Tax Policy and Maintenance Behavior

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Using novel micro data from Class I freight railroads, I find that capital maintenance demand is positive and has a price elasticity of two. Because maintenance is a tax-deductible input into capital production, it has two important effects on the transmission of capital tax policy. First, positive maintenance demand dampens the tax elasticity of capital because it is a tax shield in user cost. Second, elastic maintenance demand induces firms to substitute away from maintenance and toward investment when capital taxes decline. Together, these effects attenuate the traditional capital deepening channel emphasized by neoclassical investment theory. I show that the maintenance channel is quantitatively large in the context of the 2017 Tax Cuts and Jobs Act. A standard neoclassical model with maintenance forecasts a 0.6% increase in output per capita in the long run, which is half the increase predicted by an otherwise identical model without maintenance.

JEL-Classification: D24, E22, E62, H25

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1 Introduction

In workhorse models for tax policy analysis, there is only one input to capital production. Capital tax cuts lower the user cost of capital, which leads to capital deepening, productivity growth, and, ultimately, output and welfare gains (Hall and Jorgenson 1967; Lucas 1990). This capital deepening effect historically motivated supply-side stimulus and growth policies (Romer and Romer 2010). For example, President Kennedy introduced accelerated tax depreciation and an investment tax credit to "stimulate the investment needed for sustained expansion and longer-run growth." Debates over such policies typically hinge on the tax elasticity of investment because under single-input 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 productivity, output, and welfare.

In this paper, I present evidence that both the proponents and opponents of supply-side policies miss an important second channel that dampens the capital deepening effect: capital maintenance.[1] Despite the fact that standard models assume the demand for maintenance is inelastically zero, firms expend large sums on ensuring the continued productivity of existing capital through maintenance. This suggests maintenance should enter the cost of capital as an additional term. Omitting maintenance is surprisingly important for a simple reason: it is an operating expense and therefore subsidized at the marginal effective tax rate on capital. This implies that even if the demand for maintenance is price-inelastic but positive, maintenance attenuates the capital deepening channel through a *tax shield effect* because the maintenance share of the after-tax cost of capital is unaffected by capital tax cuts. On the other hand, if maintenance is chosen by firms, then maintenance joins investment as a second input to capital production. Because maintenance is subsidized at the marginal effective tax rate on capital, tax cuts induce firms to substitute away from maintaining existing capital and toward investing in new capital. This *input substitution effect* amplifies the tax shield effect and dampens the tax elasticity of capital, with correspondingly smaller effects on both output and welfare.

I contribute to the empirical capital literature by disentangling the tax shield and input substitution effects using a novel dataset. This requires estimating firm demand for maintenance. 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

1. Maintenance expenditures are expensed costs on capital, labor, and intermediate inputs to restore, repair, or ensure continued productivity of existing capital. 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.

many standard data sources. However, Class I freight 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 which capital is maintained 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.

To measure the elasticity of demand for maintenance, I regress the log maintenance rate on the log relative price of maintenance to investment for locomotives and freight cars across seven firms from 1999-2023 using a fixed effects model. 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.

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.I use cross-sectional variation in exposure to exogenous tax policy changes to identify the maintenance elasticity. This approach follows a methodology in the tradition of Cummins, Hassett, and Hubbard (1994) and best exemplified by Zwick and Mahon (2017) in the investment literature. The identification strategy 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 tax changes. 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 growth model (NGM) from those obtained from the NGM augmented with maintenance (NGMM). Over a ten year horizon, the output gains are only two-thirds 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.

Literature. The theoretical relationship between input substitution and capital deepening hearkens back to important theoretical work from Feldstein and Rothschild (1974) and McGrattan and Schmitz Jr. (1999), both of which argue that traditional neoclassical capital theory miss out on important aspects of investment decisions by abstracting from replacement and maintenance, respectively. In the latter paper, which is the closest to mine, McGrattan and Schmitz develop a homogeneous capital model of endogenous maintenance and investment and provide the original insight that depreciation is endogenous to tax policy. Just like in this paper, maintenance expenditures are pinned down by the relative price of maintenance to investment. The only real theoretical difference with my paper is that I allow for a more general approach to how maintenance contributes to capital accumulation. 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.[2]

2. 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

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 from 9% to 12%. 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; 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.[3]

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 approxima-

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.

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

tion 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.

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

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

Proposition 1 states the more general case.

Proposition 1. *Given a tax shock, 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.

Tax Shield Effect through γ

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 resulting 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.

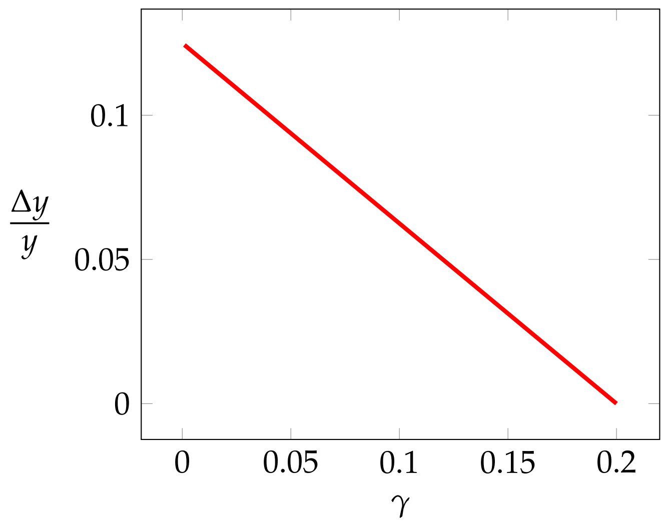


Figure 1: Proportional change in output per capita as a function of the maintenance rate. The tax reform moves the marginal tax on capital from 35% to 20%. I set $\widetilde{\Psi} = 0.2$ and $\alpha = 0.4$.

Input Substitution Effect through ω

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.[4] 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.

A second way to interpret the input substitution effect is through age variation in the capital. Tax changes could make firms maintain less because tax cuts shift the age distribution of capital. It is intuitively clear that younger cars require less maintenance because they are new. If tax cuts spur new investment, then the aggregate maintenance rate may decline because capital is younger in the aggregate. In some sense, then, ω may be interpreted as a reduced form tax elasticity for the age distribution of capital. This would speak directly to the indirect evidence in Goolsbee (2004) that lower taxes induce firms to buy capital with lower maintenance costs. As a result, the relevant question would be the persistence of the change in the age distribution of capital. If the investment rate permanently rises, then the age distribution of capital likewise permanently changes. In standard models, it would not be possible for investment rates to permanently change in response to tax policy. In this model, that *is* possible as long as maintenance rates are similarly persistent to the tax policy itself. To see that, note that the steady state investment rate is given by

$$\frac{X}{K} = \delta - \frac{\gamma}{1 - 1/\omega} (1 - \tau)^{1-\omega} .$$

As long as the demand for maintenance is elastic, *i.e.*, $\omega > 0$ then the investment rate varies with the tax rate.

Taking Stock

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. Empirically validating the relative magnitudes of the tax shield and input substitution effects are then sufficient to conduct the relative tax policy counterfactuals.

4. 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 equal to zero and 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.

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%. This, on its own, is sufficient to reject the neoclassical benchmark of inelastically zero maintenance demand. 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 Appendix B.5. 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:

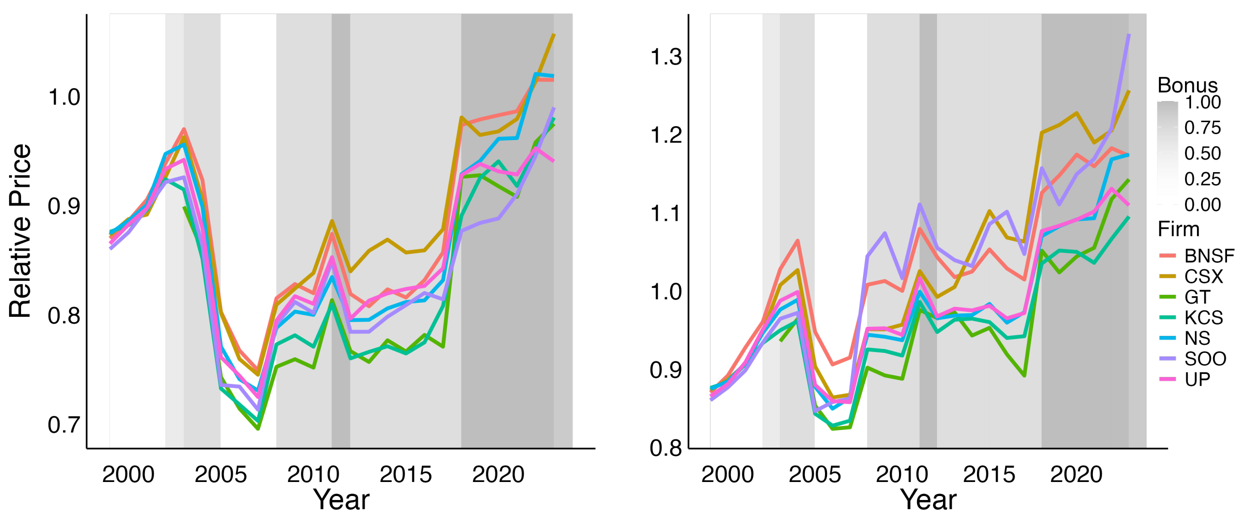
1. **Price of investment.** The price of investment does not vary by firm, only by capital type. It is simply the BLS's producer price index for locomotives and freight cars.

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, 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 and capital. 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 B.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)
$\log P_{i,j,t}$	-1.73**	-1.87***	-1.53***	-0.56**
	(0.62)	(0.43)	(0.43)	(0.19)
Age		-1.87**	-1.73**	-0.74**
		(0.77)	(0.77)	(0.29)
$\log x_{i,j,t}$			0.06***	0.01
			(0.02)	(0.02)
$\log m_{i,j,t-1}$				0.80***
				(0.07)
N	342	342	332	319
R^2	0.534	0.613	0.636	0.894
AIC	427.8	366.0	343.1	-57.0

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 1: This table estimates regressions using (6). Column 1 is the baseline regression of log maintenance rates on log relative prices. Column 2 controls for the age of capital, where age is net capital stock scaled by gross capital stock. Column 3 adds a control for investment, while Column 4 adds a control for the lagged log maintenance rate. All regressions include firm, year, and capital type fixed effects. Standard errors are clustered by firm and capital type.

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).

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 about endogeneity and external validity. I address each subsequently.

3.3 Endogeneity of Relative Prices

We should 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 internal maintenance costs is approximately 40%. Figure A.2 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 A.3 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 2 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.

	Dependent variable: $\log m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$\log P_{i,j,t}$	-1.51**			-2.04**	-2.82*
	(0.66)			(0.88)	(1.32)
Pre-Tax $\log P_{i,j,t}$		-1.89***			
		(0.47)			
$1 - \tau_{i,t}$			-1.36***		
			(0.31)		
N	316	316	316	328	314
Industry Controls	Y	Y	Y	N	N
R^2	0.491	0.501	0.445	0.538	0.545
AIC	394.9	388.5	421.9	413.9	398.8
Instrument	Oil	Tax Rate	Tax Rate	$\log P_{i,j,t-1}$	$\log P_{i,j,t-2}$
IV	Y	Y	N	Y	Y
F-test	16.6	33.1		1,272.4	453.3

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 2: Instrumental variables results for regressing the maintenance rate on a measure of the relative price. Columns 1-3 are of the form $\log m_{i,j,t} = \alpha_i + \kappa_j + \beta X_{i,j,t} + \text{Industry Controls}_t + \varepsilon_{i,j,t}$, where α_i is a firm fixed effect, κ_j is a type fixed effect, and X is some measure of the relative price. In Column 1, I use the Känzig (2021) oil news shock as an instrument for the after-tax relative price. In Column 2, I use the firm-level marginal tax rate on equipment as an instrument for the pre-tax relative price. Column 3 regresses the maintenance rate directly on the tax term $1 - \tau_{i,t}$. For each of these columns, the industry controls are the rail cost adjustment factor published by the Surface Transportation Board (STB), freight rail productivity growth from the STB, GDP growth, and a year trend. Columns 4 and 5 add a time fixed effect and do not use industry controls. Columns 4 and 5 use lags of the after-tax relative price as instruments. Every regression with instruments reports the Cragg-Donald F-statistic. Standard errors are clustered by firm and capital type.

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 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 A.2 contains summary statistics.

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.

