Capital Maintenance and Differential Capital Taxation

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Tax-deductible capital maintenance attenuates the effect of capital tax policy on capital accumulation. The strength of this channel is mediated by the effect of maintenance on depreciation, which naturally varies by capital type. Although standard macroeconomic analyses of tax policy ignore this channel, I show that this omission is positively and normatively non-trivial. Theoretically, I show that that as long as maintenance is tax deductible and depreciation technologies vary by capital type so that maintenance demand varies as well, uniform tax changes are non-neutral. Consequently, optimal policy features larger tax distortions on capital types with higher maintenance elasticities of depreciation and higher demand for maintenance. Quantitatively, this means prevailing tax policy on equipment and structures—in which the marginal effective tax rate on structures is three times higher than on equipment—is substantially less uniform than optimal. Empirically, I provide new estimates of depreciation functions for equipment and structures using a novel smooth local projections approach with a long panel of manufacturing data. Finally, I evaluate the quantitative significance of the maintenance channel using the empirical estimates.

JEL-Classification: H21, H25

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1 Introduction

Without capital maintenance, occupations such as auto mechanics would not exist, nor would internal teams to ensure equipment runs properly and janitors to keep up and repair structures. The economy would lose about one percent of value added, gross maintenance expenditures close to half of new investment, and a prominent feature of contracts to purchase or lease equipment (McGrattan and Schmitz Jr. 1999; Goolsbee 2004). In that world, the traditional neoclassical approach to user cost would be fully descriptive (Feldstein and Rothschild 1974). Instead, we live on a rather different planet, one in which the economic decision to invest in new capital or maintain old capital is fundamental to understanding long-run movements in the capital stock. In this world, taxes play a critical role in determining long-run quantities of maintenance and investment in different capital types. Maintenance is deductible from firm profits, while the after-tax price of investment is determined by the collection of tax provisions influencing investment in different assets.

This paper investigates the positive and normative consequences of relaxing the assumption implicit in standard tax policy analysis that the no-maintenance world prevails and explicit that the demand for maintenance is not only perfectly inelastic, but zero. This is particularly evident in the main tool for macroeconomic analyses of taxation, the neoclassical growth model (NGM). Expanding on earlier work from McGrattan and Schmitz Jr. (1999) on homogeneous capital with endogenous maintenance and depreciation, I build out the neoclassical growth model with maintenance (NGMM) to include heterogeneous capital. In practice, capital depreciates at different rates and the demand for maintenance varies substantially between them, which implies significant variability in depreciation technologies. I model this through a constant-elasticity depreciation function that varies by capital type through a level or "quality" parameter and through a parameter that captures the maintenance elasticity of depreciation. Putting depreciation technologies together with a realistic capital tax system yields a rich demand system for maintenance and capital.

Within the theoretical NGMM framework, I show that the assumption of perfectly inelastic and zero demand for maintenance is not innocuous when analyzing the positive effects of tax policy. In the model, the decision to maintain old capital or invest in new capital is determined by the relative price of maintenance to investment together with the depreciation technology. Reflecting current policy practice, the relevant relative price is determined by a tax on profits—from which maintenance is exempt—and an asset-specific subsidy on investment capturing policies like the investment tax credit and tax depreciation allowances. Increases in the relative price of maintenance—equivalently, decreases in the marginal effective tax rate—lead firms to substitute away from maintenance at a rate determined by the curvature of the depreciation function. Capital with a higher maintenance elasticity of depreciation is relatively shielded from changes in policy because depreciation endogenously responds, while less responsive capital types are more sensitive and hence closer to the Hall and Jorgenson (1967) benchmark. As the tax benefit to maintaining old capital declines, so does the demand for maintenance. Using the terminology of Goolsbee (2004), which identifies high-maintenance capital with low-quality capital, the relative quantity of low-quality capital declines as taxes decline. This stands in stark contrast to the NGM, where the relative quantities of capital are constant with uniform changes in tax policy.

Naturally, accounting for heterogeneously elastic demand for capital maintenance opens a new channel for heterogeneity in the elasticity of different capital types to changes in tax policy. With that in mind, I show that a simple normative extension to the NGMM results in a Ramsey planner who would optimally choose quite different tax rates on capital depending on their respective depreciation technologies. In comparison, failure to account for the maintenance channel yields a planner who chooses tax rates based only on the role of each capital type in the aggregate production function, a result from Feldstein (1990) that this model nests. Given practical variance in both depreciation technologies and observed marginal effective tax rates, the maintenance channel is critical to consider for evaluating how close current policy is to optimal policy. As a benchmark, I assume current tax rates—in which the marginal effective tax rate on equipment is about 6.5% and 20% on structures—are optimal for a planner who does not account for maintenance. A simple quantitative accounting exercise suggests that, for a grid of plausible depreciation functions for equipment and structures, taxes are too high on structures and too low on equipment. Much of this result is driven by the fact that equipment depreciates faster than structures, so that even when the structures maintenance elasticity is higher, demand for equipment maintenance may be higher. Consequently, as long as the maintenance channel exists, it is robustly true that taxes should be more uniform than they currently are when viewed through the maintenance paradigm.

Next, toward putting a point estimate on the positive and normative quantitative effects of the maintenance channel, I estimate depreciation functions for several types of capital using the Annual Survey of Manufactures. This is a difficult task because there is little data on capital maintenance, let alone broken down by type. I proceed in two steps. First, following Fisher (2006), I extend the NGMM to a stochastic setting. Second, I use theory-implied regressions to implicitly estimate the maintenance elasticity from the response of gross investment to permanent innovations in the relative price of maintenance over the period 1972-2018 for equipment and structures. Theory suggests that the long-run elasticity of the gross investment rate with respect to the relative price of maintenance is tightly related to the maintenance elasticity. I construct industry-specific shocks to this relative price building on the methodology of Fisher (2006). Then, together with a novel smooth local projections panel IV approach, I estimate the elasticity of the asset-specific gross investment rate with respect to the relative price of maintenance, which pins down the maintenance elasticity. Ten years after a unit shock to the relative price of maintenance, the implied maintenance elasticity of depreciation for equipment is 0.4, while it is 0.7 for structures.

Finally, I quantify the positive and normative relevance of the maintenance channel. First, using the NGM as a foil, I reanalyze the 2017 Tax Cuts and Jobs Act using Barro and Furman (2018). The NGMM predicts a long-run capital-labor ratio that is numerically equivalent to cutting the capital share by 15-20% in the NGM. Second, I use my empirical point estimates of depreciation functions for equipment and structures to estimate optimal tax rates. Optimal taxes are roughly 8.7% on equipment and 12.9% on structures, compared to current taxes of 6.5% and 20%.

Literature. This paper relates to several strands of literature. First, it connects to a longstanding tradition of using the Hall and Jorgenson (1967) user cost of capital to analyze tax policy. The Hall-Jorgenson approach, which assumes constant depreciation and replacement rates for existing capital, remains the gold standard for analyzing tax policy (Barro and Furman 2018; Chodorow-Reich et al. 2023). However, my work is closer to theoretical work that *deviates* from constant user cost. In particular, Feldstein and Rothschild (1974) study the conditions under which replacement investment is constant, with particular focus on whether the standard user cost formula is generally applicable. Building on that work, McGrattan and Schmitz Jr. (1999) develop a homogeneous capital model of maintenance and investment, with maintenance expenditures pinned down by the relative price of maintenance to investment. I extend their approach to many types of capital goods, connect it to optimal policy, and develop an empirical and quantitative framework. While their observations on tax policy are useful in my approach, their focus on homogeneous capital restricts them from paying close attention to changes in relative demand. Several other papers build on McGrattan and Schmitz Jr. (1999) in the areas of public capital maintenance (Kalaitzidakis and Kalyvitis 2004), cyclical fluctuations (Albonico, Kalyvitis, and Pappa 2014), and investment theory (Boucekkine, Fabbri, and Gozzi 2010; Kabir, Tan, and Vardishvili 2023). To my knowledge, my work is the first attempt to estimate depreciation functions, extend to optimal policy, and consider the role of capital heterogeneity.

Additionally, I contribute to an empirical literature documenting the empirical relevance of capital maintenance. Goolsbee (1998b) and Goolsbee (2004) present direct evidence that the maintenance channel exists. The former examines factors affecting the decision to retire airplanes. Retirement directly relates to maintenance because, rather than maintain an old airplane, a firm simply invests in a new one. As Goolsbee (1998b) notes, the capital retirement decision is not economic in the neoclassical growth model. Focusing on an investment tax credit for a 13 year-old Boeing 707, Goolsbee finds that moving the investment tax credit from zero to 10% increases the probability of retirement from 9% to 12%. If we interpret depreciation rates as reflecting the probability an asset becomes useless to the firm in a particular year—whether through obsolescence, retirement, failure, or some other cause—then Goolsbee's finding suggests that the depreciation rate is quite elastic with respect to the tax rate. Taking his estimate seriously suggests that the typical neoclassical approach overstates the elasticity of investment by around 75% (Goolsbee 1998b). Relatedly, Goolsbee (2004) convincingly argues that the quality elasticity of capital with respect to the cost of capital is around 0.5%, where quality is roughly measured with maintenance expenditures per unit of capital. Additionally, economists have documented a clear connection between maintenance and depreciation in the housing literature. For example, Knight and Sirmans (1996) study the effect of maintenance on housing depreciation and find that poorly maintained homes depreciate significantly faster than their well-maintained counterparts, while Harding, Rosenthal, and Sirmans (2007) find that housing depreciates about 0.5 percentage points less per year after accounting for maintenance. I build on this literature to estimate depreciation functions using industry-specific shocks through the framework of Fisher (2006). Using these shocks as an instrument for the relative price, I estimate asset-specific depreciation functions.

This work relates to a theoretical literature on optimal differential capital taxation. Ramsey-style optimal tax reasoning suggests that if capital is taxed, it should be taxed in inverse proportion to its tax elasticity. In standard models, this comes solely from the production function, an insight nested by Feldstein (1990), which studies differential taxation when one capital good's tax rate is fixed. The optimal tax formula I derive nests Feldstein's and adds an additional insight, namely that the maintenance channel may substantially change the results derived from looking solely at the production function. Judd (1997) argues that equipment should be given preferential tax treatment over structures because use of the former indicates greater market power and hence higher preexisting distortions that a higher tax would only exacerbate. My setting abstracts from imperfect competition. A significant body of research focuses on differential taxation for structural or redistributive reasons. For example, Slavík and Yazici (2014, 2019) find that equipment should be taxed more than structures, with an optimal differential of approximately 40 percentage points due to differential capital-skill complementarities between types of capital and types of labor. Beraja and Zorzi (2022) derive differential tax rates for automation based on an efficiency argument in favor of relaxing borrowing constaints for workers displaced by automation. Acemoglu, Manera, and Restrepo (2020), Thuemmel (2022), and Costinot and Werning (2022) derive optimal tax formulas for capital based on elasticity formulas. While I do not address these structural concerns, I sharpen the results with a simple neoclassical framework. Quantitatively, my results agree with Slavík and Yazici (2014) and Acemoglu, Manera, and Restrepo (2020) that tax rates on equipment should be higher than they are currently.

Methodologically, this paper represents an empirical advance on the identification of long-run shocks in the neoclassical model. Fisher (2006), Guerrieri, Henderson, and Kim (2020), and others, building on earlier work from Greenwood, Hercowitz, and Krusell (2000), identifies long-run investment-specific technology shocks using the theoretical restrictions implied by permanent movements in relative prices, tehcnology, and labor shocks in a structural vector autoregression. I prove that a similar approach is sensible in the NGMM, but apply it to panel data rather than macrodata. To trace out the long-run effect of shocks, I build on work from Barnichon and Brownlees (2019) and McKay and Wolf (2022) to develop smooth local projections for panel data. Whereas the former develop the method for aggregate time series data and the latter prove it is often superior to standard local projections, this paper is the first to implement it for panel data. Boehm, Levchenko, and Pandalai-Nayar (2023) similarly use standard local projections to estimate long-run trade elasticities.

Roadmap. In Sections 2 and 3, I develop a theoretical framework to analyze the positive and normative consequences of elastic and heterogeneous demand for capital maintenance. In Section 4, I evaluate the empirical relevance of the maintenance channel for tax policy. In section 5, I document the quantitative significance of the maintenance channels positively and normatively with point estimates from Section 4. I conclude in Section 6.

2 The Transmission of Capital Tax Policy with Endogenous Depreciation

In this section, I embed endogenous depreciation into a partial equilibrium neoclassical model of the firm with multiple capital types. In the model, demand for maintenance is determined by the relative price of maintenance to investment, which is a function of tax policy. The resulting parsimonious framework makes clear predictions about how accounting for endogenous depreciation affects the traditional view of differential capital taxation from a positive perspective. In particular, higher tax rates lead the private sector to substitute toward maintenance-intensive capital. Moreover, because some types of capital have a higher maintenance elasticity of depreciation, they are relatively inelastic with respect to changes in taxes, leading to substantially different equilibrium allocations of capital from the benchmark neoclassical model.

2.1 A Partial Equilibrium Neoclassical Firm

Consider a representative firm that produces an output good Y_t with N capital types and labor according to production technology

$$Y_t = F(K_{1,t}, \ldots, K_{N,t}, H_t), \tag{1}$$

where $F(\cdot)$ is twice continuously differentiable in each argument with positive and diminishing marginal products. The firm owns its own capital stock. Every period, for each capital type i, the firm chooses how much to spend on investing in new capital, $X_{i,t}$, and how much to spend on maintaining existing capital $M_{i,t}$. A depreciation technology $\delta_i(m_{i,t})$ transforms a rate of maintenance $m_{i,t} \equiv \frac{M_{i,t}}{K_{i,t}}$ into capital $K_{i,t}$. Consequently, the law of motion for capital type i is

$$K_{i,t+1} = X_{i,t} + (1 - \delta_i(m_{i,t}))K_{i,t}. \tag{2}$$

Note that indexing the depreciation function by capital type gives rise to the possibility that depreciation technologies vary across capital types. Moreover, because there is no productivity in the model, it is not possible to either make old capital more productive than new capital or for new capital to be more productive than old capital. Although Harris and Yellen (2023) show that this is an empirically important channel, I abstract away from it here because making old capital more productive than new capital would be considered new investment under the current tax code and would have to be capitalized.

With that in mind, I impose the following assumptions on the depreciation technology.

Assumption 1. *The depreciation technology for capital type i is given by*

$$\delta_i(m_{i,t}) = \gamma_i m_{i,t}^{-\omega_i}, \quad \gamma_i, \omega_i > 0.$$

Given Assumption 1, depreciation is summarized by two parameters: a level parameter γ_i and an elasticity parameter ω_i. ω_i captures the maintenance elasticity of depreciation, while γ_i captures a level effect. For the same elasticity, a higher value of γ_i leads to a higher demand for maintenance, which corresponds to the notion of quality in Goolsbee (2004). I discuss these parameters in more detail later in the section.

The firm encounters two tax policies. First, there is a tax on output net of expenditures on maintenance and labor. In practice, both are deductible from business taxes. Second, new investment $X_{i,t}$ is subsidized at rate $\tau^x_{i,t}$. One can think of this as combining the investment tax credit and the net present value of tax depreciation allowances which typically show up in a Jorgenson-style user cost approach (*e.g.*, Barro and Furman (2018)). In most models and in practice, these two aspects of the tax system account for most of why taxes differ between asset types. Throughout, I refer to $\tau^x_{i,t}$ as a depreciation allowance. Flow dividends are given by

$$d_t = (1-\tau^c_t)\left(Y_t - w_t H_t - \sum_{i=1}^{N} M_{i,t}\right) - \sum_{i=1}^{N}(1-\tau^x_{i,t})X_{i,t}. \tag{3}$$

Letting the firm's discount rate be given by r^k, the firm's objective is to maximize the present value of dividends through its choices of capital, labor, maintenance, and investment. This implies the following optimality conditions:

$$F_{H_t} = w_t \tag{4}$$

$$m_{i,t} = \left(\frac{1}{\gamma_i \omega_i}\frac{1-\tau^c_t}{1-\tau^x_{i,t}}\right)^{\frac{-1}{1+\omega_i}} \tag{5}$$

$$(1+r^k)(1-\tau^x_{i,t}) = (1-\tau^c_{t+1})F_{K_{i,t+1}} + (1-\tau^x_{i,t+1})\left(1-\gamma_i\left(1+\omega_i\right)m_{i,t+1}^{-\omega_i}\right), \tag{6}$$

where (5) and (6) apply to all capital types $i = 1, \ldots, N$. I discuss each condition subsequently.

Optimal Maintenance

The choice between maintaining old capital and investing in new capital is fully captured by (5). In the model, differences in relative prices are entirely determined by taxes. An increase in the common tax rate τ_t^c decreases the relative price of maintenance, while an increase in $\tau_{i,t}^x$ raises the relative price. Putting these together, the choice between maintenance and new investment is pinned down by the marginal effective tax rate on capital type i:

$$\tau_{i,t} = 1 - \frac{1-\tau_t^c}{1-\tau_{i,t}^x}.$$

Note that precisely because maintenance and investment are both dynamic decisions, the trade-off between them is static. Under the constant elasticity assumption, we can make a precise statement about the substitutability between investment and maintenance.

Proposition 1. *The long-run elasticity of the gross investment rate of capital type i with respect to the relative price of maintenance to investment is given by* $\frac{\omega_i}{1+\omega_i}$.

This follows directly from manipulation of the first-order conditions together with the fact that steady-state investment is equal to depreciation. Consequently, changes in the relative price of maintenance to investment lead the gross investment rate of a particular capital type to shift, in the long-run, as a direct function of its corresponding maintenance elasticity. Even outside steady-state, ω_i is an important parameter. Not only does it determine the elasticity of substitution between investment and maintenance, but it determines the elasticity of demand for maintenance. The more elastic demand is, the more maintenance changes when taxes change and, consequently, the more endogenous depreciation is with respect to tax policy.

The parameter γ_i more closely approximates quality in the sense of Goolsbee (2004). γ_i is a level shifter in maintenance demand, while ω_i determines the demand elasticity. Hence, as long as $\omega_i > 0$, γ_i amplifies the effect of the maintenance channel. Lower quality capital—in the sense of the demand curve being shifted up by γ_i—is more exposed to tax policy for precisely this reason.

