The Demand for Capital Maintenance: Some Theoretical and Empirical Results

Jackson Mejia*

August 24, 2024

Using novel micro data from Class I freight railroads, I show that the demand for capital maintenance is positive and an economic decision with a price elasticity around two. This stands in contrast to traditional capital theory, which assumes that maintenance demand is inelasticially zero. I show that positive maintenance demand is particularly important for capital tax policy. Because maintenance is subsidized at the marginal effective tax rate on capital and both maintenance and investment are inputs to capital, tax cuts induce firms to substitute investment for maintenance. This channel substantially attenuates the tax elasticity of capital and output. Calibrated to the dynamic path of the 2017 Tax Cuts and Jobs Act (TCJA), which is the largest capital tax reform in forty years, a neoclassical growth model with maintenance (NGMM) predicts output gains over the first ten years 2/3 as large as the standard NGM with convex capital adjustment costs. In the long run, the NGMM predicts output to rise by 0.6%, which is half as much as the NGM prediction.

JEL-Classification: D21, D22, D25, H25

Keywords: Capital taxation, capital maintenance

*Massachusetts Institute of Technology, jpmejia@mit.edu. I am especially grateful to Jim Poterba, Martin Beraja, and Ellen McGrattan for invaluable guidance. Additionally, Ricardo Caballero, Tomás Caravello, Janice Eberly, Joel Flynn, Jon Gruber, Sam Jordan-Wood, Pedro Martinez-Bruera, Chelsea Mitchell, Giuditta Perinelli, Iván Werning and participants in numerous seminars provided helpful comments and discussions. This material is based upon work supported by the NSF under Grant No. 1122374 and is also supported by the George and Obie Shultz Fund.

1 Introduction

Perhaps the central issue in capital theory is the fact that capital is unobserved. To varying degrees of uncertainty, we observe what are presumably inputs into capital accumulation like investment, but it has historically been a source of controversy how to translate those observations into capital itself (Hayek 1935; Pigou 1941; Feldstein and Rothschild 1974).[1] Since the seminal work of Hall and Jorgenson (1967), economists have largely constrained themselves to single-input theories of capital production, particularly for understanding the effects of supply-side tax policy on the capital stock and economic growth (Lucas 1990). Under such theories, the tax elasticity of investment is a sufficient statistic for the tax elasticity of capital and through additional structural assumptions, the tax elasticities of output and welfare. For that reason, policymakers and economists alike focus almost exclusively on the tax elasticity of investment, using it as both a tool to motivate major reforms like the 2017 Tax Cuts and Jobs Act and to evaluate the effects of tax reform (Romer and Romer 2010). However, single-input theories are insufficient to understand the consequences of tax policy changes if other inputs to capital are differentially taxed and the elasticity of demand for their services is greater than zero. One such input is capital maintenance.[2] In this paper, I investigate the price elasticity of capital maintenance and the resulting implications for tax policy analysis when capital is produced with both maintenance and investment.

Maintenance expenditures are expensed costs on capital, labor, and intermediate inputs to restore, repair, or ensure continued productivity of existing capital. By contrast, traditional investment improves existing capital or purchases new capital.[3] On the margin, firms maintain capital to make it last longer at the cost of an additional unit of new investment. For example, Burlington Northern maintains its current locomotive engines until it becomes more cost-effective to replace them. The tax code distorts these allocations. While investment is typically subject to taxation, maintenance costs are fully expensed, creating a tax wedge. If the demand for maintenance is remotely price-elastic,

1. Although the early debates were about physical capital, modern discussions of intangibles have reawakened slumbering arguments over theory and measurement in capital theory. See, for example, Peters and Taylor (2017), Haskel and Westlake (2018), and McGrattan (2020).

2. There are, of course, many ways that firms can change their capital stocks beyond investment and maintenance. Albonico, Kalyvitis, and Pappa (2014) and Kabir, Tan, and Vardishvili (2023) along with an old macroeconomic literature give a role to utilization, while Goolsbee (1998b) highlights scrappage decisions. I focus on only maintenance and investment because of the differential tax treatment.

3. An alternative definition, which I favor, comes from Scott (1984): "Gross investment expenditures are aimed at improving, while maintenance expenditures are aimed at restoring, economic arrangements." This is an economic rather than an accounting definition and so does not map neatly into the tax code or accounting data and practice.

changes in the relative price of maintenance to investment can lead firms to substitute between them. Since the capital tax wedge affects this relative price, reductions in capital taxation may prompt firms to favor new investment over maintenance. This substitution effect suggests that the tax elasticity of capital could be much smaller than traditionally estimated, with correspondingly smaller effects on output and welfare.

Like many intangible expenditures, maintenance is a *hidden* investment because it is treated as an operating expense, which means it is difficult to observe in many standard data sources. In the data we have, maintenance looks large. In Canada, for instance, maintenance expenditures are about half the size of new investment in aggregate data. The question is decisively not whether firms maintain capital—they obviously do—but whether maintenance is price-elastic.[4] I shed light on this question with a novel dataset of maintenance and investment behavior from Class I freight railroads. Every year, large railroads are required to file independently audited granular reports on their assets and operating expenses with the Surface Transportation Board. As part of that, railroads report a detailed breakdown of their expenditures on what is maintained (locomotives and freight cars) and how it is maintained (through labor, materials, and external services). Railroads also report both quantities and prices for a wide array of different capital goods. This provides an ideal and unique environment to study the elasticity of demand for maintenance; no other dataset, to my knowledge, provides such granular detail on assets, maintenance, and investment. As a first exercise, I regress the log maintenance rate on the log relative price of maintenance to investment for two capital types across seven firms from 1999-2023. The coefficient is identified through variation in the relative price of maintenance across firms and capital types driven by variation in exposure to tax policy and the labor component of maintenance expenditures. This yields an elasticity around 2, significantly larger than the neoclassical benchmark of zero. The result holds up across a wide array of robustness exercises within freight railroads.

It is natural to wonder how well a result from railroads extends to the rest of the economy. I test this using industry data from the Statistics of Income (SOI), which is a representative sample of corporate tax returns within around fifty industries. This dataset allows for two tests of the theory. First, I directly measure the maintenance elasticity of demand using an identification strategy from the investment literature. Following a

4. In single-input theory, the demand for maintenance is perfectly inelastic and zero. Alternatively, one may think of maintenance, as Poterba (1984) does, as perfectly inelastic but positive. In that sense, maintenance simply scales up with more capital and is like a depreciation cost. Lumpy investment and durable consumption theories often include maintenance as an intermediate expenditure between purchases of new capital goods (Bachmann, Caballero, and Engel 2013). However, the choice there is not economic; agents simply expend some constant maintenance rate. Moreover, maintenance is solely included to keep the drift rate of the capital stock low so that investment is sufficiently lumpy.

methodology in the tradition of Cummins, Hassett, and Hubbard (1994) and best exemplified by Zwick and Mahon (2017), I use cross-sectional variation in exposure to exogenous tax policy changes to identify the maintenance elasticity. This is possible because each tax return contains line items for both book capital and maintenance. Second, theory implies that untaxable firms should not adjust their maintenance behavior in response to changes in tax policy. Because the SOI breaks down its sample into taxable and untaxable firms, we can directly test this. The maintenance elasticity for taxable firms is remarkably similar in these data to the one obtained using freight rail data, while the maintenance elasticity is zero for untaxable firms.

What matters, however, is not merely that the price elasticity is statistically significant, but that it is economically significant. I show this quantitatively in the context of the 2017 Tax Cuts and Jobs Act (TCJA) in both the short run and the long run. I show that dynamic analyses of the capital stock diverge under the standard neoclassical model from those obtained from the NGM augmented with maintenance (NGMM). Over a ten year horizon, the output gains are only 2/3 as large in the NGMM as in the NGM. This indicates that the standard perpetual inventory model is a poor approximation for the capital stock even in the short run. In a second step, I use the neoclassical analysis of TCJA from Barro and Furman (2018) as a foil. Their careful quantitative analysis relies entirely on the user cost of capital to predict that the long-run effect of the reform would lead to a 1.2% increase in output per capita. I show that an otherwise identical model with maintenance would instead predict an increase in output of only 0.6%. This is observationally equivalent to more than halving the capital share in the standard neoclassical model.

I wrap up by analyzing the welfare cost of the maintenance-investment distortion. Building on Lucas (1990) and Chari, Nicolini, and Teles (2020), I show that it is optimal to not tax capital in the neoclassical model when there are standard macro preferences and there is positive demand for maintenance. Naturally, the welfare cost is reduced by maintenance. Under the benchmark calibration with maintenance, the consumption-equivalent welfare gain to cutting taxes to zero is 2.8%, compared to 5.1% in a model without maintenance. If we think of the cost of the maintenance-investment distortion as the difference between those two numbers, then it is approximately 2.3% of consumption-equivalent welfare.

In sum, despite a firm argument from McGrattan and Schmitz Jr. (1999) that maintenance is "too big to ignore," the channel is rarely accounted for in theoretical, empirical, or quantitative tax policy analysis. Indeed, all of the main tax policy analysis models from the government, think tanks, and academia entirely ignore maintenance when predicting the likely growth and welfare effects of policy (Auerbach et al. 2017). Of course, such models miss out on many parts of reality and by virtue of being models, that is a feature rather than a bug. This paper, with simple theory, empirics, and quantification, aims to convince tax policy researchers of all stripes that including a small adjustment for capital maintenance is worth it.

Literature. This paper connects to a theoretical literature which deviates from the Hall and Jorgenson (1967) tradition by making elements of user cost endogenous to tax policy. Although Feldstein and Rothschild (1974) laid early groundwork with their analysis of optimal capital replacement decisions, McGrattan and Schmitz Jr. (1999) inaugurated a small but robust theoretical literature on the importance of endogenous capital maintenance. That paper develops a homogeneous capital model of maintenance and investment, with maintenance expenditures pinned down by the relative price of maintenance to investment and provides the original insight that depreciation is endogenous to tax policy. Several other papers build on McGrattan and Schmitz Jr. (1999) in the areas of public capital maintenance (Kalaitzidakis and Kalyvitis 2004, 2005; Dioikitopoulos and Kalyvitis 2008), cyclical fluctuations (Albonico, Kalyvitis, and Pappa 2014), and investment theory (Boucekkine, Fabbri, and Gozzi 2010; Kabir, Tan, and Vardishvili 2023). My contribution is a parsimonious theoretical framework grounded in the McGrattan and Schmitz Jr. (1999) neoclassical model that provides a simple sufficient statistic approach to estimating the maintenance demand elasticity and its quantitative effects.[5]

I also contribute to an empirical literature documenting the economic relevance of capital maintenance. To date, most papers have relied on aggregate data from the Canadian Annual Capital Expenditures Survey because there are very few high-quality data sources. For example, Albonico, Kalyvitis, and Pappa (2014) develop parametric estimates of the cyclical elasticities of maintenance and depreciation using this source, while McGrattan and Schmitz Jr. (1999) document the cyclical properties of maintenance with the Hodrick-Prescott filter. Angelopoulou and Kalyvitis (2012) estimate an aggregate Euler equation with endogenous depreciation. In a pair of papers, Goolsbee (1998b) and Goolsbee (2004) indirectly study the determinants of capital maintenance. The former studies commercial airplane retirements in the context of tax policy and finds that that moving the investment tax credit from zero to 10% increases the probability of retirement

5. There has been significant theoretical work linking utilization to depreciation (Greenwood, Hercowitz, and Huffman 1988; Justiniano, Primiceri, and Tambalotti 2010) and utilization and maintenance together to depreciation (Boucekkine, Fabbri, and Gozzi 2010; Kabir, Tan, and Vardishvili 2023). While undoubtedly correct and important that utilization plays a role in the depreciation of capital and utilization is endogenous, I focus solely on maintenance in this paper because it more clearly isolates the theoretical channel I am interested in and is clearly differentially taxed from investment, while utilitzation is less clear.

from 9% to 12%. The latter convincingly argues that the quality elasticity of capital with respect to the cost of capital is around 0.5%, where quality is roughly measured with maintenance expenditures per unit of capital. Both papers indirectly estimate the relationship between taxes and maintenance in some sense, but do not have the requisite data to directly measure a price elasticity. Bitros (1976) and Grimes (2004) are closer to my work because they use similar freight rail data to study the determinants of maintenance decisions, but do not estimate price elasticities. Finally, housing economists have documented a clear connection between maintenance and depreciation Knight and Sirmans (1996) and Harding, Rosenthal, and Sirmans (2007). I expand on these studies by building a novel maintenance and investment dataset using financial filings from Class I freight railroads.[6]

Finally, this paper relates directly to an expansive literature on quantitative tax models, particularly those evaluating the effects of the 2017 Tax Cuts and Jobs Act. Barro and Furman (2018) use a representative firm neoclassical growth model and Sedlacek and Sterk (2019) use a heterogeneous firm model to study the long-run effects of TCJA. I build directly on the Barro and Furman analysis by layering in maintenance to an otherwise identical model and show that the maintenance channel substantially dampens the effects of tax policy. Additionally, Zeida (2022) and Chodorow-Reich et al. (2023) study the dynamic effects of TCJA. The latter is a heterogeneous firm model, while the latter is an extension of the Jorgensonian user cost model to incorporate foreign tax incentives. While both models are much richer than mine, I show that maintenance is quantitatively important in the short run. This a more general problem for single-input models analyzing dynamics because it means that the perpetual inventory equation is a poor approximation in the short run. Overall, however, the lesson for tax models of all kinds is simply that maintenance acts as a powerful dampening force regardless of frictions.

Roadmap. In Section 2, I develop a theoretical framework to analyze capital maintenance. Section 3 documents the empirical elasticity of demand for maintenance. In Section 4, I show why accounting for maintenance matters for tax policy analysis in the context of the 2017 Tax Cuts and Jobs Act. Section 5 analyzes the welfare cost of capital maintenance. Section 6 concludes.

6. In industrial organization, Rust (1987) and Harris and Yellen (2023) study maintenance but do not study the price elasticity directly.

2 A Simple Model of Capital Maintenance

How does endogenous maintenance affect the canonical model of capital accumulation? Suppose that maintenance contributes to capital accumulation through the following variation on the law of motion for capital:

$$K_{t+1} = (1 - \delta + h(m_t))\, K_t + X_t. \tag{1}$$

Here, $m_t \equiv \frac{M_t}{K_t}$ is the maintenance rate, X_t is traditional investment, and δ is an exogenous depreciation rate. Modern capital theory ypically assumes $h(m_t) = h'(m_t) = 0$. In that case, given some initial level of capital K_0, it is clear that the level of capital at any point in time is a function only of previous investment choices. Consequently, there is no room for other margins of adjustment to capital. On the other hand, this paper emphasizes instead that, as long as the demand for maintenance is price-elastic, the sequence of capital stocks is a function of choices about both maintenance and investment. That conclusion encompasses earlier work from McGrattan and Schmitz Jr. (1999), Kabir, Tan, and Vardishvili (2023), and a number of other papers, which assume that maintenance can affect capital through a depreciation technology given by $h(m_t) = -\delta(m_t)$, where $\delta(m_t)$ is typically strictly decreasing and strictly convex. I weaken those restrictions by instead placing the following assumption on the maintenance technology.

Assumption 1. *$h(m_t)$ is a weakly concave functions.*

The extent to which maintenance or investment is a better technology for changing the capital stock depends on the concavity of maintenance. If, as is a standard assumption, investment enters linearly in (1) and maintenance does too, then they are perfect substitutes, while maintenance becomes less and less substitutable for maintenance as $h(m_t)$ becomes more concave. Ultimately, the shape of $h(m_t)$ depends on the elasticity of demand for maintenance in a way that will become clear shortly.

Given (1), a firm intent on choosing a sequence of optimal maintenance expenditures would equate the marginal benefit of maintenance with its marginal cost. The marginal benefit is that maintenance contributes slightly more to capital accumulation, which is captured by $h'(m)$. The marginal cost is a unit of foregone investment, which is determined by the relative price of maintenance to investment. Letting p^m denote the pre-tax price of maintenance, p^x the pre-tax price of investment, and considering the steady state decision, the firm equates marginal benefit with marginal cost exactly when

$$h'(m) = \frac{p^m(1-\tau)}{p^x}, \tag{2}$$

where τ is the marginal tax on capital. Because maintenance is tax deductible while investment is not, it is as if tax policy subsidizes maintenance relative to investment. Inverting $h'(m)$ yields the demand for the maintenance rate, while integrating $h'(m)$ yields $h(m)$. Hence, as long as $h'(m) > 0$, the decision to maintain is economic rather than technical. The more elastic demand is, the closer to linear the maintenance technology $h(m)$ is. This implies that if we learn about the elasticity of demand for maintenance, we can learn about the shape of $h(m)$.

Incorporating maintenance leads to an additional element in the standard Jorgensonian user cost of capital, namely that an additional unit of capital must be maintained at price p^m. In steady state, with a concave production function $F(K)$, firms invest until the marginal product of capital equals the user cost Ψ:

$$F_K = \Psi = \frac{p^x}{1-\tau}\left(r^k + \delta - h(m)\right) + p^m m, \tag{3}$$

where r^k is the discount rate and m is the optimally chosen maintenance rate given the relative price. (3) is a generalization of the Hall and Jorgenson (1967) user cost; under the extreme case $h'(m) = h(m) = 0$, it is exactly the traditional user cost.

In (3), the policy variable is τ and the relevant policy question is how much more capital there is when τ decreases. That question is answered by the proportional change in user cost together with the concavity of the production function in capital. Denote a proposed policy change as τ', so that the new user cost is Ψ'. Under the benchmark case in which $h(m) = h'(m) = 0$, the proportional change in user cost is given by

$$\frac{\Psi' - \Psi}{\Psi} = \frac{\Delta\tau}{1-\tau'}. \tag{4}$$

Maintenance complicates matters. To fix ideas, suppose the demand for maintenance is a constant elasticity function parameterized by a demand elasticity ω and a level shifter γ, *i.e.*, $m = \gamma\left(1-\tau\right)^{-\omega}$. Denote the pre-tax user cost as

$$\widetilde{\Psi} \equiv r^k + \delta + \frac{\gamma}{1-\omega} m^{1-1/\omega}.$$

Proposition 1 states the more general case.

Proposition 1. *The proportional change in user cost is given by*

$$\frac{\Delta\Psi}{\Psi} = \left(\frac{\Delta\tau\left(r^k + \delta\right)}{1-\tau'} + \frac{(1-\tau)\gamma}{1-\omega}\Delta m\right)\widetilde{\Psi}^{-1}. \tag{5}$$

When $\gamma = \omega = 0$, we end up with (4). In Proposition 1, there are two ways in which maintenance affects the proportional change in user cost: a level effect and an elasticity effect. Let us go through each in turn. First, suppose $\gamma > 0$ and $\omega = 0$. In this case, demand is inelastic and (5) simplifies to

$$\frac{\Delta\Psi}{\Psi} = \frac{\Delta\tau}{1-\tau'}\left(1 - \frac{\gamma(1-\tau)}{\widetilde{\Psi}}\right)$$

Thus, the benchmark case is marked down by the maintenance share of pre-tax user cost. If the (inelastic) maintenance rate γ is large relative to the rest of user cost, then the proportional change in user cost is smaller. This is, as far as I know, is a novel point that introduces some nuance to an interesting point made by House (2014) about the price elasticity of long-lived capital. That paper makes the point that because long-lived capital has a low depreciation rate, it is more price-elastic than short-lived capital. However, positive demand for maintenance implies that short-lived capital is *less* price-elastic because maintenance becomes a larger share of user cost. This channel would not exist if there were not a maintenance-investment tax distortion. Let's fix the pre-tax user cost at $\widetilde{\Psi} = 0.25$. Suppose output per capita is given by $y = K^\alpha$ with capital share $\alpha = 0.4$ and the tax reform reduces the tax rate from $\tau = 35\%$ to $\tau' = 20\%$. Since the proportional change in output is given by

$$\frac{\Delta y}{y} = -\frac{\alpha}{1-\alpha}\frac{\Delta\Psi}{\Psi},$$

the result effect of the tax reform is straightforward to figure out. In Figure 1, I plot the percent change in output given the tax reform as a function of γ. In the benchmark case emphasized by the existing literature, $\gamma = 0$ and output would rise by 12.5% in steady state. However, in the limiting case where maintenance dominates the user cost expression, output does not change at all in response to the tax reform. Therefore, positive but inelastic demand for maintenance is a sufficient case to substantially attenuate the effectiveness of tax policy.