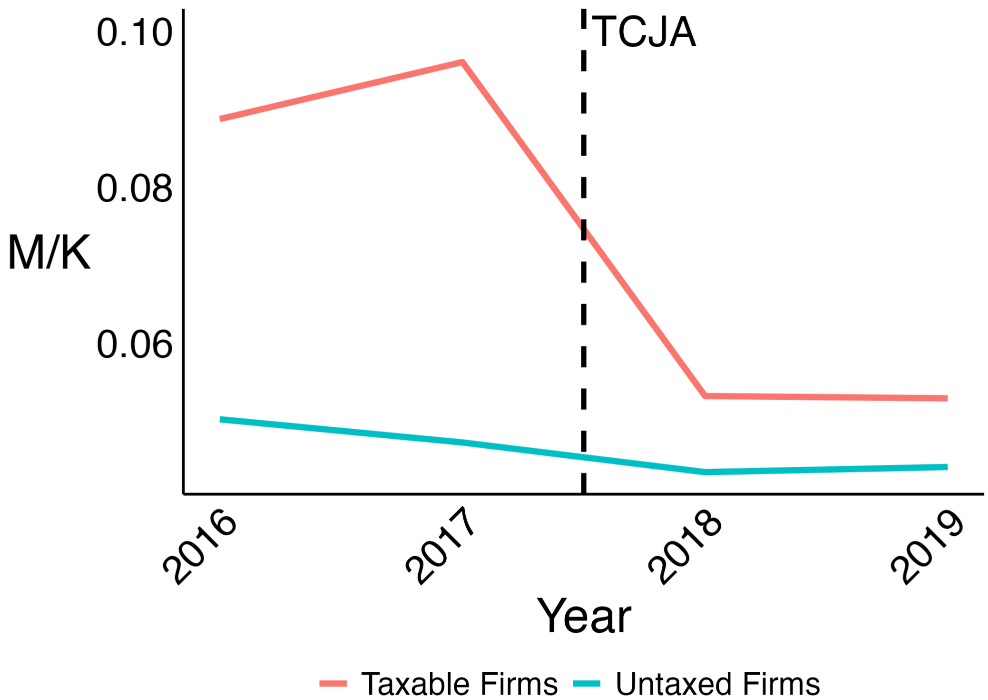


Figure 3: The average maintenance rate of taxable firms and untaxable firms plotted against the average marginal tax rate from the SOI sample. Untaxable firms had negative net income. The dashed line depicts the 2017 Tax Cuts and Jobs Act (TCJA), which passed toward the end of 2017.

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 A.5 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 A.6 shows that the business receipts per tax return followed similar trends before and after the passage of TCJA for both taxable and untaxable firms.

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

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

where α_j is an industry fixed effect and T_t is a time fixed effect. There was a great deal of policy variation in the relevant window.[5] 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 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.[6] 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 small and insignificant for untaxable firms.[7] 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 confirms that the results are not limited to freight rail and are indeed an economy-wide phenomenon.

5. I detail how I create $\tau_{j,t}$ in Appendix A.3. It is largely the same procedure as previous iterations of cross-sectional tax policy analysis from, for example, House and Shapiro (2008).

6. I show the corresponding results for the linear-linear model and the level cases in Appendix A.2.

7. The dynamic specification in column 3 yields a coefficient around -2.5 because the autocorrelation of the maintenance rate is 1/3.

	Dependent variable: $\log m_{j,t}$					
	Taxable Firms			Untaxable Firms		
	(1)	(2)	(3)	(4)	(5)	(6)
$\log(1-\tau_{j,t})$	-2.91**	-2.52**	-1.67**	0.05	-0.79	-0.87
	(1.13)	(1.00)	(0.73)	(2.47)	(2.41)	(1.69)
$x_{j,t}$		-0.05**	-0.06**		-0.03*	-0.04**
		(0.02)	(0.03)		(0.02)	(0.02)
$\log m_{j,t-1}$			0.34***			0.36***
			(0.10)			(0.07)
N	1071	1012	1005	1073	1012	1007
R^2	0.844	0.855	0.874	0.748	0.761	0.794
AIC	369.2	289.9	142.2	1187.1	1086.1	934.3

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: This table estimates regressions using (7). Column 1 is the baseline regression of log maintenance rates on the log tax rate. Column 2 controls for the investment rate, while Column 4 adds a control for the lagged log maintenance rate. The left panel is the SOI sample for firms with positive taxes and the right panel is for unprofitable firms which did not pay taxes. All regressions include industry and year fixed fixed effects. Standard errors are clustered by industry.

However, there are two potential issues with the data in this subsection. I give a detailed discussion of both in Appendix B.9. 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. Second, the capital stock is likely measured incorrectly; I discuss this source of bias in Section B.5. Third, the estimates in Table 3 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 SOI elasticities should be magnified by approximately 1.4.

3.5 Additional Results

In Appendix B, I provide additional empirical results for both R-1 and SOI data. I give a brief description of the more important results here.

Linear-Linear Model

Appendix B.1 provides results for a linear-linear model for both the R-1 and SOI datasets. This model assumes that the maintenance demand curve is linear and hence measures the parameter b in the demand curve $m = a + bP$. A linear demand curve has extreme implications; it suggests that maintenance demand would become negative for a high enough price. Conceptually, this means that firms would damage their capital on purpose. This is implausible relative to the constant-elasticity function, which suggests that firms stop maintaining for sufficiently high prices rather than actively damaging their capital. Results from freight rail data suggest that the slope parameter b is consistently statistically significant around -0.4. However, while the SOI suggests $b = -0.15$ for taxable firms and is consistently zero for nontaxable firms, the results for taxable firms are not always statistically significant.

Dynamic Effects

In Appendix B.3, I plot local projections of the log maintenance rate on tax policy. The dynamic response of maintenance is important because it is informative about adjustment costs. If the coefficient is stable across horizons, that indicates instantaneous adjustment of maintenance. With convex adjustment costs on investment or maintenance individually, the coefficient would instead gradually adjust. With a convex capital adjustment cost or no adjustment costs, maintenance instantaneously adjusts. I discuss this further in the following section show it more formally in C.2. For both the SOI and the R-1 data, the coefficient is quite stable for more than five years out, which indicates that investment adjustment costs, which are commonly used in the macro literature, are not well-supported. This echoes earlier findings from Groth and Khan (2010), which found that investment adjustment costs are not supported in industry-level investment data. The difference, of course, is that they did not have access to maintenance data.

Measurement Error in the Capital Stock

A potentially important source of measurement error is in the capital stock itself. Aside from the regressions in levels in Table A6, all regressions involve the maintenance rate.

However, theory implies that the maintenance rate is incorrectly measured in the data because it uses the perpetual inventory method. I address this in two ways.

First, I develop a *physical* measure of the physical capital stock based on the capacity of rolling stock in Appendix B.4. For locomotives, that is horsepower, while it is tons of freight for freight cars. This information comes from Schedule 710 of the R-1 reports. These measures have a high correlation (0.9) with the book value of the capital stock. As such, they yield essentially practically the same estimates for both the reduced form and instrumental variables regressions.

Next, in Appendix B.5, I correct for measurement error in the capital stock by building up freight rail capital stocks with a law of motion that accounts for maintenance through constant elasticity demand. Starting with an initial guess of 2.1 for the elasticity parameter, I iterate on the regression coefficient in Column (1) of Table 1 until the elasticity parameter converges. This results in an elasticity estimate slightly smaller than in the baseline estimate and one that is only statistically significant at the 10% level. However, the result generally holds up.

Simultaneous Determination of Maintenance & Investment

As an additional step, I estimate the maintenance elasticity using 3SLS for the freight rail data in Appendix B.6. It is possible that maintenance and investment are simultaneously determined with correlated errors, which means that it is necessary to use 3SLS. I find a similar value of the slope parameter b for the linear-linear model and a demand elasticity around 2 for the constant elasticity demand function. However, the results are problematic for investment. They suggest that investment does not respond to the relative price in the linear-linear model, while it responds in the wrong direction for the log-log model. This could be because some distinction has to be drawn between investment as improvements to existing capital and investment in entirely new capital. The former is probably correlated with maintenance, while the latter is not. Altogether, that suggests a more sophisticated model is necessary to understand choices between improvements, additions, and maintenance.

Taking Stock

Neoclassical theory assumes that the demand for capital maintenance is inelastically zero. This section conclusively shows that the demand for maintenance is positive and large. For freight rail, it is the same order of magnitude as investment. That finding validates the claims about the effects of capital stock accumulation in Section 2. Additionally, across a variety of specifications and data sources, I showed that the elasticity of demand for maintenance is plausibly around two. Hence, there is substitution from investment to maintenance when taxes rise. This amplifies the maintenance channel and substantially attenuates capital deepening channel.

4 Capital Maintenance and the 2017 Tax Cuts and Jobs Act

Theory suggests that positive and elastic maintenance demand significantly dampens traditional capital deepening effects. In late 2017, Congress passed the Tax Cuts and Jobs Act, which reduced the cost of capital in both the corporate and passthrough sectors through large tax cuts. 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.[8] The latter policy allows firms to immediately deduct investment from their tax bill, thereby eliminating the tax wedge in the maintenance-investment choice. However, only the provision for the corporate rate change is permanent, whereas the expensing components for equipment and the personal income tax cut sunset after 2026. President Trump's Council of Economic Advisors described the motivation and mechanism for the law's domestic business tax provisions through the capital deepening channel:

> A primary mechanism through which changes in corporate tax rates and depreciation allowances affect business investment is their effect on the user cost of a capital investment—which can be thought of as the rental price of capital, and is the minimum return required to cover taxes, depreciation, and the opportunity costs of investing in capital accumulation versus financial alternatives. A decrease in the user cost increases the desired capital stock, and thereby induces gross investment. (CEA 2018, p. 57)

Thus, the architects of the largest tax reform in decades largely had in mind the traditional capital deepening channel. In this section, I discuss how adapting maintenance

8. 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. 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).

into a benchmark neoclassical model from Barro and Furman (2018) alters quantitative predictions about the effects of TCJA on domestic capital deepening and productivity. Barro and Furman's model is particularly well-suited to use as a benchmark because they rely entirely on the capital deepening channel. Consequently, it is transparent how much maintenance matters relative to the baseline case.

4.1 Model and Calibration

The Barro and Furman (2018) model is a multisector Ramsey model in discrete time. There is a corporate and a passthrough sector in each model, both of which has a representative firm. Time is discrete and runs from $t = 0, \dots, \infty$. There is no household. 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

$$K_{i,j,t+1} = K_{i,j,t}\left(1 - \frac{\psi}{2}\left(\frac{K_{i,j,t+1}}{K_{i,j,t}} - 1\right)^2 - \delta(m_{i,j,t})\right) + X_{i,j,t}. \tag{9}$$

where $\delta(m_{i,j,t}) = \delta_i$ in the benchmark case and $\delta(m_{i,j,t}) = \widetilde{\delta}_{i,j} - \frac{\gamma^{1/\omega}}{1-1/\omega} m_{i,j,t}^{1-1/\omega}$ in the maintenance case. Note that $\delta_i \neq \widetilde{\delta}_i$. Because I want to compare the counterfactual effects of TCJA between the standard model and the maintenance model, the right calibration requires that both models start at the same capital-labor ratio. I set $\widetilde{\delta}_{i,j}$ to accomplish that and discuss the issue further in Appendix C. As notational shorthand, I refer to the benchmark neoclassical growth model as the NGM and the maintenance model as the NGMM.

The only differences between Barro and Furman (2018) and this model are that I add convex capital adjustment costs and maintenance demand and subtract debt-financed investment. I omit debt financing to maximally highlight the distinction between predictions before and after accounting for maintenance demand. There are two key assumptions in (9). 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 (Albonico, Kalyvitis, and Pappa 2014; Koby and Wolf 2020), it also means that maintenance instantaneously adjusts when prices change. In Appendix C.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 B.3, 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.

Although I apply maintenance demand to intangibles like R&D and other IP, it is unclear how to think about maintenance in this context. For physical capital like rolling stock, it makes sense to think of maintenance as extending the productive life of capital through physical interventions like greasing wheels, repainting cars, and so on. For intangibles like intellectual property and R&D, their value is tied up in the ability to exclude other firms from using them (Haskel and Westlake 2018). As such, we can roughly think of maintenance as expenditures to maintain the value of intangibles that would otherwise become obsolete more quickly. Expenditures in this category are broad and may range from maintaining the infrastructure to run R&D operations to security against intellectual property theft.[9]

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.[10] The firm's problem in each sector is to choose sequences of capital, investment, and maintenance to maximize

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

After substituting out for maintenance and investment, the model is fully governed by (11).

9. It is perhaps unnatural to think about intangibles and tangibles in the same Cobb-Douglas aggregator (Crouzet et al. 2022), but it is the most natural benchmark given that it is what Barro and Furman do and so do many others (McGrattan 2017). Given that the purpose is to see how maintenance demand matters under benchmark models, I keep the Cobb-Douglas aggregator assumption. With the growing interest in intangibles beyond intellectual property like sweat equity (Bhandari, Borovicka, and Ho 2019) and in how to depreciate intangibles (Li and Hall 2016), this is a promising area for more research.