Another interpretation of optimal maintenance is through *measurement error*. Because depreciation is contingent on tax policy, any measure of depreciation is a function of current policy. Note that this has potentially large implications for quantitative analyses of tax policy that rely on user cost. Long-run estimates of the effects of capital taxation will be biased by the extent to which the proposed tax policy change is different from tax policy at the time depreciation was initially measured. This is particularly relevant for the United States, where many measures of depreciation still used today are from the 1970s, when taxes were much higher than today. Canada, which updates depreciation more frequently than the United States, shows a decline of measured depreciation together with business taxes (Baldwin, Liu, and Tanguay 2015). Viewed through the first-order condition for maintenance, the degree of measurement error depends crucially on both parameters ω_i and γ_i. While a positive maintenance elasticity makes measurement possible, the quality parameter determines how much the effect is amplified. For example, the γ parameter for equipment is probably much larger than structures, which means that the degree of measurement error is likely larger in levels for equipment. In Appendix A.1, I discuss this in more detail.

Capital Euler Equation

The capital Euler equation determines the extent to which the stock of capital changes with respect to tax policy. For ease of interpretation, consider it in steady-state. Most variants of the neoclassical growth model exhibit a constant user cost of the form

$$F_{K_i} = \frac{r^k + \tilde{\delta}_i}{1 - \tau_i},$$

where r^k is the required return on capital, $\tilde{\delta}_i$ is the pre-tax cost of an additional unit of capital, and $1 - \tau_i$ summarizes tax policy. $\tilde{\delta}_i$ is usually identified with a constant, but it can also be thought of as being equivalent to a constant depreciation rate plus an exogenous maintenance rate. In the first case, the benefit of an additional unit of capital is balanced against the cost of it depreciating in the following period. In the second case, the benefit of an additional unit of capital must be balanced not only against the cost of it depreciating, but also against the cost of having to maintain it in the following period. In both of the exogenous depreciation and maintenance cases considered above, the tax elasticity of user cost is constant across capital types

$$\varepsilon_{\tau_i}^{\text{NGM}} = \frac{\tau_i}{1 - \tau_i}.$$

Consequently, the only reason different types of capital may exhibit different tax elasticities would be due to assumptions on the production function.

On the other hand, in the NGMM, user cost is

$$F_{K_i} = \frac{r^k + \delta_i(m_i) - \delta_i'(m_i)m_i}{1 - \tau_i}.$$

Here, like in the NGM with exogenous maintenance, more capital today means incurring more depreciation and maintenance costs tomorrow. However, there are two key differences. First, the curvature and level of the depreciation function implies a particular demand for maintenance, which then pins down the depreciation rate in a way that will become clear shortly. With curvature, maintenance responds to relative prices, while it does not in the NGM. Second, the NGMM features a tax elasticity of user cost approximately given by

$$\varepsilon_{\tau_i}^{\text{NGMM}} \approx \varepsilon_{\tau_i}^{\text{NGM}} \left(1 - \frac{\omega_i}{1+\omega_i}\right).$$

Thus, the tax elasticity of user cost in the NGM is essentially given a haircut by the extent to which the maintenance channel operates within a particular capital type, where the magnitude of the haircut is determined by the elasticity of substitution between maintenance and investment. Consequently, ω_i determines the extent to which maintenance attenuates the effect of tax policy on capital accumulation. Indeed, the main mechanism of the model is that the greater the maintenance elasticity, the more elastic maintenance demand is with respect to price, so that as ω_i rises, capital type i becomes more insulated from changes in tax rates because depreciation declines relatively more. In the limiting case with ω_i large, the tax elasticity of user cost approaches zero so that the production function becomes irrelevant in analyzing how the capital stock reacts to changes in tax law.

Let K_i^*/K_j^* denote the optimal ratio of capital type i to capital type j, *i.e.*, the ratio of allocations at the undistorted optimum. Careful examination of user cost in the standard NGM compared to the NGMM leads to the following conclusion.

Proposition 2. *Given a change in the uniform capital tax rate τ^c and fixing $\tau_i^x = \tau_j^x$, the equilibrium capital ratio $K_i/K_j \neq K_i^*/K_j^*$ if $\omega_i \neq \omega_j$ and $K_i/K_j > K_i^*/K_j^*$ if $\omega_i > \omega_j$ under the NGMM. Under the NGM, $K_i/K_j = K_i^*/K_j^*$ for all values of τ^c.*

Essentially, common changes in tax policy are not neutral with respect to capital ratios in the NGMM, while they are in the NGM. Therefore, conditional on taxing capital, maintaining neutral capital ratios requires differential capital taxation. This follows directly from weak concavity of the production function together with the fact that a higher maintenance elasticity implies a higher factor demand as tax rates rise. In the following subsection, I make clear numerically why this matters.

2.2 Capital Tax Policy and Equilibrium Capital Allocations in the NGMM

A simple numerical example is sufficient to evaluate the distinction between the traditional NGM and the NGMM, particularly in light of Proposition 2. To illustrate the difference, I experiment with steady-state allocations of capital, investment, and maintenance for different values of a common tax rate.

Suppose production is given by

$$Y = K_E^{\alpha_E} K_S^{\alpha_S},$$

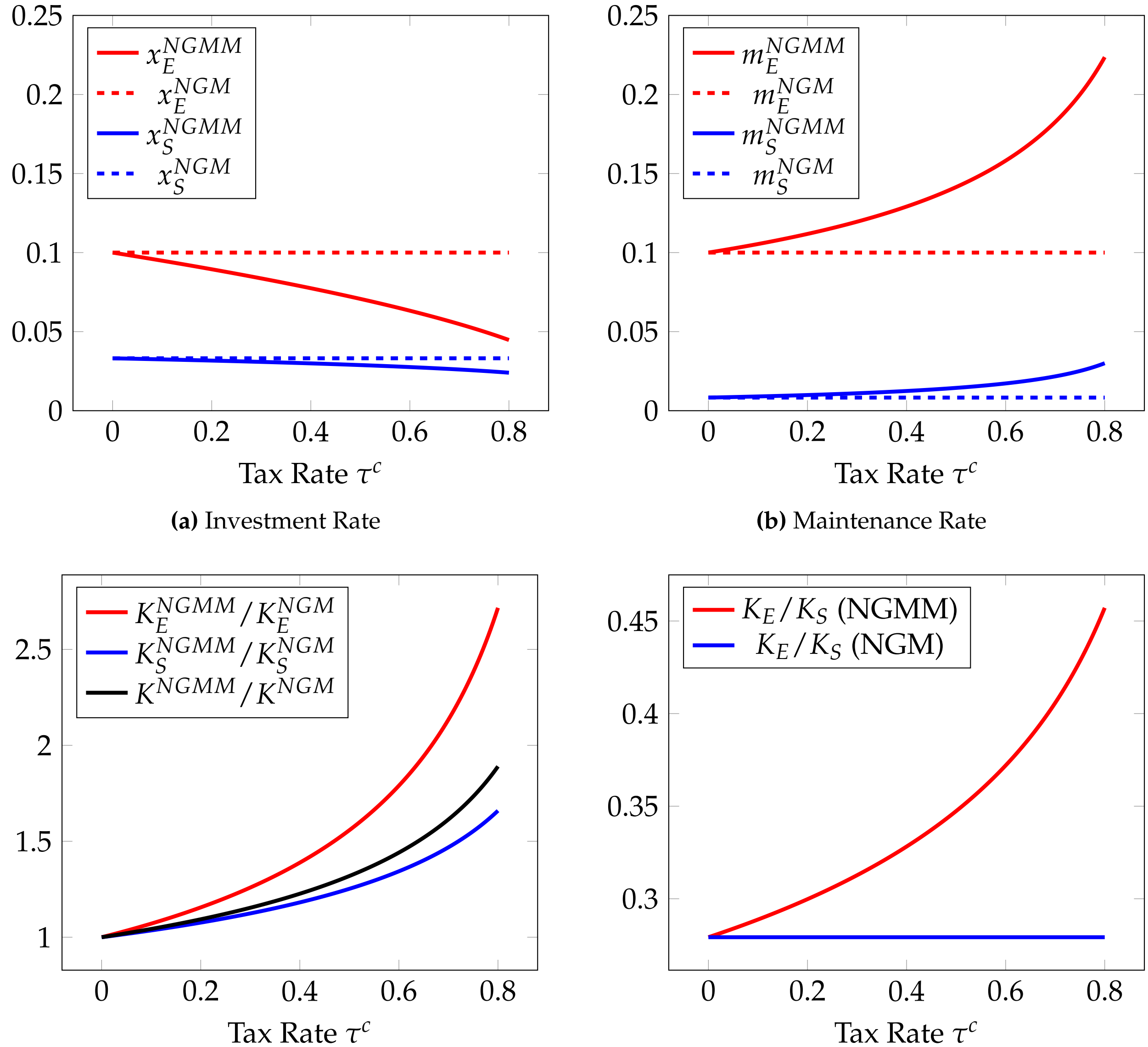
where equipment K_E and structures K_S are in intensive form. I set $\alpha_E = \alpha_S = 0.2$. Each capital type has a power depreciation function given by

$$\delta_E(m_E) = \gamma_E m_E^{-\omega_E} \quad \text{and} \quad \delta_S(m_S) = \gamma_S m_S^{-\omega_S}.$$

I set $\omega_S = 0.25$, $\omega_E = 1$, and $\gamma_E = \gamma_S = 0.01$. Under this calibration, the undistorted steady state maintenance rate and investment rate for equipment are $m_E = 0.1$ and $x_E = 0.1$, while the corresponding rates for structures are $m_S = 0.008$ and $x_S = 0.03$. Recall that the steady state depreciation rate is the investment rate. The quality parameters are equivalent to isolate the effect of the maintenance elasticity. For now, both equipment and structures are taxed at the same rate τ^c.

In Figure 1, I plot the steady state allocations of investment, maintenance, capital, and the composition of capital for a varying common tax rate τ^c for both the NGM and the NGMM. The NGM is calibrated such that it has the same initial allocations at the undistorted optimum. In Figure 1a, the steady-state investment rate (solid lines) declines for both structures and equipment under the NGMM, while there is no response of the investment rate to tax policy in the NGM (dashed lines). Because equipment has a higher maintenance elasticity than structures, the investment rate responds more for equipment, in line with Proposition 1. Figure 1b shows that as tax rates rise, NGMM maintenance rates strongly respond, while by construction the NGM maintenance rates are constant. Indeed, maintenance rates respond proportionally more than investment rates; that follows from the curvature of the depreciation technology.

The key policy question is the long-run effect of taxes on capital allocations. In Figure 1c, I plot the ratio of capital in the NGMM to its corresponding type in the NGM. For the same calibration, the effect of capital tax policy on long-run allocations is attenuated by the maintenance channel; there is about 40% more equipment in the NGMM than the NGM and 20% more structures capital. Figure 1d indicates that uniform tax policy is not neutral when depreciation technologies are not precisely equivalent. Whereas the NGM ratio of equipment to structures is invariant to tax policy, the NGMM ratio is not. In Figure 2, I plot the tax rate on equipment necessary to maintain a neutral capital ratio under the NGMM in red compared to the corresponding tax rates in the NGM. Of course, the neutral NGM tax rates are uniform. However, as long as the tax on structures is positive, a correspondingly higher tax on equipment is necessary under the NGMM.



(a) Investment Rate

(b) Maintenance Rate

(c) Ratio of NGM to NGMM Capital

(d) Capital Composition

Figure 1: Comparing NGMM to NGM investment and maintenance rates, capital allocations, and capital composition.

There are two takeaways. First, as evidenced by Figure 1c, the maintenance channel may have a practically large quantitative effect; in Section 4, I estimate approximately how large it is. At the same time, Figure 1d indicates that uniform tax rates cannot maintain capital neutrality. This is not a statement about optimality, but casual Ramsey intuition suggests that differential taxation is optimal in general equilibrium conditional on the requirement to raise revenue from capital taxes. In the following section, I turn to precisely that question.

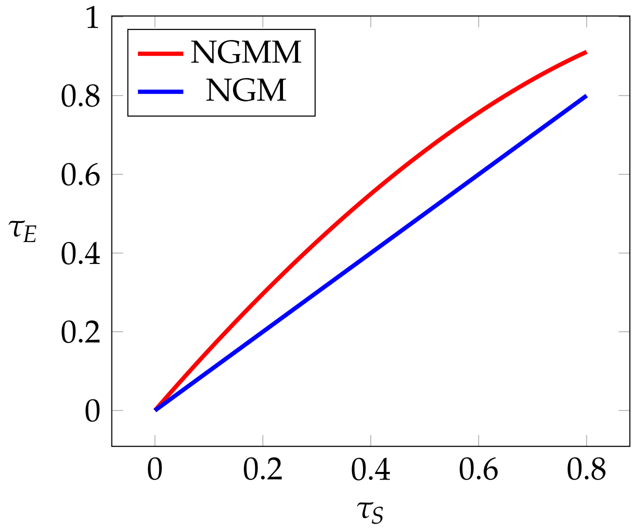


Figure 2: Given a tax rate on structures, the blue line plots the required tax rate on equipment necessary to ensure a neutral capital composition under the NGM, while the red line does the same for the NGMM.

3 A Differential Tax Optimality Result

The economics in Section 2 suggest that the maintenance channel may be important for a theory of optimal differential taxation; differing tax elasticities emerging from the maintenance channel intuitively correspond to the usual Ramsey logic about optimal taxation. Governments the world over tax capital differentially and net of maintenance expenditures. Usually, differential taxation emerges from a combination of a uniform tax on capital paired with tax depreciation allowances and credits that differ by capital type. Moreover, most types of capital tax policy changes are changes in differential capital tax policy; the profit tax—which is essentially a uniform tax on capital—is changed far less frequently (Romer and Romer 2010; Mertens and Ravn 2013). With that in mind, it is practically important to consider a second-best theory of optimal taxation that takes as given that revenue must be raised from capital and tax deductibility of capital maintenance. Toward developing such a theory, I put the partial equilibrium model of the firm in general equilibrium and solve the Ramsey problem for optimal marginal effective tax rates on each capital type. After that, I consider the quantitative implications of optimal tax theory for equipment and structures.

3.1 Analytical Optimal Tax Rates

In the traditional approach to differential capital taxation, it would be reasonable to conclude that taxes should be levied uniformly so that there are no distortions in the marginal rates of technical substitution between capital types (Diamond and Mirrlees 1971) or that taxes should only differ depending on the properties of the production function (Feldstein 1990). In the latter case, the usual Ramsey logic tells us that if the stock of a capital type is particularly elastic to changes in user cost, then its tax distortion should be relatively smaller. That channel is captured entirely by the production function in the NGM. Under the NGMM, that would only be true as a knife-edge case where depreciation technologies do not differ between capital types, which is neither empirically nor intuitively attractive. Thus, a utilitarian planner intent on levying capital taxes would need to account for both quality of capital and the maintenance elasticity in setting optimal tax rates. Toward an analytical result on optimal differential capital taxation, I extend the partial equilibrium model of Section 2 to general equilibrium. Following Chari, Nicolini, and Teles (2020), an accurate representation of the capital tax system favors a decentralization in which the firm owns the capital stock.

General Equilibrium

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 is the exactly as in (3). There two 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. Optimality conditions are exactly as in (4), (5), and (6), with $1 + r_t$ replacing $1 + r^k$ in each capital Euler equation.

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

$$\sum_{t=0}^{\infty} \beta^t \Big[u(c_t) - v(H_t) \Big] \tag{7}$$

where u is increasing, strictly concave, three times continuously differentiable, and v has similar properties. $\beta \in (0,1]$ 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

$$c_t + p_t s_{t+1} + \frac{b_{t+1}}{1+r_t} = w_t H_t + p_t s_t + d_t s_t + b_t, \tag{8}$$

where $s_0 = 1$ and initial bonds are b_0. Because government bonds are in zero net supply, household borrowing is irrelevant. Choosing sequences of consumption, labor, and shares of the firm to maximize (7) subject to (8) and a transversality condition given by $\lim_{T\to\infty} q_{t+1} b_{T+1} \geq$ yields first-order conditions given by

$$v'(H_t) = w_t u'(c_t) \tag{9}$$

$$u'(c_t) = \beta u'(c_{t+1})(1+r_t) \tag{10}$$

$$1 + r_t = \frac{p_{t+1} + d_{t+1}}{p_t}. \tag{11}$$

No-arbitrage clearly requires that the return on each capital type must equal the return on bonds.

Government. The government collects revenue from a tax τ_t^c on profits net of maintenance and wage payments to fund exogenous spending G_t and investment subsidies $\tau_{i,t}^x$.

$$G_t = \sum_{i=1}^{N} \left(\tau_t^c K_{i,t} \left(F_{K_{i,t}} - m_{i,t} \right) - \tau_{i,t}^x X_{i,t} \right) + \frac{b_{t+1}}{1+r_t} - b_t. \tag{12}$$

I assume that bonds are in zero net supply so that capital taxes are the only source of revenue for the government. Putting together the firm, the household, and the government, the aggregate resource constraint is

$$c_t + G_t + \sum_{i=1}^{N} (X_{i,t} + M_{i,t}) = Y_t. \tag{13}$$

Equilibrium Definition

For notational convenience, let symbols without subscripts denote their infinite sequence and bolded symbols denote the vector of capital types indexed by i. The equilibrium can be defined as follows.

Definition 1. *A feasible allocation is a sequence* $(\boldsymbol{K}, \boldsymbol{M}, c, H, G)$ *that satisfies the aggregate resource constraint* (13).

Definition 2. *A price system is a tuple of non-negative bounded sequences* (w, r).

Definition 3. *A government policy is a tuple of sequences* $(G, \tau^c, \boldsymbol{\tau^x}, b)$.

Definition 4. *A competitive equilibrium is a feasible allocation, a price system, and a government policy such that (a) given the price system and the government policy, the allocation solves both the firm's problem and the household's problem; and (b) given the allocation and the price system, the government policy satisfies the sequence of government budget constraints* (12).

Optimal Tax Policy

The optimal tax problem is straightforward: given a uniform capital tax rate τ^c_t, how should the planner subsidize (or tax) each each asset type using $\tau^x_{i,t}$ as an instrument. In effect, the government has N instruments. This is akin to a second-best problem in which the government chooses the marginal effective tax rate on each capital type, similarly to Feldstein (1990). Ultimately we will be concerned solely with steady state optimal tax rates.

