Capital Maintenance and Differential Capital Taxation

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In this paper, 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. I make four contributions. First, I show in a heterogeneous capital framework that because the demand for maintenance runs through its effect on the depreciation rate, capital with a high maintenance elasticity of depreciation is relatively insulated from tax changes. Consequently, the maintenance channel renders some types of capital more tax-inelastic than others, so that even a uniform tax change distorts relative capital quantities. 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, structures, and software using a novel smooth local projections approach with data from the Annual Survey of Manufactures. Finally, I evaluate the quantitative significance of the maintenance channel in two ways. First, 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%. Second, 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 taxes should be roughly uniform.

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1 Introduction

Imagine there's no maintenance. It's easy if you try: no auto mechanics, no internal teams to ensure that equipment runs properly, no janitors to keep structures in working order, and no teams of computer scientists to maintain software. In that world, the economy loses 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 such a world, capital depreciates fully exogenously and the traditional neoclassical approach to user cost is 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; maintenance is deductible from firm profits, while the after-tax price of investment is determined by the collection of tax provisions influencing investment.

This paper investigates the positive and normative consequences of relaxing the assumption explicit in the neoclassical growth model (NGM) that the no-maintenance world prevails and implicit 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, even within asset classes. 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.

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. The choice to maintain old capital or invest in new capital is determined by the relative price of maintenance to investment together with the depreciation technology. In the model, the relative price is determined by a uniform tax on profits—from which maintenance is exempt—and an asset-specific subsidy on investment capturing policies like the investment tax credit and tax depreciation allowances. Increases in the relative price of maintenance—equivalently, decreases in the marginal effective tax rate—lead firms to substitute away from maintenance at a rate determined by the curvature of the depreciation function. Capital with a higher maintenance elasticity of depreciation is relatively shielded from changes in policy because depreciation endogenously responds, while capital types that cannot do as much to respond are more sensitive. As the tax benefit to maintaining old capital declines, so does the demand for maintenance. Using the terminology of Goolsbee (2004), who 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 elasticity of different capital types to changes in tax policy. With that in mind, I show that a simple 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. Given practical variance in both depreciation technologies and observed marginal effective tax rates, this is an important channel for optimal policy.

Next, I analyze empirical evidence for the maintenance channel using the Annual Survey of Manufactures. This is a difficult task because there is little data on capital maintenance. I proceed in two steps. First, I document the existing evidence on maintenance, much of which comes from the literature on housing. 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, structures, and software. Theory suggests that the long-run elasticity of the gross investment rate with respect to the relative price of maintenance to investment 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 controlling for industry factors, which in turn pins down the maintenance elasticity. Ten years out from a unit shock to the relative price of maintenance, the maintenance elasticity for equipment is stable around 0.6, around 0.4 for structures, and 0.15 for software.

Finally, I quantify the positive and normative relevance of the maintenance channel. First, using the NGM approach from Barro and Furman (2018) 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% in the NGM. Second, I quantify optimal tax rates on equipment and structures using a range of plausible maintenance elasticities together with point estimates. The results indicate that, compared to the current system substantially favoring equipment, accounting for maintenance pushes toward uniformity.

Literature. This paper descends from an old literature that objects to the Hall and Jorgenson (1967) constant user cost framework for analyzing tax policy. There are two categories of such studies relevant here: those on replacement investment and those on endogenous depreciation via maintenance and capacity utilization.

First, this paper relates to the extant literature on replacement investment. Feldstein and Rothschild (1974) study the conditions under which replacement investment is constant, with particular focus on whether or not the standard user cost formula is generally applicable. They pay close attention to the age structure of capital, something which is undoubtedly relevant for a theory of capital maintenance, but which I abstract from here. Rust (1987) and Schiraldi (2011) study the empirical relevance of capital replacement, while Cooley, Greenwood, and Yorukoglu (1997) develop a growth model with capital replacement.

Next, this study is closest to McGrattan and Schmitz Jr. (1999). They develop a homogeneous capital model of maintenance and investment, with maintenance expenditures pinned down by the relative price of maintenance to investment. I innovate on their approach by extending it to many types of capital goods, connecting it to optimal policy, and developing 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. Although a variety of 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), not one of them, to my knowledge, attempts to credibly estimate an aggregate depreciation function, let alone an asset-specific one, extend it to optimal policy, or considers the role of capital heterogeneity, all of which I do.

Next, I build on a small empirical literature documenting deviations from the Jorgenson user cost approach. In this literature, Goolsbee (1998) and Goolsbee (2004) are the most important and together, they form, to my knowledge, the only rigorous macroeconomic demonstrations that depreciation is an economic decision and capital maintenance plays a critical role in that decision. The former studies the retirement of airplanes and shows that the decision is not mechanical, which suggests that depreciation is not mechanical either. The latter documents that, both in theory and in practice, there is an Alchian-Allen effect on capital demand resulting from tax policy: reductions in the capital tax rate lead to increases in the quality of capital, where quality is captured by the extent of capital maintenance. Goolsbee captures this empirically by showing that firms demand higher quality capital as taxes decline. I nest Goolsbee's ad-hoc model of capital quality in a general equilibrium model of capital maintenance, demonstrating that, just as he showed in partial equilibrium, the Alchian-Allen effect prevails. Additionally, economists have documented a clear connection between maintenance and depreciation in the housing literature (Knight and Sirmans 1996; Harding, Rosenthal, and Sirmans 2007). 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, using a variety of controls and model specifications, asset-specific depreciation functions.

Next, my work relates to several studies in both the macroeconomic growth and business cycle literature that takes seriously the role of shocks to the relative price of investment. Such models typically feature variable capacity utilization in response to shocks to the marginal efficiency of investment, or in multisector models, investment-specific technology shocks (Greenwood, Hercowitz, and Huffman 1988; Greenwood, Hercowitz, and Krusell 2000; Justiniano, Primiceri, and Tambalotti 2010). There, a shock to the marginal efficiency of investment is isomorphic to an investment tax shock. To my knowledge, only Greenwood, Hercowitz, and Krusell (2000) study a heterogeneous capital model, but they restrict attention to equipment and structures and assume that there are no shocks to the marginal efficiency of investment in structures. In the interest of exclusively highlighting maintenance, I abstract from utilization, but it could be incorporated similarly to the approach in Kabir, Tan, and Vardishvili (2023).

Finally, I make both a theoretical and a quantitative contribution to the literature on differential capital taxation by providing an efficiency rationale for taxing capital differentially and a simple formula for doing so. Very few papers study differential taxation from an efficiency perspective. Perhaps due to convincing early results from Harberger (1964, 1966) and Diamond and Mirrlees (1971) that capital should not be taxed differentially and arguments from Chamley (1986) and Judd (1985) that capital should not be taxed at all, the problem is understudied relative to its policy prevalence. Auerbach (1979) studies differential taxation in a dynamic setting in which the government is free to tax any kind of capital, while Feldstein (1990) studies differential taxation when one capital good's tax rate is fixed. My formula nests Feldstein's. 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. I add substantially to this literature by documenting a realistic instance in which, even under perfect competition, it may be optimal to tax capital differentially. On the other hand, most research focuses on differential taxation for redistributive reasons. For example, Slavík and Yazici (2014, 2019) find that equipment should be taxed more than structures, with an optimal differential of around 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, but for different reasons.

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

2 The Transmission of Capital Tax Policy with Endogenous Depreciation

In this section, I proceed in two steps to analyze how accounting for endogenous depreciation affects the traditional view of differential capital taxation. First, I analyze a decentralized neoclassical economy with many types of capital and show that, in general, accounting for endogenous depreciation leads to substantially different equilibrium allocations of capital from the benchmark neoclassical model given a set of capital tax rates. Second, prompted by the positive results, I show that a planner choosing optimal capital tax rates will make quite different choices from a planner in a neoclassical economy with exogenous maintenance and depreciation.

2.1 Decentralized Economy

There is a representative firm that produces an output good Y_t with N capital types and labor. I assume that the production technology $Y_t = F(K_{1,t}, \ldots, K_{N,t}, H_t)$ 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 rate w_t.[1] At an interior solution, profit maximization requires

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

$$F_{H_t} = w_t. \tag{2}$$

The representative firm rents capital and labor from a representative household with preferences over consumption c and labor H_t given by

$$U = \sum_{t=0}^{\infty} \beta^t \left(u(c_t) - v(H_t) \right) \tag{3}$$

where u is increasing, strictly concave, three times continuously differentiable, and v is strictly concave and likewise thrice continuously differentiable. $\beta \in (0, 1]$ is the discount factor embodying the required return on capital r^k.

The household supplies labor H to a representative firm in return for wage w_t. Additionally, the household saves in N discrete types of capital $K_{i,t}$, which it rents to a representative firm at rate $r_{i,t}$. Every period, the household chooses an investment quantity $X_{i,t}$ in new capital and a maintenance quantity $M_{i,t}$ in old capital type i. 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

$$K_{i,t+1} = X_{i,t} + (1 - \delta_i(m_{i,t}))K_{i,t}. \tag{4}$$

Note that indexing the depreciation function by capital types 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. This is undoubtedly an empirically important channel (see, for example, Harris and Yellen (2023)), but I neglect it here because, in principle, 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.

1. The firm rents the capital stock rather than owns it because the analytical solution to the Ramsey problem is easier with this set-up. As is well-known, the decentralized problem is the same under the conditions of this problem.

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 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 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

$$c_t + \sum_{i=1}^{N} \left[(1-\tau_t^c)M_{i,t} + (1-\tau_{i,t}^x)X_{i,t} \right] \leq w_t H_t + \sum_{i=1}^{N} (1-\tau_t^c)\, r_{i,t} K_{i,t} \tag{5}$$

Through its choices of capital, investment, maintenance, and consumption, the household maximizes (3) subject to (5) and (4), giving rise to the following first-order conditions:

$$v'(H_t) = w_t u'(c_t) \tag{6}$$

$$-\delta_i'(m_{i,t}) = \frac{1-\tau_t^c}{1-\tau_{i,t}^x} \tag{7}$$

$$u'(c_t)(1-\tau_{i,t}^x) = u'(c_{t+1})\beta \Big[(1-\tau_{t+1}^c) r_{i,t+1} + (1-\tau_{i,t+1}^x) \left(1-\delta_i(m_{i,t+1}) + \delta_i'(m_{i,t+1})m_{i,t+1}\right) \Big], \tag{8}$$

where (7) and (8) apply to all capital types $i = 1, \ldots, N$. While the marginal condition between consumption and leisure 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 (7). In the model, differences in relative prices are entirely determined by taxes. The tax on profits discounts the price of maintenance while the investment subsidy $\tau_{i,t}^x$ plays the same role for investment. Consequently, an increase in the profit tax τ_t^c corresponds to a decrease in the relative price of maintenance, while an increase in $\tau^x_{i,t}$ raises the relative price. Putting these together, the choice between maintenance and taxes is pinned down by the marginal effective tax rate on capital type i is captured by (7):

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

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.[2] 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

2. The logic continues to hold along a balanced growth path with technological and population growth. I discuss this further in Section 3.

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

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

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 neoclassical growth model with maintenance (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. 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. Second, continuing with the constant-elasticity assumption, the NGMM features a tax elasticity of user cost given by

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

Consequently, 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.[3] 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.

3. Note that this mechanism does not necessarily need to come from maintenance; capacity utilization is likewise affected by variation in tax law. In a model like in Greenwood, Hercowitz, and Huffman (1988) or its more complex descendants (e.g., Justiniano, Primiceri, and Tambalotti (2010)) investment tax shocks are isomorphic to shocks to the marginal efficiency of investment. I highlight maintenance because it is more plausible as a long-run channel affecting depreciation.

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, 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.*

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. Finally, suppose each capital type faces a common tax rate τ^c in steady-state. 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.

Start with the maintenance elasticity. As an illustration of Proposition 2, consider a variation of the 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 profit 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.