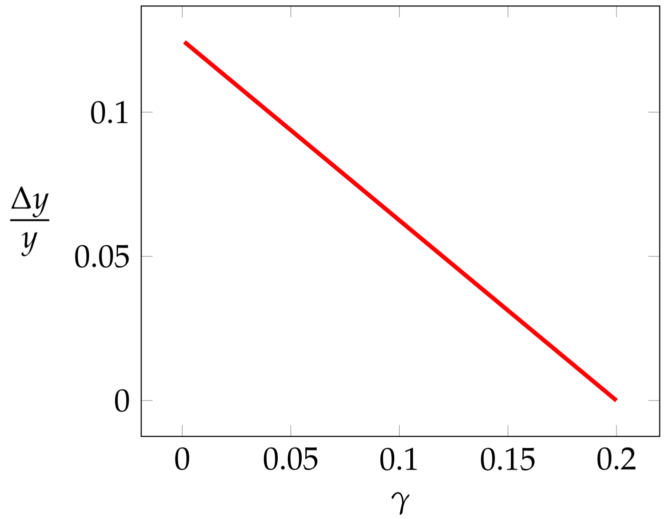


Figure 1: Proportional change in output per capita as a function of the maintenance rate. The tax reform moves the marginal tax on capital from 35% to 20%. I set $\widetilde{\Psi} = 0.2$ and $\alpha = 0.4$.

The second way maintenance alters user cost is through the change in demand for maintenance induced by the tax reform. Clearly, this depends on ω, which has two important properties. First, ω characterizes the elasticity of substitution between investment and maintenance in the production of capital. As $\omega \to \infty$, $h(m)$ becomes linear in the maintenance rate. This makes maintenance and investment perfect substitutes for producing capital. Second, ω characterizes returns to scale in maintenance. If $\omega < 1$, then there are decreasing returns. This yields an $h(m)$ conceptually equivalent to the restrictions imposed by McGrattan and Schmitz Jr. (1999), which require maintenance to only slow the depreciation of capital but not add to its stock. If $\omega > 1$, there are increasing returns to scale in maintenance. This makes maintenance *subtract* from the user cost of capital on net. Indeed, increasing returns to maintenance can make tax policy have the opposite predicted effect on capital accumulation as a single-input theory would predict by making the user cost decrease.[7] In this case, ω acts like a magnifier on γ and therefore renders user cost particularly inelastic to tax policy. In either case, the proportional change in user cost will be less than in the benchmark case of single-input theory.

In sum, there are two questions to validate empirically before figuring out how much maintenance matters quantitatively. First, we have to establish that firms have a positive demand for maintenance and how large it is. The first part of the question has an obvious answer: firms do spend money on maintaining capital. Second, we have to figure out what the elasticity of demand for maintenance is.

7. When $\omega = 1$, apply L'Hopital's to get $h(m) = g \log m$.

3 Testing Endogenous Maintenance

The testable implication of the model is whether maintenance rates respond to relative prices. Under the standard model of investment, maintenance expenditures should be completely invariant to changes in the relative price of maintenance. I test that hypothesis with data from Class I freight rail in the United States.

3.1 Estimation Strategy and Data

I use variation between firms and capital types over time to determine whether increases in the relative price of investment alter the maintenance intensity. To do that, I construct a novel dataset of maintenance and investment expenditures for Class I freight railroads using their financial filings with the Surface Transportation Board. Only freight rail and airlines are required by law to provide detailed data on their maintenance and repair expenditures. I focus on the former because its maintenance activities are significantly less regulated by the government than the airline industry's. This study follows up on Bitros (1976) and Grimes (2004), which also study the determinants of maintenance policy using freight rail data, but without the objective of studying its response to relative prices.

By regulation, any freight railroad with revenue exceeding $250 million must file an annual R-1 report with the Surface Transportation Board. The R-1 report can be thought of as a much more granular version of a 10-K filed by a publicly traded corporation. For example, it contains hundreds of line items for individual types of operating expenditures that would normally be summarized in one or two in a 10-K. It also details the size and composition of its property, plant, and equipment in value and quantities, its trackage by state, taxes paid, capital expenditures, and so on. Most importantly, it contains detailed data on maintenance expenditures by capital type as well as how those expenditures were allocated to labor and parts, both internally and externally. Every data item is independently audited by a third party firm like PwC or KPMG.

With that in mind, freight rail is an ideal setting to study maintenance decisions. Its capital stock is almost entirely physical and made up of a mix of rolling stock (locomotives and freight cars) and fixed plant. Since 1980, it has largely deregulated and since the mid-1990s, the industry has settled into a stable competitive equilibrium with around seven large companies carrying most of the United States' freight traffic: CSX Industries, Burlington Northern & Santa Fe, Union Pacific, Norfolk Southern, Kansas City Southern, Soo Line, and Grand Trunk, which is operated by the Canadian National Railway. All of these railroads own their tracks and equipment and have faced relatively little financial trouble over the past 25 years. I focus on how maintenance responds to relative prices in those seven companies from 1999-2023.

Each R-1 report contains about twenty different "schedules" which correspond to different information about the railroad. For example, Schedule 410 has several hundred line items on different operating expenses broken down by labor and material cost. These expenditures are largely maintenance on different aspects of railway operations from tracks to rail ties to electrical systems, and so on. For this paper, I maintain a narrow focus on freight cars and locomotives because they are easiest to identify in the data.

Theory suggests we require, at minimum, a maintenance rate and a relative price. I use Schedule 410 Line 202 for locomotive maintenance and Schedule 410 Line 221 for freight car maintenance. These expenditures are the only ones which clearly and directly affect only locomotives and freight cars, respectively. I use Schedules 330 and 335 to construct the denominator of the maintenance rate. Conveniently, the R-1 breaks down property, plant, and equipment into approximately forty different categories, which allows me to isolate which ones are locomotives and freight cars. By comparison, there is no way to distinguish equipment from structures in Compustat. I use the net stock of each capital type in book value as the denominator for the maintenance rate. The average maintenance rates for both locomotives and freight cars both exceed 10%. Because the whole point of this paper is that the net stock of capital is constructed incorrectly with a linear perpetual inventory method, I later construct an alternative capital stock and repeat the same analysis in Section C.1. I also use Schedules 330-335 to extract information on gross investment rates, which are the other main variables in the analysis.

The main independent variable of interest is the after-tax relative price of maintenance to investment:

$$P_{i,j,t} = \frac{p^m_{i,j,t}(1-\tau_{i,t})}{p^x_{j,t}},$$

where $p^m_{i,j,t}$ is the pre-tax maintenance price of capital good j for firm i at time t. Because of restrictions on data availability, only the pre-tax price of maintenance varies by firm type, whereas tax rates vary by firm and investment prices by capital type. I construct each as follows:

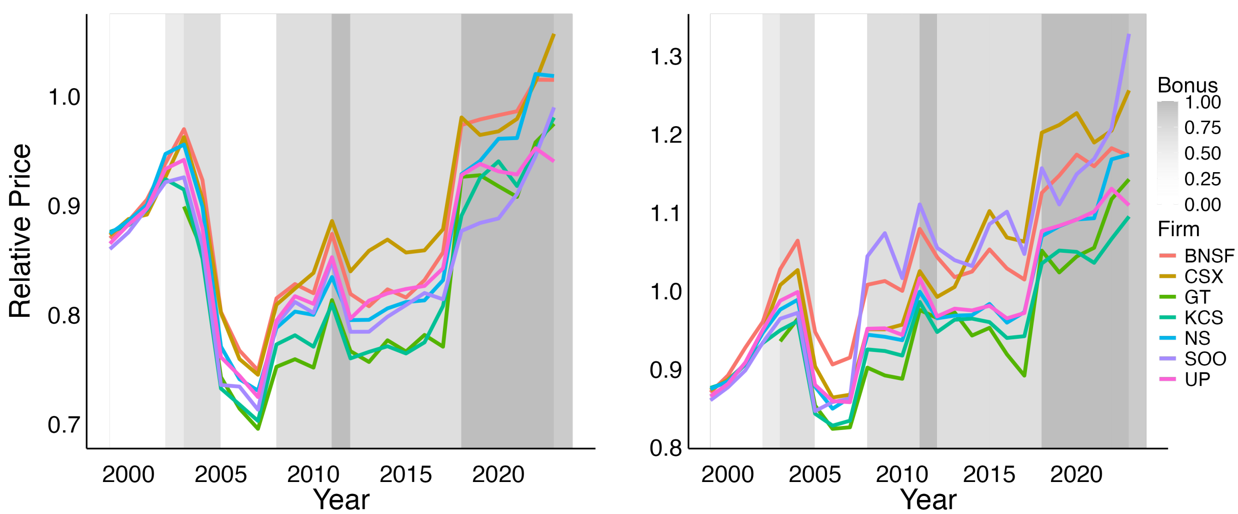
1. **Price of investment.** The price of investment does not vary by firm, only by capital type. It is simply the BLS's producer price index for locomotives and freight cars.

2. **Tax term.** The tax term varies by firm but not by capital type because rolling stock are taxed at the same rate. However, there is variation between firms because firms vary in their geographic area and hence their exposure to state tax policy. R-1 Sched-

ule 702 details the mileage of track by state for each firm. I use that information to construct a weighted tax term. I extend the dataset of Suárez Serrato and Zidar (2018) to construct the tax term through 2023.

3. **Price of maintenance.** The price of maintenance is a weighted average of labor and material costs. Labor costs are firm-specific and come from each firm's Wage Form A&B filed with the Surface Transportation Bureau. The materials cost index is from the Bureau of Labor Statistics. I weight each input with the cost share from Schedule 410, which breaks down maintenance expenditures by labor cost and materials for both locomotives and freight cars.

Putting items 1-3 together, relative prices may vary between firms and capital types for three reasons. First, because firms differ in their geographic concentration, they also vary in their exposure to state-level tax policy differences. Second, because capital types differ in their maintenance labor intensities, maintenance prices differ between capital types. Third, investment prices differ for locomotives and freight cars. Putting that together, there is variation between capital types and firms in their exposure to relative price changes. I plot that variation in Figure 2.



(a) Freight Cars **(b)** Locomotives

Figure 2: The relative price of maintaining freight cars (left) and locomotives (right). The degree of shading corresponds to the strength of bonus depreciation.

I rely on exactly that variation between firms and capital types in their exposure to relative prices to help identify the coefficient β in the panel regression

$$\log m_{i,j,t} = \alpha_i + T_t + \kappa_j + \beta \log P_{i,j,t} + \text{Controls} + \epsilon_{i,j,t}, \tag{6}$$

where $m_{i,j,t}$ is the firm i and capital type j maintenance rate at time t, α_i is a firm fixed effect, κ_j T_t is a time fixed effect, κ_j is a fixed effect for capital type j, $P_{i,j,t}$ is the relative price. The log-log specification is to accommodate a constant elasticity demand function.

3.2 Reduced Form Results

In Table 1, I present estimates of (6), where standard errors are clustered by firm. I cluster by firm because firms probably coordinate maintenance decisions across capital types. Column (1) contains the baseline relationship between the maintenance rate and the relative price. The relationship is statistically significant, negative, and large. A one percent increase in the relative price of maintenance to investment corresponds to a two percent decrease in the maintenance rate. In Appendix A.1, I present corresponding results for a linear-linear model, which is similarly statistically significant and large in magnitude.

	Dependent variable: $\log m_{i,j,t}$			
	(1)	(2)	(3)	(4)
$\log(P_{i,j,t})$	-2.101	-2.245	-1.847	-0.676
	(0.808)	(0.422)	(0.536)	(0.223)
Age		-1.902	-1.864	-0.833
		(0.590)	(0.591)	(0.323)
$\log x_{i,j,t}$			0.058	0.009
			(0.017)	(0.018)
$\log m_{i,j,t-1}$				0.778
				(0.067)
N	342	342	342	328
FE: Type	X	X	X	X
FE: Year	X	X	X	X
FE: Firm-Type	X	X	X	X

Table 1: Results for regressing a the log maintenance rate on the log relative price. Standard errors are clustered by firm.

Column (2) adds age as a covariate, where age is proxied with the ratio of net to gross capital book. A larger value for age corresponds to younger capital because less of it has depreciated. The coefficient on age is similar in magnitude and significance to the coefficient on price for both functional forms. Since a larger value for age corresponds to younger capital, it is sensible that the coefficient is negative. Column (3) adds the investment rate. This yields a puzzling result because it appears to be weakly complementary with the maintenance rate. However, that disappears after controlling for autocorrelation in the maintenance rate in column (4). Indeed, there is no relationship after controlling for past maintenance. The strong degree of autocorrelation in maintenance indicates that a large share of maintenance is required, which lends some credence to the traditional view of maintenance.

After accounting for the dynamic relationship between maintenance and prices in column (4), the coefficients are relatively stable across specifications within each functional relationship. The log relationship indicates that a one percent increase in the price of maintenance corresponds to a 2-3 percent decline in the maintenance rate. For comparison, the tax semi-elasticity of the investment rate is generally between 0.5 and 1 (Hassett and Hubbard 2002), while other studies have found values about twice as large (Zwick and Mahon 2017).

	Dependent variable: log $M_{i,j,t}$		
	(1)	(2)	(3)
log $P_{i,j,t}$	-0.695	-0.370	-0.394
	(0.353)	(0.111)	(0.114)
log $M_{i,j,t-1}$		0.885	0.888
		(0.021)	(0.022)
log $X_{i,j,t}$			-0.003
			(0.005)
N	342	328	328
FE: Firm	X	X	X
FE: Year	X	X	X
FE: Type	X	X	X

Table 2: Regression of the log-level of maintenance on the relative price for freight rail Standard errors clustered by firm.

Table 2 tests the maintenance elasticity in levels. The model does not make an unconditional prediction about the sign of the coefficient on price. If there are decreasing returns, then the level of maintenance should increase with the relative price because the corresponding increase in investment should more than compensate for the decline in maintenance. With increasing returns, the opposite is true. Across specifications, the coefficient on price is significantly negative and economically large. In particular, the price elasticity in column (3), which controls for autocorrelation in the level of maintenance, is about 3.5. This is half the size of the estimated price elasticity of investment in Zwick and Mahon (2017).

Altogether, the results reject the traditional view that maintenance does not respond to relative prices. Because the price elasticity is greater than one, this also means that the results agree that there are increasing returns to maintenance. In that case, maintenance *adds* to the capital stock rather than simply slowing its decline. It also means that the elasticity of substitution between maintenance and investment is theoretically positive, although it appears to be null in this data. From Figure 1, that means there is a point at which tax changes have the opposite effect on the user cost of capital, capital stock, and output than standard theory would predict.

On the other hand, there are significant concerns with measurement error in the capital stock, endogeneity, and external validity. I address each subsequently.

3.3 Endogeneity of Relative Prices

We should also worry about the endogeneity of the relative price of maintenance. There are three components to the relative price: a price for maintenance, a price for investment, and a tax term. The price of maintenance is made up of both the a firm-specific labor cost index and a material cost index which does not vary by firm. On average, the labor share of maintenance costs is approximately 40%. Figure 8 shows the average labor share over the sample period. Although labor shares vary across firms and capital types, there is very little variation in the labor cost index itself. That is largely because freight railroads are heavily unionized, which also means that wages are sticky and exogenous to maintenance demand shocks because they grow at a rate determined by macro price indices. However, the maintenance materials cost index is plausibly endogenous precisely because many materials are specific to the freight rail industry. Similarly, the price of investing in locomotives or freight cars is likely endogenous. Although the industry is global and so are the suppliers, U.S. freight rail is a large player in the industry as a whole and it is probably not true that they are price takers. Altogether, this suggests an instrumental variables approach is necessary to correct for endogeneity.

I use three different instruments for the relative price, each of which has its own pros and cons.

1. **Oil shocks.** Känzig (2021) creates a long time series of monthly oil news shocks. I take the annual average of these for the sample period. Because freight rail primarily runs on diesel and is a major hauler of many types of oil, oil shocks affect both the price of maintaining freight rail and investing in freight rail, but do not affect the maintenance rate. The issue is that oil shocks are common across railroads and so I replace the time fixed effect with a year trend and industry controls. The industry controls are for freight rail productivity growth, the rail cost adjustment factor, and real output growth. The Surface Transportation Board (STB) provided the first two. The rail cost adjustment factor is adjusted for productivity growth by the STB.

2. **Tax shocks.** Tax policy is exogenous to freight rail and affects maintenance only through the relative price. The reasoning is similar to the traditional public finance literature on tax policy as a natural experiment in, for example, Cummins, Hassett, and Hubbard (1994) and Zwick and Mahon (2017). However, there is no variation in tax rates between capital types and little across firms despite the fact that variation in trackage location leads to variation in tax rates. Figure 9 shows tax rates by firm over the sample period. Because of the little cross-sectional variation, I again omit a time fixed effect and instead rely on a time trend and industry controls. I first regress the maintenance rate on the tax term directly and second as an instrument for the pre-tax relative price.

3. **Lagged relative price.** In principle, the lagged relative price should only affect the maintenance rate through price autocorrelation. I also use the twice-lagged relative price as an instrument for the current relative price. The key benefit to using lagged prices is that it allows us to use time fixed effects.

Table 3 reports results for each of the specifications discussed in 1-3. The results are similar to those in the main specification for the log-log relationship. Although some are only borderline statistically significant, they are all economically significant to the same degree as the original regressions. Appendix 3.3 contains additional results for the linear specification and the same for maintenance in levels. The results again correspond to those in the main specification.

	Dependent variable: $\log m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$\log P_{i,j,t}$	-1.644	-1.662		-2.431	-3.218
	(0.920)	(0.400)		(0.990)	(1.435)
$1 - \tau_{i,t}$			-1.194		
			(0.219)		
N	316	316	316	328	314
Instrument	Oil	Tax Rate		$\log P_{i,j,t-1}$	$\log P_{i,j,t-2}$
F-test	16.6	33.1		1272.4	453.3
Industry Controls	X	X	X		
FE: firm	X	X	X	X	X
FE: type	X	X	X	X	X
FE: year				X	X

Table 3: Instrumental variables results for regressing the log maintenance rate on a measure of the relative price. The first column uses oil shock as an instrument for the log relative price. The second uses taxes as a shock for the *pre-tax* relative price. Every regression with instruments reports the Cragg-Donald F-statistic.

3.4 External Validity

It is natural to suspect that results on freight rail may not translate particularly well to the economy as a whole. After all, freight rail is a physically intensive and mature industry for which maintenance may be more important than others. However, it turns out that the results hold up economy-wide in our best representative data on the subject: industry tax data from the Internal Revenue Service's (IRS) Statistics of Income (SOI).

Corporations report a large number of operating expenses and balance sheet items as line items on their tax forms to the IRS. The SOI samples across those tax returns to provide summary measures of each line item at a roughly three-digit NAICS level going back to 1998 and through 2020. This is the only economy-wide collection of maintenance data at an annual frequency in the United States. I use Tables 12 and 13 I use Tables 12 and 13 of the SOI's Corporate Reports in combination with variation in tax policy exposure by industry over time to estimate the price elasticity of maintenance demand.