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

$$
\begin{aligned}
\left(1-\tau^x_{i,t+1}\right)\left(1+\psi\left(\frac{K_{i,j,t+1}}{K_{i,j,t}}-1\right)\right) = \frac{1}{1+r^k}\Bigg\{ & \left(1-\tau^c_{j,t}\right)\alpha_{i,j}\frac{y_{i,j,t}+1}{K_{i,j,t+1}} \\
& + \left(1-\tau^x_{i,t+1}\right)\left[1-\delta_i+\frac{\psi}{2}\left(\left(\frac{K_{i,j,t+1}}{K_{i,j,t}}\right)^2-1\right)\right. \\
& \left.-\frac{\gamma}{1-\omega}\left(\frac{1-\tau^c_{j,t+1}}{1-\tau^x_{i,t+1}}\right)^{1-\omega}\right]\Bigg\} \qquad (11)
\end{aligned}
$$

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 C. 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 6.4%. 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 conservative estimate of the effect of maintenance. Second, I set the adjustment cost parameter ψ so that the path of capital in the benchmark $\gamma = 0$ model 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 richly detailed heterogeneous firm and worker model, while the former 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 maintenance model such that the initial user costs are the same between both models.

4.2 Economic Effects of TCJA

I start by discussing the steady-state estimates of how much maintenance matters and follow it up with a discussion of financing. Starting with the steady state helps provide intuition for this section's concluding remarks on the dynamic effects of TCJA on corporate capital accumulation.

Long-Run

The natural starting place for considering the effects of TCJA is to shut down adjustment costs and compare steady states. This yields the cleanest comparison and sharpest intuition for what adding in the empirically calibrated maintenance demand function does to the capital deepening and productivity effects in the neoclassical model. See Appendix C for the calibration, which sets each capital type to have the same pre-TCJA user cost across both the NGM and the NGMM.

	Baseline UCC	NGM		NGMM	
		%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%	-6.1%	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%
%Δ K/L		+8.7%		+4.6%	
%Δ Y/L		+3.3%		+1.8%	
Passthrough Business					
Equipment	0.187	0.1%	-1.1%	0.1%	-0.8%
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	21.4%	-22.4%	16.4%	-17.1%
Other IP	0.302	0.1%	-1.0%	0.1%	-0.8%
%Δ K/L		-2.5%		-1.8%	
%Δ Y/L		-0.9%		-0.7%	

Table 4: Effects of TCJA. The top panel depicts the change in the user cost of capital and capital-labor ratio within the Barro-Furman benchmark and the maintenance model given a common baseline user cost of capital for corporate businesses. The bottom panel does the same for passthrough businesses. See Appendix C for calibrated parameters.

Table 4 presents the resulting change in user costs and capital-labor ratios for both corporate and passthrough business following TCJA for each capital type. The top panel is corporate business and the bottom panel is passthrough business. The first column contains a baseline user cost common to both the benchmark and the maintenance models. The next two columns contain the percent change in the user cost and capital-labor ratio for each type of capital under the benchmark model and the following two for the maintenance model. 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 for structures. By comparison, maintenance is a relatively small part of intellectual property, so the resulting difference in user costs is correspondingly smaller. In other words, the tax shield effect is much larger for long-lived capital, making it relatively less tax-elastic. This contrasts with House (2014), who argued that long-lived capital is theoretically more tax-elastic precisely because the depreciation rate is low.

In the corporate sector, the benchmark model predicts a capital-labor ratio and an output-labor ratio slightly less than twice as large as the maintenance. An equivalent way to summarize the result is that the effect of accounting for the maintenance channel is observationally equivalent to the benchmark model 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 maintenance model yields a total change in the capital-labor ratio that is about 70% as large as in the benchmark.

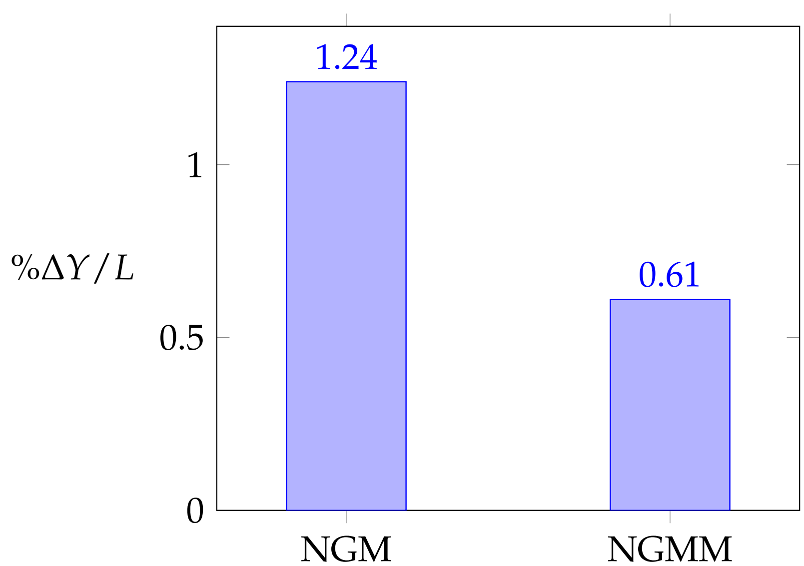


Figure 4: Increase in steady-state per capita output (productivity) in the benchmark and maintenance models.

To compute the aggregate change in output, I follow the Barro and Furman procedure. They 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 6.8% of passthrough activity shifts to the corporate sector in the long-run. I keep that assumption and then compute the total change in aggregate output. Figure 4 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.

Robustness: Financing & Crowding Out

Beyond the economic effects of tax policies, lawmakers and economists worry about how to finance them. In the model, I assume that the government budget constraint is forced to hold through lump-sum financing. This implies there are no distortionary effects of paying for the tax law. However, if Ricardian equivalence does not hold, then it is possible that the deficit effects may lead to crowding out. In this subsection, I explore how much that matters for the previously obtained capital deepening estimates.

Although economists disagree considerably about the economic impact of business tax cuts, there is very little disagreement that TCJA is expensive, with ten-year tax revenue shortfalls ranging from about \$1.5T on the low end from the Joint Comittee on Taxation to over \$2T from the Penn Wharton Budget Model. The JCT estimate is static, meaning that it holds fixed projected macroeconomic growth when scoring the bill. Following Barro and Furman (2018), I calculate a dynamic score based on the JCT estimate using the growth effects from the previous subsection. The NGM predicts TCJA to make output 1.24% higher in the long run and the NGMM predicts the same bill to generate growth of 0.61%. I take the baseline pre-reform CBO estimates of output from 2018-2027 and assume that GDP starts one percent above that baseline and converges to the steady state at five percent per year. Putting that together with the assumption that tax revenue as a share of GDP is the same as under the static score yields dynamic scores for both the NGM and the NGMM. This is the exact same procedure as in Barro and Furman (2018) and implies that the dynamic feedback from the NGMM is about \$250B over the first ten years, while the feedback from the NGM is \$300B. Thus, the dynamic score of TCJA is \$1.2 trillion under the NGM and \$1.25 trillion after accounting for maintenance. These are not large differences in financing requirements. If the economy is Ricardian, then the lump-sum cost per household would be about \$925 under the NGM estimate and \$50 higher after accounting for maintenance.

	Baseline UCC	NGM %Δ UCC	NGM %Δ K/L	NGMM %Δ UCC	NGMM %Δ K/L
Corporate Business					
Equipment	0.190	-3.3%	6.0%	-2.2%	3.4%
Structures	0.143	-10.7%	13.4%	-4.4%	5.5%
Residential Structures	0.153	-10.8%	13.5%	-4.9%	6.0%
Intellectual Property	0.188	8.3%	-5.6%	6.8%	-5.7%
Other IP	0.305	-3.0%	5.7%	-2.5%	3.6%
%Δ K/L		+7.1%		+3.1%	
%Δ Y/L		+2.7%		+1.2%	
Passthrough Business					
Equipment	0.187	1.0%	-2.6%	1.0%	-2.3%
Structures	0.139	1.8%	-3.4%	1.6%	-3.0%
Residential Structures	0.148	1.7%	-3.4%	1.5%	-2.9%
Intellectual Property	0.204	22.2%	-23.8%	17.2%	-18.5%
Other IP	0.302	0.6%	-2.3%	0.6%	-2.0%
%Δ K/L		-4.3%		-3.6%	
%Δ Y/L		-1.6%		-1.4%	

Table 5: Effects of TCJA with crowding out. The top panel depicts the change in the user cost of capital and capital-labor ratio within the Barro-Furman benchmark and the maintenance model given a common baseline user cost of capital for corporate businesses. The bottom panel does the same for passthrough businesses. See Appendix C for calibrated parameters. These figures account for an increase in the required return of 15 basis points post-TCJA.

What happens if we relax the Ricardian equivalence assumption? Laubach (2009) estimates that a one percentage point increase in the deficit/GDP ratio corresponds to a 25 basis point increase in the interest rate. Under the dynamic scoring method discussed earlier, the deficit/GDP ratio would rise by about 0.6 percentage points compared to the pre-reform baseline. After rounding, this implies the interest rate would increase by about

15 basis points.[11] These estimates are essentially the same as in Barro and Furman (2018).

Table 5 evaluates the crowding-out effects for corporate and passthrough businesses when the long-run required return increases by fifteen basis points post-TCJA. The increase in r^k raises the user cost of capital and therefore dampens the productivity effects of TCJA. The crowding-out effect is large in both the NGM and the NGMM. On the corporate side, it pushes down capital deepening from 8.7% to 7.1% in the NGM, whereas adding on maintenance cuts capital deepening from 4.6% to 3.1%. On the passthrough side, the effects are similar between the NGM and NGMM. That is because the tax change there is quite small. However, the crowding-out effect roughly doubles the decline in the capital-labor ratio for both models.

Aggregating the effects leads to a stark conclusion in the NGMM: TCJA has practically no effect on per capita output after accounting for an empirically realistic maintenance channel and crowding out. That is because layering in both maintenance and crowding out causes the productivity gain in the corporate sector to be relatively small, while crowding out makes the effect in the passthrough sector around the same order of magnitude but negative. By contrast, crowding out causes the NGM productivity to fall to about 0.76% from 1.24%, which is still higher than the predicted effect from the NGMM before accounting for crowding out. In levels, crowding out brings down both the NGM and NGMM productivity gains by around fifty basis points.

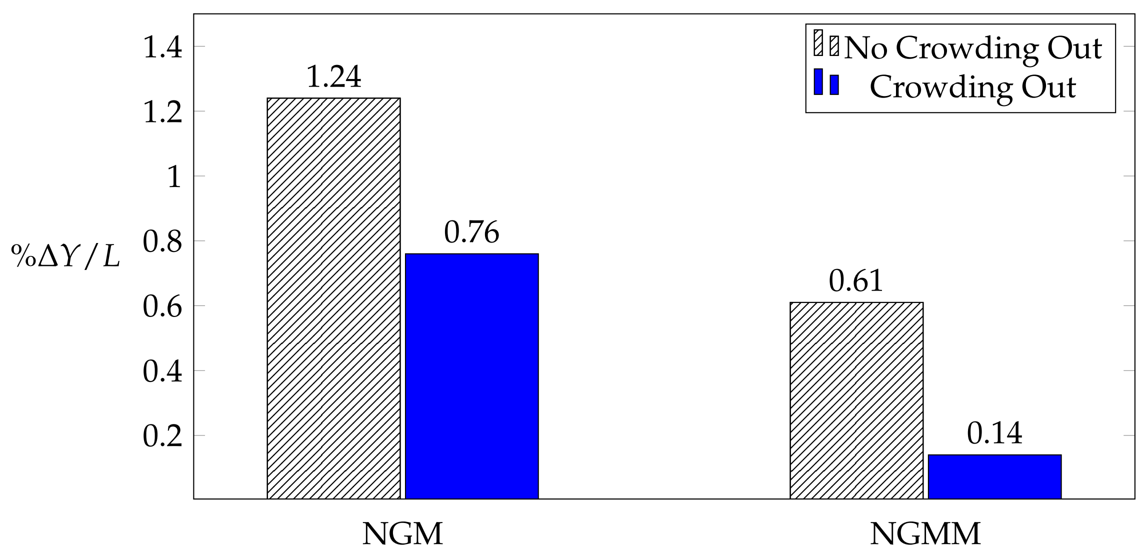


Figure 5: Increase in steady-state per capita output (productivity) in the NGM and NGMM. The blue bars correspond to the TCJA effect on productivity after accounting for crowding out.

11. There are small differences in the implied degree of crowding out between both models, but they are small enough that I simply apply the same estimate to both.