Definition 5. *Given* $K_{1,0}, \ldots, K_{N,0}$, *the Ramsey problem is to choose a competitive equilibrium that maximizes household utility subject to its budget constraint, the aggregate resource constraint, and private optimality.*

The government satisfies the Ramsey objective through its choice of tax depreciation allowances, which is akin to choosing a marginal effective tax rate on each capital type. I ignore bonds because the government must follow a balanced budget and because the relevant object is the steady-state optimum rather than the transition path. Consequently, I also set time-zero capital taxes to zero exogenously. After substituting firm optimality, the planner chooses sequences of tax depreciation allowances, consumption, labor, maintenance, and capital to maximize houshold utility. In Appendix A.3, I write out the full Lagrangian and optimality conditions.

Now, suppose government expenditures become constant after some period T and the economy converges to a steady-state.

Proposition 3. *All else equal, the optimal steady-state tax distortion on capital type i is increasing in its maintenance elasticity and decreasing in capital quality.*
Proof: See Appendix A.3.

Intuition for Proposition 3 comes directly from the previous subsection. Exactly because maintenance determines the tax elasticity of each capital type, it plays a role in determining optimal relative tax distortions for the same reasons as in the standard Ramsey commodity tax literature. Here, however, a higher elasticity of demand for maintenance corresponds to a lower tax elasticity of the capital stock, so that the optimal tax is increasing in the maintenance elasticity. Moreover, because low quality capital types correspond to high demand for maintenance, they amplify the maintenance elasticity channel and hence should be taxed at a higher rate.

Consider the result in the context of the standard Ramsey tax literature. With a positive maintenance elasticity, the capital stock—or in models with labor, the capital-labor ratio—is less sensitive to tax changes than a model without it. In neoclassical Ramsey models like Chamley (1986) and Chari, Nicolini, and Teles (2020), the optimal tax on capital is zero. In the long run, it is not optimal to tax capital because it will lead to welfare gains by way of a larger capital-labor ratio. Mechanically, introduction of endogenous maintenance reduces such gains. Following the optimality logic from above, since capital taxes vary in effect across capital types, intuitively capital taxes should be set such that the capital-labor ratio for each type of capital declines in accordance with the corresponding maintenance elasticity, which captures the degree to which the tax elasticity of a particular capital type differs from the standard constant depreciation case.

One special case of the production function is worth illuminating. Following Feldstein (1990), define the production elasticity of production factor j with respect to production factor i as

$$\varepsilon_{K_{ji}} = \frac{F_{K_j}}{F_{K_j K_i} K_j}.$$

Let $\hat{r}_i \equiv F_{K_i} - m_i$ define the return on capital net of maintenance and suppose there are no cross-partials between factors of production.

Example 1. *With no cross-partials in production, the optimal tax ratio must satisfy*

$$\frac{\tau_i}{\tau_j} = \frac{\frac{\hat{r}_j}{F_{K_j}}\varepsilon_{K_{jj}} - \frac{\omega_j}{1+\omega_j}}{\frac{\hat{r}_i}{F_{K_i}}\varepsilon_{K_{ii}} - \frac{\omega_i}{1+\omega_i}} \tag{14}$$

and if $\omega_i \to 0$ for all capital types, then the optimal tax ratio is

$$\frac{\tau_i}{\tau_j} = \frac{\varepsilon_{K_{jj}}}{\varepsilon_{K_{ii}}}. \tag{15}$$

Example 1 is convenient because it illustrates two concepts quite clearly. First, the derived formula is simply a standard Ramsey rule that would appear consistent in a different setting with, for example, commodity taxation. That is, we simply have an inverse elasticity rule with an adjustment for the maintenance elasticity. Second, inspection of (15) reveals that Feldstein (1990) is a special case of my model. This is a surprising result because his analysis is entirely static and assumes that one factor of production is untaxed, whereas mine is dynamic and makes no such assumptions about tax restrictions. Here, the analysis from Feldstein (1990) on cross-elasticities carries through, namely that taxes should be correspondingly lower when there are strong cross-elasticities in production. With maintenance, that requires an adjustment for the maintenance elasticities of other types of capital.[1]

Assuming the depreciation function is constant elasticity, we can make the following conclusion about relative tax rates:

Proposition 4. *Given a production function, relative tax rates can be fully characterized by two parameters: a constant parameter γ_i and an elasticity parameter ω_i.*

For example, in the case where we have Cobb-Douglas production and two capital types with equal capital shares, the ordering of optimal tax rates is apparent directly from examination of each capital type's depreciation function. In Barro and Furman (2018), equipment and structures have roughly equivalent roles in the aggregate production function. In the benchmark NGM, that would imply that optimal tax rates would be roughly uniform. On the other hand, consideration of the maintenance channel may suggest otherwise. In Section 4, I turn toward an empirical evaluation of the maintenance channel to answer precisely this question.

3.2 A Range of Optimal Tax Rates

Given the analytical results, a natural next step is to consider their quantitative importance for real-world capital assets. In this subsection, I quantify optimal tax rates on equipment and structures for a range of plausible depreciation functions. Equipment and structures, the main types of physical capital, have different depreciation rates, so they have different depreciation technologies.

Under permanent provisions in the tax code, the marginal effective tax rates on equipment and structures are approximately 6.5% and 20%, respectively (Barro and Furman 2018). The magnitude and sign of that tax differential is common throughout OECD countries (Office of Tax Analysis 2021), perhaps reflecting a belief among policymakers

1. Note that, with AK production, we would get a similar optimal tax formula but with additional cross-elasticities

that unmodeled differences between equipment and structures are important for setting tax rates that typically do not enter the Ramsey benchmark. For example, it may be that equipment contributes to growth uniquely (DeLong and Summers 1991) or that structures are non-tradeable across regions and hence easier to tax. Additionally, it may be that there are heterogeneous elasticities of supply between equipment and structures even though the Ramsey model assumes identically infinite elasticities of supply. Moreover, tax changes may pass through prices in different ways for equipment and structures, with correspondingly different effects on demand (Goolsbee 1998a). With that in mind, I quantify optimal tax rates on equipment and structures for a planner taking account of maintenance compared to a benchmark in which the current tax schedule is optimal for a planner who does not account for maintenance.

In the model economy, production is Cobb-Douglas in equipment, structures, and labor:

$$Y = K_E^{\alpha_E} K_S^{\alpha_S} H^{1-\alpha_S-\alpha_E}.$$

As a reduced form way of capturing concerns about tax elasticities that may motivate policymakers to set taxes at their current levels on equipment and structures, I assume that the price of capital type i is given by

$$p_i = \left(\frac{1}{1-\tau_i^x}\right)^{\phi_i}, \quad 0 < \phi < 1$$

Consequently, user cost changes correspondingly so that

$$F_{K_i} = \frac{(1-\tau_i^x)^{1-\phi_i}}{1-\tau^c}\left(r^k - \gamma_i\,(1+\omega_i)\,m_i^{-\omega_i}\right).$$

Larger values of ϕ_i imply that the effect of a larger investment subsidy is smaller in steady state. We have little substantive evidence on the long-run supply elasticities and even less on heterogeneity in those elasticities, I treat the parameters and functional form freely. Acemoglu, Manera, and Restrepo (2020) and associated comments provide a useful discussion of the current state of the evidence on capital supply elasticities, concluding that the relevant magnitudes are largely uncertain. With higher depreciation for equipment and Cobb-Douglas production, a planner would prefer to first subsidize equipment until marginal products are equalized between equipment and structures. Given that bias, $\phi_E > \phi_S$ for the current application. I discuss how I set these parameters later in the section.

Next, the government faces the following budget constraint:

$$G = \tau^c \sum_{i \in \{E,S\}} \left[\left(F_{K_i} - m_i \right) K_i \right] - \sum_{i \in \{E,S\}} \tau_i^x X_i q_i + \tau^w w H,$$

where all notation carries from Section 2, $i \in \{E, S\}$ denotes equipment and structures, and $\tau^w wH$ is labor tax income, where the linear tax on labor is exogenous.[2] Note that, as in the rest of the paper, these can be amalgamated into a single asset-specific marginal effective tax rate $\tau_i = 1 - \frac{1-\tau^c}{1-\tau_i^x}$. In steady-state, investment is simply depreciation.

To close the model, there is a representative household with flow utility over consumption and labor

$$u(c, H) = \log c - \chi \log H$$

and the resource constraint is

$$\sum_{i \in \{E,S\}} (M_i + q_i X_i) + c + G \leq K_E^{\alpha_E} K_S^{\alpha_S} H^{1-\alpha_E-\alpha_S}$$

Parameterizations are standard and are in Appendix E.2. I calibrate initial tax rates to match those in Barro and Furman (2018). Specifically, I set $\tau^c = 0.27$ and the expensing rates to 0.812 and 0.338 for each of equipment and structures so that $\tau_E = 6.5\%$ and $\tau_S = 19.7\%$. Although the federal corporate tax rate is 21% in practice, Barro and Furman (2018) argue that 27% is more accurate after taking account of various state-level taxes. I set the linear tax rate on labor exogenously to $\tau^w = 0.25$. Equilibrium conditions are exactly those in Section 3. With that, the procedure for computing optimal tax rates is straightforward. There are two major steps.

1. **Calibrate ϕ_E and ϕ_S in the benchmark NGM.** Using a bisection method, find a pair of values (ϕ_E, ϕ_S) such that current tax rates are optimal under the NGM. Here, $\omega_E = \omega_S = 0$. There are infinitely many pairs for which current policy is optimal. To fixate on one such pair, I set $\phi_S = 0.2$ and then find ϕ_E such that the government budget constraint holds and current tax rates are optimal. This results in $\phi_E = 0.54$.

2. **Compute optimal tax rates in the NGMM.** For a pair of maintenance elasticities (ω_E, ω_S), back out the value of γ_i such that steady-state depreciation matches its historical average for each capital type.[3] With those depreciation functions and us-

2. As long as the labor tax is exogenous in optimal policy, including it has no effect on the analytical results. I include it here merely to reflect some important aspects of the tax system.

3. See Appendix E.2 for a full description of parameters together with a detailed explanation for how I calculate γ_i.

ing the pair (ϕ_E, ϕ_S), recompute optimal tax rates following the same steps as above.

Following this procedure guarantees that we compare optimal tax rates under the current system as if policymakers consider everything except maintenance to an economy in which policymakers do consider maintenance.

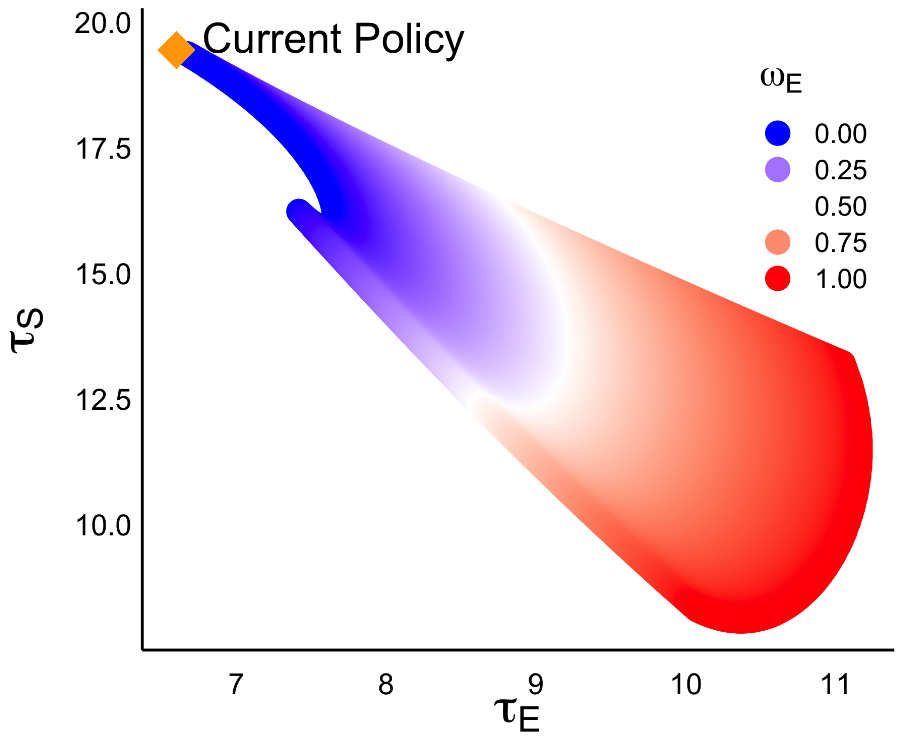


Figure 3: Optimal tax rates for each pair of maintenance elasticities in the grid $\mathcal{W} = [0, 1] \times [0, 1]$. The orange diamond represents current policy. Color intensity is determined by the equipment maintenance elasticity.

I plot optimal tax rates on equipment and structures for each pair of maintenance elasticities in the grid $\mathcal{W} = [0, 1] \times [0, 1]$ in Figure 3. The optimal tax rates are defined as $\tau_i = 1 - \frac{1-\tau^c}{1-\tau_i^x}$. Maintenance elasticities may be larger than one, but in practice, this seems unlikely and using a range from zero to one communicates the point adequately. In the figure, the color intensity is determined by the magnitude of the equipment maintenance elasticity ω_E; dark blue indicates ω_E near zero, dark red near one, and white around 0.5. The orange diamond represents current policy rates. Current tax rates are only close to optimal in the case where both maintenance elasticities are very small. Consequently, except in the unlikely case that there is no maintenance channel at all, tax rates should be higher on equipment and lower on structures. The lack of neutrality comes from the fact that the higher quality of structures suppresses demand for maintenance from structures and conversely, that the relatively high inherent depreciation rate of equipment guarantees a high demand for equipment maintenance when the maintenance channel exists. Under Proposition 3, that suggests a bias in favor of taxing equipment compared to current policy. For most of the plausible depreciation functions in $\mathcal{W}$, quantitatively it translates to taxing equipment around 9-11% and structures between 10-15%.

At this stage, we have no confidence in any particular values for (ω_E, ω_S). The task of the remainder of the paper is to place a point estimate on values for ω_E and ω_S, which implies a point estimate on optimal tax rates in Figure 3. In the process, I show that this point estimate also has strong implications for the positive quantitative analysis of tax policy.

4 The Empirical Maintenance Channel

In this section, I estimate the maintenance elasticity by asset type. This requires some creativity because a lack of available and high-quality data makes it challenging to directly estimate a depreciation function by simply regressing depreciation on maintenance. There are three central issues. First, national accounting typically assumes a constant geometric depreciation rate and does not account for the extent to which a measured depreciation rate is a function of existing policy. This issue spills over into capital stock measurement; if depreciation is mismeasured, then so are capital stocks. Second, maintenance data are scarce, generally low-quality, and not detailed at the asset-specific level. To the extent that there is variation, it is usually over the time series dimension. The paucity of data follows from the fact that maintenance expenditures typically do not receive their own accounting category and it can be difficult to distinguish maintenance from investment.[4] Third, a significant amount of maintenance activity takes place outside the marketplace. Firms employ their own dedicated maintenance staffs and maintenance takes up a substantial part of home labor.

In light of the difficulty with directly estimating depreciation functions, I use a structural approach based on the NGMM from Section 2. To indirectly estimate the maintenance elasticity by asset type, I estimate the long-run response of the gross investment rate for each asset type to permanent shocks to the relative price of investment using a long panel of detailed industry data on relative prices and investment. The remainder of this section proceeds in three steps. First, I discuss how a stochastic extension of the

4. Some industries report maintenance for regulatory reasons. For example, airlines have to report maintenance expenditures, but precisely because such expenditures are mandated, they do not typically reflect economic behavior.

NGMM allows us to indirectly estimate the maintenance elasticity. Second, I detail data construction for the relevant relative price and investment levels together with how I estimate permanent shocks. Third, I present a novel estimation strategy based on smooth local panel projections and discuss results.

4.1 The NGMM and an Indirect Approach to Estimating Maintenance Elasticities

My approach draws from Fisher (2006) and Guerrieri, Henderson, and Kim (2020) by using permanent shocks to the relative price of maintenance to investment to infer the maintenance elasticity. I focus on long-run shocks for two reasons. First, we do not know the short-run properties of the relationship between maintenance and investment. McGrattan and Schmitz Jr. (1999) argue that investment and maintenance are substitutes and document that industries facing greater uncertainty maintain their capital at higher rates. Maintenance behavior in the airline industry during the 2021-2023 supply chain crisis supports the idea that maintenance and investment are substitutable. Airlines, facing long delays on investments in new planes, strenuously maintained their aircraft (Pfeifer 2023). On the other hand, Boucekkine, Fabbri, and Gozzi (2010) argue that maintenance and investment are complementary in the short-run and, to the extent that data are usable, it supports their story. Although the disagreement is perhaps over maintenance and investment *levels* rather than *rates*, it remains unresolved and difficult to resolve with the minimal data we have on maintenance at any frequency. Second, the NGMM analyzed in this paper does not include investment or maintenance frictions—both of which are practically plentiful— so the model is not well-suited for short-run analysis. However, the NGMM does make a clear and intuitive prediction about the relationship between investment and maintenance rates in the long run. Proposition 1 states that the elasticity of the gross investment rate with respect to a change in the relative price of maintenance is given by $\frac{\omega_i}{1+\omega_i}$. This follows directly from the fact that in the NGMM, steady-state gross investment equals gross depreciation, *i.e.*,

$$\frac{X_i}{K_i} = \delta_i(m_i) = \gamma_i \left(V_i \frac{1}{\omega_i \gamma_i} \right)^{\frac{\omega_i}{1+\omega_i}}, \tag{16}$$

where $V_i \equiv \frac{q_i(1-\tau^c)}{p_i(1-\tau_i^x)}$ is the steady-state after-tax relative price of maintenance to investment in asset type i. Consequently, using permanent shocks to the relative price is convenient because it allows us to sidestep issues about short-run dynamics by simply making a statement about what should happen in the long-run.