I take maintenance, investment, and book capital stock data from the SOI corporate reports from 1998-2020 from Table 12 and Table 13. This excludes filings made with Forms 1120S, 1120-REIT, and 1120-RIC. Table 12 has all corporate filings, while Table 13 only summarizes firms with positive net income. Using both tables together, I obtain corresponding data for firms which go untaxed. This is important because theory says that the tax wedge should only matter for taxable firms. Industries vary in their exposure to tax policy because they differ in their production technologies. Some industries use more structures, while others use more equipment. The end result, due to differential capital taxation, is that marginal effective tax rates vary widely by industry. This fact lies at the center of a literature on identifying the effects of tax policy on investment going back to Cummins, Hassett, and Hubbard (1994) in the past to modern studies from Zwick and Mahon (2017). Building on this literature, I leverage the BEA's fixed asset data to create a panel of capital-weighted marginal effective tax rates by industry. Because the number of SOI industries fluctuates over time but is always weakly larger than the number of BEA industries, I map the SOI industries into BEA industries for consistency and use the latter as a unit of observation. There are fifty such industries and 49 after I exclude the financial sector. Appendix B contains summary statistics.

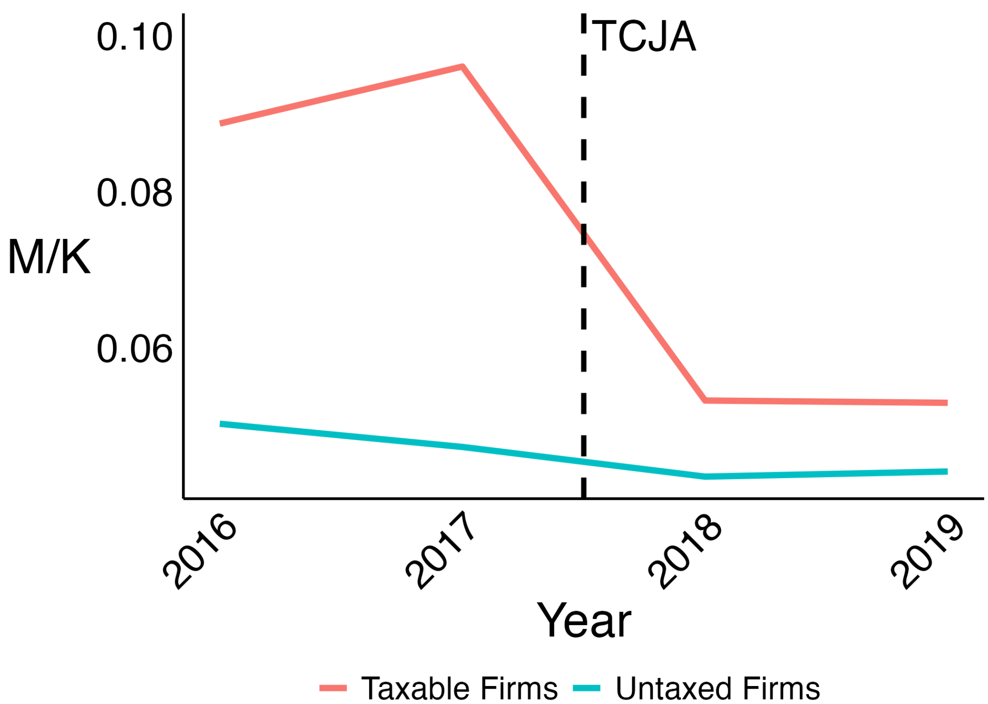


Figure 3: The average maintenance rate of taxable firms and untaxable firms plotted against the average marginal tax rate from the SOI sample. Untaxable firms had negative net income. The dashed line depicts the 2017 Tax Cuts and Jobs Act (TCJA), which passed toward the end of 2017.

Figure 3 plots the average maintenance rate of taxable and untaxable firms from 2016-

2019. I also plot an indicator for when the 2017 Tax Cuts and Jobs Act (TCJA) passed. TCJA, passed in late 2017 and taking effect in 2018, is one of the largest postwar tax reforms, involving a move toward 100% bonus depreciation for certain types of equipment and a cut in the corporate tax rate from 35% to 21%. While the maintenance rate for untaxable firms appears invariant to the large drop in the average marginal tax rate, the maintenance rate for taxable firms appears to drop nearly one-for-one with the tax rate.

Although Figure 3 is visually appealing evidence that the large change in tax policy induced large changes in maintenance rates for firms, it is difficult to be completely confident in the data because we do not have access to the underlying SOI sample. The primary issue is that we are not comparing the same firms over time; the SOI data is a repeated cross-section of industry samples. Thus, some of the firms which are taxable in 2017 may not be in 2018 because of different TCJA repatriation provisions or bonus depreciation. Similarly there are some untaxable firms which are taxable in 2018. However, the sampling evidence we do have indicates that the firms within each sample are similar between the pre- and post-TCJA windows. In the Appendix, Figure 10 plots the number of returns for both taxed and untaxed corporations over the full sample. Following the evidence in Auerbach (2018), the total number of corporations has declined considerably. However, the changes in untaxable and taxable returns tracked each other remarkably well from 2015-2019, which provides some evidence that firms previously taxable were not becoming systematically untaxable because of TCJA. Furthermore, Figure 11 shows that the business receipts per tax return followed similar trends before and after the passage of TCJA.

We can go beyond visuals to show the effects of tax policy changes on maintenance rates. Since the tax wedge is a key determinant of the relative price of maintenance, I use variation in that tax wedge from 1998-2020 to identify the coefficient in

$$\log m_{j,t} = \alpha_j + T_t + \log\left(1 - \tau_{j,t}\right) + \text{Controls} + \epsilon_{j,t}. \tag{7}$$

There was a great deal of policy variation in the relevant window.[8] Bonus depreciation, which allows firms to expense a larger share of certain equipment investment expenditures immediately and hence is a tax cut, began following 9/11 and has largely existed intact up to the present. House and Shapiro (2008) and Zwick and Mahon (2017) show that this had a substantial effect on the investment decisions of industries and firms with more exposure to that tax policy. Later, the 2017 Tax Cuts and Jobs Act (TCJA) constituted

8. I detail how I create $\tau_{j,t}$ in Appendix D. It is largely the same procedure as previous iterations of cross-sectional tax policy analysis from, for example, House and Shapiro (2008).

the largest tax reform in postwar history with both a corporate rate cut and an expansion of bonus depreciation. Kennedy et al. (2023) and Chodorow-Reich et al. (2023) show that the tax cut had a large and significant effect on corporate investment. I show the same for maintenance using similar regression specifications as for freight rail. The main difference is that the SOI does not have a measure of gross investment and net investment is occasionally negative, so I do not take a log transformation of the investment rate.

I give the results for the log-log specification in Table 3.4.[9] The coefficient on the log tax term for taxable firms is in columns 1-3 and untaxable firms in 4-6. Whereas the coefficient on the log tax term is around -2.75 for taxable firms, it is centered at zero for untaxable firms.[10] This result is useful for four reasons. First, columns 1-3 give demand elasticities of a similar magnitude and significance as in the freight rail results. Second, the tax term is a result of exogenous policy variation, which means it decisively resolves the endogeneity problem. Third, because the result only applies to taxable firms, it confirms that the driving force for the result is the distortion. It is difficult to show this for freight rail because Class I freight railroads are generally profitable. Finally, Table 3.4 confirms that the results are not limited to freight rail and are indeed an economy-wide phenomenon.

	Dependent variable: $\log m_{j,t}$					
	Taxable Firms			Untaxable Firms		
	(1)	(2)	(3)	(4)	(5)	(6)
$\log(1-\tau_{j,t})$	-2.912	-2.516	-1.665	0.010	0.004	0.000
	(1.128)	(1.003)	(0.732)	(0.093)	(0.100)	(0.067)
$x_{j,t}$		-0.052	-0.056		-0.002	-0.002
		(0.021)	(0.025)		(0.001)	(0.001)
$\log m_{j,t-1}$			0.340			0.371
			(0.098)			(0.070)
N	1071	1012	1005	1070	1009	1003
FE: Industry	X	X	X	X	X	X
FE: Year	X	X	X	X	X	X

9. I show the corresponding results for the linear-linear model and the level cases in Appendix B.
10. The dynamic specification in column 3 yields a coefficient around -2.5 because the autocorrelation of the maintenance rate is 1/3.

Table 4: Regression results of the maintenance rate on the tax term along with additional controls. Standard errors are clustered by BEA industry. The investment rate is net investment scaled by the net capital stock.

However, there are two potential issues with the data in this subsection. I give a detailed discussion of both in Appendix B.1. Briefly, there is a measurement error in the magnitude of the maintenance expenditure because it is likely the SOI only reports external maintenance expenditures rather than the sum of internal and external maintenance expenditures. This happens because firms place internal maintenance expenditures under similarly tax deductible wages rather than maintenance. Applying estimates from the more granular freight rail data, tax rates and the share of externally purchased services do not appear to be systematically related. Hence, if we can extrapolate from freight rail to the economy as a whole, then measurement error in maintenance does not affect the coefficient on the tax term in Table 3.4. Second, the capital stock is likely measured incorrectly; I discuss this source of bias in Section C.1. Third, the estimates in Table 3.4 implicitly assume a perfectly competitive supply curve for the supply of investment and maintenance. Goolsbee (1998b) shows that this is not a correct assumption. Applying his estimates implies that the elasticities in Table 3.4 should be magnified by approximately 1.4.

4 Capital Maintenance and the 2017 Tax Cuts and Jobs Act

The 2017 Tax Cuts and Jobs Act (TCJA) is among the largest tax reforms of the postwar era. It comprehensively reduced the cost of capital in both the corporate and passthrough sectors. Lawmakers permanently reduced the corporate tax rate from 35% to 21%, cut the top marginal tax rate from 39.6% to 37%, and introduced 100% bonus depreciation for certain types of equipment. The latter policy allows firms to immediately deduct investment from their tax bill, thereby eliminating the tax wedge in the maintenance-investment choice. These domestic tax policy changes were informed by economic models and represented, in some sense, the ultimate triumph of supply-side policy CEA (2018) and Gale and Haldeman (2021).[11] However, there was—and remains—substantial disagreement about how big the output effects of TCJA would be and are. Whereas the Tax Foundation predicted a long-run increase in output of around 1.7%, the Tax Policy Center and the Joint Committee on Taxation predicted no long-run effects, and the Penn Wharton

11. There were also a large number of foreign tax policy changes, which were plausibly more consequential than the domestic changes. For more details, see Gale et al. (2018). For a comprehensive evaluation of both the domestic and foreign changes, see Chodorow-Reich et al. (2023).

model was in between. Nevertheless, all of the models share a common mechanism for the transmission of capital tax policy to output. Given a marginal product of capital $F_{K_{t+1}}$, tax cuts induce output to move through

$$F_{K_{t+1}} = \frac{R}{1-\tau_{t+1}} + \Gamma\left(\boldsymbol{X}\right),$$

where R is the constant component of user cost and $\Gamma\left(\boldsymbol{X}\right)$ captures other frictions which vary by model. For example, they may include adjustment costs, crowding out, revenue feedback, debt effects, important general equilibrium distributional effects, or some other mechanism. As $\Gamma\left(\boldsymbol{X}\right) \rightarrow 0$, tax changes have larger supply-side effects. Disagreement about the likely effects of tax policy on capital accumulation and hence output therefore largely boil down to this term (Auerbach et al. 2017).

What are the dynamic and long-run effects of TCJA on capital accumulation and output when the wedge term $\Gamma\left(\boldsymbol{X}\right)$ is a function of maintenance demand as in Section 2? With elastic demand for maintenance, the 2017 tax cuts cause investment to substitute for maintenance, thereby substantially attenuating the likely effects of the law. I show the quantitative significance of this in the short-run and the long-run using the neoclassical growth model (NGM) as a foil for the otherwise identical NGM with maintenance (NGMM). I formulate the NGM using Barro and Furman (2018), which analyzed the long-run effects of TCJA.

4.1 Model and Calibration

Barro and Furman (2018) write an elegant and transparent neoclassical model to carefully analyze the long-run effects TCJA. I add convex capital adjustment costs and maintenance demand to their model so that we can properly account for both dynamics and steady state analysis. There is a corporate sector and a passthrough sector, but no household sector. I omit the household sector because the main objects of interest here are the capital-labor ratio and output-per-worker. In the Barro and Furman model, both can be obtained without specifying a particular household sector. Output per capita in each sector j is Cobb-Douglas in five capital types i:

$$y_{j,t} = \prod_{i=1}^{5} K_{i,j,t}^{\alpha_{i,j}}. \tag{8}$$

There are five capital types: equipment, non-residential structures, residential structures, R&D intellectual property, and other types of intellectual property. Each capital type evolves according to

$$K_{i,j,t+1} = K_{i,j,t}\left(1 - \delta_i - \frac{\psi}{2}\left(\frac{K_{i,j,t+1}}{K_{i,j,t}} - 1\right)^2 + \mathbb{1}_{\{NGMM\}}\frac{\gamma^{1/\omega}}{1-1/\omega}m_{i,j,t}^{1-1/\omega}\right) + X_{i,j,t}. \quad (9)$$

where the indicator function is equal to one for the NGMM and zero otherwise. There are two key assumptions here. The first is that the adjustment cost is in the growth rate of the capital stock. Although this form of adjustment costs is common in the literature (Eberly, Rebelo, and Vincent 2008; Albonico, Kalyvitis, and Pappa 2014; Koby and Wolf 2020), it also means that maintenance instantaneously adjusts when prices change. In Appendix E.2, I discuss and give alternative results when the adjustment cost is in the investment growth rate as in Christiano, Eichenbaum, and Evans (2005). I rely on capital adjustment costs in the main text here because a dynamic estimate of the coefficient on the relative price of maintenance appears fairly stable across horizons in Appendix C.2, which implies instantaneous adjustment. Second, I assume that the parameters for maintenance demand and the adjustment cost are common across sectors and capital types. This is certainly not innocuous, but there is little existing evidence to discipline the parameters heterogeneously. Later, I discuss and show results for varying these parameters.

The representative firm in each sector faces two types of taxes. The first is a tax on profits $\tau^c_{j,t}$. The second is an investment subsidy $\tau^x_{i,t}$. In most cases, the subsidy is the net present value of tax depreciation allowances for asset i allowances multiplied by the profit tax rate.[12] The firm's problem in each sector is to choose sequences of capital, investment, and maintenance to maximize

$$\max_{K_{i,j,t}, X_{i,j,t}, M_{i,j,t}} \sum_{t=0}^{\infty}\left\{\left(\frac{1}{1+r^k}\right)^t\left(1-\tau^c_{j,t}\right)\left(y_{j,t} - \sum_{i=1}^{5} M_{i,j,t}\right) - \sum_{i=1}^{5}\left(1-\tau^x_{i,t}\right)X_{i,j,t}\right\}. \quad (10)$$

After substituting out for maintenance and investment, the model is fully governed by (11). This nests Barro and Furman (2018); without maintenance and adjustment costs, it is exactly the same.[13]

12. The corporate sector receives the R&E credit for R&D intellectual property, but no other capital type receives a direct investment tax credit.

13. A slight difference is they also account for debt financing, which I ignore here. In their model, it does not make a substantial difference.

$$
\begin{aligned}
\left(1-\tau^{x}_{i,t+1}\right)\left(1+\psi\left(\frac{K_{i,j,t+1}}{K_{i,j,t}}-1\right)\right) = \frac{1}{1+r^{k}}\Bigg\{ & \left(1-\tau^{c}_{j,t}\right)\alpha_{i,j}\frac{y_{i,j,t}+1}{K_{i,j,t+1}} \\
& +\left(1-\tau^{x}_{i,t+1}\right)\left[1-\delta_{i}+\frac{\psi}{2}\left(\left(\frac{K_{i,j,t+1}}{K_{i,j,t}}\right)^{2}-1\right)\right. \\
& \left.-\mathbb{1}_{\{NGMM\}}\frac{\gamma}{1-\omega}\left(\frac{1-\tau^{c}_{j,t+1}}{1-\tau^{x}_{i,t+1}}\right)^{1-\omega}\right]\Bigg\}
\end{aligned}
\tag{11}
$$

The calibration of most economic parameters except maintenance demand and the adjustment cost function are from Barro and Furman (2018). A table of the Barro-Furman parameters is in Appendix E. I calibrate the maintenance demand function using the empirical estimates and the Statistics of Income. In that data, the mean marginal tax rate is 13.% and the mean maintenance rate for taxable firms is 0.064%. Given the estimated elasticity of two, that implies $\gamma = 0.042$. For reasons discussed in Section 3.4, this is a conservative estimate because firms likely under-report maintenance expenditures in their tax returns. Hence, the numerical estimates are probably a lower bound on the effect of maintenance. Second, I set the adjustment cost parameter ψ so that the path of capital in the NGM is similar to the path of domestic aggregate capital in the law-as-written case in Chodorow-Reich et al. (2023) and Zeida (2022). The latter is a heterogeneous firm and worker model, while the latter is neoclassical, but they both estimate similar paths for aggregate capital. Approximating their paths requires $\psi = 3$. This is substantially higher than Koby and Wolf (2020), which sets $\psi = 0.77$ or in Eberly, Rebelo, and Vincent (2008), which sets ψ closer to one. Finally, I set the depreciation rate for each asset in the NGMM such that the initial user costs are the same.

4.2 Dynamics

How did TCJA affect the dynamic accumulation of corporate capital and the resulting change in corporate output?[14] The dynamics are interesting because the only parts of the bill are permanent. Because lawmakers could not pass TCJA in a traditional way, most of its provisions are temporary and set to expire in 2027. Only the provision for the

14. I focus on the corporate sector for two reasons. First, it is far from clear how to handle the dynamics of firms switching from the passthrough sector to the corporate sector in the short run. I discuss the Barro and Furman (2018) approach to this issue in the long run in the following section. Second, some of the most detailed dynamic structural analysis of TCJA is only in the corporate sector (see, *e.g.*, Chodorow-Reich et al. (2023)). That makes it easiest to compare with existing work.

corporate rate change is permanent, whereas the expensing components for equipment sunset after 2026. There is 100% bonus depreciation on equipment until 2022.[15] After that, it declines by 20 percentage points per year until sunsetting entirely. At the same time, corporations must amortize R&D expenditures beginning in 2022. This leads to interesting time variation in capital tax rates.

Figure 18 plots the evolution of tax rates by asset. The marginal tax rate on equipment falls to zero before gradually rising as expensing phases out. I calibrate the initial tax on equipment to account for 50% bonus depreciation in 2017. R&D sees tax rates rise considerably from a net tax of nearly -10% to 0%, while other types of intellectual property see a small decline. The marginal tax rate on structures declines immediately by around ten percentage points as a result of the tax rate change. In this model, structures are a major driver of the differences in macroeconomic effects of the tax law. That is because they have the lowest depreciation rates, which means they are most sensitive to changes in prices (House 2014). However, that is not true in the NGMM because maintenance occupies a correspondingly larger importance precisely because depreciation is so small. On the other hand, the depreciation rates for intellectual property are higher, which means the opposite effect prevails.

In Figure 4, I plot the evolution of the capital-labor ratio from 2017-2050 for both the NGM and NGMM using a perfect foresight simulation. The dynamics between the standard neoclassical model and the NGMM plus maintenance are quite different. Capital grows faster and significantly more under the NGM before returning to a more moderate steady state as the TCJA provisions sunset. On the other hand, capital in the NGMM grows considerably less before the TCJA provisions sunset. In this model, the instantaneous adjustment of maintenance combined with capital adjustment costs means that the peak of the TCJA provisions before sunsetting is considerably different from the steady state, whereas the NGM steady state is similar to the peak in the mid-2020s. Evidently there is a danger of model misspecification when focusing on one capital input rather than two, which is what standard tax policy analysis models do. For example, two of the most prominent and careful structural analyses of TCJA include Zeida (2022) and Chodorow-Reich et al. (2023). Although both models are far more complex than the simple one here, they both predict increases in the domestic capital-labor ratio to a quantitatively similar

15. Bonus depreciation allows firms to deduct an extra percentage of their investment expenditures every year. Usually, firms are allowed to deduct from gross income a certain percentage of their investment according to guidance from the IRS. Let the net present value of these deductions be denoted as z_t. If the bonus depreciation percentage is θ, then the effective present value of depreciation deductions is $\tilde{z}_t = \theta + (1-\theta)\, z_t$. See House and Shapiro (2008), Kitchen and Knittel (2011), and Zwick and Mahon (2017) for detailed empirical analysis of bonus depreciation.

degree as the NGM in Figure 4. As a result, they both similarly miss out on the complex dynamics implied by accounting for maintenance, which suggest that capital is far less tax elastic than in their models.

