THREE ESSAYS ON INVESTMENT

by

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DEDICATION

This dissertation is dedicated to my family.

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TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURE

LIST OF APPENDICES

APPENDIX

CHAPTER I

INTRODUCTION

This dissertation studies the supply and demand of capital goods, and the effects of investment tax incentives. Business fixed investment is an engine of long-run economic growth, and plays a significant role in business-cycle fluctuations. Each chapter brings together empirical evidence and quantitative equilibrium modeling techniques to examine a distinct aspect of investment.

Chapter II examines the stimulus effects of investment tax incentives. Investment tax incentives have changed dramatically over time with changes in the Investment Tax Credit, changes in the taxation of capital income and changes to tax depreciation provisions (e.g., “bonus” depreciation). This chapter examines how the economy reacted to changes in investment tax subsidies in the post-war period. Clear and consistent patterns can be seen despite substantial noise in the data. Investment subsidies increase both purchases and domestic production of capital goods. The evidence suggests that purchases rise somewhat more so investment subsidies also stimulate foreign capital goods producers. Other measures of domestic capital production also respond as one would expect. At capital producing firms, wages, measured productivity, employment, hours and material inputs all increase substantially following an investment tax subsidy. In this chapter, we develop a multi-sector DSGE model capable of reproducing the observed patterns in the data. The key parameters of the model are estimated and then used to make predictions on the aggregate effects of investment tax incentives. In the estimated model, investment tax incentives are strong enough to cause noticeable changes in aggregate economic activity. The import supply elasticity is considerable, allowing investment to rise even in the short-run in response to investment subsidies. The model also implies that there is only limited reallocation of labor across sectors.

Chapter III introduces a new investment retiming friction in an equilibrium model of investment. Conventional investment models predict that firms should sharply adjust the timing of their investment decisions to take advantage of predictable changes in the prices of capital goods. This extremely high intertemporal elasticity of substitution for investment has several implications: capital goods prices should be close to random walks; transitory shocks should have little impact on capital goods prices; and the distribution of capital holdings across firms should have no consequences for the equilibrium. In this chapter, we develop an equilibrium model of investment with fixed costs at the micro-level. In the model, firms face explicit costs of adjusting the timing of their capital investments. In the benchmark case in which investment retiming costs are zero, the fixed cost model and the neoclassical model generate virtually identical aggregate predictions. If the timing adjustment costs are positive, then capital goods prices may exhibit predictable changes over time. Moreover, the distribution of capital across firms can have significant effects on the equilibrium. We use the quantitative model to analyze the effects on investment of tax subsidies, transitory investment supply shocks, and an out-of-steady state distribution of capital vintages.

Chapter IV studies the supply of capital goods. Permanent investment supply shocks, corresponding to investment-specific technology change, are a central engine of long-run economic growth. In many models of investment, temporary investment supply shocks drive business-cycle fluctuations. In this analysis, we focus on the supply of capital goods for 42 types of equipment and structures. The data indicate that for equipment, the elasticity of investment supply is considerable, while for structures the elasticity of investment supply is close to unity. After calibrating the elasticity of investment supply, investment supply shocks are recovered for each capital type. Using a mix of reduced-form and structural time-series techniques, the structural parameters of the permanent and transitory components for each series are estimated from the data.

CHAPTER II

STIMULUS EFFECTS OF INVESTMENT TAX INCENTIVES

2.1. INTRODUCTION

The neoclassical theory of investment demand implies that business investment should strongly respond to changes in the after-tax price of capital as the stock of capital adjusts. In particular, investment demand should be highly sensitive to investment tax incentives like the Investment Tax Credit (ITC) and accelerated tax-depreciation allowances, both of which exhibited sharp changes throughout the 1970s and 1980s and both of which varied substantially across different types of capital goods. In practice, however, it is not clear whether such subsidy changes have the large effects theory predicts. Our objective is to examine the response of investment to changes in investment tax incentives and then to use these estimates together with a structural general equilibrium model to quantify the potential stimulus effects of such policies.

We separately study the impact of tax subsidies on both investment purchases and investment production. This distinction is important for a number of reasons. Investment tax incentives have separate effects on current short-run economic activity and long-run capital accumulation. This is particularly so in the present-day United States when many capital goods are imported. Indeed, an investment tax incentive could cause sharp increases in purchases of capital goods but at the same time only mildly stimulate the production of new capital goods. Understanding these separate effects is central to assessing the effects of fiscal policy.

In addition to studying the differential changes in purchases and production of capital goods to investment tax incentives, we also ask how tax incentives influence the determinants of investment goods supply. Specifically, we quantify the impact of investment tax subsidies on employment, materials costs, and the measured productivity of capital goods producers. We also quantify the effect of investment tax incentives on the production of business structures.

Available investment data suffer from severe measurement limitations and are inherently volatile. Despite these empirical challenges, clear and consistent patterns are evident in the data. For equipment types for which the data are reliable, our pooled estimates imply that a one percent investment tax incentive increases *purchases* of capital goods by between 1.00 and 2.00 percent. Domestic *production* of capital goods also increases though to a smaller extent. Depending on the exact econometric specification, our pooled estimates indicate that equipment production rises by roughly 0.50–1.00 percent. Thus, tax incentives “succeed” on both margins – they both encourage businesses to expand physical capital, and encourage increased domestic production, though the response of production is attenuated by about half relative to the increase in purchases

The estimated increase in the domestic production of equipment is accompanied by corresponding increases in inputs and overall factor intensity at equipment producing firms. Following an investment tax subsidy, capital producing firms increase employment, total hours and wages. Purchases of materials and energy inputs increase concurrently with the subsidy as does measured productivity suggesting that firms respond to the subsidy by varying unmeasured production inputs in addition to measured inputs.

Importantly, we find very limited support for the conjecture that investment tax subsidies are passed-through to the pre-tax price of capital goods. Although there are specifications in which a one percent subsidy leads to roughly a one percent increase in prices, such findings are not robust to even modest changes in the econometric specification. Overall, the results suggest that either there are no discernible impacts of investment tax subsidies on prices or that true impact is difficult to measure accurately in the available data. This result differs from Goolsbee’s (1998) finding that investment subsidies push up the prices of investment goods. We replicate his findings using his sample period and vintage data, so we find that investment supply is more elastic than earlier data suggest.

Finally, business structures also react sharply to investment subsidies. For structures, there is no practical distinction between purchases and production. Based on our estimates, for a one percent subsidy, production of business structures increases by between 1.00 and 4.00 percent. Unlike the equipment price estimates, which did not reflect any consistent price response to investment tax incentives, measured structures prices do appear to react to subsidies. Our pooled estimates suggest that the reaction is between 0.50 and 1.50 percent, roughly in line with what neoclassical investment theory would predict.

In the second part of this study, we use the reduced-form estimates to construct structural estimates of a general equilibrium model of aggregate business investment. Consistent with the estimates above, the model allows for a variety of real-world features including internal and external investment adjustment costs (Mussa 1977, Shapiro 1986a), variable capital utilization and a supply function for imported capital goods. The estimated structural parameters indicate that the substitutability in labor supply across sectors is limited, effort in capital-producing firms responds to investment subsidies, and the import supply of equipment is fairly elastic. We use the model to study the general-equilibrium effects of investment subsidies. Simulations of plausible investment tax policies indicate that investment and domestic production increase in response to a subsidy shock. In the short-run, imports of equipment rise sharply and consumption briefly decreases relative to the steady state. If the subsidy is permanent, investment, domestic production, equipment exports, consumption and GDP all increase in the long-run.

2.2. RELATED LITERATURE

Economists have attempted to quantitatively address the reaction of investment spending to changes in the after-tax price of capital goods at least since Hall and Jorgensen (1967).[1] Our study adds to a resurgence of work addressing the effects of tax policy on investment. This renewed interest in investment tax policy is driven in part by the availability of new data and in part by a renewed interest on the part of policy makers in the viability of investment incentives as a policy tool.

Among the most well-known papers on this topic is Austan Goolsbee's 1998 paper examining whether investment tax subsidies bid up the price of investment goods. Goolsbee argues that the pre-tax price of investment typically increases following investment subsidies. For many of the types of capital goods in his dataset, prices appear to rise almost one-for-one with the subsidy. Goolsbee's conclusion is natural – investment tax incentives might have little impact on investment spending because the supply of new capital is effectively price-inelastic. This finding has been challenged by several recent papers including Whelan (1999), House and Shapiro (2008), Edgerton (2010), Mian and Sufi (2012) and Sallee (2011). Whelan argues that after controlling for input cost shocks, there is little evidence that investment incentives bid up prices. House and

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[1] The existing literature on investment demand and investment tax incentives is vast and an adequate summary is easily outside the scope of this study. Foundational contributions include Jorgenson (1963), Abel (1981), Hayashi (1982), and Summers (1981).

Shapiro (2008) focus on the cross-sectional impact of bonus depreciation in the early 2000's and conclude that, at least for that episode, there is no clear relationship between the subsidy and capital goods prices.

There are also recent studies that suggest that real investment spending does react to subsidies and other shocks. The estimated reactions to bonus depreciation in House and Shapiro (2008) were surprisingly large. Edgerton (2010) argues that in the mid 2000's, housing prices, farming prices and oil prices all experienced dramatic increases unrelated to the supply of capital goods. He then looks at the production and pricing of construction equipment, agricultural equipment and mining equipment and finds little evidence that prices of these goods rose despite increases in the production of these capital goods. Mian and Sufi (2012) find that the CARS program (better known as "Cash for Clunkers") sharply increased automobile purchases while the subsidy was in place. Zwick and Mahon (2014) use tax return data to re-examine the effects of bonus depreciation and find that investment responded strongly to the subsidy. Zwick and Mahon pay particular attention to financially constrained firms. They argue that these firms reacted most sharply to the bonus depreciation subsidy.

In this study, we provide new evidence on the equilibrium effects of investment tax incentives. We present reduced-form estimates using a dataset that allows us to analyze the responses of capital goods purchases, production, and measures of capital goods producer activity on a consistent basis. We find that investment subsidies increase investment, but their effect on domestic production is more attenuated, indicating that subsidies "leak" to foreign producers through imports. These conclusions are supported by simulations of tax policy in a multi-sector, open-economy model calibrated to match the reduced-form estimates.

2.3. DATA AND CONCEPTS

We use three primary datasets in the analysis. Data on investment purchases come from nominal investment spending and investment prices in the Bureau of Economic Analysis' (BEA) underlying detail tables. Our data on domestic production of equipment come from the NBER-CES Manufacturing Productivity Database. Each dataset forms a panel of investment quantities and prices by type. Finally, our data on the investment tax credit and the tax depreciation treatment of investment by type are from Dale Jorgenson. We match the BEA investment data to IRS depreciation schedules and investment tax credits. We exclude types that do not have clear matches to the IRS tax treatment. The investment tax subsidy includes both investment tax credits (ITC) and the present discounted value of tax depreciation allowances.

Investment Purchases. Our data on investment purchases come from the BEA underlying detail tables. We exclude computers and software because these categories exhibit extreme movements in prices and quantities and are notoriously difficult to measure. After excluding computers, we have 28 separate equipment investment categories. The underlying detail tables also provide data on structures investment by type. We exclude residential investment from our analysis. Our structures dataset includes 20 types of structures. The BEA data are quarterly. We confine our attention to the period 1959:1–2009:4, the period for which the NBER production and input data are available.

For each type, the BEA provides a price index and a nominal measure of total purchases. We define *real* purchases of type *m* capital as the ratio of total nominal purchases to the type-specific price index. We define the pre-tax real relative price for type *m* capital as the ratio of the type-specific price index at date *t* to the Personal Consumption Expenditures (PCE) deflator for nondurables at date *t.Domestic Investment Production.* The data on the domestic production of investment goods by type come from the NBER Productivity Database. This dataset was assembled by Eric Bartelsman, Randy Becker, Wayne Gray and Jordan Marvakov.[2] The production data exist at a much more disaggregated level than the data in the BEA detail files. Product types are identified by six-digit NAICS codes. The dataset includes nominal shipments, nominal product prices, employment, payroll, production worker wages and measured total factor productivity (TFP). Unlike the BEA data, the data in the productivity dataset are at an annual frequency.

To make the production data comparable with the BEA purchases data we aggregate groups of investment goods according to the categories in the BEA detail tables. The BEA provided us with a mapping from the underlying census data in the Productivity Database to the more aggregated investment categories in the detail files. Aggregate nominal production is simply the sum of the disaggregated nominal production. The aggregate nominal price is a weighted average of type-specific prices with weights given by the share of nominal production. With the aggregated

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[2] The raw data are freely available at the NBER data website. For more information on the NBER Manufacturing Productivity Database see Bartelsman and Gray (1996).

investment types, we then create quarterly production series by distributing the annual aggregates using the Chow-Lin (1971) procedure.[3] As above, *real* output is defined as the nominal level of shipments divided by the type specific price index, and the real relative price as the type-specific relative price divided by the PCE deflator.

Unlike equipment, where the distinction between production and purchases is important, purchases of structures are treated as being identical to the production of structures. That is, we assume that there are no imports or exports of structures.

Investment Tax Subsidies. We consider three separate measures of investment tax subsidies. The first is the investment tax credit (ITC) itself. The ITC allows firms to reduce their taxable income by a given fraction of investment purchases. The reduction typically occurs the year the asset was purchased, but can be carried forward under certain conditions. Let ITC_t^m denote the ITC for type *m* capital at time *t*. The ITC is a particularly salient form of investment tax incentive, so we consider it separately from the comprehensive measures of investment subsidies.

The second measure is a comprehensive tax subsidy which includes both the ITC and the present discounted value of tax depreciation allowances. Let z_t^m denote the present discounted value of tax depreciation allowances for type *m* capital purchased at time *t*. That is, if $1+i_t$ is the gross nominal interest rate and $\left\{D_{j,t}^m\right\}_{j=1}^R$ is a sequence of tax depreciation deductions for a unit of type *m* capital with a tax life of *R* periods, then

$$z_t^m = \sum_{j=1}^{R} \frac{D_{t,j}^m}{\prod_{s=0}^{j-1}\left(1+i_s\right)} \tag{1}$$

The comprehensive subsidy ζ_t^m is then

$$\zeta_t^m = ITC_t^m + \tau_t^\pi\left(1-\tau_t^d\right)z_t^m \tag{2}$$

Here, the measure assumes that the firm writes off depreciation deductions against the corporate rate τ_t^π and then distributes the profits to shareholders who pay a tax rate τ_t^d on dividend earnings. The comprehensive subsidy can change for a variety of reasons. Changes (or expected changes)

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[3] See Chow and Lin (1971). Our approach uses the BEA purchases data to distribute the annual production data over the quarters between observations.

in nominal interest rates, changes in depreciation schedules or changes in the corporate tax rate can all cause changes in ζ_t^m. In this way, the comprehensive subsidy is substantially less transparent than the simple ITC. The dependence of the comprehensive subsidy on the corporate tax deserves special mention. Notice that the value of the subsidy increases with τ_t^π since the firm is writing off depreciation against the corporate income tax rate. It is not necessarily true however, that an increase in τ_t^π will lead to an increase in investment demand. While the effective subsidy to new capital has gone up, the value of the capital itself may have gone down. Our third measure of the subsidy deals with this dependence.

If there were no change in the price of capital over time, the firms' first order condition for capital implies that firms would invest to the point at which the marginal product of capital is equal to the user cost of capital. In such a situation, the first order condition for type *m* capital would require

$$MP_t^{k,m} = p_t^m (r+\delta) \times \frac{\left(1-\zeta_t^m\right)}{\left(1-\tau_t^\pi\right)\left(1-\tau_t^d\right)}, \tag{3}$$

where $MP_t^{k,m}$ is the marginal product of type *m* capital and p_t^m is the real relative price of type *m* capital. Our third measure of the subsidy, which we denote as the Jorgensonian tax term, reflects the impact of taxation on the user cost in equation (3). The sign is reversed so that an increase in this measure corresponds to a positive subsidy. More specifically, the Jorgernsonian tax term is

$$\frac{\left(\zeta_t^m - 1\right)}{\left(1-\tau_t^\pi\right)\left(1-\tau_t^d\right)} = \frac{ITC_t^m + \tau_t^\pi \left(1-\tau_t^d\right) z_t^m - 1}{\left(1-\tau_t^\pi\right)\left(1-\tau_t^d\right)}. \tag{4}$$

Unlike under the comprehensive subsidy (2), under the Jorgensonian tax term (4) an increase in the corporate profit tax τ_t^π *reduces* the firm's incentives to accumulate capital. While it enhances the value of the tax subsidy (through the effect on z_t^m) it reduces the value of the after-tax marginal product by more.

The investment tax subsidy includes both investment tax credits and the present discounted value of tax depreciation allowances. The original annual data on the ITC and the discounted value of depreciation deductions are available from Jorgenson and Yun (1991).[4] To match our

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[4] We are grateful to Dale Jorgenson and Jon Samuel for providing updates to these data.

data on investment and investment prices, we construct a quarterly version of these data using the historical record of investment tax changes, some of which have effective dates that do not correspond to calendar years. Our quarterly estimates of subsidy variables are available as an online appendix.

Figure 2.1 plots measured purchases, production, prices and the investment subsidy for general equipment (one of the 40 investment categories in our equipment dataset). The top panel shows purchases and production and the lower panel shows the real relative price. The figure illustrates three noteworthy features common to most investment types in our sample.

First, the quantity series exhibit dramatic movements over time. Real quantities (for either purchases or production) regularly change by more than twenty percent from one year to the next. In contrast, real relative prices are much less volatile. The average volatility of investment purchases and production is 11 and 8 percent respectively. In contrast, the average volatility of investment prices is only two percent. Edgerton (2010) argues that, on its face, this observation by itself suggests that the supply of investment is highly elastic.

Second, while domestic production exceeds purchases for the entire sample period, the gap between the two is gradually closing. As U.S. manufacturing has declined, domestic firms have become more and more reliant on imported capital goods.

Finally, in the price data, there is a dramatic transitory downward spike in the early-mid 1970's. The cause of the spike is a sharp increase in world oil prices. Following the increase in oil prices, the PCE price series used to construct relative investment-goods prices reacts very rapidly while the investment price indices react with a modest delay. This is probably because oil prices are passed through directly to gasoline prices, which receive substantial weight in the PCE deflator. The timing of price increases across goods was also likely affected by the Nixon price controls. We address this issue in the econometric specification.

Aggregate Data. In addition to the type-specific data on investment, investment prices and investment tax subsidies, we also make use of several aggregate data series. Specifically, we use data on real GDP, real oil prices and dummy variables for the Nixon price controls. Quarterly data on real GDP are from the BEA. To construct real oil prices, we average the monthly spot oil price (West Texas Intermediate) to construct a quarterly nominal series. We then take the ratio of the quarterly oil price to the PCE deflator for non-durables. Finally, the Nixon price controls were part of the Economic Stabilization Program and went into effect on August 15, 1971 and were removed on April 30, 1974.[5] The price controls play a non-trivial role in price data for that period. We accommodate this policy with dummy variables. Given the timing of the legislation, our dummy variable for the Nixon price controls takes the value 0.6 for 1971:3 and 1.0 for 1971:4 to 1974:1.[6]

2.4. EFFECTS OF INVESTMENT SUBSIDIES

This section presents reduced-form empirical results. We begin in section 2.4.1 by discussing our basic regression specification. In section 2.4.2 we present the main estimates. The reduced-form coefficients later serve as a basis for the structural estimates of the quantitative model.

2.4.1 Econometric Specification

We estimate the effects of investment tax subsidies on the production and purchases of investment goods, their prices, imports and exports of capital goods, as well a host of variables that reflect producer activity' including employment, payroll, production employees, production hours, production wages, TFP, inventories, the cost of materials and the cost of energy used by producers. We present pooled OLS results to paint a broad picture of how tax subsidies affect the production and purchases of capital goods.

We consider three distinct measures of investment tax subsidies: the comprehensive subsidy, the investment tax credit and the Jorgensonian tax term described in Section 2.3. The basic econometric specification is given by

$$y_t^m = b_1 \times subsidy_t^m + b^m\left(t\right) + \Gamma^m \mathbf{X}_t^m + e_t^m \tag{5}$$

Here *m* denotes the type of investment good and *t* denotes time, y_t^m is any measure of interest (e.g., y_t^m could be the log of investment production, purchases, prices, employment in capital producing firms, etc.), $subsidy_t^m$ is any one of the three measures of investment tax subsidies discussed above, $\mathbf{X}_t^m$ is a set of covariates (which could include type-specific data and/or aggregate data) and Γ^m is the associated set of type-specific regressors. For each type, we also include a type-specific time

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[5] Source: National Archives. See http://www.archives.gov/research/guide-fed-records/groups/432.html.

[6] Our dates and the dummy variable specification agree with the dates used by Goolsbee (1998). Robert J. Gordon (1990) dates the expiration of the price controls as 1974:4.

trend given by $b^m(t)$. The coefficient of interest in equation (5) is b_1. This coefficient, which is constrained to be common across the types of capital goods (thus there is no superscript *m*), describes the average change in the variable of interest y_t^m associated with changes in the investment tax subsidy.

We present results for four different regression specifications. The first is a parsimonious specification including, in addition to the subsidy itself, only a constant and a linear trend. The second and third specifications include a constant, a time trend – quadratic for the price regressions and linear for all other variables – and a set of macroeconomic covariates: HP-filtered GDP and dummy variables for years affected by the price controls during the Nixon administration. The third specification also includes the real price of oil. The fourth specification uses a linear trend all macroeconomic covariates, and also includes two lags and two leads of the subsidy variable. This last specification is intended to capture anticipation effects or measurement lags in the data. Because investment and investment policy are highly correlated across time and across capital types we use the heteroskedasticity and autocovariance consistent estimate of the standard errors proposed by Driscoll and Kraay (1998).

Before proceeding to the results themselves it is appropriate to make a remark about the interpretation of the findings. In particular, we want to be upfront about the important endogeneity problems our estimates face. Investment tax policy in the U.S., while capricious, is not truly econometrically exogenous. To the extent that investment tax incentives react endogenously to economic conditions, as for instance the CARS program did in the Mian and Sufi (2012) study, our results will be biased indicators of the true causal effects of investment tax subsidies. In particular, the "bonus depreciation" allowances offered from 2001–2004.and from 2008 to the present were explicitly countercyclical. On the other hand, most of the legislative changes to investment tax incentives in our sample were exogenous, as Romer and Romer (2009) argue in their narrative analysis of postwar tax legislation. The motivations cited by law makers when they expanded investment subsidies in the 1960s and 1970s centered on increasing long-run growth by encouraging firms to increase and modernize the capital stock. When the subsidies were pared back in the 1980s, the goals were reducing the deficit and eliminating tax distortions. We present the chronology of the main legislative changes to the ITC and tax depreciation allowances in Table 2.1. Since most changes were not related to the business cycle, but motivated by supply-side considerations, the effects of endogeneity on our estimates are likely limited.

2.4.2 Reduced-Form Estimates

The reduced-form estimates are presented in Tables 2.2–2.6. Table 2.2 reports the results for how investment subsidies affect the production and purchases of capital goods. Tables 2.3 and 2.4 show how the subsidies affect employment, wages and productive inputs in equipment producing firms. Table 2.5 shows how investment incentives affect equipment prices. Table 2.6 shows how investment incentives affect the production of business structures. Each table includes the four econometric specifications discussed above and reports different sets of results for the three measures of the investment subsidy.

Purchases and Production of Capital Goods. We begin with how investment tax subsidies affect the purchases and production of new capital equipment by U.S. firms. The results are presented in Table 2.2. The dependent variable is the natural logarithm of investment production or investment purchases as indicated. The coefficients in the table are for the measure of the subsidy (in levels). The standard errors are heteroskedasticity and autocovariance consistent (Driscoll-Kraay).

As one would expect, when investment subsidies are relatively high, investment purchases and production are also relatively high. Looking across specifications, most of the results are statistically significantly different from zero. More importantly, the estimates are economically significant. Consider the first row of coefficients. The dependent variable is the natural log of investment production and the independent variable is the comprehensive investment subsidy. Looking across the row, the estimates indicate that a one percent investment subsidy is associated with an increase in investment production of between 0.78 and 1.15 percent. The second row reports the estimates for investment purchases. Again, the results are economically significant – a one percent investment incentive is associated with an increase in investment purchases of between 1.26 and 1.93 percent.

Importantly, there is some evidence of “leakage” – that is, some of the stimulus benefits foreign rather than domestic producers. The leakage of investment tax stimulus to imports is a key reason that such policies are less stimulative than their effects on investment purchases might imply.

Overall, these basic quantitative patterns carry over to the other measures of investment subsidies. Perhaps the most natural set of estimates is that for the ITC alone because the ITC is likely the most salient form of investment subsidy we consider. For the ITC measure, the results are somewhat more pronounced. Depending on the econometric specification, production increases by between 1.02 and 2.66 percent while purchases rise by between 1.69 and 3.31 percent. The bottom two rows (for the Jorgensonian tax term) show a similar pattern though it is worth noting that overall, these estimates are less statistically significant. This is not an unusual occurrence and is perhaps to be expected given the intemperate nature of the data.

Equipment Prices. Goolsbee's 1998 paper made a case that one of the main reasons that investment tax incentives were not as effective as one might hope is that much of the subsidies are passed through to capital goods prices. An investment subsidy might bid up prices of capital goods but not cause increased production.[7]

Table 2.3 presents estimates of the reaction of capital goods prices to the three measures of investment tax subsidies. As we did in Table 2.2, we report results for both the BEA purchase data and for the NBER productivity dataset. Unlike Goolsbee's estimates, our estimates show little or no price response for equipment. In fact, of the five statistically significant estimates, four have the "wrong" sign. Most of the estimates are close to zero. From the point of view of basic economic analysis, sensible estimates would be between 0.00 and 1.00. While there is again considerable variability coming from changes in econometric specification, the overall conclusion from the estimates in Table 2.3 is that prices essentially don't react to the subsidies. We have made efforts to explain the difference between our findings and the findings in Goolsbee's earlier paper. The two sets of estimates differ both in sample period (Goolsbee's sample was 1962–1988 while we use data from 1959–2009) and in the vintage of the data – that is, the data have been updated and revised substantially since Goolsbee's original paper was published. Both factors contribute to the different results. Appendix 2.A presents a detailed comparison between our findings and Goolsbee's results. In brief, we are able to replicate Goolsbee's results for his estimation period and vintage data. Our results differ mainly because we study an extended sample period and the data have been revised.

Employment, Wages, Inputs and Productivity of Capital Producers. Another way to quantify the effects of investment tax subsidies is to examine the productive inputs of capital producing firms.

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[7] The standard neoclassical theory of investment demand predicts that, particularly for temporary investment subsidies, capital goods prices must rise nearly one-for-one with the subsidy regardless of the elasticity of supply. Thus, observing sharp price increases following an investment subsidy does not suggest that the policy has little effect. See House and Shapiro (2008) for extended discussion of this point.

Table 2.4 reports results for employment, hours and wages of workers in capital producing firms. As we did above, we report results for each of the three measures of investment subsidies separately. The data on the left-hand side are from the NBER productivity dataset, so they are somewhat independent measures from those in Tables 2.2 and 2.3.

Consistent with the results from Table 2.2, employment and hours are positively associated with high investment subsidies. A one percent increase in the ITC, increases employment and hours by roughly 2 percent. Results for the comprehensive subsidy are somewhat less consistent across specifications. Most of the results are smaller than the results for the ITC alone and while most of the estimates have the “right” sign, there are specifications that give inverted results. The Jorgensonian tax term again indicates that investment subsidies increase production in capital producing firms. Given the relative scale of the Jorgensonian term and the ITC, the quantitative responses are roughly comparable to the estimates for the ITC alone. In addition to total employment and hours at capital producing firms, wages at those firms are also increase with investment subsidies. Goolsbee (1998) also emphasizes this point and our updated estimates agree with his earlier results.

Table 2.5 shows additional measures of production activity at capital-producing firms. Consistent with earlier results, materials costs, energy costs and measured total factor productivity all rise in response to investment subsidies suggesting that these firms do actively expand production of capital goods. Roughly speaking, a one percent investment subsidy is associated with increased purchases of productive inputs and measured TFP between 0.32 and 5.11 percent. All of these responses are consistent with an overall increase in production of capital goods. The increase in measured productivity suggests that firms are varying unmeasured inputs in addition to measured factor inputs such as worker effort. It is worth pointing out that many of these estimates are not fully robust to changes in econometric specification. Some of the specifications produce results at odds with the conventional understanding of how investment tax incentives work. Overall, however, the estimates in Tables 2.2, 2.4 and 2.6 are all telling the same story.

Investment Subsidies and Structures Investment. While much of the existing literature focuses on investment in equipment, U.S. tax policy also provides strong incentives for purchases of business structures. Importantly, the neoclassical theory of investment suggests that structures investment should be much more sensitive to predictable variations in its after-tax price than equipment investment (see House and Shapiro 2008). Unlike equipment investment, there is essentially no difference between domestic purchases and domestic production of business structures (i.e., there are no imported structures to speak of).

Table 2.6 presents estimates on the effect of investment subsidies for investment in business structures. The data used here come from the BEA underlying detail tables. Again we report separate results for each of our subsidy measures and separate results for prices and quantities. As we found with the effects of subsidies on purchases and production of equipment, purchases (and production) of structures respond to variations in investment tax incentives. For a one percent investment tax subsidy, structures investment rises between 0.21 and 4.73 percent. Unlike the findings for equipment and software, there is evidence that structures prices do respond to investment tax incentives though there is still substantial variation in the estimates across econometric specifications.

Although investment subsidies for structures are generally lower than subsidies for equipment, and notably structures do not receive the ITC, the estimated effects are sizeable. Overall, the reduced-form estimates for structures are larger than the estimates for equipment. This pattern could be generated by a variety of factors. First, equilibrium complementarities between equipment and structures may cause structures investment to rise when tax policies stimulate investment in equipment. Second, changes in tax depreciation allowances, which directly affect structures, are correlated with changes in the ITC. The most prominent example is Tax Reform Act of 1986, which both repealed the ITC and dramatically limited accelerated depreciation, and many other legislative changes modified both forms of tax incentives in the same direction (see Table 2.1). Lastly, structures have low rates of economic depreciation, which implies high intertemporal elasticities of substitution. As a result, structures investment is more sensitive to changes in the after-tax price of capital.

Investment Subsidies and International Trade in Equipment. The effects of investment tax incentives on equipment imports and exports are particularly interesting for assessing the general equilibrium implications of these policies. Using a separate dataset on international trade in equipment, we find clear evidence that investment tax incentives stimulate imports. In other words, investment subsidies “leak” through international trade, benefitting foreign capital producers. In addition, the data suggest that exports rise when subsidies are high. Due to inconsistencies and differences in measurement relative to our main data, the scope of our trade analysis is more limited. We present our international trade results in Appendix 2.B.

2.5. QUANTITATIVE MODEL

In this section we present a quantitative dynamic general equilibrium model with many real-world features. There are M capital producing industries, including both equipment and structures, and one industry that produces a numeraire good. The model features variable effort and capital and labor adjustment costs in all sectors. Labor income, dividends and profits are subject to distortionary taxes, while investment receives subsidies. Equipment and the numeraire good can be traded internationally. We require period-by-period balanced trade, which implies that trade in equipment is accompanied by offsetting trade flows of the final good. Structures are not traded, so the production and investment in structures are indistinguishable. We estimate the structural parameters of the model to match the reduced-form empirical results in section 2.4. We then use the model to quantify the aggregate effects of investment tax policy.