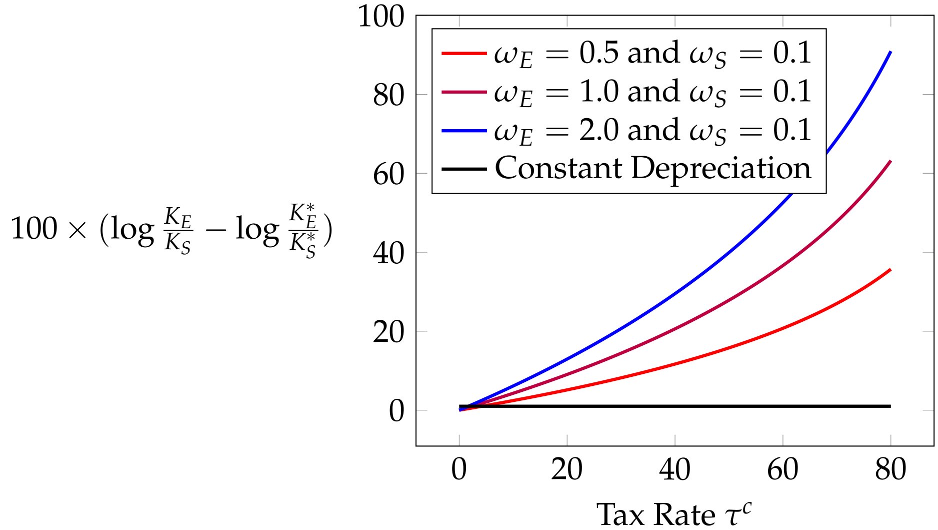

Figure 1: Log deviation of the steady-state capital equipment-structures ratio from its optimal level as a function of the corporate tax rate τ^c (multiplied by 100). For all cases, I set $\gamma_E = \gamma_S = 0.02$ and vary maintenance elasticities ω_E between 0.5, 1, and 2, while fixing $\omega_S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

The quality of capital, captured by γ_i, likewise matters for the relative responses of capital types. Informally, γ_i can be understood as reflecting the inherent level of depreciation of the capital good. 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 vary the quality of equipment and structures, holding fixed the maintenance elasticity. I fix $\gamma_E = 0.05$ and vary γ_S across the set $\{0.001, 0.005\}$. 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 that 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. Consequently, quality acts like an amplifier on deviations from the optimum.

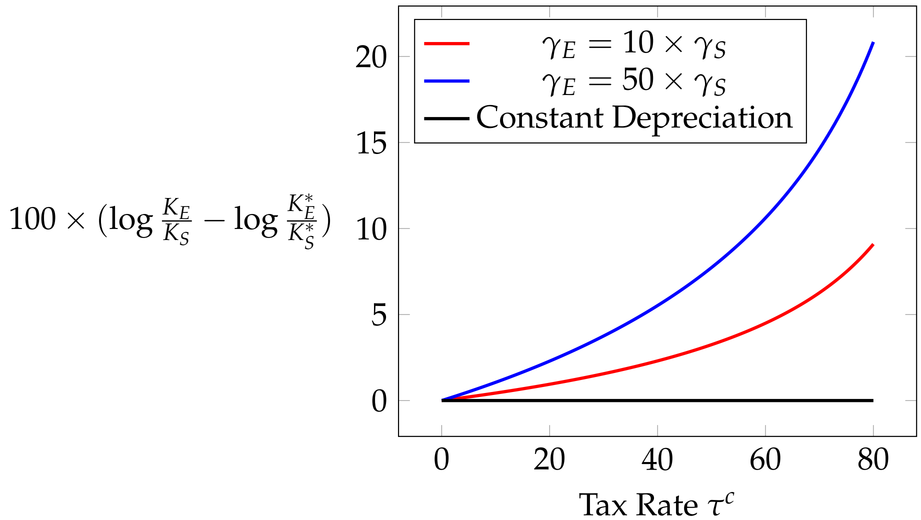

Figure 2: Log deviation of the steady-state capital equipment-structures ratio from its optimal level as a function of the corporate tax rate τ^c (multiplied by 100). For both cases, I set $\omega_E = \omega_S = 1$ and vary the quality parameter between $\gamma_S = 0.001$ and $\gamma_S = 0.005$ while fixing $\gamma_E = 0.05$. 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. The NGMM formalizes the intuition of Goolsbee (2004), who speculated 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.

2.2 A Differential Tax Optimality Result

The economics of the decentralized economy strongly suggest that a simple extension to optimal policy would be fruitful. 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. Consequently, 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 the 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 to do with alterations of depreciation schedules and tax credits than profit tax rates (Mertens and Ravn 2013). Putting together the taxes on labor, profits, and investment with a revenue requirement G_t, the government budget constraint is

$$G_t = \sum_{i=1}^{N} \left(\tau_t^c K_{i,t} \left(F_{K_{i,t}} - m_{i,t} \right) - \tau_{i,t}^x X_{i,t} \right) \tag{9}$$

Note that we could add a linear tax on labor and it would have little impact on the analytical results. 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:

$$c_t + G_t + \sum_{i=1}^{N} \left(X_{i,t} + M_{i,t} \right) = F(K_{1,t}, \ldots, K_{N,t}, H_t).\text{[4]} \tag{10}$$

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* (10).

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*

4. 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 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 (9)*.*

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.*

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 precisely 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 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.

Next, there are two special cases of production worth highlighting to give the rest of the intuition. For both, suppose there is no labor demand from the representative firm or that there is no cross-elasticity between capital and labor. Following Feldstein (1990), define the production elasticity of production factor j with respect to production factor i as

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

To start, suppose there are no cross-partials in production and let $\hat{r}_i \equiv F_{K_i} - m_i$ define the return on capital net of maintenance.

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

$$\frac{\tau_i}{\tau_j} = \frac{\frac{\hat{r}_j}{F_{K_j}} \varepsilon_{K_{jj}} - \frac{\omega_j}{1+\omega_j}}{\frac{\hat{r}_i}{F_{K_i}} \varepsilon_{K_{ii}} - \frac{\omega_i}{1+\omega_i}} \tag{11}$$

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

$$\frac{\tau_i}{\tau_j} = \frac{\varepsilon_{K_{jj}}}{\varepsilon_{K_{jj}}}. \tag{12}$$

Example 2. *With AK production, the optimal tax ratio is*

$$\frac{\tau_i}{\tau_j} = \frac{\frac{\hat{r}_i}{F_{K_j}} \varepsilon_{K_{jj}} - \frac{\omega_j}{1+\omega_j}}{\frac{\hat{r}_i}{F_{K_i}} \varepsilon_{K_{ii}} - \frac{\omega_i}{1+\omega_i}} \frac{\boldsymbol{\varepsilon}_i}{\boldsymbol{\varepsilon}_j}, \tag{13}$$

where $\boldsymbol{\varepsilon}_i$ is independent of Lagrange multipliers and a function of the cross-elasticities and tax rates of other capital types.

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 (12) 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.

Feldstein places particular emphasis on the assumption that it is necessary to assume that one type of capital is untaxed; clearly that is not required in this context. 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.

Together, these examples are in the spirit of Goolsbee (2004), who suggests that increases in tax rates penalize adoption of high quality capital, where quality is defined according to the amount of necessary maintenance. Consequently, these results formalize Goolsbee's intuition, while nesting the original Feldstein (1990) formula and adding an additional relevant elasticity.

Toward concrete interpretation of the results, for the remainder of the paper, suppose the depreciation technology for capital type i is given by

$$\delta_i(m_i) = \gamma_i m_i^{-\omega_i}, \quad \gamma_i, \omega_i > 0. \tag{14}$$

Two parameters—capturing quality γ_i and the maintenance elasticity ω_i— drive the difference between the standard neoclassical growth model and the neoclassical growth model augmented with maintenance: a quality parameter γ_i and an elasticity parameter ω_i.

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.*

In the case where, for example, we have Cobb-Douglas production and three 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, structures, and intangibles all 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 the following section, I turn toward an empirical evaluation of the maintenance channel to answer precisely this question.

3 The Empirical Maintenance Channel

In this section, I first discuss existing evidence on the maintenance channel. Following that, I turn to the model to indirectly estimate maintenance elasticities by asset type.

3.1 Evidence on the Maintenance Channel

There is some existing direct evidence on the maintenance channel, but not across asset types. To my knowledge, among developed nations, only Canada publishes aggregate maintenance data as part of its Capital Expenditures Survey. Using this data, McGrattan and Schmitz Jr. (1999) present casual evidence on the substitutability between investment and maintenance, noting that the volatility of the former is much larger than the latter. At the same time, McGrattan and Schmitz Jr. (1999) document that industries facing more uncertainty tend to maintain their old capital rather than invest in new capital. Kabir, Tan, and Vardishvili (2023), using an Indian dataset, calibrate the maintenance elasticity to 0.4 but do not estimate across capital types.

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 depreciation rate. Taking his estimate seriously suggests that the typical neoclassical approach overstates the elasticity of investment by around 75% (Goolsbee 1998). Additionally, 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. Taken together, these results strongly support the existence of the maintenance channel.

There is also an extensive literature on maintenance of housing capital which also points toward a significantly positive maintenance elasticity. 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, which is precisely the relevant channel in this paper. Harding, Rosenthal, and Sirmans (2007) find a similar result, namely that housing depreciates about 0.5 percentage points less per year after accounting for maintenance. Finally, Hernandez and Trupkin (2021) study the income elasticity of housing maintenance, finding that it significantly declines as incomes rise. Their findings are consistent with the notion in this paper that maintenance is a function of the relative price of maintenance.

3.2 Estimated Elasticities

Given the evidence pointing toward the existence of the maintenance channel, my interest is in decomposing that channel between different types of capital. One would ideally simply regress depreciation on maintenance directly. There are two reasons why this is problematic. First, maintenance data are scarce, generally low-quality, and not detailed at the asset-specific level. To the extent 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. 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. Additionally, a significant portion of maintenance expenditures enter the original purchase contract for capital, and so they are fixed over the warranty period of the asset. These factors make it difficult to directly test for variation in maintenance at higher frequencies. Second, most estimates of depreciation presuppose a particular geometric or hyperbolic depreciation schedule, which goes against the spirit of depreciation reacting endogenously to maintenance. Tax depreciation schedules may have little to do with either accounting or economic depreciation and accounting depreciation is often, at best, a very rough approximation of economic depreciation.[5]

Instead of using the preferred specification, I test for curvature in the depreciation function using a model-implied econometric setting. At best, this will yield rough estimates. Returning to the neoclassical growth model with maintenance and N capital types, Proposition 1 tells us that there is a close relationship between the gross investment rate and the maintenance elasticity in the long run. In particular, a permanent increase in the relative price of maintenance to investment implies a permanent increase in the gross investment rate. In particular, Proposition 1 tells us that the price elasticity of the gross investment rate β relates to the maintenance elasticity as $\beta = \frac{\omega}{1+\omega}$, so an empirical estimate of β allows us to recover the maintenance elasticity. With data on gross investment rates, relative prices, and permanent shocks to the relative price, we can appropriately infer the maintenance elasticity given the long-run elasticity of the gross investment rate to changes in the relative price as long as we control for other factors that would affect the gross investment rate. In a multi-sector model like Greenwood, Hercowitz, and Krusell

5. National accounting for depreciation often relies on dated studies, but for countries that rigorously account for depreciation, they find substantial movement along the time series dimension driven by changes in capital quality and maintenance (Baldwin, Liu, and Tanguay 2015).

(2000) or a single-sector model as in Fisher (2006), that means controlling for productivity and hours because both should affect the investment rate.

Toward implementing Proposition 1, I leverage detailed industry data from 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 to indirectly estimate the maintenance elasticity.[6] The latter contains real and nominal investment and capital stocks at six-digit NAICS detail for equipment, structures, and software over the period 1952-2020 covering around 350 industries. The ASM contains net investment expenditures on plant and equipment, but gross investment is preferable and the FRB data contains software. The ASM contains data on productivity, industry-specific deflators, hours, and employment at the six-digit NAICS level over the period 1959-2018.