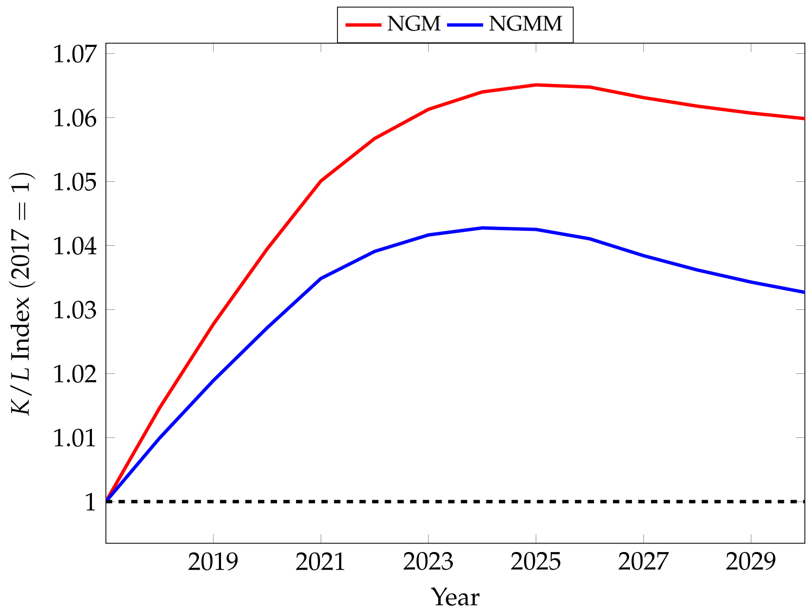


Figure 4: Capital-labor ratio in the NGM and NGMM given a sequence of tax rates from the 2017 Tax Cuts and Jobs Act.

From 2018-2027, when the temporary provisions all expire, the predicted cumulative gain in output per capita is about 2/3 as large in the NGMM as in the NGM. Indeed, the NGM predicts output to be about 2.3% larger in 2027 than in 2017 as a result of TCJA, which is on par with the Tax Foundation's model. By contrast, the NGMM predicts output to be only 1.4% higher. The NGMM figure is more in line with tax models from the Joint Committee on Taxation and the Penn-Wharton Budget Model, which predict more moderate effects of TCJA in the short run than the neoclassical model. However, those models incorporate far different wedges than the parsimonious model here, which suggests that if they incorporated maintenance in their settings, then the predicted effects would be even smaller.

Unpacking Capital Accumulation Dynamics

What drives the major difference in capital stocks between the NGMM and the NGM? Ultimately, of course, it entirely boils down to accounting for maintenance. In the NGMM, investment and maintenance both respond to tax changes, which leads to quite different Figure 5 plots the log-difference of aggregate maintenance and investment in both the NGMM and the NGM from the initial steady state. The aggregates are weighted sums of maintenance and investment in individual capital types with weights given by capital shares. Of course, maintenance in the NGM does not respond at all because the demand for maintenance is inelastically zero, whereas maintenance in the NGMM declines by 20%. However, investment in the NGMM is substantially more elastic than investment in the NGM; its peak elasticity response is three times larger.[16]

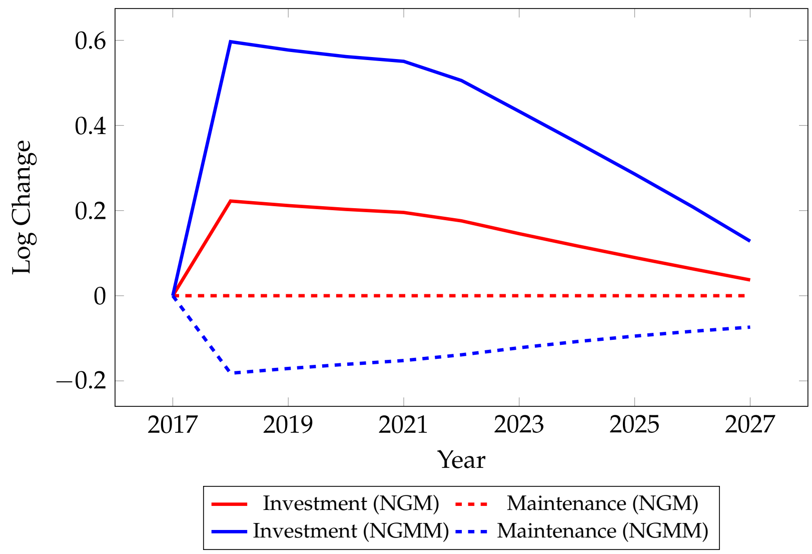


Figure 5: Dynamic responses of maintenance and investment in the NGM and NGMM given a sequence of tax rates from the 2017 Tax Cuts and Jobs Act. Here, the dynamic response is the log-difference from the initial 2017 steady state.

The large difference in investment elasticities between models suggests a previously unrealized difficulty in interpreting the effects of tax reforms and TCJA in particular. In general, the tax elasticity of investment is underestimated in standard work because of omitted variable bias. If there is more than one input to capital production, then simply regressing investment on a tax term or user cost suffers from omitted variable bias because it fails to account for substitutability between maintenance and investment. This is a direct result of Proposition 1, which suggests that the true exposure of investment to tax policy must account for maintenance. The insight is analogous to the lesson of Goolsbee (1998a), which emphasizes that the supply of investment goods is not perfectly competitive, so one cannot simply regress investment on a tax term and omit prices. In the same way that regressing investment on a tax term alone assumes perfect competition in the supply of investment goods, so too does omitting maintenance imply a particular model of capital production. In that sense, there are no model-free analyses of tax policy.

16. The quantitative predictions are quite sensitive to the choice of adjustment cost function. Appendix E.2 contains the same impulse responses but with an investment adjustment cost function. Qualitatively, the results are the same, but more dramatic.

The omitted variable bias spills over into empirical analyses of tax policy. Economists use tax reforms as natural experiments to determine the tax elasticity of investment, but such analyses necessarily assume an underlying model (Summers 1981; Cummins, Hassett, and Hubbard 1994). For example, regressions of some measure of investment on the tax term $1/(1-\tau)$ follow directly from the observation that the tax semi-elasticity of user cost is the tax term. Among many others, recent examples on bonus depreciation include House and Shapiro (2008), Kitchen and Knittel (2011), and Zwick and Mahon (2017), while similar work on TCJA includes Kennedy et al. (2023) and Crawford and Markarian (2024). Historically, the empirical focus on investment follows from an underlying standard single-input model, in which taxes lower the user cost of capital, leading to capital deepening and ultimately output growth through increased demand for investment. Such studies tend to systematically underestimate the tax elasticity of investment.

In the usual underlying models, the tax elasticity of investment *is* the tax elasticity of capital, which is why economists and policymakers care so much about it. However, the two-input model introduces a separate peculiarity: although we are systematically underestimating the tax elasticity of investment, that parameter is also considerably less important when there are two inputs to capital production. In that case, the tax elasticity of investment is *not* the tax elasticity of capital. That is particularly important to remember when comparing the TCJA predictions here to those from, for example, Chodorow-Reich et al. (2023). That paper states explicitly that their empirical estimates of the tax elasticity of investment map directly into the tax elasticity of capital:

> We start with a (nearly) "model-free" quantification. Column (1) of Table 6 reports the steady state partial equilibrium change in domestic capital (or equivalently investment), computed as the capital-weighted fitted values using the regressions (p. 39).

But as we have seen, the tax elasticity of capital is almost surely not the tax elasticity of investment. This is especially troublesome for Chodorow-Reich et al. (2023) because they use their short-run investment elasticities to infer long-run elasticities, which means they are compounding two problems over time. The first and more trivial problem is that their estimated investment elasticities are biased downward. The second and more troubling issue is that the investment elasticities are uninformative about the underlying capital stock in the short run, which makes using them for the long run an even more dubious exercise. That leads to the rather stark difference in predictions between the two-input model here and the single-input models favored by Chodorow-Reich et al. (2023) and others.

4.3 Long Run Analysis

A second class of TCJA analyses focuses on the long-run impact. By comparing steady states across a range of provisions and assumptions in this section's neoclassical model, Barro and Furman (2018) provide the simplest and cleanest long-run benchmark with which to compare the NGMM. In this subsection, I do exactly that under the "law-as-written" scenario, which assumes that bonus depreciation does not extend into the long run.

Under the benchmark NGM, the Barro and Furman analysis yields promising results for the TCJA, predicting large increases in the capital-labor ratio and, as a direct consequence, significantly higher output per capita. Their approach amounts to simply computing the analytical steady state under different capital tax policies while implicitly assuming that the demand for maintenance is perfectly inelastic and zero. I focus on bringing maintenance into their environment. For each capital type, it simply comes down to analyzing the effect of tax policy on the marginal product of capital

$$MPK_i = \Psi_i = \frac{1-\lambda_i\tau^c}{1-\tau^c}\left(r^k + \delta - \mathbb{1}_{\{NGMM\}}\frac{\gamma_i^{1/\omega}}{\omega-1}m_i^{1-1/\omega}\right), \tag{12}$$

where $m_i = \gamma_i\left(\frac{1-\tau^c}{1-\lambda_i\tau^c}\right)^{-\omega}$ is pinned down by tax policy. Let $1-\tau \equiv \frac{1-\tau^c\lambda}{1-\tau^c}$. Proposition 1 yields an easy comparison between the two models. We already know from Section 2 that the long-run effects will be scaled down by the maintenance channel. Clearly, if $\gamma = 0$, then the tax elasticities of capital are the same in the NGM and the NGMM. But as γ and ω rise, that is no longer true.[17] This is the same logic as Proposition 1. Our goal is to compare the predicted change in the user cost of capital, the capital to labor ratio, and the resulting change in the output to labor ratio between the NGM and NGMM. I focus on the baseline "law as written" scenario for TCJA and ignore debt incurred by firms. See Appendix E for the calibration, which sets each capital type to have the same pre-TCJA user cost.

Table 5 presents the resulting change in user costs for both corporate and passthrough

17. With more than one capital type, the proportional change in the capital-labor ratio is given by

$$\frac{\Delta(K_i/L)}{K_i/L} = -\frac{1}{1-\sum_i \alpha_i}\left[\left(1-\sum_{j\neq i}\alpha_j\right)\frac{\Delta\Psi_i}{\Psi_i} + \sum_{j\neq i}\alpha_j\frac{\Delta\Psi_j}{\Psi_j}\right].$$

The model implies that the elasticity will be smaller for each capital type in the NGMM. Indeed, even if the change in user cost is the same in both models for one capital type, the proportional change will be smaller in the capital-labor ratio will be smaller in the NGMM as long as at least one other capital type has an active maintenance channel.

business following TCJA. The top panel is corporate business and the bottom panel is passthroughs. The first column contains a baseline user cost common to both the NGM and the NGMM. The next two columns contain the percent change in the user cost and capital-labor ratio for each type of capital under the NGM and the following two for the NGMM. For structures, the percent change in user cost is more than twice as high for the NGM than the NGMM, while the difference is smaller for equipment and intellectual property. The reason for that follows from the fact that maintenance is a larger share of user cost in the NGMM. By comparison, maintenance is a relatively small part of other IP, so the difference in user costs is correspondingly smaller.

		NGM		NGMM	
	Baseline UCC	%Δ UCC	%Δ K/L	%Δ UCC	%Δ K/L
Corporate Business					
Equipment	0.190	-4.2%	+7.5%	-3.1%	+ 4.8%
Structures	0.143	-12.2%	+15.5%	-5.7%	+7.5%
Residential Structures	0.153	-12.2%	+15.5%	-6.2%	+7.9%
Intellectual Property	0.188	+7.6%	-4.3%	+6.1%	-4.3%
Other IP	0.305	-3.6%	+6.9%	-3.0%	+4.8%
%ΔK/L		+8.7%		+4.7%	
%ΔY/L		+3.3%		+1.8%	
Passthrough Business					
Equipment	0.187	+0.1%	-1.1%	+0.1%	-0.9%
Structures	0.139	+0.4%	-1.3%	+0.2%	-0.8%
Residential Structures	0.148	+0.4%	-1.3%	+0.2%	-0.9%
Intellectual Property	0.204	+21.5%	-22.4%	+16.4%	-17.1%
Other IP	0.302	+0.1%	-1.1%	+0.1%	-0.8%
%ΔK/L		-2.5%		-1.8%	
%ΔY/L		-1.0%		-0.7%	

Table 5: Effects of TCJA in the NGM and NGMM. The top panel depicts the change in the user cost of capital and capital-labor ratio within the NGM and the NGMM given a common baseline user cost of capital for corporate businesses. The bottom panel does the same for passthrough businesses. See Barro and Furman (2018) for calibrated parameters.

In the corporate sector, the NGM predicts a capital-labor ratio and an output-labor ratio slightly less than twice as large as the NGM. An equivalent way to summarize the result is that the NGMM is observationally equivalent to the NGM with a capital share that has been halved. In the passthrough sector, the change in user cost for most capital types is driven by a small increase in the personal income tax rate. But the sum of these differences in the NGMM yields a total change in the capital-labor ratio that is about 70% as large as in the NGM.

To compute the aggregate change in output, I assume that the pre-reform shares of output are 39%, 36%, and 25% for the corporate, passthrough, and government sectors, respectively. Given the change in the tax favorability of corporate ownership, Barro and Furman assume that in the long-run 6.8% of passthrough activity shifts to the corporate sector. I keep that assumption and then compute the total change in aggregate output. Figure 6 puts together the changes in the corporate and passthrough sectors into an aggregate change in the output-labor ratio for both the NGM and the NGMM. In total, the NGMM predicts that TCJA would increase the output-labor ratio about 50% as much as the NGM suggests it would. This is a significant difference and requires no frictions to arrive there. The long-run NGM productivity increase is in line with most estimates from both think tanks and academics, but lags substantially behind others which take into account business dynamism (Sedlacek and Sterk 2019; Zeida 2022).

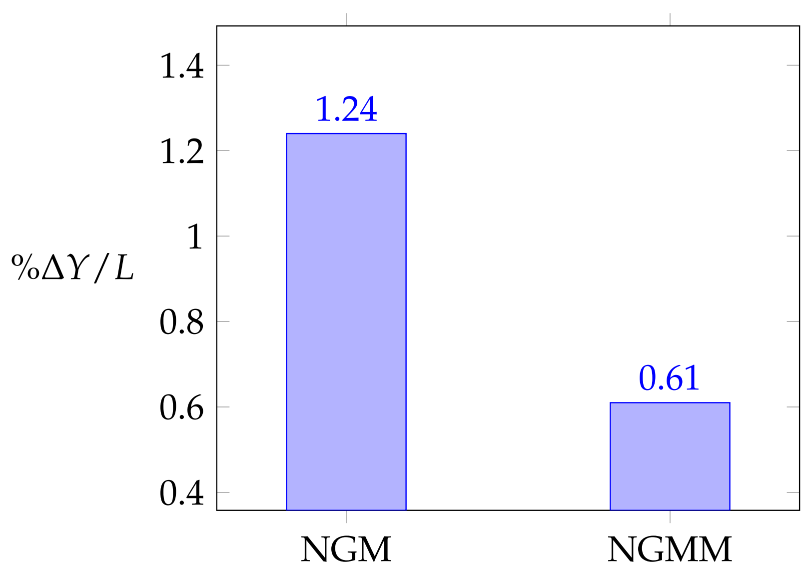


Figure 6: Increase in steady-state per capita output (productivity) in the NGM and the NGMM.

5 The Welfare Cost of Maintenance

As a final application, I analyze the welfare cost of capital maintenance. Perhaps the most famous result in optimal capital taxation is that the optimal tax is zero. Although the result is not particularly durable (Straub and Werning 2020), Chari, Nicolini, and Teles (2020) reaffirm the Chamley-Judd result in standard macro environments. In that environment, Lucas (1990) found that cutting capital taxes from 40% to zero percent would raise consumption-equivalent welfare by 10% across steady states. To put a quantitative figure on the importance of maintenance for optimal tax policy, I nest the partial equilibrium model in Section 2 into the general equilibrium environment of Chari, Nicolini, and Teles (2020) and repeat the Lucas exercise of comparing welfare across steady states.

Because the setup is fairly standard and derivation of optimal tax policy is likewise standard, I defer details of both to Appendix F and give a short description here instead. There is no uncertainty. Time is infinite and runs from $t = 0, \ldots, \infty$. There is a representative household with isoelastic preferences over consumption and labor. The household can save in bonds and shares of the representative firm. The firm is the same as throughout Section 2 but discounts the future using the household discount factor. A Ramsey planner sets capital and labor taxes to maximize household utility. In this setting, maintenance does not fundamentally alter the planner's problem from the benchmark without maintenance. It reduces the tax elasticity of capital stock but because capital is only completely tax-inelastic in the limiting case, the planner still wants to set capital taxes to zero and shift the burden entirely to labor taxes. Indeed, it is straightforward to show that zero capital taxation is optimal.

Proposition 2. *Suppose the economy converges to a steady state. The long-run optimal tax on capital is zero.*
Proof: See Appendix F.2.

In fact, Proposition 2 holds for all periods because I assumed additively separable and homothetic preferences. That is, simply introducing maintenance does nothing to make a Ramsey planner want to distort intertemporal allocations. On the other hand, the quantitative gains from refraining from intertemporal distortions may be substantially smaller than the standard model because the tax elasticity is lower. McGrattan and Schmitz Jr. (1999) point this out in their early work on capital maintenance, but do not quantify it.

In this exercise, I use the calibration for corporate capital from the previous section and compute consumption-equivalent welfare from cutting capital taxes to zero. The initial calibration takes the law-as-written case from TCJA as its baseline. Household flow utility over consumption and labor is $u(c, n) = \log c + \theta \log(1-n)$ with θ set such that $n = 1/3$ at the initial steady state with the capital tax rate set to 40%. I evaluate welfare with the consumption-equivalent welfare gain λ_ω, which I solve for in

$$u\left(c_0(1+\lambda_w), n_0\right) = u\left(c_{\text{reform}}, n_{\text{reform}}\right),$$

where the zero subscript corresponds to initial allocations and the reform subscripts denotes allocations after the tax reform.

Figure 7 plots the percent gain in consumption equivalent welfare λ_w as a function of the level parameter γ. I plot it as a function of γ because, as Section 2 shows, the level parameter γ is first-order in determining the effects of maintenance on capital accumulation. In the benchmark case with $\gamma = 0$, welfare rises by 5.1% when taxes are cut to zero. With $\gamma = 0.042$, which is highlighted with the vertical dashed line as the calibration from the SOI, welfare rises by 2.8%. Clearly, welfare is monotonically decreasing in γ.

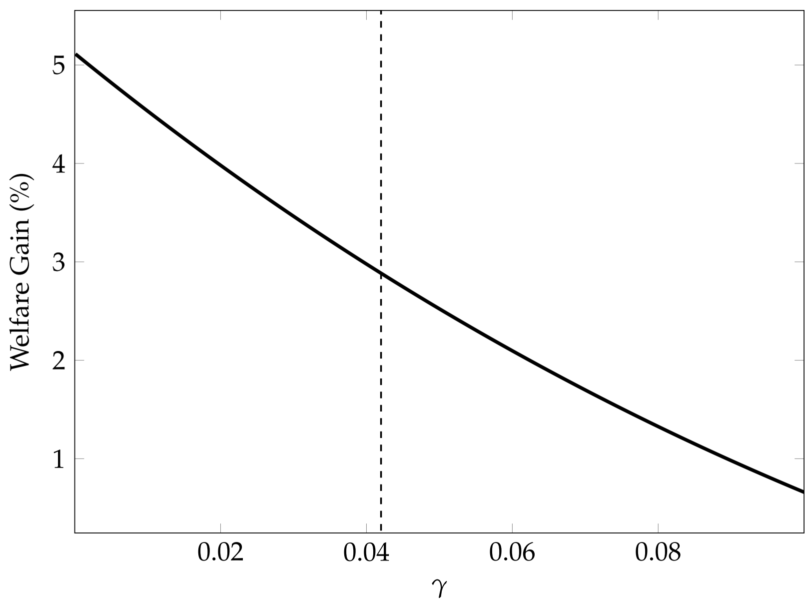


Figure 7: Welfare gain from cutting capital taxes to zero as a function of the maintenance level parameter γ.