Toward implementing the long-run approach and build on the identification scheme of Fisher (2006), I alter the NGMM to include stochastic processes. Suppose a firm produces according to

$$Y_t = z_t \left(\chi_t H_t\right)^{1-\Omega} \prod_{i=1}^{N} K_{i,t}^{\alpha_i}$$

with $\sum_i \alpha_i = \Omega < 1$. Hicks-neutral productivity follows the stochastic process

$$z_t = z_{t-1} + \varepsilon_{z,t}, \quad \varepsilon_{z,t} \sim \mathcal{N}(0, \sigma_z),$$

and Harrod-neutral productivity follows

$$\chi_t = \chi + \varepsilon_{\chi,t}, \quad \epsilon_{\chi,t} \sim \mathcal{N}(0, \sigma_\chi).$$

Harrod-neutral productivity shocks capture labor demand shocks. Following the notation above, let the inverse price of investment be given by V_i, which follows a stochastic process given by

$$V_{i,t} = V_{i,t-1} + \varepsilon_{i,t}, \quad \varepsilon_{i,t} \sim N(0, \sigma_i).$$

The first-order condition for maintenance becomes, after rearranging,

$$m_{i,t} = \left(V_{i,t} \frac{1}{\omega_i \gamma_i}\right)^{\frac{-1}{1+\omega_i}}.$$

In steady-state, this becomes (16), so that a unit shock to V_i yields the required long-run elasticity.

Proposition 5. *In the long run, a positive shock to the relative price of maintenance to investment in asset type i causes productivity and hours to permanently rise with no effect on other relative prices. A positive productivity shock has no effect on relative prices but causes hours to rise in the long run. A positive shock to hours has no long-run effect on relative prices or productivity.*

Proposition 5 implies a parsimonious framework for analyzing substitutability between maintenance and investment in the long run, which in turn yields maintenance elasticities. Because there are multiple capital types, that also implies the overidentifying restrictions that shocks to V_i cannot affect V_j in the long-run and hence cannot affect the gross investment rate in asset type j. Given data on investment rates, relative prices, productivity, and hours, we can infer maintenance elasticities by examining the long-run response of the gross investment rate to a relative price shock. In the following subsection, I discuss how to implement that in practice.

4.2 Data and Shock Construction

The previous subsection suggests that if we identify permanent shocks to relative prices, productivity, and labor supply, then we can infer maintenance elasticities. Toward that end, I put together a panel dataset on prices, productivity, and capital stocks on six-digit NAICS industries in the manufacturing sector at an annual frequency using data from the Bureau of Economic Analysis (BEA), the NBER-CES dataset of the Annual Survey of Manufactures (ASM), and the Federal Reserve Bank Estimates of Manufacturing Investment, Capital Stock, and Capital Services produced under the industrial capacity program. The final sample is a balanced panel of 335 industries from 1972-2018. With those data, I construct industry-specific productivity shocks, labor supply shocks, and asset-specific shocks to the relative price of maintenance following the methodology of Fisher (2006) for equipment and structures. Using permanent shocks to relative prices as instruments for relative prices, we can recover the maintenance elasticity by using a panel local projections framework. Following Boehm, Levchenko, and Pandalai-Nayar (2023), the long-run elasticity is where the point estimate settles down after a sufficiently long period of time.

Data Construction

In this subsection, I briefly discuss data construction. See Appendix B for more detailed information. The relative price of maintenance to investment for asset i in industry j at time t is

$$V_{i,j,t} = \frac{q_{j,t}}{p_{i,j,t}} \frac{1-\tau_t^c}{1-\tau_{i,j,t}^x},$$

where $q_{j,t}$ is the pre-tax price of maintenance, $p_{i,j,t}$ is the pre-tax price of investment, τ_t^c is the corporate tax rate, and $\tau_{i,j,t}^x$ collects asset-i-by-industry-j specific tax provisions like the investment tax credit and tax depreciation allowances. For the price of maintenance, I use the ASM to construct a unit labor cost index specific to each industry but common across asset types. Maintenance is largely an internal operation so an internal indicator of labor costs the relevant indicator of maintenance costs.[5] Consequently, the price of maintenance is common across asset types within each industry. For $p_{i,j,t}$, the price of investment in asset i, I construct a weighted investment deflator in each capital type using detailed data from the BEA at the three-digit NAICS level. Each three-digit NAICS price is then matched to its more disaggregated six-digit NAICS counterpart. I construct tax policy

5. In principle, a weighted metric of internal and external labor, capital, and materials cost would be superior. However, there is currently no clear way to do this. As a result, some measurement error surely enters the result through this channel.

data by hand using a variety of different sources. See Appendix B.2 for more details. Next, we require a measure of the gross investment rate,

$$x_{i,j,t} = \frac{X_{i,j,t}}{K_{i,j,t}}.$$

Both gross investment and the capital stock of asset i in industry j come from the Federal Reserve Bank Estimates of Manufacturing Investment, Capital Stock, and Capital Services produced under the industrial capacity program.[6] Finally, productivity and hours per worker come from the ASM.

Shock Construction

The remainder of this subsection discusses how I construct permanent shocks to the relative price of investment, productivity, and hours. Appendix B.3 contains a more detailed description.

Fisher (2006) and a subsequent literature on investment-specific technology (IST) shocks identifies the latter along with productivity and labor supply shocks by imposing long-run restrictions. From the perspective of earlier iterations of the neoclassical model with IST shocks like Greenwood, Hercowitz, and Huffman (1988) and Greenwood, Hercowitz, and Krusell (2000), a permanent shock to the relative price of investment to consumption has a permanent effect on the relative price, productivity, and hours. A shock to productivity cannot affect relative prices but does permanently affect hours, while a shock to hours can only affect hours. Clearly, this is analogous to Proposition 5, in which the only difference has to do with the denominator of the relative price. Whereas for the NGM, the relevant relative price is investment over consumption, here it is maintenance over investment.

To impose the long-run restrictions of Proposition 5, I follow an analogous strategy to Fisher (2006) and Shapiro and Watson (1988) by exploiting time series properties of the price, productivity, and hours variables. Note that a differenced stationary variable cannot have a long-run effect in levels on a stationary variable; by construction the effect of an innovation to the differenced stationary variable on a stationary variable is transient. Permanent shocks to the relative price of maintaining equipment are standardized

6. The NBER-CES variant of the ASM also puts together data on capital stocks. I prefer the FRB dataset because it uses a more sophisticated perpetual inventory method and price data than the NBER-CES variant by assuming the efficiency of assets is non-constant and using asset-by-industry specific deflators rather than aggregate deflators.

residuals of the following two-way fixed effects regression up to p lags

$$\begin{aligned}\Delta\log V_{E,j,t} =& \alpha_j + T_t + \sum_{s=1}^{p}\beta_{V_E}\Delta\log V_{E,j,t-s} + \sum_{s=0}^{p-1}\beta_{V_S}\Delta^2\log V_{S,j,t-s} \\ &+ \sum_{s=0}^{p-1}\beta_{\text{Prod}}\Delta^2\text{Prod.}_{j,t-s} + \sum_{s=0}^{p-1}\beta_{\text{Hrs}}\Delta\text{Log Hrs}_{j,t-s} + \mu_{E,j,t}.\end{aligned} \tag{17}$$

α_j is an industry fixed effect, T_t is a time fixed effect, $\log V_{E,j,t}$ is the log relative price of maintenance in equipment, $\log V_{S,j,t}$ is the log relative price of maintenance in assets other than equipment, $\text{Prod.}_{j,t}$ is a log-transformed index of labor productivity in sector j, and $\text{Log Hrs}_{j,t}$ is a log-transformed index of hours per worker in sector j. Following Shapiro and Watson (1988), I instrument for overdifferenced variables with their stationary lags and for stationary variables with their lags. The residuals $\mu_{j,t}$ scaled by the industry-specific standard deviation of $\mu_{j,t}$ then form the industry-specific shocks to the relative price of investment. Proposition 5 tells us that, in theory, shocks to other relative prices, productivity, or hours should have no effect. Consequently, in (17), all of those variables are differenced once from their stationary form.

I run a similar regression to produce permanent shocks to relative prices for structures. Next, I obtain productivity shocks by running a similar regression, allowing all three relative prices to affect productivity permanently, and including the estimated relative price shocks in the regression. A similar procedure yields shocks to hours. Following this procedure yields industry-specific shocks to the relative price of maintaining each asset, productivity, and hours. The instrument I use in practice uses $p = 2$ lags. Further details are in Appendix B.3.

4.3 Estimated Elasticities

This subsection discusses the final estimation steps for inferring the maintenance elasticities and presents results. My approach relies on local projections (LP). For up to h horizons, I estimate, for each capital type i in industry j at time t,

$$\log x_{i,j,t+h} - \log x_{i,j,t-1} = \alpha_j + T_t + \beta_{i,h}\log V_{i,j,t} + \mathbf{X}_{i,j,t}\zeta_{i,h} + \eta_{i,j,t+h}, \tag{18}$$

where α_j is an industry fixed effect, T_t is a time fixed effect, and $\mathbf{X}_{i,j,t}$ is a vector of controls. The regression computes the price elasticity of the gross investment rate $x_{i,j,t+h}$ in asset i in industry j for up to h horizons ahead given a one percent increase in the industry-j and asset-i relative price of maintenance, $V_{i,j,t}$. I instrument for the relative price of maintenance with the industry-by-asset permanent shocks obtained in the previous subsection. I also control for productivity growth and growth in hours, instrumenting for both with the industry-specific productivity and labor supply shocks. Additionally, I include two lags each of the asset-specific log gross investment rate, the log relative price of investment, and productivity growth, and hours growth.[7] Because the time dimension is large—greater than forty years for all capital types—the extent of Nickell bias is small, though it is increasing in the forecast horizon.

However, rather than rely on standard LP, I develop a new method to estimate the long-run effects of shocks with panel data. While a key benefit of the atheoretical impulse responses generated by LPs is their unbiasedness, the estimator often generate large and theoretically unappealing fluctuations in their impulse responses. Toward a middle ground between the theoretically appealing but biased impulse responses from SVARs and the theoretically unappealing but unbiased impulse responses from LPs, Barnichon and Brownlees (2019) develop smooth local projections (SLP) by making the local projection impulse response a smooth function of the forecast horizon through B-splines. SLP is often preferable to standard LP because it disciplines the IRF to fit a polynomial of some degree chosen by the researcher.[8] I extend the methodology of Barnichon and Brownlees (2019) to panel data, developing smooth local projections for panel data (SLPP) to estimate (18). See Appendix D for a full description of how the SLPP estimator works along with results from a standard LP estimator.

I use the SLPP estimator to penalize the impulse response to a line for each capital type for up to ten years and plot the coefficients $\beta_{i,h}$ for each of equipment and structures in Figures 10a and 10b together with a 90% wild cluster bootstrap confidence interval with 2500 replications. The IRFs are statistically distinguishable from zero for all horizons for equipment, while results for structures become slightly insignificant around year ten. From year seven onward, the equipment maintenance elasticity stabilizes to around 0.4, while it stabilizes on structures around 0.7 after a permanent relative price shock. In Appendix C, I include additional results varying both lag length and the polynomial order. After estimating the coefficient $\beta_{i,h}$ on the relative price of investment, I infer the

7. Montiel Olea and Plagborg-Møller (2021) show that this is sufficient to account for non-stationarity with local projections, so I do not bother with unit root or cointegration procedures. Because the relative price and the investment rate are both persistent series, it is important to include lags of both. Indeed, for all capital types, there is surely some adjustment cost, so inclusion of lags is critical (Eberly, Rebelo, and Vincent 2012; Caballero and Engel 1999).

8. Li, Plagborg-Møller, and Wolf (2021) show that, in a time series context, standard LP is unbiased but inefficient enough that applied researchers should avoid using them.

maintenance elasticity for capital type i at each horizon h by estimating

$$\hat{\omega}_{i,h} = \frac{\hat{\beta}_{i,h}}{1 - \hat{\beta}_{i,h}}$$

and infer uncertainty around the estimate with a wild cluster bootstrap with 2500 replications. I plot the resulting estimates for the maintenance elasticities together in Figure 4, while estimates along with standard errors are in Figures 11a and 11b. The estimates are statistically significant for equipment at all horizons and nearly the same holds for structures.[9]

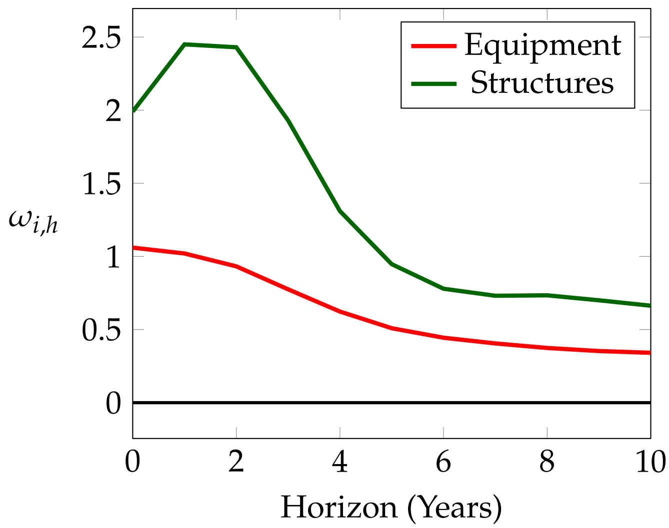


Figure 4: Maintenance elasticities for each capital type.

Given point estimates for depreciation functions for equipment and structures, we can begin to analyze with greater precision how accounting for the maintenance channel affects the positive and normative consequences of tax policy. I do that in the following section.

9. Aside from the fact that substantial measurement error is surely in the estimates, it must be noted that measurement of the gross investment rate itself is inconsistent with the thrust of this paper. My main argument is that depreciation is a function of policy, which implies that investments should not be depreciated with constant depreciation rates in the face of changing policy. However, these measures of the capital stock do rely on constant depreciation rate, which introduces a further source of measurement error. Another issue is that doing inference with the quantity $\frac{\hat{\beta}_{i,h}}{1-\hat{\beta}_{i,h}}$ means that standard errors blow up as $\hat{\beta}_{i,h}$ approaches one. This does not happen in the main specification but may happen as the polynomial order increases since the LP estimate of the structures $\beta_{i,h}$ approaches one at horizons two and three.

5 Quantifying the Importance of Maintenance

In this section, I carry out two counterfactual quantitative exercises. First, I quantify the estimated effect of the 2017 Tax Cuts and Jobs Act with the NGMM and compare it to estimates made with the benchmark NGM from Barro and Furman (2018). Second, I quantify optimal tax rates on equipment and structures.

5.1 Positive: The 2017 Tax Cuts and Jobs Act

The 2017 Tax Cuts and Jobs Act (TCJA) remains the largest tax reform of the postwar era. It substantially cut corporate tax rates from 35% to 21% and altered tax wedges between assets; lawmakers gave equipment 100% bonus depreciation and altered the cost of capital for different types of intangibles. At the same time, policymakers introduced new measures to combat profit shifting from tax havens abroad. For a full description of the various changes, see Barro and Furman (2018) and Gale et al. (2018).

Here, I focus on the impact of considering maintenance on the predicted long-run effects of the domestic tax changes. Barro and Furman (2018) provide the ideal setting for doing so; they analyze the long-run effects of TCJA through the lens of a standard neoclassical model with heterogeneous capital. The Barro and Furman analysis yields promising results for the TCJA, predicting large increases in the capital-labor ratio and, as a direct consequence, significantly higher output per capita. Their approach amounts to simply computing the analytical steady-state under different capital tax policies and examining the results while implicitly assuming that the demand for maintenance is perfectly inelastic and zero. Thus, it is a convenient setting to add endogenous maintenance and compare the quantitative predictions of both models.

Barro and Furman (2018) feature five types of capital: equipment, residential structures, nonresidential structures, R&D intellectual property, and other intellectual property. Using income share data, they then calibrate a Cobb-Douglas production function with those five capital types plus labor for the corporate and passthrough sectors. Comparative statics on the cost of capital for each capital type then furnish predictions about the capital-labor ratio, productivity, and output for the corporate sector and the non-corporate sector. Aside from the depreciation functions, I rely on the exact same calibrations as Barro and Furman. For this analysis, I use the estimated depreciation function for equipment and the estimated depreciation function for structures for non-residential structures and residential structures calibrated such that pre-reform user cost is the same for both the NGM and the NGMM. See Appendix E.2 for more details on how I set the level parameters given equipment and structures elasticities of 0.4 and 0.7, respectively. I assume, somewhat conservatively, that the intangible maintenance elasticity is the same as equipment at 0.4. The latter assumption may be improper, but the goal here is simply a back-of-the-envelope estimate of how much it matters to include maintenance.

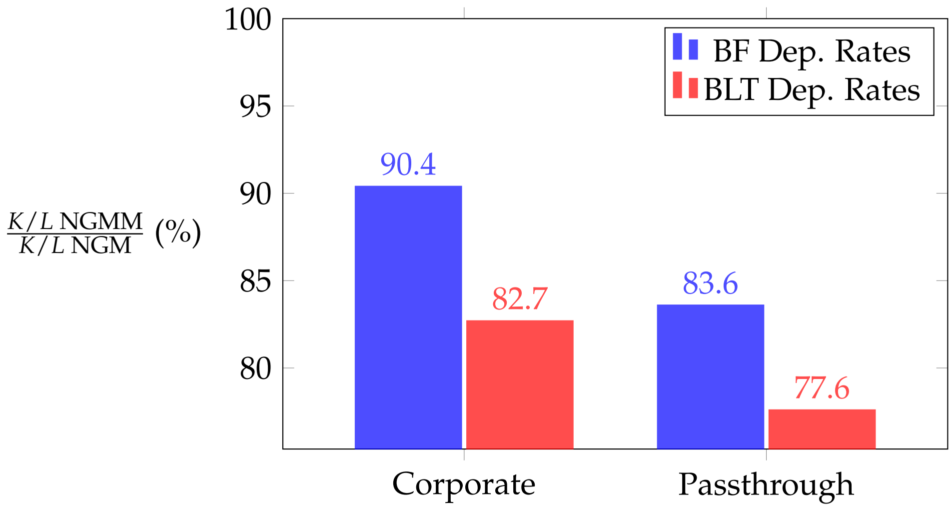


Figure 5: The predicted effect of the TCJA on capital-labor ratios under the NGMM as a share of the predicted effect under the NGM. The BF depreciation rates come from Barro and Furman (2018) and the BLT depreciation rates come from Baldwin, Liu, and Tanguay (2015).