2.5.1. Households

The representative household consumes the non-durable final good, supplies labor and effort on the job, saves at the risk-free rate, pays taxes and owns the capital stock. The household derives utility from consumption and disutility from labor and effort. The household's utility function is

$$U\left(C_t, V_t, e_t^1, \ldots, e_t^M, e_t^Q\right) = \frac{C_t^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} - \phi \frac{V_t^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} - \psi\left(e_t^Q n_t^Q + \sum_{m=1}^{M} e_t^m n_t^m\right). \tag{6}$$

We start by describing the household's labor supply in the M + 1 sectors of the economy. The household spends n_t^m hours working in each capital-producing sector m and n_t^Q hours working in the final goods sector. For each hour of labor, the household receives pre-tax real wages W_t^m and W_t^Q in the capital industries and the numeraire sector, respectively. We assume that the household's aggregate labor index has the constant elasticity of substitution (CES) form

$$V_t = \left[a^Q \left(n_{t+j}^Q\right)^{1+\psi_n} + \sum_{m=1}^{M} a^m \left(n_{t+j}^m\right)^{1+\psi_n}\right]^{\frac{1}{1+\psi_n}} \tag{7}$$

The elasticity of labor substitution across sectors is ψ_n. If $\psi_n > 0$, then there is only limited substitutability of labor across sectors. In this case, a permanent investment tax subsidy will drive a permanent wedge between wages in subsidized and not-subsidized sectors. This specification also nests the special case when $\psi_n = 0$ and the household supplies labor to each sector symmetrically.

Total hours spent working is denoted by

$$N_t = n_t^Q + \sum\nolimits_{m=1}^{M} n_t^m \,. \tag{8}$$

In the steady state, the CES labor aggregate and total hours are equivalent, more specifically, $V = N$. This relationship is obtained by choosing the constant terms a^Q, a^m in the labor aggregate such that $a^m = \left(n^m / N\right)^{-\psi_n}$ for $m = 1,\ldots,M$. Effort in each capital-goods producing sector *m* is denoted by e_t^m and e_t^Q indicates effort in the numeraire sector. Each hour of effort entails a utility cost of ψ.

Formally, the household seeks to maximize its expected discounted utility

$$E_t\left[\sum_{j=0}^{\infty}\beta^j\left\{\frac{C_{t+j}^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}}-\phi\frac{V_{t+j}^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}}-\psi\left(e_{t+j}^Q n_{t+j}^Q+\sum_{m=1}^{M}e_{t+j}^m n_{t+j}^m\right)\right\}\right] \tag{9}$$

subject to the budget constraint

$$\begin{aligned}\left(1-\tau^N\right)\left[W_t^Q n_t^Q+\sum_{m=1}^{M}W_t^m n_t^m\right]+\left(1-\tau_t^d\right)\left(1-\tau_t^\pi\right)\sum_{m=1}^{M}R_t^m K_t^m+T_t+S_{t-1}\left(1+r_{t-1}\right)\\ =C_t+S_t+\sum_{m=1}^{M}P_t^m\left[1-\zeta_t^m\right]\left(I_t^m+IMP_t^m\right),\end{aligned} \tag{10}$$

and the capital accumulation constraints

$$K_{t+1}^m = K_t^m\left(1-\delta^m\right)+I_t^m+IMP_t^m. \tag{11}$$

The representative household owns the capital stock K_t^m for all types $m = 1,\ldots,M$. The household may purchase new capital from domestic producers I_t^m or from importers IMP_t^m. The pre-tax price of type *m* capital in units of the numeraire good at date *t* is P_t^m. The pre-tax real rental price of type *m* capital is R_t^m. Each type of capital has a type-specific depreciation rate δ_t^m. As we show in Section 2.5.7, depreciation rates play a key role in how each type responds to investment subsidies. In addition to investing in physical capital, the household saves in bonds S_t, which earn the net real safe rate of return r_t.

A key feature of the model is its realistic treatment of tax policy, which allows analyzing the aggregate effects of investment tax incentives once we estimate the structural parameters. Purchases of capital goods receive type-specific investment subsidies. The comprehensive investment tax subsidy for type *m* at date *t* is ζ_t^m. Capital income is taxed twice – once at the profit tax rate τ_t^π and again according to the tax rate on distributed capital earnings τ_t^d. Labor income is taxed at the constant rate τ^N. In addition to the distortionary taxes τ^N, τ_t^d and τ_t^π the government also remits excess revenue to the household through a lump-sum transfer (or tax) T_t.

The solution to the household's optimization problem requires the following first order conditions,

$$W_t^m = \frac{C_t^{\frac{1}{\sigma}}}{1-\tau^N}\left[\phi V_t^{\frac{1}{\eta}}\left(\frac{V_t}{V}\right)^{-\psi_n}\left(\frac{n_t^m}{n^m}\right)^{\psi_n} + \psi e_t^m\right] , \tag{12}$$

$$C_t^{-\frac{1}{\sigma}} = \beta\left(1+r_t\right)E_t\left[C_{t+1}^{-\frac{1}{\sigma}}\right], \tag{13}$$

$$q_t^m = \beta E_t\left[C_{t+1}^{-\frac{1}{\sigma}}\left(1-\tau_{t+1}^\pi\right)\left(1-\tau_{t+1}^d\right)R_{t+1}^m + q_{t+1}^m\left(1-\delta^m\right)\right], \tag{14}$$

$$q_t^m = C_t^{-\frac{1}{\sigma}}P_t^m\left[1-\zeta_t^m\right]. \tag{15}$$

Equation (12) is the household's labor supply condition for sector *m* (abusing notation somewhat, we include the first order condition for *m* = *Q* in equation (12) as well). This equation serves as the effort-wage menu faced by the firms. Equation (13) is the stochastic Euler equation. Equation (14) is the shadow value of type *m* capital and equation (15) is investment demand for type *m* capital (either imported or domestically produced).

2.5.2. Firms and Production

Aggregate Capital Services. The individual capital types $m = 1...M$ owned by the household are aggregated to produce a single capital input. The aggregate capital good is denoted by H_t and is produced according to the Cobb-Douglas production function

$$H_t = \left(\prod_{m=1}^{M} \gamma_m^{-\gamma_m} \right) \left(\prod_{m=1}^{M} \left(K_t^m \right)^{\gamma_m} \right). \tag{16}$$

We assume that $\sum_{m=1}^{M} \gamma_m = 1$ so the production of the aggregate capital good has constant returns to scale. Firms that produce the capital aggregate sell the aggregate good for a rental price R_t and pay type-specific rental prices R_t^m. Each period these firms choose $\left\{ K_t^m \right\}_{m=1}^{M}$ to maximize profits

$$R_t H_t - \sum_{m=1}^{M} R_t^m K_t^m \tag{17}$$

subject to the production function (16). The first order condition for the choice of K_t^m is

$$R_t \gamma_m \frac{H_t}{K_t^m} = R_t^m. \tag{18}$$

The scalar term $\prod_{m=1}^{M} \gamma_m^{-\gamma_m}$ in (16) ensures that the rental price for the capital aggregate is a weighted average of the rental prices of the type-specific rental prices. In equilibrium profits are zero for these firms.

The Numeraire Good. The numeraire good can be used as either the final consumption good, government purchases, payment for purchases of imported capital goods or as material input for the capital goods industries. The numeraire good is produced with aggregate capital h_t^Q, labor n_t^Q and effort e_t^Q. The output elasticity of effort is given by the parameter θ. The production function is

$$Q_t = A \left[h_t^Q \right]^{\alpha} \left[\left(e_t^Q \right)^{\theta} n_t^Q \right]^{1-\alpha}. \tag{19}$$

The producers of the numeraire good rent capital and labor and choose effort to maximize their discounted profits

$$E_t\left[\sum_{j=0}^{\infty}\beta^j C_{t+j}^{-\frac{1}{\sigma}}\left\{Q_{t+j}-W_{t+j}^Q n_{t+j}^Q-R_{t+j}h_{t+j}^Q-\frac{\xi^n}{2}n_{t+j-1}^Q\left(\frac{n_{t+j}^Q-n_{t+j-1}^Q}{n_{t+j-1}^Q}\right)^2-\frac{\xi^h}{2}h_{t+j-1}^Q\left(\frac{h_{t+j}^Q-h_{t+j-1}^Q}{h_{t+j-1}^Q}\right)^2\right\}\right] \quad (20)$$

subject to the production function (19) and the wage-effort supply schedule (12). The parameters ξ^n and ξ^h are adjustment cost parameters for labor and capital. Adjustment costs are standard in the DSGE literature. It is important to note that in a multi-sector model adjustment costs act through two distinct channels: they temper both the intertemporal substitution and the reallocation of capital and labor inputs across sectors.

Firms may ask workers to provide additional effort but doing so requires a higher wage. Note that, as long as the production elasticity of effort is below unity ($\theta<1$), the firm's demand for additional effort will be bounded. Another interpretation of effort input, which is effectively equivalent with the specification we adopt in this study, is overtime to extend the work week. In this case, the output elasticity of effort θ represents the shift premium households require to compensate them for working outside standard work hours. Including effort as a separate input allows measured TFP to increase in response to investment tax incentives, as it does in the data. This simple specification imparts realism to the model, but as we show in section 2.5.7 below, it remains somewhat limited in its ability to match the magnitude of the TFP response in our reduced-form estimates.

The solution to the firm's optimization problem requires the following first order conditions,

$$\xi^h\left(\frac{h_t^Q-h_{t-1}^Q}{h_{t-1}^Q}\right)=\left[\alpha\frac{Q_t}{h_t^Q}-R_t\right]+\beta E_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\sigma}}\frac{\xi^h}{2}\left(\frac{h_{t+1}^Q-h_t^Q}{h_t^Q}\right)\left(\frac{h_{t+1}^Q+h_t^Q}{h_t^Q}\right)\right], \quad (21)$$

$$\xi^n\left(\frac{n_t^Q-n_{t-1}^Q}{n_{t-1}^Q}\right)=\left[(1-\alpha)\frac{Q_t}{n_t^Q}-W_t^Q\right]+\beta E_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\sigma}}\frac{\xi^n}{2}\left(\frac{n_{t+1}^Q-n_t^Q}{n_t^Q}\right)\left(\frac{n_{t+1}^Q+n_t^Q}{n_t^Q}\right)\right], \quad (22)$$

and

$$\psi n_t^Q=C_t^{-\frac{1}{\sigma}}\left(1-\tau^N\right)\theta(1-\alpha)\frac{Q_t}{e_t^Q}. \quad (23)$$

Equations (21) and (22) are the firm's intertemporal demand curves for capital and labor respectively. Equation (23) gives the firm's effort demand choice. This condition says that the firm's choice of effort balances the after-tax marginal benefit of additional effort (the left-hand-side) with the marginal cost of additional effort (the right-hand-side). Not surprisingly, effort is an increasing function of the marginal product of labor.

Domestic Capital Producers. Each type of capital is produced with units of the capital aggregate h_t^m, labor n_t^m, effort e_t^m and materials x_t^m (units of the numeraire good). The production function for each type of capital is

$$I_t^m = B^m \left\{ \mu_x \left(x_t^m\right)^{\frac{\rho-1}{\rho}} + \left(1-\mu_x\right)\left[\left(h_t^m\right)^{\mu_h}\left(e_t^m\right)^{\theta\left(1-\mu_h\right)}\left(n_t^m\right)^{\left(1-\mu_h\right)}\right]^{\frac{\rho-1}{\rho}}\right\}^{\frac{\rho}{\rho-1}}. \tag{24}$$

The capital producers maximize the expected discounted value of profits,

$$E_t\left[\sum_{j=0}^{\infty}\beta^j C_{t+j}^{-\frac{1}{\sigma}}\left\{P_{t+j}^m I_{t+j}^m - W_{t+j}^m n_{t+j}^m - x_t^m - \frac{\xi^n}{2} n_{t+j-1}^m\left(\frac{n_{t+j}^m - n_{t+j-1}^m}{n_{t+j-1}^m}\right)^2 - \frac{\xi^h}{2} h_{t+j-1}^m\left(\frac{h_{t+j}^m - h_{t+j-1}^m}{h_{t+j-1}^m}\right)^2\right\}\right] \tag{25}$$

The first order conditions for the optimal choices of x_t^m, n_t^m, h_t^m and e_t^m are

$$1 = P_t^m \mu_x \left(B^m\right)^{\frac{\rho-1}{\rho}}\left(\frac{I_t^m}{x_t^m}\right)^{\frac{1}{\rho}}, \tag{26}$$

$$\xi^n\left(\frac{n_t^m - n_{t-1}^m}{n_{t-1}^m}\right) = \left[P_t^m MP_t^{n,m} - W_t^m\right] + \beta E_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\sigma}}\frac{\xi^n}{2}\left(\frac{n_{t+1}^m - n_t^m}{n_t^m}\right)\left(\frac{n_{t+1}^m + n_t^m}{n_t^m}\right)\right], \tag{27}$$

$$\xi^h\left(\frac{h_t^m - h_{t-1}^m}{h_{t-1}^m}\right) = \left[P_t^m MP_t^{h,m} - R_t\right] + \beta E_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\sigma}}\frac{\xi^h}{2}\left(\frac{h_{t+1}^m - h_t^m}{h_t^m}\right)\left(\frac{h_{t+1}^m + h_t^m}{h_t^m}\right)\right], \tag{28}$$

and
$$\psi n_t^m = C_t^{-\frac{1}{\sigma}}\left(1-\tau^N\right)\theta\left(1-\mu\right)\frac{P_t^m I_t^m}{e_t^m}. \tag{29}$$

The marginal product of labor and the marginal product of capital are given by

$$MP_t^{m,h} \equiv \mu_h\left(1-\mu_x\right)\left(B^m\right)^{\frac{\rho-1}{\rho}}\left(\frac{I_t^m}{U_t^m}\right)^{\frac{1}{\rho}}\frac{U_t^m}{h_t^m}, \tag{30}$$

and
$$MP_t^{m,n} \equiv \left(1-\mu_h\right)\left(1-\mu_x\right)\left(B^m\right)^{\frac{\rho-1}{\rho}}\left(\frac{I_t^m}{U_t^m}\right)^{\frac{1}{\rho}}\frac{U_t^m}{n_t^m}, \tag{31}$$

where $U_t^m \equiv \left(h_t^m\right)^{\mu_h} \left(e_t^m\right)^{\theta(1-\mu_h)} \left(n_t^m\right)^{(1-\mu_h)}$. Equations (26), (27) and (28) are the firm's demand curves for materials, labor hours and the aggregate capital input, respectively. Equation (29), which is analogous to (23), is the firm's effort demand curve.

Imported Capital. International trade in equipment is a prominent feature of the U.S. economy. In our data, equipment investment differs substantially from domestic production. Figure 2.1 illustrates the time-varying wedge between the purchases and the domestic production of general industrial equipment, one of the capital types in our dataset. International trade offers an additional margin for increasing investment in response to investment subsidies. In Appendix 2.B, we present evidence that imports rise sharply when investment tax incentives are high. Including capital imports in the model is thus essential given that estimation strategy is to match the empirical reduced-form estimates in Section 2.4.2 with the corresponding estimates obtained from simulated model data. We adopt a simple specification that abstracts from international borrowing and lending, assuming that there are no trade deficits or surpluses.

We model the international trade margin with a simple investment import supply curve. We assume that in the initial non-stochastic steady state, there are no imported capital goods. The parametric form for the import supply curve is

$$IMP_t^m = \bar{I}^m \left[\left(\frac{P_t^m}{P^m} \right)^{\chi} - 1 \right] \tag{32}$$

where $\bar{I}^m$ is the amount of type *m* capital produced in the steady state and χ is the import supply elasticity. If $\chi = 0$ then the model collapses to a closed economy with no interaction with foreign capital importers. If $\chi = \infty$ then the model becomes a "small open economy" with regard to the capital goods markets. In this latter case, the domestic price of capital goods will be pinned down by the importing firms. Finally, we assume period-by-period balanced trade, which requires that international trade in equipment is accompanied by offsetting trade flows of the final consumption good. We describe the role of imports in how the economy responds to investment tax incentives in Section 2.5.7.

2.5.3. Resource Constraints and Real GDP

The total amount of the numeraire good is used for either consumption of the final good, materials inputs for the capital producers, government purchases or payment for imported capital goods from abroad. Formally, the resource constraint for the numeraire good is

$$Q_t = C_t + X_t + \sum_{m=1}^{M} P_t^m IMP_t^m + G_t \tag{33}$$

Aggregate capital and materials must satisfy

$$H_t = h_t^Q + \sum_{m=1}^{M} h_t^m \tag{34}$$

and

$$X_t = \sum_{m=1}^{M} x_t^m \tag{35}$$

Real gross domestic product (GDP) is the sum of all final goods and services produced in a given period evaluated at the steady state pre-tax prices. We let Y_t denote real GDP. Thus,

$$Y_t = C_t + \sum_{m=1}^{M} P^m I_t^m + G_t . \tag{36}$$

Note that imports do not enter the real GDP identity (36) because the model assumes period-by-period balanced trade. While equipment can be imported, equal exports of the numeraire good are offered in exchange.

2.5.4. Exogenous Processes

The model dynamics are generated by exogenous structural innovations to the taxation of capital income (τ_t^π and τ_t^d) and investment subsidies $\left(\left\{\zeta_t^m\right\}_{m=1}^{M}\right)$. For simplicity, we suppress other sources of uncertainty typically present in DSGE models. Let

$$\Xi_t = \left[\tilde{\tau}_t^\pi, \tilde{\tau}_t^d, \tilde{\zeta}_t^1, \ldots, \tilde{\zeta}_t^M\right]' \tag{37}$$

denote the vector of deviations for the structural exogenous variables at date *t*. We assume that Ξ_t follows a known VAR process

$$\Xi_t = \Lambda \Xi_{t-1} + \boldsymbol{\varepsilon}_t , \tag{38}$$

where $\boldsymbol{\varepsilon}_t$ is the date-t vector of structural innovations and $E[\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}'] = \Omega$ is a known variance-covariance matrix. For the simulations below, we assume that the autoregressive matrix Λ is diagonal. In our baseline specification we set $\Lambda = \mathbf{I}$ so all shocks are perceived to be "permanent" by the firms and workers.

2.5.5. Steady State and Calibrated Parameters

Non-Stochastic Steady State. We choose the scaling parameters ϕ, ψ and $B^m = B$ to ensure that $P^m = P = N = e = 1$ in the non-stochastic steady state. With this normalization, it is easy to show that, in the steady state, the investment ratios must satisfy

$$I^m = \left[\frac{\gamma_m \delta^m}{\gamma_1 \delta^1}\left(\frac{r+\delta^1}{r+\delta^m}\right)\left(\frac{1-\zeta^1}{1-\zeta^m}\right)\right] I^1 = \Psi^m I^1. \tag{39}$$

Additionally, $n^m = \Psi^m n^1$ and $x^m = \Psi^m x^1$ so there is a constant material to labor ratio across investment sectors. Similarly, $K^m = (\delta^m / \delta^1)\Psi^m K^1$ and $h^m = \Psi^m h^1$ for all *m*.

Calibration. Many of the parameters are calibrated to "standard" values used in the macroeconomic literature. We set the quarterly discount factor β to 0.97 which implies a 4 percent annual real interest rate. The Frisch labor supply elasticity η is set to 0.5, in line with recent estimates (see Farber 2005 and Kimball and Shapiro 2008). We set σ, the elasticity of intertemporal substitution, to 0.2, roughly the average of the estimates in Hall (1988), Campbell and Mankiw (1989) and Barsky, *et al*. (1997). Based on calculations in House and Shapiro (2008), we set the steady state tax rates to $\tau^N = 0.36$, $\tau^d = 0.30$ and $\tau^\pi = 0.22$.

To calibrate labor's share for the numeraire (*Q*) sector, we take total employee compensation as a fraction of total GDP less proprietors' income. This share has been roughly constant in the post war period and, using data up to 2009, implies $1-\alpha = 0.62$.[8] This calculation implicitly assumes that proprietors' income is divided proportionally between labor income and capital income.

We allow for *M* = 35 different types of capital. There are 24 equipment classes and 11 structures classes. For the most part, the types conform to the BEA investment categories. There are some types which are grouped together because they have the same investment subsidy

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[8] See Elsby *et al*. (2013) for a discussion of recent changes to the U.S. labor's share.

treatments and the same economic depreciation rates. In addition, unlike we do in the empirical specification, we include computers and software and residential investment in the model. Investment in computers and software is a significant fraction of total equipment investment and thus its tax treatment influences the equilibrium. The economic rates of depreciation for each type of capital are based primarily on Fraumeni (1997), who has estimated depreciation using techniques established by Hulten and Wykoff (1981a, 1981b). Together with data on average investment shares (I^m / I^1) and average investment subsidies (ζ^m) we use equation (39) to calculate implied values for γ_m. Tables 2.8 and 2.9 list the capital classes in the model together with their associated depreciation rates, investment shares (as a fraction of total investment) and their average investment subsidies.

To calibrate the share parameters μ_h and μ_x we use data on input shares from the NBER productivity dataset. Relative to labor's share for GDP, labor's share of gross investment output (for equipment production) is quite low and has been falling over our sample period. Averaging over all of the types in our data, labor's share fell from roughly 20 percent in the late 1960's to roughly 9 percent by 2009. For purposes of calibrating the model we assume that labor's share of gross output in the capital producing sectors is 14 percent (roughly the average over all types and time periods). This corresponds to an average labor's share in the value-added production functions of 25 percent. Material's share of gross output is approximately 45 percent.[9] Taken together, the implied capital share in gross output is in steady state, $Rh^m \big/ Wn^m = \mu_h \big/ (1-\mu_h)$ which implies $\mu_h = 0.75$:

$$\frac{Rh^m}{Wn^m} = \frac{0.41}{0.14} = 2.93. \tag{40}$$

We use the same parameters for structures as for equipment though we have no independent data for structures. We calibrate the parameter μ_x to match the observed materials ratio X^m / I^m given the elasticity of substitution ρ. In the steady state,

$$\mu_x = \varphi^{\frac{1-\rho}{\rho}} \left[\frac{X^m}{I^m - X^m}\right]^{\frac{1}{\rho}} \left(1 + \varphi^{\frac{1-\rho}{\rho}} \left[\frac{X^m}{I^m - X^m}\right]^{\frac{1}{\rho}}\right)^{-1}. \tag{41}$$

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[9] We include energy in total material inputs. Energy is a small fraction of gross investment output, roughly 1 percent.

For each substitution parameter ρ, we set μ_x according to (41) to match a materials to investment ratio $X^m / I^m = 0.45$. For our baseline calibration we set $\rho = 0.01$ which implies that there is essentially no substitution between materials and the input composite U_t^m (for this value of ρ, the implied calibration for μ_x is quite small).[10]

Labor and Capital Adjustment Costs. The labor and capital adjustment cost parameters ξ^n and ξ^h are calibrated using combined evidence from several different studies. Caballero and Engel (1993) use data on gross and net employment flows for U.S. manufacturing from the Bureau of Labor Statistics. They estimate a quadratic adjustment cost parameter of 0.53 for net flows and 0.28 for gross flows, although they prefer a specification with fixed costs.[11] Shapiro (1986b) estimates employment adjustment costs of 0.23–0. 34 for non-production workers, and zero for all other workers.

To calibrate capital adjustment costs, we consider the literature on the Q-elasticity of investment, as well as studies that directly estimate adjustment costs. If the capital adjustment cost is quadratic, as in our model, the adjustment cost parameter ξ^h is inversely proportional with the Q elasticity, which can be estimated using an equation of the form

$$\frac{I_t}{K_t} = a_0 + a_1 Q_t + bX_t + \varepsilon_t , \tag{42}$$

where I_t is investment, K_t is the capital stock, and X_t is a vector of covariates. Gilchrist and Himmelberg (1995) use annual firm-level data from Compustat to measure the elasticity of investment to both "fundamental" Q and Tobin's Q, finding elasticities between 0.33 and 0.1 respectively once they adjust for cash flow. For durable goods firms only, the elasticity estimates are 0.12 for fundamental Q and 0.06 for Tobin's Q. Cooper and Ejarque (2003) use a structural model to estimate Q elasticities of between 0.165–0.231. Shapiro (1986b) estimates investment adjustment costs of 0.21–0.25.

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[10] If we estimate the materials substitution elasticity (ρ) the estimates are pushed to 0.00. We suspect this reflects the fact that there is a high degree of correlation between production and materials throughout the data sample. This estimate echoes a recent finding by Boehm *et al*. (2014). See also Atalay (2014).

[11] Cooper and Willis (2009) use the empirical results of Caballero and Engel (1993) to estimate a set of structural models with asymmetric labor adjustment costs. Their estimates for the quadratic costs specification are 7.9 for positive adjustment and -0.28 for negative adjustment, however neither coefficient is statistically significant.

In our multi-sector model, adjustment costs represent both frictions related to the intertemporal adjustment of the capital and employment within industries, as well as frictions arising when factors of production are reallocated across industries. The investment tax subsidies in the model produce strong incentives to substitute across types, which may be quite difficult in reality. For example, Ramey and Shapiro (2001) document substantial costs of moving capital from the aerospace industry to other sectors.

Given the relatively wide range of adjustment costs estimated in the literature, and the fact that we specify a multi-sector model rather than a single sector like in most of these studies, we consider three distinct calibrations of the adjustment cost parameters. In the low-cost calibration, we set $\xi^n = 0$ and $\xi^h = 3.30$; in the medium-cost calibration, $\xi^n = 0.10$ and $\xi^h = 10$; finally, in the high-cost calibration, $\xi^n = 0.30$ and $\xi^h = 20$.

2.5.6. Estimated Parameters

The remaining parameters $\theta,\ \chi,\ \psi^n$ are estimated. We use an indirect inference approach similar to the one proposed by Gourieroux, Montfort and Renault (1993). Specifically, let $\Theta = \left[\theta, \chi, \psi^n\right]$ denote the vector of parameters. Our procedure is roughly as follows. For any given parameter vector Θ we simulate the post-war investment trajectories implied by the model using shocks to investment subsidies and tax rates as forcing variables. We run regressions of the form (5) for the simulated data and recover the implied reduced-form coefficients. We then choose the parameters Θ to make the simulated regression coefficients and their reduced-form analogues match as closely as possible.

Simulating the Path of Investment Subsidies in the Post-War Period. Equation (38) describes the evolution of the exogenous forcing processes. Given the matrix Λ we can construct a path of shocks that generates the investment subsidies and tax rates observed over the time period of our data sample. Specifically, given our observations on the subsidy ζ_t^m and the tax rates τ_t^π, τ_t^d we construct the structural innovations as

$$\boldsymbol{\varepsilon}_t = \Xi_t - \Lambda \Xi_{t-1}. \tag{43}$$

Since our baseline calibration is $\Lambda = \mathbf{I}$, the shocks are simply the observed differences in the calculated subsidy and the tax rates. Because the subsidy and the tax rates are mechanically related to each other (recall (2) and (4)), it is important to include the exact path of rates in the simulation. With the structural innovations, we can simulate the economy's dynamic reaction to the shocks.

Indirect Inference. Given a parameter vector $\Theta = [\theta, \chi, \psi_n]$, we simulate paths for the endogenous variables $\{I_t^m(\Theta), n_t^m(\Theta), W_t^m(\Theta), x_t^m(\Theta), IMP_t^m(\Theta), TFP_t^m(\Theta)\}$ taking the other calibrated parameters as given as described above. We then run regressions of the form (5) on the simulated data.[12] Let $\mathbf{b}(\Theta)$ denote the vector of regression coefficients associated with the simulation for a given parameter vector Θ and let $\hat{\mathbf{b}}^{\text{data}}$ be the corresponding vector of coefficient estimates from the data. Our parameter estimate $\hat{\Theta}$ is the solution to the minimum distance problem

$$\hat{\Theta} = \arg\min_{\Theta} \left\{ \left[\hat{\mathbf{b}}^{data} - \mathbf{b}(\Theta) \right]' \hat{\Omega}^{-1} \left[\hat{\mathbf{b}}^{data} - \mathbf{b}(\Theta) \right] \right\} \tag{44}$$

where $\Omega = \text{Var}\left[\hat{\mathbf{b}}^{data}\right]$.[13] Under the usual conditions, the estimate is asymptotically normally distributed with a finite covariance matrix $\hat{\Theta} \sim N\left(\Theta^{*}, \Sigma\right)$. The estimated covariance matrix of the indirect inference estimator is a natural function of the covariance matrix of the reduced-form parameter estimates

$$\hat{\Sigma} = \left[\left(\frac{\partial \mathbf{b}\left(\hat{\Theta}\right)}{\partial \Theta} \right) \hat{\Omega}^{-1} \left(\frac{\partial \mathbf{b}\left(\hat{\Theta}\right)}{\partial \Theta} \right)' \right]^{-1} . \tag{45}$$

Since the estimated variance covariance matrix $\hat{\Omega}$ is heteroskedasticity and autocovariance consistent, the estimated variance covariance matrix $\hat{\Sigma}$ will be as well.

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[12] We include GDP in the regressions on the simulated data but we exclude the remaining macroeconomic covariates. There are neither oil shocks nor price-controls in the model. Excluding GDP could have a modest influence on the results since tax policy likely has a non-negligible influence on aggregate economic activity.

[13] We solve for the parameters that minimize the distance between the reduced-form coefficients obtained from the data and from the model by solving a bounded optimization problem. For each structural parameter, we define a set of admissible values. We start the optimization from a set of random points in the admissible parameter space to avoid convergence to a local minimum.

The indirect inference estimates are reported in upper panel of Table 2.7. There are several noteworthy features of these estimates. First, the estimates for the import supply elasticity (χ) are substantial – between 2 and 4. These estimates suggest that, at least for capital goods, U.S. markets are closely tied to international pricing. Second, the production elasticity of effort (θ) is fairly high – about 0.65. This says that a one percent increase in effort is essentially equivalent to two thirds of a percent increase in effective labor. Lastly, the elasticity of type-specific labor substitution (ψ_n) is considerable at 2.23–2.52, which suggests that there are significant barriers to reallocating employment across industries.

The lower panel of Table 2.7 compares the regression coefficients for the estimated model with the corresponding reduced-form regression coefficients from the actual data. We include the coefficients for effort and capital, which do not have empirical analogues, but add insight into the dynamics of the model. The model fits reasonably well along some dimensions, but does not successfully replicate all empirical coefficients. As in the data, equipment purchases increase by roughly 1.5 percent, about twice as much as investment production. Both responses are close to those in the data, but somewhat more muted. In contrast, structures investment is more responsive in the model, suggesting that although structures differ from equipment in their depreciation rates and subsidy rates, the model does not capture all sources of heterogeneity present in reality. The coefficients for the wage bill and material inputs are materially similar to the reduced-form estimates.

The response of productivity (TFP) is considerably more attenuated in the model, where it exclusively reflects increased effort, while in the data there are additional factors that push up productivity, such as increased capital utilization. Although effort strongly reacts to the subsidy – the estimates suggest investment subsidies drives up effort one to one – it is not sufficient to generate an increase in TFP of the same magnitude as in the data. Similarly, the model increase in hours is only about half of that measured in the historical time series.

2.5.7. Reaction to Investment Subsidies

In this section, we evaluate the effects of an investment subsidy on investment, the prices of capital goods, the productivity of capital producers, and macroeconomic aggregates. The model is simulated with the estimated parameters in Table 2.7. We consider the simulated response to an investment subsidy that applies only to equipment. Structures do not qualify. This distinction between equipment and structures mirrors the typical investment tax credit. The typical depreciation allowances are offered for all types of investment, however their present discounted value is inversely related to the life of the asset, thus they are more limited for structures. In the model, the steady state subsidy equals the average historical subsidy for each type.

