Capital Maintenance and Differential Capital Taxation

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I study the positive and normative consequences of relaxing the standard assumption that the demand for capital maintenance is perfectly inelastic, typically zero, and identical across capital types. Noting that tax policy incentivizes maintaining old capital over investing in new capital, I make four contributions. First, I show in a heterogeneous capital framework that because the demand for maintenance is inversely related to the marginal effective tax rate on new investment and runs through its effect on the depreciation rate, capital with a high maintenance elasticity of depreciation is relatively insulated from tax changes, so uniform capital taxation is not neutral. Second, a simple extension to optimal policy reveals that a second-best Ramsey planner would place higher tax distortions on capital types with higher maintenance elasticities and higher demand for maintenance. Third, I provide new estimates of depreciation functions for equipment and structures using a novel smooth local projections approach with data from the Annual Survey of Manufactures. Finally, I evaluate the positive and normative quantitative significance of the maintenance channel. Positively, compared to a standard neoclassical analysis of the 2017 Tax Cuts and Jobs Act, inclusion of the maintenance channel is numerically equivalent to cutting the capital share by 15-20%. Normatively, assuming that the current capital tax schedule is optimal—in which the marginal tax rate on structures is three times higher than on equipment—accounting for maintenance implies tax rates should be roughly uniform.

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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, janitors to keep up and repair structures, nor teams of computer scientists to maintain software. 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 the neoclassical growth model (NGM) that the no-maintenance world prevails and explicit that the demand for maintenance is not only perfectly inelastic, but zero. 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 by allowing depreciation technologies to vary between capital types, leading to a rich demand system for maintenance of old capital and investment in new capital, all of which depends on the diverse array of taxes distorting the relative price of maintenance to investment for each asset type.

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 uniform tax on the gross return on capital—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. Using current policy as a benchmark—in which the marginal effective tax rate on equipment is about 6.5% and 20% on structures—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.

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 1972-2015 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 0.5, while it is 0.2 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. Compared to the current system substantially favoring equipment, accounting for maintenance suggests taxes should be roughly uniform.

Literature. This paper relates to several strands of literature. First, it connects to a long-standing 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 (1998) and Goolsbee (2004) present clear 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 (1998) 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 1998). 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 Auerbach (1979), which studies differential taxation in a dynamic setting in which the government is free to tax any kind of capital, and 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 pre-existing 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 extend a heterogeneous capital neoclassical growth model to include endogenous depreciation via maintenance. In the model, demand for maintenance is determined by the relative price of maintenance to investment, which I assume is a function of tax policy to reflect current practice insulating maintenance expenditures from income taxes. 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 Decentralized Economy

Consider an economy populated by a representative firm, a representative household, and a government. The firm produces an output good Y_t with N capital types and labor with 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 rents each capital type from the household at rate $r_{i,t}$ and labor at wage rate w_t. At an interior solution, profit maximization requires

$$F_{K_{i,t}} = r_{i,t}, \qquad i = 1, \ldots, N \tag{2}$$

$$F_{H_t} = w_t. \tag{3}$$

The representative firm rents each capital type and hires labor from a representative household with preferences over consumption c and labor H given by

$$\sum_{t=0}^{\infty} \beta^t \Big[u(c_t) - v(H_t) \Big] \tag{4}$$

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.

In addition to earning wage rate w_t for supplying labor H_t, the household saves in N discrete types of capital $K_{i,t}$, each of which generates return $r_{i,t}$. Every period, for each capital type i, the household 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

$$K_{i,t+1} = X_{i,t} + (1 - \delta_i(m_{i,t}))K_{i,t}. \tag{5}$$

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 regularity conditions on the depreciation technology.

Assumption 1. *$\delta_i(m_{i,t})$ is strictly convex, strictly decreasing, twice continuously differentiable, and exhibits constant elasticity parameterized by ω_i, where*

$$\omega_i = \frac{-\delta_i'(m_{i,t})m_{i,t}}{\delta_i(m_{i,t})}.$$

The representative agent encounters two capital tax policies. First, the gross return on all capital types is taxed uniformly at rate τ_t^c with maintenance subsidized at a corresponding rate. This is to mimic the fact that, in practice, a profit tax levied on the firm is effectively a uniform tax on capital and maintenance is subsidized at that rate. Second, new investment $X_{i,t}$ is subsidized at rate $\tau_{i,t}^x$. 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 $\tau_{i,t}^x$ as a depreciation allowance. Finally, the household earns a wage w_t from supplying labor to the firm. Consequently, the household budget constraint is

$$c_t + \sum_{i=1}^{N} \left[(1 - \tau_t^c)M_{i,t} + (1 - \tau_{i,t}^x)X_{i,t} \right] \leq w_t H_t + \sum_{i=1}^{N} (1 - \tau_t^c)\, r_{i,t} K_{i,t}. \tag{6}$$

Through its choices of capital, investment, maintenance, and consumption, the household maximizes (4) subject to(5) and (6), giving rise to the following first-order conditions:

$$v'(H_t) = w_t u'(c_t) \tag{7}$$

$$-\delta_i'(m_{i,t}) = \frac{1-\tau_t^c}{1-\tau_{i,t}^x} \tag{8}$$

$$u'(c_t)(1-\tau_{i,t}^x) = u'(c_{t+1})\beta\Big[(1-\tau_{t+1}^c)r_{i,t+1} + (1-\tau_{i,t+1}^x)\left(1-\delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1})m_{i,t+1}\right)\Big], \tag{9}$$

where (8) and (9) apply to all capital types $i = 1, \ldots, N$. While the marginal condition between consumption and labor is completely standard, it is worth considering in more detail the optimality condition for the capital maintenance and Euler equations.

Optimal Maintenance

The choice between maintaining old capital and investing in new capital is fully captured by (8). 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.

Capital Euler Equation

For the remainder of the paper, I make the equilibrium substitution that the rental rate is equal to the marginal product of capital. 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 given by

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

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. 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.

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. For now, set aside any revenue requirements of the government and observe instead a couple of different experiments with capital tax policy; I will close the model by describing government policy shortly.

Suppose, with constant returns Cobb-Douglas production, there are two capital types in intensive form: equipment and structures, each of which has a power depreciation function given by

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

The parameter ω_i captures the maintenance elasticity, while γ_i more closely approximates quality in the sense of Goolsbee (2004). Since capital with higher γ_i will demand more maintenance all else equal, it is considered lower quality. Suppose each capital type faces a common tax rate τ^c in steady-state with $\tau_i^x = \tau_j^x$. To demonstrate each parameter's relevance, I experiment with different values of each in comparison to the standard NGM, where the standard NGM refers to a model with constant depreciation.

As an illustration of Proposition 2, consider a first an economy in which we vary the maintenance elasticity of equipment between $\omega_E = 0.5$, $\omega_E = 1$, and $\omega_E = 2$ for a fixed structures elasticity of $\omega_S = 0.1$ with $\gamma_S = \gamma_E = 0.02$. In Figure 1, I plot the log-difference between the steady-state equipment-structures ratio as a function of the common tax rate against and the efficient steady-state capital ratio, leaving the expensing rate fixed at zero. Because $\omega_E > \omega_S$, equipment depreciation responds relatively more than structures depreciation to changes in the tax rate, so that the stock of equipment is relatively insulated from changes in the common tax rate. In a constant depreciation model, K_E/K_S is constant across τ^c, all else equal. Clearly, the difference between the undistorted allocation and the the distorted allocation is an increasing function of the equipment maintenance elasticity.

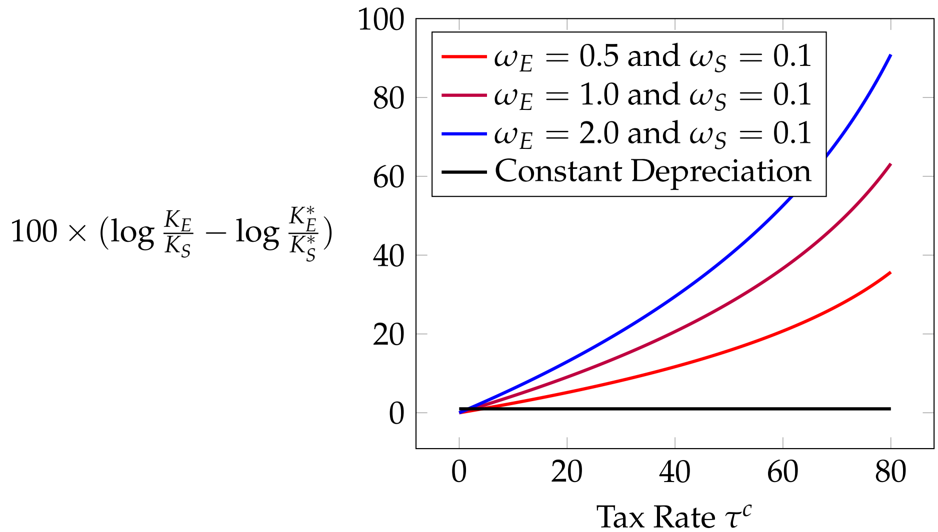

Figure 1: Log deviation of the steady-state capital equipment-structures ratio from its optimal level as a function of the corporate tax rate τ^c (multiplied by 100). For all cases, I set $\gamma_E = \gamma_S = 0.02$ and vary maintenance elasticities ω_E between 0.5, 1, and 2, while fixing $\omega_S = 0.1$. The required return is $r^k = 2\%$.

The quality of capital, captured by γ_i, likewise matters for the relative responses of capital types. Consider, for example, a comparison between two types of drill presses with the quality of the first greater than the second. Because they are in the same category of capital good, they share the same maintenance elasticity, but because the second drill press is lower quality, it requires more maintenance to have the same depreciation rate.

Such differences would be reflected in the parameter γ_i. To illustrate the relevance of quality, I fix $\gamma_S = 0.001$ and vary γ_E across the set $\{0.005, 0.025\}$ while holding fixed the maintenance elasticity. In Figure 2, I plot the log deviation of the steady-state capital stock ratio K_E/K_S from the efficient allocation as a function of the tax rate τ^c. Clearly, for the same maintenance elasticity, tax increases induce reallocation from high-quality to lower-quality capital and the degree of misallocation is increasing in the quality difference. With constant depreciation technology for both types, uniform taxation does not induce any misallocation between factors of production precisely because both capital types have the same tax elasticity. Thus, quality acts like an amplifier on deviations from the optimum.