Recall that two factors make both the maintenance and crowding out channels more modest than they would otherwise be. First, the maintenance demand function is set such that $\gamma = 0.042$. If we used freight rail as a guide instead of the SOI, this parameter would be about three times larger, which would lead to a larger decline in the effect of TCJA and perhaps even make its effect on growth negative after considering financing concerns. Second, the JCT static score is on the lower end of the cost of TCJA. If we used a larger estimate, then the crowding out effect may even make the net impact of TCJA on growth negative in the long run.

Dynamic Effects of Tax Policy & Empirical Tax Policy Analysis

With intuition about the long run established, it is easier to now consider the short run. The short-run analysis is important because it helps facilitate a comparison between the effects of TCJA in this model and other leading estimates, while also shedding light on the informativeness of standard empirical tax policy analysis. Turning on adjustment costs, I plot a perfect foresight simulation of maintenance and investment in the NGMM and the NGM in Figure 6. Maintenance in the NGMM declines by 20%. Investment in the NGMM is substantially more elastic than investment in the NGM; its peak elasticity response is three times larger.[12] The empirical evidence on the input substitution effect and the tax shield effect therefore suggest a very different outcome for both investment and maintenance flows than the typical model would suggest.

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

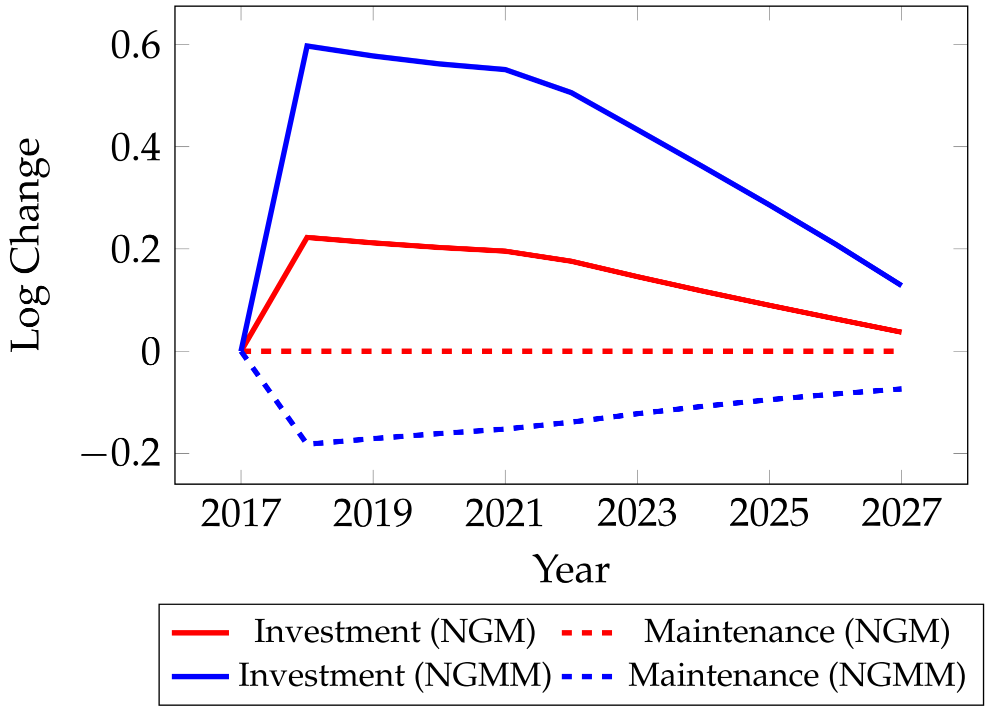


Figure 6: Dynamic responses of corporate maintenance and investment in the NGM and NGMM given a sequence of tax rates from the 2017 Tax Cuts and Jobs Act. Here, the dynamic response is the log-difference from the initial 2017 steady state. The aggregates are weighted sums of maintenance and investment in individual capital types with weights given by capital shares.

In Figure 7, I plot the evolution of the capital-labor ratio from 2017-2030 for both the NGM and NGMM. 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 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 eventual 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 degree as the NGM in Figure 7.

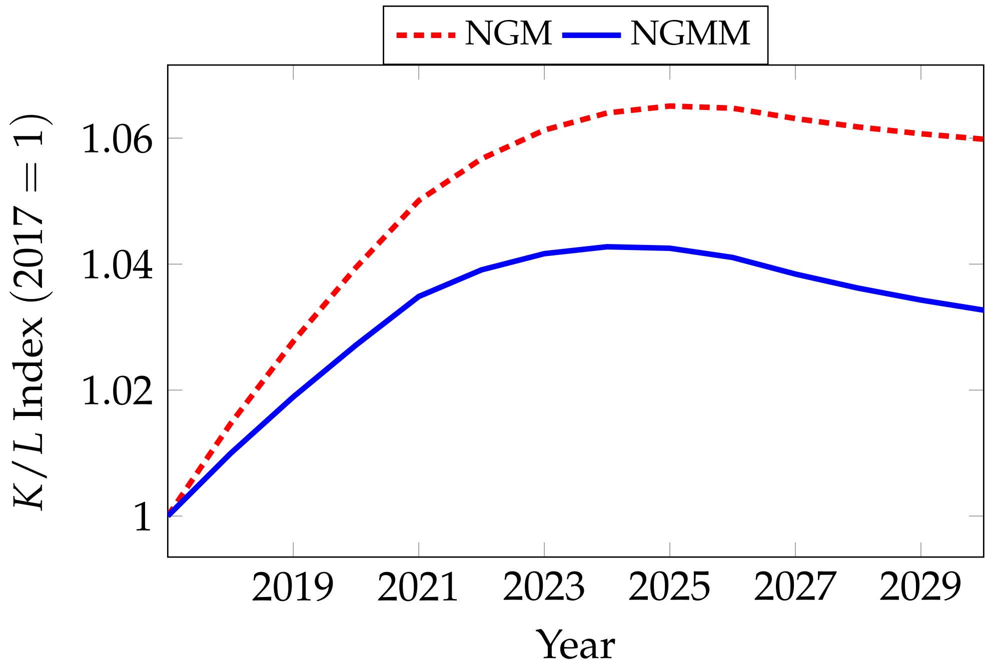


Figure 7: Capital-labor ratio in the NGM and NGMM given a sequence of tax rates from the 2017 Tax Cuts and Jobs Act.

These results point to a new difficulty in empirical public finance, which is typically informed by structural models. Empirical tax policy analysis typically focuses on the short run and uses estimates of the tax elasticity of investment to make an inference about the capital stock. Such analyses are universally informed by models of capital accumulation. Capital itself is unobserved, which means that economists must rely on a mapping from the demand for capital into the demand for its inputs, which requires a model like q-theory or the benchmark neoclassical 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 in the benchmark Hall and Jorgenson (1967) models. 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 Chodorow-Reich et al. (2023). Given the clear empirical significance of maintenance demand, solely looking at the tax elasticity of investment does not allow one to infer what is going on with the tax elasticity of capital. That accounts for a large amount of the disagreement between this paper's estimate of the capital stock following TCJA and others, like in Chodorow-Reich et al. (2023).

Because investigations of the tax elasticity of investment typically do not account for maintenance, the regression is misspecified. That is because the demand for investment depends on the demand for maintenance. This implies an omitted variable bias in standard regressions which biases downward estimated investment elasticities. Indeed, one can see this implicitly through Proposition 1, which suggests that the true exposure of investment to tax policy must account for substitution between maintenance induced by tax policy. The insight is analogous to the lesson of Goolsbee (1998a), which emphasizes that an underlying model of a perfectly competitive capital goods market leads to an underestimate of the investment demand elasticity if the supply of equipment is not perfectly competitive. 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.

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 D and give a short description here instead. There is no uncertainty. Time is infinite and runs from $t = 0, \dots, \infty$. 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 D.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 8 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 8 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.

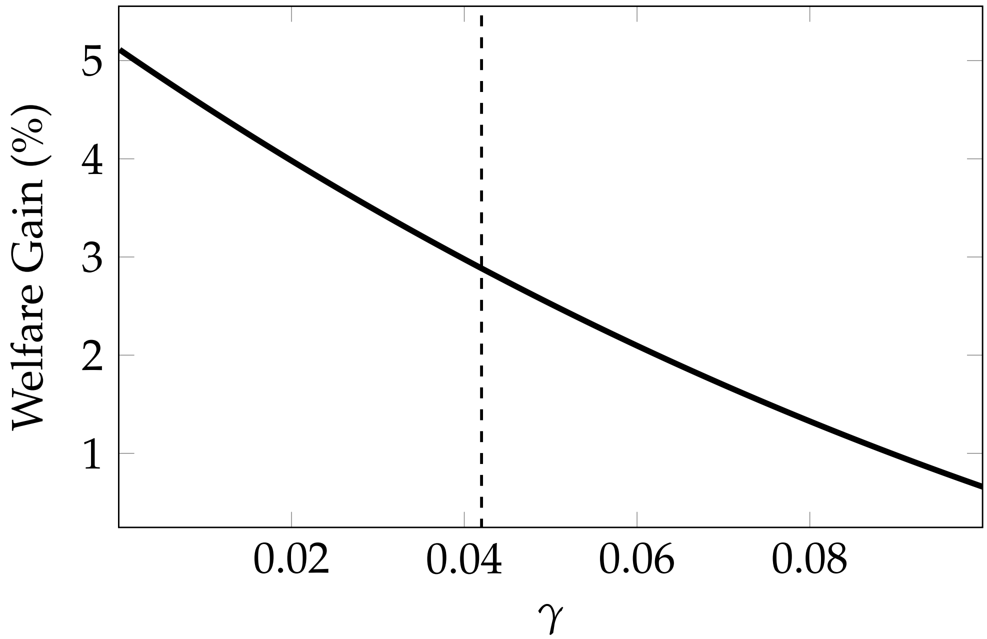


Figure 8: Welfare gain from cutting capital taxes to zero as a function of the maintenance level parameter γ.

6 Concluding Remarks

In this paper, I discuss the theoretical, empirical, and quantitative relevance of physical capital maintenance behavior around 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. 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.

Positive and elastic maintenance demand raises troubling questions for standard approaches to capital theory and measurement. 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). In recent years, this issue has become particularly salient for many types of intangible capital (Peters and Taylor 2017; Haskel and Westlake 2018; McGrattan 2020). A differentially taxed secondary input for physical capital production implies that measurement issues are perhaps as abundant for physical capital production as they are for intangibles. This finding raises a host of difficult questions far beyond the issues discussed in this paper around tax policy counterfactuals. Indeed, practically any researcher who relies on proper measurement of the capital stock and the cost of capital must consider the extent to which their question is contaminated by maintenance, which extends from growth accounting to the labor share and beyond.

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.

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Appendices

A Data

A.1 Freight Rail

Group	Variable	Mean	10th Percentile	Median	90th Percentile	Count
Freight Cars	Age	0.646	0.518	0.616	0.845	171
	$\log X_{i,j,t}$	9.141	5.539	10.327	11.828	171
	$m_{i,j,t}$	0.222	0.079	0.158	0.454	171
	$P_{i,j,t}$	0.857	0.757	0.857	0.964	171
	$\log X_{i,j,t}$	11.462	10.135	11.655	12.745	171
	$x_{i,j,t}$	0.086	0.002	0.054	0.187	171
Locomotives	Age	0.692	0.593	0.661	0.806	171
	$\log X_{i,j,t}$	11.193	9.112	11.681	13.019	171
	$m_{i,j,t}$	0.169	0.080	0.140	0.296	171
	$P_{i,j,t}$	0.995	0.870	0.973	1.147	171
	$\log X_{i,j,t}$	11.736	10.145	12.112	13.113	171
	$x_{i,j,t}$	0.149	0.031	0.099	0.283	171
Common Variables	$\Delta \log \mathrm{TFP}_t$	0.007	-0.028	0.005	0.041	171
	$\Delta \log \mathrm{GDP}_t$	0.022	0.001	0.024	0.040	171
	$\Delta \log \mathrm{RCAFA}_t$	-0.742	-0.976	-0.727	-0.561	171
	Oil Shock	0.011	-0.224	0.023	0.165	171
	$1 - \tau_{i,t}$	0.929	0.870	0.923	0.991	171
	year	2011.246	2001.000	2011.000	2021.000	171

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

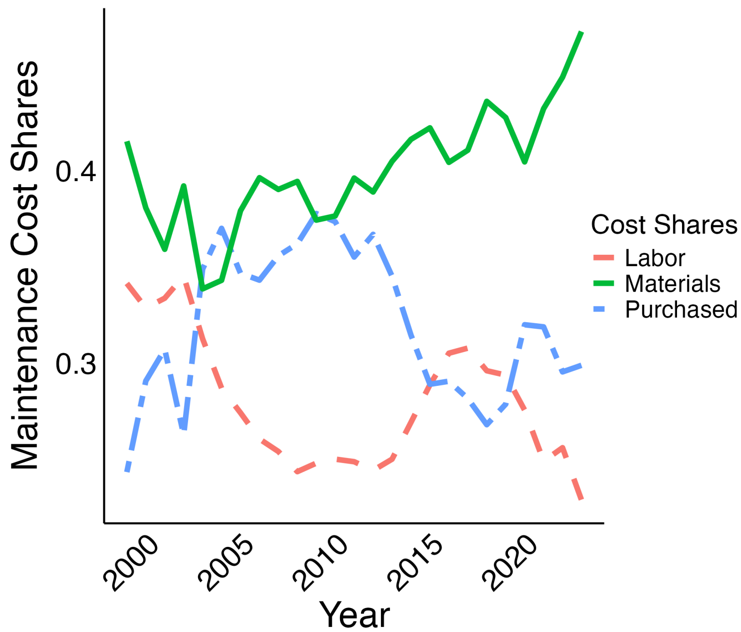


Figure A.1: Average costs shares for all maintenance costs from 1999-2023.