The disadvantage of the panel data strategy is that, while it provides additional evidence on variation in gross investment rates, it prevents me from leveraging changes in an asset-specific price because, by assumption, changes in prices are common across industries. Consequently, I instead construct industry-specific composite investment prices. For each type of capital, I collect the aggregate deflator, $P_{i,t}$. Then, using tax policy data from the FRB/US macroeconometric model which cover 1972-2015, I calculate the aggregate after-tax price of investment as $\tilde{P}_{i,t} = \frac{1-\tau^x_{i,t}-ITC_{i,t}}{1-\tau^c_t} P_{i,t}$, where $\tau^x_{i,t}$ is the net present value of depreciation allowances for asset i, $ITC_{i,t}$ is the corresponding investment tax credit, and τ^c_t is the common corporate tax rate. Next, for each industry j, I construct a composite price $\tilde{p}_{j,t} = \sum_i \alpha_{i,j,t} \tilde{P}_{i,t}$, where α_i is the share of capital type i in total capital services for the previous three years in industry j. Finally, to put together the composite relative price, I take the ratio of unit labor cost in each industry to the composite investment price. Because maintenance is quite labor-intensive, I think of it as corresponding to labor costs in each industry. I defer discussion of remaining variables (productivity, employment, hours, and the gross investment rate) to Appendix D.

Clearly, we cannot simply regress the gross investment rate on the relative price of maintenance plus some vector of controls. To estimate even the most basic model requires instrumenting for the relative price of maintenance with some exogenous permanent shock to relative prices. Toward that end, I construct year-by-industry shocks to the relative price of maintenance by appealing to the identification strategy of Fisher (2006). In a one-sector model, Fisher (2006) shows that the econometrician can separately identify structural shocks to the marginal efficiency of investment (or, alternatively, an

6. Of course, the problem with using these data is that they rely on capitalizing investment with constant depreciation rates that are at odds with the theory in this paper.

investment-specific technology shock), productivity shocks, and shocks to hours by imposing long-run restrictions. The scheme works by imposing that, in a recursively ordered VAR, shocks to the relative price of investment (IST shocks) only have a long-run effect on that variable, both productivity and IST shocks can affect long-run productivity, and so on. The idea here is to take Fisher's scheme and apply it on the industry level to get sector-specific IST, productivity, and hours shocks. I discuss some of the difficulties with this approach later in the section.

To construct the instruments, I use a trivariate system of the log-differenced relative price of maintenance, labor productivity growth, and the log-level of hours per worker. To impose the assumptions about long-run effects, I difference a stationary variable when that variable should not have a long-run effect. For example, I assume that only shocks to the relative price of maintenance should have a long run effect on the relative price of maintenance. Consequently, every other variable is differenced from its stationary form. The residuals to that regression can then be interpreted as structural shocks to the relative price of maintenance. For a more concrete example, I run the following TWFE regression for equipment for up to p lags:

$$\Delta\tilde{q}_{j,t} = \alpha_j + T_t + \sum_{j=1}^{p} \beta_{\tilde{q}} \Delta\tilde{q}_{j,t-j} + \sum_{j=0}^{p-1} \beta_{\text{Prod}} \Delta^2 \text{Prod.}_{i,t-j} + \sum_{j=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{i,t-j} + \mu_{i,t}. \quad (15)$$

α_j is an industry fixed effect, T_t is a time fixed effect, $\tilde{q}_{j,t}$ is the log relative price of maintenance, $\text{Prod.}_{j,t}$ 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. 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. I run a similar regression to produce productivity shocks $\eta_{j,t}$, except that the $\mu_{j,t}$ is included as an explanatory variable and innovations to productivity are allowed to affect its long-run level. Finally, innovations from all three variables can affect hours in the long run, so all variables are in their stationary form to recover shocks to hours. Following this procedure yields industry-specific IST shocks, productivity, and hours. The instrument I use in practice uses $p = 2$ lags. I give further detail in Appendix D.2.

Of course, my procedure for identifying sectoral shocks has some shortcomings. In particular, it ignores the input-output structure of the manufacturing sector and ignores common correlated shocks between clusters of industries. Inclusion of a time fixed effect mitigates this to some extent. Additionally, Fisher's original identification scheme is suitable for a one-sector economy, but it does not port over cleanly to this model. Recent work has shown that multisector models can accommodate Fisher's scheme (Guerrieri, Henderson, and Kim 2020), but with the purpose of aggregating shocks rather than identifying them at the sectoral level.

3.3 Results

I estimate the price elasticity of the gross investment rate for each of equipment, structures, and software using local projections. In recent work, Boehm, Levchenko, and Pandalai-Nayar (2023) take a similar approach in a different context. I use a local projections approach together with two-way fixed effects to For up to h horizons, I estimate, for each capital type i in industry j at time t,

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

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. For the relative price of maintenance to investment, I use the industry-specific relative price defined previously. Consequently, the same relative price of maintenance is used for all three capital types. The vector of controls includes two contemporaneous variables: demeaned productivity growth and demeaned growth in hours per production worker. From a structural perspective, it makes little sense to exclude productivity and employment growth. In principle, along a balanced growth path, the investment rate would be stationary since investment and capital grow at the same rate, but shocks to productivity and employment would change the gross investment rate. Additionally, I include three lags each of the asset-specific log gross investment rate, the log relative price of investment, and demeaned productivity growth and hours growth.[7] 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). Because the time dimension is large—greater than forty years for all capital types—the extent of Nickell bias is small. I also include three lags of lagged employment. Across all specifications, I instrument for the contemporaneous relative price of investment, productivity growth, and hours growth with the investment specific technology shock, productivity shocks, and hours shocks derived in the previous subsection.

Rather than use standard local projections , I build on smooth local projections (SLP) from Barnichon and Brownlees (2019) to develop smooth local projections for panel data

7. Montiel Olea and Plagborg-Møller (2021) show that this is sufficient to account for non-stationarity with local projections, so I do not bother with unit root or cointegration procedures.

(SLPP). Briefly, this differs from standard local projections by making the impulse response a smooth function of the forecast horizon through B-splines. In Appendix C, I detail how to estimate SLPP. In this context, SLPP is preferable to standard LP because it allows me to discipline the long-run impulse response by forcing the IRF to fit a polynomial of order q.[8]

I use the SLPP estimator to penalize the impulse response to a line for each capital type for up to ten years. I plot the coefficients $\beta_{i,h}$ for each of equipment, structures, and software in Figures 8a, 8b, and 8c together with a 90% wild cluster bootstrap confidence interval. The coefficient on equipment is stable around 0.6, on structures around 0.4, and software around 0.15. In Table 1, I tabulate the F-statistic at each horizon for each capital type. At all horizons, the instrument set is strong. In Appendix B, I include additional results dropping varying both lag length and the polynomial order.

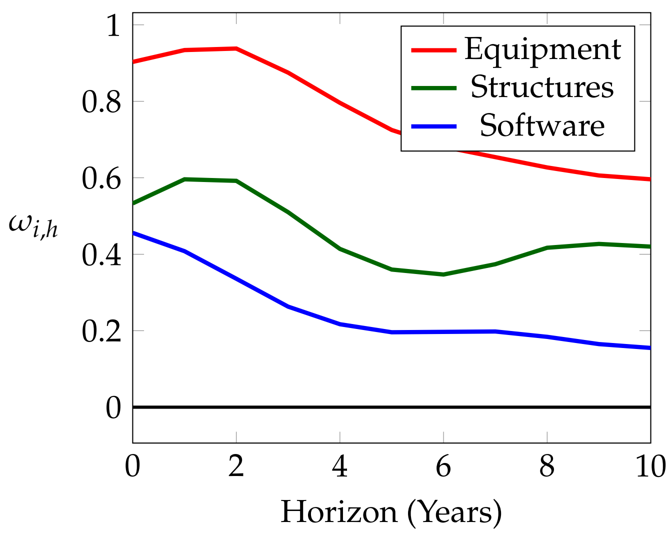

Figure 3: Maintenance elasticities for each capital type.

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 point estimate with a wild cluster bootstrap. I plot the resulting point estimates for the maaintenance elasticities together in Figure 3, while point estimates along with standard errors are in Figures 9a, 9b, 9c.

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

Given point estimates for each capital type, I solve for and plot estimated depreciation functions for each of equipment, structures, and software capital in Figure 4. This requires inferring the value of γ_i for each capital type. To do this, first fix a constant measured depreciation rate $\tilde{\delta}_i$. I use the average depreciation rate for each capital type from Baldwin, Liu, and Tanguay (2015). From the first-order condition on maintenance, we know that

$$\tilde{\delta}_i = \gamma_i \left(\frac{1}{\gamma_i \omega_i} \frac{q_i}{p_i} \right)^{\frac{\omega_i}{1+\omega_i}}.$$

Using the time series average of the relative price of maintenance to investment together with the year-ten implied maintenance elasticities is sufficient to recover γ_i. Consequently, the implied functions for each of equipment, structures, and intangibles are

$$\begin{aligned} \delta_E(m_E) &= 0.07 \times (m_E)^{-0.6} \\ \delta_S(m_S) &= 0.02 \times (m_S)^{-0.4} \\ \delta_I(m_I) &= 0.19 \times (m_I)^{-0.15}. \end{aligned}$$

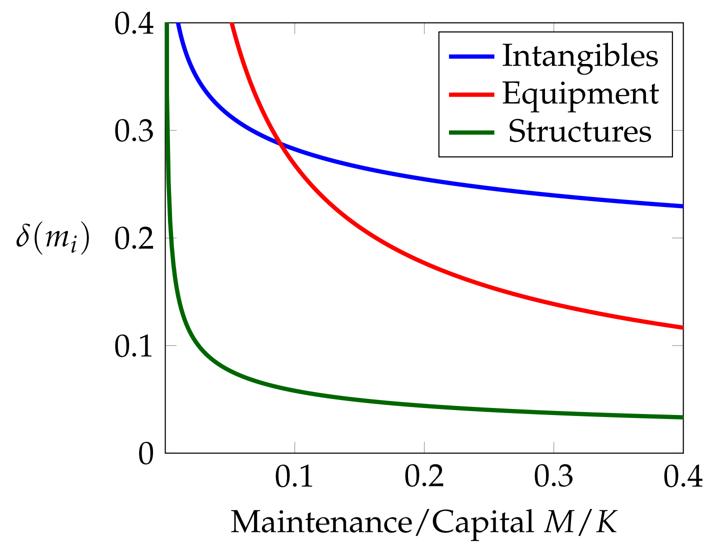

Figure 4: Estimated depreciation functions for each capital type.

4 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.

4.1 Positive: The 2017 Tax Cuts and Jobs Act

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

Here, I focus on the impact of considering maintenance on the predicted long-run effects of the domestic tax changes. Barro and Furman (2018) provide the ideal setting for doing so; they analyze the long-run effects of TCJA through the lens of a standard neoclassical model with heterogeneous capital. The Barro and Furman analysis yields promising results for the TCJA, predicting large increases in the capital-labor ratio. It 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. Consequently, it is a convenient setting to simply 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, the estimated depreciation function for structures for non-residential structures and residential structures, and apply the software depreciation function for intangibles. 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 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 maintenance and resale data.[9] Because the capital-labor ratio maps easily to productivity and output, I simply report the capital-labor figure for each of the corporate sector and the non-corporate sector. Despite small differences in capital shares between sectors, the effect of including maintenance is largely similar between. 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.

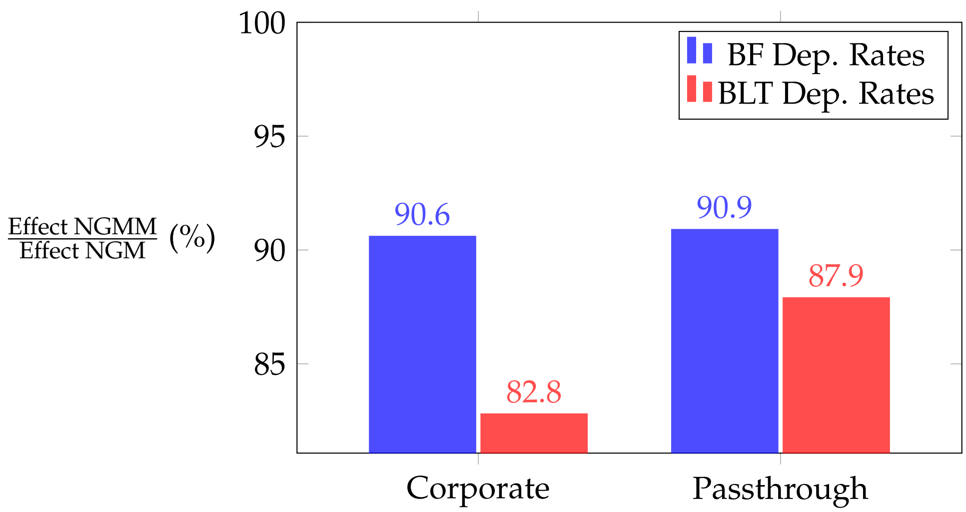

Figure 5: The predicted effect of the TCJA on capital-labor ratios under the NGMM as a share of the predicted effect under the NGM. The BF depreciation rates come from Barro and Furman (2018) and the BLT depreciation rates come from Baldwin, Liu, and Tanguay (2015).