Figure 7 can be understood as reflecting the cost of leaving the maintenance-investment distortion in the tax code *before* lowering tax rates on capital. That is, if maintenance remains distorted before lowering tax rates, then depreciation adjusts upward and capital does not increase as much as expected. In that sense, the government works at cross purposes with itself by leaving the maintenance-investment decision distorted prior to embarking on pro-growth tax policies which litter the history of postwar tax reform (Romer and Romer 2010). At the same time, removing the distortion would likely induce capital to depreciate faster, so it is far from obvious how to time removing the distortion given that it is already baked into tax codes around the world.

6 Concluding Remarks

In this paper, I discuss the theoretical, empirical, and quantitative relevance of accounting for endogenous maintenance in the context of capital tax policy. I provide a parsimonious and flexible framework for evaluating the likely consequences on the short-run and long-run impacts on allocations of maintenance, investment, and capital for heterogeneous capital. Additionally, I provide two novel sources of evidence on the price elasticity of maintenance. First, I put together an entirely new dataset on the maintenance and investment behavior of Class I freight railroads using financial filings from the Surface Transportation Board. Second, I leveraged maintenance data from corporate tax returns at the industry level from the IRS. These sources agree that the maintenance demand elasticity is plausibly around one. Quantitatively, this indicates a tax elasticity of the capital stock about half as large as we would predict using a single-input neoclassical model. Importantly, it does not require any frictions and in fact relies on an entirely neoclassical mechanism.

Arguably, the key limitation to this study relates precisely to other types of "hidden" investment like intangibles (Crouzet et al. 2022) and sweat equity (Bhandari and McGrattan 2021). Depreciation is made up of two components: obsolescence and physical wear and tear. The type of maintenance in this paper only addresses the latter and not the former because it is entirely about physical capital. However, the majority of the capital stock is arguably intangible (Bhandari and McGrattan 2021), which means that its depreciation is largely obsolescence and hence has little to do with this paper's concept of maintenance.[18] As a result, this study only speaks to the physical capital stock, which is a small share of the total capital stock. However, both quantitative and empirical tax analyses continue to focus almost exclusively on tangible capital. Tax policy models from the Joint Committee on Taxation, the Penn Wharton Budget Center, the Congressional Budget Office, the Tax Foundation and many other workhorse models for tax policy analysis focus largely on tangible capital. This signals that there is utility in measuring tangible capital maintenance properly even if it has to be scaled down in importance by the extent

18. Exercise of market power would have large effects on depreciation of this kind of capital and in that sense, could be thought of as maintenance.

to which intangibles are more significant.

More work needs to be done by economists on rigorously evaluating the empirical maintenance demand curves by capital type, which requires, in turn, that government agencies take a more active role in making maintenance data available to them. Given the groundwork laid here and in prior work by McGrattan and Schmitz Jr. (1999) and Goolsbee (2004), the case for public finance and macroeconomists to undertake these studies is, I think, too big to ignore.

References

Albonico, Alice, Sarantis Kalyvitis, and Evi Pappa. 2014. "Capital maintenance and depreciation over the business cycle." *Journal of Economic Dynamics and Control* 39 (February): 273–286. ISSN: 01651889. https://doi.org/10.1016/j.jedc.2013.12.008.

Angelopoulou, Eleni, and Sarantis Kalyvitis. 2012. "Estimating the Euler Equation for Aggregate Investment with Endogenous Capital Depreciation." *Southern Economic Journal* 78, no. 3 (January): 1057–1078. ISSN: 0038-4038. https://doi.org/10.4284/0038-4038-78.3.1057.

Auerbach, Alan J. 1983. "Corporate Taxation in the United States." *Brookings Papers on Economic Activity* 2.

———. 2018. "Measuring the Effects of Corporate Tax Cuts." *Journal of Economic Perspectives* 32 (4): 97–120.

Auerbach, Alan J., Itai Grinberg, Thomas Barthold, Nicholas Bull, W. Gavin Elkins, Pamela Moomau, Rachel Moore, Benjamin Page, Brandon Pecoraro, and Kyle Pomerleau. 2017. "MACROECONOMIC MODELING OF TAX POLICY." *National Tax Journal* 70, no. 4 (December): 819–836. ISSN: 0028-0283. https://doi.org/10.17310/ntj.2017.4.06.

Bachmann, Rüdiger, Ricardo J. Caballero, and Eduardo M. R. A. Engel. 2013. "Aggregate Implications of Lumpy Investment: New Evidence and a DSGE Model." *American Economic Journal: Macroeconomics* 5, no. 4 (October): 29–67. ISSN: 1945-7707. https://doi.org/10.1257/mac.5.4.29.

Baldwin, John, Huju Liu, and Marc Tanguay. 2015. " An Update on Depreciation Rates for the Canadian Productivity Accounts." *The Canadian Productivity Review.*

Barro, Robert J., and Jason Furman. 2018. "The macroeconomic effects of the 2017 tax reform."

Bhandari, Anmol, and Ellen R McGrattan. 2021. "Sweat Equity in U.S. Private Business*." *The Quarterly Journal of Economics* 136, no. 2 (March): 727–781. ISSN: 0033-5533. https://doi.org/10.1093/qje/qjaa041.

Bitros, George C. 1976. "A Statistical Theory of Expenditures in Capital Maintenance and Repair." *Journal of Political Economy* 84, no. 5 (October): 917–936. ISSN: 0022-3808. https://doi.org/10.1086/260490.

Boucekkine, R., G. Fabbri, and F. Gozzi. 2010. "Maintenance and investment: Complements or substitutes? A reappraisal." *Journal of Economic Dynamics and Control* 34, no. 12 (December): 2420–2439. ISSN: 01651889. https://doi.org/10.1016/j.jedc.2010.06.007.

Brazell, David W., Lowell Dworin, and Michael Walsh. 1989. "A History of Federal Tax Depreciation Policy." May.

CEA. 2018. *Economic Report of the President.* Technical report.

Chari, V.V., Juan Pablo Nicolini, and Pedro Teles. 2020. "Optimal capital taxation revisited." *Journal of Monetary Economics* 116 (December): 147–165. ISSN: 03043932. https://doi.org/10.1016/j.jmoneco.2019.09.015.

Chodorow-Reich, Gabriel, Matthew Smith, Owen Zidar, and Eric Zwick. 2023. "Tax Policy and Investment in a Global Economy."

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy* 113, no. 1 (February): 1–45. ISSN: 0022-3808. https://doi.org/10.1086/426038.

Crawford, Steven, and Garen Markarian. 2024. "The effect of the Tax Cuts and Jobs Act of 2017 on corporate investment." *Journal of Corporate Finance* 87 (August): 102619. ISSN: 09291199. https://doi.org/10.1016/j.jcorpfin.2024.102619.

Crouzet, Nicolas, Janice Eberly, Andrea Eisfeldt, and Dimitris Papanikolaou. 2022. *A Model of Intangible Capital.* Technical report. Cambridge, MA: National Bureau of Economic Research, August. https://doi.org/10.3386/w30376.

Cummins, Jason G., Kevin A. Hassett, and R. Glenn Hubbard. 1994. "A Reconsideration of Investment Behavior Using Tax Reforms as Natural Experiments." *Brookings Papers on Economic Activity* 2:1–74.

Dioikitopoulos, Evangelos V., and Sarantis Kalyvitis. 2008. "Public capital maintenance and congestion: Long-run growth and fiscal policies." *Journal of Economic Dynamics and Control* 32, no. 12 (December): 3760–3779. ISSN: 01651889. https://doi.org/10.1016/j.jedc.2008.04.001.

Eberly, Janice, Sergio Rebelo, and Nicolas Vincent. 2008. *Investment and Value: A Neoclassical Benchmark.* Technical report. Cambridge, MA: National Bureau of Economic Research, March. https://doi.org/10.3386/w13866.

Feldstein, Martin S., and Michael Rothschild. 1974. "Towards an Economic Theory of Replacement Investment." *Econometrica* 42 (3): 393–424.

Gale, William G., Hilary Gelfond, Aaron Krupkin, Mark J. Mazur, and Eric Toder. 2018. *Effects of the Tax Cuts and Jobs Act: A Preliminary Analysis.* Technical report. Tax Policy Center (Urban Institute and Brookings Institution).

Gale, William G., and Claire Haldeman. 2021. "The Tax Cuts and Jobs Act: Searching for Supply-Side Effects." *National Tax Journal* 74, no. 4 (December): 895–914. ISSN: 0028-0283. https://doi.org/10.1086/717132.

Goolsbee, Austan. 1998a. "Investment Tax Incentives, Prices, and the Supply of Capital Goods." *The Quarterly Journal of Economics* 113, no. 1 (February): 121–148. ISSN: 0033-5533. https://doi.org/10.1162/003355398555540.

———. 1998b. "The Business Cycle, Financial Performance, and the Retirement of Capital Goods." *Review of Economic Dynamics* 1, no. 2 (April): 474–496. ISSN: 10942025. https://doi.org/10.1006/redy.1998.0012.

———. 2004. "Taxes and the quality of capital." *Journal of Public Economics* 88, nos. 3-4 (March): 519–543. ISSN: 00472727. https://doi.org/10.1016/S0047-2727(02)00190-1.

Gormsen, Niels, and Kilian Huber. 2022. "Discount Rates: Measurement and Implications for Investment."

Greenwood, Jeremy, Zvi Hercowitz, and Gregory Huffman. 1988. "Investment, Capacity Utilization, and the Real Business Cycle." *American Economic Review* 78 (3): 402–417.

Grimes, George Avery. 2004. "Recovering Capital Expenditures: The Railroad Industry Paradox." PhD diss., University of Illinois at Urbana-Champaign. https://railtec.illinois.edu/wp/wp-content/uploads/pdf-archive/DissertationText-39-Final.pdf.

Hall, Robert E., and Dale Jorgenson. 1967. "Tax Policy and Investment Behavior." *American Economic Review* 57:391–414.

Harding, John P., Stuart S. Rosenthal, and C.F. Sirmans. 2007. "Depreciation of housing capital, maintenance, and house price inflation: Estimates from a repeat sales model." *Journal of Urban Economics* 61, no. 2 (March): 193–217. ISSN: 00941190. https://doi.org/10.1016/j.jue.2006.07.007.

Harris, Adam, and Maggie Yellen. 2023. "Decision-Making with Machine Prediction: Evidence from Prediction Maintenance in Trucking."

Haskel, Jonathan, and Stian Westlake. 2018. *Capitalism without Capital: The Rise of the Intangible Economy.* Princeton University Press. ISBN: 9780691175034.

Hassett, Kevin A., and R. Glenn Hubbard. 2002. "Tax Policy and Business Investment," 1293–1343. https://doi.org/10.1016/S1573-4420(02)80024-6.

Hayek, Friedrich A. 1935. “The Maintenance of Capital.” *Economica* 2 (7): 241–276.

House, Christopher L, and Matthew D Shapiro. 2008. “Temporary Investment Tax Incentives: Theory with Evidence from Bonus Depreciation.” *American Economic Review* 98, no. 3 (May): 737–768. ISSN: 0002-8282. https://doi.org/10.1257/aer.98.3.737. https://pubs.aeaweb.org/doi/10.1257/aer.98.3.737.

House, Christopher L. 2014. “Fixed costs and long-lived investments.” *Journal of Monetary Economics* 68 (November): 86–100. ISSN: 03043932. https://doi.org/10.1016/j.jmoneco.2014.07.011.

Jorgenson, Dale W., and Kun-Young Yun. 1991. *Tax Reform and the Cost of Capital.* Oxford University Press, August. ISBN: 0198285930. https://doi.org/10.1093/0198285930.001.0001.

Justiniano, Alejandro, Giorgio E. Primiceri, and Andrea Tambalotti. 2010. “Investment shocks and business cycles.” *Journal of Monetary Economics* 57, no. 2 (March): 132–145. ISSN: 03043932. https://doi.org/10.1016/j.jmoneco.2009.12.008.

Kabir, Poorya, Eugene Tan, and Ia Vardishvili. 2023. “ Does Marginal Product Dispersion Imply Productivity Losses? The Case of Maintenance Flexibility and Endogenous Capital User Costs.”

Kalaitzidakis, Pantelis, and Sarantis Kalyvitis. 2004. “On the macroeconomic implications of maintenance in public capital.” *Journal of Public Economics* 88, nos. 3-4 (March): 695–712. ISSN: 00472727. https://doi.org/10.1016/S0047-2727(02)00221-9.

———. 2005. ““New” Public Investment and/or Public Capital Maintenance for Growth? The Canadian Experience.” *Economic Inquiry* 43, no. 3 (July): 586–600. ISSN: 00952583. https://doi.org/10.1093/ei/cbi040.

Känzig, Diego R. 2021. “The Macroeconomic Effects of Oil Supply News: Evidence from OPEC Announcements.” *American Economic Review* 111, no. 4 (April): 1092–1125. ISSN: 0002-8282. https://doi.org/10.1257/aer.20190964.

Kennedy, Patrick J, Christine Dobridge, Paul Landefeld, and Jacob Mortenson. 2023. *The Efficiency-Equity Tradeoff of the Corporate Income Tax: Evidence from the Tax Cuts and Jobs Act.* Technical report.

Kitchen, John, and Matthew Knittel. 2011. “Business Use of Special Provisions for Accelerated Depreciation: Section 179 Expensing and Bonus Depreciation, 2002-2009.” *SSRN Electronic Journal,* ISSN: 1556-5068. https://doi.org/10.2139/ssrn.2789660.

Knight, John R., and C.F. Sirmans. 1996. “Depreciation, Maintenance, and Housing Prices.” *Journal of Housing Economics* 5, no. 4 (December): 369–389. ISSN: 10511377. https://doi.org/10.1006/jhec.1996.0019.

Koby, Yann, and Christian K. Wolf. 2020. “Aggregation in Heterogeneous-Firm Models: Theory and Measurement.”

Lucas, Robert E. 1990. “Supply-Side Economics: An Analytical Review.” *Oxford Economic Papers* 42 (2): 293–316.

McGrattan, Ellen R. 2020. “Intangible capital and measured productivity.” *Review of Economic Dynamics* 37 (August): S147–S166. ISSN: 10942025. https://doi.org/10.1016/j.red.2020.06.007. https://linkinghub.elsevier.com/retrieve/pii/S1094202520300466.

McGrattan, Ellen R., and James A. Schmitz Jr. 1999. “Maintenance and Repair: Too Big to Ignore.” *Federal Reserve Bank of Minneapolis Quarterly Review,* no. Fall, 213.

Mejia, Jackson. 2024. “Smooth Local Panel Projections.”

Peters, Ryan H., and Lucian A. Taylor. 2017. “Intangible capital and the investment-q relation.” *Journal of Financial Economics* 123 (2): 251–272. ISSN: 0304405X. https://doi.org/10.1016/j.jfineco.2016.03.011.

Pigou, A. C. 1941. “Maintaining Capital Intact.” *Economica* 8, no. 31 (August): 271. ISSN: 00130427. https://doi.org/10.2307/2549333.

Poterba, James M. 1984. "Tax Subsidies to Owner-Occupied Housing: An Asset-Market Approach." *The Quarterly Journal of Economics* 99, no. 4 (November): 729. ISSN: 00335533. https://doi.org/10.2307/1883123.

Romer, Christina D, and David H Romer. 2010. "The Macroeconomic Effects of Tax Changes: Estimates Based on a New Measure of Fiscal Shocks." *American Economic Review* 100 (3): 763–801.

Rust, John. 1987. "Optimal Replacement of GMC Bus Engines: An Empirical Model of Harold Zurcher." *Econometrica* 55, no. 5 (September): 999. ISSN: 00129682. https://doi.org/10.2307/1911259.

Scott, Maurice. 1984. "Maintaining Capital Intact." *Oxford Economic Papers* 36:59–73.

Sedlacek, Petr, and Vincent Sterk. 2019. "Reviving american entrepreneurship? tax reform and business dynamism." *Journal of Monetary Economics* 105 (August): 94–108. ISSN: 03043932. https://doi.org/10.1016/j.jmoneco.2019.04.009.

Straub, Ludwig, and Iván Werning. 2020. "Positive Long-Run Capital Taxation: Chamley-Judd Revisited." *American Economic Review* 110, no. 1 (January): 86–119. ISSN: 0002-8282. https://doi.org/10.1257/aer.20150210.

Suárez Serrato, Juan Carlos, and Owen Zidar. 2018. "The structure of state corporate taxation and its impact on state tax revenues and economic activity." *Journal of Public Economics* 167 (November): 158–176. ISSN: 00472727. https://doi.org/10.1016/j.jpubeco.2018.09.006.

Summers, Lawrence H. 1981. "Taxation and Corporate Investment: A q-Theory Approach." *Brookings Papers on Economic Activity* 1:67–127.

Zeida, Teegawende H. 2022. "The Tax Cuts and Jobs Act (TCJA): A quantitative evaluation of key provisions." *Review of Economic Dynamics* 46 (October): 74–97. ISSN: 10942025. https://doi.org/10.1016/j.red.2021.08.003.

Zwick, Eric, and James Mahon. 2017. "Tax Policy and Heterogeneous Investment Behavior." *American Economic Review* 107, no. 1 (January): 217–248. ISSN: 0002-8282. https://doi.org/10.1257/aer.20140855. https://pubs.aeaweb.org/doi/10.1257/aer.20140855.

A Freight Rail

Group	Variable	Mean	10th Percentile	Median	90th Percentile	Count
Freight	Age	0.646	0.518	0.616	0.845	171
	$m_{i,j,t}$	0.177	0.055	0.127	0.377	171
	$P_{i,j,t}$	0.857	0.757	0.857	0.964	171
	$x_{i,j,t}$	0.062	0.002	0.039	0.130	171
Locomotives	Age	0.692	0.593	0.661	0.806	171
	$m_{i,j,t}$	0.138	0.048	0.113	0.251	171
	$P_{i,j,t}$	0.995	0.870	0.973	1.147	171
	$x_{i,j,t}$	0.127	0.025	0.082	0.256	171

Table A1: Summary statistics for variables from R-1 financial statements.

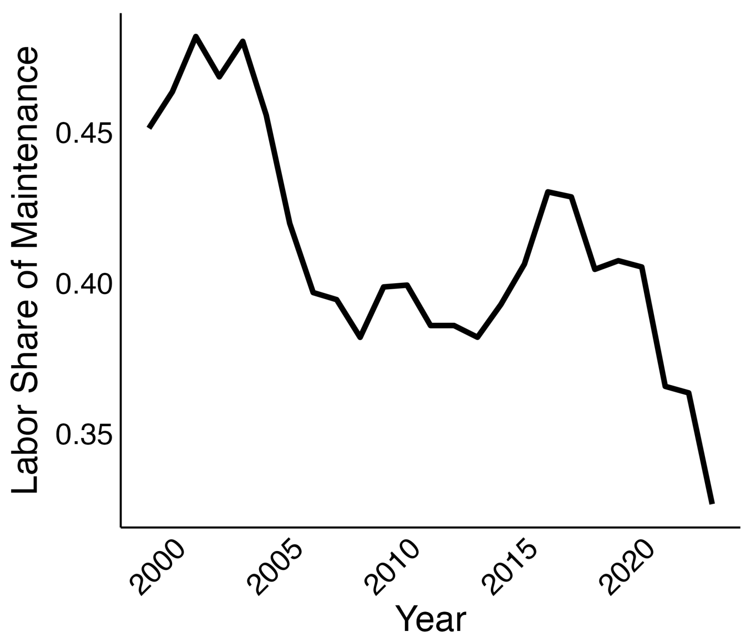


Figure 8: Average labor share of maintenance costs by year from 1999-2023. Computed by adding up all labor maintenance costs and dividing by total maintenance costs. The remainder is material costs.