We consider three policy experiments. Figure 2.4 shows the reaction to a permanent subsidy in the baseline model. In Figure 2.5, we consider a closed economy to illustrate the role of imports. We set the import supply elasticity to zero, and all remaining parameters remain as in the baseline specification. In Figure 2.6, we consider a temporary subsidy, specified as an autoregressive process with half-life of one year. This approximation was chosen for tractability, while loosely corresponding to historical situations when the subsidy was set to expire, but there was uncertainty about the precise timing of its expiration. For example, the Economic Stimulus Act of 2008 offered bonus depreciation, allowing firms to deduct 50 percent of the cost of qualifying capital purchases in addition to the regular depreciation allowance during that year. The subsidy was extended through 2009 by The American Recovery and Reinvestment Act, then extended again in subsequent years (at 100 percent for 2011). Bonus depreciation is currently set to expire in 2016.

For each experiment, we report impulse response paths selected capital types. In the top left panel of Figures 2.4–2.6 we show industrial equipment, which accounts for 5.55 percent of aggregate investment between 1990–2009 and has a depreciation rate of 11 percent, relatively low among equipment types. Both investment and domestic production rise immediately then continue rising for roughly four years, after which they start to level off toward a permanently higher steady state. Investment starts out higher than production, with the difference consisting of imports. The gap narrows and reverses over time. In the new steady state, the economy exports industrial equipment. In the top right panel, we show aircraft, which has the same depreciation rate of 11 percent, but represents a smaller share of aggregate investment at only 1.57 percent. The response of aircraft is only slightly more attenuated than that of industrial equipment. In contrast, computers and software, shown in the lower left panel, account for a similar share of aggregate investment as industrial equipment, but have a much higher depreciation rate of 30 percent. Imports rise more sharply immediately after the subsidy is offered, but peak after only a few quarters and at a lower level than for industrial equipment. The adjustment to steady state is significantly faster. In the lower right panel we present the response of manufacturing structures, which did not qualify for the subsidy. Initially, investment falls as the response is dominated by substitution to subsidized types. After roughly four years, investment recovers, then continues to increase to a permanently higher level as the general equilibrium effects of higher production capacity take over. In all four cases, investment prices start out in the same direction as investment purchases, and settle to a slightly lower level in the new steady state.

The model features multiple sources of heterogeneity across capital goods types. Equipment and structures differ fundamentally because only equipment can be imported. For structures, investment equals domestic production. Furthermore, as in reality, investment subsidies are more favorable for equipment. Within each of these two broad categories of capital goods, types also differ in their economic depreciation rates and their role in the production of aggregate capital. We calibrate the model to match actual investment shares from 1990–2009, reported in Table 2.7. The impulse responses in Figure 2.4 show that in equilibrium, economic depreciation plays a significant role in each type's response to investment subsidies. Industrial equipment and aircraft, which have the same depreciation rate of 11 percent, have similar responses. The response of aircraft, a significantly smaller sector, is only slightly attenuated. In contrast, computers and software, which have a high depreciation rate of 30 percent, feature a considerably lower response. Capital types with lower depreciation rates have higher elasticities of intertemporal substitution, thus they are more responsive to changes in after-tax prices.

Figure 2.5 presents impulse responses to a 10 percent permanent subsidy for the same four types as in Figure 2.4, but assuming a closed economy. Unsurprisingly, the short-run increase in investment is significantly lower than in the open economy. The peak response occurs later and it is slightly lower in magnitude, but the final steady state is virtually identical. Figure 2.6 considers a temporary 10 percent investment subsidy in the baseline open economy. All three equipment types feature a dramatic immediate jump in investment, most of which is achieved through imports. Investment gradually declines, while production rises for several quarters before it starts reverting. Interestingly, industrial equipment and aircraft, the equipment types with lower depreciation rates, undershoot for an extended period of time before returning to the initial steady state. Investment in manufacturing structures initially falls, then temporarily rises above steady state levels. These impulse responses suggest that the temporary subsidy initially succeeds to stimulate investment in the eligible types. For longer-lived assets, however, it creates a capital overhang which results in lower investment at extended horizons. During this period, the economy substitutes to types that did not receive the subsidy, such as manufacturing structures. Temporary subsidies simply bring forward investment. Mian and Sufi (2012) found evidence for a similar effect in their study of the CARS program. These dynamic effects of temporary investment policies in general equilibrium highlight the need for policy makers to consider the potential distortionary implications of temporary versus permanent subsidies.

Figure 2.7 shows cross-sectional and aggregate impulse response functions to a 10 percent permanent investment subsidy. The upper right panel shows the capital goods production trajectories for the various types in the model. Both the qualified investment types and the ineligible investment categories react to the subsidy. The model features substitution across types. Production for the subsidized capital types rises in the short-run while production for unqualified investment types falls. For most subsidized types, it takes five years for investment production to increase by the full amount. In the long run, the production of aggregate capital, production of all types, is permanently higher. This result arises from complementarities between types in the production of aggregate capital. In the new steady state, total investment and the aggregate capital stock are higher, as seen in the aggregate impulse responses shown in the lower right panel.

The figure also reports impulse responses for capital goods prices (upper left panel) and measured productivity (lower right panel) to a 10 percent permanent investment subsidy. In the short run, prices for subsidized types increase and prices for ineligible types fall. The investment supply curve is upward sloping. For imports, we have explicitly assumed in equation (32) that import supply slopes upward. Capital adjustment costs in domestic production also generate an upward sloping relationship between investment and the pre-tax price for each type. In the long run, as the productive capacity of the economy increases, the investment supply curve expands and prices for all types are permanently lower. Importantly, the effect of the subsidy on prices is significantly smaller than the effect on production.

The lower left panel of Figure 2.7 reports the impulse responses of sector-specific productivity to the 10 percent permanent investment subsidy. Changes in measured productivity reflect exclusively variation in effort in the quantitative model, which abstracts from other factors that affect TFP in the real economy. In the short run, productivity for subsidized types increases, while productivity for structures falls. In the new steady state, productivity is higher for all types. As for prices, the magnitude of the effect is small. These effects reflect equilibrium changes in effort inputs as capital producing firms change their production levels relative to steady state. Firms producing subsidized equipment types increase production and effort, while firms producing ineligible structure types decrease production and effort in the short-run.

The lower right panel shows the impulse response functions for aggregate investment, consumption, employment and GDP. In aggregate terms, there is a substantial immediate increase in aggregate investment while GDP, consumption and employment are only slightly affected. Most of this increase is made up of imported capital goods.

2.6. CONCLUSION

We study the effects of investment tax incentives on investment, investment prices, the domestic production of equipment, and measures of activity at equipment-producing firms. Our reduced-form estimates indicate that investment subsidies are successful at increasing investment in both equipment and structures. Domestic production rises in response to investment tax incentives, but less than investment, as the subsidies "leak" to foreign producers through imports of capital goods. Employment, hours, material use and inputs at capital goods-producers also increase. Unlike Goolsbee (1998), we do not find evidence that investment subsidies affect the prices of investment goods.

We use the reduced-form estimates to calibrate a structural general equilibrium model with capital and labor adjustment costs, variable effort and international trade in equipment. The structural estimates of the model parameters indicate that the import supply of equipment is fairly elastic. In response to investment subsidies, there is strong variation in effort in equipment production. The model also indicates that there is limited substitutability in labor supply across sectors.

The model generates sharp general-equilibrium predictions of the effects of plausible investment tax incentives to equipment on investment and macroeconomic aggregates. The impulse response paths confirm the interpretation of our reduced-form results. In response to investment subsidies, investment increases more than production, with equipment imports accounting for the difference. Across capital types, the magnitude of the response largely depends on the economic depreciation rate of each type. In the short run, the response features substitution from ineligible types to subsidized types. If the subsidy is permanent, it also increases structures investment in the long run. If the subsidy is temporary, investment in long-lived equipment types experiences a "pothole" in the medium-run before the economy returns to the initial steady state.

Investment tax incentives increase hours, effort and measured productivity at equipment-producing firms. Capital goods prices, total hours and aggregate consumption are only slightly affected.

The reduced-form estimates and simulated policy experiments imply that investment tax incentives successfully stimulate investment in both equipment and structures. Permanent subsidies result in a higher aggregate capital stock and thus promote long-run economic growth. As a stabilization policy, however, temporary investment tax incentives have clear disadvantages. While temporary subsidies increase investment and equipment production, their effectiveness as macroeconomic stimulus is reduced because a significant fraction of the subsidies “leaks” to foreign producers. Additionally, their benefits for long-lived capital types are less clear, as the initial stimulus is followed by a decrease in the medium run after the subsidies expire. Lastly, in the simulated data, the effects of temporary subsidies on the aggregate production of the final consumption good are negligible.

TABLE 2.1. LEGISLATIVE HISTORY OF INVESTMENT TAX INCENTIVES

Law Name	Public Law	Romer and Romer (2009) Classification	Motivation	Intended Duration	Investment Tax Credit	Depreciation Allowance
Internal Revenue Code of 1954	83-591	Exogenous	Long-run	Permanent		Double-declining balance method
Small Business Tax Revision Act of 1958	85-699	Exogenous	Long-run	Permanent		First-year depreciation for long-lived assets
Revenue Act of 1962	87-834	Exogenous	Long-run	Permanent	Introduced 7% ITC Limited for short-lived assets Public utilities excluded	100% basis adjustment for ITC
Tax Rate Extension Act of 1962	87-507	Exogenous	Long-run	Permanent	Public utilities eligible for 3%	
Revenue Act of 1964	88-272	Exogenous	Long-run	Permanent	Simplified ITC	Removed basis adjustment
Suspension of Investment Tax Credit of 1966	89-800	Endogenous	Countercyclical	Temporary	Suspended ITC	Limited accelerated depreciation
Restoration of Investment Tax Credit	90-26	Exogenous	Long-run	Permanent	Reinstated ITC and increased ceiling	
Tax Reform Act of 1969	91-172	Exogenous Endogenous	Long-run Countercyclical	Permanent	Repealed ITC	
Reform of Depreciation Rules of 1971		Exogenous	Long-run	Permanent		Shortened the assumed life of equipment and allowed more first year depreciation
Revenue Act of 1971	92-178	Exogenous	Long-run	Permanent	Restored ITC at 7% Limited for short-lived assets Public utilities eligible for 4%	Introduced ADR system Lowered asset lifetimes

Law Name	**Public Law**	**Romer and Romer (2009) Classification**	**Motivation**	**Intended Duration**	**Investment Tax Credit**	**Depreciation Allowance**
Tax Reduction Act of 1975	94-12	Endogenous	Countercyclical	Temporary	Increased to 10% Extended 10% ITC to public utilities	
Tax Reform Act of 1976	94-455	Exogenous	Long-run	Temporary	Extended 10% ITC through 1980	
Revenue Act of 1978	95-600	Exogenous	Long-run	Permanent	Made 10% ITC permanent	
Economic Recovery Tax Act of 1981	97-34	Exogenous	Long-run	Permanent	Extended 10% ITC to short-lived assets	Replaced ADR with ACRS Simplified asset-life classes Accelerated depreciation deductions
Tax Equity and Fiscal Responsibility Act of 1982	97-248	Exogenous	Deficit-driven	Permanent		Repealed accelerated depreciation
Deficit Reduction Act of 1984	98-369	Exogenous	Deficit-driven	Permanent		Lengthened asset lives from 15 years to 18 years
Tax Reform Act of 1986	99-514	Exogenous	Long-run	Permanent	Repealed ITC	Replaced ACRS with MACRS Reduced depreciation allowances
Tax Relief Act of 1997	105-34	Exogenous	Deficit-driven	Permanent		Harmonized asset lives for alternative minimum tax with regular tax lives
Job Creation and Worker Assistance Act of 2002	107-147	Endogenous	Countercyclical	Temporary		30% bonus depreciation

Law Name	Public Law	Romer and Romer (2009) Classification	Motivation	Intended Duration	Investment Tax Credit	Depreciation Allowance
Jobs and Growth Tax Relief Reconciliation Act of 2003	108–27	Endogenous	Countercyclical	Temporary		Extended bonus depreciation 50% for given asset classes
The Economic Stimulus Act of 2008	110–185	Endogenous	Countercyclical	Temporary		Reintroduced 50% bonus depreciation
American Recovery and Reinvestment Act of 2009	111-5	Endogenous	Countercyclical	Temporary		Extended 50% bonus depreciation
Small Business Jobs Act of 2010	111-240	Endogenous	Countercyclical	Temporary		Extended 50% bonus depreciation
Tax Relief, Unemployment Insurance Reauthorization, Job Creation Act of 2010	111-312	Endogenous	Countercyclical	Temporary		Extended and increased bonus depreciation to 100%
The American Taxpayer Relief Act of 2012	112–240	Endogenous	Countercyclical	Temporary		Extended and reduced bonus depreciation to 50%
The Tax Increase Prevention Act of 2014	113-295	Endogenous	Countercyclical	Temporary		Extended 50% bonus depreciation

Notes. The legislative history from 1954–2003 comes from Romer and Romer (2009), who labeled each law as “exogenous” or “endogenous,” and attributed its motivation to one of three cateogries: long-run, countercyclical or deficit-driven. In this context, exogeneity should not be understood in the strict sense of the term, but rather as describing laws that were not motivated by the contemporaneous state of the economy. The classification reported in this table pertains specifically to investment subsidies and in some cases differs from the general motivations of the main legislative act. We augmented the effects of each law on the ITC and depreciation allowances with information from Gravelle (1994). We extended the Romer and Romer narrative history with legislation affecting investment subsidies between 2003 and 2015.

TABLE 2.2. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT PRODUCTION AND PURCHASES

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
Production	1.09	0.78	1.11	1.04
	(0.35)	(0.26)	(0.32)	(0.40)
Purchases	1.90	1.26	1.93	1.70
	(0.43)	(0.34)	(0.37)	(0.45)
INVESTMENT TAX CREDIT				
Production	2.09	1.02	2.12	2.66
	(0.50)	(0.42)	(0.45)	(0.52)
Purchases	2.94	1.69	2.97	3.02
	(0.64)	(0.56)	(0.56)	(0.65)
JORGENSONIAN TAX TERM				
Production	1.08	0.54	1.08	1.02
	(0.32)	(0.25)	(0.30)	(0.36)
Purchases	1.41	0.59	1.41	1.04
	(0.42)	(0.30)	(0.40)	(0.48)

Notes. The dependent variable is the natural logarithm of equipment production or equipment purchases as indicated. The coefficients are for the measure of the subsidy (in levels). Driscoll-Kraay standard errors are shown in parentheses.

TABLE 2.3. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT PRICES

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
Production prices	-0.12	-0.02	-0.01	0.08
	(0.10)	(0.06)	(0.06)	(0.08)
Purchase prices	-0.34	-0.15	-0.15	-0.04
	(0.12)	(0.07)	(0.06)	(0.08)
INVESTMENT TAX CREDIT				
Production prices	0.02	-0.11	-0.11	0.14
	(0.13)	(0.10)	(0.09)	(0.13)
Purchase prices	-0.20	-0.20	-0.24	-0.08
	(0.14)	(0.10)	(0.09)	(0.14)
JORGENSONIAN TAX TERM				
Production prices	0.06	-0.05	-0.04	0.06
	(0.07)	(0.06)	(0.06)	(0.07)
Purchase prices	0.02	-0.04	-0.03	0.04
	(0.07)	(0.06)	(0.06)	(0.08)

Notes. Driscoll-Kraay standard errors are shown in parentheses.

TABLE 2.4. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT EMPLOYMENT

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
Production employees	0.99	0.36	1.03	0.73
	(0.60)	(0.28)	(0.61)	(0.61)
Production hours	0.76	0.34	0.80	0.63
	(0.59)	(0.30)	(0.58)	(0.61)
Production wages	1.29	0.70	1.37	0.15
	(1.23)	(0.23)	(1.23)	(1.11)
INVESTMENT TAX CREDIT				
Production employees	2.24	0.77	2.29	2.79
	(0.68)	(0.46)	(0.66)	(0.83)
Production hours	1.92	0.67	1.98	2.65
	(0.69)	(0.49)	(0.65)	(0.80)
Production wages	3.64	1.04	3.75	3.85
	(0.94)	(0.37)	(0.92)	(1.48)
JORGENSONIAN TAX TERM				
Production employees	1.16	0.26	1.17	1.07
	(0.43)	(0.24)	(0.44)	(0.53)
Production hours	1.03	0.18	1.05	1.06
	(0.42)	(0.24)	(0.42)	(0.50)
Production wages	2.12	0.38	2.16	1.85
	(0.55)	(0.22)	(0.57)	(0.81)

Notes. Driscoll-Kraay standard errors are shown in parentheses.

TABLE 2.5. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT, OTHER VARIABLES

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
TFP	0.32	0.14	0.31	0.27
	(0.17)	(0.12)	(0.16)	(0.18)
Cost of materials	0.86	0.62	0.91	0.78
	(0.58)	(0.35)	(0.55)	(0.56)
Cost of energy	2.23	1.36	2.31	0.28
	(1.42)	(0.31)	(1.39)	(1.23)
INVESTMENT TAX CREDIT				
TFP	0.58	0.27	0.57	0.69
	(0.25)	(0.18)	(0.22)	(0.25)
Cost of materials	1.93	1.04	2.01	2.69
	(0.69)	(0.54)	(0.62)	(0.76)
Cost of energy	5.01	2.04	5.11	3.98
	(1.06)	(0.50)	(1.00)	(1.51)
JORGENSONIAN TAX TERM				
TFP	0.32	0.12	0.32	0.30
	(0.14)	(0.10)	(0.13)	(0.13)
Cost of materials	1.03	0.48	1.06	1.04
	(0.40)	(0.29)	(0.39)	(0.47)
Cost of energy	2.78	0.92	2.84	1.92
	(0.69)	(0.35)	(0.67)	(0.78)

Notes: Driscoll-Kraay standard errors are shown in parentheses.

Table 2.6. Effects of Investment Subsidies: Structures Production and Prices

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
Comprehensive Subsidy				
Purchases	0.88	1.00	1.06	0.46
	(0.31)	(0.23)	(0.32)	(0.31)
Prices	0.53	0.33	0.58	0.36
	(0.12)	(0.08)	(0.13)	(0.12)
Investment Tax Credit				
Purchases	4.73	3.83	4.82	3.97
	(0.59)	(0.59)	(0.53)	(0.76)
Prices	0.73	1.10	0.73	-0.68
	(0.20)	(0.13)	(0.20)	(0.35)
		-		
Jorgensonian Tax Term				
Purchases	0.44	0.21	0.62	0.28
	(0.27)	(0.20)	(0.29)	(0.26)
Prices	-0.04	0.02	-0.01	-0.07
	(0.05)	(0.06)	(0.05)	(0.05)

Notes. Driscoll-Kraay standard errors are shown in parentheses.

TABLE 2.7. INDIRECT INFERENCE ESTIMATES AND COMPARISON

Adjustment Cost Calibration		Low	Medium	High
Capital Adjustment Cost (ξ^n)		3.30	10.00	20.00
Labor Adjustment Cost (ξ^h)		0.00	0.10	0.30
Parameter Estimates				
Import Supply Elasticity (χ)		3.55	2.55	1.95
		(0.39)	(0.35)	(0.34)
Production Elasticity of Effort (θ)		0.65	0.63	0.66
		(0.12)	(0.11)	(0.11)
Type Specific Labor Substitution (ψ^n)		2.23	2.52	2.25
		(0.49)	(0.55)	(0.48)
Variable	Reduced Form Coefficient	Model Coefficient		
Equipment Production	1.11	0.76	0.72	0.74
	(0.32)			
Equipment Investment	1.93	1.51	1.54	1.54
	(0.37)			
Hours	0.80	0.37	0.38	0.45
	(0.58)			
Wage Bill	1.37	1.15	1.29	1.45
	(1.23)			
Material Inputs	0.91	0.77	0.72	0.75
	(0.55)			
Productivity (TFP)	0.31	0.07	0.08	0.10
	(0.16)			
Structures Investment	1.06	2.17	2.02	1.90
	(0.32)			
Effort		0.82	0.98	1.10
Capital		0.29	0.23	0.16

TABLE 2.8. EQUIPMENT TYPES: DEPRECIATION RATES, INVESTMENT SHARES AND SUBSIDIES

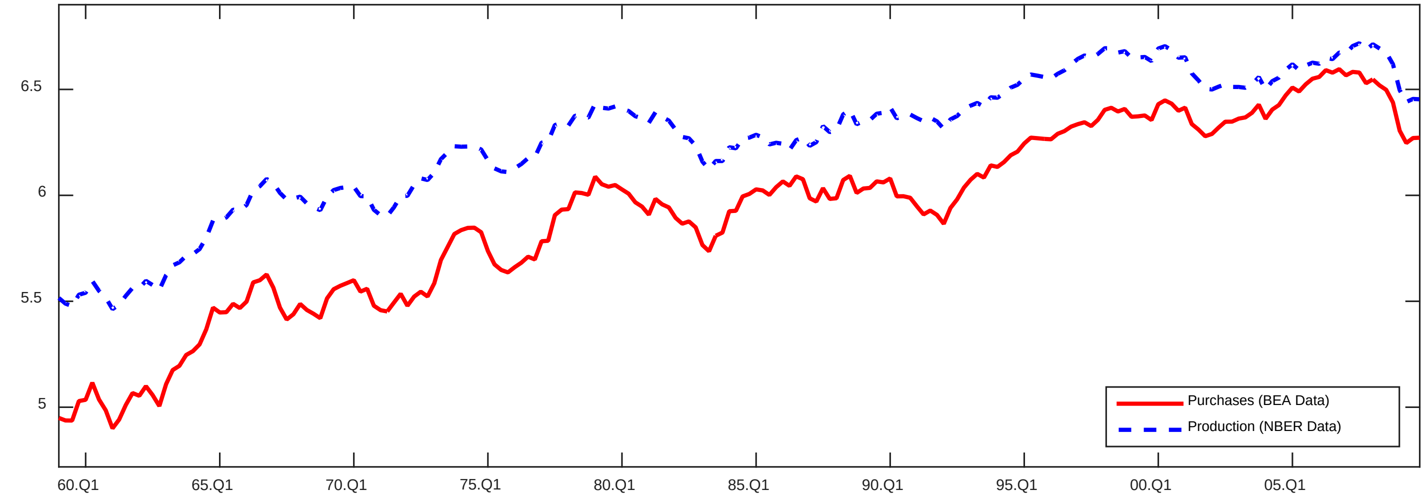
	Depreciation (δ)	Investment Share (1990–2009)	Average Subsidy
Computers, software and office equipment	0.30	15.50%	0.40
Communication equipment	0.13	5.64%	0.38
Instruments	0.14	3.99%	0.39
Photocopy and related equipment	0.18	0.82%	0.40
Fabricated metal products	0.09	0.92%	0.39
Steam engines	0.05	0.31%	0.35
Internal combustion engines	0.21	0.14%	0.35
Metalworking machinery	0.12	1.81%	0.39
Industrial Equipment	0.11	5.51%	0.39
Electrical transmission and distribution	0.05	1.51%	0.38
Trucks, buses, and truck trailers	0.19	4.44%	0.40
Autos	0.17	2.84%	0.40
Aircraft	0.11	1.46%	0.40
Ships and boats	0.06	0.23%	0.37
Railroad equipment	0.06	0.41%	0.38
Household furniture	0.14	0.14%	0.40
Other furniture	0.12	2.16%	0.40
Farm tractors	0.15	0.42%	0.39
Other agricultural machinery	0.12	0.82%	0.39
Construction tractors	0.16	0.15%	0.40
Other construction machinery	0.16	1.32%	0.40
Mining and oilfield machinery	0.15	0.40%	0.40
Service industry machinery	0.17	1.29%	0.40
Household appliances and miscellaneous	0.18	0.31%	0.40

TABLE 2.9. STRUCTURES TYPES: DEPRECIATION RATES, INVESTMENT SHARES AND SUBSIDIES

	Depreciation (d)	Investment Share (1990–2009)	Average Subsidy
Hospitals, medical, religious and educational structures	0.02	2.91%	0.23
Commercial structures	0.02	2.75%	0.30
Warehouses	0.02	0.76%	0.23
Manufacturing	0.03	2.62%	0.26
Electric	0.02	1.63%	0.31
Other power, petroleum and natural gas	0.02	2.95%	0.31
Communication	0.02	1.10%	0.32
Mining	0.07	0.18%	0.39
Railroads	0.03	0.37%	0.25
Farm structures	0.02	0.33%	0.29
Residential structures	0.02	31.89%	0.26