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.

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

4.2 Normative: Optimal Tax Rates

Under permanent provisions in the tax code, the marginal effective tax rate 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. In this subsection, I quantify optimal tax rates on equipment and structures taking account of maintenance compared to a benchmark economy in which the current tax schedule is optimal when policymakers ignore the maintenance channel.

Consider a government with the following budget constraint:

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

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

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

I calibrate initial tax rates to match those in Barro and Furman (2018). Specifically, I set $\tau^c = 0.27$ and the expensing rates to 0.812 and 0.338 for each of equipment and structures so that $\tau_E = 6.5\%$ and $\tau_S = 19.7\%$. Although the federal corporate tax rate is 21% in practice, Barro and Furman (2018) argue that 27% is more accurate after taking account of various state-level taxes.

There is a representative firm with constant returns to scale production technology. The firm produces with two types of capital and labor. Production is Cobb-Douglas

$$Y_t = K_{E,t}^{\alpha_E} K_{S,t}^{\alpha_S} H_t^{1 - \sum_{i \in \mathcal{K}} \alpha_i},$$

where $\mathcal{K}$ denotes the set of capital types. The firm chooses its next-period capital stock for each capital type via its choices of maintenance maintenance and investment. The law of motion for each capital type follows (4) 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 firm 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 elasticity. 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.

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

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

Parameterizations are standard and are in Appendix E.2. Equilibrium conditions are exactly those in Section 2, so I do not repeat them here. 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. 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 yields a positive value for ι_E around one. This indicates that, to generate the current tax system as optimal under the neoclassical paradigm, we need to have equipment far more sensitive to changes in the tax rate than structures. Empirically, this seems to be true, with much higher tax elasticities of equipment capital than structures Wen, Yilmaz, and Trejo (2020). But it also nests other unmodeled policy concerns, namely that structures are easier to tax and that equipment may be more important for growth.

I start by plotting 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 6. The idea behind this exercise is that, while the empirical exercise is useful and informative in Section 3, there is much to quibble with an exercise that only indirectly estimates the maintenance elasticity and relies on a frictionless model to do so. Consequently, a more robust exercise, as a first step, considers a range of plausible values for each maintenance elasticity. 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 black diamond represents current policy rates. Current tax rates are only optimal in the case where both maintenance elasticities are very small. Consequently, except in the unlikely case that there is no maintenance channel at all, tax rates should be higher on equipment and lower on structures. .

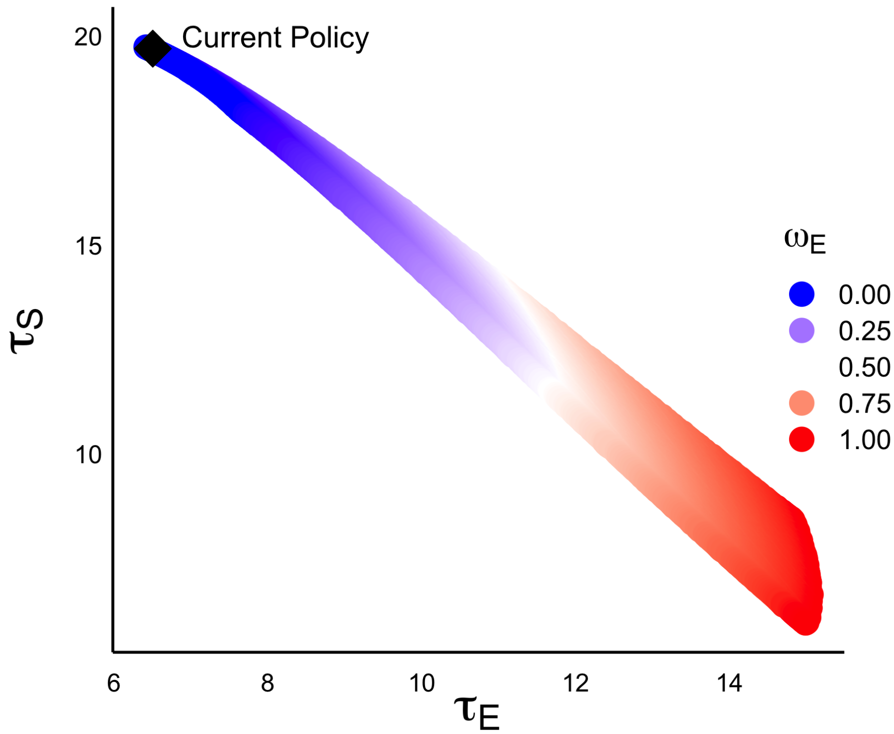

Figure 6: Optimal tax rates for each pair of maintenance elasticities in the grid $\mathcal{W} = [0.1] \times [0, 1]$. The black diamond represents current policy. Color intensity is determined by the equipment maintenance elasticity.

Now, given the point estimates in Section 3, I zoom in on the most likely candidate pair $\omega_E = 0.6$ and $\omega_S = 0.4$. The key result is in Figure 7. 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.

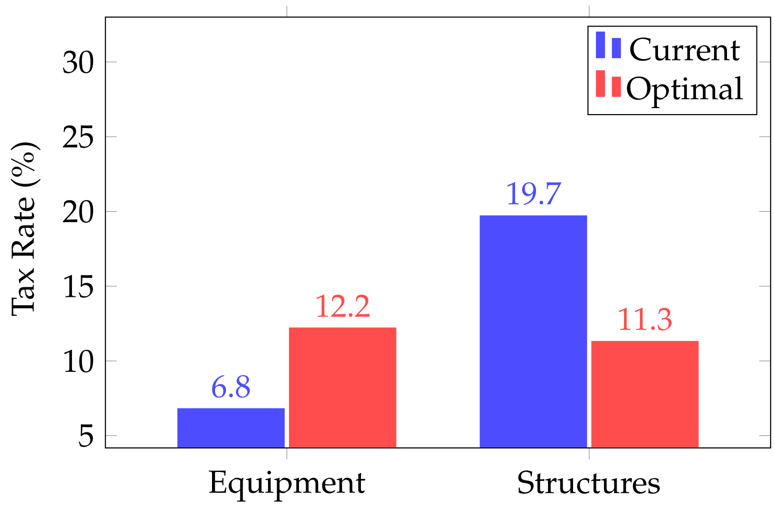

Figure 7: Current tax rates compared to optimal tax rates on equipment and structures when accounting for maintenance.

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

5 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, no country does places investment and maintenance on the same plane. 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

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

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

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

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

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

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

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

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

A.1 Proof of Proposition 1

Proposition 1. *The tax elasticity of the user cost of capital is strictly smaller when depreciation is a strictly decreasing function of the marginal effective tax rate on capital.*

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,

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

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 net output. To complete the proof, we only require first-order conditions for maintenance and capital. Those equilibrium conditions are given in (25), capital (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 (27) yields

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

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

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

From household optimality,

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

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

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

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),

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

Manipulate this expression to yield

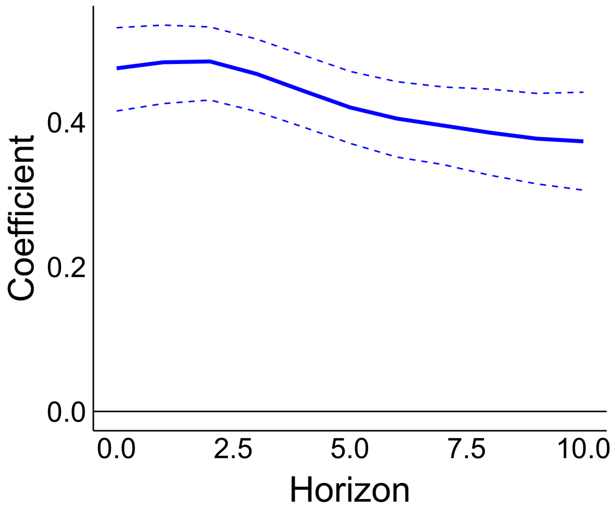
$$
\tau_i=\left(\frac{\hat{r}_i}{F_{K_i}}\varepsilon_{K_{ii}}-\frac{\omega_i}{1+\omega_i}\right)^{-1}\boldsymbol{\varepsilon}_i, \tag{31}
$$

where

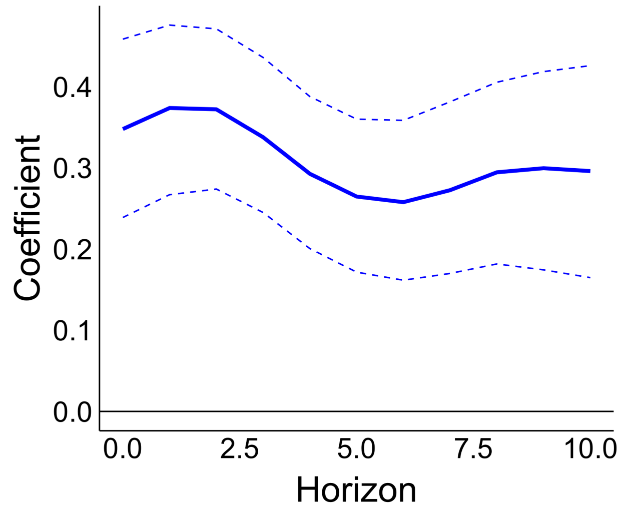
$$
\boldsymbol{\varepsilon}_i=\sum_{\substack{j=1\\ j\neq i}}^{N}\frac{\omega_i}{1+\omega_i}\frac{\varepsilon_{K_{ii}}}{\varepsilon_{K_{ji}}}\frac{F_{K_j}}{F_{K_i}}\tau_j-\frac{1}{\theta+\psi}\left(\theta\sum_{j=1}^{N}\frac{\varepsilon_{K_{ii}}}{\varepsilon_{K_{ji}}}\frac{F_{K_j}}{F_{K_i}}+\vartheta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

is a function of cross-elasticities.