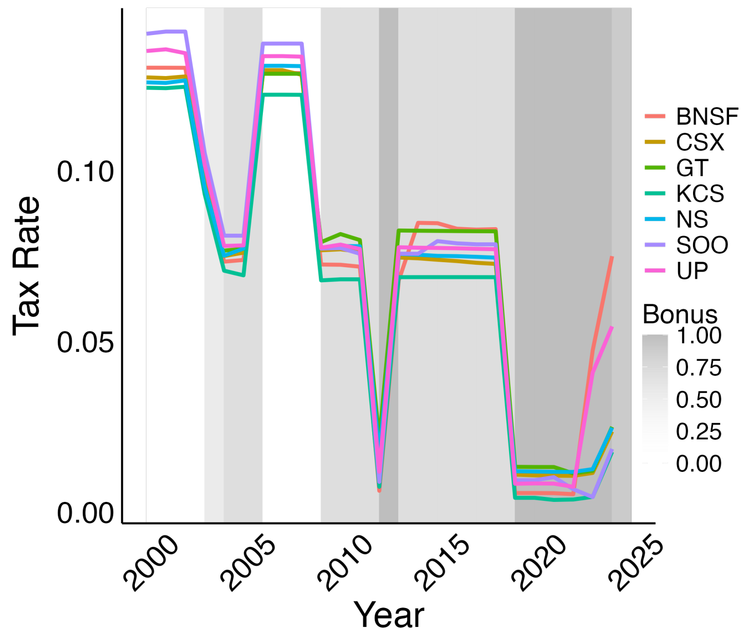


Figure 9: Tax rates by Class I freight rail firm from 1999-2023. Tax rates are computed by taking a weighted average of state tax rates based on miles of trackage operated by firm.

A.1 Linear Model

	Dependent variable: $m_{i,j,t}$			
	(1)	(2)	(3)	(4)
$P_{i,j,t}$	-0.372	-0.438	-0.381	-0.133
	(0.169)	(0.088)	(0.090)	(0.063)
Age		-0.444	-0.420	-0.228
		(0.110)	(0.122)	(0.090)
$x_{i,j,t}$			0.204	0.132
			(0.064)	(0.132)
$m_{i,j,t-1}$				0.650
				(0.117)
N	342	342	342	328
FE: Type	X	X	X	X
FE: Year	X	X	X	X
FE: Firm-Type	X	X	X	X

Table A2: Results for regressing the maintenance rate on the relative price of maintenance. The top panel takes a logarithmic transformation of the maintenance rate and the relative price, while the bottom panel is linear. Standard errors are clustered by firm.

	Dependent variable: $m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$P_{i,j,t}$	-0.190	-0.315		-0.397	-0.479
	(0.192)	(0.122)		(0.225)	(0.349)
$1 - \tau_{i,t}$			-0.215		
			(0.059)		
Year Trend	-0.005	-0.005	-0.005		
	(0.003)	(0.001)	(0.001)		
ΔTFP_t	-0.080	-0.019	-0.170		
	(0.193)	(0.113)	(0.096)		
$\Delta \log \text{GDP}_t$	-0.284	-0.268	-0.246		
	(0.198)	(0.271)	(0.231)		
$\log \text{RCAF}_t$	0.107	0.100	0.099		
	(0.040)	(0.059)	(0.058)		
N	316	316	316	328	314
Instrument	Oil	Tax Rate		$\log P_{i,j,t-1}$	$\log P_{i,j,t-2}$
F-test	15.7	30.5		1214.6	486.2
FE: firm	X	X	X	X	X
FE: type	X	X	X	X	X
FE: year				X	X

Table A3: Instrumental variables results for regressing the maintenance rate on a measure of the relative price. The first column uses oil shock as an instrument for the relative price. The second uses taxes as a shock for the *pre-tax* relative price. Every regression with instruments reports the Cragg-Donald F-statistic.

B SOI

I report summary statistics for the primary variables in the SOI in Table A4. The data for untaxed firms comes from subtracting the relevant figures for taxable firms in Table 13 from the corresponding figures for *all* firms in Table 12. The distribution of maintenance rates in Table A4 is quite low relative to the best data we have. Canada is the only country with good national data on maintenance and it has typically been the centerpiece of studies on maintenance (McGrattan and Schmitz Jr. 1999). However, the national maintenance rate in Canada is close to 12%, whereas the maintenance rate here is closer to 5%. That can be partially but not fully explained by the fact that depreciation rates in Canada are roughly twice as high as in the United States (Baldwin, Liu, and Tanguay 2015). A secondary explanation is that it is quite difficult to track maintenance expenditures. Only airlines and freight rail are required to meticulously track maintenance expenditures independently of other types whereas other industries do not have the same incentive. It could easily be the case that a large share of maintenance expenditures go under labor cost or some other part of costs of goods sold. From the perspective of the firm, it is irrelevant how such expenditures are allocated because they are not regulated at all and are tax deductible regardless.

Variable	Mean	10th Percentile	Median	90th Percentile	Count
$1 - \tau_{j,t}$	0.863	0.791	0.860	0.931	1071
Taxable Firms					
$m_{j,t}$	0.051	0.018	0.038	0.100	1071
$x_{j,t}$	-0.131	-0.610	0.049	0.468	1071
Age	0.463	0.342	0.459	0.591	1071
Untaxable Firms					
$m_{j,t}$	0.049	0.013	0.036	0.094	1071
$x_{j,t}$	-0.156	-0.644	0.025	0.455	1071
Age	0.495	0.364	0.486	0.653	1071
year	2008.580	2000.000	2008.000	2018.000	1071

Table A4: Summary statistics for the SOI.

Regression results for the linear-linear model are in Table A5. The results here do not line up as well with the freight rail results as they do in the log-log case, but are still significant for most specifications. Adding age as a covariate makes the tax term insignificant.

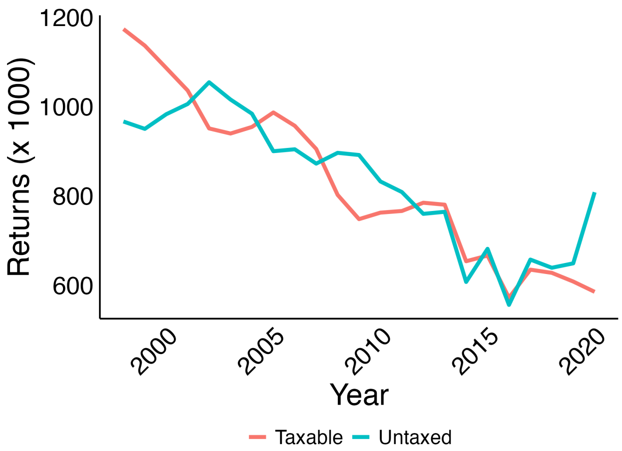


Figure 10: Caption

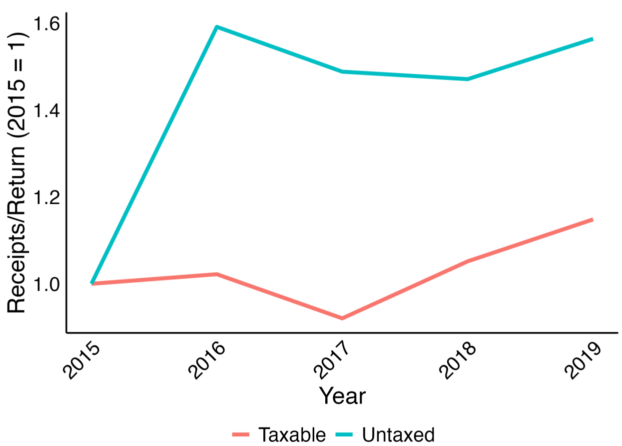


Figure 11: Caption

	Dependent variable: $m_{j,t}$					
	Taxable Firms			Untaxable Firms		
	(1)	(2)	(3)	(4)	(5)	(6)
$1-\tau_{j,t}$	-0.145	-0.122	-0.072	0.025	0.019	0.007
	(0.073)	(0.065)	(0.042)	(0.109)	(0.117)	(0.077)
$x_{j,t}$		-0.003	-0.003		-0.002	-0.002
		(0.001)	(0.001)		(0.001)	(0.001
$m_{j,t-1}$			0.456			0.371
			(0.056)			(0.070)
N	1071	1012	1005	1070	1009	1003
FE: Industry	X	X	X	X	X	X
FE: Year	X	X	X	X	X	X

Table A5: Linear Regression results of the maintenance rate on the tax term. Standard errors are clustered by BEA industry. The investment rate is net investment scaled by the net capital stock.

I report regression results for all firms in the SOI in Table A6.

	Dependent variable:					
	$\log m_{j,t}$			$m_{j,t}$		
	(1)	(2)	(3)	(4)	(5)	(6)
$\log(1-\tau_{j,t})$	-2.363	-2.166	-1.014			
	(1.271)	(1.178)	(0.586)			
$1-\tau_{j,t}$				-0.085	-0.074	-0.033
				(0.064)	(0.063)	(0.021)
$x_{j,t}$		-0.117	-0.166		-0.006	-0.007
		(0.050)	(0.038)		(0.002)	(0.003)
$\log m_{j,t-1}$			0.613			
			(0.097)			
$m_{j,t-1}$						0.703
						(0.034)
Num.Obs.	1117	1066	1059	1117	1066	1059
FE: Industry	X	X	X	X	X	X
FE: Year	X	X	X	X	X	X

Table A6: Linear Regression results of the maintenance rate on the tax term. Standard errors are clustered by BEA industry. The investment rate is net investment scaled by the net capital stock.

Table A7 shows the maintenance elasticity in levels for the SOI data. The coefficient is negative but not significant for taxable firms. Because the theory is about the maintenance rate rather than maintenance in levels, it is ex ante ambiguous what the sign should be. If there are decreasing returns to maintenance intensity, then the sign should be positive because in that case maintenance and investment are complements in *levels*. If there are increasing returns, then the sign should go the other way.

	Dependent variable: $\log M_{j,t}$	
	SOI	
	Taxable Firms	Untaxable Firms
$1-\tau_{j,t}$	-1.587	2.883
	(1.369)	(2.533)
$\log M_{j,t-1}$	0.527	0.443
	(0.098)	(0.063)
N	1005	1003

Table A7: Regression of the log-level of maintenance on the tax term for the SOI data. The SOI regressions have two-way fixed effects. Standard errors are clustered by BEA industry.

B.1 Bias in the SOI Maintenance Coefficient

Measurement Error in the Maintenance Rate

There is likely a substantial amount of measurement error in the SOI measure of maintenance. Maintenance and repairs can be done internally by teams employed by the firm or externally through contracted work. Oftentimes the latter is part of an original purchase agreement for a piece of equipment. The issue here is whether internal maintenance services are assigned to maintenance in the SOI or not, and I suspect that the answer is "no" for two reasons. First, internal maintenance can be assigned to other, similarly tax deductible categories. For example, the wages paid to workers may be billed to wages rather than maintenance. Outside of freight rail and a select couple of other industries, firms are not required to keep close track of what is maintenance and what is not, so there is no incentive for firms to actually make the proper category assignment. This leads to a significant underestimate of the actual quantity of maintenance. For example, take the SOI industry containing freight rail: Air, Freight, and Water Transportation Services. In the SOI data, the maintenance rate is only approximately 5% on average, while it is nearly three times higher in the far more granular freight rail data which takes close account of how to assign expenditures properly. Figure 12 plots the share of externally purchased services.

The SOI maintenance measurement error only matters if the proportion of purchased maintenance services systematically varies with tax policy. If the share of external maintenance declines when taxes increase, then the coefficient on the tax term is biased down-

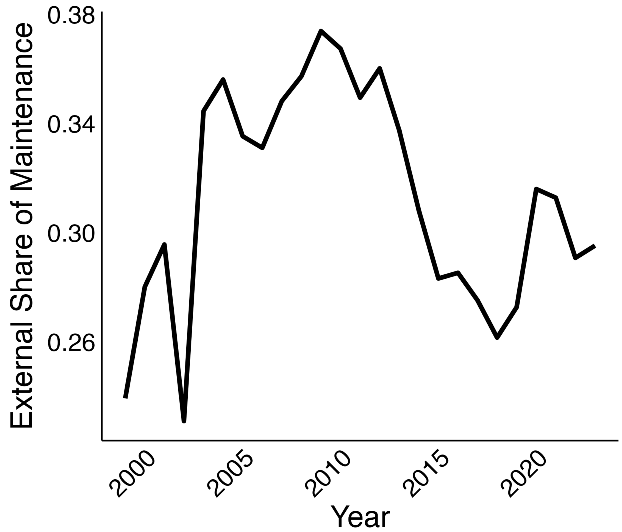


Figure 12: Share of external services in total maintenance expenditures for Class I freight rail. Taken as the sum of external expenditures by year divided by the sum of total maintenance expenditures.

ward. The easiest test for this is to regress the share of external maintenance on tax policy using the freight rail data. Table B.1 does exactly that. Because there is not enough variation between firms in tax policy, I use industry controls and a time trend. Column (1) indicates that there is a strong systematic relationship between the tax rate and the share of external services. However, Column (2) indicates that, after controlling for the lagged share of external services, this relationship goes away. The strength of the autocorrelation indicates a large degree of persistence in the share of external services by firm and type. From Column (2), I interpret the degree of autocorrelation as indicating that the bias is not important after accounting for the lagged expenditure share.

	Dependent variable: External Service Share$_{i,j,t}$	
	(1)	(2)
$\tau_{i,t}$	-0.281	-0.048
	(0.062)	(0.085)
External Service Share$_{i,j,t-1}$		0.929
		$(6.16e^{-8})$
N	315	312
Industry Controls	X	X
FE: firm	X	X
FE: type	X	X

Table A8: Regression of the external maintenance service share on the tax rate for freight rail. Tax rates only vary by firm and not by capital type. Industry controls are a cost index from the Surface Transportation Board, the GDP growth rate, and freight rail productivity growth.

Omitted Variable Bias

Recall that the simplest version of the first-order condition for maintenance equates the marginal benefit of maintenance to the after-tax relative price of maintenance to investment:

$$h'(m) = \frac{p^m (1-\tau)}{p^x}.$$

In the SOI data, we do not have a credible way to estimate either p^m or p^x by industry. Instead, the implicit assumption is that changes in tax policy do not affect the pre-tax relative price, and so taking logs on both sides simply makes the error term swallow the relative price. Under that assumption, I would have to claim that the supply curves for maintenance and investment are flat. Goolsbee (1998b) shows that the slope of the investment supply curve is close to one. If we presume that maintenance prices are stickier than investment prices, then the coefficient on the tax term is biased downward in absolute value.

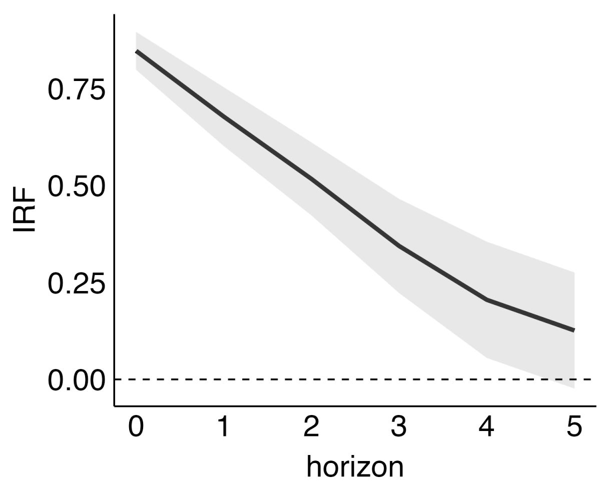
We can directly apply the estimates of Goolsbee (1998b). That paper estimates that approximately 60% of the incidence of tax policy goes to buyers of capital, 30% to suppliers, and 10% to the wages of capital producers. If we assume some symmetry in the wages of capital *maintainers* and capital producers, then we can use the corresponding relationship to adjust the relative price following a tax change. In particular, suppose the labor share of maintenance is typically around 0.4. That is true in the freight rail data. Applying his estimates implies that if the pre-tax relative price of maintenance is 1, it would decline to approximately 0.68 following a percentage point cut in the marginal tax rate.[19] Consequently, if the tax rate declines by 1 pp, then the actual decline in the relative price of maintenance is closer to 0.68. On average, that implies the price elasticity is underestimated by approximately 40% in the SOI data.

B.2 Price Dynamics

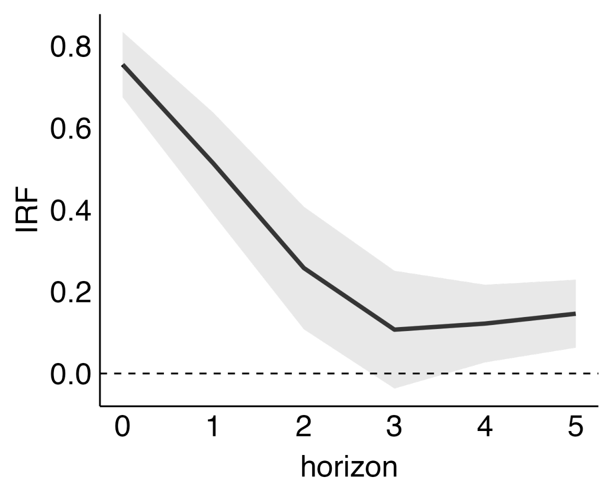
Figure 13 plots the dynamic evolution of the relative price following a unit increase. The left panel is for freight rail and is the result of the regression

$$\text{Log Relative Price}_{i,j,t} = \alpha_i + \kappa_j + T_t + \beta_h \text{Log Relative Price}_{i,j,t-h} + \varepsilon_{i,j,t},$$

where $h = 1, \ldots, 6$. The same regression is run on the right panel for tax policy in the SOI data, but using industry and year fixed effects.



(a) Freight rail price persistence



(b) Tax policy persistence (SOI)

Figure 13: The left panel plots the persistence of the log relative price of maintenance for freight rail and the right does the same for log tax policy. Each regression plots the coefficient on lagged relative price for 1-6 years out. The freight rail contains year, firm, and type fixed effects, while the tax policy data from SOI includes industry and year fixed effects.

C Additional Empirical Results

19. Given a 1 p.p. tax cut, Goolsbee estimates that the price of an investment good rises by approximately 5%. About 20% of that price rise is driven by an increase in wages. Hence $(0.4 \times 0.1 + 0.6 \times 0.05)/0.5 = 0.68$.

C.1 Measurement Error in Capital Stocks

The key source of measurement error in the main specification is the capital stock, which is the denominator for the maintenance rate. Throughout, I have used the net book capital stock, which is formed from the perpetual inventory method according to $K_{t+1} = K_t (1 - \delta) + X_t$.[20] On the other hand, the whole point of this paper is that precisely because maintenance is price-elastic, it is incorrect to apply the standard perpetual inventory method. Instead, capital stocks should be formed according to (1).

I correct for bias with an iterative structural approach. The idea is to take an initial guess for the parameters in the function $h(m_t)$ and use that to iterate forward an initial capital stock using observed maintenance levels and capital expenditures. Using that synthetic capital stock, I rerun the regression (6) without controls until the estimated parameters converge. For both the log-log and linear-linear cases, we cannot recover the level parameter, and so we are really estimating the elasticity parameter for the former and the slope parameter for the latter. I use the estimates in column (1) of Table 1 as initial guesses. In both cases, I calibrate the remaining parameters such that the maintenance rate is 5% when $P = 1$. I also set $\delta = 10\%$ in line with the estimate for rolling stock in Baldwin, Liu, and Tanguay (2015).

Figure 14 compares the coefficients on the bias-corrected series to the original coefficients. While the absolute value of the coefficient in the log-log specification shrinks to approximately 1.6, the coefficient on the linear-linear specification rises moderately to 0.5. In both cases, there is very little practical economic or statistical difference between parameter estimates.