FIGURE 2.1. PURCHASES, PRODUCTION AND PRICES, GENERAL INDUSTRIAL EQUIPMENT

Real Purchases and Production, General Industrial Equipment, 1959-2009



Real Prices, General Industrial Equipment, 1959-2009

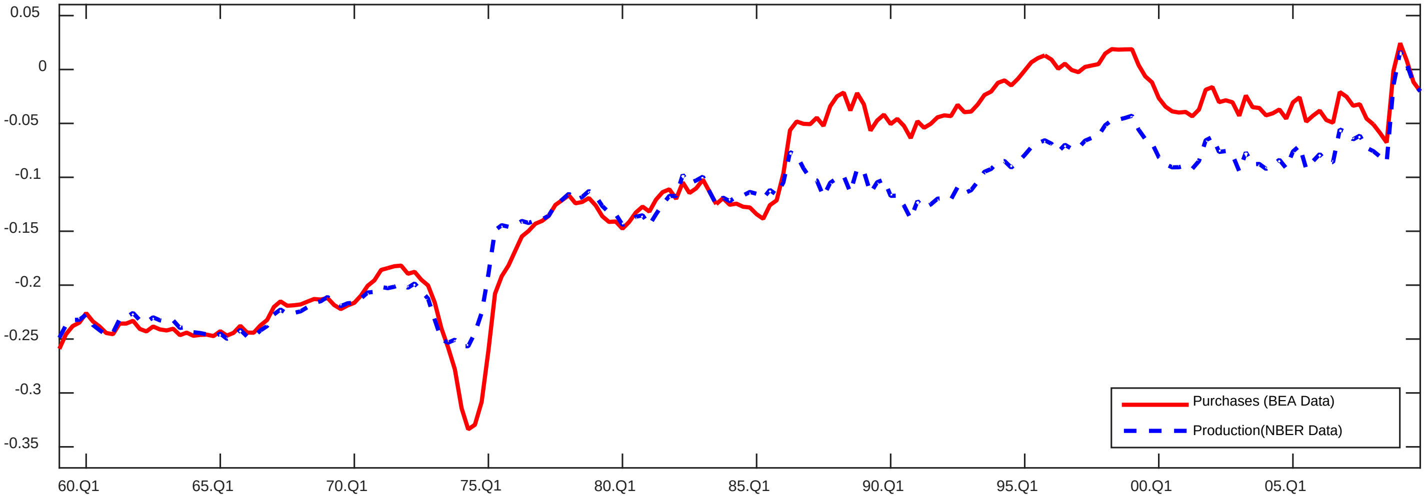


FIGURE 2.2. INVESTMENT SUBSIDY, GENERAL INDUSTRIAL EQUIPMENT

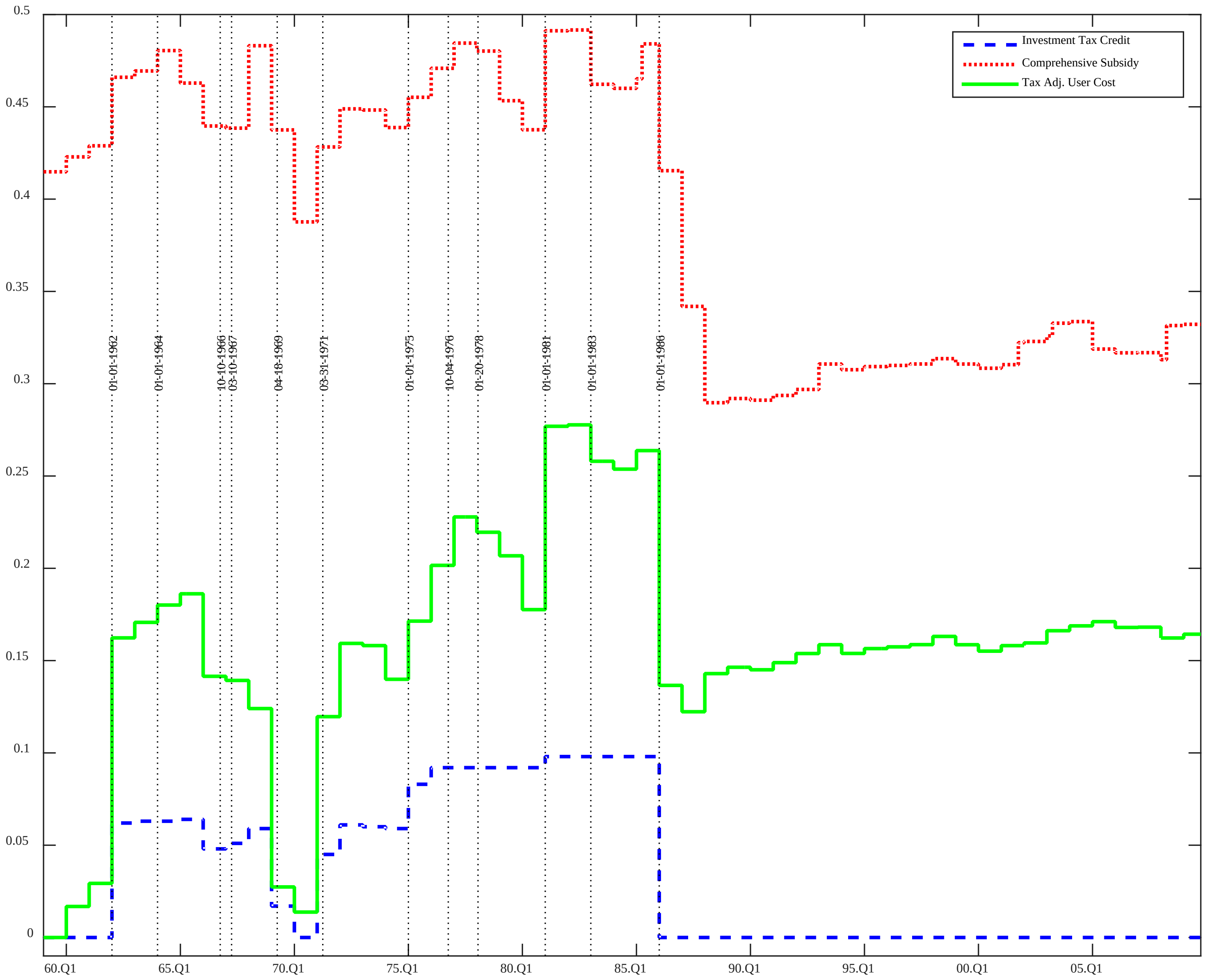


FIGURE 2.3. COMPREHENSIVE SUBSIDY BY INVESTMENT TYPE

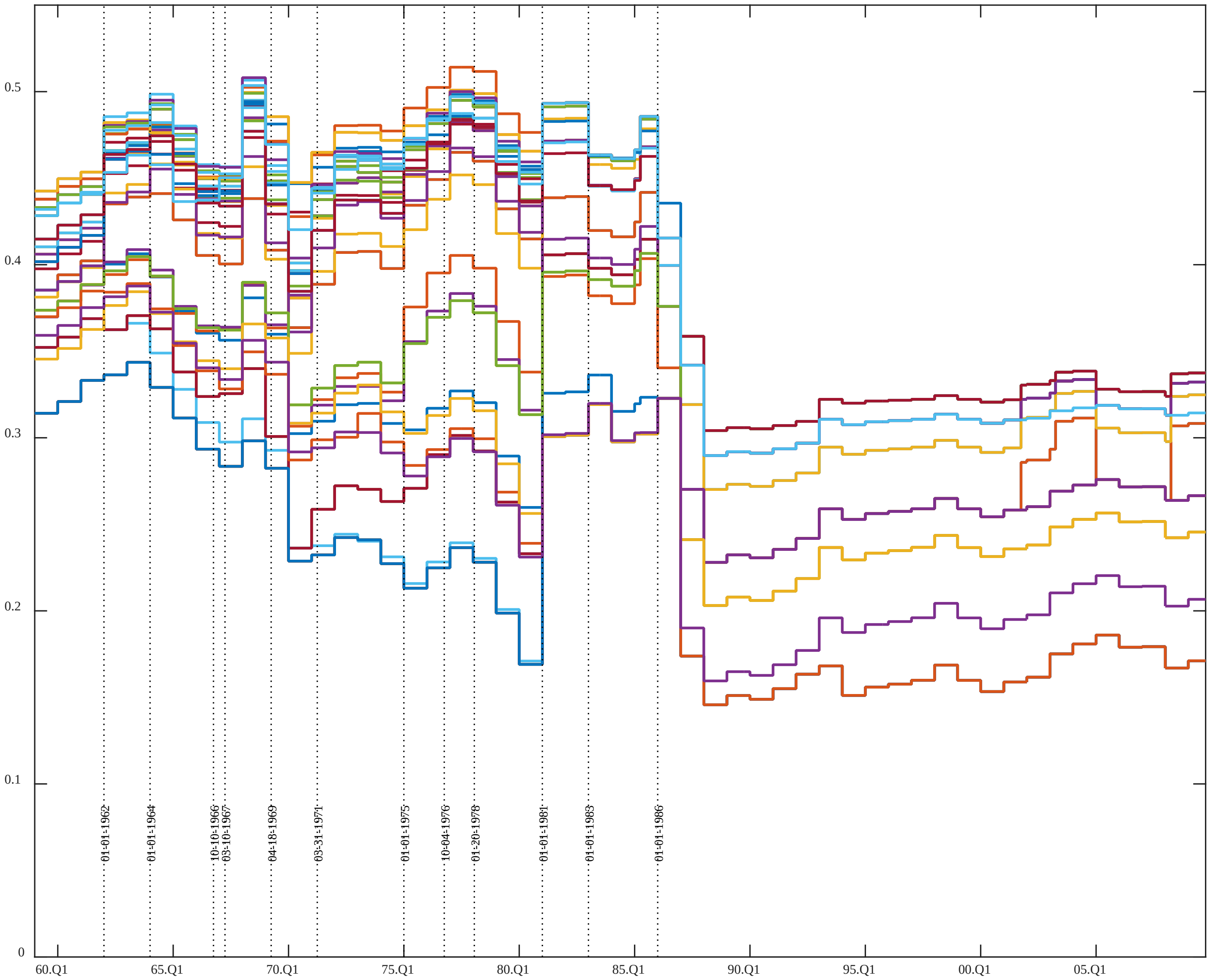


Figure 2.4. Reaction to a 10 Percent Permanent Investment Subsidy for Equipment

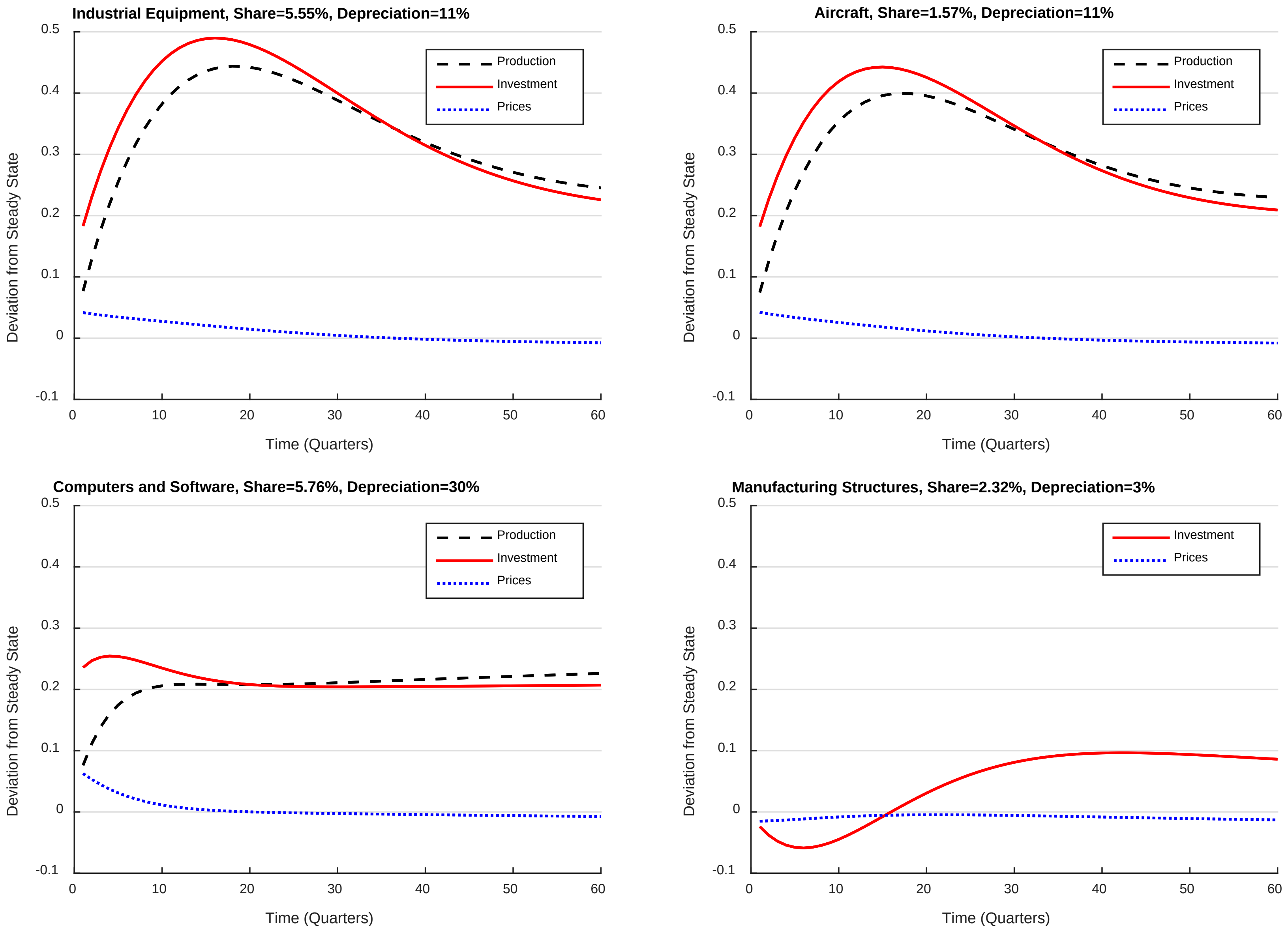


Figure 2.5. Reaction to a 10 Percent Permanent Investment Subsidy for Equipment, Closed Economy

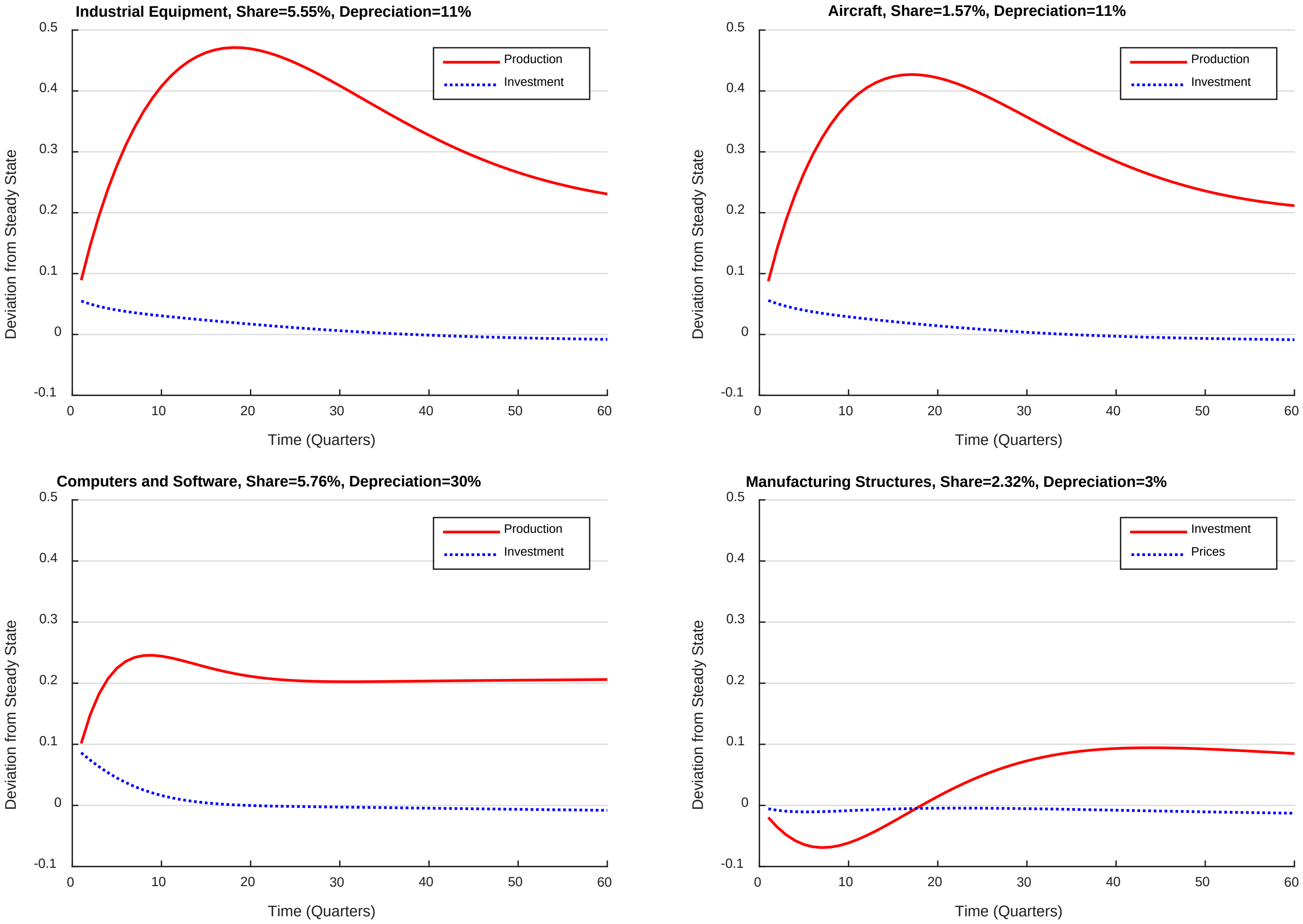
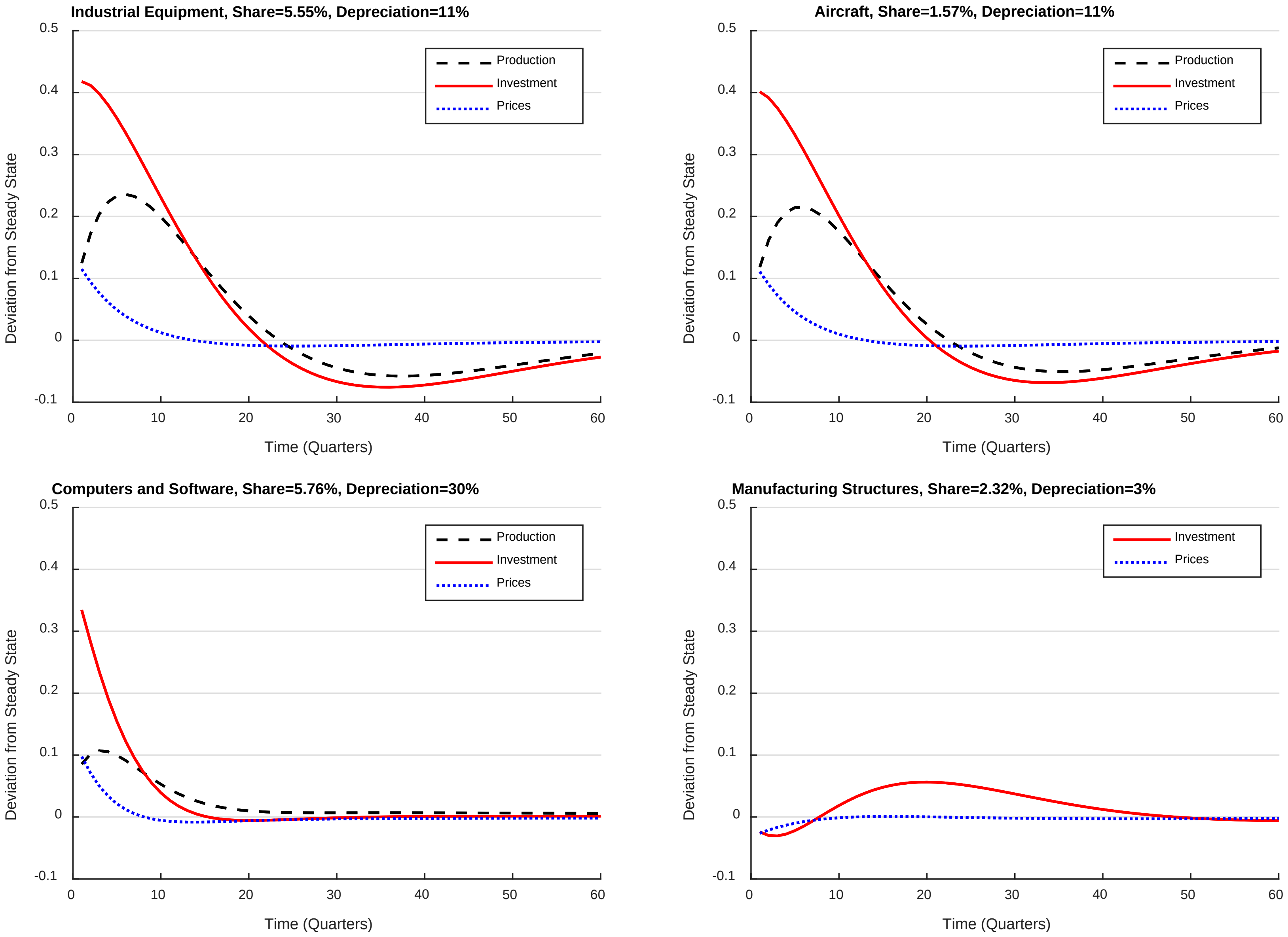


Figure 2.6. Reaction to a 10 Percent Temporary Investment Subsidy for Equipment



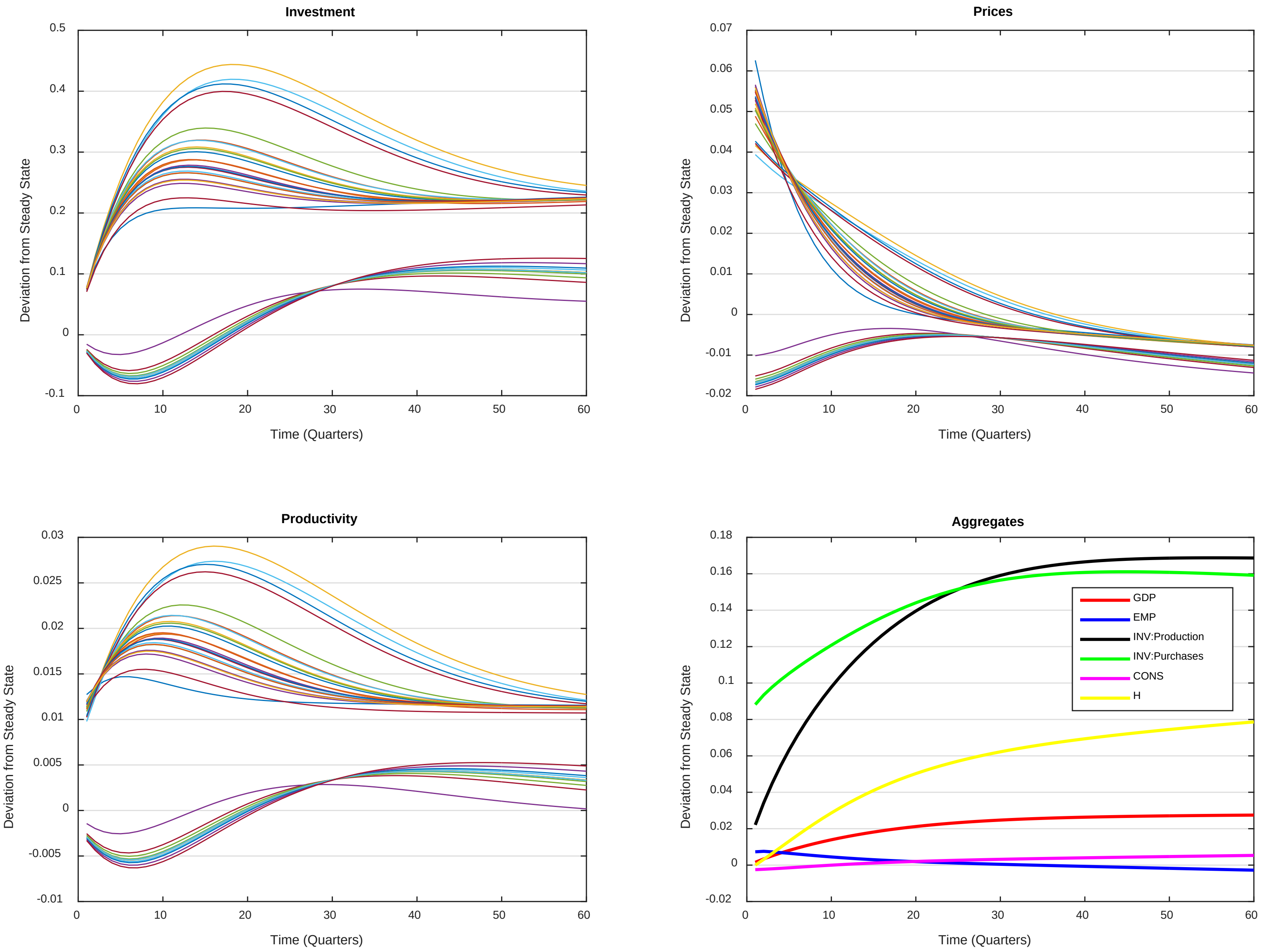
Industrial Equipment, Share=5.55%, Depreciation=11%

Aircraft, Share=1.57%, Depreciation=11%

Computers and Software, Share=5.76%, Depreciation=30%

Manufacturing Structures, Share=2.32%, Depreciation=3%

Figure 2.7. Reaction to a 10 Percent Permanent Investment Subsidy to Equipment, Cross Section


Investment

Prices

Productivity

Aggregates

APPENDIX 2.A

COMPARISON WITH GOOLSBEE (1998)

Goolsbee (1998) is one of the most influential studies of the effects of investment tax incentives on the market for capital goods. The main finding of Goolsbee's paper is that investment subsidies increase equipment prices and benefit not only firms that invest, but also capital suppliers. This result was robust to alternative specifications, and was present in two distinct datasets – investment price deflators from the BEA, and equipment output deflators from the NBER Manufacturing Industry Database. Furthermore, Goolsbee estimated investment supply elasticities, finding evidence in favor of upward sloping supply curves for equipment goods. If the supply of new capital is price inelastic, economic theory predicts that investment tax incentives have little effect on investment demand, and instead succeed only in driving up equipment prices.

In contrast, we find that investment tax incentives do not have a clear effect on investment goods prices, and that investment demand strongly responds to subsidies. Under our preferred specification, a one percent subsidy increases equipment investment by roughly 2 percent, investment production by 1.25 percent, and structures investment by one. The reduced-form analysis in our study is closely related to Goolsbee's work – we set out to measure many of the same relationships, and our empirical specifications are inspired by those in Goolsbee (1998). In this appendix, we attempt to meticulously reconstruct the methodology and data used by Goolsbee at the time when he published his paper. We consider differences in specification, data revisions, and differences in the time period included in each of the two studies, and we demonstrate that restatements in price deflators are the likely reason our findings depart from Goolsbee's. The replication allows us to approximately reproduce Gooslbee's main findings. The main differences are primarily due to differences in sample periods, but also from differences in econometric specification.

Starting with the data and covariates in Section 2.3, we vary the empirical model by incrementally changing different features of the specification. Each variant brings us closer to the empirical model in Goolsbee's paper. The results are reported in Table 2.A.1. Our baseline specification, presented in column (1), is a pooled regression of the log real relative investment prices on a constant, linear trend (allowing for a trend break), investment tax incentives, HP-filtered GDP, dummies for the Nixon price controls and real oil prices. Real prices are calculated using the deflator for nondurable personal consumption expenditures. The data cover the period from 1959–2009. This specification closely resembles that used for our main estimates, the only differences being that we use annual instead of quarterly data, and we align the equipment types to those present in the BEA dataset used by Goolsbee (1998). As for our main estimates, we consider three measures of investment subsidies: the Jorgensonian tax term, the investment tax credit, and the comprehensive investment subsidy. Our pooled estimates of the effect of tax incentives on investment prices are not statistically significant.

This result is robust to changing the time period to 1959–1997, as shown in column (2), as well as to modifying the specification to match the covariates in Goolsbee's paper, more specifically a constant term, linear trend (without a trend break), the growth rate of GDP, dummies for the Nixon price controls and the real exchange rates of U.S. dollars to German marks and Japanese yen. The latter set of estimates, reported in column (5), include both an OLS regression and a regression with quasi-differenced data to remove serial correlation in the variables, as in Goolsbee (1998). None of these estimates indicate that investment subsidies drive up the prices of equipment goods.

Our last variant, presented in column (4), regresses vintage BEA data on investment prices and other macroeconomic variables that was available at the time of Goolsbee's analysis. The data were published by the U.S. Department of Commerce in a volume called *Fixed Reproducible Tangible Wealth in the United States: 1925–1989*. These last estimates are statistically significant and show a positive relationships between investment subsidies and equipment prices. The results are qualitatively similar to those in Goolsbee's paper, which are reproduced in column (5). Taken as a whole, the variants summarized in Table 2.A.1 strongly suggest that restatements of equipment prices account for the fact that, unlike Goolsbee, we no longer find evidence that investment tax incentives affect prices.

It is not surprising that data revisions are so material that they yield different conclusions. Equipment prices are notoriously subject to measurement error due to dramatic quality improvements in capital goods. As described in the N.I.P.A. Handbook (2014), the times series for equipment prices are compiled from multiple sources, primarily BLS PPI and CPI series. Figure 2.A.1 presents the vintage and current real prices of equipment, showing that for many series data revisions are indeed substantial.

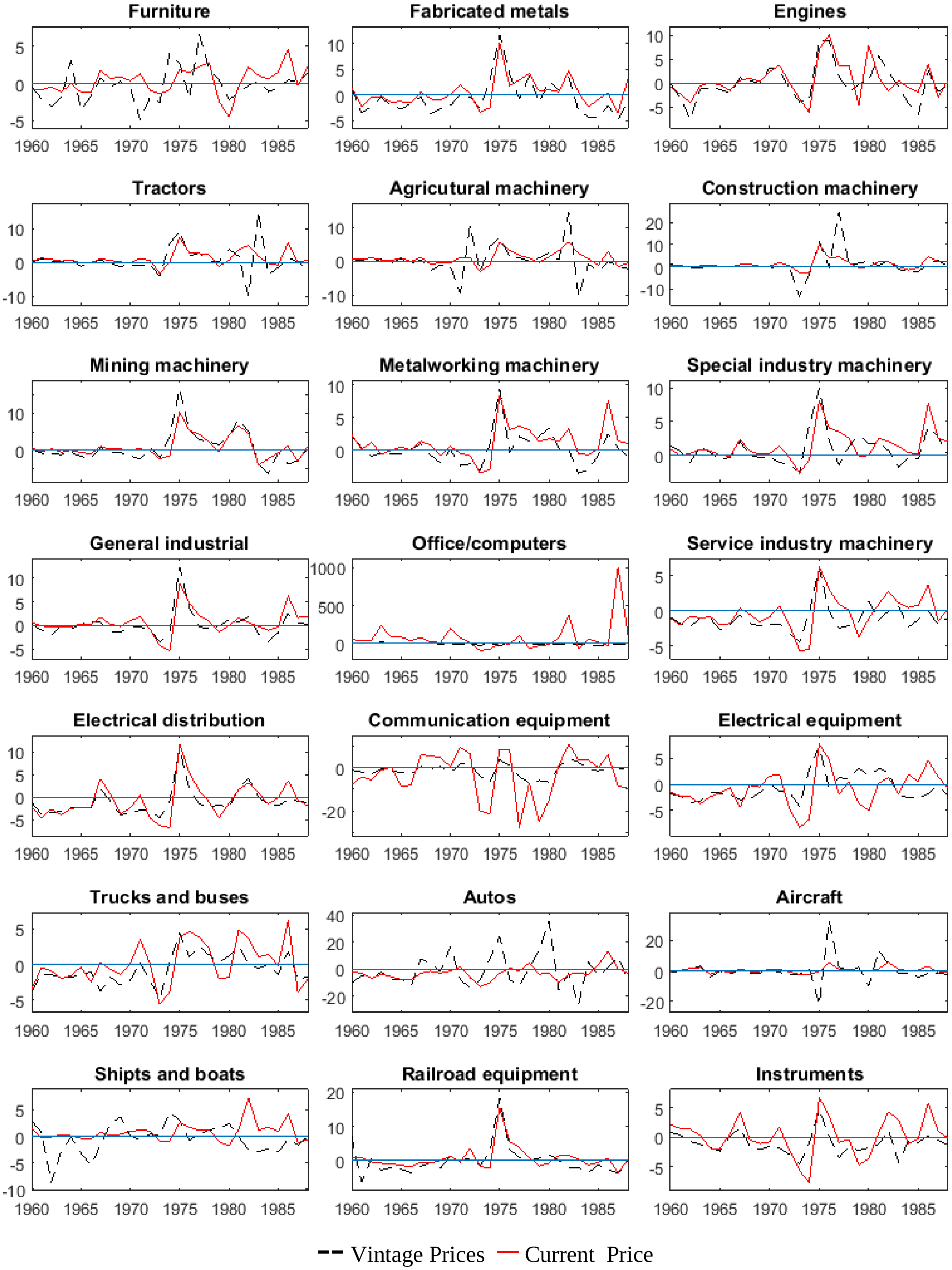
Although we have replicated the qualitative results in Goolsbee's paper, our estimates are not numerically identical. We note two factors that likely contribute to this difference. First, we were not able to obtain vintage data for investment subsidies, nor for the German and Japanese price indices we used to calculate real exchange rates. Second, our implementation of the AR(2) quasi-differencing procedure used to address serial correlation may differ from that in Goolsbee's paper. The algorithm relies on numerical convergence, and we have verified that the choice of stopping criteria can affect estimates.

TABLE 2.A.1. COMPARISON WITH GOOLSBEE (1998)

	(1) Current Data 1 t1 t2 hpY Nix Oil 1959-2009		(2) Current Data 1 t1 t2 hpY Nix Oil 1959-1988		(3) Current Data 1 t gY Nix DM Yen 1959-1988		(4) Vintage Data 1 t gY Nix DM Yen 1959-1988		(5) Goolsbee (1998)
	OLS	Quasi Diff	OLS	Quasi Diff	OLS	Quasi Diff	OLS	Quasi Diff	Quasi Diff
COMPREHENSIVE INVESTMENT SUBSIDY	-0.788	N.A.	-0.074	N.A.	-1.029	-0.265	0.501	0.280	N.A.
	(0.246)		(0.238)		(0.389)	(0.231)	(0.110)	(0.061)	
INVESTMENT TAX CREDIT	-0.242	N.A.	0.122	N.A.	-1.070	-0.284	0.551	0.177	0.390
	(0.360)		(0.342)		(0.457)	(0.269)	(0.129)	(0.074)	(0.036)
JORGENSONIAN TAX TERM	-0.045	N.A.	0.109	N.A.	-0.445	0.041	0.263	0.133	0.170
	(0.185)		(0.148)		(0.262)	(0.144)	(0.075)	(0.042)	(0.028)

Notes. OLS standard errors are shown in parentheses. The notation in column headings represents the covariates in each specification as follows: “1” for the constant term; “t” for a linear trend without trend break; “t1 t2” for a linear term allowing a trend break; “hpY” for HP-filtered GDP; “NIX” for Nixon price controls dummies; “OIL” for real oil prices; “gY” for the growth rate of GDP; “DM” for the real exchange rate between U.S. dollars and German marks; “YEN” for the real exchange rate between U.S. Dollars and Japanese yen. We apply quasi-differencing for AR(2) serial correlation only to specifications that do not contain a trend break.

FIGURE 2.A.1. VINTAGE AND CURRENT EQUIPMENT PRICES, ANNUAL PERCENT CHANGE



APPENDIX 2.B

EFFECTS OF INVESTMENT SUBSIDIES ON EQUIPMENT TRADE

In this appendix, we present evidence on the effects of investment tax incentives on the imports and exports of equipment. A comprehensive study of investment subsidies would ideally describe their effects not only on the production and business investment in capital goods, but on all components of the capital accounting identity

$$Y = I + C + G + IMP + EXP \qquad (1)$$

where Y denotes the domestic output of capital goods, I is investment, C is private consumption of capital goods, G is government purchases, IMP is imports and EXP is exports of capital goods. For all types of equipment, trade is substantial, while for a subset of types, such as autos, private and government consumption are also considerable. As an example, the top panel of Figure 2.1 shows the gap between domestic production and purchases of general industrial equipment.

Investment tax incentives are often offered with the goal to stimulate the economy. Understanding if increased investment comes at the cost of crowding out purchases of capital goods by households and the government is therefore important for evaluating the effects of investment subsidies. Similarly, the stimulus effect of subsidies is subject to “leakage” through international trade and can potentially benefit not only domestic, but also foreign producers of capital goods.

Data availability has limited our ability to study the general-equilibrium effects of investment on all aspects of economic activity. To the best of our knowledge, data on consumption and government purchases of capital goods at the level of aggregation in the BEA detail tables do not exist. We compiled an annual dataset of equipment imports and exports that partially aligns with the capital types studied in our main analysis, for the time period from 1959–1994. Data on the imports and exports of capital goods were assembled from the NBER database on U.S. imports and exports by four-digit SIC industry. We mapped these data to 1987 SIC using the concordance table in Bartelsman and Gray (1996), then retained only data for 1987 SIC codes that could be matched unequivocally to six-digit NAICS codes based on the concordance table published by the Census Bureau. We then followed the same procedure as for the production data to aggregate to the equipment types in the BEA detail tables, however some of the NAICS codes in the production data were not present in the resulting trade data, so the mapping of trade to our main production, purchases and subsidies series is only partially complete. After 1994, international trade data is available only under the Harmonized System product nomenclature, which is not compatible with NAICS. As a result, we were not able to extend the equipment exports and imports data by BEA investment types beyond 1994.