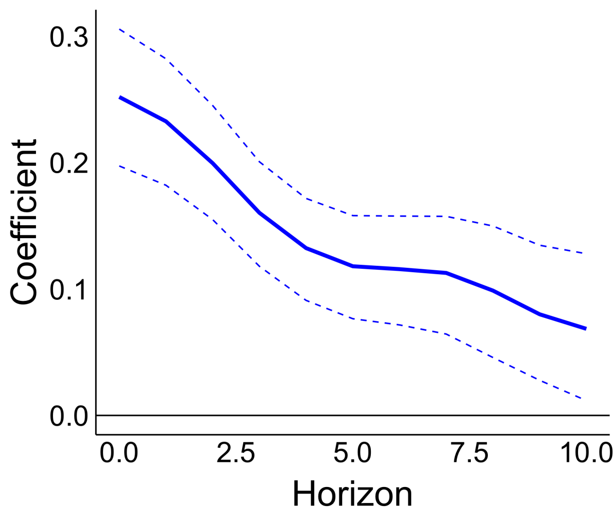
B Empirical Results



(a) Equipment

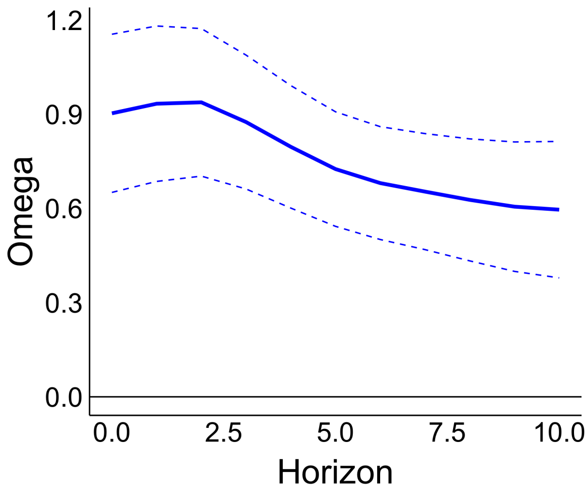


(b) Structures

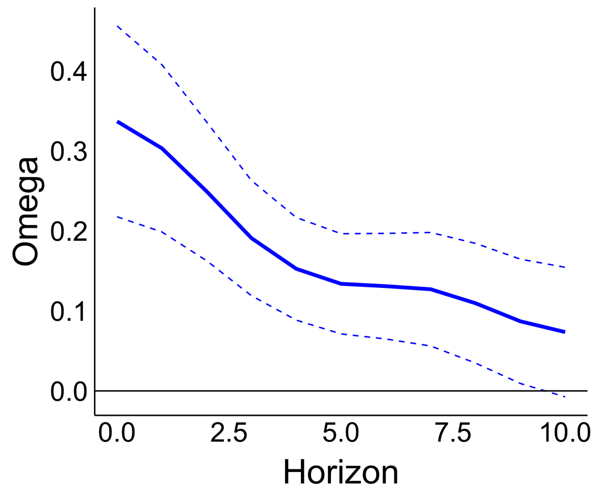


(c) Software

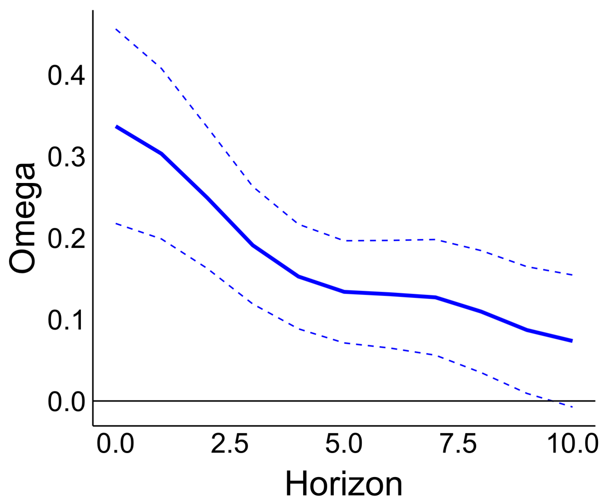
Figure 8: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment in (16) for up to ten years as described in main text along with a 90% confidence interval. Standard errors from wild cluster bootstrap.



(a) Equipment



(b) Structures



(c) Software

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.

	F-Statistic			
Horizon	Equipment	Structures	Software	N
0	4091.58	3176.13	3259.424	13761
1	4026.524	3136.375	3218.02	13444
2	3957.573	3099.504	3181.726	13127
3	3930.318	3091.449	3174.738	12810
4	3811.322	3009.205	3094.589	12493
5	3788.994	2997.428	3081.628	12176
6	3696.547	2935.133	3026.5	11859
7	3607.022	2872.305	2970.418	11542
8	3518.864	2807.056	2906.166	11225
9	3365.263	2633.957	2740.031	10908
10	3328.078	2606.057	2714.998	10591

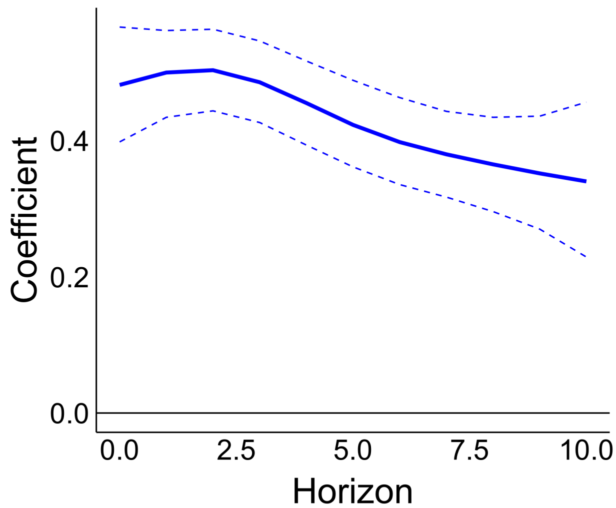
Table 1: First Stage Diagnostics. F-statistics for the first-stage main specification described in the main text. The F-statistic is the Cragg-Donald statistic. I also include the number of observations at each horizon for each regression.

B.1 Robustness

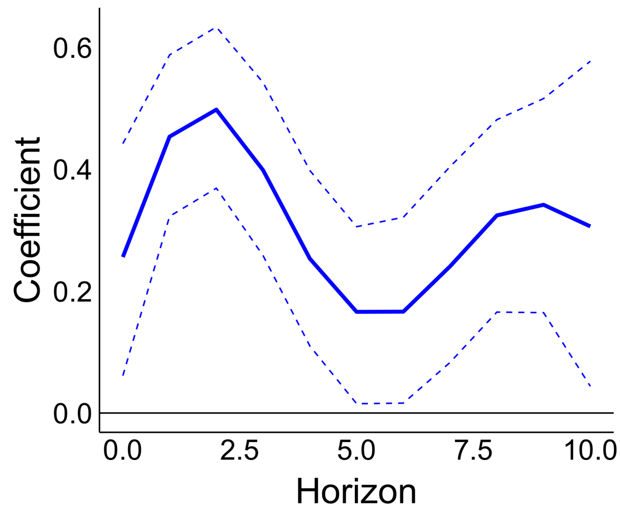
In this subsection, I present robustness checks by first varying the polynomial fit. Results for equipment are largely similar across specifications, but, naturally, the fit changes for structures and software because their respective IRFs from standard LP are far lumpier. In the following appendix, I detail the procedure for smooth LP and show the standard LP fit.

Varying Polynomial Fit

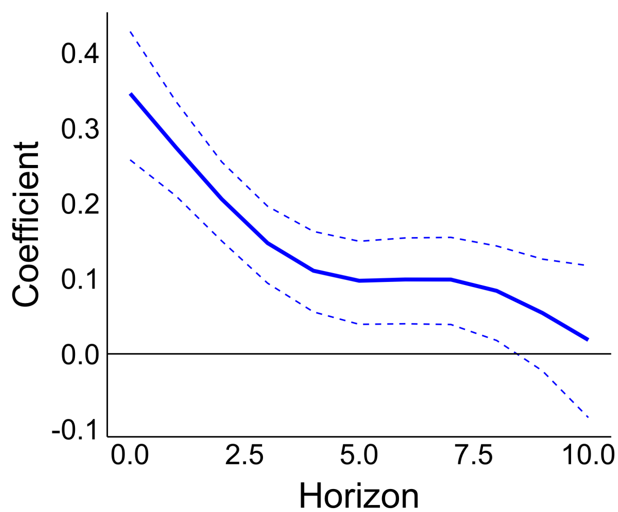
Penalized to Quadratic



(a) Equipment

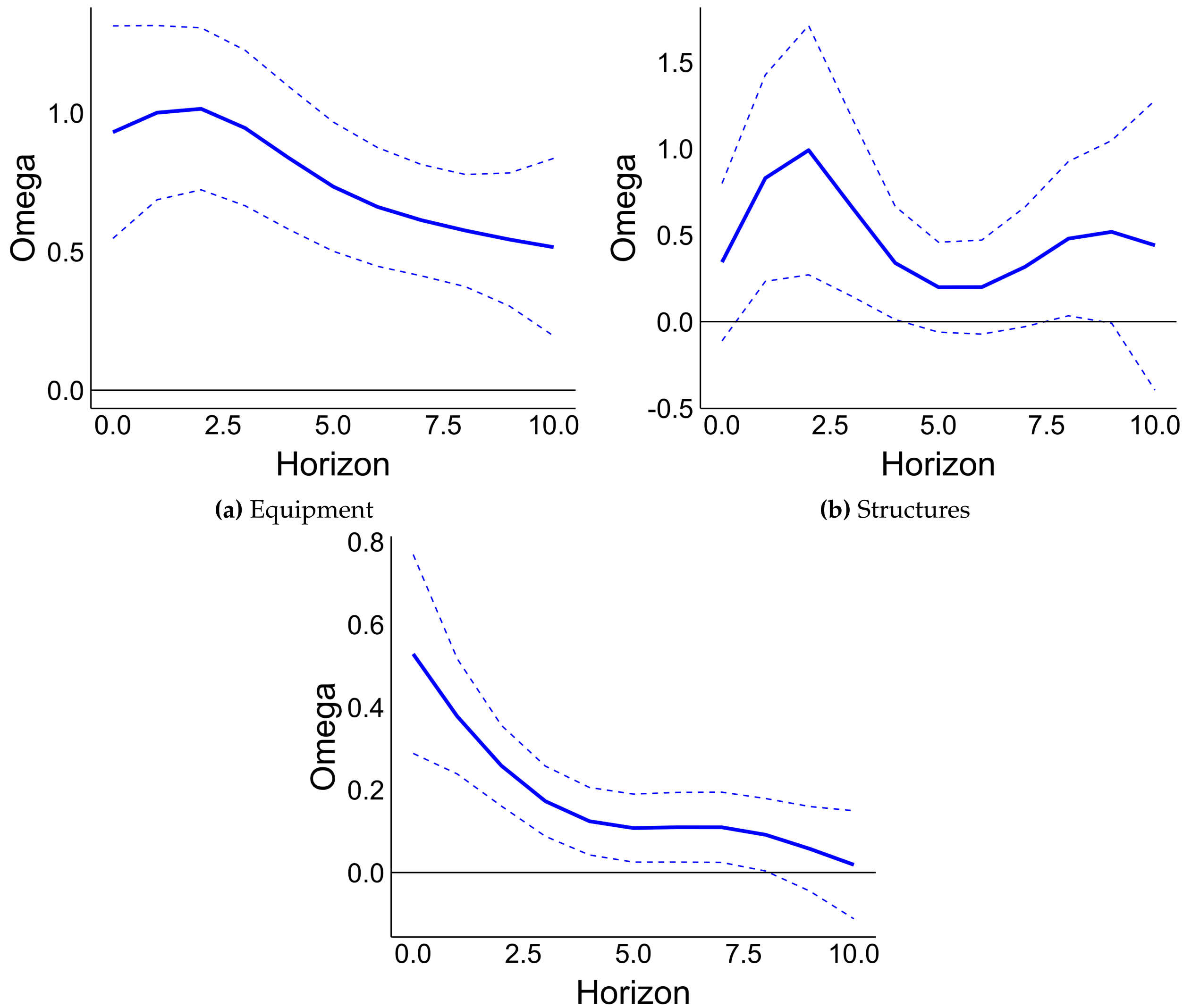


(b) Structures



(c) Software

Figure 10: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years penalized to a quadratic with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.



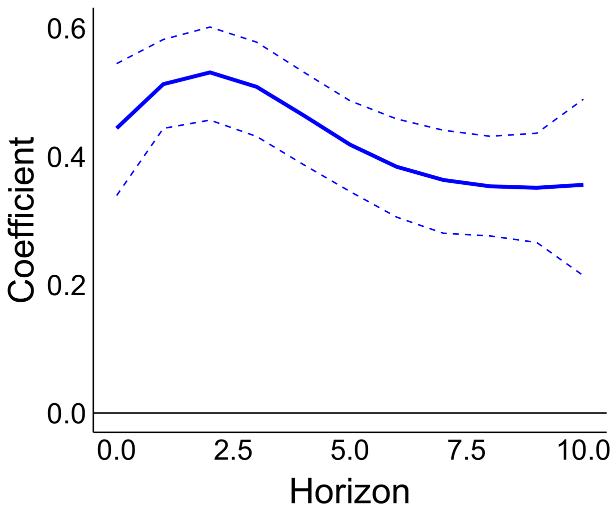
(a) Equipment

(b) Structures

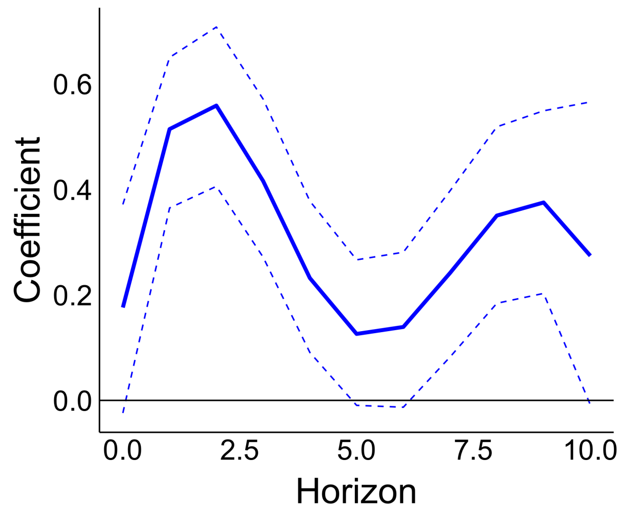
(c) Software

Figure 11: Estimates for the maintenance elasticity by capital type for up to ten years penalized to a quadratic with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.