Although the coefficients turn out to be fairly similar, the capital stocks do not. Figure 15 compares the resulting synthetic capital stock series to the one used in the main specifications for both freight cars and locomotives. Each series takes a simple sum over firm capital stocks within each capital type for the synthetic series K_t^S and divides by the original capital stock K_t^O. The left-hand panel uses the linear-linear specification while the right-hand panel is the log-log. In both cases, the synthetic capital stock series is substantially smaller than the original by the end of the sample, reaching around 40-50% as large for the linear specification and 60-70% for the log specification. The constant elasticity functional form attenuates the effect of large changes in maintenance while linear demand does not, which leads to the large difference between the two.

20. There is no need to worry about aggregating over capital types because there is a separate capital stock and depreciation rate for each type of capital.

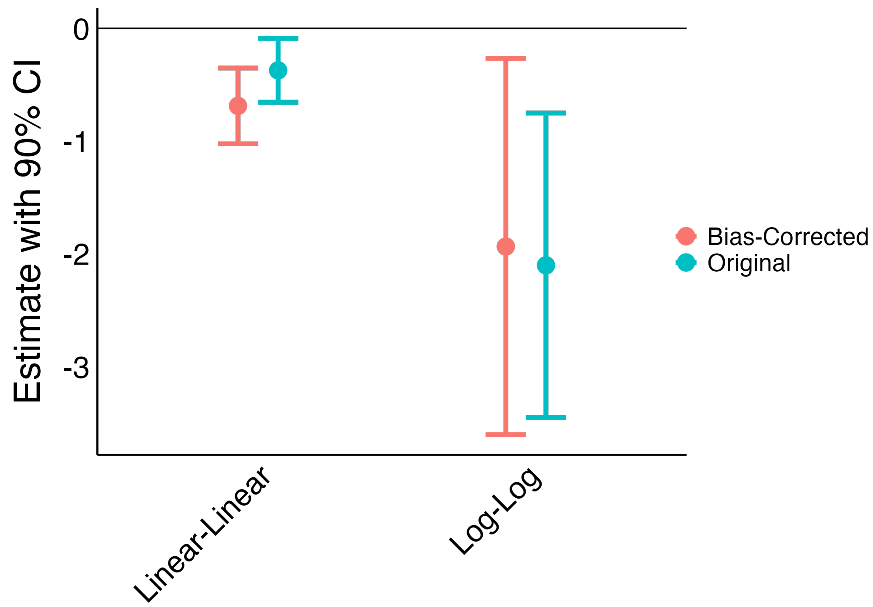
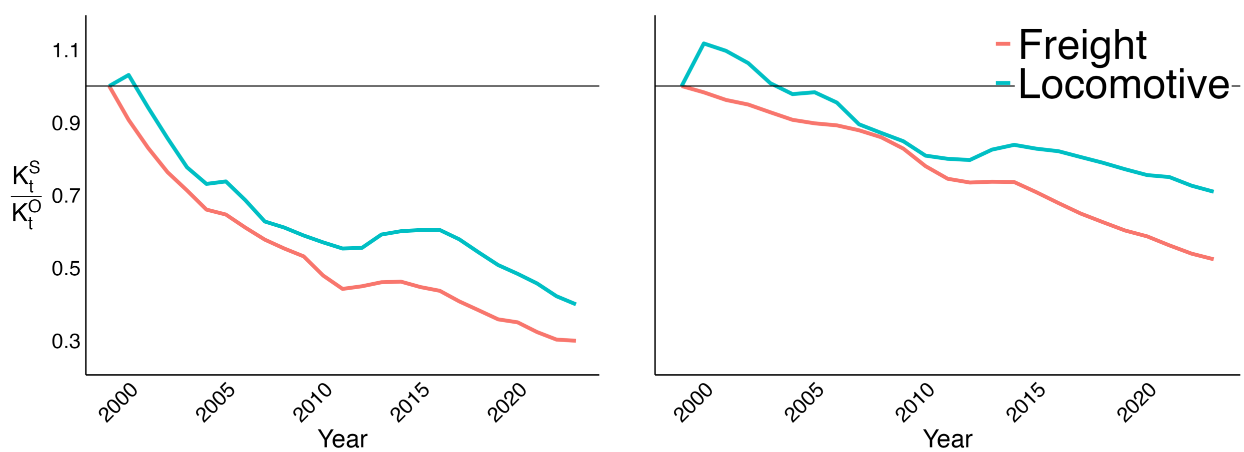


Figure 14: Bias-corrected coefficients compared to baseline estimates. The bias correction comes from creating a synthetic capital stock given each $h(m)$ and iterating over parameters until the estimates converge.



(a) Linear Demand

(b) Constant Elasticity Demand

Figure 15: Comparing the synthetic capital stock for freight and locomotives to the original. The synthetic capital stock K_t^S is the sum over firms within capital types at year t, while K_t^0 is the same for the book value used in the baseline estimates. Panel (a) uses the linear-linear specification and Panel (b) is the log-log specification.

C.2 Dynamic Effects

The results for freight rail and the SOI indicate that the demand for maintenance is neither perfectly inelastic nor zero. This opens the question of the dynamic stability of the coefficient. It could be the case that price changes temporarily induce firms to change maintenance behavior despite the fact that the price changes are themselves more persistent, which would indicate that the model is likely misspecified. From Figure 2, relative price changes for freight rail seem to be persistent. Similarly, tax changes have been persistent throughout the 21st century aside from the occasional lapse in bonus depreciation.[21] To address this question, I run local projections of the same specifications used for the static regressions for the freight rail and SOI data. In particular, I run

$$\log m_{i,j,t+h} = \alpha_i + T_t + \kappa_j + \beta_h \log P_{i,j,t} + \epsilon_{i,j,t} \tag{A.1}$$

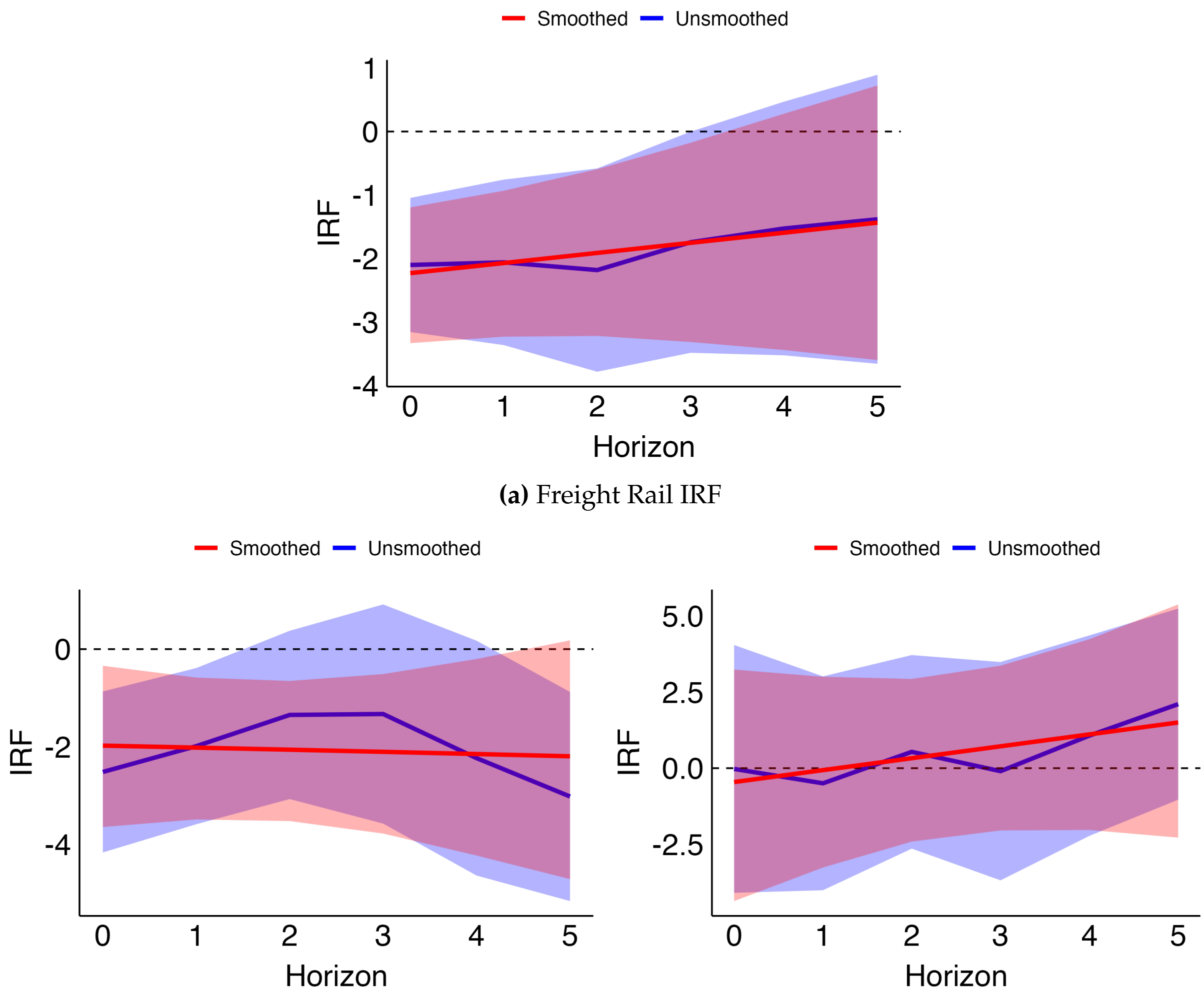
for the freight rail data and

$$\log m_{i,t+h} = \alpha_i + T_t + \beta_h \log(1 - \tau_{i,t}) + \epsilon_{i,j,t} \tag{A.2}$$

for the SOI data. I run each regression for up to $h = 5$ years after a shock. Again, I cluster the freight rail data by firm and the SOI data by industry. Figure 16 plots the results for the baseline specification. The top panel plots the impulse response to a price shock for the maintenance rail data. The bottom left panel plots the impulse response to a tax shock for taxable firms and the right panel for untaxable firms in the SOI data. The red line plots an impulse response function from a smoothed local projection from Mejia (2024) and the blue line is a standard panel local projection.

For both the freight rail and SOI data, the coefficient is stable and significant across multiple years. In particular, taxable firms in the SOI show no decline in the maintenance rate five years out from a shock, whereas there is some attenuation from freight rail. At the same time, the statistical significance declines because the sample size gets substantially smaller for each horizon, particularly for the freight rail data. As a check, the coefficient on untaxed firms remains zero at all horizons.

21. Figure 13 in the appendix plots the sequence of coefficient from a regression of the relative price of maintenance on its lags for freight rail and tax policy.



(a) Freight Rail IRF

(b) SOI: Taxable Firm IRF

(c) SOI: Untaxed Firm IRF

Figure 16: Impulse responses of the log maintenance rate to a unit increase in the log relative price of maintenance. The regressions are simply dynamic versions of the static specifications, where the impulse response is the sequence of coefficients β_h on the price shock from horizons $h = 0, \ldots, 5$.

D Tax Policy Construction

Toward creating a database of industry marginal effective tax rates (METR) on corporate capital, I combine data from the BEA and the IRS to follow the methodology of House and Shapiro (2008). Tax rates may differ between industries because there are differences in how assets are taxed and the mix of assets owned by industries may differ. Consequently, as long as we know who owns which assets and the tax rates on those assets, we can construct an industry-specific marginal effective tax rate. The Fixed Asset Tables from the BEA are convenient for this purpose for two reasons. First, Section 2 of the Fixed Asset tables contains data on 36 physical assets which are relatively easy to map to tax policy, make up the vast majority of physical investment, and can be categorized as either equipment or structures. I focus on these assets over the period 1971-2021, which spans the Asset Depreciation Range (ADR) System from 1971-1981, the Accelerated Cost Recovery System (ACRS) from 1982-1986, and the Modified Accelerated Cost Recovery System from 1987-2021. Second, the underlying detailed estimates for nonresidential investment can be mapped from BEA industries into three-digit NAICS codes. The BEA provides a bridge for this purpose.

There are three steps to constructing industry-specific marginal effective tax rates:

1. Calculate asset-specific marginal effective tax rates $\tau_{i,t}$ for asset i.
2. For each industry j, compute asset weights $\alpha^a_{i,j,t}$.
3. Putting Steps 1 and 2 together, compute the industry-specific tax rate as

$$\tau_{j,t} = \sum_{i=1}^{N} \alpha_{i,j,t} \tau_{i,t}$$

   where there are N types of capital and $\sum_{i=1}^{N} \alpha_{i,j,t} = 1$.

I go through each step in turn.

Asset-Specific Tax Rates

Define the asset-specific METR as

$$\tau^a_{i,t} = 1 - \frac{1 - \tau^c_t}{1 - \mathrm{ITC}^a_{i,t} - z^a_{i,t} \tau^c_t}, \tag{A.3}$$

where τ^c_t is the corporate tax rate, $\mathrm{ITC}_{i,t}$ is the investment tax credit on asset i, and $z_{i,t}$ is the net present value of tax depreciation allowances on asset i. Hence there are three components for each asset. First, the corporate tax rate τ^c_t is straightforward to obtain. Second, the investment tax credit $\mathrm{ITC}_{i,t}$ is slightly more difficult. Investment tax credits vary substantially by asset type but have been irrelevant since the Tax Reform Act of 1986. I take the ITC for each asset from House and Shapiro (2008), who study the effects of bonus depreciation on investment across the same 36 assets from the BEA that I use to construct this database. They originally obtained data on the ITC from Dale Jorgenson.

$z_{i,t}$ is more difficult and requires some level of judgment. Suppose an asset has allowable depreciation $D^a_{i,t}$ and define $d^a_{i,t}$ as the share of the asset's allowable depreciation under tax law each period. This is nontrivial because companies are allowed to use different methods of depreciation. For each asset j, I define the present value of depreciation allowances as

$$z^a_{i,t} = \sum_{t=0}^{\infty} \left(\frac{1}{1+r^k}\right)^t d^a_{i,t}.$$

I assume that $r^k = 0.06$. While this assumption is clearly not innocuous, it is comparable to some of the recent literature. This is the same discount rate as in Chodorow-Reich et al. 2023, but is lower than in Barro and Furman (2018) and Gormsen and Huber (2022). Earlier literature on tax policy from the 1980s (see, e.g., Auerbach (1983) and Jorgenson and Yun (1991)) tends to use lower discount rates. $z_{i,t}$ varies both across assets and between tax eras. I discuss each era in chronological order. I relied heavily on Brazell, Dworin, and Walsh (1989) for understanding each era.

ADR (1971-1981. The ADR period marked a simplification from the earlier Bulletin F period, where there were hundreds of asset classes. However, the ADR period was still more complex than the tax rules that would follow. Most assets were depreciated according to standards that were industry-specific, which makes it challenging to map them to modern BEA tables. However, because the BEA asset categories are relatively broad and the ADR-recommended live lengths are similar among the assets that would go in each category, I simply assign the most common median life length within each category. Because the life length determination requires some judgment, there is surely some degree of error. For equipment, I assume firms follow a double declining balance method, while structures use straightline depreciation. I use the Treasury publication "Asset Depreciation Range System" published in 1971 to assign life lengths.

ACRS (1982-1986). The ACRS simplified the ADR into eight asset classes and significantly decreased depreciation lives. I assigned each BEA asset into its a class using IRS publication 534 and used the double-declining balance method for all assets.

MACRS (1987-Present). The Tax Reform Act of 1986 changed depreciation schedules and got rid of the ITC while retaining much of the simplicity of the ACRS era. House and Shapiro (2008) map each asset to a corresponding depreciation table in IRS Publication 946. I use their matching scheme and assumptions about which depreciation method firms use. For example, most equipment is depreciated with the double-declining balance method, while structures are often depreciated with the straightline method. Using the House-Shapiro mapping scheme, it is straightforward to compute $z_{i,t}$. However, the U.S. government has allowed firms to take bonus depreciation on certain types of capital investment. Defining θ_t as the allowable bonus depreciation in year t, let the net present value of tax depreciation allowances be

$$\tilde{z}^a_{i,t} \begin{cases} \theta + (1-\theta_t) z^a_{i,t} & \text{if eligible} \\ z^a_{i,t} & \text{if ineligible,} \end{cases} \tag{A.4}$$

where $\tilde{z}^a_{i,t}$ takes the place of $z^a_{i,t}$ in equation A.3. At various points, $\theta = 1$ for some assets, so the marginal effective tax rate is zero. Conveniently, House and Shapiro (2008) also map whether or not each BEA asset is eligible for bonus depreciation, so I use their mapping.

Weights

To get the industry-asset weights $\alpha_{i,j,t}$ within each major asset category, I use the underlying detail data from the BEA Fixed Asset Table. Each BEA industry has a matrix of assets for nominal investment, real investment, and historical and current-cost net capital stocks and depreciation. I use capital weights from the current year to determine weights on each asset for each industry. That is,

$$\alpha_{i,j,t} = \frac{k^a_{i,j,t}}{K^a_{j,t}},$$

where $k_{i,j,t}$ is stock of capital type i from industry j and $K_{j,t}$ is the total capital stock in year t by industry j in the corresponding major asset category. I restrict attention to the 36 assets I obtain METRs for. Of course, I could have also used stocks as weights or previous year investment flows or some rolling average of investment flows. The results are largely similar regardless.

Putting together weights weights and marginal tax rates, the marginal effective tax rate on industry j is

$$\tau_{j,t} = \sum_{i=1}^{36} \alpha_{i,j,t} \tau_{i,t}.$$

Using the BEA-NAICS bridge, we then have prices and tax rates for each three-digit NAICS industry. I plot the time series of tax rates for each industry in Figure 17.

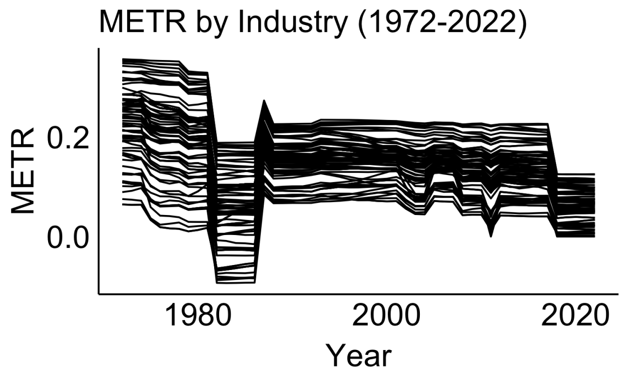


Figure 17: Marginal effective tax rates for NAICs industries from 1971-2022.

E Quantitative Model

E.1 Calibration

The majority of the calibrated parameters are in Table A9, most of which are drawn from Barro and Furman (2018). As discussed in the main text, I set the adjustment cost parameter ψ to match the path of capital in Zeida (2022) and Chodorow-Reich et al. (2023). Additionally, I set the level parameter for maintenance demand to match the average level of the maintenance rate in the SOI given the average tax rate and the estimated elasticity of demand.