We present two sets of empirical results using the same specifications described in Section 2.4.1. In table 2.B.1, we show pooled estimates of the effects of investment subsidies on imports and exports for all equipment types. In table 2.B.2, we restrict the dataset to the equipment types for which we captured all underlying NAICS codes that make up the corresponding BEA definitions, thus the trade data is aligned with the other series in our data, most importantly with investment subsidies. We find that equipment imports respond sharply to investment tax incentives. An investment subsidy of 1 percent is associated with an increase of roughly 2 to 3 percent in equipment imports. These estimates suggest that when subsidies are offered, increased investment demand is partially met through imports, thus investment tax incentives “leak” to foreign capital producers. Interestingly, we find that exports also increase when investment subsidies are high, although less sharply than imports. The exports results are somewhat less conclusive as many estimates are not statistically significant, in particular when all types are included in the regression. Overall, the evidence suggests that domestic producers of capital goods benefit from investment subsidies through two separate channels: higher domestic demand for their output, as well as an incentive to invest themselves, increasing production and exports.

The quantitative model in Section 2.5 is consistent with the empirical evidence on equipment trade. In the model, as in the data, net imports of equipment sharply increase following a positive investment subsidy shock. However, we do not use the imports and exports estimates in the indirect inference procedure to calibrate the model. Due to the shortcomings in the trade data described above, the imports and exports results are not directly comparable with the main estimates in Section 2.4.2. Additionally, the model abstracts from private and government consumption of capital goods, which introduces another source of inconsistency with the data.

TABLE 2.B.1. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT IMPORTS AND EXPORTS, ALL TYPES

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
Imports	2.95	2.87	3.13	2.05
	(0.96)	(0.84)	(0.95)	(0.75)
Exports	1.35	0.83	-0.37	-0.68
	(0.91)	(0.71)	(0.73)	(0.51)
INVESTMENT TAX CREDIT				
Imports	3.36	3.31	3.32	0.79
	(1.44)	(1.35)	(1.64)	(0.94)
Exports	2.10	2.02	0.11	-0.41
	(0.95)	(0.96)	(1.02)	(0.67)
JORGENSONIAN TAX TERM				
Imports	1.50	1.43	0.70	-0.11
	(1.00)	(1.02)	(1.10)	(0.60)
Exports	0.84	0.80	0.11	-0.08
	(0.39)	(0.40)	(0.28)	(0.26)

Notes. The dependent variable is the natural logarithm of equipment imports or equipment exports as indicated. The coefficients are for the measure of the subsidy (in levels). Driscoll-Kraay standard errors are shown in parentheses.

TABLE 2.B.2. EFFECTS OF INVESTMENT SUBSIDIES: EQUIPMENT IMPORTS AND EXPORTS, SELECTED TYPES

	Specification			
	Constant and linear trend	Macro covariates except OIL	Macro covariates	Macro covariates with leads and lags
COMPREHENSIVE SUBSIDY				
Imports	3.27	3.31	3.26	1.80
	(0.94)	(0.84)	(1.08)	(1.34)
Exports	1.88	1.82	0.45	1.37
	(0.96)	(1.02)	(1.05)	(0.93)
INVESTMENT TAX CREDIT				
Imports	3.76	3.89	3.41	0.20
	(1.46)	(1.36)	(1.97)	(1.20)
Exports	2.94	2.86	1.25	0.79
	(1.18)	(1.24)	(1.50)	(0.98)
JORGENSONIAN TAX TERM				
Imports	1.64	1.68	0.50	-0.97
	(1.11)	(1.15)	(1.23)	(0.71)
Exports	1.84	1.79	0.85	0.52
	(0.66)	(0.71)	(0.47)	(0.38)

Notes. The dependent variable is the natural logarithm of equipment imports or equipment exports as indicated. The coefficients are for the measure of the subsidy (in levels). The equipment types included in these results are: metalworking machinery; electrical transmission and distribution; mining and oilfield machinery. Driscoll-Kraay standard errors are shown in parentheses.

CHAPTER III

INVESTMENT TIMING IN FIXED-COST MODELS

3.1. INTRODUCTION

Most investment models imply that firms are willing to sharply change the timing of their investment decisions to take advantage of small predictable movements in the after-tax purchase price of new capital. In many settings, the intertemporal elasticity of substitution for investment is nearly infinite. This extreme sensitivity to price changes implies that, in equilibrium, there cannot be substantial predictable changes in investment prices. If prices were expected to fall, firms would simply delay their investment to take advantage of the lower prices. A high intertemporal elasticity of substitution for investment also implies that the distribution of capital holdings across firms will not affect equilibrium investment. If many firms with outdated capital want to invest, investment demand will be high and there will be upward pressure on prices. Because of the near-infinite elasticity of investment demand, any price increase will sharply reduce equilibrium investment. Firms that would otherwise adjust, instead delay their investment to avoid the temporarily high prices. Thus, because of the extreme price-sensitivity of investment timing, variations in the distribution of capital holdings across firms play no role in governing the equilibrium.

In this study, we develop an equilibrium model of investment in which firms face explicit costs to adjusting the *timing* of their investment purchases. We do not explicitly consider the source of these costs. The investment retiming costs could reflect planning costs, costs associated with predictable rapid depreciation, complementarity with other predetermined factors of production, or behavioral costs associated with constantly tracking investment prices. If these retiming costs are sufficiently high, firms will not retime their investment to take advantage of predictable changes in investment prices and thus, forecastable price changes may exist in equilibrium.

In the model, firms also face fixed investment adjustment costs. As a consequence, firms make infrequent, large adjustments to their capital stocks. Not all firms adjust their capital at the same time and thus not all firms have the same capital stocks. At any point in time, some firms that have adjusted recently have new capital, while other firms that have not adjusted for some time have relatively outdated capital. The distribution of capital holdings across firms evolves over time as the market for investment goods experiences shocks to supply and demand. As discussed above, if there are no costs to retiming investment, this distribution has no impact on the equilibrium, as in House (2014), Thomas (2002), Khan and Thomas (2004, 2008). If, on the other hand, there are costs to retiming investment, then the distribution may influence the equilibrium price and quantity of investment. If investment demand is unusually high because many firms have outdated capital, then investment prices can be high without causing many firms to adjust the timing of their capital investments.

The investment model we present nests two special cases. If there are no costs to retiming investment, the model collapses to a standard investment model with fixed adjustment costs. Earlier literature shows that at the aggregate level, equilibrium investment models with fixed costs behave virtually the same as standard neoclassical investment models—see among others, House (2014), Thomas (2002), Khan and Thomas (2004, 2008). If investment retiming costs approach infinity, the model reduces to an (s,S) adjustment model of the sort analyzed in the literature on lumpy adjustment. If there is an intermediate level of investment retiming costs, equilibrium price and quantity movements will reflect an elasticity of investment demand which is bounded away from zero and infinity.

The potential implications of lumpy-investment behavior at the micro-level have been a focus of much of the recent research on investment. Many of the recent contributions to this literature have focused on numerical solutions to particular calibrated models. These models largely consist of a fixed-adjustment-cost framework built on an underlying neoclassical substructure. For the most part these numerical explorations suggest that the influence of lumpy investment on aggregate investment dynamics is negligible. Put differently, in the numerical trials one would get essentially the same aggregate predictions from a standard neoclassical investment model as from the more elaborate investment models with micro-level heterogeneity and infrequent lumpy adjustment. These studies have led some researchers to conclude that lumpy adjustment simply does not matter for understanding aggregate investment.

This study draws attention to an underappreciated property of the neoclassical model on which the lumpy-investment models are built. Namely, in neoclassical models, firms have extremely high intertemporal price elasticities of investment demand. Thus, the investment dynamics associated with micro-heterogeneity and infrequent investment may be suppressed because the firms are simply too eager to change the timing of their investments in response to predictable price movements. In a sense, the existing models with fixed costs are examining a joint null in which there is both lumpy investment and the firms are extraordinarily price sensitive. In this study we modify the lumpy-investment model to temper the firms' incentives to retime investment. We show that in our modified setting, distributional dynamics associated with micro-level heterogeneity do emerge as a quantitatively important state variable and there are clear differences in the behavior of the lumpy-investment model and the neoclassical model.

The retiming costs we study in this study are conceptually similar to the "gestation lags" in Millar (2005). In his paper, Millar argued that typical adjustment cost models fail to stand the test of Tobin's Q regressions precisely because they abstract from planning and setup time required before new investment can become productive capital. If such lags exist in the data, future Q rather than current Q determines current investment. Millar found that reduced-form estimates using aggregate investment and Tobin's Q data are consistent with a simple investment model with gestation lags. Unlike Millar, we use our investment model with retiming costs to simulate the behavior of investment in response to various shocks, and describe the implications of planning frictions for fiscal stimulus.

The remainder of the chapter is set out as follows. Section 3.2 describes the model. Section 3.3 presents numerical experiments and discusses their implications. Section 3.4 concludes.

3.2. QUANTITATIVE MODEL

We consider a partial equilibrium investment supply and demand model. The model is based loosely on the framework in Caplin and Leahy (2004, 2006). In addition to standard fixed costs, firms in this model also face an additional of friction, a cost to changing the timing of their investment decisions. We then use the model to illustrate the behavior of the system under different parameterizations and we analyze the implications of retiming costs for investment tax policy.

The supply side of the model consists of an isoelastic supply curve which experiences shocks over time. The demand side consists of a fixed population of firms that infrequently update their capital stock due to a fixed cost. The firms choose when to update based on the current after-tax price of capital goods and the realization of a productivity shock. The firms also pay a cost to deviating from their steady state adjustment pattern. If this cost is zero, then the model is identical to the state dependent (s,S) model in Thomas (2002), Gourio and Kashyap (2007) and House (2014). In this case, firms are extremely willing to change the timing of their investment decisions to take advantage of predictable movements in after-tax prices of capital goods. This high elasticity of demand dictates that after-tax prices should be close to a random walk. In contrast, with substantial costs of retiming investment, firms do not react as sharply to anticipated changes in capital goods prices. As a result, the after-tax price of capital may exhibit some predictability. As the costs of retiming investment approach infinity, the model collapses to the fixed (s,S) model in Caballero and Engel (1999) and Caplin and Leahy (2004). In this study, we focus on describing the implications of the model for investment dynamics and tax policies that stimulate investment.

The quantitative model is cast in discrete time with time intervals of size Δ. Firms discount the future at the annual rate r and capital depreciates at the annual rate δ. Given the time interval Δ, the discount factor is $\beta = e^{-r\Delta}$ and the depreciation rate satisfies $(1-\delta) = e^{-\delta\Delta}$.

Flow profits are $\Delta A Z_t k_t^{\alpha}$, where k_t is capital at the firm-level, $0 < \alpha < 1$, A is a scaling constant, and Z_t is a productivity shock to the value-added production function; we assume that this shock is common to all firms. When a firm adjusts its capital stock it incurs two costs.

The first cost is a stochastic adjustment cost $\varepsilon_{i,t} > 0$, which is incurred only when firm-level investment is non-zero. To model the adjustment cost, we follow Thomas (2002) and assume that firms draw idiosyncratic costs of adjustment each period. Thus, instead of facing a known fixed cost F each period, firm i faces the stochastic cost $\varepsilon_{i,t}$, where $\varepsilon_{i,t} \sim \Psi(\varepsilon)$, $E\left[\varepsilon_{i,t}\right] = F$, $\varepsilon_{i,t} \geq 0$ and $\varepsilon_{i,t}$ is *i.i.d.* across time periods and across firms. The stochastic adjustment cost implies that firm-level investment is lumpy, but aggregate investment is relatively smooth. For the numerical solution, we assume that $\varepsilon_{i,t}$ is a mixture of a log-normal random variable and a wide uniform.[14]

The second cost is a cost per unit of investment $p_t(1-\iota_t)\cdot\left[k_t^* - k_{j,t}\right]$, where p_t is the pre-tax price of new investment, ι_t is an investment tax subsidy at time *t*, k_t^* is the reset capital stock chosen by the firm and $k_{j,t}$ is the current capital stock. The index *j* denotes the age or vintage of the firm's capital stock.

If the firm does not adjust, its capital stock depreciates according to $k_{j+1,t+1} = (1-\delta)k_{j,t}$. For tractability, we assume that firms may not delay updating their capital stock longer than *J* periods. As a result, there are *J* possible capital vintages $j = 1,\ldots,J$. The oldest possible vintage is vintage *J*. In practice, we set *J* to be sufficiently large such that this limit is not binding for any reasonable set of parameter values.

The central feature of the model is a third friction, a *retiming cost* incurred when the firm changes its adjustment policy relative to its normal (steady-state) adjustment rule. We describe these retiming costs in detail after we introduce additional concepts below.

Steady State. In the steady state, there are no productivity shocks and no investment supply shocks, and capital goods prices are constant. As a result, firms invest at the same regular time interval and always reset their capital stocks to the same level. Let *T* denote the steady state adjustment horizon (in years) and let k^* be the steady state reset level of capital. This lumpy firm-level investment pattern arises from the stochastic costs incurred when firms adjust their capital stock. Absent adjustment costs, firms would invest every period and maintain a constant capital stock of $k = 1$.[15]

Investment Adjustment. In each time period, the firm decides whether to adjust its capital stock and pay the adjustment cost $\varepsilon_{i,t}$. The stochastic nature of the cost implies that some firms adjust even if they are far from the steady-state adjustment horizon *T*. Consider a firm with capital stock $k_{j,t}$ of vintage *j* at time *t*. We define $V_{j,t}^{adj}$ as the value of adjusting the capital stock for this firm,

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[14] The numerical method was developed jointly by Robert King, Julia Thomas and Marcelo Veracierto. For examples see Dotsey, King and Wohlman (1999), Thomas (2002), Veracierto (2002), King and Thomas (2006) and Gourio and Kashyap (2007).

[15] We normalize the steady state price *p* and the steady state level of productivity *Z* to 1. We set the scaling parameter as $A = (r+\delta)\cdot\alpha^{-1}$.

and $V_{j,t}^{non}$ the value of not adjusting. As the firm chooses optimally between these two options, we can write the firm's value as

$$V_{j,t}\left(\varepsilon_{i,t}\right) = \max\left\{V_{j,t}^{adj} - \varepsilon_{i,t}, V_{j,t}^{non}\right\}. \tag{1}$$

Prior to the realization of the adjustment cost $\varepsilon_{i,t}$, the expected value of having capital stock of vintage *j* at time *t* is

$$v_{j,t} = \int_0^\infty V_{j,t}\left(\varepsilon\right) d\Psi\left(\varepsilon\right) \tag{2}$$

The value of not adjusting is then

$$V_{j,t}^{non} = \Delta \cdot AZ_t k_{j,t}{}^{\alpha} + \beta E_t\left[v_{j+1,t+1}\right], \tag{3}$$

in other words the firm derives flow profits from its current vintage *j* capital stock $k_{j,t} = (1-\delta)^j k_{t-j}^*$, and receives the expected continuation value of having capital stock $k_{j+1,t+1} = (1-\delta)^{j+1} k_{t-j}^*$ of vintage *j*+1 in the following time period.

The value of adjusting (once the firm has paid the stochastic adjustment cost) is

$$V_{j,t}^{adj} = \max_{k_t^*}\left\{\Delta \cdot AZ_t\left(k_t^*\right)^{\alpha} + \beta E_t\left[v_{1,t+1}\right] - p_t\left(1-\iota_t\right)k_t^*\right\} + p_t\left(1-\iota_t\right)k_{j,t}. \tag{4}$$

In this case, the firm pays the per unit cost associated with adjusting its capital stock from its current level $k_{j,t}$ to the optimal reset level k_t^* and receives the continuation value of having capital stock $k_{1,t+1} = (1-\delta)k_t^*$ of vintage one in the following time period. Firms with capital vintage *J* must adjust and they pay *F* with certainty. The value of having capital of vintage *J* is thus

$$v_{J,t} = V_{J,t} = V_{J,t}^{adj} - F. \tag{5}$$

The values $v_{j,t}$ and $V_{j,t}$ are functions of the reset capital stock at time $t-j$, k_{t-j}^*. The optimal reset capital stock is not vintage specific, so every firm that adjusts its capital stock at time *t* makes the same choice k_t^*. The optimal capital stock satisfies the first order condition

$$\Delta \cdot \alpha AZ_t\left(k_t^*\right)^{\alpha-1} + \beta E_t\left[\frac{\partial v_{1,t+1}}{\partial k_t^*}\right] = p_t\left(1-\iota_t\right), \tag{6}$$

which simply says that the shadow value of an additional unit of capital at time *t* must be equal to its after-tax marginal cost.

Equilibrium Adjustment Policy. Firms follow a one-sided (s,S) investment rule characterized by a cutoff adjustment cost, denoted $\hat{\varepsilon}_{j,t}$. If the realization of the adjustment cost is below the cutoff, the firm adjusts its capital stock and pays the adjustment cost. On the other hand, if the realization of the cost is above the cutoff, the firm does not adjust. The cutoff is a function of the firm's capital stock and of aggregate state variables, including the productivity shock and investment supply shock. Together with the distribution of the shocks, the cutoff determines the fraction of firms that adjust in each period.

Investment Retiming Costs. In this study, we introduce a new type of friction that has not been previously studied in the investment literature. More specifically, firms incur a cost when their adjustment policy differs from their steady state adjustment pattern. This investment *retiming cost* captures time to plan and build required before the actual investment occurs. If firms set their plans before observed investment expenditures, they are less willing to change their planned investment in response to shocks. An alternative interpretation is that monitoring markets to learn the current values of state variables entails cognitive costs. We model this planning friction by assuming that firms incur costs whenever they alter the cutoffs $\hat{\varepsilon}_{j,t}$ relative to their steady state values $\hat{\varepsilon}_{j}$ .Mechanically, if a firm wants to adjust early or late, it must change the cutoff shock $\hat{\varepsilon}_{j,t}$ that characterizes its (s,S) investment rule. We assume retiming costs take the form

$$\frac{\zeta}{2}\left(\hat{\varepsilon}_{j,t}-\hat{\varepsilon}_{j}\right)^{2}, \tag{7}$$

where the parameter ζ determines the magnitude of the costs. The firm incurs retiming costs even if it does not adjust its capital stock.

To understand how retiming costs affect the firm's decision, consider the expected value of a firm with capital of vintage *j* at time *t* prior to the realization of the stochastic adjustment cost. Specifically, the value $v_{j,t}$ satisfies

$$v_{j,t}=\max_{\hat{\varepsilon}_{j,t}}\left\{\int_{0}^{\hat{\varepsilon}_{j,t}}\left[V_{j,t}^{adj}-\varepsilon\right]d\Psi\left(\varepsilon\right)+\int_{\hat{\varepsilon}_{j,t}}^{\infty}V_{j,t}^{non}d\Psi\left(\varepsilon\right)-\frac{\zeta}{2}\left(\hat{\varepsilon}_{j,t}-\hat{\varepsilon}_{j}\right)^{2}\right\}. \tag{8}$$

If $\zeta=0$ then there are no costs to deviating from the steady state adjustment profile. In this case, the optimal cutoff adjustment cost is simply $\hat{\varepsilon}_{j,t}=V_{j,t}^{adj}-V_{j,t}^{non}$. This is exactly the case considered by Thomas (2002). At the other extreme, if $\zeta=\infty$, then firms never deviate from their steady state adjustment policy, so $\hat{\varepsilon}_{j,t} = \hat{\varepsilon}_j$. For values of the retiming cost parameter ζ between zero and infinity, the optimal cutoff is a weighted average of the two extreme cases:

$$\hat{\varepsilon}_{j,t} = \left(1 - \frac{\zeta}{1+\zeta}\right)\left(V_{j,t}^{adj} - V_{j,t}^{non}\right) + \frac{\zeta}{1+\zeta}\hat{\varepsilon}_j. \tag{9}$$

When firms face retiming costs, they are less willing to deviate from their steady state adjustment patterns in response to changes in capital goods prices and investment subsidies. This effect tempers the high elasticity of intertemporal substitution typical of conventional fixed-cost and neoclassical investment models. In Section 3.3, we conduct a series of numerical experiments to highlight the effects of investment retiming costs on aggregate investment under an investment supply shock, a temporary investment subsidy, and an out-of-state distribution of firms over capital vintages. We show that retiming costs generate specific patterns in aggregate investment and have sharp implications for investment tax policy.

To interpret the retiming cost parameter, we express ζ in terms of the minimum benefit *b* the firm requires to be willing to bear the costs associated with changing the adjustment cutoff by *F*, the mean of the fixed cost distribution. In absolute terms, the costs to the firm associated with this change are $\left(\zeta/2\right)F^2$, so the minimum required benefit, as a fraction of firm value, is

$$b = \frac{\zeta}{2}\left(\frac{F^2}{V}\right) \tag{10}$$

Aggregation. Aggregate investment I_t is the sum of firm-level investment. If a firm with capital stock *j* chooses to adjust, its investment is $k_t^* - k_{t-j}^*\left(1-\delta\right)^j$. Therefore, aggregate investment is

$$I_t = \sum_{j=1}^{J} \Psi\left(\hat{\varepsilon}_{j,t}\right) f_{j,t}\left[k_t^* - k_{t-j}^*\left(1-\delta\right)^j\right], \tag{11}$$

where $f_{j,t}$ is the fraction of firms with capital stock of vintage *j* at time *t*. The distribution of firms over capital vintages evolves according to

$$f_{j,t} = f_{j-1,t-1}\left[1 - \Psi\left(\hat{\varepsilon}_{j-1,t-1}\right)\right] \tag{12}$$

for $1 \le j \le J$. For $j = 0$, we have

$$f_{0,t} = \sum_{j=1}^{J} \Psi\left(\hat{\varepsilon}_{j,t}\right) f_{j,t}\,. \tag{13}$$

Investment Supply. The supply of investment is governed by an isoelastic supply curve

$$p_t = X_t \cdot \left(I_t / \overline{I}\right)^{\frac{1}{\xi}}, \tag{14}$$

where ξ is the elasticity of investment supply, $\overline{I}$ is steady state investment and X_t is a cost shock.

Shocks. The investment supply shock has a permanent component, and a transitory component, which is assumed to be AR(2):

$$\begin{aligned} x_t &= x_t^{perm} + x_t^{trans}, \\ x_t^{perm} &= x_{t-1}^{perm} + \varepsilon_t^{perm}, \\ x_t^{trans} &= \rho_1 x_{t-1}^{trans} + \rho_2 x_{t-2}^{trans} + \varepsilon_t^{trans}. \end{aligned} \tag{15}$$

The productivity shock is a random walk with drift:

$$z_t = z_{t-1} + \varepsilon_t^z. \tag{16}$$

In addition to the supply and demand shocks, the model also features investment subsidy shocks ι_t, which are assumed to be temporary and unanticipated.

3.3. NUMERICAL EXPERIMENTS

We illustrate the effects of investment retiming costs by simulating the behavior of the model in response to three types of shocks. We consider an investment supply shock, an investment tax subsidy like the one in Adda and Cooper (2000), and the equilibrium associated with an initial out-of-steady-state distribution of firms over capital holdings. We consider five different values of the investment retiming costs. As a fraction of total firm value, these values are 0, 0.05 percent, 0.1 percent, 0.5 percent, and one percent. The higher values exceed the range we would expect to find in the data, however including these values is useful as an upper bound on the magnitude of the effects our model is able to generate using reasonable parameter values.

Calibration and Solution. To illustrate the behavior of the model, we calibrate it with a set of plausible initial parameter values. We then catalogue the model's reaction to a variety of shocks. We set the returns to scale parameter α to 0.9 and the investment supply elasticity ξ to 5, which is close to the estimates in House and Shapiro (2008). The baseline depreciation rate δ is 10 percent annually. The baseline discount rate *r* is 2 percent annually. A 10 percent depreciation rate is similar to the depreciation rates of many types of equipment. Cooper *et al*. (1999) find that each year, roughly one out of every five manufacturing plants experiences an "investment spike," which they define as an increase in plant-level capital of at least 20 percent.[16] The autoregressive parameters of the investment supply shocks, ρ_1 and ρ_2 are set to 1.6 and -0.65... The baseline parameter values are summarized in Table 3.1.

The equations governing the model are linearized around a non-stochastic steady state and a rational expectations equilibrium is computed with the Anderson-Moore (AIM) algorithm. The remaining details of the numerical procedure are presented in Appendix 3.A.

Supply Shock. We consider a positive temporary innovation of one percent to the investment supply shock X_t in equation (14). This shock temporarily increases the price of capital goods, but it does not have substantial consequences for the long-run value of investment. The literature on investment supply shocks, notably Justiniani, Primiceri and Tambalotti (2011) and Schmitt-Grohe and Uribe (2012) interprets temporary investment supply shocks as distortions to the marginal efficiency of investment, for example disturbances to the financial sector to transform savings into future capital input, and account for most of the business cycle variation in the models considered by these authors.

Figure 3.1 shows the system's reaction to the temporary supply shock. The top panel shows the supply shock variable itself, which features a hump-shaped response to the innovation because it is modeled as an AR(2) process. The middle panel shows the response of aggregate investment and the lower panel shows the response of the price level under the five adjustment costs parameters listed above.

In the absence of retiming costs (blue line), aggregate investment sharply drops as firms delay adjusting their capital stocks. In the first period, the one percent investment supply shock causes investment to fall by almost 5 percent and the equilibrium price of new capital goods changes only slightly in response to the shock. This response illustrates the high intertemporal elasticity of investment in conventional fixed-cost models. If the intertemporal elasticity of investment demand were infinite, then the price would not change at all and there would be exactly a 5 percent change in the quantity of investment (recall that our calibration of the supply elasticity

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[16] Cooper *et al*. [1999] base their findings on data from the Longitudinal Research Database (LRD), which includes most U.S. manufacturing plants.

was 5.0). The actual elasticity is not infinite but it is so large that the actual equilibrium outcome is close to this limiting case.

In contrast, investment retiming costs reduce the number of firms who delay adjustment in response to the supply shock. The drop in aggregate investment is less pronounced as retiming costs increase, while prices substantially increase. For sufficiently high investment retiming costs, aggregate investment increases above its steady state level in the first period as firms anticipate high capital goods princes in future periods.

Lastly, investment retiming costs also induce predictable changes in the prices of investment goods in the long run. The response of the system to the supply shock displays a modest, but clear echo effect at the baseline capital adjustment horizon of 10 years. The echo reflects a fraction of firms who had delayed their investment when the shock hit the system. These firms remain on a delayed adjustment schedule, reducing investment demand and causing a drop in investment prices, while investment retiming costs prevent other firms from adjusting the pattern of their investment decisions to take advantage of temporarily low prices. In contrast, without investment retiming costs, the near infinite elasticity of intertemporal substitution causes firms to arbitrage away predictable movements in prices and thus eliminates the echo effects.

If we interpret temporary investment supply shocks as disturbances to the financial sector, these results indicate that retiming costs play an important role in limiting the ability of these disturbances to drive business cycle fluctuations. In the model, even moderate retiming costs of 0.05 percent reduce the short-run fall in aggregate investment by almost half. To the extent that retiming costs vary by industry, evidence of retiming costs in the data would help policy makers identify which sectors of the economy are more resilient to temporary investment supply disruptions.

Investment Tax Subsidy. We consider a sequence of back-to-back temporary investment tax subsidies of 10 percent. This experiment is a stylized version of the policy variations studied by Adda and Cooper (2000). Adda and Cooper analyze a French auto scrapping subsidy which paid individuals to scrap their old cars and purchase new ones. They focus on the evolution of the cross-sectional distribution of car vintages in response to the policy and argue that the resulting distributional dynamics would alter the outcome of the tax policy.

The top panel of Figure 3.2 shows the two temporary 10 percent subsidies, each lasting for one year, timed so that the second subsidy arrives one year after the end of the first one. We assume each subsidy is unanticipated. The middle panel shows the response of aggregate investment and the lower panel shows the response of investment prices. In the conventional case of no retiming costs, both aggregate investment and capital goods prices rise sharply. The ten percent incentive causes investment to increase by roughly 50 percent while the incentive is in effect. The second subsidy is almost equally effective in stimulating investment as the first round. While aggregate investment slightly falls after each subsidy expires, the effect is barely noticeable.

Investment retiming costs temper the effects of the subsidies. Notice that the response to the second subsidy is markedly less pronounced than the response to the first round in the presence of the retiming costs. Many firms who have just adjusted their capital stocks during the first subsidy are not willing to invest again when the second subsidy is offered because two back-to-back investment episodes would represent a large, costly deviation from their steady-state investment timing. This is exactly the type of effect that Adda and Cooper (2000) anticipated, though our result relies directly on the investment retiming friction.

A striking implication of retiming costs is that investment *falls* immediately after the subsidy expires. For sufficiently high values of the retiming cost parameter, the increase in investment during the subsidy is almost entirely offset by the investment decline following the expiration of the subsidy. The subsidy causes some firms to invest while it is in effect. These firms will then be unwilling to invest again after the subsidy expires because such investment would happen too soon relative to the firms' steady state adjustment horizon.

The drop in investment immediately after a temporary subsidy is a feature of many partial equilibrium investment models. Indeed, it is also present in our specification without retiming costs, although in that case it is extremely attenuated. Cohen and Cummins (2006) exploited the "pothole" effect to examine the effectiveness of the 2002 and 2003 "bonus depreciation" episode. Businesses were temporarily allowed to deduct an additional 30 percent, later expanded to 50 percent, of the cost of qualifying investment in the first year. Cohen and Cummins used a differences-in-differences identification strategy, which in addition to the pothole considers cross-sectional variation in the useful lives of equipment, and found only limited evidence that bonus depreciation affected spending. Their conclusions are consistent with the adjustment cost specifications in our model, which produce more attenuated investment dynamics following the temporary subsidy.

Mian and Sufi (2012) drew similar conclusions in their study of a related form of fiscal stimulus, the 2009 Cars Allowance Rebate System (CARS) program, also known as Cash for Clunkers. The program offered temporary incentives for households to trade in their older vehicles for new fuel-efficient cars. Using variation in the distribution of clunkers across cities before the policy, Mian and Sufi showed that the program succeeded only in shifting the timing of car purchases. Although households increased purchases contemporaneously with the subsidy, this increase was followed by an offsetting decline after the incentive expired.

Lastly, we note that as in the case of the investment supply shock, high investment adjustment costs induce echo effects in investment and capital goods prices at the 10-year steady-state adjustment horizon.

An Out-of-Steady State Initial Distribution. In our third experiment, we consider the equilibrium path of investment and prices when the system begins with an out-of-steady-state distribution.[17] The specific example considered is a distribution with an unusually large number of firms with capital between 4 and 6 years old. The distribution is depicted in the top panel of Figure 3.3. The steady state distribution (dark line) is included for comparison. Because the out-of-steady-state distribution has twice as many firms with five-year-old capital, one would anticipate that, in roughly 5 years, prices and investment would rise dramatically as these firms approach the adjustment trigger. If firms could not change the timing of investment at all, then aggregate investment would rise by 100 percent in roughly 5 years.

Figure 3.3 presents the equilibrium path of investment given the initial distribution shown in the top panel. The middle panel shows the reaction of aggregate investment. Without investment retiming costs, or with sufficiently low investment retiming costs, the distorted initial distribution has little bearing on the equilibrium. The conventional supply and demand prediction that prices and investment should rise as the mass of firms adjusts is present, but is quantitatively negligible relative to the magnitude of the distributional change. While there are twice as many firms with five-year-old capital, instead of an increase of 100 percent, investment rises by less of one percent.