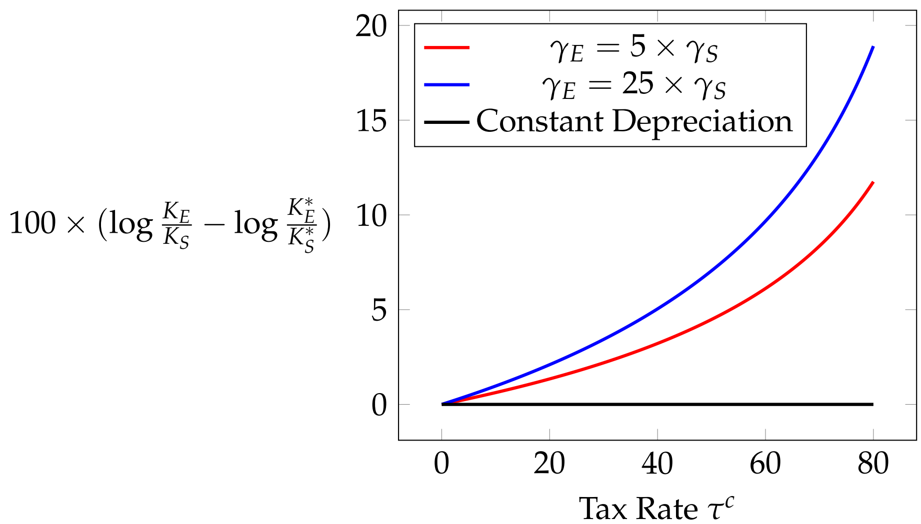

Figure 2: Log deviation of the steady-state capital equipment-structures ratio from its optimal level as a function of the corporate tax rate τ^c (multiplied by 100). For both cases, I set $\omega_E = \omega_S = 1$ and vary the quality parameter between $\gamma_E = 0.005$ and $\gamma_E = 0.025$ while fixing $\gamma_S = 0.001$. The required return is $r^k = 2\%$ with equal capital shares $\alpha_i = 0.5$.

The key takeaway is that accounting for endogenous depreciation via maintenance implies quite different equilibrium capital ratios than in the NGM, which suggests that if capital is going to be taxed, it should be taxed differentially. The NGMM formalizes the intuition of Goolsbee (2004), which theorizes that, all else equal, a decline in a common tax rate has an Alchian-Allen effect on capital allocations. That is, as taxes decline, the value of maintenance as a tax shield declines, leading to a decline in the demand for maintenance and relatively higher demand for higher quality capital.

3 A Differential Tax Optimality Result

The economics of the decentralized economy strongly suggest that a simple extension to optimal policy would be fruitful; differing tax elasticities emerging from the maintenance channel intuitively correspond to the usual Ramsey logic about optimal taxation. In this section, I approach optimal taxation in two steps. First, I develop a second-best problem of optimal taxation in the Ramsey tradition and derive an analytical solution. Second, with that theory, I quantify optimal tax rates on equipment and structures for a range of plausible depreciation functions.

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.

To illustrate the point more concretely, suppose a planner takes as given the uniform capital tax rate τ_t^c but chooses the subsidy $\tau_{i,t}^x$ for each asset type. 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). It is perhaps empirically more realistic than the more traditional approach in optimal capital taxation in which the government chooses the entire tax system; most reforms in practice are quite marginal and most changes in capital tax policy have more to do with alterations of depreciation schedules and tax credits than profit tax rates (Mertens and Ravn 2013). As such, given the demonstrated preference for a positive uniform tax on capital and the desire to raise capital tax revenue, the decision on how to set marginal effective tax rates across asset types is practically important. Putting together the taxes on capital with an exogenous revenue requirement G_t, the government budget constraint is

$$G_t = \sum_{i=1}^{N} \left(\tau_t^c K_{i,t} \left(F_{K_{i,t}} - m_{i,t} \right) - \tau_{i,t}^x X_{i,t} \right). \tag{10}$$

Then, continuing with the earlier model and putting the household, the firm, and the government together, output has four potential uses. It can consumed by the household, consumed by the government, invested, or spent on capital maintenance:

$$c_t + G_t + \sum_{i=1}^{N} (X_{i,t} + M_{i,t}) = F(K_{1,t}, \ldots, K_{N,t}, H_t).\text{[1]} \tag{11}$$

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* (11).

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

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

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* (10).

Optimal Tax Policy

The Ramsey problem is defined as follows.

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.*

1. It is important to make an accounting distinction. Output inclusive of depreciation and maintenance corresponds to gross output, whereas output net of maintenance and depreciation corresponds to a net income concept which we would map empirically to gross domestic product. The latter is frequently the objective of policymakers when considering tax reform (Romer and Romer 2010).

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. To keep the focus on the steady-state optimum, I 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.1, 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.1.

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*

$$\frac{\tau_i}{\tau_j} = \frac{\frac{\hat{r}_j}{F_{K_j}}\varepsilon_{K_{jj}} - \frac{\omega_j}{1+\omega_j}}{\frac{\hat{r}_i}{F_{K_i}}\varepsilon_{K_{ii}} - \frac{\omega_i}{1+\omega_i}} \tag{12}$$

and if the maintenance elasticity is zero for all capital types, then the optimal tax ratio is

$$\frac{\tau_i}{\tau_j} = \frac{\varepsilon_{K_{ii}}}{\varepsilon_{K_{jj}}}. \tag{13}$$

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 (13) 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. But we also observe something else: that the optimal tax rate is increasing in the maintenance rate.[2]

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

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

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 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. 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.

Consider a government with the following budget constraint:

$$G_t = \tau_t^c \sum_{i \in \{E,S\}} \Big[(r_{i,t} - m_{i,t})\, K_{i,t} \Big] - \sum_{i \in \{E,S\}} \tau_{i,t}^x X_{i,t},$$

where all notation carries from Section 2 and $i \in \{E, S\}$ denotes equipment and structures, respectively. Note that, as in the rest of the paper, these can be amalgamated into a single asset-specific marginal effective tax rate $\tau_{i,t} = 1 - \frac{1-\tau_t^c}{1-\tau_{i,t}^x}$.

There is a representative firm with constant returns to scale production technology. The firm produces with two types of capital and labor, renting all three from the household. Production is Cobb-Douglas

$$Y_t = K_{E,t}^{\alpha_E} K_{S,t}^{\alpha_S} H_t^{1-\alpha_S-\alpha_E}.$$

Next, there is a representative household with flow utility over consumption and labor

$$u(c_t, H_t) = \log c_t - \chi \log H_t.$$

The household chooses the next-period capital stock for each capital type via its choices of maintenance and investment.[3] The law of motion for each capital type follows (5) with a power depreciation function governed by parameters γ_i and ω_i. There is one deviation in the setup from the analysis of Section 2. In this section, the household pays an additional cost $\iota_i \tau_i$ for every unit of capital it owns so that steady-state user cost becomes

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

The cost $\iota_i \tau_i$ serves two purposes. First, I use ι_i as a free parameter to residually justify the current tax system as optimal in this economy. As discussed above, there are myriad factors that policymakers may consider as important for setting tax rates that are not considered in this paper; ι_i is meant to capture those factors in a reduced form way. Second, the cost $\iota_i \tau_i$ amplifies changes in the tax rate, which addresses addresses the debate over the capital supply. Under the standard Ramsey framework, the supply elasticity is infinite; the functional form assumption here is roughly equivalent to making the interest rate a function of the tax rate and inducing some degree of crowding out if $\iota < 0$. Acemoglu, Manera, and Restrepo (2020) and associated comments provide a useful discussion of the current state of the evidence on capital supply elasticities. Because we have little substantive evidence on the long-run supply elasticities and even less on heterogeneity in those elasticities, I treat the parameter ι and the functional form freely.

Of course, there are many ways to mathematically capture the relevant economic concerns over policymaker beliefs and capital supply elasticities. The key benefit of my approach is that it allows me to isolate the effect of the maintenance channel against the relevant benchmark of current optimality without introducing complications that would otherwise turn the model into a black box. For the quantitative exercise, I fix $\iota_S = 0$ and focus only on ι_E because all that matters is the relative distance in user cost between equipment and structures. Under this assumption $\iota_E > 0$ because an amplified tax elasticity of user cost for equipment relative to structures is exactly what is necessary to achieve the outcome that the current system is optimal.

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 expens-

3. Note that with this set-up, Modigliani-Miller holds and it does not matter who owns the capital stock.

ing 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. Equilibrium conditions are exactly those in Section 2. With that, the procedure for computing optimal tax rates is straightforward. There are two major steps.

1. **Calibrate ι_E in the benchmark NGM.** Using a bisection method, find the value of ι_E such that current tax rates are optimal under the NGM. Here, $\omega_E = \omega_S = 0$. For each bisection point, do the following:

    (a) Under current policy tax rates, find the value of χ such that steady-state labor supply is $1/3$ and residually recover the amount of capital tax revenue raised.

    (b) Over a dense grid of depreciation allowances τ_E^x, find the value of τ_S^x using a bisection method such that the government budget constraint holds.

    (c) Repeat (a) and (b) until ι_E guarantees that the current capital tax schedule is optimal.

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.[4] With those depreciation functions and using the value of ι_E, 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. Step one $\iota_E \approx 0.6$. This indicates that, to generate the current tax system as optimal under the neoclassical paradigm, equipment must be more sensitive to tax policy than structures. Empirically, this seems to be true (Wen, Yilmaz, and Trejo 2020).

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. 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

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

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. Under Proposition 3, that suggests a bias in favor of taxing equipment. For most of the plausible depreciation functions in $\mathcal{W}$, quantitatively it translates to taxing equipment around 10-12% and structures between 3-10%.