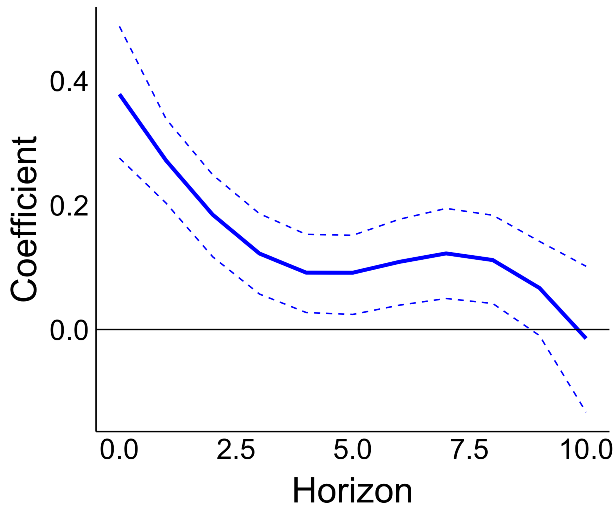
Penalized to Cubic



(a) Equipment

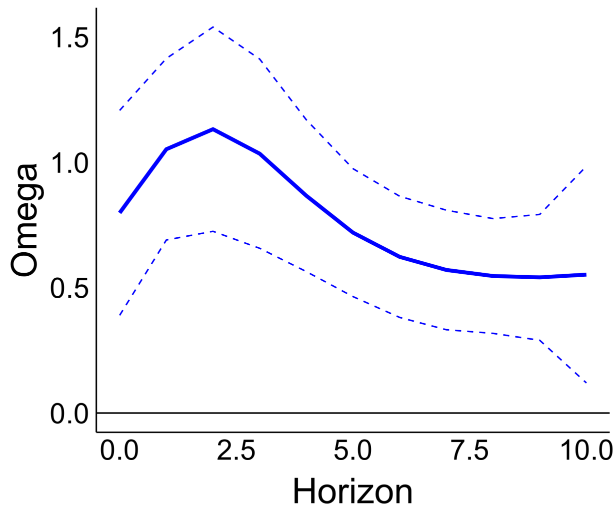


(b) Structures

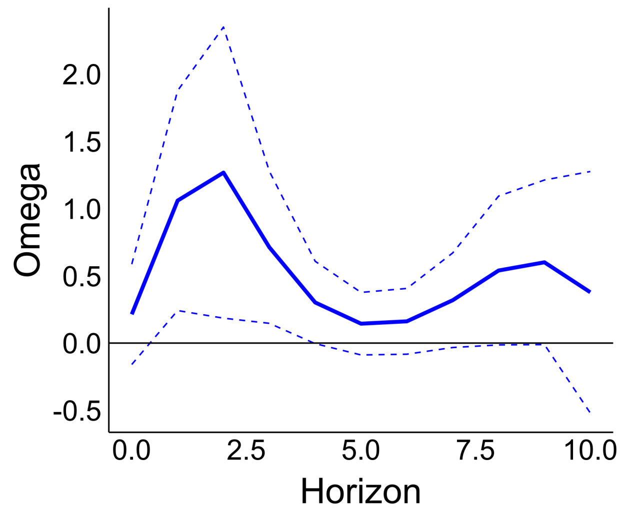


(c) Software

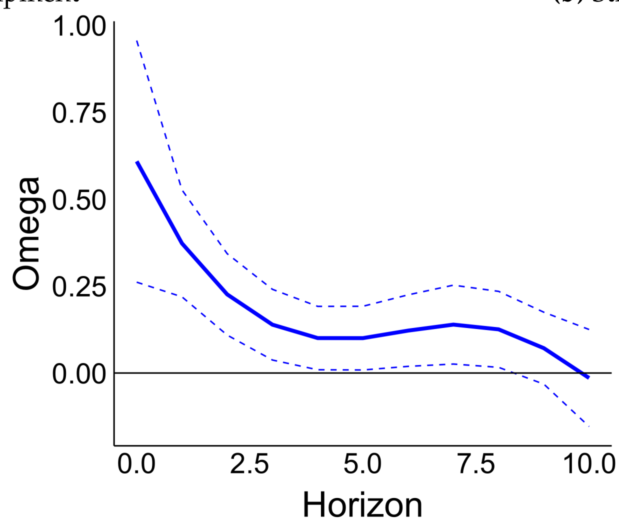
Figure 12: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years penalized to a cubic with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.



(a) Equipment



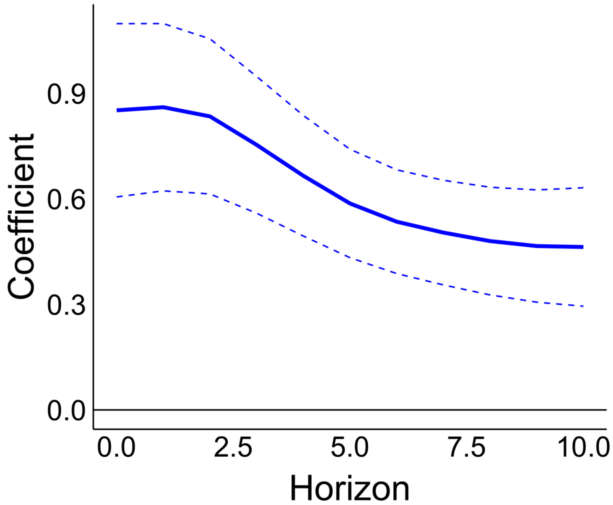
(b) Structures



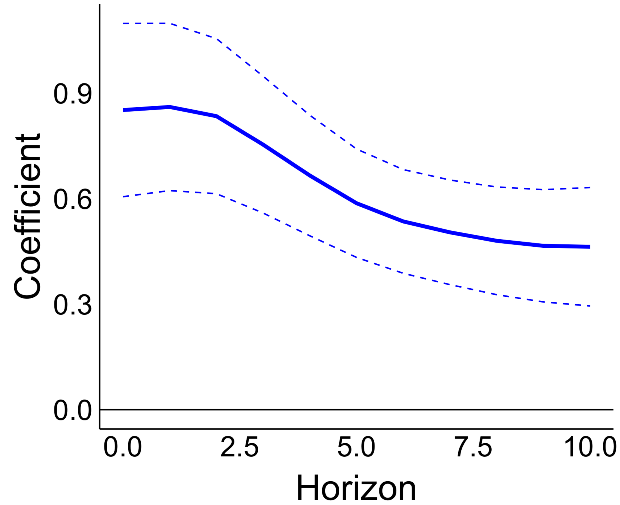
(c) Software

Figure 13: Estimates for the maintenance elasticity by capital type for up to ten years penalized to a cubic with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.

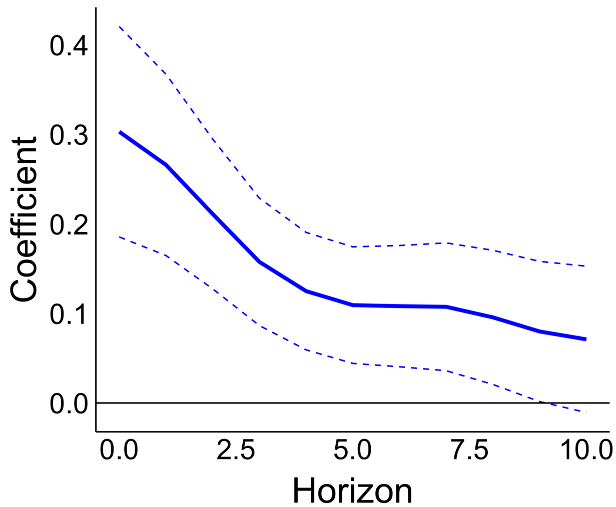
Three Lags



(a) Equipment

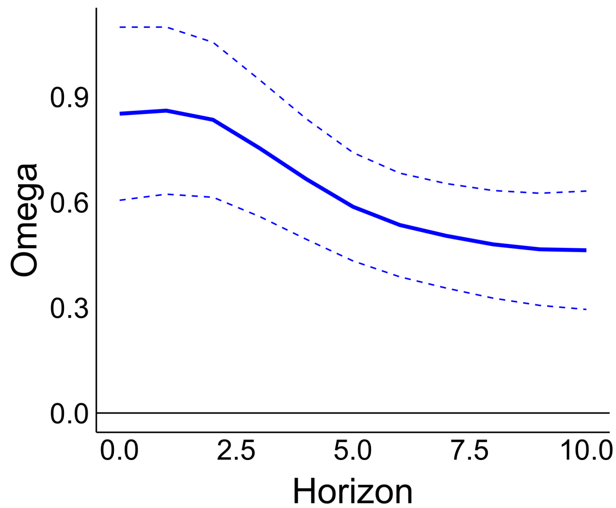


(b) Structures

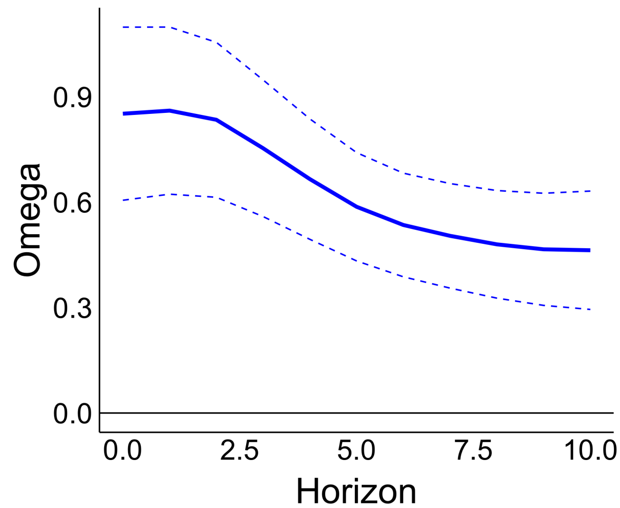


(c) Software

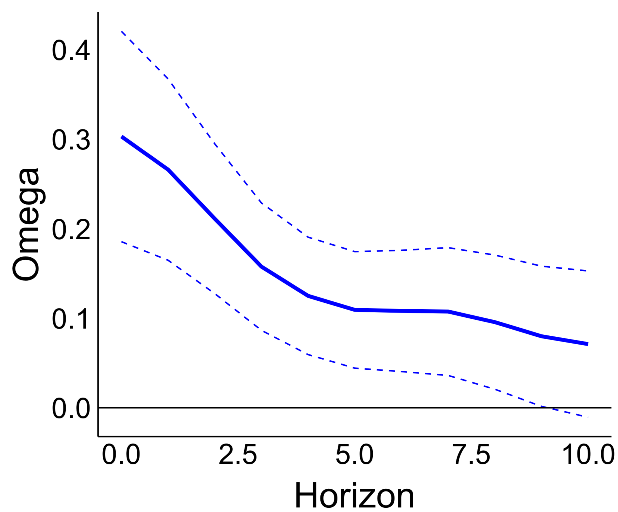
Figure 14: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years penalized to a line with a 90% confidence interval with four lags in the control variables. Standard errors constructed with wild cluster bootstrap.