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[17] This experiment is inspired by Gourio and Kashyap (2007). House (2014) also considers the Gourio and Kashyap experiment in his analysis of long-lived investment.

Investment retiming costs amplify fluctuations in aggregate investment and prices resulting from the out-of-steady-state distribution. If investment retiming costs are roughly 5 percent then aggregate investment rises by more than 10 percent when the mass of firms with five-year-old initial capital reach their adjustment trigger. The magnitude of the effect increases sharply with retiming costs. If retiming costs equal 10 percent, aggregate investment rises by more than 15 percent. As in the other two numerical experiments, there is a noticeable echo effect at the 10-year adjustment horizon.

Summary. Several clear patterns emerge from the numerical experiments presented above. First, in the presence of investment retiming costs, investment is less sensitive to shocks to the supply of capital goods. Second, the effectiveness of temporary investment subsidies is reduced. Lastly, with retiming costs, there can be predictable variations in after-tax investment prices. Without retiming costs, anticipated changes in after-tax prices would cause a large number of firms to alter the timing of their investment decisions, arbitraging away such price changes. The retiming costs limit the extent to which this arbitrage occurs. Third, with retiming costs, variations in the distribution of capital holdings across firms have quantitatively significant influences on economic activity. Finally, both investment and prices display noticeable echo effects.

If there are costs of adjusting the timing of investment then we would expect to observe the same patterns described above in the actual investment data. In particular, we would expect that changes in capital goods prices would be somewhat predictable and we would expect to find a relatively large autocovariance occurring at the typical investment horizon. Estimates of actual autocovariance functions for real investment spending do in fact suggest that autocovariances are particularly high for some investment types at horizons of roughly 5 years. In addition, actual real relative prices for investment goods are moderately forecastable at horizons of 1-2 years suggesting that the elasticity of investment demand is not as high as neoclassical investment models would indicate. While such statistics would be expected in the presence of investment timing adjustment costs, they are not direct evidence of the timing adjustment costs themselves and so we do not pursue these empirical tests further in this study. Appendix 3.A presents a short discussion of these empirical patterns as they relate to investment timing adjustment costs.

Empirical evidence. Empirical evidence for the retiming costs considered in this study can in theory be obtained by estimating the structural parameters of the model, including the adjustment cost parameter b. In the presence of retiming costs, we would expect to find the same patterns described above in the actual investment data. For plausible values of the retiming costs, however, the magnitude of the effects would be subtle, which poses challenges for identification. Indeed, we find only limited evidence that firms face costs when they retime their investment decisions. We describe our estimation approach, results, and identification challenges in Appendix 3.A.

In Figure 3.4, we present visual evidence that retiming costs generate realistic investment autocovariances. that would otherwise not emerge in the fixed costs model. We compare the autocovariance function for fabricated metal[18] with autocovariances from the model with different retiming cost parameters. The simulations use an adjustment horizon $T = 5$ years and the depreciation rate of fabricated metals $\delta = 0.09$ annually. The other parameters are the baseline parameters in Table 3.1. The figure shows that without retiming costs, the model produces a smoothly declining autocovariance series. As retiming costs increase, the series becomes hum-shaped and is close to the curve obtained from the actual data for $b = 0.01$ and $b = 0.05$. Although for other types of capital goods the simulated patterns are not as close to the data as for fabricated metals, this suggests that a different identification strategy may be able to take advantage of these patterns and estimate adjustment costs in the data. We leave this exercise for future research.

3.4. CONCLUSION

We analyze a model of lumpy investment in which firms face both standard adjustment costs and investment retiming frictions that temper firms' intertemporal elasticity of substitution. We use the model to simulate the response of investment and capital goods prices to an investment supply shock, a temporary investment subsidy, and we explore the effects of an out-of-steady state distribution of firms over capital vintages for aggregate investment. We find that in the presence of retiming costs, the implications of the model are substantially different than those of conventional fixed-costs investment model.

With retiming costs, micro-level heterogeneity in the distribution of capital holdings across firms affects the dynamics of aggregate investment quantities and prices. Retiming costs induce predictable movements in the prices of capital goods, as firms are less willing to deviate from their steady-state investment patterns, thus do not arbitrage away such movements. Importantly, if

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[18] The shape of the autocovariance function is not an artifact of the HP filter used to detrend the data. In Figure 3.5, we show that the shape of the autocovariance series is preserved for reasonable smoothing parameters.

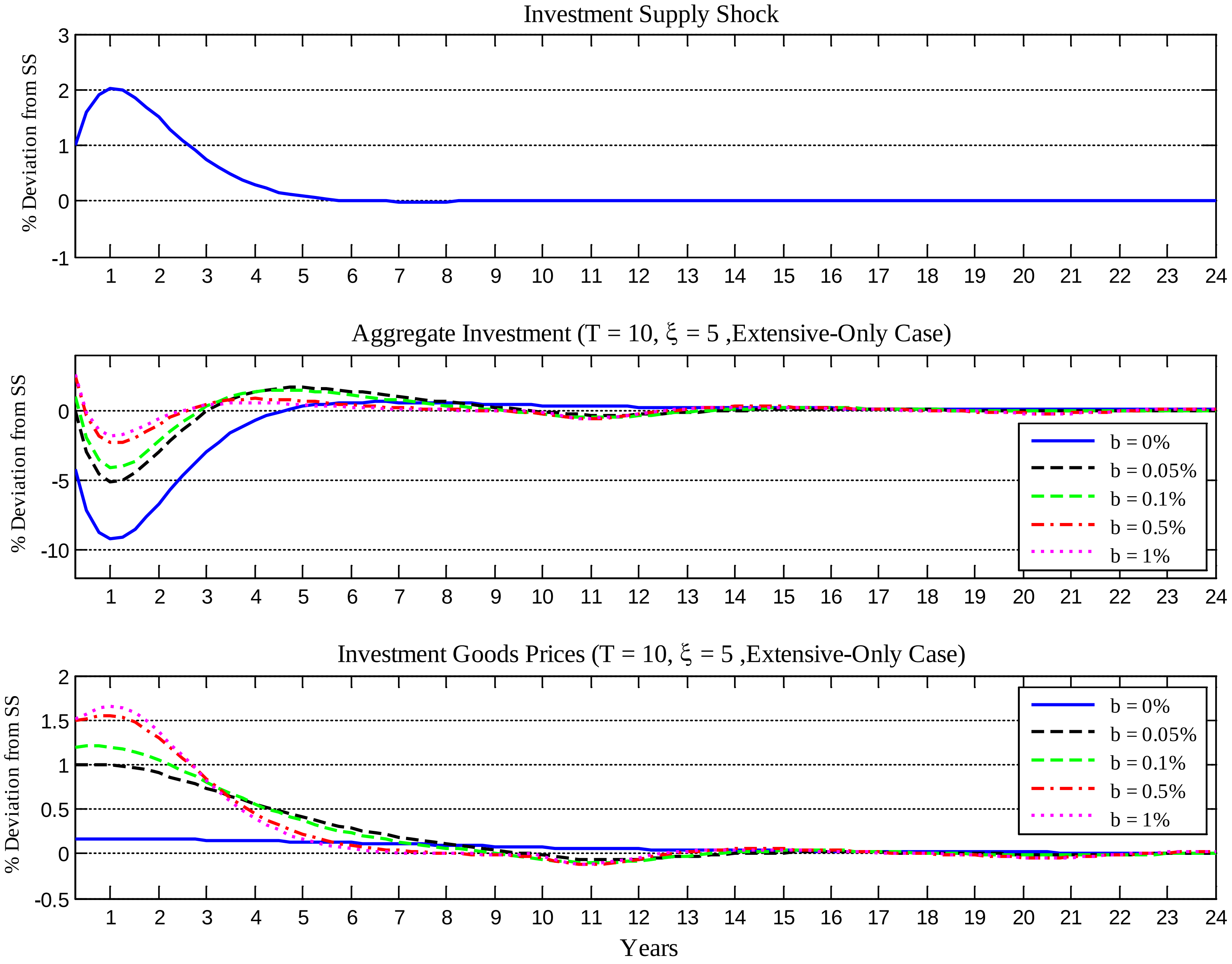
retiming costs are high, investment is less responsive to temporary investment supply shocks that drive business cycle fluctuations.

The model offers sharp predictions for the effectiveness of temporary investment stimulus. Without retiming costs, temporary subsidies strongly increase investment contemporaneously, while the decline in investment after the subsidies expire is negligible. In contrast, if firms do face retiming costs, they are less willing to increase investment while subsidies are in effect. Furthermore, the temporary increase in investment is followed by a substantial, potentially offsetting decline once the subsidy is no longer offered. In this case, the dynamic effects limit the overall effectiveness of the subsidy, which succeeds only in shifting the timing of investment.

TABLE 3.1. RETIMING COSTS MODEL: BASELINE PARAMETERS

Parameter	Baseline Value
Discount rate, annual (r)	0.02
Depreciation rate, annual (δ)	0.10
Curvature of profit function (α)	0.90
Steady state adjustment horizon (T) (years)	10.00
Elasticity of aggregate investment supply (ξ)	5.00
First autoregressive root of supply shock (ρ_1)	1.60
First autoregressive root of supply shock (ρ_2)	-0.65

FIGURE 3.1. EQUILIBRIUM RESPONSE TO AN INVESTMENT SUPPLY SHOCK



Investment Supply Shock

Aggregate Investment (T = 10, ξ = 5 ,Extensive-Only Case)

Investment Goods Prices (T = 10, ξ = 5 ,Extensive-Only Case)

FIGURE 3.2. EQUILIBRIUM RESPONSE TO A SEQUENCE OF TEMPORARY ITC SHOCKS

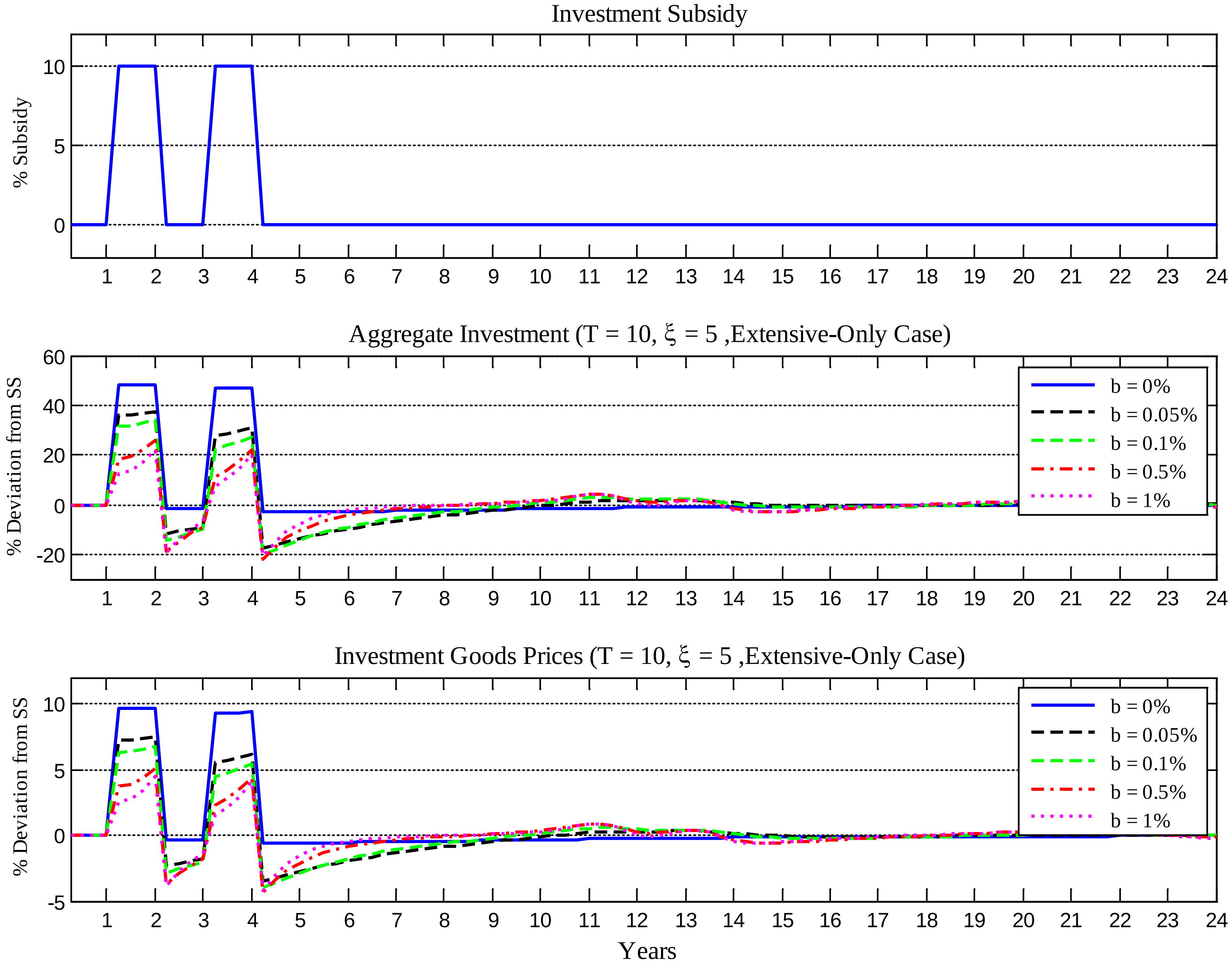
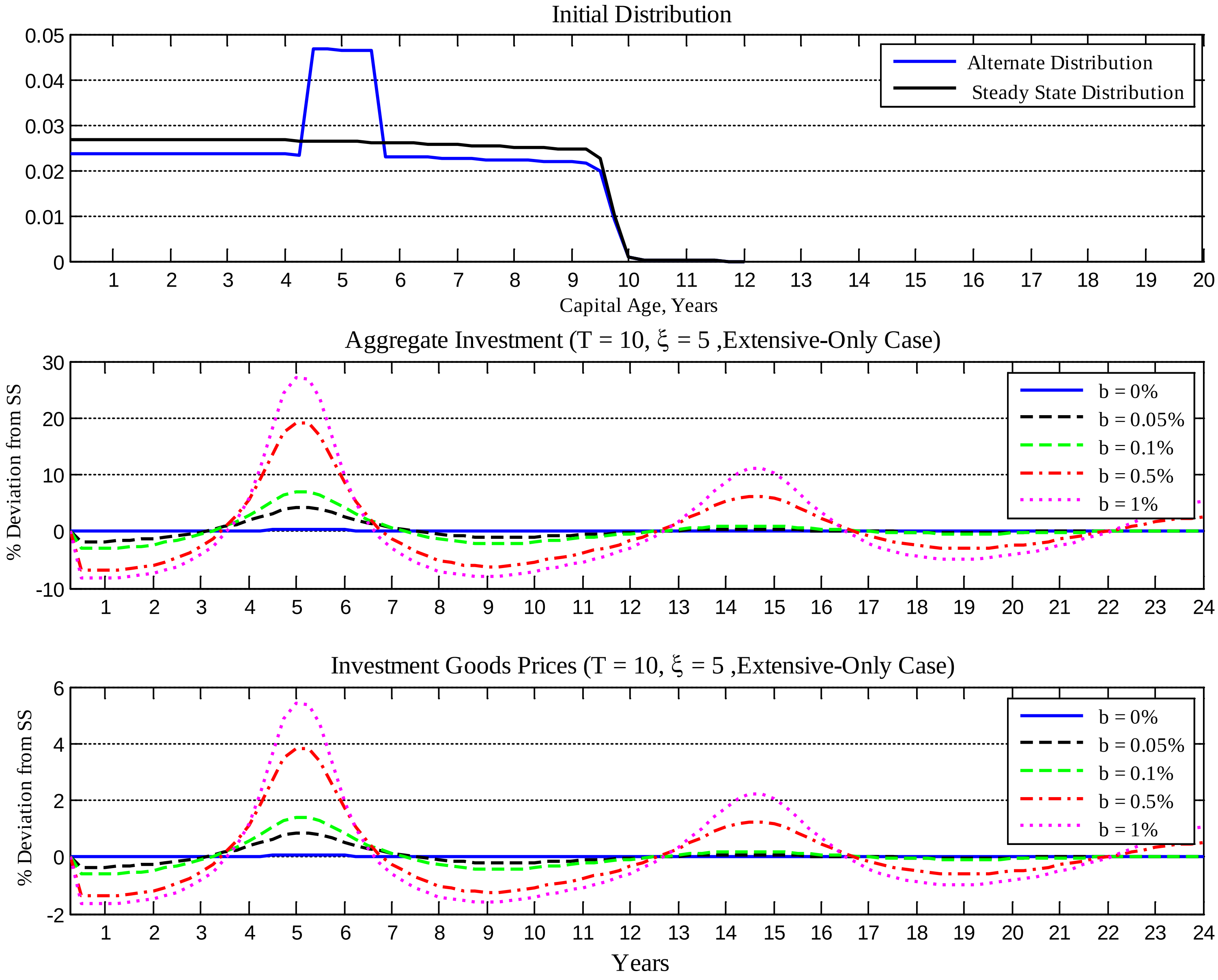


FIGURE 3.3. AN OUT-OF-STEADY-STATE DISTRIBUTION

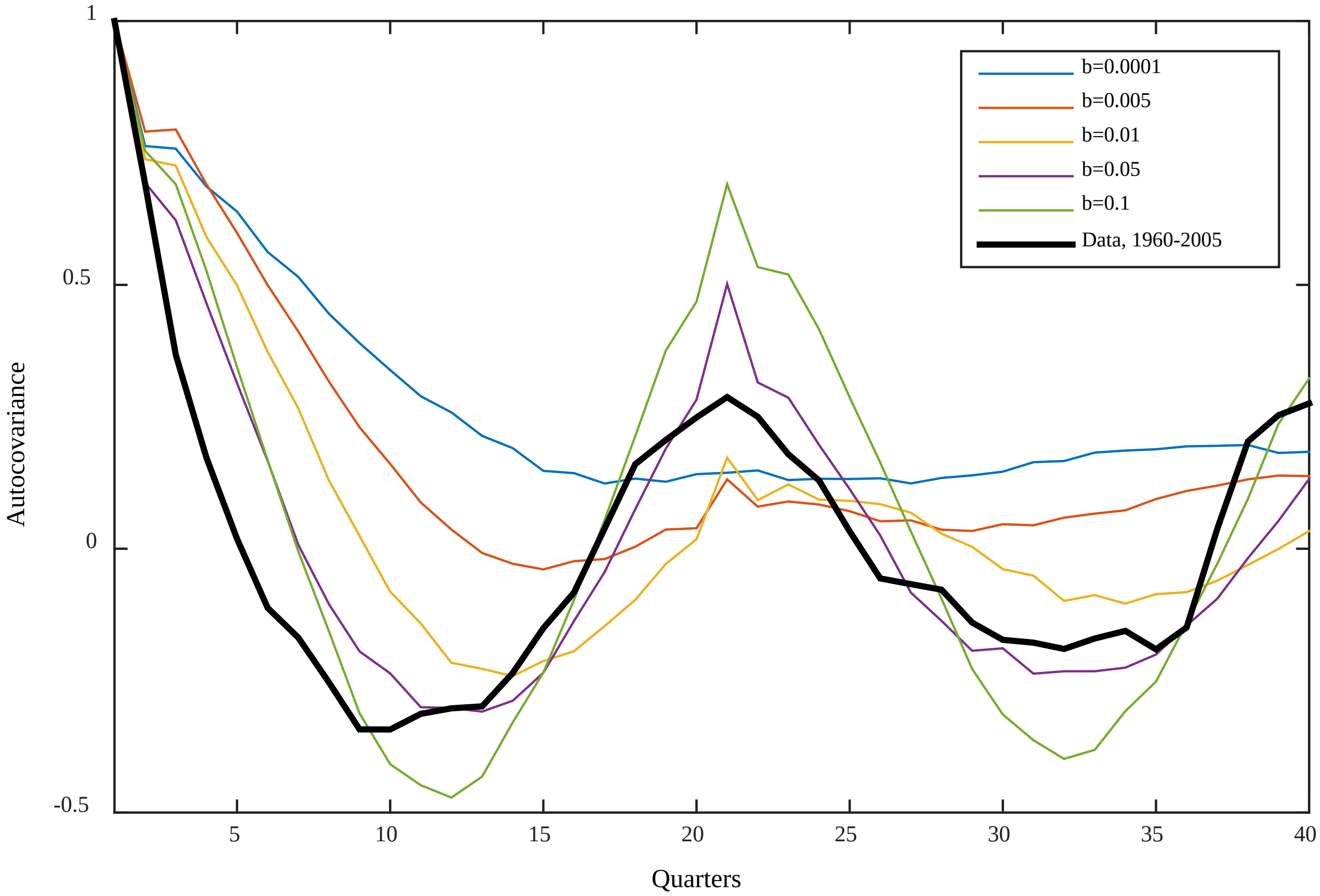


Initial Distribution

Aggregate Investment (T = 10, ξ = 5 ,Extensive-Only Case)

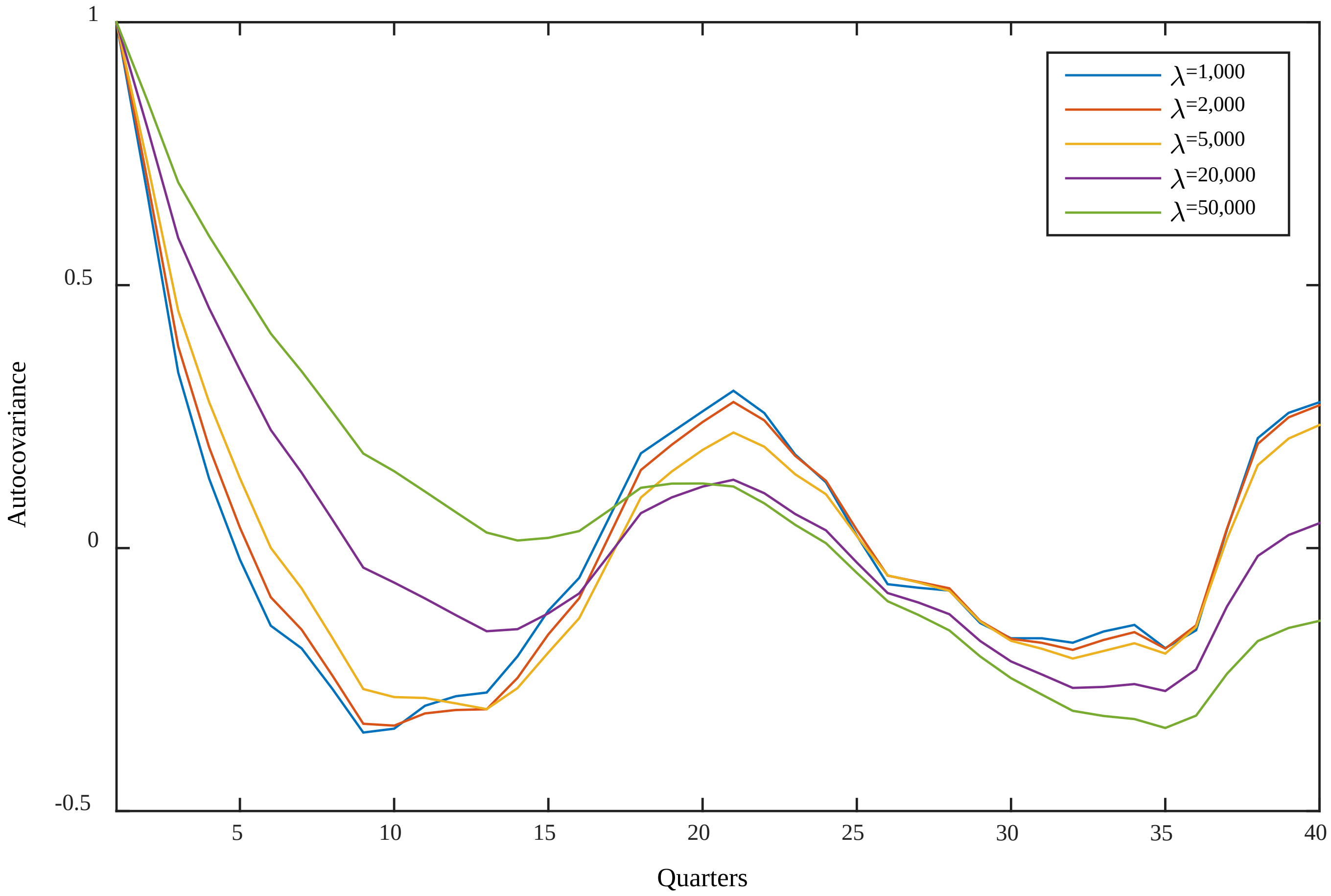
Investment Goods Prices (T = 10, ξ = 5 ,Extensive-Only Case)

FIGURE 3.4. FABRICATED METALS: DATA AND MODEL AUTOCOVARIANCE FUNCTION



Notes. The black line gives the point estimate of the autocovariance of real investment spending in fabricated metals. The log of real investment spending was detrended with an HP-filter with a smoothing parameter (λ) of 1600. We simulated investment paths from the quantitative model calibrated using a steady-state adjustment horizon of $T = 5$ years, and the annual depreciation rate for fabricated metals $\delta = 0.09$ annually. All other parameters are set as in the baseline parameterization in Table 3.1.

FIGURE 3.5. FABRICATED METALS: AUTOCOVARIANCE FUNCTIONS, ALTERNATE HP SMOOTHING PARAMETERS



Notes. Each line corresponds to an estimate of the autocovariance function for investment in fabricated metals. In each case, the log of real investment is detrended by a different HP smoothing parameter (listed above). This figure shows that the peak in the autocovariance at approximately 5 years is not an artifact of the smoothing parameter used by the HP filter.

APPENDIX 3.A

RETIMING COSTS MODEL SOLUTION AND STRUCTURAL ESTIMATION

In this appendix, we discuss the direct inference structural estimation of the model parameters. The empirical strategy is to match moments generated by the model with their reduced-form analogues estimated using data on investment, capital goods prices and investment subsidies. We start by presenting the data and methodology, then we present our results and expand on the reasons the identification of the structural parameters faces considerable challenges.

Research Design. Our empirical research design uses data on aggregate investment quantities and prices. The data is disaggregated according to BEA underlying detail tables for investment. Unlike many other papers in the literature, we do not use "micro-data" to study the effects of lumpy investment.

Micro-data sets like the Longitudinal Research Database (LRD) have some advantages that we forego in our analysis. Among other things, micro-data offer detailed information on plant level investment.[19] The lack of direct observations on firm-level investment and on the distribution of firms across capital holdings is a serious drawback of our empirical approach. Firm-level adjustment patterns and the distribution of capital holdings feature prominently in the theory and in much of the existing empirical research on lumpy investment. That said, there are reasons that such observations may not be essential to understand aggregate investment. Indeed, in conventional models with no retiming costs, the distribution of firms over capital holdings has virtually no implications for the timing of investment at all.

At the same time, our aggregate data has advantages relative to micro-data. First, the investment figures in micro-data sets are a combination of many different types of capital goods, some which are subject to fixed adjustment costs and some which are not. Furthermore, the micro-

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[19] See for example, Cooper and Haltiwanger (1993), Doms and Dunne (1998).

data sets contain virtually no information on investment prices. The main advantage of our approach is the explicit treatment of prices. Current and expected future prices of capital goods are critical factors for firms' investment decisions. The dynamics of aggregate prices offer insight into the investment adjustment process at the firm level. Our numerical experiments illustrate the specific patterns that may provide evidence of investment retiming costs. In the presence of such costs, aggregate investment prices should display predictable changes over time. In contrast, without retiming costs, prices should roughly follow a random walk.

Data. We use data on nominal investment spending and investment prices from the Bureau of Economic Analysis' (BEA) underlying detail tables and data on the production of capital goods from the NBER Productivity Database. These data form a panel of investment quantities and prices by type. We exclude computers and software because these categories exhibit extreme movements in prices and are notoriously difficult to measure. Depreciation rates for each type come from Fraumeni (1997). Our panel has 42 types of investment goods with quarterly observations from 1965:1 to 2005:4. Let $m = 1, ..., 42$ denote an arbitrary type of investment. Real investment purchases of type m investment are calculated by dividing nominal investment purchases for type m by the price index for that type. The pre-tax relative price for type m capital is defined as the m^{th} price index divided by the price index for nondurable consumption from the National Income and Product Accounts (NIPA).

Investment Supply. We specify an isoelastic investment supply curve for aggregate investment. The baseline supply elasticity is a supply elasticity of 0.74 for equipment and 1.16 for structures. Because the supply elasticity has important effects on the behavior of the system, we also conduct a sensitivity analysis in which we consider higher elasticities.

Investment Demand Estimation. We investigate the extent to which the key determinants of investment demand at the firm-level can explain the observed features of aggregate investment and investment goods prices. We model investment demand as described in Section 3.2. In the model, the response of firms to investment goods prices and current macroeconomic conditions is governed by several parameters: the cost of retiming investment b, the adjustment horizon T, returns to scale at the firm-level α and the variance of productivity shocks σ_Z^2. For each type of investment m, we estimate $\left[b^m, T^m, \alpha^m, \sigma_Z^{2,m}\right]$ by the method of simulated moments (MSM).

Extensive-Only Case. The quantitative model assumes each firm is free to choose its optimal reset capital stock. The firm faces two decisions: on the extensive margin, the firm decides whether to adjust its capital stock in the current period; on the intensive margin, the firm chooses the optimal level of the reset capital stock. We refer to this setting as the *intensive* case. For the purpose of structural estimation, we consider a simplified version of the model in which the firm is constrained to adjust to a fixed (time-invariant) reset capital stock every period. We refer to this variant of the model as the *extensive-only* case. This assumption allows us to isolate the implications of retiming costs when firms experience various shocks.

Moments: The features of the data we would like to match include the variances and the covariance of investment quantities and prices; the response of investment goods prices to investment subsidies; the forecastability of investment goods prices; and the cyclical properties of investment. Therefore the moments we match are the OLS estimates for a series of equations specified to capture these empirical features.

The moments include the variances and covariance of investment and prices for each type *m*, denoted $\hat{v}_I^m$, $\hat{v}_p^m$ and $\hat{c}_{I,p}^m$. We use the natural log of the aggregate investment and price series, detrended with the HP filter with smoothing parameter 1,600. These moments help identify the variance of investment demand shock, and their magnitude relative to investment supply shocks.

The effect of investment subsidies on the prices of investment goods is estimated using a specification inspired by Goolsbee (1998):

$$\ln p_t^m = \beta_0^m + \beta_1^m t + \beta_2^m t^2 + \beta_3^m \iota_t^m + \Gamma^m Q_t + \nu_t^{1,m}, \tag{1}$$

where Q_t is a vector of macroeconomic covariates – detrended log GDP, the log of oil prices, a dummy variable for the Nixon price controls, and a measure of stock market volatility. In our MSM procedure, we match the coefficient for the comprehensive tax subsidy β_3^m.

In the model, firms that face substantial costs to retiming their investment decisions are not able to take advantage of forecastable changes in after-tax prices. Consequently, the after-tax prices of capital goods may display forecastable movements in equilibrium. In contrast, if the costs to deviating from the steady state adjustment pattern are negligible, the after-tax prices of investment goods will be close to a random walk. The forecastability of after-tax prices has, therefore, important implications for the parameters of our model. We capture the extent to which prices are forecastable by matching a simple reduced-form auto-regression of the subsidized price:

$$\Delta \ln\left[p_t^m(1-\iota_t^m)\right] = \gamma_0^m + \sum_{j=1}^{4} \gamma_j^m \left(\Delta \ln\left[p_{t-j}^m(1-\iota_{t-j}^m)\right]\right) + \nu_t^{2,m}. \tag{2}$$

The coefficients γ_j^m serve as additional moments for our MSM procedure. The coefficient estimates from real after-tax price regression for Fabricated Metals are presented in Table 3.A.1.