Parameter Name	Symbol	Value	Source
Maintenance Demand Elasticity	ω	2	Table 1
Maintenance Demand Level	γ	0.042	SOI
Adjustment Cost	ψ	3	See text
Discount Rate	r^k	0.082	Barro and Furman (2018)
Corporate Capital Shares			
Equipment	$\alpha_{1,c}$	0.13832	Barro and Furman (2018)
Non-residential Structures	$\alpha_{2,c}$	0.12274	Barro and Furman (2018)
Residential Structures	$\alpha_{3,c}$	0.00722	Barro and Furman (2018)
R&D Intellectual Property	$\alpha_{4,c}$	0.04522	Barro and Furman (2018)
Other Intellectual Property	$\alpha_{5,c}$	0.0665	Barro and Furman (2018)
Passthrough Capital Shares			
Equipment	$\alpha_{1,p}$	0.1224	Barro and Furman (2018)
Non-residential Structures	$\alpha_{2,p}$	0.1311	Barro and Furman (2018)
Residential Structures	$\alpha_{3,p}$	0.0688	Barro and Furman (2018)
R&D Intellectual Property	$\alpha_{4,p}$	0.0232	Barro and Furman (2018)
Other Intellectual Property	$\alpha_{5,p}$	0.0342	Barro and Furman (2018)

Table A9: Calibrated Parameters for Quantitative Models

All calibrated tax rates are from the "law as written" case and come from Barro and Furman (2018). They are largely the same in both the dynamic and long-run exercises. There is one exception. In the dynamic exercise, I set the initial (pre-reform) tax subsidy on equipment $\tau^x_{1,2017}$ to be equal to $0.906 \times \tau^c_{c,2017}$ to reflect the 50% bonus depreciation at the time the reform had been enacted. In the long-run exercise I set the initial subsidy to $0.812 \times \tau^c_{c,2017}$. This is for two reasons. First, it is what Barro and Furman (2018) do and I want to make a direct comparison. Second, the goal is to compare long-run steady states and not to trace out the path of capital following reform. Because the 50% bonus depreciation was not part of the law at the time, is entirely sensible to use $0.812 \times \tau^c_{c,2017}$. In Figure 18 I plots the dynamic path of tax rates for each capital type for corporate capital (and ignore passthrough tax rates because I do not analyze the path of passthrough capital). The tax rate I plot is the marginal effective tax rate defined as

$$\tau_{i,j,t} = \frac{1 - \tau^c_{j,t}}{1 - \tau^x_{i,t}}.$$

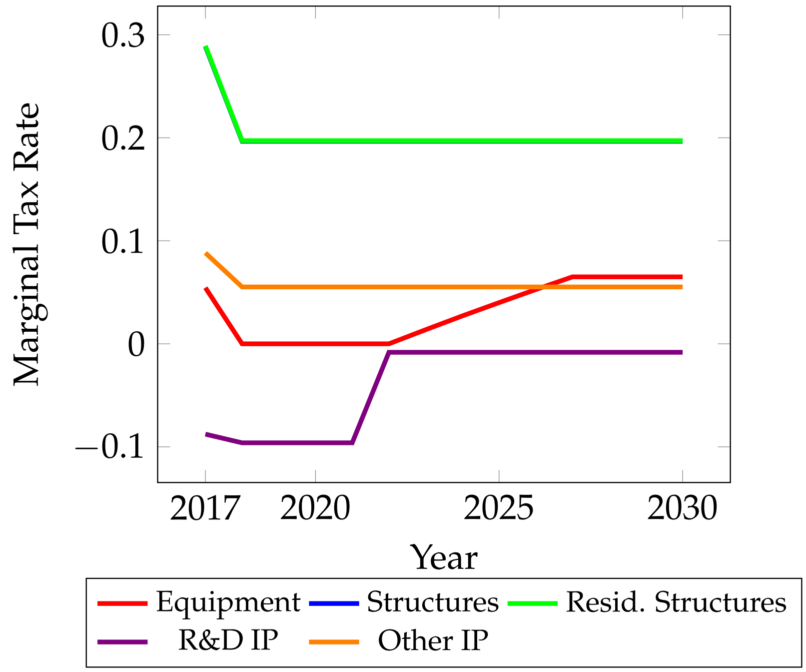


Figure 18: Marginal tax rates by asset.

Table A10 tabulates the marginal tax rates on each capital type for the steady state comparison exercise.

	Corporate		**Passthrough**	
Capital Type	Initial	Final	Initial	Final
Equipment	0.103	0.065	0.093	0.094
Non-residential Structures	0.289	0.197	0.265	0.267
Residential Structures	0.289	0.197	0.265	0.268
R&D Intellectual Property	-0.088	-0.008	0	0.193
Other Intellectual Property	0.088	0.055	0.079	0.080

Table A10: Marginal tax rates for each capital type for the steady state comparison exercise. All rates come from the Barro and Furman (2018). The common tax rate for the corporate sector declines from 0.38 to 0.27 while the common tax through pass rate rises marginally from 0.352 to 0.355. The tax subsidies are the same across steady states (except for R&D Intellectual property, which sees the present value of depreciation allowances decline from 1 to 0.785 and a slight change in the R&E credit in the corporate sector). The MACRS depreciation allowances for equipment, non-residential structures, residential structures, and other intellectual property are 0.812, 0.338, 0.336, and 0.842, respectively.

Depreciation is more difficult to calibrate because it differs by model. The NGM calibration comes entirely from Barro and Furman (2018). I set the NGMM depreciation rate such that the NGM and NGMM have the same initial user cost before TCJA. Because maintenance demand subtracts from user cost in the NGMM, that means depreciation is larger in the NGMM for each capital type. So, for example, that means solving for NGMM depreciation $\tilde{\delta}_i$ in the following equation

$$\underbrace{\frac{r^k + \delta_i}{1 - \tau_{i,j}}}_{\text{NGM User Cost}} = \underbrace{\frac{r^k + \tilde{\delta}_i + \frac{\gamma}{1-\omega}(1 - \tau_{i,j})^{1-\omega}}{1 - \tau_{i,j}}}_{\text{NGMM User Cost}}.$$

As discussed above, the initial tax rate on equipment is slightly higher for the steady state comparison exercise. This means that equipment depreciation will be slightly different for that exercise, but the difference is very small. For the dynamic analysis, it is 0.1324, compared to 0.1348 in the long-run comparison. Table A11 presents the rest of the parameters.

Capital Type	**NGM δ_i**	**NGMM δ_i (Passthrough)**	**NGM δ_i (Corporate)**
Equipment	0.088	0.134	0.135
Non-residential Structures	0.02	0.077	0.079
Residential Structures	0.027	0.084	0.086
R&D Intellectual Property	0.122	0.164	0.161
Other Intellectual Property	0.196	0.242	0.242

Table A11: Calibrated Depreciation Parameters. All NGM depreciation rates come from Barro and Furman (2018). The NGMM depreciation rate is set such that the initial user cost is the same in both models. Because tax rates are different in the passthrough and corporate sectors, the calibrated depreciation rates likewise differ in the NGMM model (but are common across sectors in the NGM).

E.2 Investment Adjustment Costs

Suppose that adjustment costs are instead in the investment growth rate, *i.e.*, capital accumulates according to

$$K_{i,j,t+1} = K_{i,j,t}\left(1 - \delta_i + h(m_{i,j,t})\right) + X_{i,j,t}\left(1 - \frac{b}{2}\left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1\right)^2\right), \qquad \text{(A.5)}$$

where $h(m_{i,j,t})$ is the usual constant elasticity maintenance function. This adjustment cost function, originally popularized by Christiano, Eichenbaum, and Evans (2005), is common in the macroeconomics literature. Using the same model as before, the first-order conditions for maintenance, investment, and capital are

$$m_{i,j,t} = \gamma \left(\frac{1-\tau^c_{j,t}}{\lambda_{i,j,t}} \right)^{-\omega} \tag{A.6}$$

$$1-\tau^x_{i,t} = \lambda_{i,j,t} \left(1 - b \left(\frac{1}{2} \left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1 \right)^2 + \left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1 \right) \frac{X_{i,j,t}}{X_{i,j,t-1}} \right) \right) \tag{A.7}$$

$$+ \frac{\lambda_{i,j,t+1} b}{1+r^k} \left(\frac{X_{i,j,t+1}}{X_{i,j,t}} - 1 \right) \left(\frac{X_{i,j,t+1}}{X_{i,j,t}} \right)^2$$

$$\lambda_{i,j,t} = \frac{1}{1+r^k} \left\{ \left(1-\tau^c_{i,j,t+1}\right) \alpha_{i,j} \frac{y_{i,j,t+1}}{K_{i,j,t+1}} + \lambda_{i,j,t+1} \left(1 - \delta_i - \mathbb{1}_{\{NGMM\}} \frac{\gamma^{1/\omega}}{1-\omega} m^{1-1/\omega}_{i,j,t+1} \right) \right\} \tag{A.8}$$

Whereas in the main text maintenance responds instantaneously to relative prices, it responds with lag here induced by sluggishness in investment growth. With $b > 0$, $\lambda_{i,j,t} \neq 1 - \tau^x_{i,t}$. This means that maintenance adjusts more slowly as well and it can even induce overshooting in both the paths of maintenance and investment. To see that, I replicate Figures 4 and **??** in Figures 19 and 20. I set the parameter $b = 0.88$ following Eberly, Rebelo, and Vincent (2008). In this case, the NGMM predicts only 1/3 as much growth as the NGM from 2018-2027.[22]

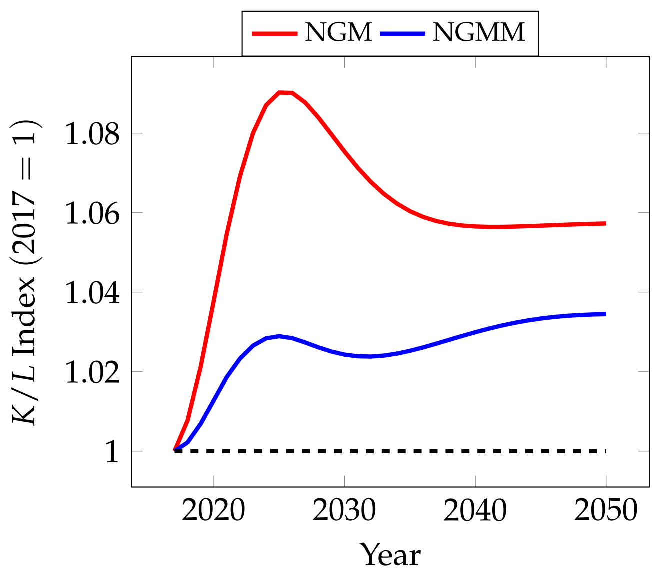


Figure 19: Capital Accumulation with investment adjustment costs.

22. Note, however, that this is not a direct comparison with the other case of adjustment costs because the steady states are not the same. Due to problems with computing the perfect foresight solution with low depreciation rates on structures, I set them to 0.055 for the NGM. This happens because in the NGMM with this type of adjustment cost, gross investment can become negative if depreciation is too low.

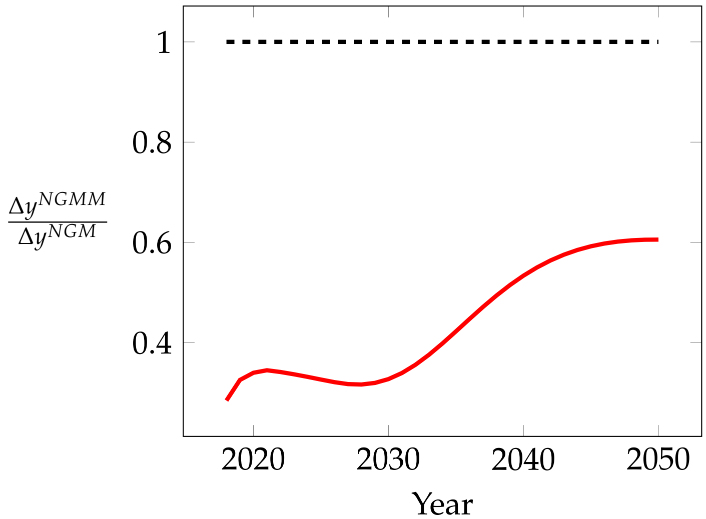


Figure 20: Relative Output Growth with investment adjustment costs.

F Optimal Policy

This subsection discusses the model environment for the optimal tax problem. I largely follow the derivation of Chari, Nicolini, and Teles (2020) to show how maintenance alters the benchmark. Time is discrete and runs $t = 0, 1, \ldots, \infty$. There is no uncertainty. There is a representative firm, a representative household, and a government which sets taxes to maximize household utility. For the sake of clarity, I assume the pre-tax prices of maintenance and investment are equal to one.

Representative Firm. The representative firm is largely the same as in Section 2. It chooses sequences of capital, investment, maintenance, and labor to maximize the present value of dividends $\sum_{t=0}^{\infty} q_t d_t$, where

$$d_t = (1 - \tau_t^c) \left(F\left(K_{1,t}, \ldots, K_{N,t}, n_t\right) - w_t n_t - \sum_{i=1}^{N} M_{i,t} \right) - \sum_{i=1}^{N} \left(1 - \tau_{i,t}^x\right) X_{i,t}$$

There are three differences. The first, which is inconsequential, is how the firm discounts the future. Letting q_t represent the price of one unit of the period-t good in terms of a good in period zero, the interest rate between periods is given by

$$\frac{q_t}{q_{t+1}} \equiv 1 + r_t, \quad q_0 = 1.$$

Second, I assume that the production function is constant returns to scale. Third, I assume there are no adjustment costs because the ultimate focus is on the steady state. Optimality conditions are the same as in Section 2. Combining these conditions implies that the present discounted value of dividends is given by

$$\sum_{t=0}^{\infty} q_t d_t = \sum_{i=1}^{N} K_{i,0} \Big[(1-\tau_0^c) \left(F_{K_{i,0}} - m_{i,0} \right) + \left(1-\tau_{i,0}^x\right) \left(1-\delta_i + h\left(m_{i,0}\right)\right) \Big]. \tag{A.9}$$

Representative Household. A representative household has preferences over consumption c and labor n given by

$$\sum_{t=0}^{\infty} \beta^t u(c_t, n_t). \tag{A.10}$$

Because I am explicitly interested in only showing the effect of one deviation from the standard case, suppose preferences are standard in the sense of Chari, Nicolini, and Teles (2020), *i.e.*, they are homothetic and additively separable. $\beta \in (0,1]$ is the discount factor embodying the required return on capital r^k. The household earns labor income $w_t h_t$ and dividend income from the representative firm and trades shares of the firm s_{t+1} at ex-dividend price p_t, leading to the budget constraint

$$c_t + p_t s_{t+1} + \frac{b_{t+1}}{1+r_t} = (1-\tau_t^h) w_t n_t + p_t s_t + d_t s_t + b_t, \tag{A.11}$$

where $s_0 = 1$ and initial bonds are b_0. Choosing sequences of consumption, labor, and shares of the firm to maximize (A.10) subject to (A.11) and a transversality condition given by $\lim_{T\to\infty} q_{t+1} b_{T+1} \geq$ yields first-order conditions given by

$$-u'(n_t) = (1-\tau_t^h) w_t u'(c_t) \tag{A.12}$$

$$u'(c_t) = \beta u'(c_{t+1})(1+r_t) \tag{A.13}$$

$$1 + r_{t+1} = \frac{p_{t+1} + d_{t+1}}{p_t}. \tag{A.14}$$

We can put together the household budget constraint with the net present value of the firm and the no-Ponzi condition to arrive at a lifetime budget constraint for the household. No-arbitrage clearly requires that the return on each capital type must equal the return on bonds. The transversality condition implies that the price of the stock equals the present value of future dividends, *i.e.*,

$$p_t = \sum_{s=0}^{\infty} \frac{q_{t+1+s}}{q_t} d_{t+1+s}. \tag{A.15}$$

We can combine the transversality condition and the flow budget constraint to obtain a lifetime budget constraint:

$$\sum_{t=0}^{\infty} q_t \left[c_t - \left(1-\tau_t^h\right) w_t n_t\right] \leq p_0 s_0 + d_0 s_0 + b_0 \tag{A.16}$$

Substituting for the price of the stock and applying (A.9), we arrive at

$$\sum_{t=0}^{\infty} q_t \left[c_t - \left(1-\tau_t^h\right) w_t h_t\right] \leq W_0, \tag{A.17}$$

where

$$W_0 \equiv b_0 + \sum_{i=1}^{N} K_{i,0}\Big[\left(1-\tau_0^c\right)\left(F_{K_{i,0}} - m_{i,0}\right) + \left(1-\tau_{i,0}^x\right)\left(1-\delta_i + h\left(m_{i,0}\right)\right)\Big].$$

Finally, the aggregate resource constraint is

$$c_t + G_t + \sum_{i=1}^{N} \left(X_{i,t} + M_{i,t}\right) = Y_t, \tag{A.18}$$

where $Y_t \equiv F\left(K_{1,t}, \ldots, K_{N,t}, n_t\right)$. I do not explicitly specify the government budget constraint because it is implied by market clearing and the household budget constraint.

Definition 1. *A competitive equilibrium for this economy is a set of allocations $\{c_t, n_t, d_t, s_t\}$ and $\{K_{1,t+1}, \ldots, K_{N,t}, M_{1,t}, \ldots, M_{N,t}\}$, prices $\{q_t, p_t, w_t\}$ and policies $\{\tau_t^c, \tau_t^h, \tau_{1,t}^x, \ldots, \tau_{N,t}^x\}$ given initial allocations $\{K_{0,1}, \ldots, K_{1,N}, b_0, s_0\}$ such that households maximize utility subject to their constraints, firms maximize the net present value of dividends subject to their constraints, markets clear such that the aggregate resource constraint is satisfied, and $s_t = 1$ for $t = 1, \ldots, \infty$.*

F.1 The Policy Cost of Maintenance

The first-best problem allows the government to set taxes freely on capital of all types and labor. To characterize first-best policy, I take the primal approach. That is, I substitute prices and taxes from the household's optimality conditions into the budget constraint to obtain the set of implementable allocations:

$$\sum_{t=0}^{\infty} \beta^t \left[u'(c_t)c_t + u'(n_t)n_t\right] \geq u'(c_0)W_0 \tag{A.19}$$

Proposition 3. *Any implementable allocation satisfies* (A.18) *and* (A.19).

I omit the proof because it follows directly from Chari, Nicolini, and Teles (2020). The Ramsey problem is to choose an allocation that maximizes household utility subject to implementability and feasibility. Let Φ be a multiplier on (A.19) and define the transformed utility function

$$V\left(c_t, n_t, \Phi\right) = u(c_t, n_t) + \Phi\left(u'(c_t)c_t + u'(n_t)n_t\right). \tag{A.20}$$

Now, with the Lagrangian

$$\begin{aligned}\mathcal{J} = \sum_{t=0}^{\infty} \beta^t \Bigg\{ & V(c_t, n_t, \Phi) \\ & + \theta_t \left[F(K_{1,t}, \ldots, K_{N,t}, n_t) + \sum_{i=1}^{N} \left[(1-\delta_i(m_{i,t}))K_{i,t} - K_{i,t+1} - M_{i,t} \right] - G_t - c_t \right] \Bigg\} \\ & - \Phi u'(c_0)W_0 \end{aligned} \tag{A.21}$$

and the first-order conditions to (A.21), we can arrive immediately at our main result for this subsection.

F.2 Proof of Proposition 2

Proposition 2. *Suppose the economy converges to a steady state. The steady state optimal tax on capital is identically zero across all capital types.*

Proof. For $t \geq 1$, the first-order conditions to (A.21) are:

$$V'(c_t) = \beta V'(c_{t+1}) \left(F_{K_{i,t+1}} + 1 - \delta + h(m_{i,t+1}) - h'(m_{i,t+1})m_{i,t+1} \right) \quad \text{for } i = 1, \ldots, N \tag{A.22}$$

$$V'(n_t) = -V'(c_t)F_{n_t} \tag{A.23}$$

$$h'(m_{i,t+1}) = 1 \quad \text{for } i = 1, \ldots, N \tag{A.24}$$

There are two proof options. First, the more traditional route is to focus on the Euler equations. If the economy converges to a steady state, then $V'(c_t)$ converges to a constant. This is guaranteed immediately from the assumption on preferences. Hence the planner's

Euler equation for each capital type becomes

$$1 = \beta \left(F_{K_i} + 1 - \delta + h(m_i) - h'(m_i) m_i \right). \tag{A.25}$$

Note, moreover, that $1 + r_t$ must converge to $1/\beta$. Consequently, no arbitrage across bonds and capital requires that

$$1 = \beta \left[\frac{1 - \tau^c}{1 - \tau_i^x} F_K + 1 - \delta + h(m_i) - h'(m_i) m_i \right] \quad \text{for } i = 1, \ldots, N \tag{A.26}$$

Clearly, (A.25) and (A.26) together imply that $\tau_i \equiv 1 - \frac{1-\tau^c}{1-\tau_i^x} = 0$. However, a simpler route is instead to compare the decentralized first-order condition for maintenance with the planner's. The planner's first-order condition for maintenance features no distortions, from which it is immediate that there are no intertemporal distortions in steady state. □