(a) Equipment



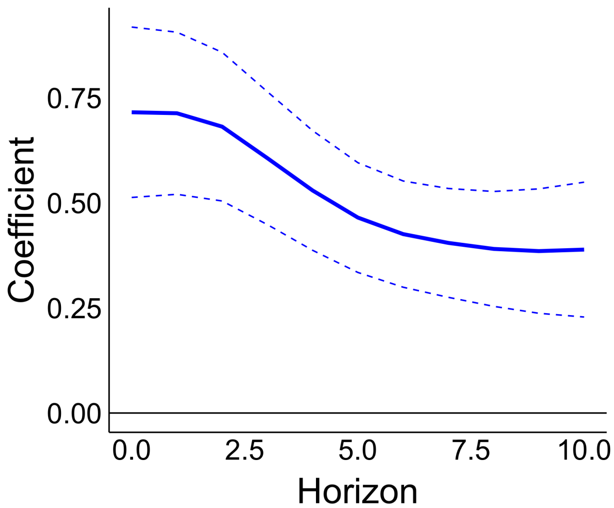
(b) Structures



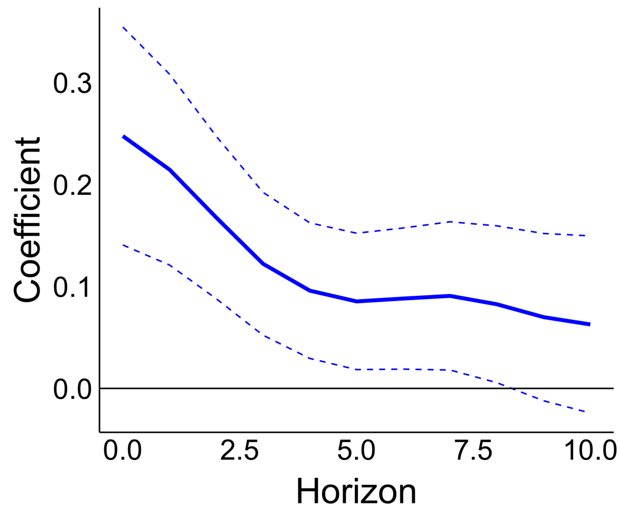
(c) Software

Figure 15: Estimates for the maintenance elasticity by capital type for up to ten years penalized to a line with three lags in the controls confidence interval with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.

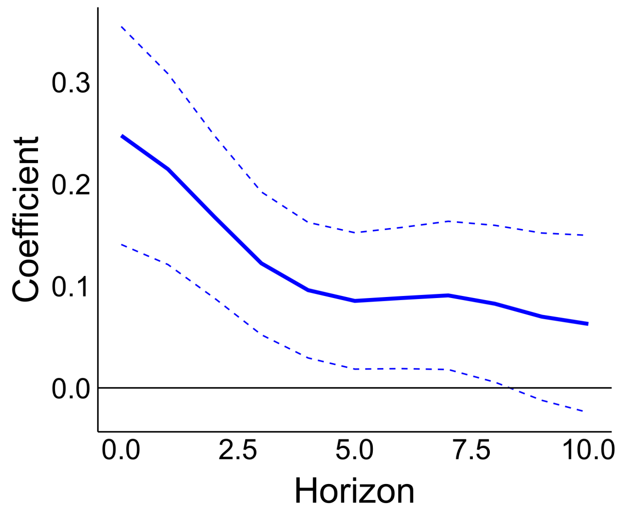
Four Lags



(a) Equipment

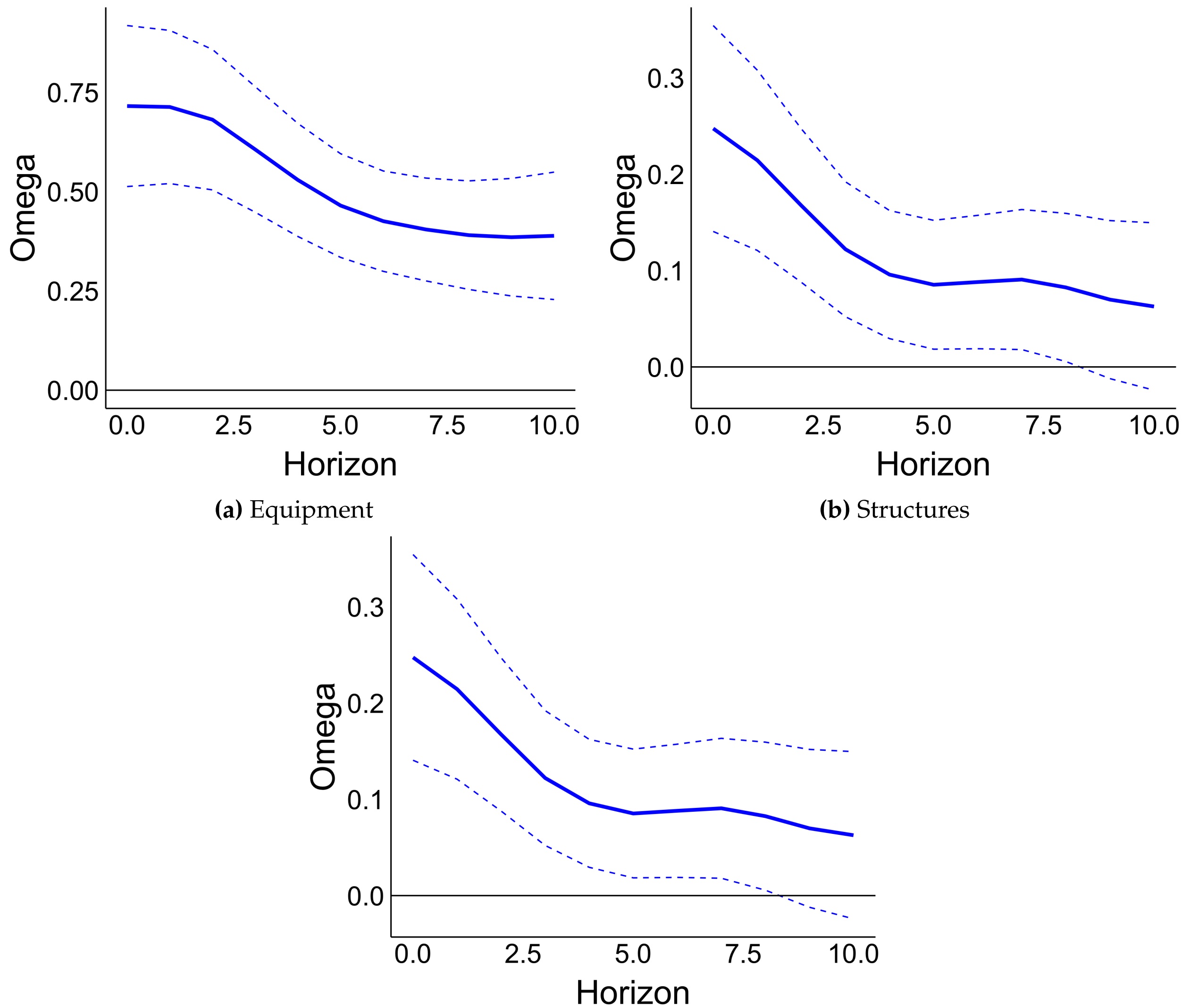


(b) Structures



(c) Software

Figure 16: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years penalized to a line with a 90% confidence interval with three lags in the control variables. Standard errors constructed with wild cluster bootstrap.



(a) Equipment

(b) Structures

(c) Software

Figure 17: Estimates for the maintenance elasticity by capital type for up to ten years penalized to a line with four lags in the confidence interval with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.

C Smooth Local 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

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

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 18, 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.

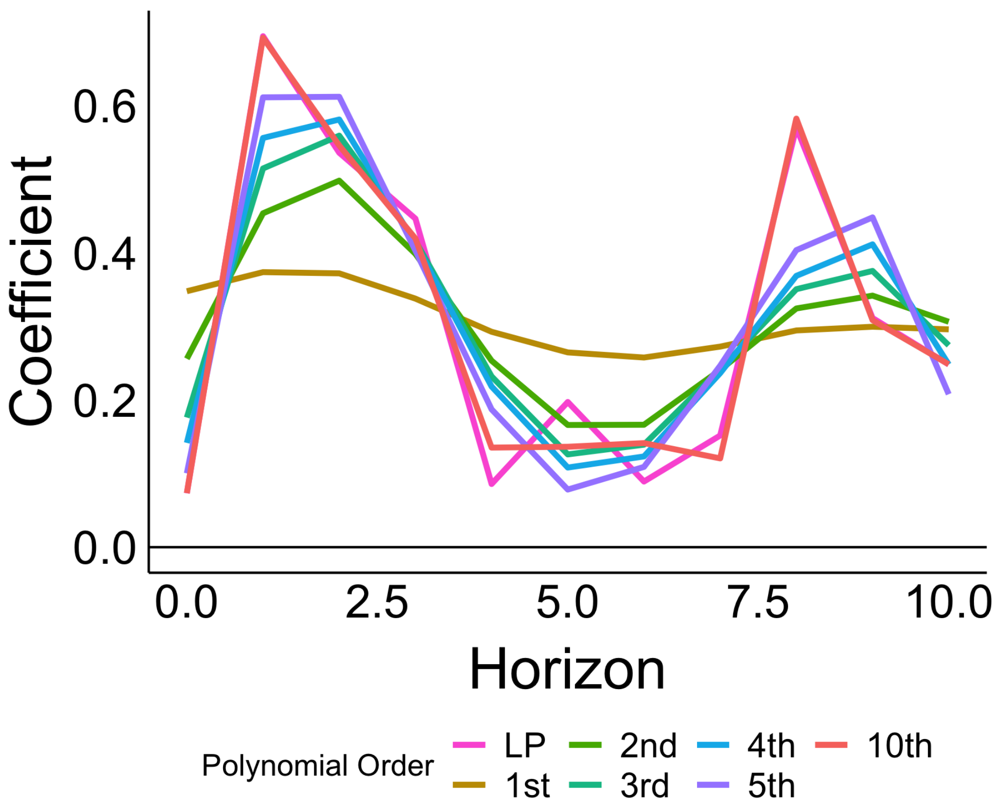
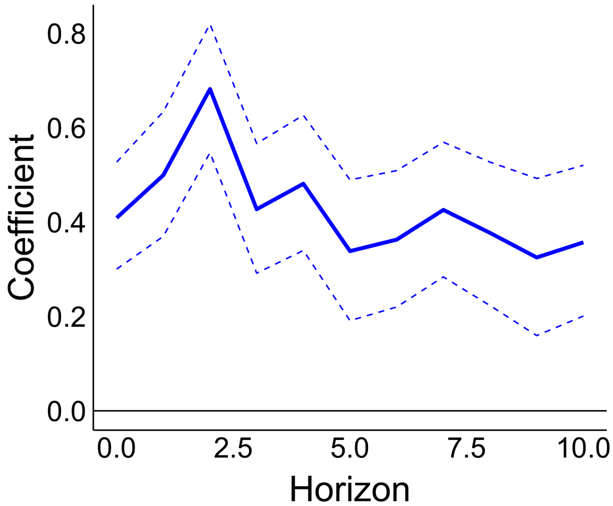
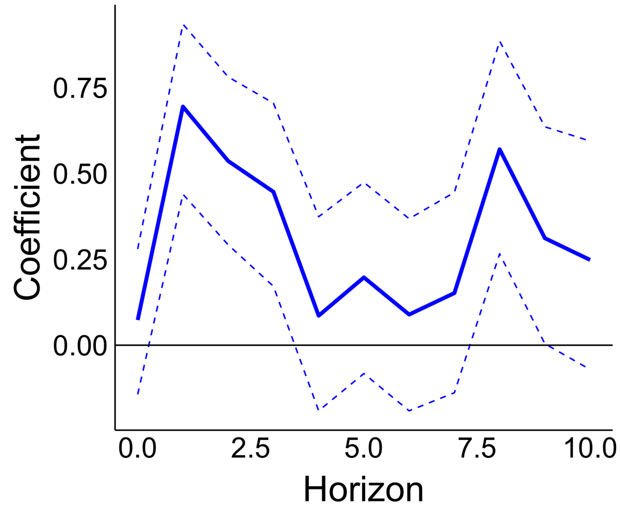


Figure 18: Comparison between standard local projections and smooth local projections penalized toward differing polynomial orders using the structures specification from the main text.