In Figure 5, I plot the predicted effect of the TCJA on the capital-labor ratio using the NGMM as a share of the predicted effect of the NGM, where the latter predictions come from Barro and Furman (2018). I plot the NGMM predicted K/L ratio for two sets of depreciation rates. The first, denoted BF, uses depreciation rates from Barro and Furman, which in turn come from the BEA. The second set of depreciation rates comes from Canada, denoted BLT (Baldwin, Liu, and Tanguay 2015). The key difference is that the latter are roughly twice as large for each asset class. I prefer the Canadian depreciation rates because they are more rigorously estimated; whereas many of the BEA depreciation rates were estimated in the 1970s and 1980s, Canadian depreciation rate estimates are modern, updated regularly, and use extensive microdata on capital resales.[10] Because the capital-labor ratio maps easily to productivity and output, I simply report the capital-labor figure for each of the corporate sector and the non-corporate sector. In sum, the NGMM predicts the TCJA effect on the capital-labor ratio to be about 80-90% as large as the standard NGM predicts when using the BEA depreciation rates and about 75-85% as large using the BLT

10. For that reason, the BEA and BLS are strongly considering updating their methods in line with Canada's (Giandra et al. 2022). In fact, usage of Canada's depreciation rates implies a U.S. net capital stock approximately 60% as large as claimed by the BEA, something not widely appreciated.

depreciation rates. The difference between the corporate and passthrough sectors largely comes from the structures share, which is much larger in the passthrough sector.

Another way to interpret the magnitude of the result is through the capital share. In the baseline calibration from Barro and Furman (2018), which I use, the capital share is calibrated to be 0.38. In the steady-state NGM, the capital share entirely determines the elasticity of the capital stock with respect to changes in taxes. One could equivalently achieve the results of the NGMM by considering instead an aggregate production with a capital share about 15% smaller using the BEA depreciation rates or about 20% smaller using the BLT depreciation rates.

5.2 Normative: Optimal Tax Rates

In Section 3, I showed that accounting for maintenance with equipment and structures suggests the current tax schedule is overly privileged in favor of equipment for a range of plausible depreciation functions, with the degree of privilege determined by the pair of maintenance elasticities (ω_E, ω_S). Now, given the point estimates in Section 4, I zoom in on the most likely candidate pair $\omega_E = 0.4$ and $\omega_S = 0.7$. The key result is in Figure 6. Compared to current tax rates, consideration of the maintenance channel pushes the optimal rates toward being more uniform. Under the calibrations from the empirical section, the demand for maintenance is both higher and more elastic for equipment than structures, which under the optimal tax theory derived in Section 2 implies that optimal tax rates should be pushed higher on equipment and reduced on structures. However, even though the optimal tax on structures is 1.5 times larger than on equipment rather than three times as in current practice is not necessarily a tremendous indictment of current policy. Theory and evidence combine to give a minor reform to how the government taxes equipment and structures.

Adding more types of capital, altering the functional forms for production, depreciation, or changing the way current policy optimality is ensured would surely change the results quantitatively and perhaps qualitatively. But focusing here on two types of capital and the simplest forms allow for maximal transparency while making the point that consideration of the maintenance channel should point policymakers toward significantly updating toward changing tax rates to reflect that. The evidence here indicates that a move toward the Diamond and Mirrlees (1971) uniform tax standard would be ideal.

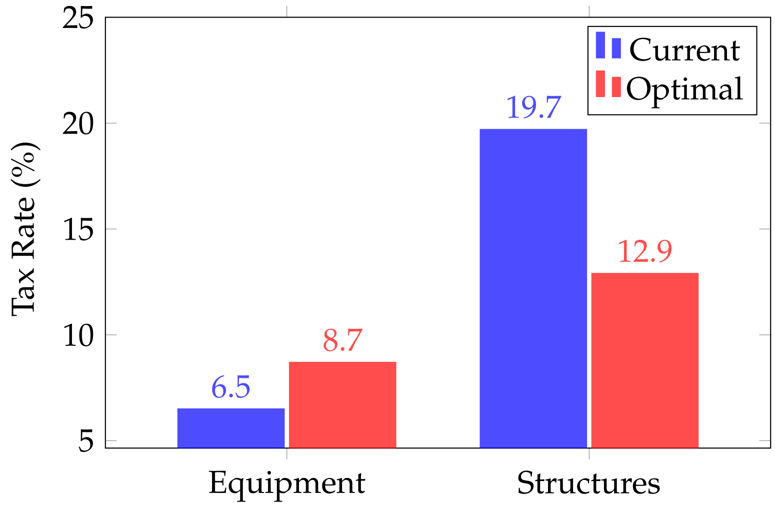


Figure 6: Current tax rates compared to optimal tax rates on equipment and structures when accounting for maintenance.

6 Concluding Remarks

In this paper, I highlight an understudied channel in the transmission of capital tax policy. To my knowledge, the theoretical and empirical results are completely unknown in the otherwise expansive literature on both positive and normative aspects of tax policy. Although I impose additional conditions for the sake of clarity, there are really only three that matter. First, the decision to maintain old capital must be an economic one. That is, the demand curve for maintenance must have some curvature. Second, depreciation technologies must vary between at least two capital types. In other words, at least one capital type must differ from another in its associated demand for maintenance. Finally, maintenance and investment must not be treated identically in the tax code. Although that would be efficient, tax policy generally does not treat maintenance and investment equally. Together, these distinguish the heterogeneous capital NGMM from its traditional counterpart, leading to the relevant positive and normative conclusions together with the subsequent empirical results.

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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A Model

A.1 Depreciation Measurement Error

The degree of potential for measurement error is useful to illustrate numerically. Suppose there are two capital types: E and S. Depreciation functions are parameterized by $\gamma_E = \gamma_S = 0.01$ with $\omega_E = 1$ and $\omega_S = 0.1$. Hence type E has a higher maintenance elasticity. Suppose depreciation was initially measured when $\tau_E = \tau_S = 50\%$. Let measurement error for capital type $i = E, S$ be defined as

$$\text{Measurement Error}_i = 100 \times \left(\gamma_i \left(\frac{1-\tau_i}{\gamma_i \omega_i} \right)^{\frac{\omega_i}{1+\omega_i}} - \gamma_i \left(\frac{1-0.5}{\gamma_i \omega_i} \right)^{\frac{\omega_i}{1+\omega_i}} \right).$$

A measurement error of two would correspond to actual depreciation two percentage points higher than the official depreciation rate. In Figure 7, I plot measurement error curves for both capital types as a function of the tax rate τ_i. Larger elasticities correspond to larger measurement error.

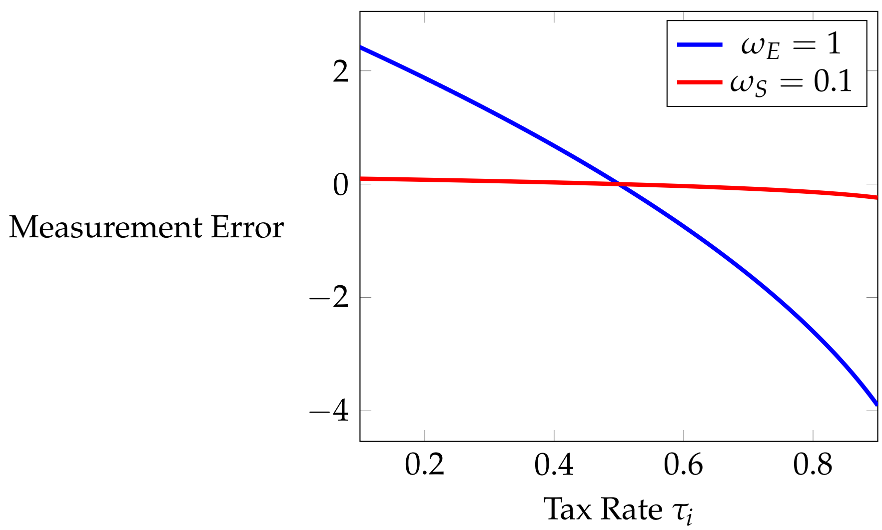


Figure 7: Measurement error curves for differing values of the maintenance elasticity, holding quality fixed at $\gamma_E = \gamma_S = 0.01$.

The quality of capital amplifies the degree of measurement error for a given maintenance elasticity. Now suppose the depreciation functions are parameterized by $\gamma_E = 0.05$ and $\gamma_S = 0.005$ with $\omega_E = \omega_S = 1$. This implies capital type E is lower quality and hence depreciates faster. In Figure 8, I plot measurement error curves for both capital types as a function of the tax rate τ_i. Clearly, the extent of measurement error is more serious for lower quality capital. When the marginal effective tax rate is zero percent, measurement error is five for capital type E compared to two for capital type S. Practically speaking, this may be an important issue for equipment and structures, which have quite different depreciation rates and have both seen large declines in marginal effective tax rates since initial measurement. In quantitative models featuring depreciating capital, failure to account for this may lead to incorrect conclusions.

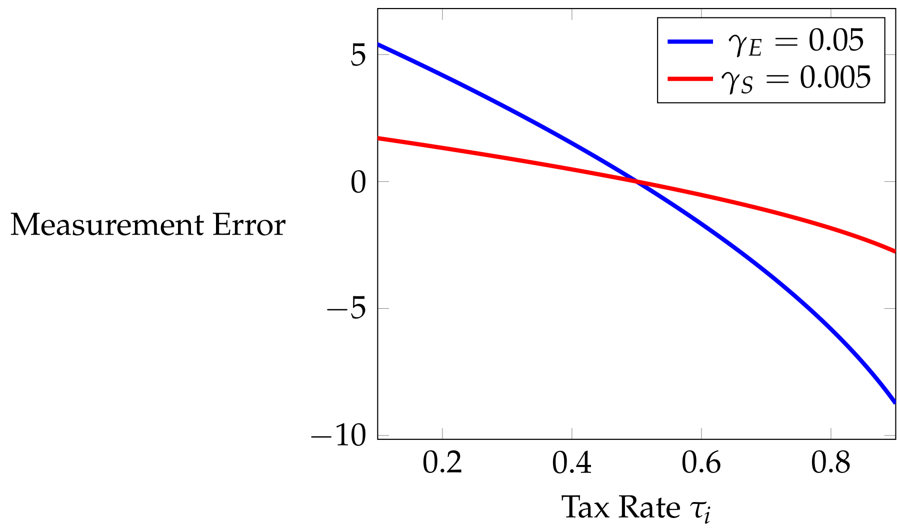


Figure 8: Measurement error curves for differing values of capital quality, holding fixed the maintenance elasticity at $\omega_E = \omega_S = 1$.

A.2 Ramsey Planner's Problem

The planner's Lagrangian is given by

$$\mathcal{L} = \sum_{t=0}^{\infty} \beta^t \Bigg\{ u(c_t) - v(H_t) \tag{19}$$

$$+ \theta_t \left[\sum_{i=1}^{N} \left(\tau_t^c K_{i,t} \left(F_{K_{i,t}} - m_{i,t} \right) - \tau_{i,t}^x \left(K_{i,t+1} - (1 - \delta_i(m_{i,t+1}) K_{i,t} \right) \right) - G_t \right] \tag{20}$$

$$+ \Psi_t \left[F(K_{1,t}, \ldots, K_{N,t}, H_t) - \sum_{i=1}^{N} \left[M_{i,t} + \left[K_{i,t+1} - (1 - \delta_i(m_{i,t}))\, K_{i,t} \right] \right] - c_t - G_t \right] \tag{21}$$

$$+ \sum_{i=1}^{N} \phi_{i,t} \Big[\beta u'(c_{t+1}) \Big\{ (1 - \tau_{t+1}^c) F_{K_{i,t+1}} + \left(1 - \tau_{i,t+1}^x\right) \left(1 - \delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1}) m_{i,t+1}\right) \Big\}$$

$$- u'(c_t)(1 - \tau_{i,t}^x) \Big] \tag{22}$$

$$+ \sum_{i=1}^{N} \mu_{i,t} \left[\frac{1 - \tau_t^c}{1 - \tau_{i,t}^x} + \delta_i'(m_{i,t}) \right] \tag{23}$$

$$+ \vartheta_t \left[F_{H_t} u'(c_t) - v'(H_t) \right] \Bigg\}, \tag{24}$$

where choices of capital, maintenance, labor, consumption, and asset-specific taxes determine the solution to the planner's problem.

A.3 Proof of Proposition 3

Proposition 3. *All else equal, the optimal steady-state tax distortion on capital type i is increasing in its maintenance elasticity and decreasing in capital quality.*

It is most convenient to formulate the problem as if the government chooses the sequence $\boldsymbol{\tau^x}$ through its choice of maintenance. From the private first-order condition on maintenance, we have that $-\delta_i'(m_{i,t}) = \frac{1-\tau^c}{1-\tau_{i,t}^x}$, so

$$\tau_{i,t}^x = \frac{1-\tau^c}{\delta_i'(m_{i,t})} + 1.$$

Using this, we can substitute for the tax on investment everywhere, so that the optimal choice of maintenance by the planner pins down the optimal tax. After substituting the law of motion for each capital type in, the government budget constraint becomes

$$\begin{aligned} G_t &= \sum_{i=1}^{N} \left[\tau^c \left(F_{K_{i,t}} - m_{i,t} \right) K_{i,t} - \tau_{i,t}^x \left(K_{i,t+1} - (1-\delta_i(m_{i,t}))K_{i,t} \right) \right] \\ &= \sum_{i=1}^{N} \left[\tau_t^c \left(F_{K_{i,t}} - m_{i,t} \right) K_{i,t} - \left(1 + \frac{1-\tau_t^c}{\delta_i'(m_{i,t})} \right) \left(K_{i,t+1} - (1-\delta_i(m_{i,t}))K_{i,t} \right) \right] \\ &= \sum_{i=1}^{N} \left[K_{i,t} \left(\tau_t^c \left(F_{K_{i,t}} - m_{i,t} \right) + (1-\tau_t^c) \frac{m_{i,t}}{\omega_i} - \delta_i(m_{i,t}) + \left(1 + \frac{(1-\tau_t^c)}{\delta_i'(m_{i,t})} \right) \right) - \left(1 + \frac{(1-\tau_t^c)}{\delta_i'(m_{i,t})} \right) K_{i,t+1} \right] \end{aligned} \tag{25}$$

The same substitution can be made in each Euler equation to yield, after rearranging,

$$u'(c_t) \left(\frac{1-\tau_t^c}{-\delta_i'(m_{i,t})} \right) = \beta u'(c_{t+1}) \left[\left(1-\tau_{t+1}^c\right) F_{K_{i,t+1}} - \frac{1-\tau_{t+1}^c}{\delta_i'(m_{i,t+1})} - (1-\tau_{t+1}^c) m_{i,t+1} \left(1 + \frac{1}{\omega_i} \right) \right]. \tag{26}$$

After replacing the government budget constraint and the household Euler equation with (25) and (26), the planner chooses sequences of maintenance, capital, consumption, and labor to maximize utility. To complete the proof, we only require first-order conditions for maintenance and capital. Those equilibrium conditions are given in (27) and (28), respectively.

$$\begin{aligned} \frac{u'(c_t)(1-\tau_t^c)}{K_{i,t}} \left(\phi_{i,t-1} \left(\frac{1+\omega_i}{\omega_i} - \frac{\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})^2} \right) + \phi_{i,t} \frac{\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})^2} \right) &= -\Psi_t \left(1 + \delta_i'(m_{i,t}) \right) \\ + \theta_t \left(-\tau_t^c + \frac{1-\tau^c}{\omega_i} - \delta_i'(m_{i,t}) + \frac{(1-\tau_t^c)\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})} \frac{1}{K_{i,t}} \left(K_{i,t+1} - K_{i,t} \right) \right) \end{aligned} \tag{27}$$

$$
\begin{aligned}
\Psi_t + \theta_t \left(1 + \frac{1-\tau_t^c}{\delta_i'(m_{i,t})}\right) =& \beta\Bigg\{ \theta_{t+1} \Bigg[\tau_{t+1}^c F_{K_{i,t+1}} - \delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1}) m_{i,t+1} + \left(1 + \frac{1-\tau_{t+1}^c}{\delta_i'(m_{i,t+1})}\right) \\
& - \frac{(1-\tau_{t+1}^c)\delta_i''(m_{i,t}+1)}{\delta_i'(m_{i,t})} \frac{m_{i,t+1}}{K_{i,t+1}} (K_{i,t+2} - K_{i,t+1}) + \sum_{j=1}^{N} \tau_{t+1}^c F_{K_{j,t+1}K_{i,t+1}} K_{j,t+1} \Bigg] \\
& + \Psi_{t+1} \left(F_{K_{i,t+1}} + 1 - \delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1}) m_{i,t+1} \right) \\
& + \frac{u'(c_{t+1})(1-\tau_{t+1}^c) m_{i,t+1}}{K_{i,t+1}} \Bigg[\phi_{i,t} \left(\frac{1+\omega_i}{\omega_i} - \frac{\delta_i''(m_{i,t+1})}{\delta_i'(m_{i,t+1})} \right) \\
& + \phi_{i,t+1} \left(\frac{\delta_i''(m_{i,t+1})}{\delta_i'(m_{i,t+1})} \right) \Bigg] + \sum_{j=1}^{N} \phi_{j,t} u'(c_{t+1})(1-\tau_{t+1}^c) F_{K_{j,t+1}K_{i,t+1}} \\
& + \vartheta_{t+1} u'(c_{t+1}) F_{H_{t+1}K_{i,t+1}} \Bigg\}
\end{aligned} \tag{28}
$$