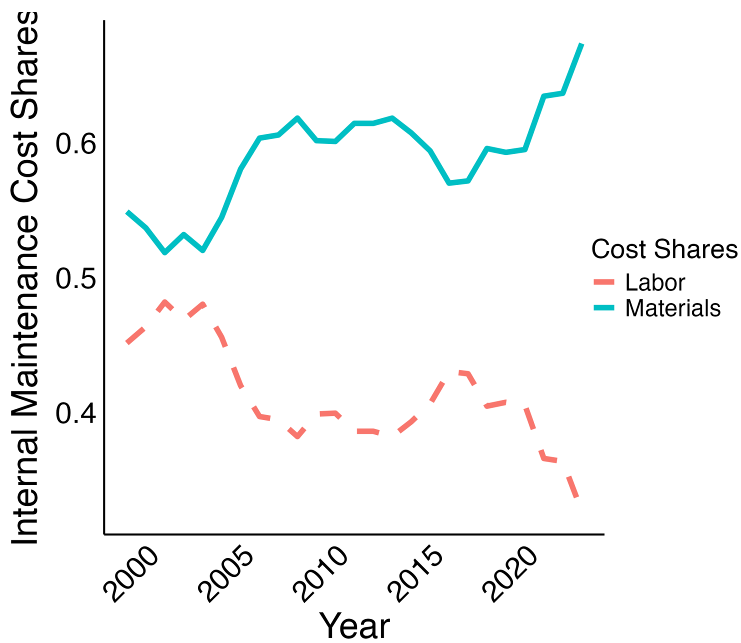


Figure A.2: Average share of internal maintenance costs for materials and labor by year from 1999-2023. Computed by adding up all labor maintenance costs and dividing by the sum of material and labor costs (and similarly for materials).

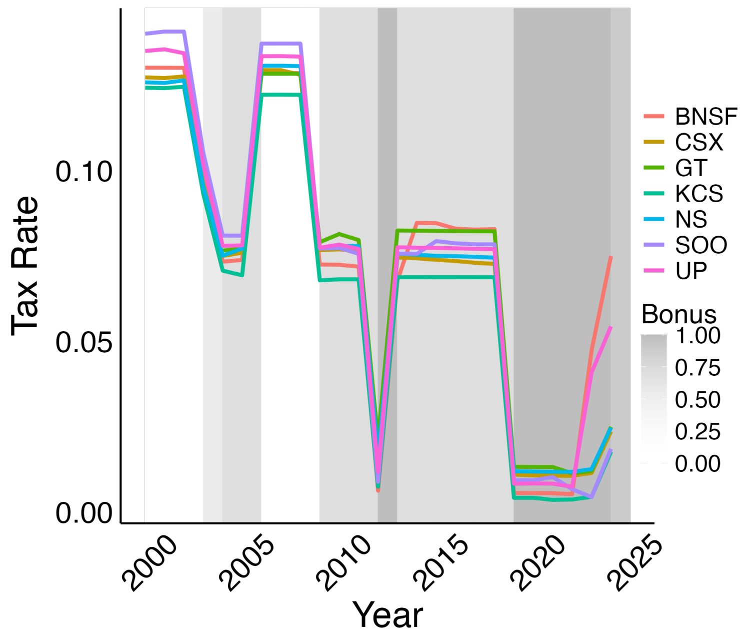
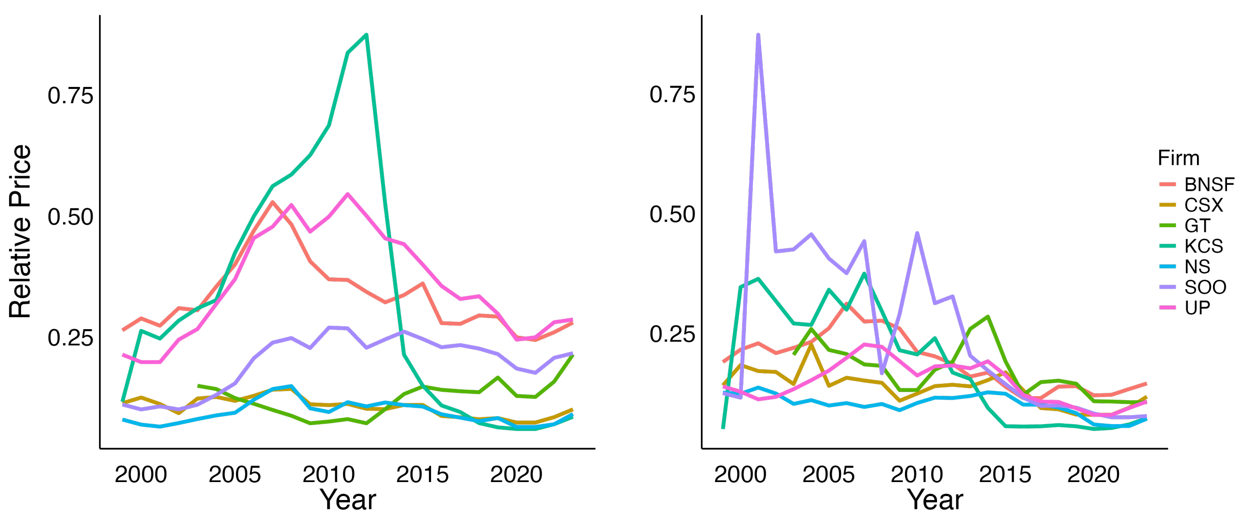


Figure A.3: Tax rates by Class I freight rail firm from 1999-2023. Tax rates are computed by taking a weighted average of state tax rates based on miles of trackage operated by firm.



(a) Freight Cars

(b) Locomotives

Figure A.4: The freight car maintenance rate (left) and locomotive maintenance rate (right).

A.2 SOI

I report summary statistics for the primary variables in the SOI in Table A2. 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 A2 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 A2: Summary statistics for the SOI.

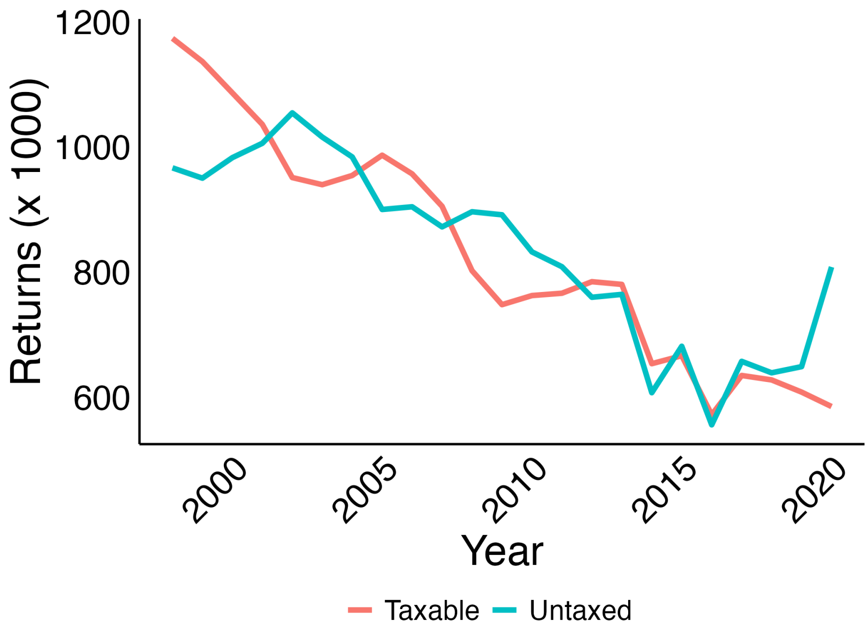


Figure A.5: Number of returns filed by year for taxable and untaxable firms.

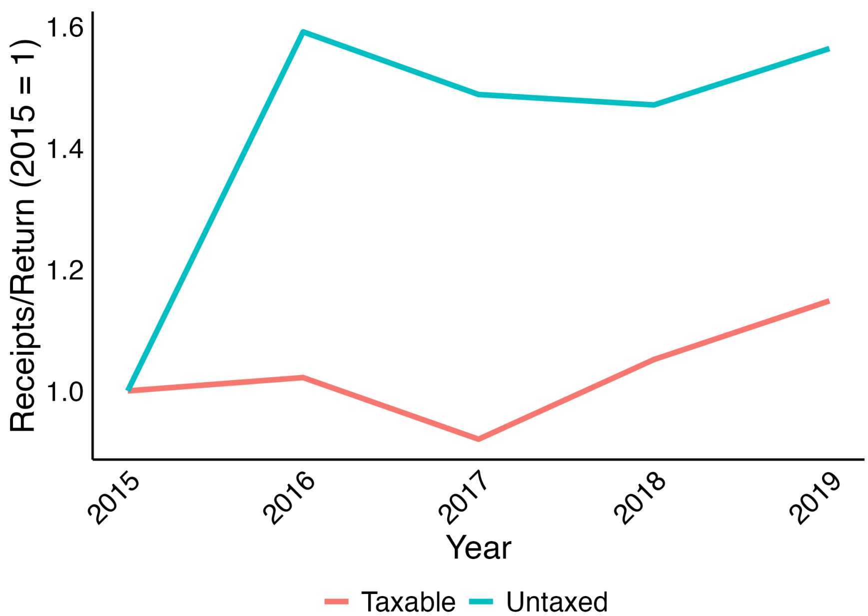


Figure A.6: Business receipts of taxable and untaxable firms.

A.3 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

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

where τ^c_t is the corporate tax rate, $\text{ITC}_{i,t}$ 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 $\text{ITC}_{i,t}$ 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.

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

$$\tilde{z}^a_{i,t} \begin{cases} \theta + (1-\theta_t) z^a_{i,t} & \text{if eligible} \\ z^a_{i,t} & \text{if ineligible,} \end{cases} \tag{A.2}$$

where $\tilde{z}^a_{i,t}$ takes the place of $z^a_{i,t}$ in equation A.1. 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.

B Additional Empirical Results

B.1 Linear-Linear Models

Freight Rail

	Dependent variable: $m_{i,j,t}$			
	(1)	(2)	(3)	(4)
$P_{i,j,t}$	-0.42**	-0.49***	-0.42***	-0.13
	(0.16)	(0.16)	(0.13)	(0.08)
Age		-0.50**	-0.47**	-0.24*
		(0.19)	(0.19)	(0.11)
$x_{i,j,t}$			0.22***	0.11
			(0.05)	(0.13)
$m_{i,j,t-1}$				0.70***
				(0.13)
N	342	342	342	328
R^2	0.448	0.560	0.605	0.835
AIC	-536.8	-612.3	-647.0	-894.8

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3: This table estimates regressions of the form $m_{i,j,t} = \alpha_i + T_t + \kappa_j + \beta P_{i,j,t} + \text{Controls}_t + \varepsilon_{i,j,t}$. Column 1 is the baseline regression of the maintenance rate on the relative price. Column 2 controls for the age of capital, where age is net capital stock scaled by gross capital stock. Column 3 adds a control for investment, while Column 4 adds a control for the lagged log maintenance rate. All regressions include firm, year, and capital type fixed effects. Standard errors are clustered by firm and capital type.