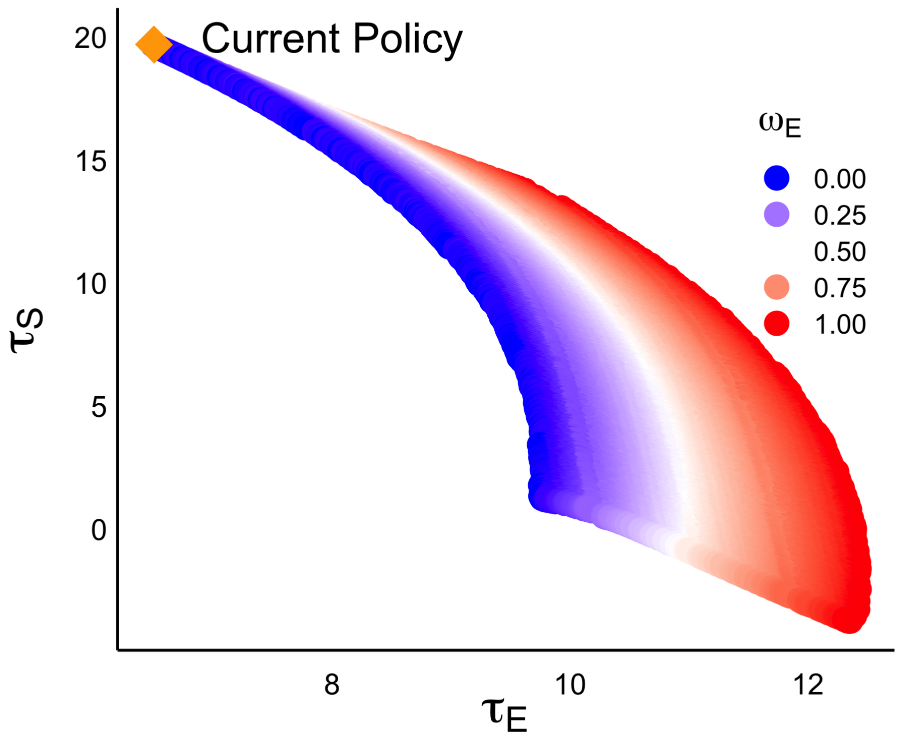

Figure 3: Optimal tax rates for each pair of maintenance elasticities in the grid $\mathcal{W} = [0,1] \times [0,1]$. The orange diamond represents current policy. Color intensity is determined by the equipment maintenance elasticity.

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.[5] 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 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

5. 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.

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.*,

$$\frac{X_i}{K_i} = \delta_i(m_i) = \gamma_i \left(V_i \frac{1}{\omega_i \gamma_i} \right)^{\frac{\omega_i}{1+\omega_i}}, \tag{14}$$

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. In Appendix A.2, I lay out the full model; here I give the relevant alterations to the model from Section 2. Following the notation above, let the inverse price of investment be given by V_i, which follows a stochastic process given by

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

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 (14), so that a unit shock to V_i yields the required elasticity.

Now, let production be given by $Y_t = z_t H_t^{1-\Omega} \prod_{i=1}^{N} K_{i,t}^{\alpha_i}$ with $\sum_i \alpha_i = \Omega < 1$ and Hicks-neutral productivity following the stochastic process

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

Finally, suppose there are shocks to labor supply. In particular, let period utility be given by

$$u(c_t, H_t) = \log c_t - \chi_t \log H_t,$$

where $\chi_t = \chi + \varepsilon_{\chi,t}$, and $\epsilon_{\chi,t} \sim \mathcal{N}(0, \sigma_\chi)$. Putting all of this together yields the NGMM version of the results from Fisher (2006) in the NGM.

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 effect on relative prices or productivity.*

Proof: Appendix A.2.

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 1968-2015. 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

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

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 $\tau_{i,t}^x$ collects asset-i 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.[6] 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. Tax policy data come from the FRB-US macroeconometric model. 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

6. 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.

produced under the industrial capacity program.[7] 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.2 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 residuals of the following two-way fixed effects regression up to p lags

$$\begin{aligned}\Delta \log V_{E,j,t} =&\alpha_j + T_t + \sum_{s=1}^{p} \beta_{V_E} \Delta \log V_{E,j,t-s} + \sum_{s=0}^{p-1} \beta_{V_S} \Delta^2 \log V_{S,j,t-s} \\ &+ \sum_{s=0}^{p-1} \beta_{\text{Prod}} \Delta^2 \text{Prod.}_{j,t-s} + \sum_{s=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{j,t-s} + \mu_{E,j,t}.\end{aligned} \tag{15}$$

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

7. 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.

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 15, 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.2.

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,

$$\log x_{i,j,t+h} - \log x_{i,j,t-1} = \alpha_j + T_t + \beta_{i,h} \log V_{i,j,t} + \mathbf{X}_{i,j,t}\zeta_{i,h} + \eta_{i,j,t+h}, \tag{16}$$

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 three lags each of the asset-specific log gross investment rate, the log relative price of investment, and productivity growth, hours growth, and employment.[8] Because the time dimension

8. 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).

is large—greater than forty years for all capital types—the extent of Nickell bias is small.

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.[9] I extend the methodology of Barnichon and Brownlees (2019) to panel data, developing smooth local projections for panel data (SLPP) to estimate (16). 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 8a and 8b 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. The coefficient on equipment is stable around 0.5 and on structures around 0.2 seven years 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 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 9a and 9b. The estimates are statistically significant for equipment at all horizons and nearly the same holds for structures.[10]

9. 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.

10. 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 is-

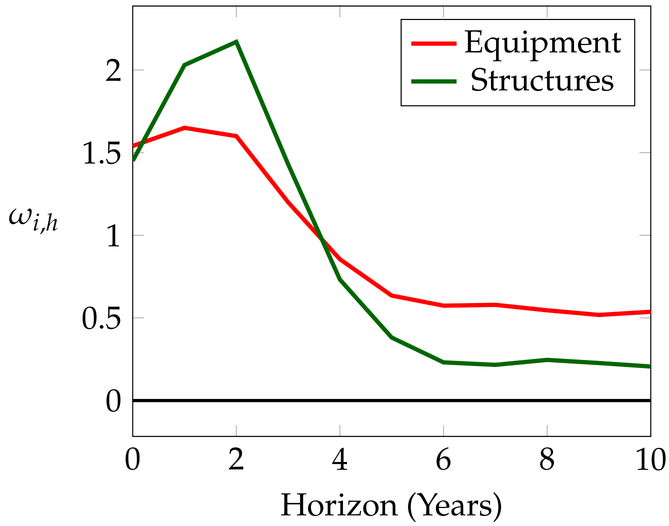

Figure 4: Maintenance elasticities for each capital type.

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.

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).

sue 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.

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. For intangibles, I assume the maintenance elasticity is the 0.35, or right in between equipment and structures. 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. In Appendix F, I discuss intangible depreciation in greater detail.

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.[11] Because the

11. For that reason, the BEA and BLS are strongly considering updating their methods in line with

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 90% as large as the standard NGM predicts when using the BEA depreciation rates and about 80-85% as large using the BLT depreciation rates. The difference between the corporate and passthrough sectors largely comes from the structures share, which is much larger in the passthrough sector.

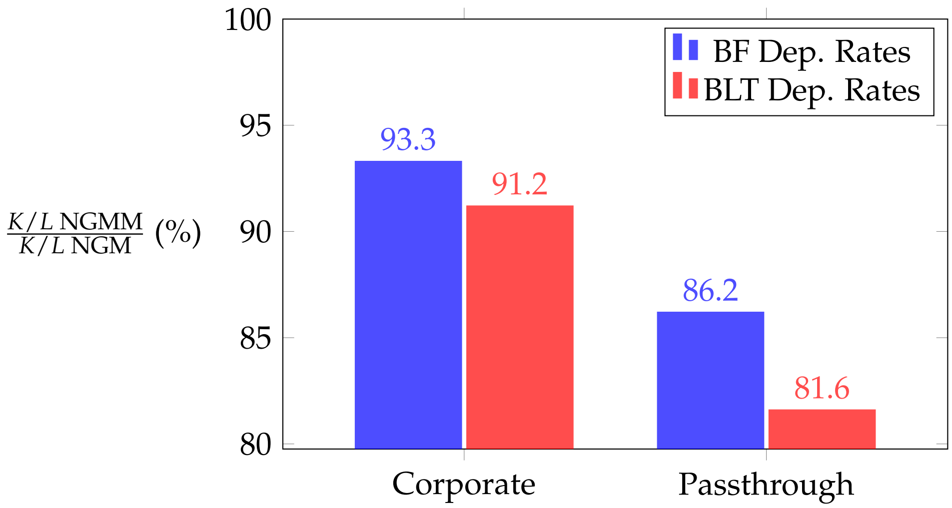

Figure 5: The predicted effect of the TCJA on capital-labor ratios under the NGMM as a share of the predicted effect under the NGM. The BF depreciation rates come from Barro and Furman (2018) and the BLT depreciation rates come from Baldwin, Liu, and Tanguay (2015).

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 10% 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

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.

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 $\omega_E = 0.6$ and $\omega_S = 0.4$. The key result is in Figure 6. Compared to current tax rates, consideration of the maintenance channel pushes the optimal rates toward being effectively 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. Numerically, this suggests that, even if policymakers are currently taking all other factors into account, tax rates should be roughly uniform on equipment and structures.

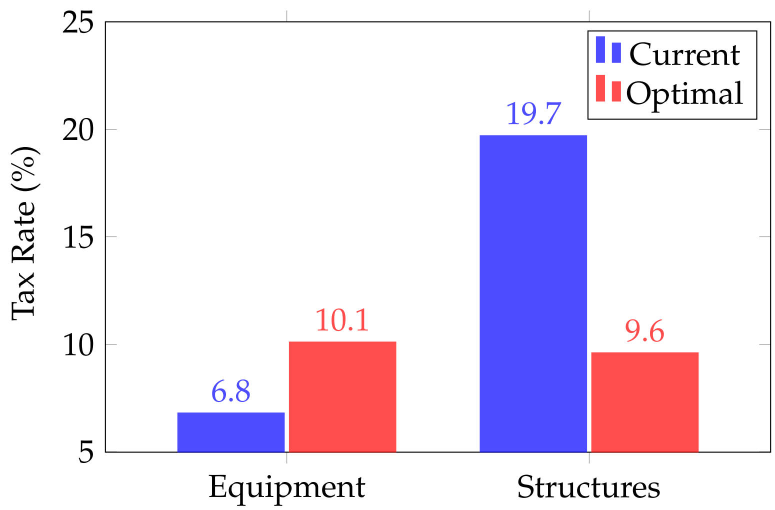

Figure 6: Current tax rates compared to optimal tax rates on equipment and structures when accounting for maintenance.