Substituting (27) into (28) yields

$$
\begin{aligned}
\Psi_t + \theta_t \left(1 + \frac{1-\tau_t^c}{\delta_i'(m_{i,t})}\right) =& \beta\Bigg\{ \theta_{t+1} \Bigg[\tau_{t+1}^c \hat{r}_{i,t+1} - \delta_i(m_{i,t+1}) + \frac{(1-\tau_{t+1}^c) m_{i,t+1}}{\omega_i} + \left(1 + \frac{1-\tau_{t+1}^c}{\delta_i'(m_{i,t+1})}\right) \\
& + \sum_{j=1}^{N} \tau_{t+1}^c F_{K_{j,t+1}K_{i,t+1}} K_{j,t+1} \Bigg] \\
& + \Psi_{t+1} \left(F_{K_{i,t+1}} + 1 - \delta_i(m_{i,t+1}) - m_{i,t+1} \right) \\
& + \sum_{j=1}^{N} \phi_{j,t} u'(c_{t+1})(1-\tau_{t+1}^c) F_{K_{j,t+1}K_{i,t+1}} \\
& + \vartheta_{t+1} u'(c_{t+1}) F_{H_{t+1}K_{i,t+1}} \Bigg\},
\end{aligned} \tag{29}
$$

where $\hat{r}_i \equiv F_{K_i} - m_i$. In steady-state, this becomes

$$
\begin{aligned}
\theta \left(1 + \frac{1-\tau^c}{\delta_i'(m_i)}\right) \left(\frac{1}{\beta} - 1\right) + \Psi \left(\frac{1}{\beta} - F_{K_i} - 1 + \delta_i(m_i) - m_i\right) =& \sum_{j=1}^{N} \phi_j u'(c)(1-\tau^c) F_{K_j K_i} \\
+ \theta \left(\tau^c \hat{r}_i - \delta_i(m_i) + \frac{(1-\tau^c) m_i}{\omega_i} + \sum_{j=1}^{N} \tau^c F_{K_j K_i} K_j \right) & + \vartheta u'(c) F_{HK_i}.
\end{aligned} \tag{30}
$$

From household optimality,

$$
\frac{1}{\beta} = \frac{1-\tau^c}{1-\tau_i^x} F_{K_i} + 1 - \delta_i(m_i) + \delta_i'(m_i) m_i,
$$

so

$$
\Psi \left(\frac{1}{\beta} - F_{K_i} + \delta_i(m_i) + m_i\right) = -\Psi \tau_i \hat{r}_i.
$$

Recall that τ_i is the marginal effective tax rate on capital type i. Using the same substitution,

$$\theta\left[\left(1+\frac{1-\tau^c}{\delta_i'(m_i)}\right)\left(\frac{1}{\beta}-1\right)-\tau^c\hat{r}_i+\delta_i(m_i)-\frac{(1-\tau^c)m_i}{\omega_i}\right]=-\theta\tau_i\hat{r}_i.$$

Consequently, we have

$$-(\theta+\Psi)\tau_i\hat{r}_i=\sum_{j=1}^{N}\left(u'(c)\phi_i(1-\tau^c)+\theta\tau^c K_j\right)F_{K_jK_i}+\vartheta u'(c)F_{HK_i} \tag{31}$$

To make more progress, note that in steady-state, the optimality condition for maintenance can be written as

$$\phi_i u'(c)(1-\tau^c)=K_i\frac{\omega_i}{1+\omega_i}\left(\theta\left(\frac{1}{\omega_i}-\tau^c\left(\frac{1+\omega_i}{\omega_i}\right)-\delta_i'(m_i)\right)-\Psi(1+\delta_i'(m_i))\right) \tag{32}$$

Substituting back in to (31),

$$\begin{aligned}-(\theta+\Psi)\tau_i\hat{r}_i=&-\sum_{j=1}^{N}\Psi\left(1+\delta_i'(m_i)\right)\frac{\omega_j}{1+\omega_j}F_{K_jK_i}K_j+\sum_{j=1}^{N}\theta\frac{\omega_j}{1+\omega_j}\left(\frac{1}{\omega_j}-\delta_i'(m_i)\right)F_{K_jK_i}K_j+\vartheta u'(c)F_{HK_i}\\=&-(\Psi+\theta)\frac{\omega_i}{1+\omega_i}\frac{F_{K_i}}{\varepsilon_{K_{ii}}}\tau_i-\Psi\sum_{\substack{j=1\\j\neq i}}^{N}\frac{\omega_j}{1+\omega_j}\frac{F_{K_j}}{\varepsilon_{K_{ji}}}\tau_j+\theta\sum_{\substack{j=1\\j\neq i}}^{N}\frac{F_{K_i}}{\varepsilon_{K_{ji}}}+\vartheta u'(c)F_{HK_i}\end{aligned}$$

Manipulate this expression to yield

$$\tau_i=\left(\frac{\hat{r}_i}{F_{K_i}}\varepsilon_{K_{ii}}-\frac{\omega_i}{1+\omega_i}\right)^{-1}\boldsymbol{\varepsilon}_i, \tag{33}$$

where

$$\boldsymbol{\varepsilon}_i=\sum_{\substack{j=1\\j\neq i}}^{N}\frac{\omega_i}{1+\omega_i}\frac{\varepsilon_{K_{ii}}}{\varepsilon_{K_{ji}}}\frac{F_{K_j}}{F_{K_i}}\tau_j-\frac{1}{\theta+\psi}\left(\theta\sum_{j=1}^{N}\frac{\varepsilon_{K_{ii}}}{\varepsilon_{K_{ji}}}\frac{F_{K_j}}{F_{K_i}}+\vartheta u'(c)\frac{\varepsilon_{K_{ii}}}{\varepsilon_{HK_i}}\frac{F_H}{F_{K_i}}\right)$$

is a function of cross-elasticities. This gives the required result.

B Data

B.1 Data Construction

To estimate the maintenance elasticity for equipment, structures, and software, I pull data from three different sources: the Annual Survey of Manufactures (compiled by NBER-CES), the Federal Reserve Board's Manufacturing Investment and Capital Stock data, and the BEA's detailed data on fixest assets by type by industry. The former two are organized according to the 2012 NAICS industry classification at the six-digit NAICS level.[11] I use the latter exclusively for data on gross investment rates. The former only includes net investment in plant and equipment. However, the ASM has detailed information at the industry level on hours, the number of production workers, prices, and the value of shipments. Below, I document the variables and their sources:

- **Gross investment rate (FRB).** I take the period t value of gross investment $X_{i,t}$ for asset i and divide it by the lagged estimate of the capital stock for asset i. Winsorized by year at the 1% and 99% level.

- **Price of maintenance (ASM).** Because maintenance is typically quite labor-intensive, I identify it with industry-specific unit labor cost. I construct this measure by first deflating the nominal value of shipments with the price deflator for that industry's shipments and scaling the resulting value of real shipments with the number of production workers. Next, I created an industry-specific output per worker index using 2012 as base year. Dividing this through by an hours per production worker index (also with base year 2012) yields labor productivity. Finally, I construct an index of nominal labor costs obtained by dividing the total wage bill by the number of production workers. Dividing this index by labor productivity corresponds to unit labor cost. I winsorize this variable by year at the 1% and 99% levels.[12]

- **Price of investment (BEA).** Using detailed data on investment from the BEA, I compute a weighted price of investment for each of equipment and structures for each manufacturing industry at the three-digit level. For each asset type, I first obtain deflators by dividing the nominal series by its real counterpart. Then, for each industry, I find investment weights within each asset type and compute an industry investment price for each asset by multiplying the weights by the corresponding price series and summing. I then match each three-digit NAICS price to the more detailed six-digit NAICS industry.

11. Results change very little if instead SIC codes are used. I use NAICS codes to avoid the somewhat arbitrary choice of assigning investment to old industry codes. Whereas categories like hours, employment, and value added have weighted bridges constructed by the US Census Bureau, investment does not. Consequently, it would be a difficult task to confidently assign investment to different industry codes.

12. I also winsorize all growth rates at the 1% and 99% level.

- **Relative price of maintenance to investment for asset i.** Taken as dividing the price of maintenance (identified with unit labor cost) with the asset-specific price (defined in the main text). I then multiply this relative price by the standard user cost tax term $\frac{1-\tau_t^c}{1-\tau_{i,j,t}^x}$, where $\tau_{i,j,t}^x$ collects asset- and industry-specific tax provisions like the investment tax credit and tax depreciation. I describe where these values come from in Appendix B.2. I remove all values that have a relative price of maintenance to investment greater than fifteen. These constitute large outliers and imply a very steep drop in relative prices in the early sample period. To construct the instrument, I winsorize growth rates in the relative price of maintenance by year at the 2% and 98% levels. After winsorization, I reconstruct an index of the relative price of investment from the winsorized growth rates.

- **Productivity growth (ASM).** See the description in the price of maintenance variable. I log-difference the level of labor productivity. The ASM provides four- and five-variable TFP measures which are highly correlated. In the actual regressions, I demean productivity growth. This variable is winsorized by year at the 2% and 98% levels.

- **Hours (ASM).** I create an index of hours per production worker with 2012 as the base year and log-transform. The change in hours—which enters all regressions demeaned—is winsorized by year at the 2% and 98% levels.

- **Employment (ASM).** Certain specifications control for industry size via employment. This variable is simply the logarithm of the employment variable in the ASM.

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Year	13,760	1,997.000	12.410	1,976	1,986	2,008	2,018
Equip. Invest. Rate	13,760	0.078	0.035	0.0004	0.055	0.095	0.599
Struct. Invest. Rate	13,760	0.026	0.025	0.000	0.011	0.033	0.587
Inv. Rel. Price Equip	13,760	1.395	0.640	0.424	1.025	1.545	8.248
Inv. Rel. Price Struct	13,760	1.782	0.969	0.469	1.086	2.129	10.763
Hours Growth	13,760	0.00003	0.034	−0.292	−0.017	0.018	0.310
Log Emp.	13,760	3.241	0.915	−0.105	2.639	3.857	6.463
Productivity Growth	13,760	0.019	0.070	−0.320	−0.020	0.058	0.370
Equip Shock	13,760	−0.000	0.988	−3.825	−0.615	0.618	4.334
Struct Shock	13,760	0.000	0.988	−3.890	−0.599	0.604	4.453
Productivity Shock	13,760	−0.000	0.988	−4.607	−0.592	0.606	4.426
Hours Shock	13,760	0.000	0.988	−5.149	−0.583	0.607	4.639

Table 1: Summary Statistics

B.2 Tax Policy Construction

Toward creating a database of industry-by-asset-specific marginal effective tax rates (METR) on corporate capital, I combine data from the BEA and the IRS. 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 $\tau^a_{i,t}$ for sub-asset i in the broader class of assets $a \in \{\text{Equipment, Structures}\}$.

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 on equipment and structures (separately) as
$$\tau^a_{j,t} = \sum_{i=1}^{N} \alpha^a_{i,j,t} \tau^a_{i,t}, \quad a \in \{E, S\}$$
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 within major category $a \in \{E, S\}$ as

$$\tau^a_{i,t} = 1 - \frac{1 - \tau^c_t}{1 - \text{ITC}^a_{i,t} - z^a_{i,t}\tau^c_t}, \tag{34}$$

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_t^c is straightforward to obtain. Second, the investment tax credit $\text{ITC}_{i,t}^a$. 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.

$z_{i,t}^a$ is more difficult and requires some level of judgment. Suppose an asset has allowable depreciation $D_{i,t}^a$ and define $d_{i,t}^a$ 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

$$z_{i,t}^a = \sum_{t=0}^{\infty} \left(\frac{1}{1+r^k} \right)^t d_{i,t}^a.$$

Throughout, I assume that the required return on capital $r^k = 0.1$. While this assumption is clearly not innocuous, it is comparable to some of the recent literature. For example, Gormsen and Huber (2022) find that the average required return from firms is around 15%, while Barro and Furman (2018) use a required return of 10% (after inflation) in their analysis of the 2017 Tax Cuts and Jobs Act. Earlier literature on tax policy from the 1980s (see, e.g., Auerbach (1983) and Jorgenson and Yun (1991)) tends to use lower discount rates. $z_{i,t}$ varies both across assets and between tax eras. I discuss each era in chronological order. I relied heavily on Brazell, Dworin, and Walsh (1989) for understanding each era.

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

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

MACRS (1987-Present). The Tax Reform Act of 1986 changed depreciation schedules and got rid of the ITC while retaining much of the simplicity of the ACRS era. House and Shapiro (2008) map each asset to a corresponding depreciation table in IRS Publication 946. I use their matching scheme and assumptions about which depreciation method firms use. For example, most equipment is depreciated with the double-declining balance method, while structures are often depreciated with the straightline method. Using the House-Shapiro mapping schema, 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, define the net present value of tax depreciation allowances as

$$\tilde{z}^a_{i,t} \begin{cases} \theta + (1-\theta_t) z^a_{i,t} & \text{if eligible} \\ z^a_{i,t} & \text{if ineligible,} \end{cases} \tag{35}$$

where $\tilde{z}^a_{i,t}$ takes the place of $z^a_{i,t}$ in equation 34. 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 $\alpha^a_{i,j,t}$ 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 real investment flows from the current year to determine weights on each asset for each industry. That is,

$$\alpha^a_{i,j,t} = \frac{x^a_{i,j,t}}{X^a_{j,t}},$$

where $x_{i,j,t}$ is real investment in asset i from industry j within a major category a (equipment or structures) and $X_{j,t}$ is total investment 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 for each asset in major category $a \in \{E, S\}$ can then be defined as

$$\tau^a_{j,t} = \sum_{i=1}^{36} \alpha^a_{i,j,t} \tau^a_{i,t}.$$

I do the exact same thing to get average investment prices for each industry. Using the BEA-NAICS bridge, we then have prices and tax rates for each three-digit NAICS industry.

B.3 Shock Construction

Here, I provide a more detailed description of the shock construction procedure used in the main text. The approach is built on Fisher (2006). By assumption, the relative price of maintenance to investment is non-stationary, so its first difference is stationary. I provide evidence of this for both equipment and structures in Figures 9a and 9b, where I plot relative prices for equipment and structures for each industry in the sample along with the median. First-differencing results in a stationary relative price. Similarly, I assume that productivity growth and hours per worker are stationary. Again, there is evidence for this in Figures 9c and 9d.

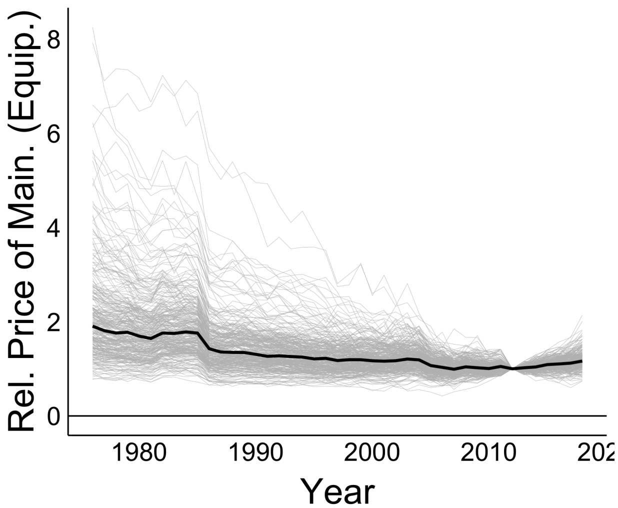
The main text describes shock construction for relative prices, productivity, and hours. Essentially, I rely on the time series properties of the data to construct permanent shocks. Shocks to relative prices can affect all variables except other relative prices, shocks to productivity cannot affect relative prices but can affect hours, and shocks to hours can only affect hours. An overdifferenced variable, by construction cannot have a long-run effect. First-differenced relative prices and productivity are stationary, while hours per worker is a stationary variable. Consequently, to implement Proposition 5, we can borrow from Fisher (2006) and Shapiro and Watson (1988). For example, to get permanent shocks to relative prices for equipment, we would run the following regression:

$$\begin{aligned}\Delta \log V_{E,j,t} =& \alpha_j + T_t + \sum_{s=1}^{p} \beta_{V_E} \Delta \log V_{E,j,t-s} + \sum_{s=0}^{p-1} \beta_{V_S} \Delta^2 V_{S,j,t-s} \\ &+ \sum_{s=0}^{p-1} \beta_{\text{Prod}} \Delta^2 \text{Prod}._{j,t-s} + \sum_{s=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{j,t-s} + \mu_{E,j,t}.\end{aligned} \tag{36}$$

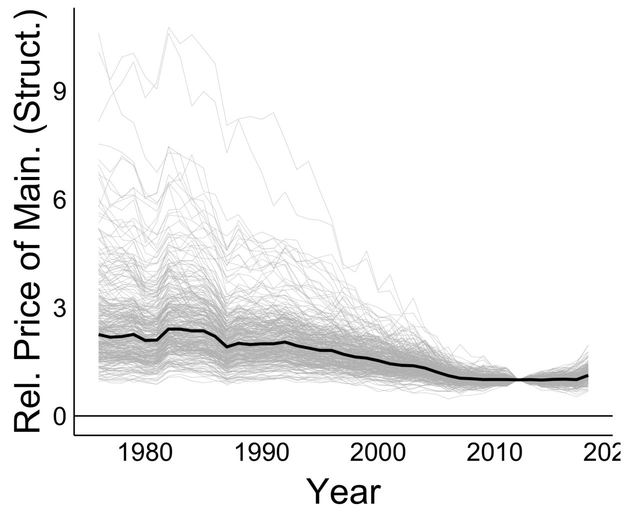
To get shocks to structures, we simply swap out $V_{S,j,t}$ for $V_{E,j,t}$ in (36). Then, with shocks to equipment, $\mu_{E,j,t}$ and $\mu_{S,j,t}$ in hand, we can get productivity shocks from

$$\begin{aligned}\Delta \text{Prod}._{j,t} =& \alpha_j + T_t + \sum_{s=1}^{p} \beta_{V_E} \Delta \log V_{E,j,t-s} + + \sum_{s=1}^{p} \beta_{V_S} \Delta \log V_{S,j,t-s} \\ &+ \sum_{s=1}^{p} \beta_{\text{Prod}} \Delta \text{Prod}._{j,t-s} + \sum_{s=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{j,t-s} + + \mu_{E,j,t} + \mu_{S,j,t} + \eta_{j,t}.\end{aligned} \tag{37}$$

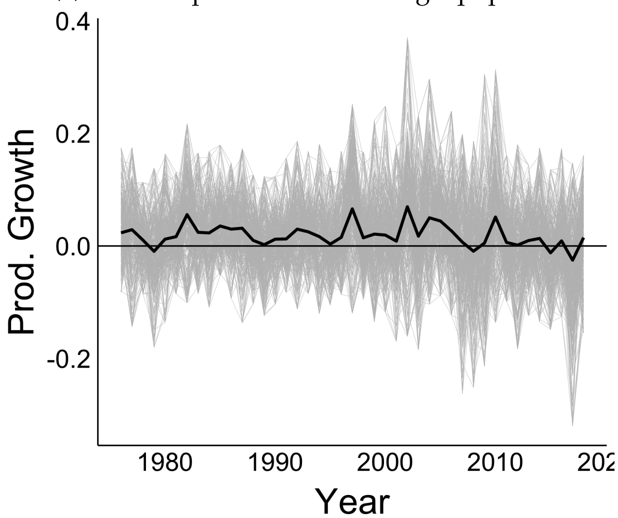
The final regression uncovers the hours shock and is similar to the productivity regression, except it uses the log level of hours as the dependent variable and has both the productivity and relative price shocks entering contemporaneously. Each shock series is then the standardized residual within each industry.