	Dependent variable: $m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$P_{i,j,t}$	-0.21			-0.44*	-0.56
	(0.22)			(0.21)	(0.34)
Pre-Tax $P_{i,j,t}$		-0.42**			
		(0.15)			
$1 - \tau_{i,t}$			-0.28***		
			(0.09)		
N	316	316	316	328	314
Industry Controls	Y	Y	Y	N	N
R^2	0.396	0.418	0.365	0.449	0.453
AIC	-488.2	-499.8	-472.2	-505.7	-476.3
Instrument	Oil	Tax Rate	Tax Rate	$P_{i,j,t-1}$	$P_{i,j,t-2}$
IV	Y	Y	N	Y	Y
F-test	15.7	30.5		1,214.6	486.2

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A4: Instrumental variables results for regressing the maintenance rate on a measure of the relative price. Columns 1-3 are of the form $m_{i,j,t} = \alpha_i + \kappa_j + \beta X_{i,j,t} + \text{Industry Controls}_t + \varepsilon_{i,j,t}$, where α_i is a firm fixed effect, κ_j is a type fixed effect, and X is some measure of the relative price. In Column 1, I use the Känzig (2021) oil news shock as an instrument for the after-tax relative price. In Column 2, I use the firm-level marginal tax rate on equipment as an instrument for the pre-tax relative price. Column 3 regresses the maintenance rate directly on the tax term $1 - \tau_{i,t}$. For each of these columns, the industry controls are the rail cost adjustment factor published by the Surface Transportation Board (STB), freight rail productivity growth from the STB, GDP growth, and a year trend. Columns 4 and 5 add a time fixed effect and do not use industry controls. Columns 4 and 5 use lags of the after-tax relative price as instruments. Every regression with instruments reports the Cragg-Donald F-statistic. Standard errors are clustered by firm and capital type.

SOI

The analogous linear-linear specification for the SOI is

$$m_{j,t} = \alpha_j + T_t + \beta \left(1 - \tau_{j,t}\right) + \text{Controls} + \epsilon_{j,t}, \tag{A.3}$$

where α_j is an industry fixed effect and T_t is a time fixed effect. Table A5 reports results. Here, the freight rail results are generally only borderline significant for the taxable firms and insignificant for the untaxable firm sample.

	Dependent variable: $m_{j,t}$					
	Taxable Firms			Untaxable Firms		
	(1)	(2)	(3)	(4)	(5)	(6)
$1-\tau_{j,t}$	-0.14*	-0.12*	-0.07*	0.03	0.02	0.01
	(0.07)	(0.07)	(0.04)	(0.11)	(0.12)	(0.08)
$x_{j,t}$		0.00**	0.00***		0.00**	0.00**
		(0.00)	(0.00)		(0.00)	(0.00)
$m_{j,t-1}$			0.46***			0.36***
			(0.06)			(0.07)
N	1071	1012	1005	1073	1012	1007
R^2	0.879	0.890	0.911	0.793	0.797	0.825
AIC	-6182.2	-5917.3	-6091.9	-5512.9	-5185.5	-5299.8

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A5: This table estimates regressions using (A.3). Column 1 is the baseline regression of the maintenance rate on the tax rate. Column 2 controls for the investment rate, while Column 4 adds a control for the lagged maintenance rate. The left panel is the SOI sample for firms with positive taxes and the right panel is for unprofitable firms which did not pay taxes. All regressions include industry and year fixed fixed effects. Standard errors are clustered by industry.

B.2 Regressions in Levels

Table A6 tests the maintenance elasticity in levels through the specification

$$\log M_{i,j,t} = \alpha_i + \kappa_j + T_t + \beta \log P_{i,j,t} + \text{Controls} + \varepsilon_{i,j,t}. \tag{A.4}$$

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 5. This is close to the size of the estimated price elasticity of investment in Zwick and Mahon (2017).

	Dependent variable: log $M_{i,j,t}$		
	(1)	(2)	(3)
log $P_{i,j,t}$	-0.70	-0.65	-0.49***
	(0.51)	(0.49)	(0.14)
log $X_{i,j,t}$		0.04	0.01
		(0.02)	(0.01)
log $M_{i,j,t-1}$			0.90***
			(0.02)
N	342	330	317
R^2	0.961	0.961	0.992
AIC	-10.4	-13.0	-502.4

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Results for estimating (A.4) with freight rail data. The second column adds a control for the real value of investment and the third controls for the lagged log level of real maintenance expenditures. Standard errors clustered by firm and capital type.

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
$1-\tau_{j,t}$	-1.29	2.87
	(1.26)	(2.53)
$\log M_{j,t-1}$	0.54	0.43
	(0.10)	(0.06)
N	1023	1021

Table A7: Results for estimating $\log M_{j,t} = \alpha_j + T_t + \beta(1-\tau_{j,t}) + \varepsilon_{j,t}$ with SOI data. The left panel is for taxable firms and the right panel is for untaxable firms. Standard errors clustered by industry.

B.3 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.[13] 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

$$\log m_{i,j,t+h} = \alpha_i + T_t + \kappa_j + \beta_h \log P_{i,j,t} + \epsilon_{i,j,t} \tag{A.5}$$

for the freight rail data and

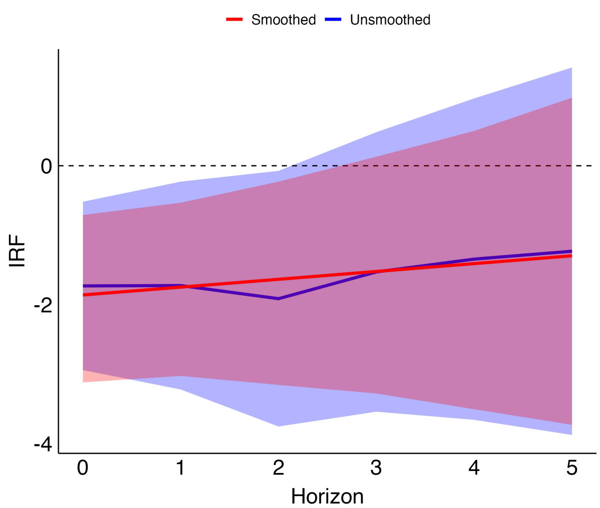
$$\log m_{i,t+h} = \alpha_i + T_t + \beta_h \log(1-\tau_{i,t}) + \epsilon_{i,j,t} \tag{A.6}$$

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 A.7 plots the results for

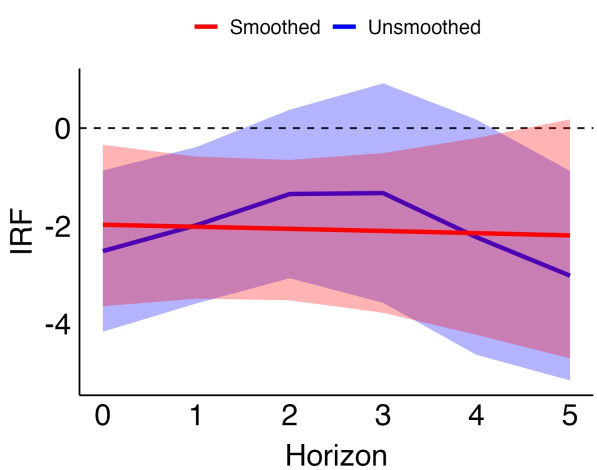
13. Figure A.8 in the appendix plots the sequence of coefficient from a regression of the relative price of maintenance on its lags for freight rail and tax policy.

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.

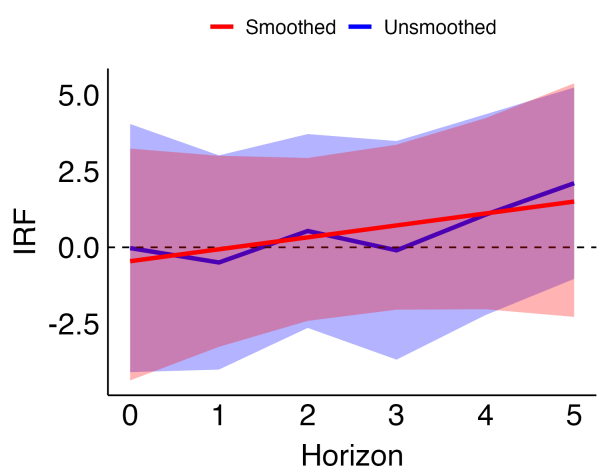
For both the freight rail and SOI data, the coefficient is stable and significant across multiple years. In particular, taxable firms in the SOI show no decline in the maintenance rate five years out from a shock, whereas there is some attenuation from freight rail. At the same time, the statistical 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.



(a) Freight Rail IRF



(b) SOI: Taxable Firm IRF



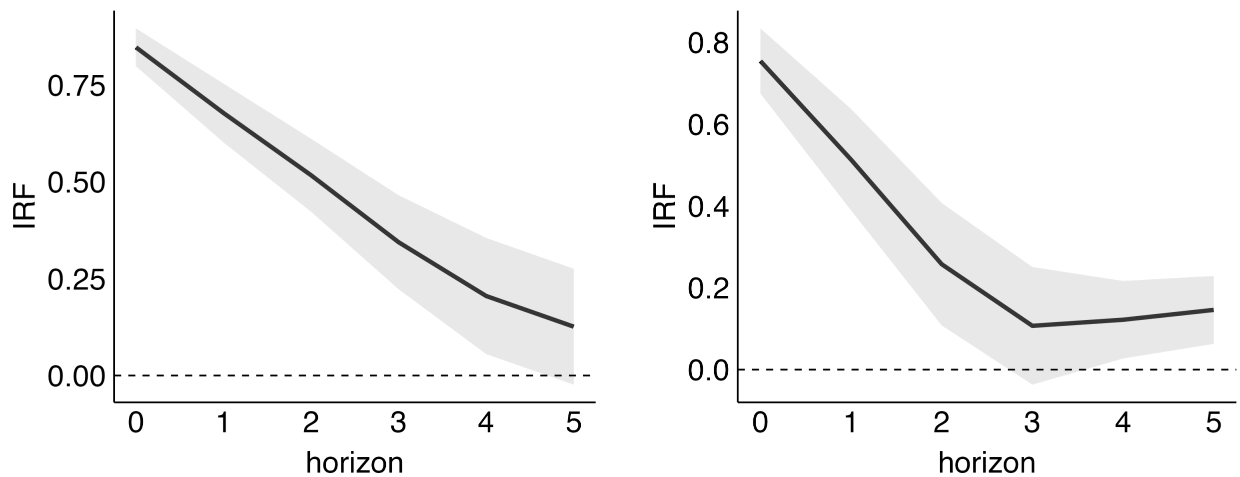
(c) SOI: Untaxed Firm IRF

Figure A.7: 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 $h = 0, \ldots, 5$.

Figure A.8 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 A.8: 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.

B.4 Physical Capital Stock

In this subsection, I construct a measure of the capital stock which is purely physical rather than in dollar value. The stock of locomotive capital is measure in units of horsepower, while it is measured in tons of capacity for freight cars. Both figures come from Schedule 710 of the R-1 report. In this case, I also measure the investment rate in units of capacity. For example, if CSX added 10,000 horsepower to their fleet on an existing capacity of 100,000 horsepower, they would have an investment rate of 10%. In contrast to the investment rate in the main regressions, this investment rate is a *net* investment rate. Table A8 reports summary statistics for the capital stock (in levels), the investment rate, and the new version of the maintenance rate. Note that the units are not comparable across locomotives and freight cars and that the maintenance rates here are lower than when the denominator is the book value of the capital stock.

Group	Variable	Mean	10th Percentile	Median	90th Percentile	Count
Freight Cars	$x_{i,j,t}$	-0.018	-0.084	-0.024	0.044	171
	Capital Stock (tons)	5328377.786	1210341.400	5788291.800	9545984.000	171
	$m_{i,j,t}$	0.026	0.015	0.024	0.041	171
Locomotives	$x_{i,j,t}$	0.018	-0.059	0.007	0.090	171
	Capital Stock (HP)	12525383.626	1398800.000	12119344.000	30316556.000	171
	$m_{i,j,t}$	0.019	0.013	0.018	0.028	171

Table A8: Summary statistics for alternative measures of the capital stock, investment rate, and maintenance rate from R-1 financial statements. The alternative measure is in physical capacity of each capital type.

	Dependent variable: $\log m_{i,j,t}$			
	(1)	(2)	(3)	(4)
$\log P_{i,j,t}$	-1.76**	-1.75**	-1.71**	-0.32*
	(0.62)	(0.60)	(0.58)	(0.15)
Age		0.11	0.09	-0.01
		(0.32)	(0.29)	(0.07)
$x_{i,j,t}$			1.13***	0.20**
			(0.22)	(0.09)
$\log m_{i,j,t-1}$				0.91***
				(0.02)
N	326	326	324	308
R^2	0.482	0.483	0.523	0.926
AIC	168.8	170.3	146.9	-426.0

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A9: This table estimates regressions using (6) using the definition of capital in terms of its physical capacity. Column 1 is the baseline regression of log maintenance rates on log relative prices. Column 2 controls for the age of capital, where age is net capital stock scaled by gross capital stock. Column 3 adds a control for investment, while Column 4 adds a control for the lagged log maintenance rate. All regressions include firm, year, and capital type fixed effects. Standard errors are clustered by firm and capital type.