The cyclical properties of investment provide information about both the steady-state adjustment horizon T from the model, and the magnitude of retiming costs. The model predicts that in the presence of substantial retiming costs, the investment series will display echo effects at the adjustment horizon. In the data, these echoes roughly correspond to long-run humps in the autocovariogram of investment. We estimate autocorrelations up to $L = 40$ quarters for each investment type *m* using equations of form

$$\tilde{I}_t^m = \pi_0^{m,l} + \pi_1^{m,L} \tilde{I}_{t-l}^m + \nu_t^{l+2,m}, \tag{3}$$

for $l = 1,\ldots,L$, where $\tilde{I}_t^m$ is the natural log of investment for type *m,* detrended with the HP filter with smoothing parameter 1,600. The complete set of moments for each type of investment goods *m* is $M^m = \left[\hat{v}_I^m, \hat{v}_p^m, \hat{c}_{I,p}^m, \hat{\beta}_3^m, \hat{\gamma}_1^m, \hat{\gamma}_2^m, \hat{\gamma}_3^m, \hat{\gamma}_4^m, \hat{\pi}_1^{m,1}, \ldots, \hat{\pi}_1^{m,L}\right]'$. We estimate a total of *L*+5 regressions for each type. The residuals from these regressions, $\nu^{1,m}, \nu^{2,m}, \ldots, \nu^{L+5,m}$, are used to construct an approximate covariance matrix for the moments, whose inverse becomes the weighting matrix for MSM estimation.

<u>Weighting Matrix</u>: We exploit the covariance of the moments to improve the efficiency of our MSM estimator. The covariance matrix of the moments is

$$\hat{V}_M^m = (Q^m{}'Q^m)^{-1} Q^m{}' \hat{V}_\nu^m Q^m (Q^m{}'Q^m)^{-1}, \tag{4}$$

where $\hat{V}_\nu^m$ is an estimate of the contemporaneous covariance of the errors from all of the regressions, and Q^m is a block-diagonal matrix, with each block made up of the covariates from one of the *L*+5 regressions. The covariance of the errors $\hat{V}_\nu^m$ is constructed using two simplifying assumptions. First, the errors for each regression are homoskedastic without serial correlation. Second, we estimate only the contemporaneous cross-correlations between errors from different regressions. The weighting matrix for the MSM procedure for investment type *m* is then $W^m = \left(\hat{V}_M^m\right)^{-1}$.

Simulation: The equations governing the model are linearized around the non-stochastic steady state. Using the Anderson-Moore (AIM) algorithm, we compute a rational expectations equilibrium. The linear solution of the model implies a VAR process

$$Y_t = F\left(\theta^m\right)Y_{t-1} + G\left(\theta^m\right)\varepsilon_t . \tag{5}$$

Here θ^m is a vector of known and unknown parameters and *Y* is a vector of all variables in the system including the shocks, and the distribution of capital holdings across firms. The parameter vector θ^m includes investment supply parameters $\theta_S^m = [\xi, \rho_{x,1}^m, \rho_{x,2}^m, \sigma_x^{m,perm}, \sigma_x^{m,trans}]$ estimated as described above, as well as investment demand parameters $\theta_D^m = [b^m, T^m, \alpha^m, \sigma_Z^m]$. The transition matrix *F* and the matrix *G* that relates structural and reduced-form innovations are functions of the parameter vector θ^m.

Given a set of parameters, we draw $N = 500$ sets of normally distributed permanent supply, transitory supply and permanent demand shocks[20], and we generate simulated investment and investment price series of the same length as the observed data series from the BEA. Firms are allowed to adjust only at the *extensive* margin. Although this assumption is restrictive, it helps identify the planning horizon *T* and the adjustment retiming cost parameter b, eliminating variation in the simulated series due to changes in the reset capital stock. The depreciation rate for each type is as taken from Fraumeni (1997). The real rate of return r is set to 2 percent annually, consistent with U.S. post-war real interest rates. The investment subsidy variables correspond to the observed ITC and tax depreciation schedules (including the so-called bonus depreciation policy in 2002–2005). For purposes of forming expectations, we assume that firms view all changes in investment tax subsidies as permanent.[21] Therefore, expectations of the ITC are governed by:

$$\iota_t = \iota_{t-1} + \varepsilon_t^{\iota} . \tag{6}$$

This strong assumption may have a material effect on our estimates. However, it is a reasonable characterization of U.S. tax policy, considering that temporary subsidies often become long-lasting. Furthermore, estimates of the persistence of the investment subsidy are unable to reject a unit root.

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[20] The "permanent" shocks in the system are actually trend stationary. The AR roots are set to $1-1\times10^{-10}$, as our solution method requires that the system is strictly stationary.

[21] As above, for strict stationarity, the ITC has an AR coefficient of $1-1\times10^{-10}$.

For each simulated series $n = 1,\ldots,N$, we estimate the moments $M^{m,n}(\theta_D^m)$ by OLS as described above, treating the simulated data symmetrically to the observed data series.[22] The MSM estimator is

$$\hat{\theta}_D^m = \arg\min_{\theta_D^m} \left[M^m(\theta_D^m) - M^m \right]' W^m \left[M^m(\theta_D^m) - M^m \right]. \tag{7}$$

Here $M^m(\theta_D^m)$ is the average of the moments over the N simulations, i.e. $M^m(\theta_D^m) = \left(1/N\right)\sum_{n=1}^{N} M^{m,n}(\theta_D^m)$. We minimize the MSM objective function numerically. We compute analytical standard errors based on the asymptotic distribution of the MSM estimator as a special case of a direct inference estimator in Gourieroux, Montfort and Renault (1993).

Structural Estimates. In this section, we present our structural estimates for the extensive-only specification. Table 3.A.2 shows results for equipment, and Table 3.A.3 shows results for structures.

Retiming Costs. Of particular interest to our study is the degree to which firms can adjust the timing of large investment episodes. This is captured by the parameter b, which represents the minimum benefit, expressed as a fraction of firm value that the firm requires to alter the timing of its investment relative to the steady-state pattern, given investment retiming costs. For many types, this parameter estimate is less than one percent of the steady-state value of the firm. However, there are several types of equipment investment goods in Table 3.A.2 that appear to have substantial costs associated with varying the timing of adjustment. Medical equipment and instruments, nonmedical instruments, metalworking machinery, general industrial equipment and automobile investment all have retiming costs that exceed one percent. Some of the estimates exceed 10 percent of the value of the firm. In Table 3.A.3, we do not find evidence of high retiming costs for any type of structures investment. Surprisingly, among equipment investment, but not among structures investment, there are several types of capital goods that seem to exhibit empirical patterns that are close to fixed (s,S) rules *at the aggregate level*.

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[22] The macroeconomic covariates Q_t are excluded from equation (1), since these variables play no role in the quantitative model. This will not bias the coefficient estimate in the model though with a finite sample of observations it would reduce the precision of the estimate. This is fortunately not a concern for the simulation since we simulate a sufficiently large set of observations so that the coefficient is determined exactly.

Adjustment Horizon. The estimated adjustment horizons *T* display wide variation, ranging between 8 and 20 years for most types. Furthermore, some of our preliminary estimates are as high as 25 years. The standard errors are extremely large in many cases, indicating that the timing horizon is imprecisely estimated. Even in our numerical exercises, the echo effects that would help identify this horizon are modest. If such dynamics are present in the data, they may be obscured by various other shocks affecting the demand and supply of investment goods.

Our adjustment horizon estimates are high relative to standard calibrations in the literature. Many other researchers calibrate models to imply an average adjustment horizon of roughly 5 to 6 years. This calibration is based on patterns of "investment spikes" taken from micro data. Since investment spikes occur in roughly 20 percent of year-plant observations, calibrated models typically have 5-year adjustment horizons. However, the definition of an investment spike is arbitrary. Cooper and Haltiwanger (1993, 2006) define an investment spike as a year plant observation in which capital increases by more than 30 percent. If this cutoff were increased, the micro data would indicate a lower frequency of lumpy investment and thus a longer adjustment horizon.

Returns to scale. The returns to scale parameter α is also of interest.[23] The estimates of this parameter vary between 0.45 and 0.99, with an average of roughly 0.80. There are no systematic differences between returns to scale for equipment and structures. This range is comparable to the estimates in Cooper and Haltiwanger (2006).

Interpretation and implications. Our estimates suggest that there is at least some evidence that for certain types of capital goods firms are resistant to making large changes in the timing of investment. We should emphasize that these estimates correspond to aggregate behavior and it is not necessary for these estimates to match up with micro estimates. For a stark example of this, suppose most of the firms as the micro level follow fixed (s,S) rules but that there is a modest fraction that follow state-dependent (s,S) policies as in Thomas (2002), Gourio and Kashyap (2007) and House (2008). In this case, the micro data would suggest that most firms were unable (or unwilling) to change the timing of their investment decisions. In contrast, the firms that are able to change their investment timing effectively arbitrage predictable movements in after-tax

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[23] The returns to scale parameter may not reflect technical or productive returns to scale but may instead reflect market power as described by Cooper and Haltiwanger 2006).

prices. In this example, while the micro estimates would indicate that most firms were reluctant to change the timing of investment, the aggregate estimates support modeling aggregate investment as though firms could alter investment timing freely. In this situation, researchers could use standard neoclassical investment models to describe equilibrium investment and prices.

Although we find considerable heterogeneity across the types of investment goods included in our analysis, the estimates suggest that in some cases retiming costs are substantial. For these types of investment goods, the cross-sectional distribution of capital holdings matters at the aggregate level. Our model with explicit costs of retiming investment decisions offers an advantage over conventional investment models for these types. For many other types of investment goods, however, we do not find compelling evidence that retiming frictions affect the aggregate dynamics of investment and capital goods prices.

Identification. For many types of investment goods, the key parameters that govern investment demand at the firm level are imprecisely estimated. If investment retiming costs are low, returns to scale α, the steady-state timing horizon T and the variance of investment demand shocks σ_Z^2 are not well identified. Indeed, the numerical experiments in Section 3.3 suggest that absent substantial retiming costs, predictable movements in aggregate investment prices—echo effects at the adjustment horizon and any effects of the distribution of firms across capital holdings on the equilibrium are negligible. Furthermore, if returns to scale at the firm level α are close to unity, firms are more willing to retime their investment decisions. With constant returns to scale, the value of an additional unit of capital is roughly constant, regardless if firms have outdated capital stock, or have adjusted their capital stock recently. We find that for many types of investment goods, returns to scale are indeed close to unity. In this case, we expect that we are not able to precisely estimate the other parameters governing firms' investment decisions.

In other words, the identification of the key parameters of investment demand does not depend only on the data, but also on the values of the true parameters. Simulation experiments confirm this intuition. We consider three different values of the retiming cost parameter b: 0.0001, 0.01 and 0.1, and three values for returns to scale α: 0.6, 0.8 and 0.99. For all combinations of the two parameters, we simulate aggregate investment and price series of the same length as the panel of BEA data. We then estimate the parameters governing investment demand (b, T, α, σ_Z^2) using the same MSM procedure presented in the appendix 3.A that we apply to actual data. We repeat the experiment for each combination of parameters, and compare both the average estimates to the true parameters of the model, as well as the standard deviation of the estimates to the average analytical standard errors. Table 3.A.4. summarizes the results of these experiments. As expected, when the retiming cost parameter is low, the other parameters are imprecisely estimated. The analytical standard errors are much larger than the empirical standard deviations, and both types of standard errors are significant.

When firms face costs to retiming their investment decisions, they are less willing to delay or accelerate investment relative to steady state patterns to take advantage of predictable movements in investment goods prices. Aggregate prices should, therefore, display such movements in equilibrium. In contrast, in the absence of retiming costs, firms arbitrage away any predictable variations in prices, and prices should be close to a random walk. The identification of investment retiming costs in our model thus relies crucially on the properties of aggregate price series. We conduct augmented Dickey-Fuller (ADF) tests for the presence of unit roots in after-tax real investment prices for each of the 42 types of capital goods in our panel. Both the estimated regression model and the underlying data generating process are assumed to have a drift and a time trend. We consider two specifications: in the first version, we impose four lags for all types; in the second, we allow for lag order uncertainty and estimate the lag order using the criterion proposed by Ng and Perron (1995). When we impose the lag order, we fail to reject the null of a unit root at the 10% confidence level for all types of investment goods, with the exception of other power equipment and railroads, for which we only fail to reject the null at the 5% confidence level. When we estimate the lag order, we still fail to reject the presence of a unit root at the 10% level for most types. We fail to reject it at the 5% level for manufacturing equipment and mining equipment, and reject it for other power equipment and single-family structures. The ADF statistics are presented in Table 3.A.5. Although ADF tests are biased towards failing to reject the null, these results indicate that the prices of investment goods are indeed close to a random walk.

TABLE 3.A.1. FORECASTABILITY OF INVESTMENT PRICES: FABRICATED METALS

Real After-Tax Price Regression				
$\Delta \ln\left[p_t(1-\iota_t)\right] = \gamma_0 + \sum_{j=1}^{4} \gamma_j \left(\Delta \ln\left[p_{t-j}(1-\iota_{t-j})\right]\right) + \nu_t$				
constant	γ_1	γ_2	γ_3	γ_4
0.1882	-0.0024	-0.0644	0.0775	0.1158
(0.2246)	(0.0800)	(0.0798)	(0.0798)	(0.0804)

TABLE 3.A.2. INVESTMENT DEMAND ESTIMATES: EQUIPMENT

	b	α	σ_Z^2	T		b	α	σ_Z^2	T
Communication equipment	0.21	0.77	0.01	11.23	Aircraft	0.00	0.45	0.01	17.53
	(0.03)	(0.09)	(1.10)	(1.31)		(0.00)	(0.14)	(0.33)	(14.46)
Medical equipment and instruments	0.04	0.99	0.01	12.99	Ships and boats	0.00	0.99	0.01	9.08
	(0.37)	(0.03)	(1.96)	(43.01)		(0.00)	(0.97)	(1.92)	(144.85)
Nonmedical instruments	0.10	0.98	0.01	17.24	Railroad equipment	0.00	0.99	4.70	10.64
	(0.10)	(0.22)	(3.00)	(32.18)		(0.00)	(8.63)	(2.00)	(588.82)
Photocopy and related equipment	0.04	0.99	0.01	23.30	Farm tractors	0.00	0.96	0.16	6.87
	(0.11)	(0.01)	(0.36)	(58.50)		(0.01)	(0.55)	(2.65)	(11.45)
Office and accounting equipment	0.00	0.99	0.00	7.97	Other agricultural machinery	0.00	0.95	0.03	6.35
	(0.00)	(0.01)	(0.92)	(2.70)		(0.00)	(0.22)	(1.49)	(3.62)
Fabricated metal products	0.00	0.77	0.01	5.22	Construction tractors	0.00	0.47	4.25	25.00
	(0.00)	(4.34)	(2.27)	(5.60)		(0.00)	(0.04)	(1.19)	(10.00)
Steam engines	0.00	0.98	14.23	8.99	Other construction machinery	0.06	0.45	4.15	18.01
	(0.00)	(10.28)	(11.39)	(394.59)		(0.02)	(0.04)	(1.77)	(1.78)
Internal combustion engines	0.16	0.93	3.55	13.24	Mining and oilfield machinery	0.00	0.99	0.06	25.00
	(0.22)	(0.77)	(1.70)	(3.24)		(0.00)	(0.05)	(0.04)	(263.60)
Metalworking machinery	0.05	0.98	0.01	15.91	Service industry machinery	0.16	0.95	0.01	11.92
	(0.02)	(0.25)	(1.18)	(10.14)		(0.21)	(0.35)	(2.53)	(4.13)
Special industry machinery, n.e.c.	0.07	0.52	3.64	16.67	Household furniture	0.00	0.73	0.00	24.99
	(0.01)	(0.05)	(3.70)	(0.84)		(0.00)	(0.06)	(0.29)	(9.76)
General industrial	0.07	0.99	0.01	18.17	Other furniture	0.05	0.45	0.01	20.33
	(0.07)	(0.01)	(2.89)	(28.10)		(0.01)	(0.11)	(0.60)	(4.66)
Electrical transmission, dist	0.00	0.45	8.55	6.06	Household appliances	0.00	0.89	0.00	6.34
	(0.00)	(1.80)	(4.77)	(0.25)		(0.00)	(1.39)	(0.31)	(20.02)
Trucks, buses, and truck trailers	0.00	0.87	3.44	6.92	Other electrical equipment	0.00	0.65	0.01	5.82
	(0.00)	(2.69)	(1.11)	(54.00)		(0.00)	(0.13)	(7.62)	(22.55)
Autos	0.13	0.91	8.28	14.47					
	(0.02)	(0.34)	(2.97)	(1.46)					

TABLE 3.A.3. INVESTMENT DEMAND ESTIMATES: STRUCTURES

	b	α	σ_Z^2	T
Commercial, including office	0.00	0.45	0.01	24.65
	(0.00)	(0.13)	(2.03)	(12.45)
Hospitals and special care	0.00	0.45	0.01	10.72
	(0.00)	(1.96)	(3.64)	(11.65)
Manufacturing	0.00	0.99	0.01	12.40
	(0.00)	(3.56)	(2.42)	(94.53)
Electric	0.00	0.45	0.01	13.88
	(0.00)	(3.80)	(2.65)	(60.66)
Other power	0.00	0.98	0.01	11.29
	(0.00)	(2.94)	(15.71)	(205.40)
Communication	0.00	0.99	0.01	19.68
	(0.00)	(0.87)	(1.98)	(527.56)
Petroleum and natural gas	0.00	0.45	42.54	18.64
	(0.00)	(0.46)	(12.63)	(7.50)
Mining	0.00	0.45	0.01	24.06
	(0.00)	(0.12)	(1.25)	(1.42)
Religious	0.00	0.99	0.01	18.56
	(0.00)	(0.71)	(1.83)	(147.18)
Educational	0.00	0.94	0.00	25.00
	(0.00)	(0.33)	(1.48)	(57.97)
Railroads	0.00	0.98	0.03	8.32
	(0.00)	(4.07)	(4.33)	(70.67)
Farm	0.00	0.99	0.01	18.25
	(0.01)	(4.06)	(1.79)	(1748.92)
Single-family structures	0.00	0.99	0.03	8.65
	(0.00)	(5.78)	(3.41)	(517.35)
Multifamily structures	0.00	0.75	0.02	21.77
	(0.00)	(0.88)	(0.60)	(65.00)
Other residential structures	0.00	0.99	0.01	16.05
	(0.01)	(0.79)	(3.67)	(661.87)

TABLE 3.A.4. IDENTIFICATION OF INVESTMENT DEMAND PARAMETERS

	Estimates				True parameter values	
	b	α	σ_Z^2	T	b	α
Estimates	0.000	0.742	0.048	12.589	0.0001	0.6
Standard deviation	(0.002)	(0.190)	(0.095)	(7.779)		
Analytical standard errors	(0.004)	(1.512)	(1.078)	(114.433)		
Estimates	0.000	0.799	0.104	15.812	0.0001	0.8
Standard deviation	(0.000)	(0.161)	(0.366)	(8.631)		
Analytical standard errors	(0.002)	(1.723)	(0.711)	(121.872)		
Estimates	0.001	0.875	0.334	16.826	0.0001	0.99
Standard deviation	(0.004)	(0.130)	(0.662)	(8.249)		
Analytical standard errors	(0.008)	(1.312)	(0.894)	(297.817)		
Estimates	0.091	0.853	1.681	14.533	0.01	0.6
Standard deviation	(0.048)	(0.206)	(2.958)	(2.773)		
Analytical standard errors	(0.127)	(0.452)	(9.561)	(13.060)		
Estimates	0.058	0.758	0.253	15.750	0.0001	0.8
Standard deviation	(0.033)	(0.255)	(1.110)	(4.131)		
Analytical standard errors	(0.121)	(0.389)	(4.864)	(13.179)		
Estimates	0.071	0.695	0.704	15.789	0.0001	0.99
Standard deviation	(0.049)	(0.251)	(1.694)	(4.000)		
Analytical standard errors	(0.100)	(0.354)	(6.610)	(10.534)		
Estimates	0.152	0.763	13.303	9.629	0.1	0.6
Standard deviation	(0.098)	(0.183)	(16.958)	(1.878)		
Analytical standard errors	(0.052)	(0.188)	(80.460)	(1.886)		
Estimates	0.131	0.766	9.969	10.696	0.0001	0.8
Standard deviation	(0.073)	(0.199)	(18.230)	(1.825)		
Analytical standard errors	(0.070)	(0.308)	(49.480)	(3.524)		
Estimates	0.120	0.722	18.195	9.337	0.0001	0.99
Standard deviation	(0.094)	(0.223)	(28.210)	(1.896)		
Analytical standard errors	(0.084)	(0.168)	(79.163)	(2.581)		

Notes. For each combination of parameters, the table presents average estimates, empirical standard errors, and the average analytical standard errors. In all simulations, the variance of demand shocks is $\sigma^2_Z = 1$ and the steady-state adjustment horizon is $T = 10$ years.

TABLE 3.A.5. UNIT ROOT TESTS: AFTER-TAX REAL CAPITAL GOODS PRICES

	A. Lag Order *L* = 4	B. Estimated Lag Order			A. Lag Order *L* = 4	B. Estimated Lag Order	
	ADF Statistic	Lag Order	ADF Statistic		ADF Statistic	Lag Order	ADF Statistic
Communication equipment	-0.581	7	-0.834	Mining and oilfield machinery	-2.096	6	-1.759
Medical equipment and instruments	-1.373	6	-1.213	Service industry machinery	-1.842	6	-1.730
Nonmedical instruments	-1.666	6	-1.548	Commercial, including office	-2.970	1	-2.679
Photocopy and related equipment	-1.251	6	-1.144	Hospitals and special care	-2.989	1	-2.729
Office and accounting equipment	-1.702	6	-1.622	Manufacturing	-2.920	5	-3.306
Fabricated metal products	-2.258	6	-2.166	Electric	-2.275	5	-3.018
Steam engines	-1.073	6	-1.099	Other power	-3.407	5	-3.924
Internal combustion engines	-1.728	6	-1.563	Communication	-2.753	1	-2.143
Metalworking machinery	-1.657	6	-1.328	Petroleum and natural gas	-1.084	6	-0.667
Special industry machinery, n.e.c.	-1.360	6	-1.223	Mining	-2.495	5	-3.146
General industrial	-1.955	6	-1.904	Religious	-2.987	1	-2.730
Electrical transmission, dist.	-1.461	6	-1.525	Educational	-2.995	1	-2.728
Trucks, buses, and truck trailers	-1.173	4	-1.173	Railroads	-3.147	1	-3.091
Autos	-2.047	7	-2.486	Farm	-3.013	1	-2.596
Aircraft	-2.142	6	-2.052	Single-family structures	-3.080	5	-3.471
Ships and boats	-2.092	1	-2.354	Multifamily structures	-2.607	1	-2.694
Railroad equipment	-2.526	6	-2.188	Other residential structures	-2.882	1	-2.517
Farm tractors	-1.121	6	-0.974	Household furniture	-1.771	6	-1.698
Other agricultural machinery	-1.915	6	-1.650	Other furniture	-2.005	6	-1.977
Construction tractors	-1.137	5	-1.596	Household appliances	-2.680	6	-2.494
Other construction machinery	-2.312	6	-2.150	Other electrical equipment	-2.138	1	-1.880

Notes. The estimated process and the true data generating process are assumed to include a drift and a trend. The critical values are -3.142 at the 5% confidence level and -3.442 at the 10% confidence level. These values are calculated by interpolation for the sample size based on the table in Ha4milton (1994).

CHAPTER IV

INVESTMENT SUPPLY SHOCKS

4.1. INTRODUCTION

Shocks to physical investment in equipment and structures drive both long-run economic growth and business-cycle fluctuations. The investment literature distinguishes between two broad types of shocks: investment-specific technology change, which govern the production of investment goods, and shocks to the transformation of investment goods into productive capital. The central role of investment-specific technology for long-run growth is undisputed, while existing evidence about the ability of either type of shock to replicate stylized facts about comovements in output, consumption, investment and hours at business cycle frequencies is mixed, and is sensitive to modeling choices and identification strategy. In this chapter, we approach the identification of investment shocks from a new perspective and provide a disaggregated view that reflects the considerable heterogeneity present in the data across different types of investment goods.

Our study of investment supply and investment shocks uses simple reduced-form and structural time series methods, in contrast to the SVAR and large-scale DSGE methods used by other researchers. We start by specifying an isoelastic investment supply curve for each type of capital. We calibrate the elasticity of investment supply using empirical evidence on the magnitude of the elasticity for equipment and structures. We assume investment supply shocks consist of a permanent and a transitory component. We estimate drift in the permanent shock and the persistence of the transitory shock from the equivalent reduced-form time series model. Finally, we use the Kalman filter to estimate the variances of the two components and recover the shock processes.

Our approach requires only mild structural assumptions to characterize the supply of new capital goods. The estimates provide useful insights about the properties and magnitude of investment shocks. The shock processes we recover from the data can be used in conjunction with other evidence to understand the short-run and long-run effects of investment disturbances on economic fluctuations and growth. Additionally, the shocks can be embedded into equilibrium models as a realistic source of business-cycle fluctuations.

In Section 4.2, we survey the literature on investment shocks. Section 4.3 presents our empirical strategy and the main results. Section 4.4 concludes.

4.2. RELATED LITERATURE

The second half of the twentieth century featured extraordinary technological advances in investment goods. In the economics literature, there is a long tradition of attributing a substantial share of economic growth to investment-specific technological change, starting with Solow (1960), and followed by the seminal contributions of Hulten (1992) and Greenwood, Hercowitz and Krusell (1997). Using a vintage capital DSGE model, Greenwood *et al*. found that approximately 60 percent of labor productivity growth is due to advances in investment-specific technology, while the remaining 40 percent is attributed to neutral technological progress. Their identification strategy relies on the assumption that observed changes the equilibrium price of investment goods are a direct reflection of technological improvements in the production of investment goods.[24]

Fisher (2006) uses the distinction between neutral and investment-specific technology shocks to impose long-run restrictions on a structural VAR model of labor productivity. He finds that in addition to driving economic growth, investment-specific technological change is also a determinant of short-run fluctuations in output and hours. Other researchers reach the same conclusion in large-scale DSGE models, notably Fernandez-Villaverde and Rubio-Ramirez (2007) and Justiniano, Primiceri and Tambalotti (2010). The Fernandez-Villaverde and Rubio-Ramirez (2007) study uses data on real relative investment prices in a model inspired by Greenwood et al. (1997) and Fisher (2006) with stochastic volatility. The authors find that variations in the volatility of investment-specific technology shocks have a large effect on the volatility of output growth in the post-war period. Justiniano *et al*. (2010) show that investment shocks are the main

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[24] The assumption that the real relative price of investment reflects productivity innovations in investment is common to most papers discussed in this section, however models where this relationship breaks have been formulated. See, for example, Floetotto, Jaimovich and Pruitt (2009) who analyze noncompetitive markets and nominal rigidities, or Guerrieri, Henderson and Kim (2014), who consider two sectors with different factor intensities.

determinants of business cycle fluctuations in an estimated New-Keynesian DSGE model. However, they do not impose restrictions arising from the behavior of investment prices, and conclude that this shock is only loosely correlated with the relative price of investment goods, as well as considerably more volatile.

In contrast, a host of newer studies that distinguish between investment-specific technology shocks and shocks to the transformation of investment goods into productive capital contradict the earlier evidence, finding that technological advances in the production of investment goods play no role in short-run fluctuations. Schmitt-Grohe and Uribe (2012) investigate the role of anticipated productivity shocks in creating business cycles in an RBC model featuring real rigidities and structural shocks with anticipated and unanticipated components. They consider two investment shocks: the permanent shock, identified from the relative price of investment, has a negligible contribution to output fluctuations, while the transitory shock explains 28% of output and 63% of investment variation. Justiniano, Primiceri and Tambalotti (2011) likewise conclude that shocks to the marginal efficiency of investment (MEI) are the main drivers of business cycle fluctuations. In their specification, investment-specific technology shocks affect only long-run growth. Liu, Waggoner and Zha (2009) find that “depreciation shocks,” similar to the MEI shocks considered by Justiniano *et al*. (2011), also play an important role in generating business cycle comovement.

This new class of temporary disturbances to the process by which investment goods become productive capital supports a wide range of interpretations. One possibility is that these shocks reflect the efficiency of the financial sector, as in the financial accelerator model of Carlstrom and Fuerst (1997) or variations in borrowing costs for firms who purchase investment goods. Another possible interpretation is that they reflect sudden economic obsolescence for certain capital goods producing sectors. An attractive feature of these shocks is that they succeed in reproducing the comovements between output, consumption, investment and hours observed in the post-war US economy. In particular, these shocks generate a counter-cyclicality in the real relative price of investment goods. In our study, these investment shocks they correspond to the transitory component of investment supply shocks.

It is worthwhile noting that empirical evidence about investment-specific technology shocks can be gleaned not only from the relative prices of investment goods, but also from other observables. Papanikolaou (2011) measures investment shocks from asset prices, under the assumption that they are reflected in the relative stock returns of investment goods producers. This approach offers high-frequency and forward-looking measures of investment shocks.

4.3. EMPIRICAL ANALYSIS

In this section, we use data on investment, capital goods prices and investment tax subsidies to evaluate the elasticity of investment supply ξ. Instead of estimating elasticities directly, we use a robust inference procedure proposed by Chernozhukov and Hansen (2008) to obtain evidence about the magnitude of the elasticity. We then calibrate the elasticity and estimate the structural parameters of the investment supply shock processes for 45 types of capital goods. Section 4.3.1 briefly describes the data. In section 4.3.2, we give an overview of the empirical research design and identification strategy. Section 4.3.3 presents the estimation of the investment supply parameters, and section 4.3.4 describes the reduced-form ARIMA estimates for the implied type-specific supply shocks.

4.3.1 Data

We use data on nominal investment spending and investment prices from the Bureau of Economic Analysis' (BEA) underlying detail tables and data on the production of capital goods from the NBER Productivity Database. These data form a panel of investment quantities and prices by type. We exclude computers and software because these categories exhibit extreme movements in prices and are notoriously difficult to measure. Our panel includes 45 types of equipment and structures with quarterly observations from 1959:1 to 2009:4. Let $m = 1, \ldots, 42$ denote an arbitrary type of investment. Real investment purchases of type m investment are calculated by dividing nominal investment purchases for type m by the price index for that type. The pre-tax relative price for type m capital is defined as the m^{th} price index divided by the price index for nondurable consumption from the National Income and Product Accounts (NIPA).

We match the investment data to IRS depreciation schedules and investment tax credits. We exclude investment types that do not have clear matches to the IRS tax treatment. The investment tax subsidy includes both investment tax credits (ITC) and the present discounted value of tax depreciation allowances. The original data on the ITC and the discounted value of depreciation deductions are available from Jorgenson and Yun (1991).[25] Tables 4.1 and 4.2 present the list of the types used in our analysis with their annual depreciation rates. See the discussion in Chapter 2 for a detailed description of how the investment subsidies are calculated.