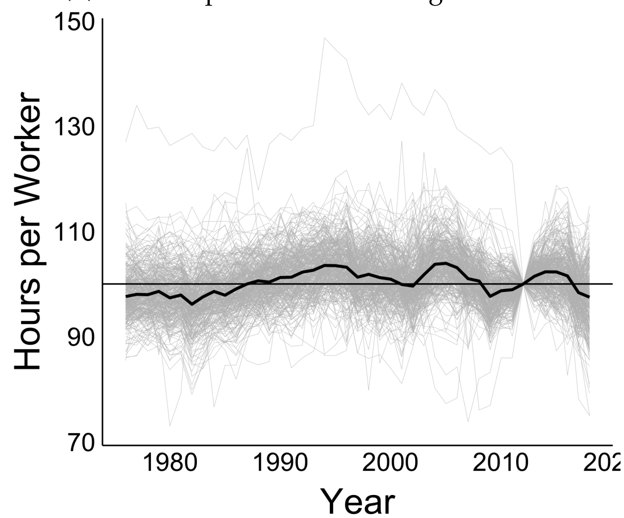
(a) Relative price of maintaining equipment



(b) Relative price of maintaining structures



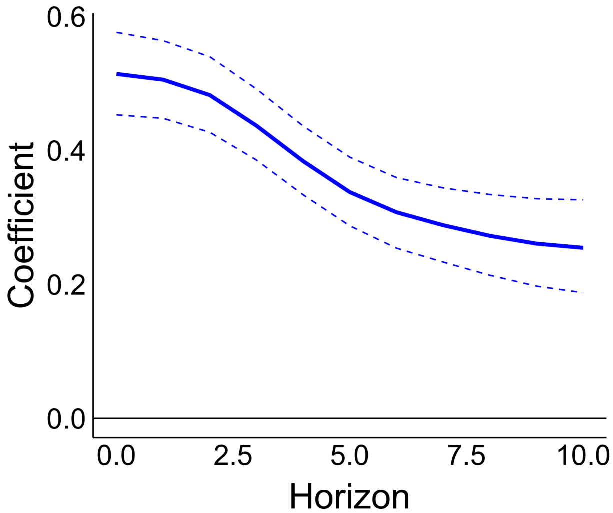
(c) TFP Growth



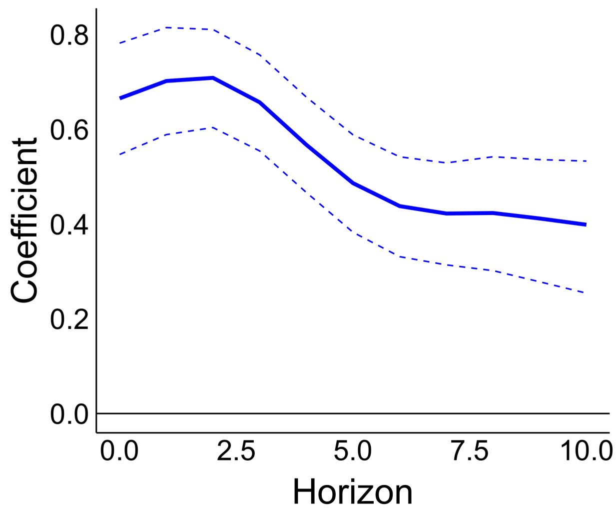
(d) Hours per worker (2012 = 100)

Figure 9: Variables for constructing idiosyncratic permanent shocks to the relative price maintaining equipment, relative price of maintenance in structures, productivity, and hours. Thick black lines are yearly medians.

C Empirical Results

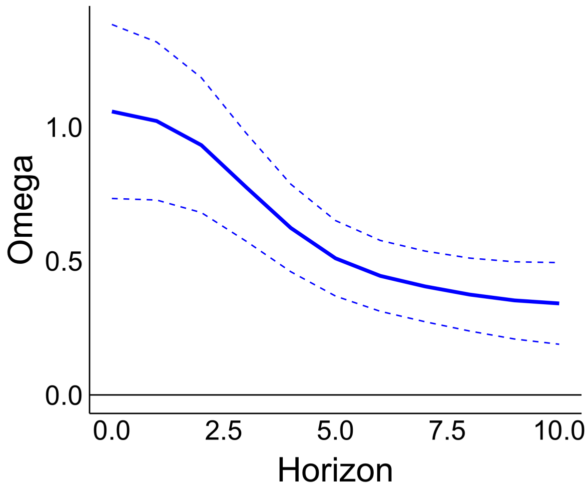


(a) Equipment

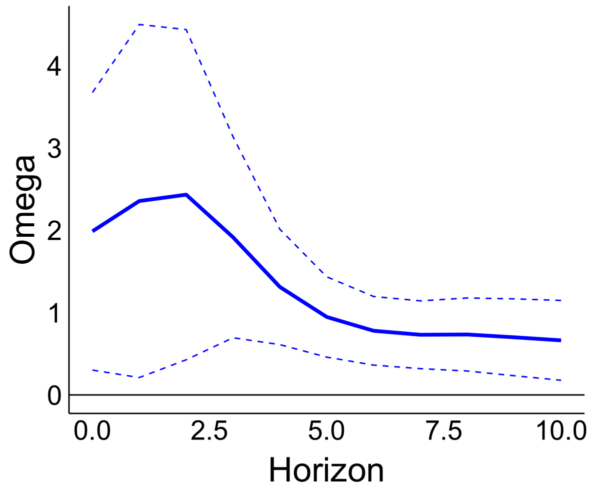


(b) Structures

Figure 10: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 2$.



(a) Equipment



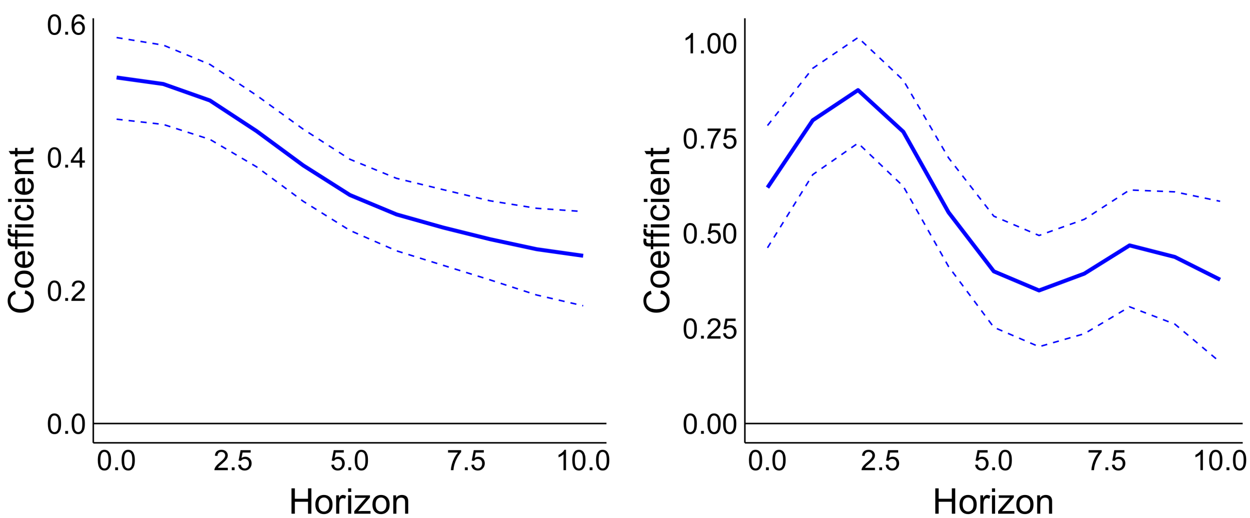
(b) Structures

Figure 11: Estimates for $\omega_{i,h}$ for each capital type i at horizon h along with associated standard errors, which are constructed via wild cluster bootstrap.

C.1 Robustness

In this subsection, I present robustness checks by varying the polynomial fit and lag length. Point estimates are largely similar across specifications. In Appendix D, I detail the procedure for estimating the SLPP IRFs and show how it compares to the standard panel LP IRF.

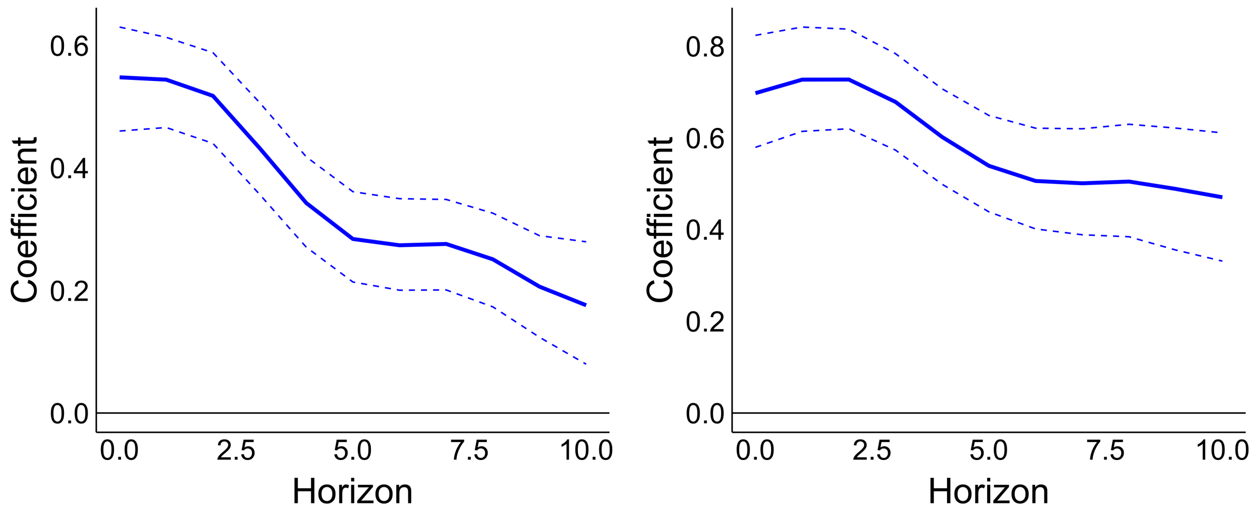
Penalized to Line



(a) Equipment

(b) Structures

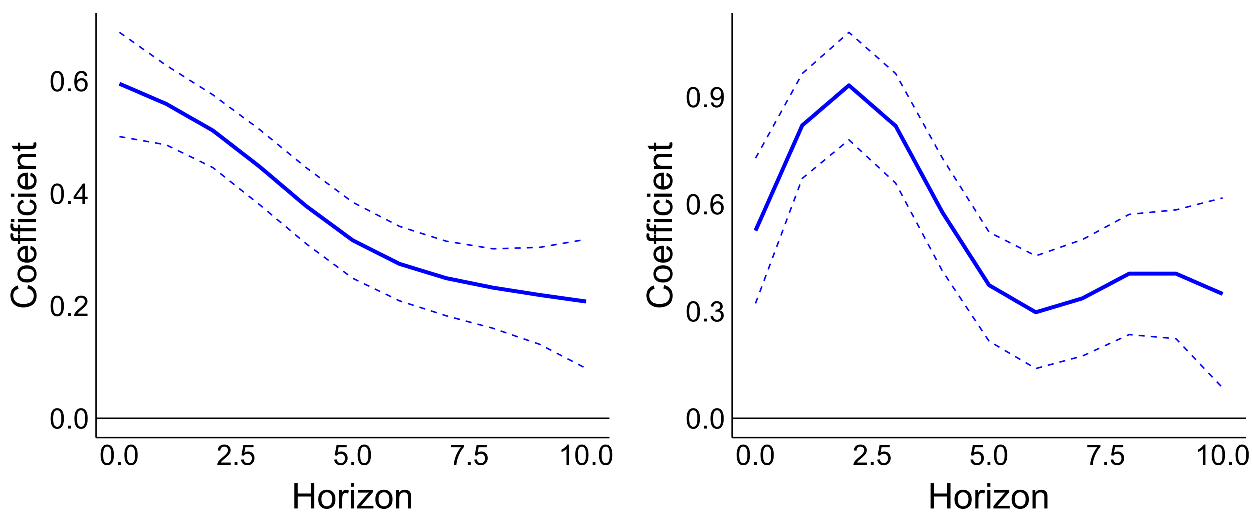
Figure 12: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 3$.



(a) Equipment **(b)** Structures

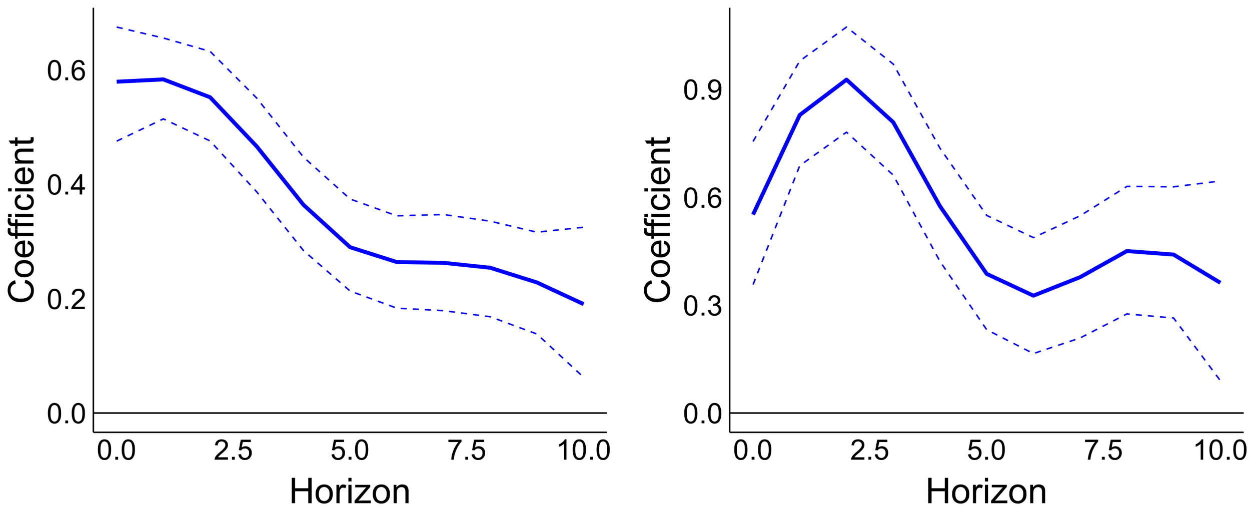
Figure 13: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 4$.

Penalized to Quadratic



(a) Equipment **(b)** Structures

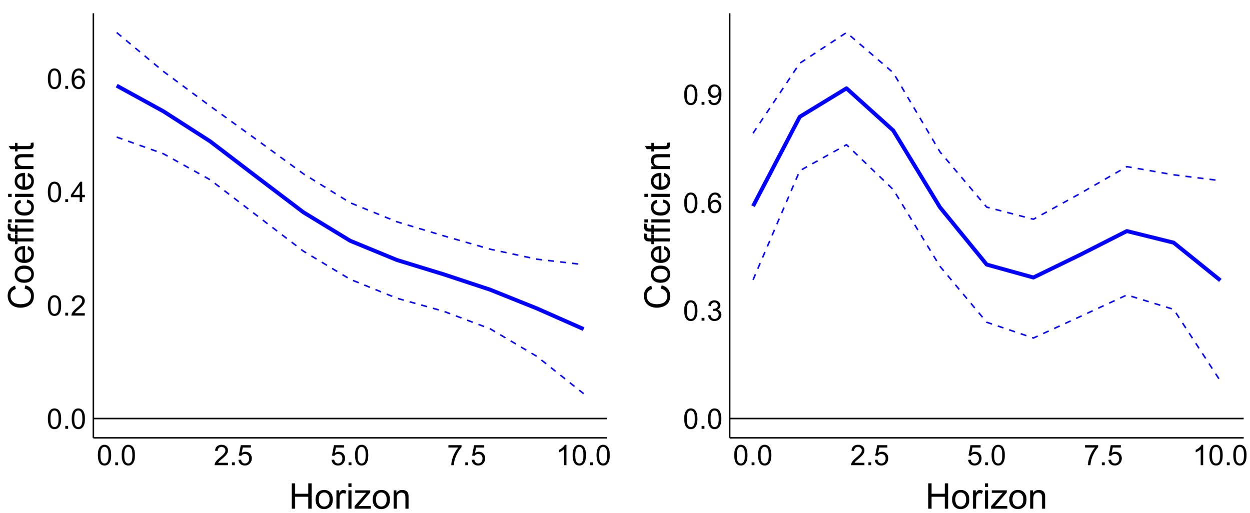
Figure 14: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 2$ with the impulse response penalized to a quadratic function.



(a) Equipment

(b) Structures

Figure 15: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 3$ with the impulse response penalized to a quadratic function.