	Dependent variable: $m_{i,j,t}$			
	(1)	(2)	(3)	(4)
$P_{i,j,t}$	-0.04**	-0.04***	-0.04***	-0.01
	(0.01)	(0.01)	(0.01)	(0.00)
Age		0.00	0.00	0.00
		(0.01)	(0.01)	(0.00)
$x_{i,j,t}$			0.03***	0.00
			(0.01)	(0.00)
$m_{i,j,t-1}$				0.90***
				(0.02)
N	326	326	324	308
R^2	0.479	0.479	0.522	0.912
AIC	-2250.3	-2248.8	-2258.5	-2656.0

* p $<$ 0.1, ** p $<$ 0.05, *** p $<$ 0.01

Table A10: This table estimates regressions of the form $m_{i,j,t} = \alpha_i + T_t + \kappa_j + \beta P_{i,j,t} + \text{Controls}_t + \varepsilon_{i,j,t}$. Here, I use the definition of capital in terms of its physical capacity. Column 1 is the baseline regression of the maintenance rate on the relative price. Column 2 controls for the age of capital, where age is net capital stock scaled by gross capital stock. Column 3 adds a control for investment, while Column 4 adds a control for the lagged log maintenance rate. All regressions include firm, year, and capital type fixed effects. Standard errors are clustered by firm and capital type.

	Dependent variable: $\log m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$\log P_{i,j,t}$	-1.76***			-2.22**	-2.90*
	(0.45)			(0.79)	(1.00)
Pre-Tax $\log P_{i,j,t}$		-0.69***			
		(0.46)			
$1 - \tau_{i,t}$			-0.49***		
			(0.35)		
N	312	312	312	326	312
Industry Controls	Y	Y	Y	N	N
R^2	0.427	0.440	0.407	0.480	0.463
AIC	157.0	149.6	167.7	170.2	175.9
Instrument	Oil	Tax Rate	Tax Rate	$\log P_{i,j,t-1}$	$\log P_{i,j,t-2}$
IV	Y	Y	N	Y	Y
F-test	16.8	30.9		1,281.5	456.2

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A11: Instrumental variables results for regressing the maintenance rate on a measure of the relative price. Columns 1-3 are of the form $\log m_{i,j,t} = \alpha_i + \kappa_j + \beta X_{i,j,t} + \text{Industry Controls}_t + \varepsilon_{i,j,t}$, where α_i is a firm fixed effect, κ_j is a type fixed effect, and X is some measure of the relative price. Here, I use the definition of capital in terms of its physical capacity. In Column 1, I use the Känzig (2021) oil news shock as an instrument for the after-tax relative price. In Column 2, I use the firm-level marginal tax rate on equipment as an instrument for the pre-tax relative price. Column 3 regresses the maintenance rate directly on the tax term $1 - \tau_{i,t}$. For each of these columns, the industry controls are the rail cost adjustment factor published by the Surface Transportation Board (STB), freight rail productivity growth from the STB, GDP growth, and a year trend. Columns 4 and 5 add a time fixed effect and do not use industry controls. Columns 4 and 5 use lags of the after-tax relative price as instruments. Every regression with instruments reports the Cragg-Donald F-statistic. Standard errors are clustered by firm and capital type.

	Dependent variable: $m_{i,j,t}$				
	(1)	(2)	(3)	(4)	(5)
$P_{i,j,t}$	-0.05***			-0.05**	-0.06**
	(0.01)			(0.02)	(0.02)
Pre-Tax $P_{i,j,t}$		-0.02			
		(0.01)			
$1 - \tau_{i,t}$			-0.01		
			(0.01)		
N	312	312	312	326	312
Industry Controls	Y	Y	Y	N	N
R^2	0.417	0.438	0.413	0.478	0.471
AIC	-2155.4	-2166.3	-2152.8	-2250.0	-2142.8
Instrument	Oil	Tax Rate	Tax Rate	$P_{i,j,t-1}$	$P_{i,j,t-2}$
IV	Y	Y	N	Y	Y
F-test	15.9	38.5		1,215.0	488.1

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A12: Instrumental variables results for regressing the maintenance rate on a measure of the relative price. Columns 1-3 are of the form $m_{i,j,t} = \alpha_i + \kappa_j + \beta X_{i,j,t} + \text{Industry Controls}_t + \varepsilon_{i,j,t}$, where α_i is a firm fixed effect, κ_j is a type fixed effect, and X is some measure of the relative price. Here, I use the definition of capital in terms of its physical capacity. In Column 1, I use the Känzig (2021) oil news shock as an instrument for the after-tax relative price. In Column 2, I use the firm-level marginal tax rate on equipment as an instrument for the pre-tax relative price. Column 3 regresses the maintenance rate directly on the tax term $1 - \tau_{i,t}$. For each of these columns, the industry controls are the rail cost adjustment factor published by the Surface Transportation Board (STB), freight rail productivity growth from the STB, GDP growth, and a year trend. Columns 4 and 5 add a time fixed effect and do not use industry controls. Columns 4 and 5 use lags of the after-tax relative price as instruments. Every regression with instruments reports the Cragg-Donald F-statistic. Standard errors are clustered by firm and capital type.

B.5 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 $K_{t+1} =$

$K_t(1-\delta)+X_t$.[14] 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 4.2% when $P = 1$. I also set $\delta = 11\%$ in line with the estimate for rolling stock in Baldwin, Liu, and Tanguay (2015).

Figure A.9 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 A.10 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.

14. 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.

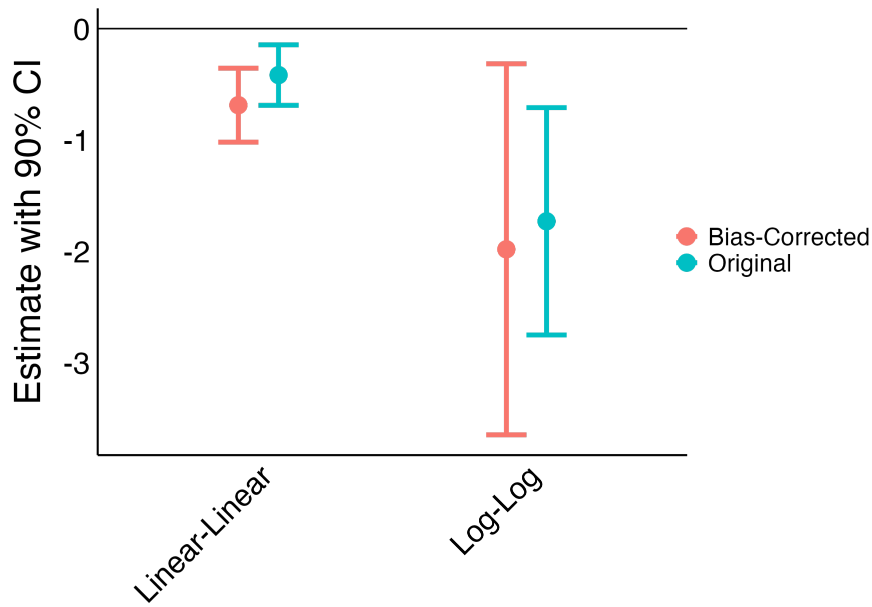
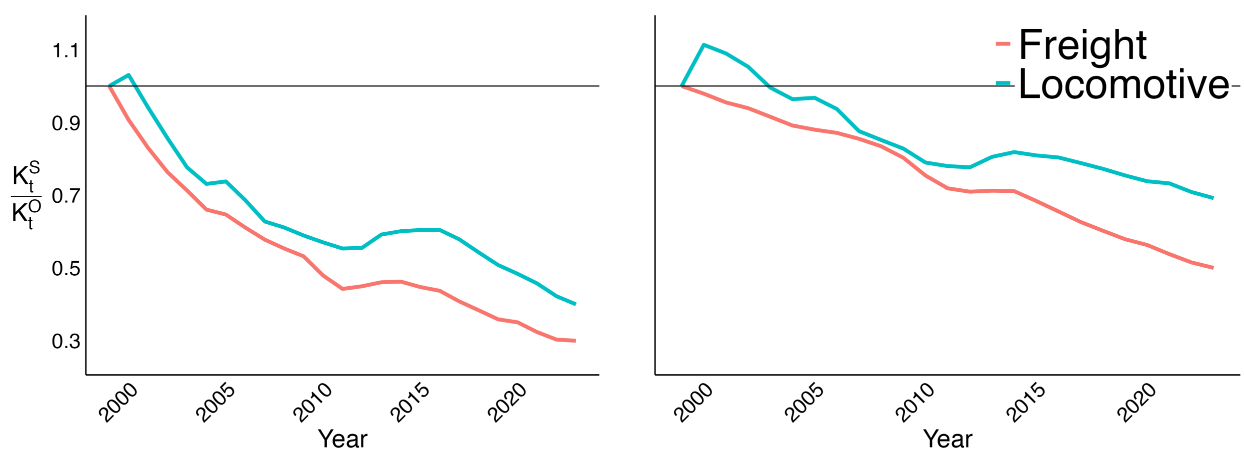


Figure A.9: Bias-corrected coefficients compared to baseline estimates. The bias correction comes from creating a synthetic capital stock given each $h(m)$ and iterating over parameters until the estimates converge.



(a) Linear Demand

(b) Constant Elasticity Demand

Figure A.10: 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.

B.6 Simultaneous Determination of Maintenance and Investment

A significant source of concern is that maintenance and investment are simultaneously determined by the relative price of maintenance to investment. In the model, maintenance decisions are independent of investment decisions, but investment decisions depend on maintenance decisions. However, this is only true under a particular type of capital adjustment costs. To address some of the potential issues there, I employ the Three-Stage Least Squares (3SLS) estimation method to account for potential correlations across the error terms in different equations using the freight rail data. The system of equations estimated by 3SLS is specified as follows:

$$g(m_{i,j,t}) = \alpha_i + \kappa_j + T_t + \beta_1 f\left(P_{i,j,t}\right) + \varepsilon_{1,i,j,t} \tag{A.7}$$

$$g(x_{i,j,t}) = \alpha_i + \kappa_j + T_t + \beta_2 f\left(P_{i,j,t}\right) + \varepsilon_{2,i,j,t} \tag{A.8}$$

where g is some transformation of the maintenance or investment rate (linear or log), f is a similar transformation of the relative price, α_i is a firm fixed effect, κ_j is a capital type fixed effect, and T_t is a time fixed effect. I instrument for investment with lagged maintenance rate and for maintenance with the lagged investment rate.

	Linear-Linear		Log-Log	
	$m_{i,j,t}$	$x_{i,j,t}$	$\log m_{i,j,t}$	$\log x_{i,j,t}$
$P_{i,j,t}$	-0.41***	-0.25		
	(0.15)	(0.20)		
$\log P_{i,j,t}$			-1.88	-7.07
			(0.59)	(1.61)
N	626		626	

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A13: 3SLS estimates of the system in (A.7)-(A.8). I instrument for maintenance with lagged investment and for investment with lagged maintenance.

Table A13 presents results for both the linear-linear and the log-log models. The coefficient on the relative price terms are similar to the OLS and 2SLS estimates for maintenance in Columns 1 and 3. However, the behavior for investment does not accord with theory. In the linear-linear model, investment does not have a statistically significant response to a relative price change, but the direction is qualitatively wrong. In the log-log model, the investment rate response in the wrong way but this time with a statistically significant and large response.

B.7 An Alternative Measure of the SOI Maintenance Rate

The SOI maintenance rate is imperfectly constructed. In the main text, it is defined as $m_{j,t} = M_{j,t}/K_{j,t}$, where $K_{j,t}$ is end of year book capital. The problem is that the SOI is a repeated cross-section with firms that change from year to year and so lagged book capital for taxable firms is not necessarily representative of lagged book capital for firms that are currently taxable. This subsection re-estimates the regression equation (7) in Table A14 using lagged book capital as the denominator. The results are substantively similar for the coefficient on maintenance. Indeed, the maintenance demand elasticity is considerably larger here than in the main text for taxable firms, while untaxable firms continue to show no response to tax policy.

	Dependent variable: $\log m_{j,t}$					
	Taxable Firms			Untaxable Firms		
	(1)	(2)	(3)	(4)	(5)	(6)
$\log(1-\tau_{j,t})$	-4.27***	-2.87**	-2.22**	0.35	0.52	0.53
	(1.31)	(1.16)	(1.02)	(2.71)	(2.37)	(2.30)
$x_{j,t}$		0.27***	0.29***		0.32***	0.33***
		(0.04)	(0.04)		(0.02)	(0.02)
$\log m_{j,t-1}$			0.14**			0.09*
			(0.06)			(0.05)
N	1021	1014	953	1021	1012	951
R^2	0.745	0.847	0.853	0.584	0.728	0.738
AIC	1062.4	522.8	464.3	1968.2	1525.4	1427.9

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A15: 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.

B.8 SOI: All Firm Sample

I report regression results for all firms in the SOI in Table A16. The left panel is for the log-log specification and the right panel is for the linear-linear specification.