Adding more types of capital, altering the functional forms for production, depreciation, or changing $\iota_i \tau_i$ 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.

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

The planner's Lagrangian is given by

$$\mathcal{L} = \sum_{t=0}^{\infty} \beta^t \Bigg\{ u(c_t) - v(H_t) \tag{17}$$

$$+ \theta_t \left[\sum_{i=1}^{N} \left(\tau_t^c K_{i,t} \left(F_{K_{i,t}} - m_{i,t} \right) - \tau_{i,t}^x \left(K_{i,t+1} - (1 - \delta_i(m_{i,t+1}) K_{i,t} \right) \right) - G_t \right] \tag{18}$$

$$+ \Psi_t \left[F(K_{1,t}, \ldots, K_{N,t}, H_t) - \sum_{i=1}^{N} \left[M_{i,t} + \left[K_{i,t+1} - (1 - \delta_i(m_{i,t}))\, K_{i,t} \right] \right] - c_t - G_t \right] \tag{19}$$

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

$$- u'(c_t)(1 - \tau_{i,t}^x) \Big] \tag{20}$$

$$+ \sum_{i=1}^{N} \mu_{i,t} \left[\frac{1 - \tau_t^c}{1 - \tau_{i,t}^x} + \delta_i'(m_{i,t}) \right] \tag{21}$$

$$+ \vartheta_t \left[F_{H_t} u'(c_t) - v'(H_t) \right] \Bigg\}, \tag{22}$$

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

A.1 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

$$
\begin{aligned}
G_t &= \sum_{i=1}^{N}\left[\tau^c\left(F_{K_{i,t}} - m_{i,t}\right)K_{i,t} - \tau^x_{i,t}\left(K_{i,t+1} - (1-\delta_i(m_{i,t}))K_{i,t}\right)\right] \\
&= \sum_{i=1}^{N}\left[\tau^c_t\left(F_{K_{i,t}} - m_{i,t}\right)K_{i,t} - \left(1 + \frac{1-\tau^c_t}{\delta_i'(m_{i,t})}\right)\left(K_{i,t+1} - (1-\delta_i(m_{i,t}))K_{i,t}\right)\right] \\
&= \sum_{i=1}^{N}\left[K_{i,t}\left(\tau^c_t\left(F_{K_{i,t}} - m_{i,t}\right) + (1-\tau^c_t)\frac{m_{i,t}}{\omega_i} - \delta_i(m_{i,t}) + \left(1 + \frac{(1-\tau^c_t)}{\delta_i'(m_{i,t})}\right)\right) - \left(1 + \frac{(1-\tau^c_t)}{\delta_i'(m_{i,t})}\right)K_{i,t+1}\right]
\end{aligned}
\tag{23}
$$

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

$$
u'(c_t)\left(\frac{1-\tau^c_t}{-\delta_i'(m_{i,t})}\right) = \beta u'(c_{t+1})\left[\left(1-\tau^c_{t+1}\right)F_{K_{i,t+1}} - \frac{1-\tau^c_{t+1}}{\delta_i'(m_{i,t+1})} - (1-\tau^c_{t+1})m_{i,t+1}\left(1+\frac{1}{\omega_i}\right)\right]. \tag{24}
$$

After replacing the government budget constraint and the household Euler equation with (23) and (24), 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 (25) and (26), respectively.

$$
\begin{aligned}
\frac{u'(c_t)(1-\tau^c_t)}{K_{i,t}}\left(\phi_{i,t-1}\left(\frac{1+\omega_i}{\omega_i} - \frac{\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})^2}\right) + \phi_{i,t}\frac{\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})^2}\right) &= -\Psi_t\left(1+\delta_i'(m_{i,t})\right) \\
&+ \theta_t\left(-\tau^c_t + \frac{1-\tau^c}{\omega_i} - \delta_i'(m_{i,t}) + \frac{(1-\tau^c_t)\delta_i''(m_{i,t})}{\delta_i'(m_{i,t})}\frac{1}{K_{i,t}}\left(K_{i,t+1} - K_{i,t}\right)\right)
\end{aligned}
\tag{25}
$$

$$
\begin{aligned}
\Psi_t + \theta_t\left(1 + \frac{1-\tau^c_t}{\delta_i'(m_{i,t})}\right) =& \beta\Bigg\{\theta_{t+1}\Bigg[\tau^c_{t+1}F_{K_{i,t+1}} - \delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1})m_{i,t+1} + \left(1 + \frac{1-\tau^c_{t+1}}{\delta_i'(m_{i,t+1})}\right) \\
&- \frac{(1-\tau^c_{t+1})\delta_i''(m_{i,t}+1)}{\delta_i'(m_{i,t})}\frac{m_{i,t+1}}{K_{i,t+1}}\left(K_{i,t+2} - K_{i,t+1}\right) + \sum_{j=1}^{N}\tau^c_{t+1}F_{K_{j,t+1}K_{i,t+1}}K_{j,t+1}\Bigg] \\
&+ \Psi_{t+1}\left(F_{K_{i,t+1}} + 1 - \delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1})m_{i,t+1}\right) \\
&+ \frac{u'(c_{t+1})(1-\tau^c_{t+1})m_{i,t+1}}{K_{i,t+1}}\Bigg[\phi_{i,t}\left(\frac{1+\omega_i}{\omega_i} - \frac{\delta_i''(m_{i,t+1}}{\delta_i'(m_{i,t+1}}\right) \\
&+ \phi_{i,t+1}\left(\frac{\delta_i''(m_{i,t+1}}{\delta_i'(m_{i,t+1}}\right)\Bigg] + \sum_{j=1}^{N}\phi_{j,t}u'(c_{t+1})(1-\tau^c_{t+1})F_{K_{j,t+1}K_{i,t+1}} \\
&+ \vartheta_{t+1}u'(c_{t+1})F_{H_{t+1}K_{i,t+1}}\Bigg\}
\end{aligned}
\tag{26}
$$

Substituting (25) into (26) yields

$$
\begin{aligned}
\Psi_t + \theta_t \left(1 + \frac{1-\tau_t^c}{\delta_i'(m_{i,t})}\right) =& \beta \Bigg\{ \theta_{t+1} \Bigg[\tau_{t+1}^c \hat{r}_{i,t+1} - \delta_i(m_{i,t+1}) + \frac{(1-\tau_{t+1}^c)m_{i,t+1}}{\omega_i} + \left(1 + \frac{1-\tau_{t+1}^c}{\delta_i'(m_{i,t+1})}\right) \\
&+ \sum_{j=1}^{N} \tau_{t+1}^c F_{K_{j,t+1}K_{i,t+1}} K_{j,t+1} \Bigg] \\
&+ \Psi_{t+1} \left(F_{K_{i,t+1}} + 1 - \delta_i(m_{i,t+1}) - m_{i,t+1} \right) \\
&+ \sum_{j=1}^{N} \phi_{j,t} u'(c_{t+1})(1-\tau_{t+1}^c) F_{K_{j,t+1}K_{i,t+1}} \\
&+ \vartheta_{t+1} u'(c_{t+1}) F_{H_{t+1}K_{i,t+1}} \Bigg\},
\end{aligned}
\tag{27}
$$

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

$$
\begin{aligned}
\theta \left(1 + \frac{1-\tau^c}{\delta_i'(m_i)}\right)\left(\frac{1}{\beta} - 1\right) + \Psi \left(\frac{1}{\beta} - F_{K_i} - 1 + \delta_i(m_i) - m_i\right) &= \sum_{j=1}^{N} \phi_j u'(c)(1-\tau^c) F_{K_j K_i} \\
+ \theta \left(\tau^c \hat{r}_i - \delta_i(m_i) + \frac{(1-\tau^c)m_i}{\omega_i} + \sum_{j=1}^{N} \tau^c F_{K_j K_i} K_j \right) &+ \vartheta u'(c) F_{HK_i}.
\end{aligned}
\tag{28}
$$

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

$$
-(\theta + \Psi)\tau_i \hat{r}_i = \sum_{j=1}^{N} \left(u'(c)\phi_i(1-\tau^c) + \theta \tau^c K_j \right) F_{K_j K_i} + \vartheta u'(c) F_{HK_i} \tag{29}
$$

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

$$
\phi_i u'(c)(1-\tau^c) = K_i \frac{\omega_i}{1+\omega_i} \left(\theta \left(\frac{1}{\omega_i} - \tau^c \left(\frac{1+\omega_i}{\omega_i} \right) - \delta_i'(m_i) \right) - \Psi(1 + \delta_i'(m_i)) \right) \tag{30}
$$

Substituting back in to (29),

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

Manipulate this expression to yield

$$\tau_i = \left(\frac{\hat{r}_i}{F_{K_i}}\varepsilon_{K_{ii}} - \frac{\omega_i}{1+\omega_i}\right)^{-1}\boldsymbol{\varepsilon}_i, \tag{31}$$

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.

A.2 Shocks in the NGMM

In this subsection, I prove that shocks to the relative price of maintenance affect productivity and hours, that shocks to productivity only affect productivity and hours, and shocks to hours only affect hours. This Cholesky-type result is very similar to Fisher (2006) and in fact the proof concept is so similar to Fisher (2006) that a reader familiar with that paper will not need to read the following.