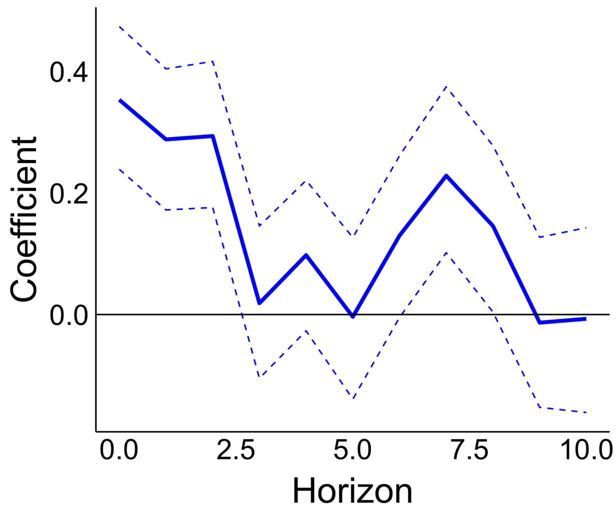
In Figure 19, I plot the standard local projections estimator for each of the specifications in the main text along with associated confidence intervals, while I plot the maintenance elasticities for the corresponding capital types in Figure 20. Evidently, only equipment is stable, while structures and 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

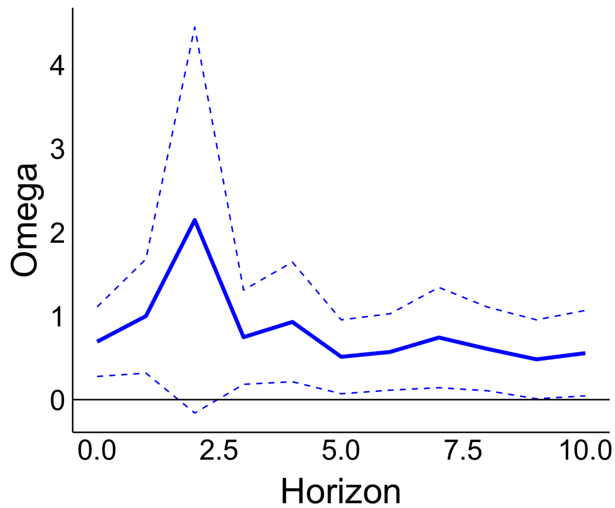


(b) Structures

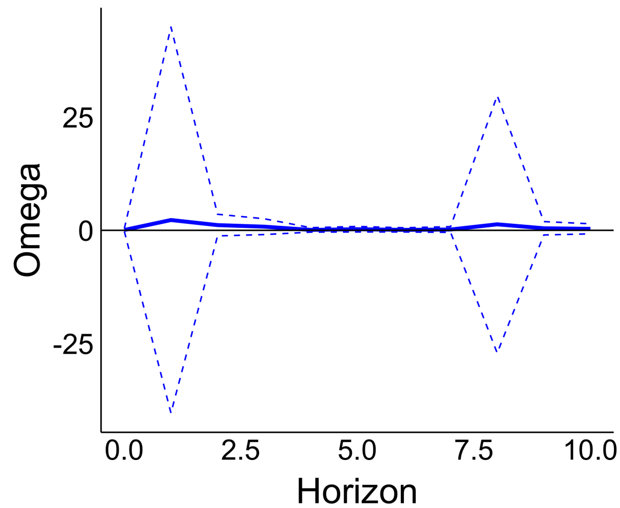


(c) Software

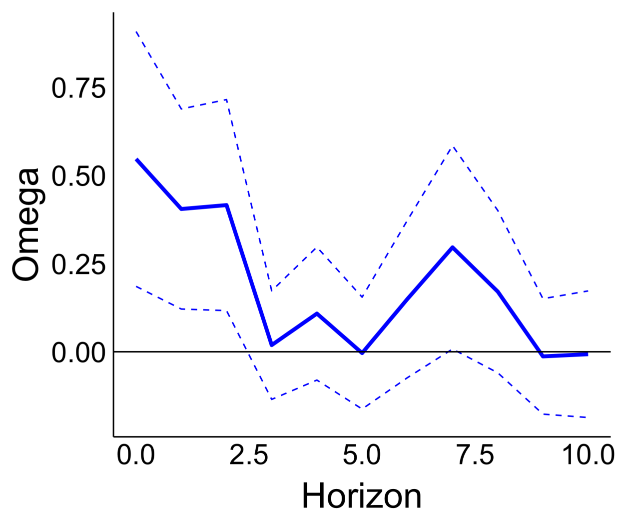
Figure 19: Smooth local projections for the coefficient $\beta_{i,h}$ on the relative price of maintenance to investment for up to ten years for standard local projections with a 90% confidence interval. Standard errors constructed with wild cluster bootstrap.



(a) Equipment



(b) Structures



(c) Software

Figure 20: Estimates for the maintenance elasticity by capital type for up to ten years for standard local projections. Standard errors constructed with wild cluster bootstrap.

D Data

D.1 Data Construction

To estimate the maintenance elasticity for equipment, structures, and software, I pull data from two different sources: the Annual Survey of Manufactures (compiled by NBER-CES) and the Federal Reserve Board's Manufacturing Investment and Capital Stock data. Both are organized according to the 2012 NAICS industry classification at the six-digit NAICS level.[10] 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.[11]

- **Synthetic Investment deflator (FRB).** I use the synthetic deflator to construct the micro IST shock in the main text. It is obtained by taking a rolling average of real capital services in each asset for the previous five years. Taking as weights each asset's share of capital services for that period, I multiply the current period's aggregate price deflator for that asset by its respective weight. Finally, I lag the resulting synthetic deflator by one period. The evolution and distribution of the contribution of each capital type to the synthetic deflator by industry is in Figure 21.

- **Relative price of maintenance to investment for asset i.** Taken as dividing the price of maintenance (identified with unit labor cost) with the synthetic price deflator (defined in the main text). I remove all values that have a relative price of maintenance to investment greater than ten. 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 2.5% and 97.5% levels. After winsorization, I reconstruct an index of the relative price of investment from the winsorized growth rates.

10. 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.

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

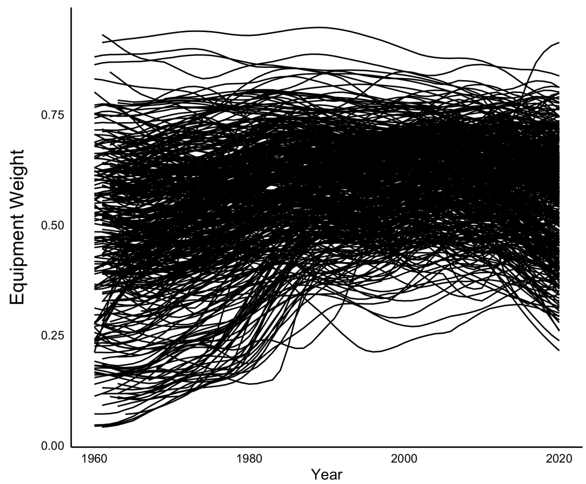
- **Productivity growth (ASM).** See the description in the price of maintenance variable. I log-difference the level of labor productivity. The ASM provides four- and five-variable TFP measures which are highly correlated. In the actual regressions, I demean productivity growth. This variable is winsorized by year at the 2.5% and 97.5% 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 2.5% and 97.5% levels.

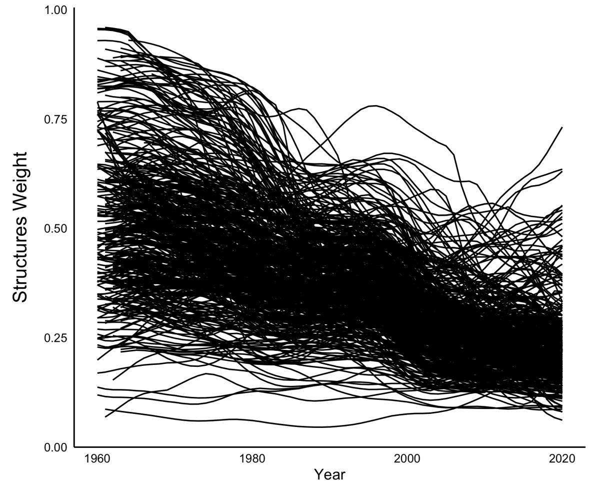
- **Employment (ASM).** Certain specifications control for industry size via employment. This variable is simply the logarithm of the employment variable in the ASM.

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Year	14,395	1,992.766	13.152	1,970	1,981	2,004	2,015
Equip. Invest. Rate	14,395	0.077	0.033	0.005	0.054	0.094	0.394
Struct. Invest. Rate	14,395	0.029	0.027	0.0001	0.013	0.037	0.978
Soft. Invest. Rate	14,395	0.384	0.106	0.011	0.318	0.450	0.953
Log Synthetic Rel. Price	14,395	0.258	0.359	−0.828	0.004	0.428	2.222
Hours Growth	14,395	0.00005	0.051	−0.543	−0.028	0.026	0.510
Log Emp.	14,395	3.399	0.892	−0.105	2.779	3.999	6.463
Productivity Growth	14,395	0.022	0.068	−0.330	−0.016	0.059	0.372
IST Shock	13,761	−0.000	0.988	−3.897	−0.603	0.600	5.064
Productivity Shock	13,761	0.000	0.988	−5.739	−0.609	0.617	5.036
Hours Shock	13,761	−0.000	0.988	−4.694	−0.592	0.615	4.704

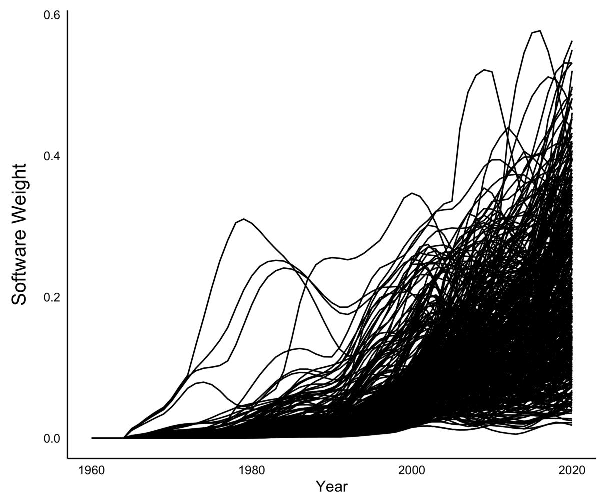
Table 2: Summary Statistics



(a) Equipment



(b) Structures



(c) Software

Figure 21: Evolution and distribution of the weight of each capital type in constructing the synthetic price of investment for each industry.

D.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). The minimal specification requires the growth rates of the relative price of maintenance to investment, productivity growth, and the log-level of hours. I describe construction of each variable above. For the IST shock, I use the synthetic relative price of investment before taxes. This is to adjust for the fact that some taxes will be long-run shocks and some will not (because some will be temporary). To get the industry specific IST shock, I use the standardized residual from the following equation:

$$\Delta\tilde{p}_{i,t} = \alpha_i + \tau_t + \sum_{j=1}^{p} \beta_{\tilde{p}} \Delta\tilde{p}_{i,t-j} + \sum_{j=0}^{p-1} \beta_{\text{Prod}} \Delta^2 \text{Prod.}_{i,t-j} + \sum_{j=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{i,t-j} + \mu_{i,t}, \tag{32}$$

where α_i is an individual fixed effect, τ_t is a time fixed effect, and I use $p = 3$ lags. I use lags 1-3 of $\Delta\tilde{p}_{i,t}$, productivity growth, and the log-level of hours as instruments. Then, to get the industry-specific productivity shock, I run

$$\Delta\text{Prod.}_{i,t} = \alpha_i + \tau_t + \sum_{j=1}^{p} \beta_{\tilde{p}} \Delta\tilde{p}_{i,t-j} + \sum_{j=1}^{p} \beta_{\text{Prod}} \Delta\text{Prod.}_{i,t-j} + \sum_{j=0}^{p-1} \beta_{\text{Hrs}} \Delta \text{Log Hrs}_{i,t-j} + \mu_{i,t} + \zeta_{i,t}, \tag{33}$$

where $\mu_{i,t}$ is the IST shock. I use the same set of instruments. 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 IST shocks entering contemporaneously. Each shock series is then the standardized residual within each industry. The industry-specific shocks span 1965-2018.

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 3
ω_S	0.4	Figure 3
γ_E	0.6	Set to match $\tilde{\delta}_E = 0.1$ in SS with $\tau_E = 0$
γ_S	0.4	Set to match $\tilde{\delta}_S = 0.03$ in SS with $\tau_S = 0$
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	0.97	Own calculation

Table 3: Calibrated parameters