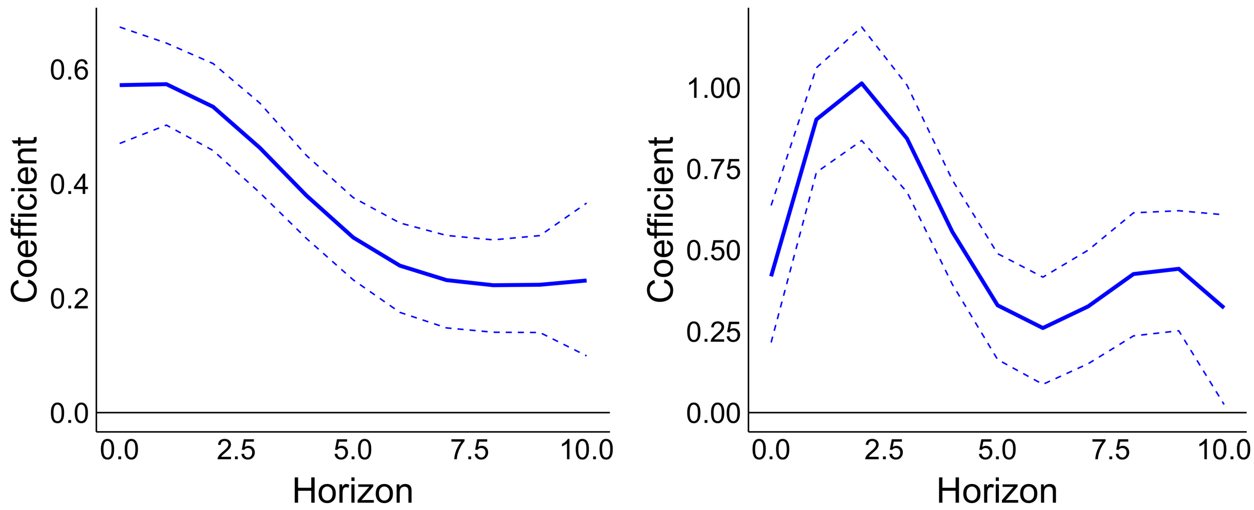


(a) Equipment

(b) Structures

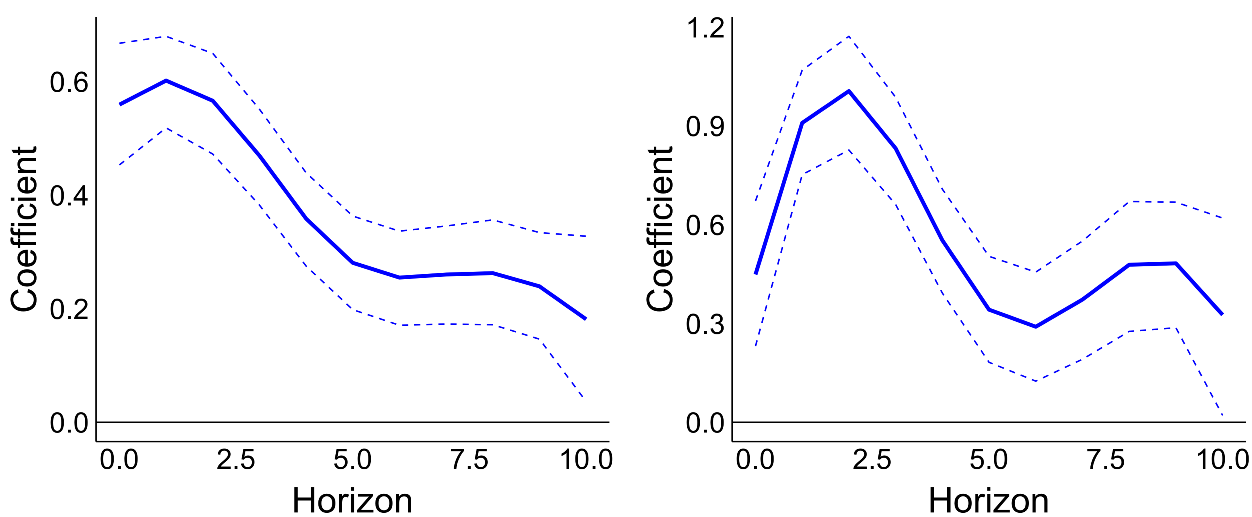
Figure 16: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 4$ with the impulse response penalized to a quadratic function.

Penalized to Cubic



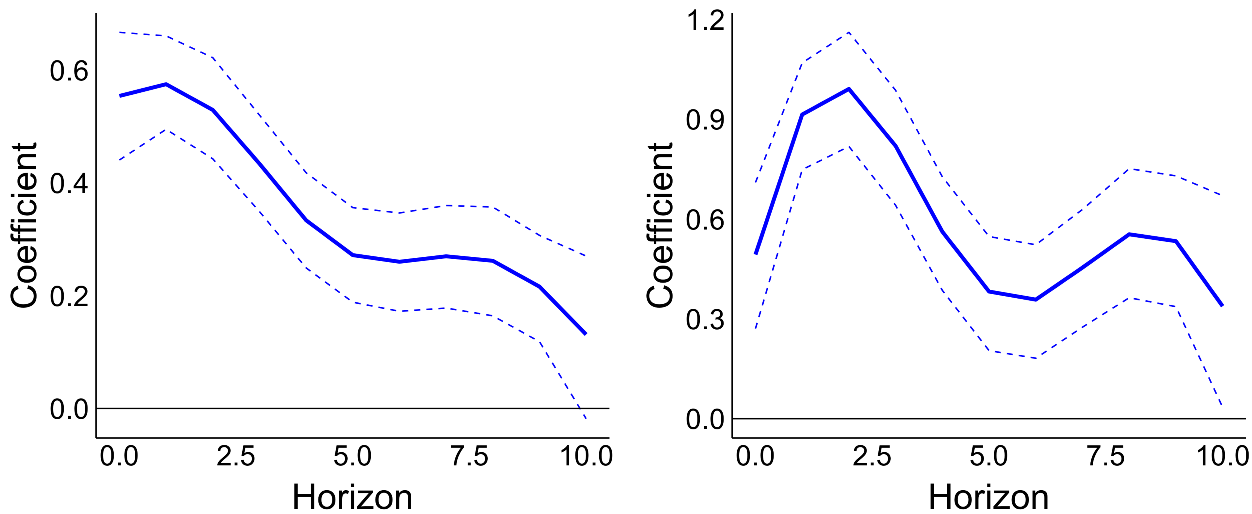
(a) Equipment **(b)** Structures

Figure 17: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 2$ with the impulse response penalized to a cubic function.



(a) Equipment **(b)** Structures

Figure 18: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 3$ with the impulse response penalized to a cubic function.



(a) Equipment

(b) Structures

Figure 19: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (18) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 4$ with the impulse response penalized to a cubic function.

D Smooth Local Panel Projections

In this section, I outline the procedure for estimating smooth local projections for panel data. The idea expands on Barnichon and Brownlees (2019), who first proposed smooth local projections for time series data. Essentially, the same procedure can be followed. Consider a typical dynamic panel regression

$$y_{i,t+h} = \alpha_i + \tau_t + x_{i,t}\beta_h + \nu_{i,t+h},$$

for $i = 1, \ldots, N$ and $t = 1, \ldots, T$, where α_i is an individual fixed effect and τ_t is a time fixed effect. For simplicity, let $x_{i,t}$ be the only variable of interest. As in Barnichon and Brownlees (2019), the goal is to make the coefficient β_h a smooth function of the impulse horizon. To do that, we simply use a B-spline basis function to approximate the coefficient

$$\beta_h \approx \sum_{k=1}^{K} b_k B_k(h)$$

for K sufficiently large (in the paper, I use 13). Let H_{max} denote the maximum forecast horizon. To set notation, let $\boldsymbol{y}_{i,t}$ denote the vector $(y_{i,t}, \ldots, y_{\{i,\min\{T,t+H_{\max}\}\}})'$ with length d_t. Let $\boldsymbol{x}_{i,t}$ for $t = 1, \ldots, T$ denote the $d_t \times K$ matrix with element (h, K) equal to $B_k(h)x_{i,t}$. Next, let $\mathcal{Y}$ denote the stacked vector individual vectors $y_{i,t}$ and $\mathcal{X}$ denote the stacked matrices for individuals $\boldsymbol{x}_{i,t}$. Finally, let θ denote the vector of B-splines coefficients $(b_1, \ldots, b_K)$. With that notation, the procedure is as follows.

1. **Demean data with respect to relevant fixed effects.** In the paper, that means demeaning $y_{i,t+h} - y_{i,t-1}$ and demeaning the rest of the variables in a standard way with respect to NAICS code and year.

2. **Construct matrices $\mathcal{Y}$ and $\mathcal{X}$.** Note that maintaining order is crucial for the demeaned data. In particular, demeaned data must be ordered within individual clusters by time and horizon.

3. **Estimate ridge regression**:

$$\begin{aligned}\hat{\theta} &= \arg\min_{\theta}\{\|\mathcal{Y} - \mathcal{X}\theta|^2 + \lambda\theta'\boldsymbol{P}\theta\} \\ &= \left(\mathcal{X}'\mathcal{X} + \lambda\boldsymbol{P}\right)^{-1}\mathcal{X}'\mathcal{Y},\end{aligned}$$

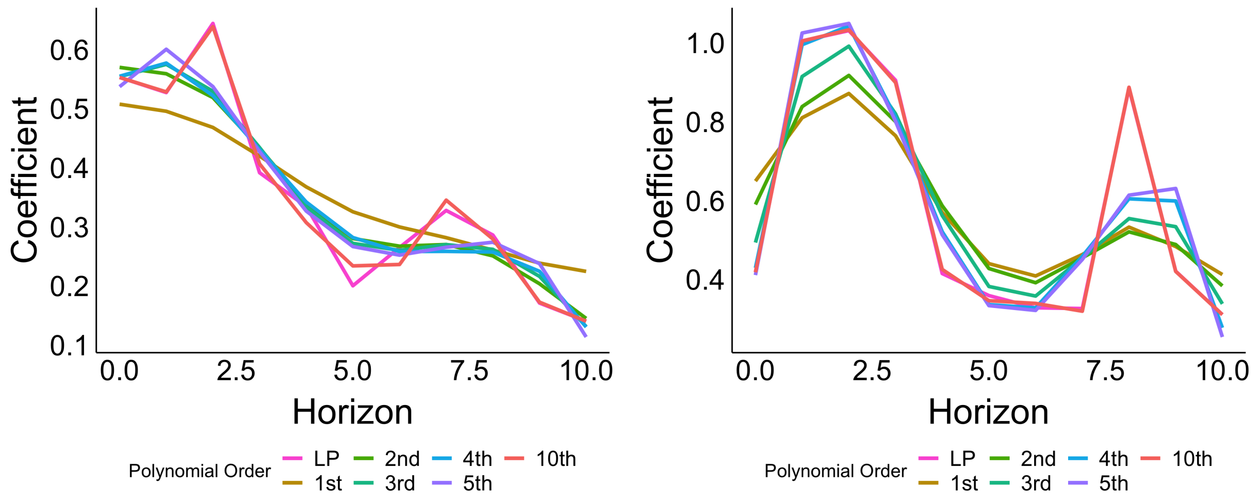
   where $\lambda > 0$ is a shrinkage parameter and P is a symmetric positive semidefinite penalty matrix. λ determines the bias/variance trade-off.

4. **Use $k-$fold cross validation by cluster and time** to select a penalty parameter to penalize toward a polynomial of order q.

5. **Construct confidence bands** using wild cluster bootstrap.

Note that there are only a couple of difference from Barnichon and Brownlees (2019). First, we must be careful about maintaining the order of the data so that the demeaned matrices represent the local projection correctly. Second, the $k-$fold validation procedure is different. Because we have panel data, it is best to validate using both the cross-sectional and the time series dimension. In the paper, I use three folds for the time dimension and five for clusters. Finally, we do inference with a wild cluster bootstrap. As of now, we do not know the bias/variance trade-off between standard panel local projections and smooth local projections.

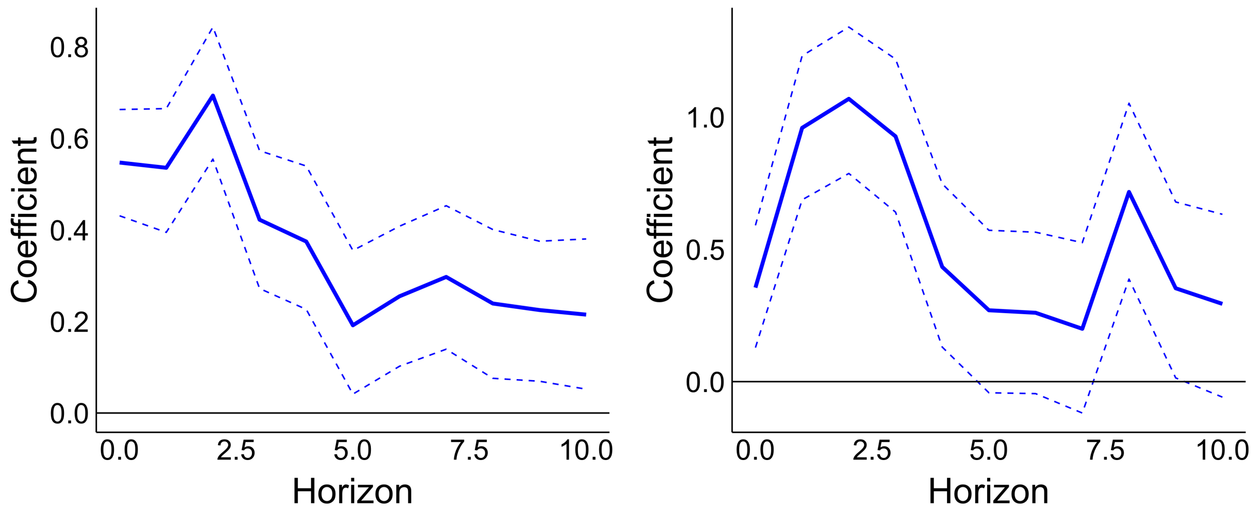
In Figure 20, I plot the point estimate of the impulse response function for standard LP compared to varying polynomial orders for the smooth local projection estimator. Evidently, as the polynomial order increases, it converges to the standard LP estimator.



(a) Equipment **(b)** Structures

Figure 20: Comparison between standard local projections and smooth local projections penalized toward differing polynomial orders using the structures specification from the main text.

In Figure 21, I plot the standard local projections estimator for each of the specifications in the main text along with associated confidence intervals. Evidently, only equipment is stable, while structures and software similarly lumpy and it is difficult to reject a zero coefficient for the maintenance elasticity at certain horizons. Part of the problem with the maintenance elasticity is that it requires inverting a confidence interval, a procedure which can substantially blow up standard errors. That is quite clear for structures, with explosive standard errors at horizons one and eight.



(a) Equipment

(b) Structures

Figure 21: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years for standard local projections with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.

E Quantification

E.1 TCJA Analysis Calibration

Calibration of parameters is entirely from Barro and Furman (2018), with the exception of depreciation rates. For one set of analyses, I use depreciation rates from Baldwin, Liu, and Tanguay (2015) and for another, I use depreciation rates from the BEA.

E.2 Optimal Tax Rates

See the main text for a discussion of how I solved for ϕ_i and calibrated the government budget constraint.

To calibrate γ_i, I use the first-order condition for maintenance together with the steady-state capital accumulation equation. Putting those together implies

$$\tilde{\delta}_i = \gamma_i \left(V_i \frac{1}{\gamma_i \omega_i} \right)^{\frac{\omega_i}{1+\omega_i}},$$

where $V_i \equiv \frac{q_i}{p_i} \frac{1-\tau^c}{1-\tau_i^x}$ is the after-tax relative price of maintenance to equipment and $\tilde{\delta}_i$ is an estimated depreciation rate. Given V_i, $\tilde{\delta}_i$, and ω_i, we can solve for γ_i. Because the paper implies that estimates of depreciation are dependent on prevailing policy, which is captured in the term V_i, I use estimates of the relative price of maintenance from 1980. That is because most estimates of depreciation used by the BEA for structures and equipment come from Hulten and Wykoff (1981a) and Hulten and Wykoff (1981b). To remain consistent with the data, I use the median relative prices of maintenance from the industry-level data in Section 4, which implies $V_S \approx 3$ and $V_E \approx 1.4$. That, paired with $\tilde{\delta}_E = 0.1$ and $\tilde{\delta}_S = 0.03$ is sufficient to recover a value for γ_i given an assumed maintenance elasticity for each capital type. In Figure 22, I plot the value of γ_i for each of equipment and structures as a function of the assumed maintenance elasticity for $\omega_i \in [0, 1]$.

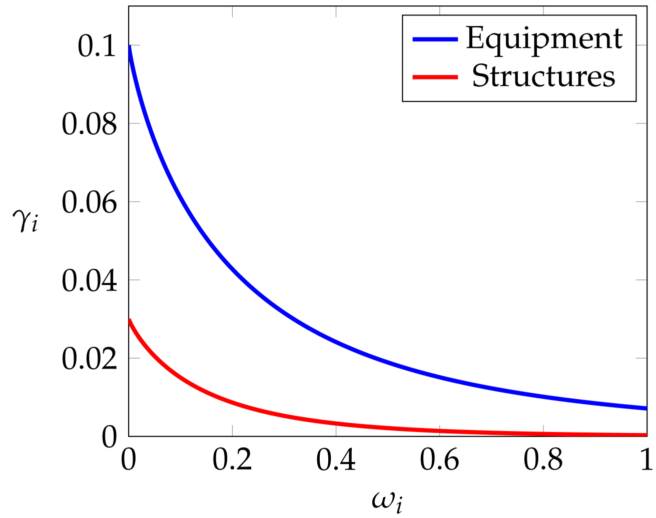


Figure 22: Calibration of γ_i for equipment and structures as a function of the maintenance elasticity ω_i. I assume that the values for steady-state depreciation are $\tilde{\delta}_E = 0.1$ and $\tilde{\delta}_S = 0.03$, and for relative prices are $V_E = 1.4$ and $V_S = 3$.

Parameter	Value	Source
r^k	0.1	
α_E	0.175	
α_S	0.175	
$\mathcal{W}$	$[0,1] \times [0,1]$	Grid of plausible maintenance elasticities
ω_E	0.4	Figure 4 (for point estimate)
ω_S	0.7	Figure 4 (for point estimate)
γ_E		Set to match $\tilde{\delta}_E = 0.1$ and $V_E \approx 1.4$. See text below.
γ_S		Set to match $\tilde{\delta}_S = 0.03$ and $V_S \approx 3$. See text below.
τ^c	0.27	Barro and Furman (2018)
χ		Set to match $H = 1/3$ at initial tax rates
$\tilde{\delta}_E$	0.1	
$\tilde{\delta}_S$	0.03	
τ_E^{init}	0.068	Own calculation (Initial tax rate for equipment)
τ_S^{init}	0.197	Own calculation (Initial tax rate for structures)
ϕ_E	0.54	Own calculation
ϕ_E	0.2	Own calculation

Table 2: Calibrated parameters