For now, abstract from tax policy and government spending. Since the welfare theorems hold in the NGMM, we can consider the economy from the perspective of the social planner.[12] The planner chooses sequences of consumption c_t, labor, H_t, investment, $X_{i,t}$, maintenance, $M_{i,t}$, and tomorrow's capital stock, $K_{i,t+1}$ for each capital type to maximize household utility subject to the aggregate resource constraint, the law of motion for each capital type, and the $N+2$ exogenous processes for the inverse price of investment

12. We can only do this by rewriting in terms of relative prices and abstracting from taxes.

$V_{i,t}$ (which captures relative prices), productivity z_t, and the disutility of labor B_t:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log c_t - \chi_t \log H_t\right) \qquad \text{subject to}$$
$$c_t + \sum_{i=1}^{N} \left(\frac{1}{V_{i,t}} X_{i,t} + M_{i,t} \right) \leq z_t H_t^{1-\sum_{i=1}^{N} \alpha_i} \prod_{i=1}^{N} K_{i,t}^{\alpha_i}, \quad \alpha_i > 0 \forall i \quad \text{and} \quad \sum_{i=1}^{N} \alpha_i = \Omega < 1$$
$$K_{i,t+1} \leq X_{i,t} + (1 - \delta_i(m_{i,t}))K_{i,t} \quad \forall i \tag{32}$$
$$V_{i,t} = V_{i,t-1} + \epsilon_{i,t}, \quad \epsilon_{i,t} \sim N(0, \sigma_v)$$
$$z_t = z_{t-1} + \varepsilon_{z,t}, \quad \varepsilon_{z,t} \sim \mathcal{N}(0, \sigma_z)$$
$$\chi_t = \chi + \varepsilon_{\chi,t}, \quad \epsilon_{\chi,t} \sim \mathcal{N}(0, \sigma_\chi)$$

where $V_{i,t}$ is the inverse price of investment in capital type i and the depreciation technologies have the same properties as in the main text. The planner takes K_0, V_0, z_0, and B_0 as given (all strictly positive).

In steady state, the following relationships must hold in equilibrium. Normalizing so that all variables are in per-capita terms (denoted by tilde), we have

$$m_i = \left(V_i \frac{1}{\gamma_i \omega_i} \right)^{\frac{-1}{1+\omega_i}} \tag{33}$$
$$x_i = \gamma_i m_i^{-\omega_i} \tag{34}$$
$$\alpha_i \frac{\tilde{y}}{\tilde{K}_i} = \frac{1}{V_i} \left(r^k + (1 + \gamma_i) m_i^{-\omega_i} \right) \tag{35}$$
$$\tilde{c} = \frac{1}{\chi} (1 - \Omega) \tilde{y} \tag{36}$$
$$\tilde{y} = z \prod_{i=1}^{N} \tilde{K}_i^{\alpha_i} \tag{37}$$

Note that, in expectation, $V_i = V_{0,i}$, χ is its steady-state value, and $z = z_0$. Suppose V_i increases by one percent, which decreases the relative price of investment. Clearly, this will decrease the maintenance rate m_i by $\frac{1}{1+\omega_i}$ percent and increase the investment rate by $\frac{\omega_i}{\omega_i+1}$ percent, but have no effect on the gross investment rate or relative prices of other capital goods. Similarly, the effective capital stock of type i will increase and so will output, hours, and output per capita. However, a unit shock to productivity clearly does not affect the relative price and so has no effect on either the maintenance rate or the investment rate in the long run. Finally, simple observation implies a shock to labor disutility has no effect on the maintenance rate or investment rate in the long run.

Because only shocks to the relative price of maintenance to investment have an effect in the long run on both the gross investment rate and the maintenance rate, we can use the long run response of the gross investment rate to permanent relative price shocks to infer the maintenance elasticity of depreciation.

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.[13] 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.[14]
- **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

13. 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.

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

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.

- **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 $\frac{1-\tau_t^c}{1-\tau_{i,t}^x}$, where $\tau_{i,t}^x$ collects asset-specific tax provisions like the investment tax credit and tax depreciation. These values come from the FRB-US macroeconometric model. 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	13,860	1,993.500	12.699	1,972	1,982.8	2,004.2	2,015
Equip. Invest. Rate	13,860	0.077	0.034	0.0003	0.054	0.094	0.400
Struct. Invest. Rate	13,860	0.028	0.027	0.000	0.012	0.036	0.587
Inv. Rel. Price Equip	13,860	1.293	0.602	0.421	0.976	1.405	8.347
Inv. Rel. Price Struct	13,860	2.224	1.492	0.472	1.209	2.656	18.403
Hours Growth	13,860	0.001	0.033	−0.292	−0.017	0.018	0.310
Log Emp.	13,860	3.270	0.919	−0.105	2.660	3.888	6.463
Productivity Growth	13,860	0.021	0.069	−0.262	−0.018	0.058	0.370
Equip Shock	13,860	−0.000	0.989	−3.976	−0.614	0.606	4.393
Struct Shock	13,860	0.000	0.989	−3.961	−0.609	0.607	4.500
Productivity Shock	13,860	0.000	0.989	−5.742	−0.604	0.611	4.833
Hours Shock	13,860	−0.000	0.989	−5.271	−0.596	0.611	4.738

Table 1: Summary Statistics

B.2 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 7a and 7b, 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 7c and 7d.

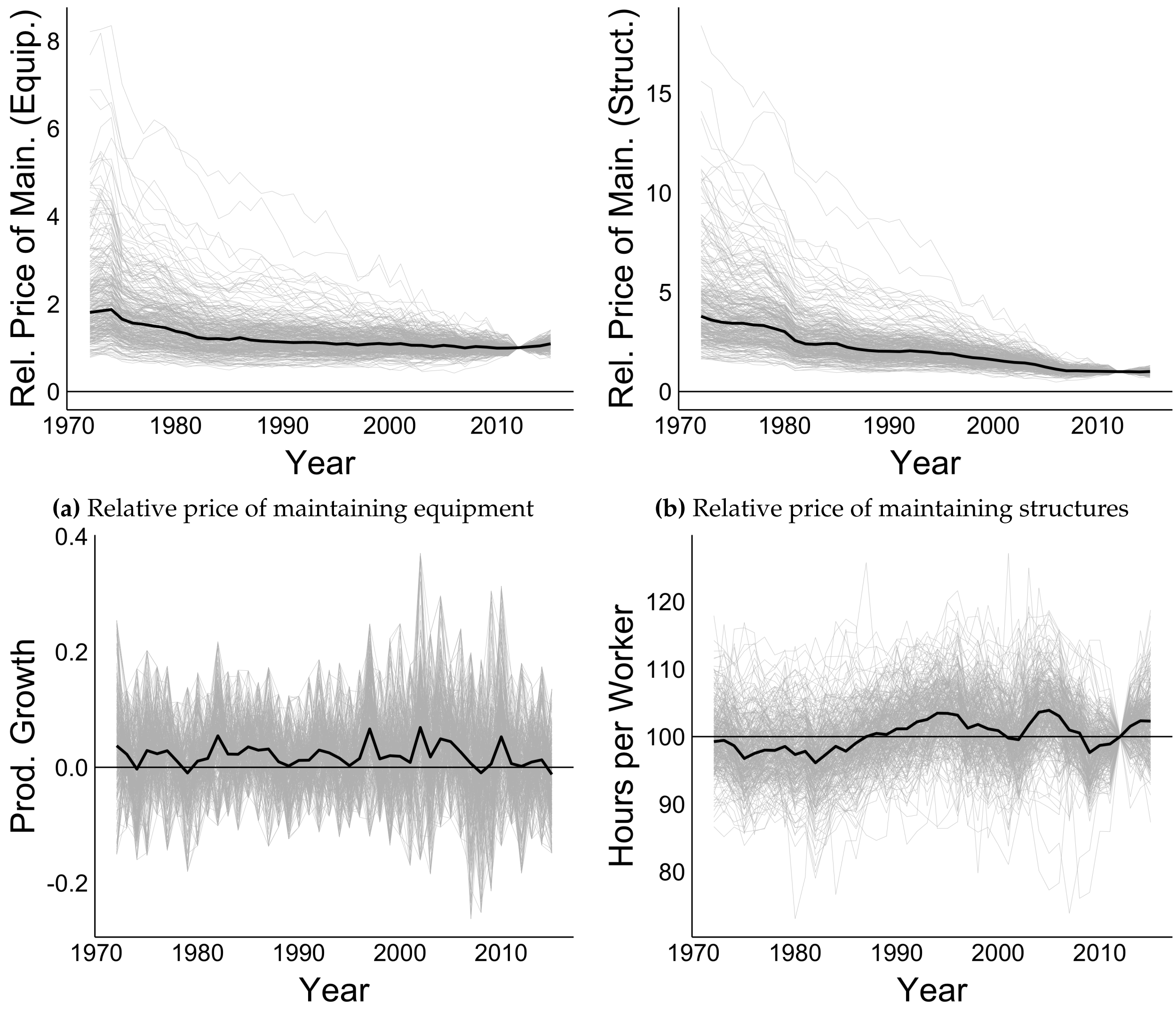
The main text describes shock construction for relative prices, productivity, and hours. Essentially, I rely on the time series properties of the data to construct permanent shocks. Shocks to relative prices can affect all variables except other relative prices, shocks to productivity cannot affect relative 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:

$$
\begin{aligned}
\Delta \log V_{E,j,t} = & \alpha_j + T_t + \sum_{s=1}^{p} \beta_{V_E} \Delta \log V_{E,j,t-s} + \sum_{s=0}^{p-1} \beta_{V_S} \Delta^2 V_{S,j,t-s} \\
& + \sum_{s=0}^{p-1} \beta_{\text{Prod}} \Delta^2 \text{Prod.}_{j,t-s} + \sum_{s=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{j,t-s} + \mu_{E,j,t}.
\end{aligned} \tag{38}
$$

To get shocks to structures, we simply swap out $V_{S,j,t}$ for $V_{E,j,t}$ in (38). Then, with shocks to equipment, $\mu_{E,j,t}$ and $\mu_{S,j,t}$ in hand, we can get productivity shocks from

$$
\begin{aligned}
\Delta \text{Prod.}_{j,t} = & \alpha_j + T_t + \sum_{s=1}^{p} \beta_{V_E} \Delta \log V_{E,j,t-s} + + \sum_{s=1}^{p} \beta_{V_S} \Delta \log V_{S,j,t-s} \\
& + \sum_{s=1}^{p} \beta_{\text{Prod}} \Delta \text{Prod.}_{j,t-s} + \sum_{s=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{j,t-s} + + \mu_{E,j,t} + \mu_{S,j,t} + \eta_{j,t}.
\end{aligned} \tag{39}
$$

