sides by P_t and X_0, we get

$$\frac{P_0^t}{P_t} = \frac{w_tL_t + i_0K_t + r_0R_t}{w_tL_t + i_tK_t + r_tR_t} \tag{5}$$

whence, from eq. (3), we reach the desired equation

$$TFP_{t/0} = \frac{P_0}{P_0^t}. \tag{6}$$

The index of total factor productivity is, therefore, nothing more than the ratio of the actual price of output in the base year to the price that would

[106] I am grateful to Dorothy Brady for suggesting this price index variation to my original proof. It is useful since it points up the omnipresent duality between price and quantity results in a competitive equilibrium framework. The simplicity of this dual relationship for the Kendrick arithmetic index is a virtue that has gone unnoticed. It helps to offset the valid criticism of its unconvincing production implications. Because both geometric and arithmetic indexes give similar results over reasonable ranges, the practical advantages of the Kendrick index are enhanced by the ease of its alternative value formulation.

have prevailed in the absence of change in the technological coefficients. $P_0 = P_0^t$ if the matrix of technical coefficients, L/X, K/X, and R/X, remains constant; $P_0 > P_0^t$ if the technology at t is superior, and $P_0 < P_0^t$ if technology at t is inferior. In the case at hand, because t precedes the base period in time, $TFP_{t/0}$ less than one, as it is, constitutes progress between the two dates.

It is now possible to measure the significance of the selected innovations relative to all influences operative on productivity advance. The P_0^t that emerges from the previous cost calculations is partial, encompassing only the effects of the four innovations. Consequently the ratio of this limited $P_0'^t$ to the total P_0^t is an index of their explanatory power. There are three alternative P_0^t's to choose among, the highest one corresponding to the original productivity calculations and the other lower two reflecting the alternative capacity utilization adjustments made earlier. The respective ratios $\frac{P_0'^t - P_0}{P_0^t - P_0}$ are .36, .42, and .75.[107] Roughly, therefore, the technical changes dealt with account for half the productivity gains registered in the railway sector between 1870 and 1910.[108]

From the standpoint of the limited variety of changes taken up, this accomplishment is no mean achievement. From another aspect, however, it is a rather small contribution compared with what might have been anticipated. The two innovations of greater engine power and freight-car capacity include a host of lesser changes that are reflected in the final result: increased steam pressure, substitution of steel trucks, etc. Thus, the cost reductions made possible by these two advances sum up much of the residual technical change that occurred; it is not surprising that they make up almost two-thirds of the $1.3 billion estimate. The fact that, despite this, only half the productivity change from 1870 to 1910 can be accounted for shows how thick is the veil of ignorance surrounding the causes of the rapid increases that advanced economies have experienced in output per unit of input.

[107] What is termed the total P_0^t is, of course, the actual 1910 price divided by the productivity index. It is easiest to work in 1910 relatives throughout, however, which then makes P_0^t/P_0 simply equal to the inverse of the productivity index.

Note that the ratio used in the text is preferable to the alternative $\frac{P_0'^t}{P_0^t}$ because, in the absence of economic impact, $P_0'^t = P_0$; such a ratio would then be greater than zero regardless of the lack of change.

[108] It will be remembered that the capacity utilization adjustment obtained by holding the capital-output ratio constant at its 1910 level exaggerated the explanatory value of this factor. Hence the .75 ratio credits too much to technology in a relative sense, because the denominator is too small.

In part, this doubt will be resolved by extending the analysis to factors not taken up here, such as the increased educational level of railway employees and the value of an experienced labor force. In part, too, it must be resolved by a finer analysis of technical progress than has been performed here. The underlying engineering relationships employed, such as that relating the wear of rails to tonnage passing over them, can be made more sophisticated and exact. Testing these against actual experience is also necessary. Likewise, the cost relationships taken on the authority of Wellington can find more accurate substitutes in statistical cost functions fitted to the data. A third direction of advance is the use of smaller time intervals than the forty-year period employed here. The relative importance of innovations within shorter spans may be quite different. It is possible that between 1870 and 1890 the substitution of steel rails made up much more of the productivity gain than over the longer haul since it was concentrated in those earlier years.

Despite these admitted deficiencies of the present calculations, they do point to certain conclusions that seem likely to hold up under closer scrutiny. One of these is the limited economic significance of air brakes and automatic couplers in the array of late nineteenth century improvements. Another is the important role of the larger engines, a trend that is not attributable to a sudden major breakthrough, but rather to a cumulation of knowledge of design. The apparent sudden increase in the ratio of load to dead weight in freight cars in the late 1870's is more of a discontinuity. Yet virtually nothing has been done to determine the origins and causes of this major shift. Finally, these quantitative results confirm one major contention on which historians have been nearly unanimous: the importance of steel rails. Yet even in this instance, an amendment is necessary. What made such rails so crucial was less their wearing properties than their strength, and the opportunity thus presented for heavier trains.

Concluding Comments

Economists have come more and more to appreciate the role increased efficiency plays in the present growth of income per capita. The American economy in the nineteenth century was probably no exception. Economic historians must evaluate and interpret that experience from the same vantage point. In this paper we have made a tentative start in this direction in the railway sector. Two objectives have been pursued: first, extension and correction of the underlying data to provide a reasonably firm long-term record of inputs and outputs in the industry; second, explanation of the notable productivity growth that emerges. The latter endeavor also illustrated the wider possibilities of placing the analysis of specific innovations within an aggregate context, as well as yielding important substantive results.

Obviously, there is much left to do. Within the railway sector, the tasks range from more detailed evaluation of the factors influencing productivity advance to application of such information to such important historical questions as regional rate differences, discrimination between short and long hauls, and excessively high railway profits. All of the latter topics need to be restudied with more reliance upon underlying and changing conditions of production of railway services. Railroads, however important, are only one activity among many. Other industry studies must be carried out too. These conference proceedings include three such ventures into the extractive industries, albeit with rather limited attention to productivity per se. For manufacturing, there is nothing, however. Recalcitrance of the data helps to explain this, although one suspects that this is an area of research where important gains can be and are yet to be made.