	Dependent variable:					
	$\log m_{j,t}$			$m_{j,t}$		
	(1)	(2)	(3)	(4)	(5)	(6)
$\log(1-\tau_{j,t})$	-2.36*	-2.17*	-1.01*			
	(1.27)	(1.18)	(0.59)			
$x_{j,t}$		-0.12**	-0.17***		-0.01**	-0.01***
		(0.05)	(0.04)		(0.00)	(0.00)
$\log m_{j,t-1}$			0.61***			
			(0.10)			
$1-\tau_{j,t}$				-0.09	-0.07	-0.03
				(0.06)	(0.06)	(0.02)
$m_{j,t-1}$						0.70***
						(0.03)
Num.Obs.	1117	1066	1059	1117	1066	1059
$R^2$2	0.894	0.901	0.940	0.930	0.934	0.968
AIC	-103.7	-153.4	-679.4	-7213.6	-6922.6	-7638.0

Table A16: Regression results for the log-log specification and the linear-linear specification using the SOI sample for all firms. The left panel is the log-log specification and the right panel is the linear-linear specification. Standard errors are clustered by BEA industry. The investment rate is net investment scaled by the net capital stock.

B.9 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 A.1 plots the share of externally purchased services in total maintenance expenditures.

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 downward. The easiest test for this is to regress the share of external maintenance on tax policy using the freight rail data. Table A17 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)
$\tau_{i,t}$	-0.28*	-0.05
	(0.16)	(0.08)
External Service Share$_{i,j,t-1}$		0.93***
		0.03
N	315	312
Industry Controls	X	X
FE: firm	X	X
FE: type	X	X

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A17: 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. There are firm and capital type fixed effects and standard errors are clustered by firm and capital type.

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.[15] 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.

C Quantitative Model

C.1 Calibration

The majority of the calibrated parameters are in Table A18, 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.

15. 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 $(0.4 \times 0.1 + 0.6 \times 0.05)/0.5 = 0.68$.

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 A18: 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 A.11 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

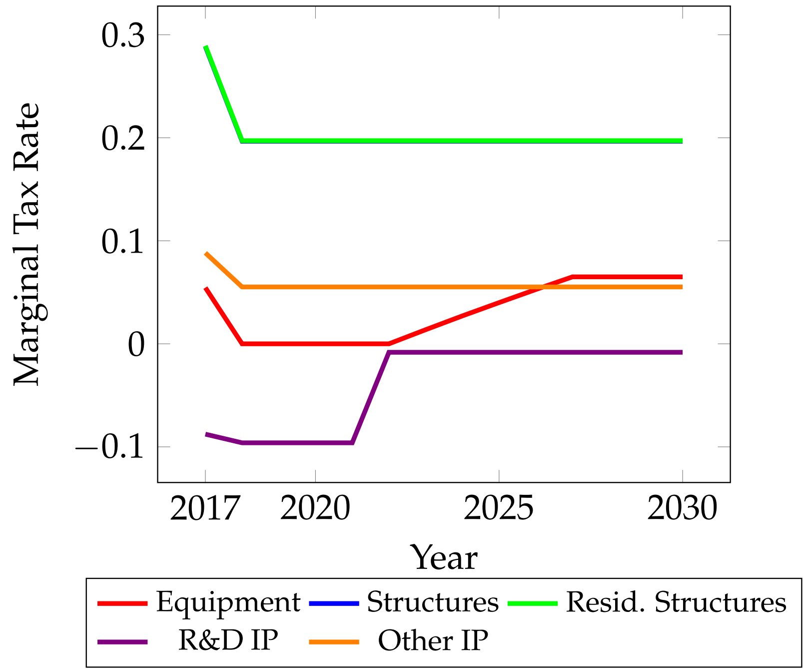


Figure A.11: Marginal tax rates by asset.

capital). The tax rate I plot is the marginal effective tax rate defined as

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

Table A19 tabulates the marginal tax rates on each capital type for the steady state comparison exercise.

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

Capital Type	**Corporate** Initial	Final	**Passthrough** 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 A19: 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.

0.1324, compared to 0.1348 in the long-run comparison. Table A20 presents the rest of the parameters.

Capital Type	**NGM δ_i**	**NGMM δ_i (Passthrough)**	**NGMM 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 A20: 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).

C.2 Investment Adjustment Costs

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

$$K_{i,j,t+1} = K_{i,j,t}\left(1 - \delta_i + h(m_{i,j,t})\right) + X_{i,j,t}\left(1 - \frac{b}{2}\left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1\right)^2\right), \tag{A.9}$$

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

$$m_{i,j,t} = \gamma\left(\frac{1 - \tau^c_{j,t}}{\lambda_{i,j,t}}\right)^{-\omega} \tag{A.10}$$

$$\begin{aligned} 1 - \tau^x_{i,t} = {} & \lambda_{i,j,t}\left(1 - b\left(\frac{1}{2}\left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1\right)^2 + \left(\frac{X_{i,j,t}}{X_{i,j,t-1}} - 1\right)\frac{X_{i,j,t}}{X_{i,j,t-1}}\right)\right) \\ & + \frac{\lambda_{i,j,t+1} b}{1 + r^k}\left(\frac{X_{i,j,t+1}}{X_{i,j,t}} - 1\right)\left(\frac{X_{i,j,t+1}}{X_{i,j,t}}\right)^2 \end{aligned} \tag{A.11}$$

$$\lambda_{i,j,t} = \frac{1}{1 + r^k}\left\{\left(1 - \tau^c_{i,j,t+1}\right)\alpha_{i,j}\frac{y_{i,j,t+1}}{K_{i,j,t+1}} + \lambda_{i,j,t+1}\left(1 - \delta_i - \mathbb{1}_{\{NGMM\}}\frac{\gamma^{1/\omega}}{1 - \omega}m^{1-1/\omega}_{i,j,t+1}\right)\right\} \tag{A.12}$$

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 7 in Figures A.12 and A.13. 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.[16]

16. 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.

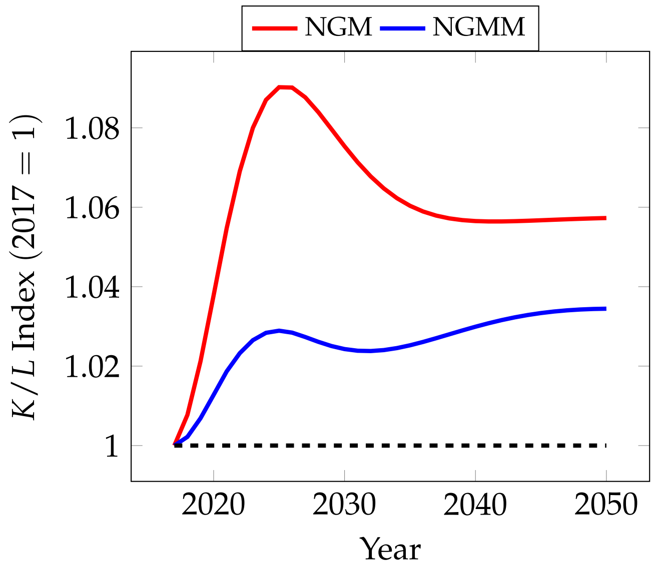


Figure A.12: Capital Accumulation with investment adjustment costs.

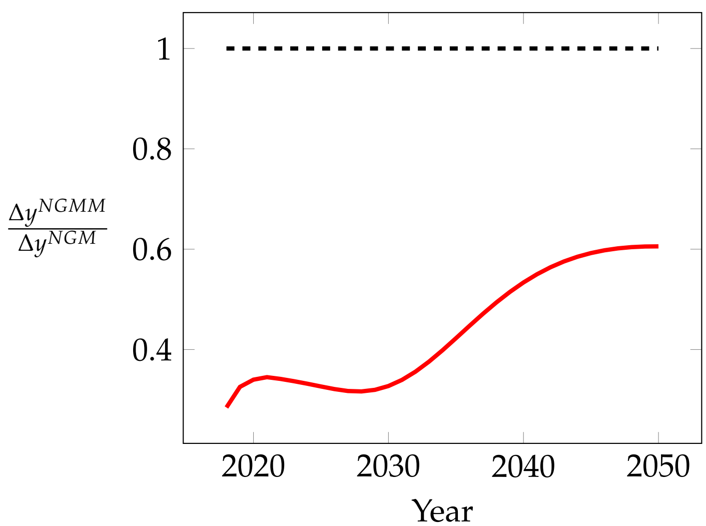


Figure A.13: Relative Output Growth with investment adjustment costs.

D 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

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

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

$$\sum_{t=0}^{\infty} q_t d_t = \sum_{i=1}^{N} K_{i,0} \Big[(1 - \tau_0^c) \left(F_{K_{i,0}} - m_{i,0} \right) + \left(1 - \tau_{i,0}^x\right) (1 - \delta_i + h(m_{i,0})) \Big]. \tag{A.13}$$

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

$$\sum_{t=0}^{\infty} \beta^t u(c_t, n_t). \tag{A.14}$$

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

$$c_t + p_t s_{t+1} + \frac{b_{t+1}}{1+r_t} = (1-\tau_t^h) w_t n_t + p_t s_t + d_t s_t + b_t, \tag{A.15}$$

where $s_0 = 1$ and initial bonds are b_0. Choosing sequences of consumption, labor, and shares of the firm to maximize (A.14) subject to (A.15) and a transversality condition given by $\lim_{T\to\infty} q_{t+1} b_{T+1} \geq$ yields first-order conditions given by

$$-u'(n_t) = (1-\tau_t^h) w_t u'(c_t) \tag{A.16}$$

$$u'(c_t) = \beta u'(c_{t+1})(1+r_t) \tag{A.17}$$

$$1 + r_{t+1} = \frac{p_{t+1} + d_{t+1}}{p_t}. \tag{A.18}$$

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.*,

$$p_t = \sum_{s=0}^{\infty} \frac{q_{t+1+s}}{q_t} d_{t+1+s}. \tag{A.19}$$

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

$$\sum_{t=0}^{\infty} q_t \left[c_t - \left(1 - \tau_t^h\right) w_t n_t \right] \leq p_0 s_0 + d_0 s_0 + b_0 \tag{A.20}$$

Substituting for the price of the stock and applying (A.13), we arrive at

$$\sum_{t=0}^{\infty} q_t \left[c_t - \left(1 - \tau_t^h\right) w_t h_t \right] \leq W_0, \tag{A.21}$$

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

$$c_t + G_t + \sum_{i=1}^{N} (X_{i,t} + M_{i,t}) = Y_t, \tag{A.22}$$

where $Y_t \equiv F(K_{1,t}, \ldots, K_{N,t}, n_t)$. 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* $t = 1, \ldots, \infty$.

D.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:

$$\sum_{t=0}^{\infty} \beta^t \left[u'(c_t)c_t + u'(n_t)n_t \right] \geq u'(c_0)W_0 \tag{A.23}$$

Proposition 3. *Any implementable allocation satisfies* (A.22) *and* (A.23).

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.23) and define the transformed utility function

$$V(c_t, n_t, \Phi) = u(c_t, n_t) + \Phi \left(u'(c_t)c_t + u'(n_t)n_t \right). \tag{A.24}$$

Now, with the Lagrangian

$$\begin{aligned}\mathcal{J} = \sum_{t=0}^{\infty} \beta^t \Bigg\{ & V(c_t, n_t, \Phi) \\ & + \theta_t \left[F(K_{1,t}, \dots, K_{N,t}, n_t) + \sum_{i=1}^{N} \left[(1 - \delta_i(m_{i,t}))K_{i,t} - K_{i,t+1} - M_{i,t} \right] - G_t - c_t \right] \Bigg\} \\ & - \Phi u'(c_0) W_0 \end{aligned} \tag{A.25}$$

and the first-order conditions to (A.25), we can arrive immediately at our main result for this subsection.

D.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.25) are:

$$V'(c_t) = \beta V'(c_{t+1}) \left(F_{K_{i,t+1}} + 1 - \delta + h(m_{i,t+1}) - h'(m_{i,t+1}) m_{i,t+1} \right) \quad \text{for } i = 1, \dots, N \tag{A.26}$$

$$V'(n_t) = -V'(c_t) F_{n_t} \tag{A.27}$$

$$h'(m_{i,t+1}) = 1 \quad \text{for } i = 1, \dots, N \tag{A.28}$$

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

$$1 = \beta \left(F_{K_i} + 1 - \delta + h(m_i) - h'(m_i) m_i \right). \tag{A.29}$$

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

$$1 = \beta \left[\frac{1-\tau^c}{1-\tau_i^x} F_K + 1 - \delta + h(m_i) - h'(m_i) m_i \right] \quad \text{for } i = 1, \ldots, N \tag{A.30}$$

Clearly, (A.29) and (A.30) 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. $\square$