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

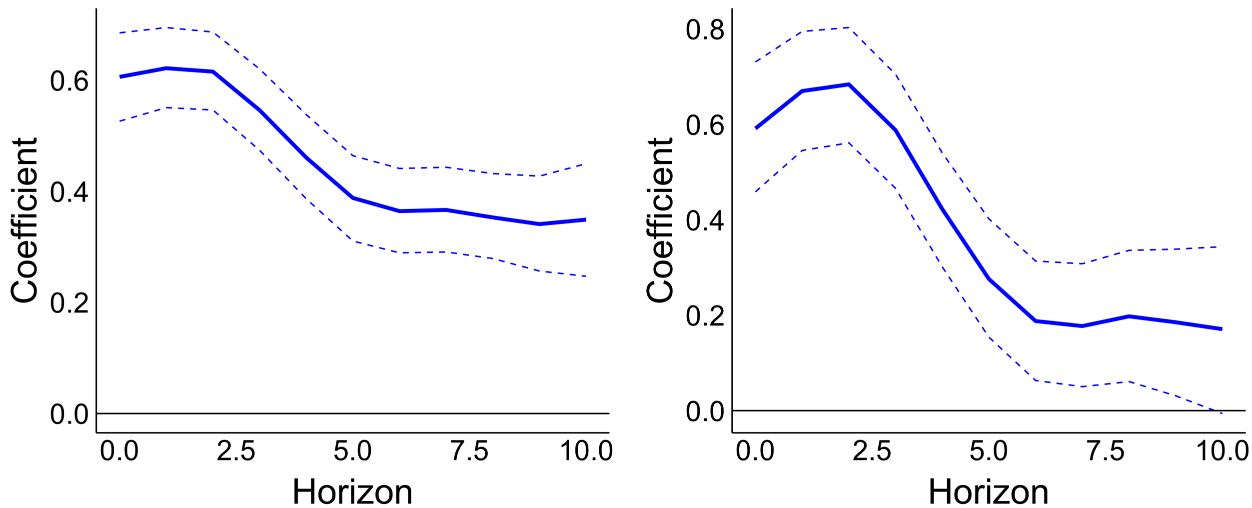
(b) Relative price of maintaining structures

(c) TFP Growth

(d) Hours per worker (2012 = 100)

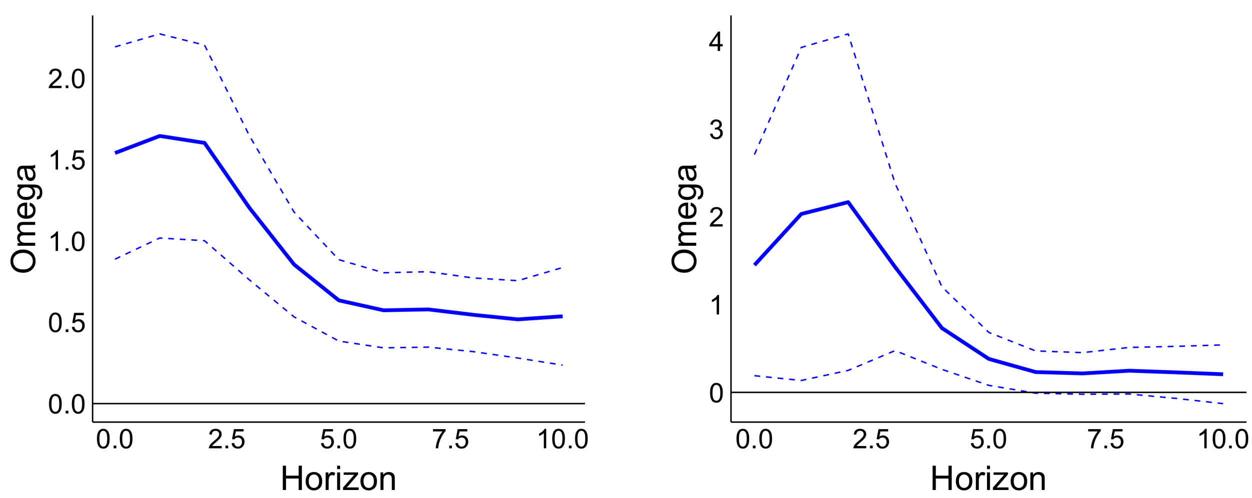
Figure 7: Variables for constructing idiosyncratic permanent shocks to the relative price maintaining equipment, relative price of maintenance in structures, productivity, and hours. Thick black lines are yearly medians.

C Empirical Results



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

Figure 8: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 3$.



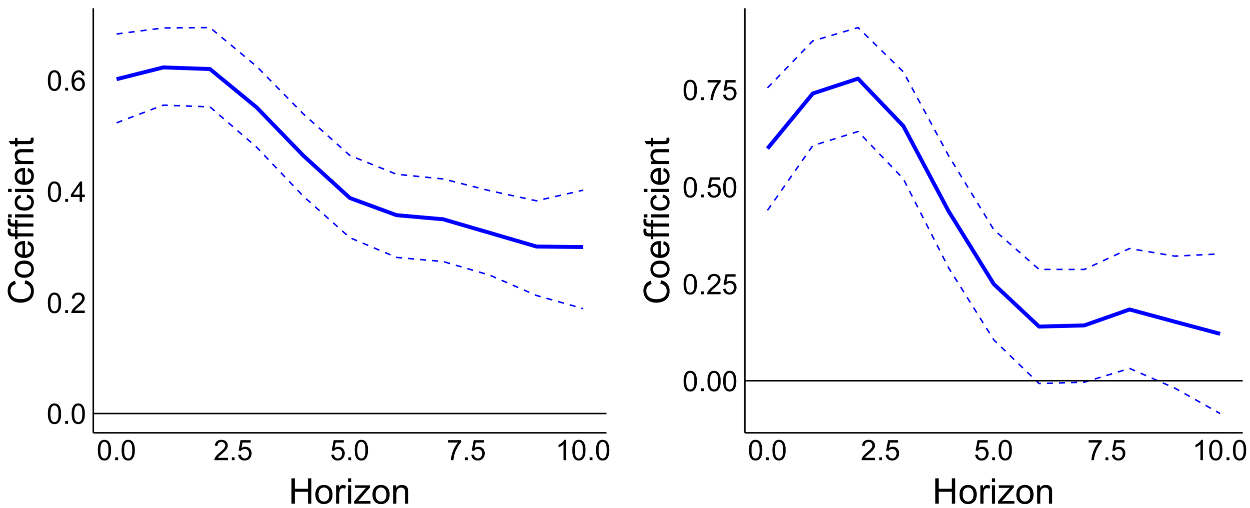
(a) Equipment **(b)** Structures

Figure 9: 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

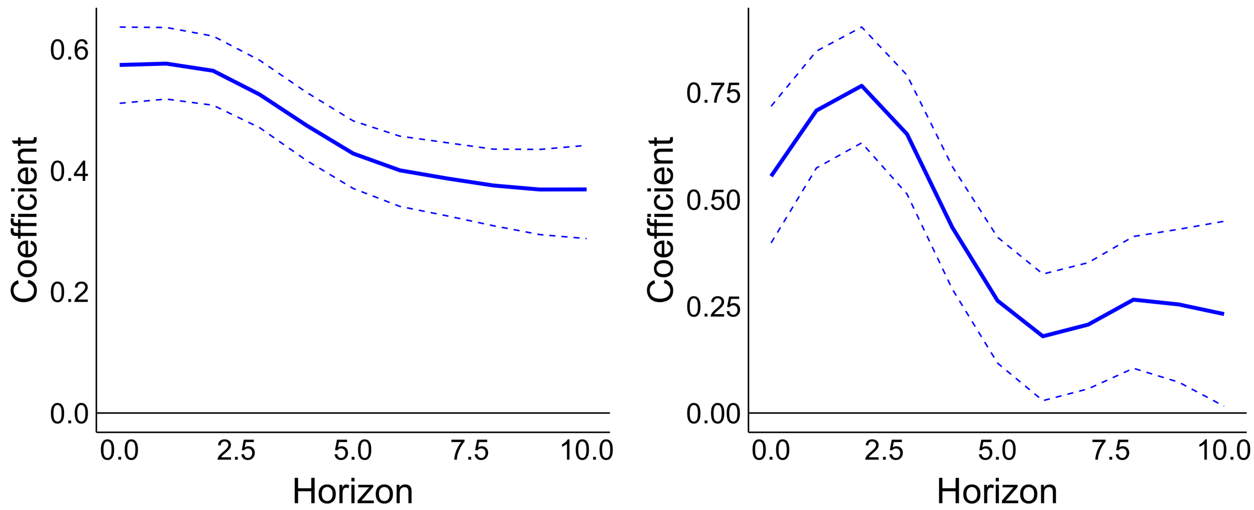
In this subsection, I present robustness checks by varying the polynomial fit and lag length. Point estimates are largely similar across specifications. In Appendix D, I detail the procedure for estimating the SLPP IRFs and show how it compares to the standard panel LP IRF.

Penalized to Line



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

Figure 10: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 2$.

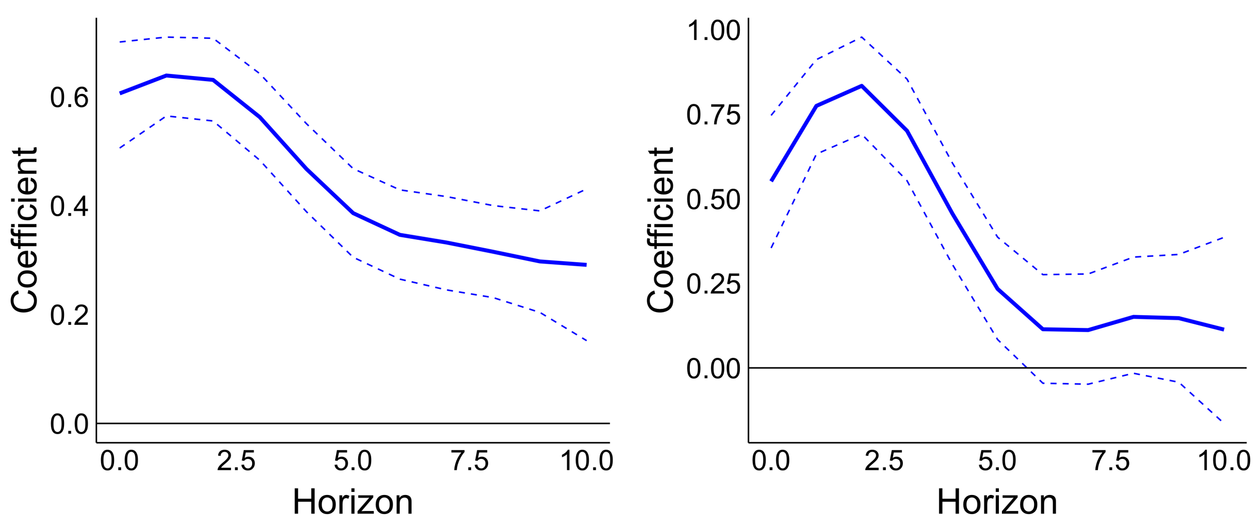


(a) Equipment

(b) Structures

Figure 11: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 4$.

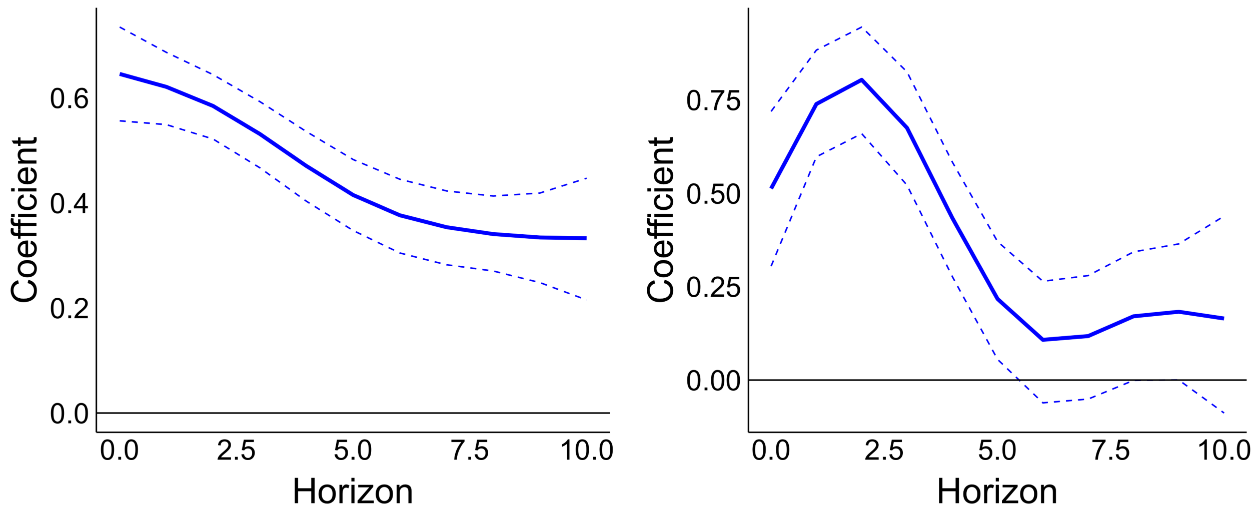
Penalized to Quadratic



(a) Equipment

(b) Structures

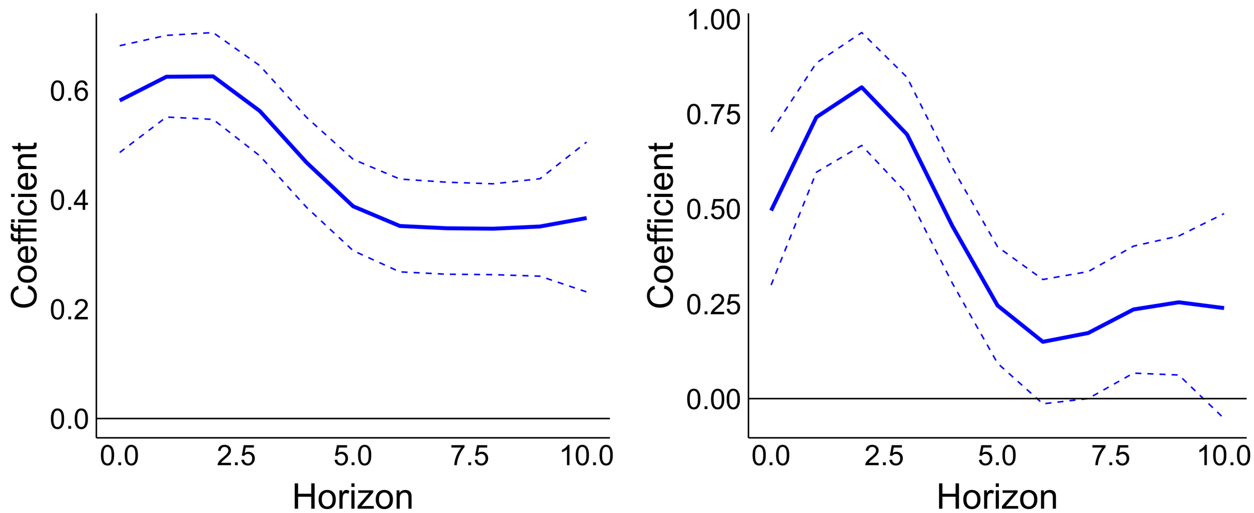
Figure 12: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 2$ with the impulse response penalized to a quadratic function.



(a) Equipment

(b) Structures

Figure 13: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) 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.

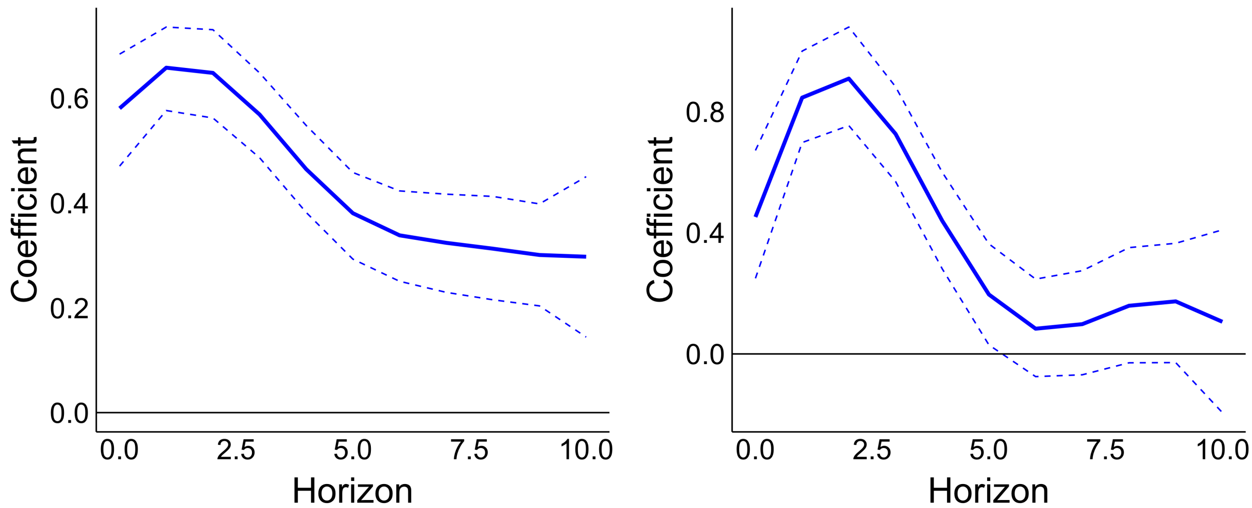


(a) Equipment

(b) Structures

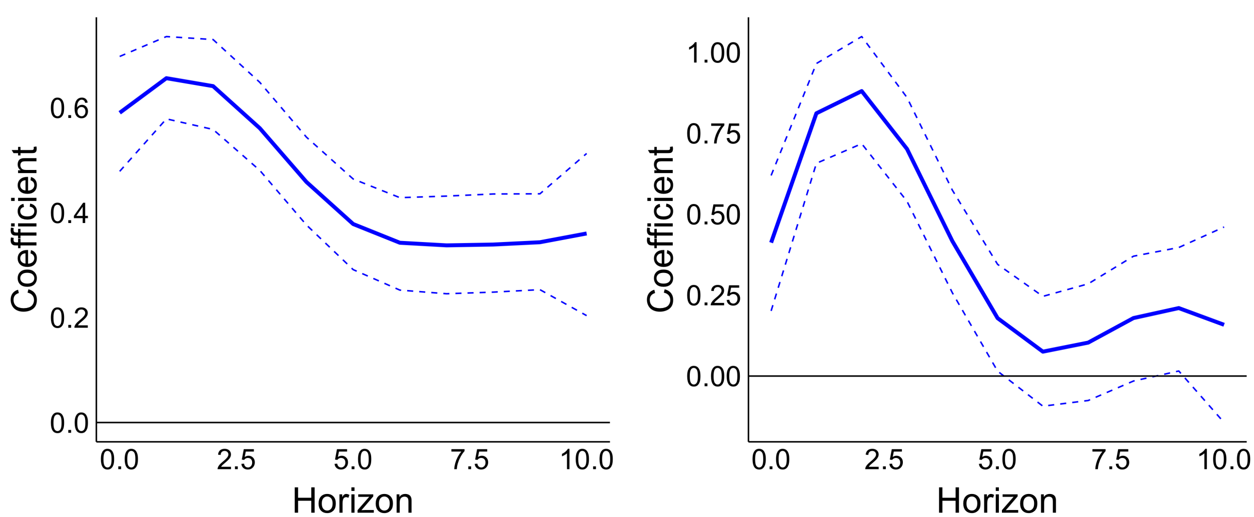
Figure 14: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap. Lag length $p = 4$ with the impulse response penalized to a quadratic function.

Penalized to Cubic



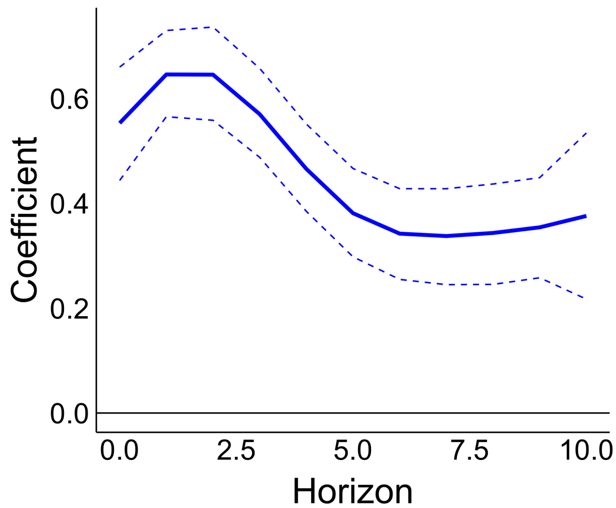
(a) Equipment **(b)** Structures

Figure 15: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) 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.

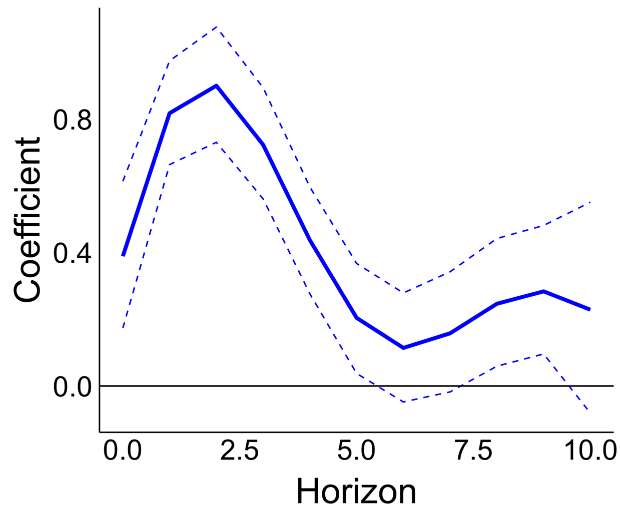


(a) Equipment **(b)** Structures

Figure 16: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) 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 17: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) 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**:

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

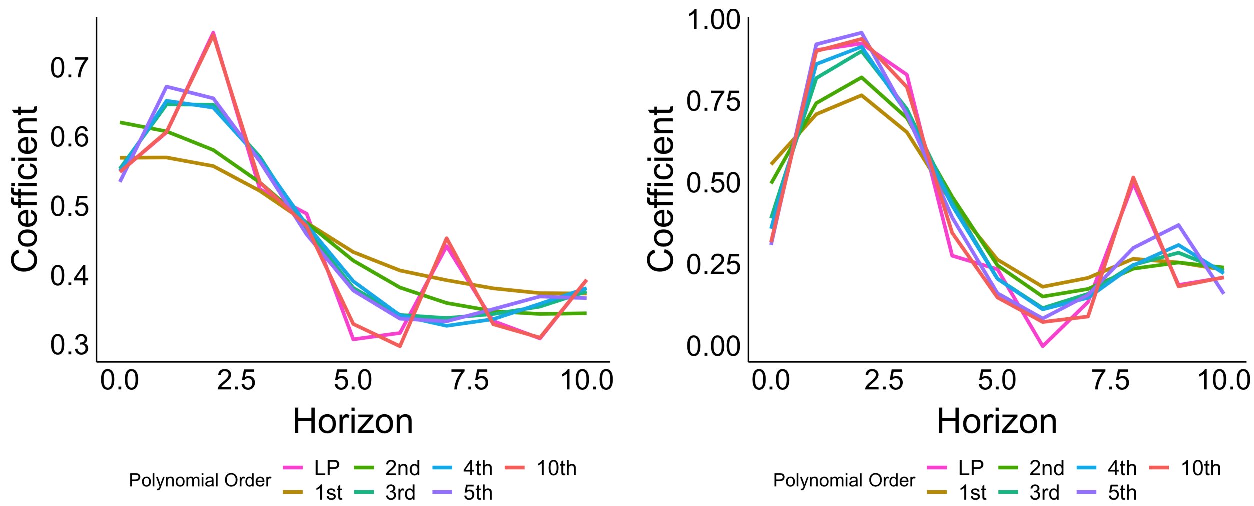
   where $\lambda > 0$ is a shrinkage parameter and P is a symmetric positive semidefinite penalty matrix. λ determines the bias/variance trade-off.

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 18b, 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.

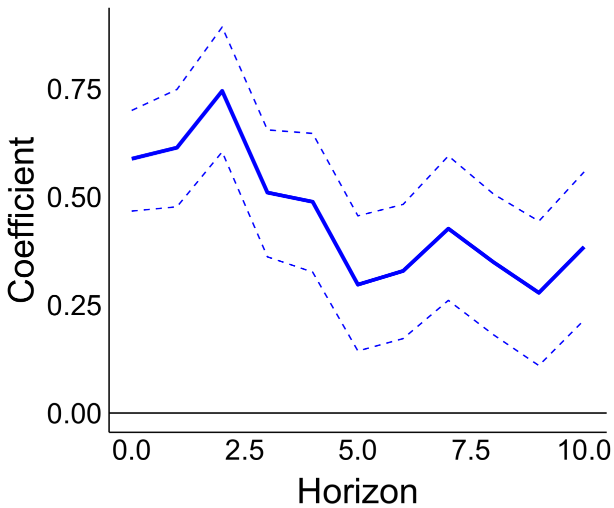


(a) Equipment

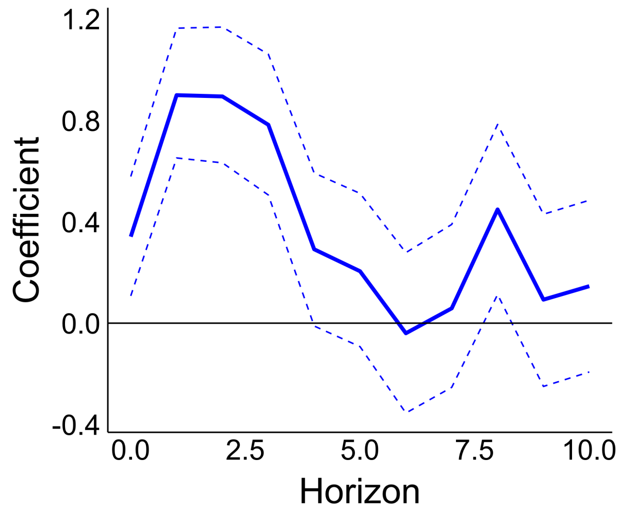
(b) Structures

Figure 18: Comparison between standard local projections and smooth local projections penalized toward differing polynomial orders using the structures specification from the main text.

In Figure 19, 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 19: 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 ι_E and calibrated the government budget constraint.

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	0.6	Figure 4
ω_S	0.4	Figure 4
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)
ι_E	0.5922	Own calculation

Table 2: Calibrated parameters

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

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

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 20, I plot the value of γ_i for each of equipment and structures as a function of the assumed maintenance elasticity for $\omega_i \in [0, 1]$.

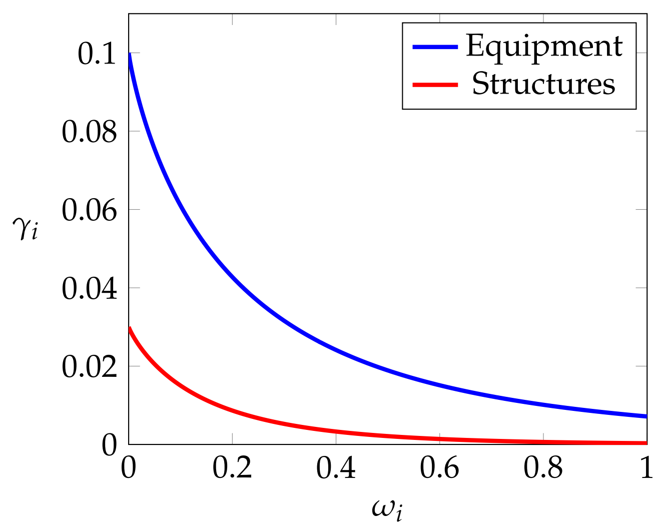


Figure 20: Calibration of γ_i for equipment and structures as a function of the maintenance elasticity ω_i. I assume that the values for steady-state depreciation are $\tilde{\delta}_E = 0.1$ and $\tilde{\delta}_S = 0.03$, and for relative prices are $V_E = 1.4$ and $V_S = 3$.

F Intangible Depreciation Redux

Depreciation is not merely physical. Intuitively, we think in physical terms with, for example, car maintenance or adjusted utilization of machinery to allow for firms to control their depreciation rates. However, firm control over depreciation stems not only from physical manipulation, but economic factors. Hearkening back to an old debate on the nature of capital between Hayek (1935), Pigou (1941), and Hicks (1942), the value of the capital stock in an economy may be considered either physical in nature or measured intangibly. Economists have long since concluded that Hayek's position settled the debate, namely that capital is measurable in money-metric terms (Break 1954). Consequently, depreciation must likewise be measured in money-metric terms.

Precisely because depreciation is economic in nature, it is necessary to consider non-physical factors that affect the depreciation rate. Technological obsolescence and market power, two factors closely associated with intangible capital, come to mind (Haskel and Westlake 2018). Intangible capital is becoming, perhaps inexorably, the most significant type of capital in the economy. From organizational capital to brand names to R&D and sweat equity, intangibles make up an important share of the economy (Corrado, Hulten, and Sichel 2009; McGrattan 2020; Bhandari and McGrattan 2021). Even so, measurement of intangible depreciation remains exceptionally difficult, particularly across the vast spectrum of intangible varieties (Li and Hall 2016).

With economic depreciation in mind, it strains credulity to think that intangible depreciation is constant. For example, to prevent intellectual property rights from expiring, firms spend large sums of money on reusing old characters from movies or books and thereby maintain the value of the asset (Kaiser, Cuntz, and Peukert 2023). For example, the notoriously terrible movie *Hellraiser: Revelations* was made on a shoestring budget by Dimension Films with the express purpose of maintaining its intellectual property right and therefore prevent the total depreciation of the asset. With that activity in mind, perhaps it is reasonable to think of many types of intellectual property as roughly following a one-hoss-shay depreciation profile, with firm "maintenance" extending the asset's life. On the other hand, intangibles like software may have a more straightforward maintenance interpretation. Rather than release an entirely new software product, a firm may release patches or fixes. With that in mind, a purely physical conception of depreciation is an inadequate barometer for distinguishing gross from net intangible investment.