Our empirical approach uses data on investment tax subsidies. However, only domestic investment spending benefits from subsidies. For many types of equipment goods, private consumption, government spending and international trade introduce a substantial gap between investment and domestic production. To illustrate this fact, we present nominal domestic purchases and production of capital goods by type in Tables 4.1 and 4.2. We have completed the analysis using both investment and production data. The results are qualitatively equivalent. For the sake of exposition, we present only our results using investment data in this study. For structures, Investment is virtually identical to production so this distinction is not necessary.

Chapter 2 includes additional details about the typical patterns in investment time series. Figure 2.1 presents real production, purchases and prices for general industrial equipment. Figure 2.2 plots the comprehensive investment subsidy for general equipment. The subsidy is strictly positive reflecting the fact that investment expenditures always receive some form of accelerated tax depreciation. The subsidy also exhibits substantial variation over time. Most of the variation is due to legislative changes in the ITC.

4.3.2. Model Specification

The supply of each type of capital good m is governed by an isoelastic supply curve

$$p_t^m = X_t^m \cdot \left(\frac{I_t^m}{\overline{I^m}} \right)^{\frac{1}{\xi^m}} . \tag{1}$$

The parameter ξ^m is the supply elasticity, $\overline{I^m}$ is steady state investment and X_t^m is an investment supply shock. Although assuming that the supply of capital goods is isoelastic may appear restrictive, this specification is more general than the typical assumption in the investment literature which in most cases assumes an infinite elasticity of investment supply—this is equivalent to setting $\xi^m = \infty$ in equation (1).

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[25] We are grateful to Jon Samuel for assistance in assembling this data. We also thank Matthew Shapiro for crucial assistance with constructing a modified quarterly subsidy data set.

For each type of capital *m*, the type-specific supply shock is the sum of a permanent shock and a transitory shock. The permanent shock is a random walk with drift. The transitory shock is assumed to be an AR(1) process. Thus, the supply shock is governed by the following equations where x_t^m denotes the natural logarithm of the supply shock X_t^m:

$$x_t^m = x_t^{m,perm} + x_t^{m,trans}, \tag{2}$$

$$x_t^{m,perm} = \mu^m + x_{t-1}^{m,perm} + \varepsilon_t^{m,perm}, \tag{3}$$

$$x_t^{m,trans} = \rho^m x_{t-1}^{m,trans} + \varepsilon_t^{m,trans} \tag{4}$$

The permanent component can be seen as an investment-specific technology shock. The transitory component then is the reduced-form analogues to a shock to the marginal efficiency of investment of the type studied in Justiniano *et al*. (2011) and Schmitt-Grohe and Uribe (2012). Instead of directly estimating the structural unobserved components model implied by equations (2)–(4), we fist consider the observationally equivalent reduced-form ARIMA(1,1,1) process for each type of investment

$$\Delta x_t^m = \mu^m \left(1-\rho^m\right) + \rho^m \Delta x_{t-1}^m + e_t + \theta^m e_{t-1}. \tag{5}$$

The derivation of the ARIMA process (5) from the unobserved component model in equations (2)–(4) is presented in Appendix 4.A. We impose the reduced-form parameter estimates and estimate the covariance matrix of the two innovations $\varepsilon_t^{m,perm}$ and $\varepsilon_t^{m,trans}$ by maximum likelihood. Finally, we recover the two permanent and temporary investment shock series for each type using the Kalman filter.

4.3.3 Calibration of the Investment Supply Elasticity

We calibrate the investment supply elasticity for equipment and structures rather than estimating it directly from the data because of well-known endogeneity issues affecting quantities and prices in equilibrium. Goolsbee (1998), one of the most influential studies of investment supply, circumvented these issues by using investment tax incentives as instruments for capital goods prices. More recently, however, several studies challenged Goolsbee's conclusions. Using an updated data set on capital goods prices, as well as a longer sample than Goolsbee, we found in Chapter 2 that investment subsidies have a negligible effect on capital goods prices. Other recent papers reached similar conclusions—see, for example Whelan (1999) and House and Shapiro

(2008). Without a strong link between investments subsidies and prices, a direct instrumental variables estimator would be subjects to the weak instruments problem.

Empirical Evidence on the Investment Supply Elasticity for Equipment and Structures. The structural investment supply curve (1) for type *m* implies the reduced form regression

$$\ln I_t^m = \alpha + \xi \cdot \ln p_t^m + e_t^m \ . \tag{6}$$

The reduced-form relationship between capital goods prices p_t^m and investment subsidies ι_t^m is

$$\ln p_t^m = \beta + \delta \cdot \iota_t^m + \eta_t^m \ . \tag{7}$$

Equations (6) and (7) represent a system of simultaneous equations. Although we do not directly estimate the parameters due to the weak instruments problem noted above, we evaluate the magnitude of the investment supply elasticity for equipment and structures using an indirect method proposed by Chernozhukov and Hansen (2008). Chernozhukov and Hansen show that their approach to inference is robust to weak identification, as well as to heteroskedasticity and serial correlation in the data. For a given candidate value ξ_0 of the investment supply elasticity, we regress the transformed dependent variable $\ln I_t^m - \xi_0 \cdot \ln p_t^m$ on the instrument, in this case the investment subsidy:

$$\ln I_t^m - \xi_0 \cdot \ln p_t^m = \gamma_0 + \gamma_1 \cdot \zeta_t^m + u_t^m. \tag{8}$$

Under the null hypothesis, the exclusion restriction implies that $\gamma_1 = 0$. Therefore, a test of the null that $\gamma_1 = 0$ in equation (8) is effectively a test of the hypothesis that $\xi = \xi_0$.

This approach is however, not without pitfalls, as it still requires that the instrument is exogenous. In the case of investment subsidies, most legislative changes were motivated by exogenous, long-run considerations, but there are also exceptions when investment subsidies were intended to provide countercyclical stabilization. An important and recent example is “bonus depreciation.” Chapter 2 discusses additional details about the nature of investment subsidies.

We consider a range of plausible values for the investment supply elasticity: 0.5, 1, 2, 5, 10 and 15. Pooled OLS results from the Chernozhukov-Hansen procedure with robust standard errors are presented in Table 4.3. For equipment, we fail to reject the medium to high elasticity scenarios $\xi = 5$, $\xi = 10$ and $\xi = 15$. This outcome is not surprising – in the data, equipment investment is more variable than equipment prices, which suggests that the elasticity of investment supply is high. For structures, we fail to reject the case when $\xi = 2$ and we strongly fail to reject the case when $\xi = 1$. These results indicate that the supply elasticity for structures is close to unity.

Our equipment results are consistent with the investment supply estimates in House and Shapiro (2008), who exploit theoretical arguments that elasticities for long-lived capital goods can be inferred directly from quantities when these assets receive temporary subsidies. Using the same dataset as in this study, and variation in investment during from the "bonus depreciation" period in 2002 and 2003, House and Shapiro estimate that the elasticity of investment supply is between 6 and 14 across several reduced-form specifications. These estimates were obtained by pooling both equipment and structures.

For structures, however, the Chernozhukov-Hansen inference method favors a low investment supply elasticity close to unity. Our analysis does not explain why the elasticity for structures is substantially lower than that for equipment. It is possible that the supply of structures is fundamentally different from the supply of equipment, particularly as equipment can be imported and exported, while for structures, production and purchases are virtually identical.

4.3.4 Estimation of the Stochastic Process for Investment Supply Shocks

Given the supply elasticity for type *m*, we can recover the implied time series of investment supply shocks directly from the supply equation (6). More precisely, the natural logarithm of the supply shock for a given type is

$$x_t^m = \ln p_t^m - \frac{1}{\xi^m} \ln I_t^m \tag{9}$$

We calibrate the elasticity of investment supply to ξ^{eqp} = 10 for equipment and ξ^{str} = 1.25 for structures based on the empirical evidence from section 4.3.3. above.

For all types of capital goods, the shock series implied by equation (9) is nonstationary. In Table 4.4 we show the results of augmented Dickey-Fuller tests for each capital types. We used a test specification with four lags and a trend. In almost all cases, we were not able to reject the null of a unit root in levels. We then estimate a reduced-form ARIMA(1,1,1) model for reach type, which is observationally equivalent to the unobserved components model in equations (2)–(4). The reduced-form estimates for equipment are reported in table 4.5 and the estimates for structures are reported in table 4.6.

From the reduced-form estimates, we calculate the structural parameters of the supply shock process for reach type, more specifically the drift in the permanent component μ^m and the autoregressive root in the transitory component ρ^m. Equipment types with economically significant drift parameters μ^m include communication equipment, electro-medical equipment and instruments, photocopy equipment and autos. Medical instruments and electrical transmission equipment also feature considerable drift parameters. In contrast, the drift estimates for structures are smaller than those for equipment, and most of them are not statistically significant. Among structures, they types with considerable drift are hospitals, medical buildings, communication and mining structures. If we interpret the permanent supply shock as investment-specific technological progress, these estimates imply a quarterly rate of technological advance on the order of one to two percent. In the data, negative drift parameters reflect the systematic decline in the real relative price of most types of investment goods over the past fifty years.

The autoregressive parameter ρ^m measures the persistence of transitory supply shocks. The estimates are generally indicate low to moderate persistence. No clear patterns in terms of the sign or magnitude of the parameters emerge. In the literature on investment shocks, transitory supply shocks correspond to the type of disturbances that drive business cycles.

Finally, we impose the structural parameters identified using the reduced-form results and we estimate the covariance matrix of the permanent and transitory components by maximum likelihood using the Kalman filter. Our variance estimates, presented in Tables 4.5 and 4.6, indicate that for most types of capital goods, both permanent and temporary shocks are substantial. The magnitude of the estimates is consistent with the investment shocks literature, particularly Justiniani et al. 2011 and Schmitt-Grohe and Uribe 2012 who found evidence that that temporary investment shocks are core drivers of business-cycle fluctuations. On average for equipment, the standard deviation of permanent shocks is 0.018 and that of temporary shocks is 0.010 in quarterly data. For structures, the standard deviation of permanent shocks is 0.004 and the standard deviation of temporary shocks is 0.002. Equipment types feature larger supply shocks. For both equipment and structures, permanent shocks are about twice as large as temporary shocks.

Interestingly, the temporary and permanent components are strongly negatively correlated. On average, the correlation of the shocks is -0.93 for equipment and -0.71 for structures. Investigating the reason we observe this pattern in the data is outside the scope of this analysis. If we adopt the interpretation that permanent shocks reflect technology change, and transitory shocks reflect disturbances in the marginal efficiency of the process through which the financial system converts savings into investment, the development of new technologies may be accompanied by inefficiencies in the financial sector, as financial intermediaries face a learning period to understand the innovations. Other studies have similarly found a negative correlation between the permanent and transitory components of GDP, notably Gali (1999), who provided evidence that hours and productivity are negatively correlated with technology shocks and used a New Keynesian model with monopolistic competition and sticky prices to reproduce these facts.

Our variance and correlation estimates are similar to those obtained by Morley *et al.* (2003), who studied the difference between the decomposition of GDP into its trend and cycle components using Beveridge-Nelson and an unobserved components model with uncorrelated shocks. The Beveridge-Nelson decomposition implies that the permanent trend is the primary source of variation, while the uncorrelated unobserved components decomposition indicates the opposite that the cycle dominates. However, once they authors relax the uncorrelated assumption, they find a negative correlation of -0.9, and the unobserved components implications are reversed—the permanent component assumes the primary role, as in the Beveridge Nelson decomposition. We also find that the permanent component of investment supply shocks is relatively more important than the transitory component.

The estimates of the permanent and temporary shocks are likely influenced by the prominent drop in real relative capital goods prices lasting approximately two years during the early 1970s. After a sharp increase in oil prices, the PCE price series used to construct relative investment-goods prices reacted very rapidly while the investment price indices reacted with a modest delay. The Nixon price controls also likely contributed to this episode, which is discussed in more detail in Chapter 2. The estimation procedure attributes this large, persistent drop to both the permanent and the transitory component. Researchers often assume that the innovations are uncorrelated in unobserved components models, however, in this case, allowing for correlation provides more flexibility for the estimation procedure to contend with the rich variation in the investment data.

With the estimated parameters, we use the Kalman filter to recover the smoothed shock series for each type. In Figure 4.1 we present investment, prices, and the two shocks for general industrial equipment, a representative equipment type. In Figure 4.2 we present the same series for manufacturing structures.

4.4. CONCLUSION

In this chapter, we characterize investment supply from a semi-structural perspective. We present empirical evidence that equipment supply is highly elastic, while the elasticity of structures supply is close to unity. We calibrate an isoelastic investment supply curve for each of 45 types of capital in our panel data. We assume that investment supply shocks, mechanically the residuals of the supply equation, consist of a permanent and transitory component. We estimate the parameters of the structural time-series model for each type and find that permanent and temporary investment supply shock are both considerable. For most types, temporary shocks generally have moderate persistence, and are negatively correlated with the permanent shocks. These results are consistent with the DSGE literature on investment supply shocks, which finds that both permanent and transitory investment supply shocks are substantial. The shock series obtained in this study can be embedded in structural general equilibrium models to generate aggregate fluctuations. We leave this exercise to future research.

TABLE 4.1. EQUIPMENT TYPES

	Depreciation (δ)	Investment Share (1990-2009)	Average Subsidy (1990-2009)
Computers and software	0.30	5.76%	41%
Communication equipment	0.30	6.05%	38%
Instruments	0.14	3.78%	40%
Photocopy and related equipment	0.18	0.68%	40%
Office and accounting equipment	0.15	0.41%	41%
Fabricated metal products	0.09	0.81%	39%
Steam engines	0.05	0.30%	35%
Internal combustion engines	0.21	0.13%	37%
Metalworking machinery	0.12	1.88%	40%
Industrial Equipment	0.11	5.55%	39%
Electrical transmission and distribution	0.05	1.46%	38%
Trucks, buses, and truck trailers	0.19	5.20%	40%
Autos	0.17	2.78%	40%
Aircraft	0.11	1.57%	41%
Ships and boats	0.06	0.22%	37%
Railroad equipment	0.06	0.41%	38%
Household furniture	0.12	0.14%	40%
Other furniture	0.12	2.22%	40%
Farm tractors	0.15	0.39%	40%
Other agricultural machinery	0.12	0.75%	40%
Construction tractors	0.16	0.15%	41%
Other construction machinery	0.16	1.33%	41%
Mining and oilfield machinery	0.15	0.32%	40%
Service industry machinery	0.17	1.26%	40%
Household appliances	0.17	0.31%	40%

Notes. Purchases data is from the BEA, production data from the NBER Productivity Database and depreciation rates come from Fraumeni (1997).

TABLE 4.2. STRUCTURES TYPES

	Depreciation (δ)	Investment Share (1990-2009)	Average Subsidy (1990-2009)
Commercial structures	0.02	6.86%	0.24
Hospitals, religious, education	0.02	3.15%	0.23
Manufacturing structures	0.03	2.32%	0.27
Electric structures	0.02	1.29%	0.32
Other power	0.02	0.46%	0.32
Communication	0.02	1.06%	0.33
Petroleum	0.06	1.99%	0.40
Railroad structures	0.02	0.35%	0.34
Farm structures	0.02	0.33%	0.29
Residential structures	0.01	34.14%	0.27

Notes. Purchases data is from the BEA, production data from the NBER Productivity Database and depreciation rates come from Fraumeni (1997).

TABLE 4.3. CHERNOZHUKOV-HANSEN TEST FOR THE INVESTMENT SUPPLY ELASTICITY

Equipment			Structures		
Supply Elasticity	χ_1^2 Statistic	p value	Supply Elasticity	χ_1^2 Statistic	p value
0.5	16.87	0.00	0.5	4.40	0.04
1	12.50	0.00	1	0.39	0.53
2	7.02	0.01	2	3.94	0.05
5	1.69	0.19	5	44.93	0.00
10	0.27	0.61	10	88.91	0.00
15	0.04	0.84	15	107.8	0.00

Notes. The Chernozhukov-Hansen test uses investment subsidies as instruments to test the null hypothesis that the investment supply elasticity $\xi = \xi_0$. Under the null hypothesis, we fail to reject the null that the estimates from a regression of $I - \xi p$ on the investment subsidy is significantly different from zero. The results indicate that the equipment supply is highly elastic, and that the elasticity of structures supply is close to unity.

TABLE 4.4. AUGMENTED DICKEY-FULLER TEST FOR UNIT ROOT IN INVESTMENT SUPPLY SHOCKS

Equipment	ADF Statistic	p value	Structures	ADF Statistic	p value
Communication equipment	0.38	1.00	Hospitals	-3.80	0.02
Electro-medical equipment	-0.88	0.96	Special care	-2.54	0.31
Medical instruments	-2.08	0.56	Medical buildings	-2.25	0.46
Nonmedical instruments	-2.56	0.30	Multimerchandise shopping	-2.27	0.45
Photocopy and related equipment	-1.37	0.87	Food and beverage	-0.29	0.99
Office and accounting equipment	-1.25	0.90	Warehouses	-1.44	0.85
Fabricated metal products	-2.10	0.54	Other commercial	-0.10	0.99
Steam engines	-2.41	0.37	Manufacturing	-3.00	0.13
Internal combustion engines	-1.74	0.73	Electric	-2.07	0.56
Metalworking machinery	-1.38	0.87	Other power	-4.15	0.01
Special industry machinery, n.e.c.	-1.50	0.83	Communication	-1.82	0.69
General industrial	-3.34	0.06	Petroleum and natural gas	-0.99	0.95
Electrical transmission, distribution	-3.32	0.06	Mining	-1.65	0.77
Trucks, buses, and truck trailers	-2.21	0.49	Religious	-1.40	0.86
Autos	-1.66	0.77	Educational	-1.31	0.88
Aircraft	-2.59	0.28	Railroads	-2.04	0.58
Ships and boats	-1.85	0.68	Farm	-1.76	0.72
Railroad equipment	-2.09	0.55	Multifamily structures	-2.32	0.42
Household furniture	-1.51	0.83			
Other furniture	-3.17	0.09			
Farm tractors	-1.35	0.88			
Other agricultural machinery	-1.64	0.78			
Construction tractors	-2.32	0.42			
Other construction machinery	-2.24	0.47			
Mining and oilfield machinery	-1.56	0.81			
Service industry machinery	-2.61	0.28			
Miscellaneous electrical	-2.54	0.31			
Household appliances	-2.73	0.23			

TABLE 4.5. INVESTMENT SUPPLY ESTIMATES: EQUIPMENT

	ARIMA				UC		
	$\mu(1-\rho)$	μ	ρ	θ	$\sigma_{x,perm}$	$\sigma_{x,trans}$	*corr*
Communication equipment	-0.009	-0.016	0.433	-0.018	0.020	0.013	-0.998
	(0.002)		(0.110)	(0.122)	(0.008)	(0.003)	(0.120)
Electro-medical equipment	-0.005	-0.009	0.405	-0.071	0.020	0.012	-0.951
	(0.002)		(0.212)	(0.217)	(0.009)	(0.004)	(0.193)
Medical instruments	-0.003	-0.003	-0.184	0.525	0.014	0.004	-0.964
	(0.001)		(0.183)	(0.176)	(0.007)	(0.004)	(0.231)
Nonmedical instruments	-0.001	-0.001	0.072	0.321	0.016	0.010	-0.946
	(0.002)		(0.224)	(0.227)	(0.007)	(0.004)	(0.182)
Photocopy and related equipment	-0.009	-0.018	0.521	-0.267	0.019	0.007	-0.878
	(0.002)		(0.215)	(0.245)	(0.008)	(0.004)	(0.216)
Office and accounting equipment	-0.006	-0.012	0.469	-0.083	0.015	0.010	-0.856
	(0.002)		(0.134)	(0.142)	(0.006)	(0.006)	(0.426)
Fabricated metal products	0.001	0.001	0.362	-0.031	0.016	0.004	-0.986
	(0.002)		(0.179)	(0.193)	(0.006)	(0.004)	(0.235)
Steam engines	0.001	0.000	-1.035	1.035	0.030	0.026	-0.988
	(0.002)		(0.001)	(0.001)	(0.012)	(0.016)	(0.440)
Internal combustion engines	0.001	0.001	0.433	-0.268	0.018	0.015	-0.987
	(0.002)		(0.357)	(0.369)	(0.007)	(0.009)	(0.480)
Metalworking machinery	0.001	0.001	0.274	0.171	0.015	0.010	-0.951
	(0.002)		(0.163)	(0.182)	(0.006)	(0.003)	(0.220)
Special industry machinery, n.e.c.	0.002	0.002	0.023	0.284	0.015	0.011	-0.973
	(0.001)		(0.206)	(0.208)	(0.006)	(0.005)	(0.261)
General industrial	0.001	0.001	-0.053	0.437	0.015	0.009	-0.905
	(0.001)		(0.178)	(0.177)	(0.006)	(0.003)	(0.236)
Electrical transmission, distribution	-0.002	-0.004	0.429	0.000	0.015	0.005	-0.873
	(0.002)		(0.138)	(0.157)	(0.006)	(0.003)	(0.238)

Notes. These estimates assume the elasticity of equipment supply is $\xi^{eqp} = 10$. On average, the variance of the permanent shock is 0.018 and the variance of the temporary shock is 0.010. The correlation of the two shocks is = -0.927.

TABLE 4.5. INVESTMENT SUPPLY ESTIMATES: EQUIPMENT (CONTINUED)

	ARIMA				UC		
	$\mu(1-\rho)$	μ	ρ	θ	$\sigma_{x,perm}$	$\sigma_{x,trans}$	*corr*
Trucks, buses, and truck trailers	-0.001	-0.002	0.244	0.280	0.020	0.012	-0.925
	(0.003)		(0.118)	(0.114)	(0.008)	(0.003)	(0.208)
Autos	-0.005	-0.006	0.178	0.139	0.022	0.017	-0.999
	(0.003)		(0.215)	(0.228)	(0.008)	(0.007)	(0.235)
Aircraft	0.002	0.001	-0.691	0.619	0.018	0.010	-0.915
	(0.002)		(0.407)	(0.426)	(0.008)	(0.004)	(0.141)
Ships and boats	0.002	0.005	0.623	-0.735	0.017	0.013	-0.962
	(0.001)		(0.187)	(0.174)	(0.007)	(0.005)	(0.256)
Railroad equipment	0.001	0.001	-0.060	0.364	0.022	0.017	-0.999
	(0.002)		(0.205)	(0.202)	(0.009)	(0.006)	(0.227)
Household furniture	-0.001	-0.001	-0.421	0.626	0.014	0.004	-0.788
	(0.001)		(0.248)	(0.228)	(0.006)	(0.003)	(0.385)
Other furniture	0.000	0.000	-0.315	0.651	0.015	0.010	-0.983
	(0.001)		(0.156)	(0.137)	(0.006)	(0.003)	(0.151)
Agricultural machinery	0.002	0.001	-0.488	0.762	0.021	0.008	-0.887
	(0.001)		(0.154)	(0.108)	(0.009)	(0.005)	(0.200)
Construction machinery	0.002	0.002	-0.329	0.601	0.020	0.007	-0.853
	(0.002)		(0.174)	(0.158)	(0.010)	(0.005)	(0.251)
Mining and oilfield machinery	0.002	0.003	0.346	-0.260	0.017	0.005	-0.964
	(0.002)		(0.529)	(0.523)	(0.007)	(0.004)	(0.191)
Service industry machinery	-0.001	-0.001	-0.325	0.612	0.019	0.004	-0.982
	(0.001)		(0.183)	(0.165)	(0.007)	(0.004)	(0.246)
Miscellaneous electrical	-0.003	-0.003	-0.010	0.267	0.016	0.005	-0.904
	(0.002)		(0.228)	(0.209)	(0.007)	(0.004)	(0.187)
Household appliances	-0.003	-0.002	-0.584	0.682	0.017	0.006	-0.884
	(0.001)		(0.293)	(0.281)	(0.007)	(0.004)	(0.194)

Notes. These estimates assume the elasticity of equipment supply is $\xi^{eqp} = 10$. On average, the variance of the permanent shock is 0.018 and the variance of the temporary shock is 0.010. The correlation of the two shocks is = -0.927.

TABLE 4.6. INVESTMENT SUPPLY ESTIMATES: STRUCTURES

	ARIMA				UC		
	$\mu(1-\rho)$		ρ	θ	$\sigma_{x,perm}$	$\sigma_{x,trans}$	$corr$
Hospitals	-0.003	-0.004	0.206	-0.009	0.003	0.002	-0.987
	(0.003)		(0.324)	(0.334)	(0.000)	(0.000)	(0.317)
Special care	-0.001	-0.002	0.269	-0.019	0.004	0.001	-0.777
	(0.004)		(0.264)	(0.273)	(0.001)	(0.000)	(0.323)
Medical buildings	-0.002	-0.003	0.249	0.006	0.003	0.001	-0.853
	(0.004)		(0.259)	(0.260)	(0.001)	(0.000)	(0.272)
Multimerchandise shopping	0.001	0.002	0.549	-0.304	0.004	0.002	-0.989
	(0.005)		(0.245)	(0.262)	(0.001)	(0.001)	(0.319)
Food and beverage	0.003	0.004	0.431	-0.337	0.004	0.004	-0.986
	(0.005)		(0.683)	(0.692)	(0.001)	(0.003)	(0.842)
Warehouses	0.000	0.001	0.580	-0.300	0.004	0.003	-0.997
	(0.005)		(0.142)	(0.158)	(0.001)	(0.001)	(0.279)
Other commercial	0.001	0.003	0.563	-0.273	0.004	0.002	-0.919
	(0.005)		(0.213)	(0.250)	(0.001)	(0.000)	(0.268)
Manufacturing	0.000	-0.001	0.653	-0.419	0.005	0.000	-0.938
	(0.006)		(0.180)	(0.210)	(0.001)	(0.000)	(0.419)
Electric	-0.001	0.000	-0.816	0.914	0.004	0.001	-0.322
	(0.004)		(0.081)	(0.058)	(0.001)	(0.001)	(1.496)
Other power	0.001	0.003	0.559	-0.150	0.007	0.001	-0.919
	(0.007)		(0.102)	(0.100)	(0.001)	(0.000)	(0.167)
Communication	-0.004	-0.007	0.343	-0.268	0.003	0.000	-0.475
	(0.003)		(0.752)	(0.775)	(0.000)	(0.000)	(1.020)
Petroleum and natural gas	0.007	0.009	0.126	0.062	0.007	0.005	-0.999
	(0.006)		(0.279)	(0.291)	(0.001)	(0.001)	(0.328)
Mining	-0.003	-0.007	0.534	0.261	0.006	0.001	-0.984
	(0.008)		(0.092)	(0.098)	(0.001)	(0.000)	(0.090)
Religious	0.004	0.005	0.203	-0.278	0.002	0.002	-0.966
	(0.003)		(0.783)	(0.772)	(0.000)	(0.002)	(0.805)
Educational	0.001	0.008	0.930	-0.911	0.004	0.003	-0.869
	(0.005)		(0.231)	(0.262)	(0.001)	(0.036)	(12.409)
Railroads	0.000	0.000	-0.499	0.068	0.002	0.001	0.475
	(0.003)		(0.101)	(0.137)	(0.000)	(0.001)	(0.143)
Farm	0.004	0.007	0.444	-0.225	0.004	0.003	-0.998
	(0.004)		(0.274)	(0.288)	(0.001)	(0.001)	(0.320)
Multifamily structures	-0.003	-0.003	0.171	-0.405	0.001	0.000	0.769
	(0.002)		(0.218)	(0.213)	(0.000)	(0.000)	(0.245)

Notes. These estimates assume the elasticity of structures supply is ξ^{str} = 1.25. On average, the variance of the permanent shock is 0.004 and the variance of the temporary shock is 0.002. The correlation of the two shocks in -0.707.

FIGURE 4.1. INVESTMENT PRICES AND INVESTMENT SUPPLY SHOCKS, GENERAL INDUSTRIAL EQUIPMENT

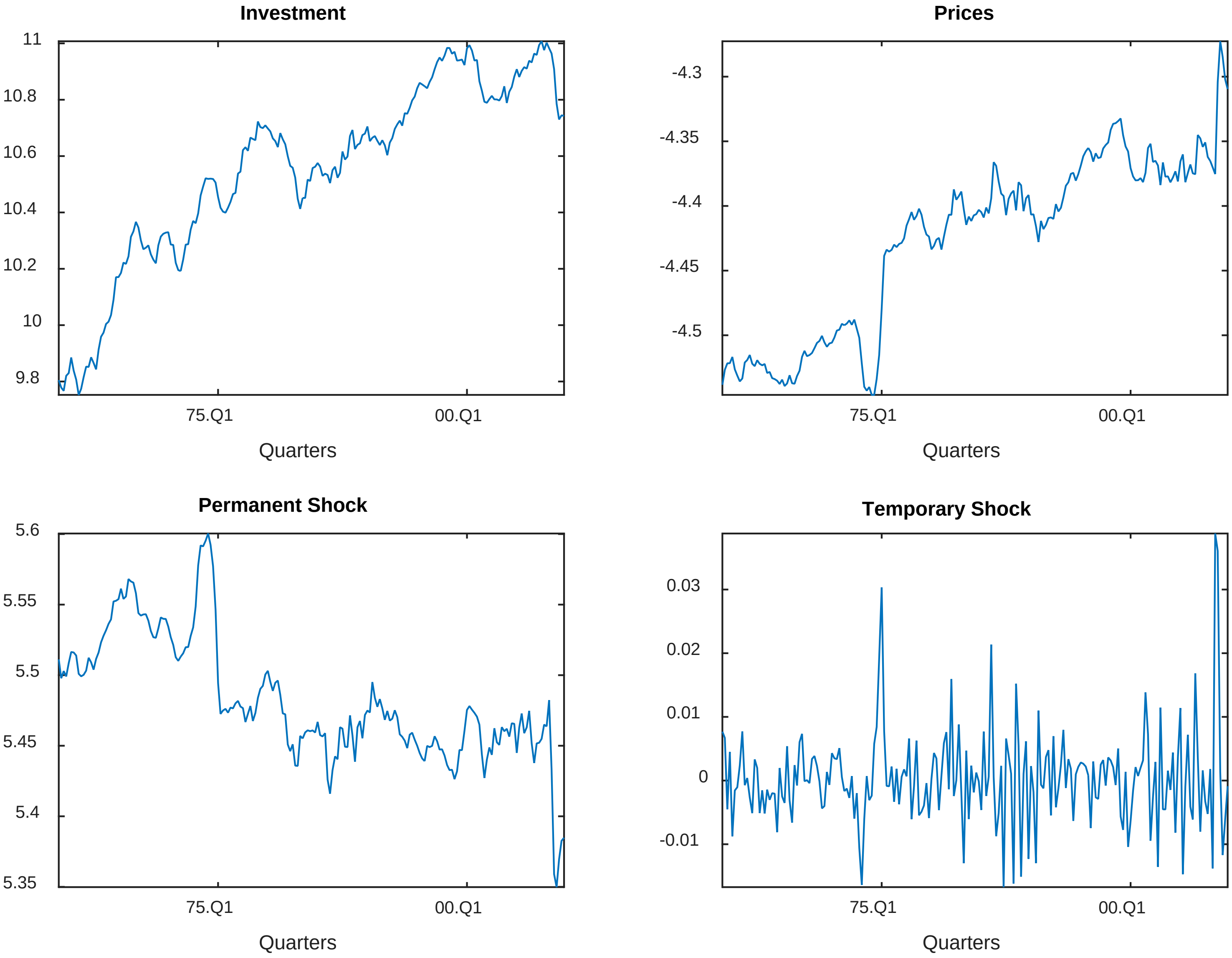
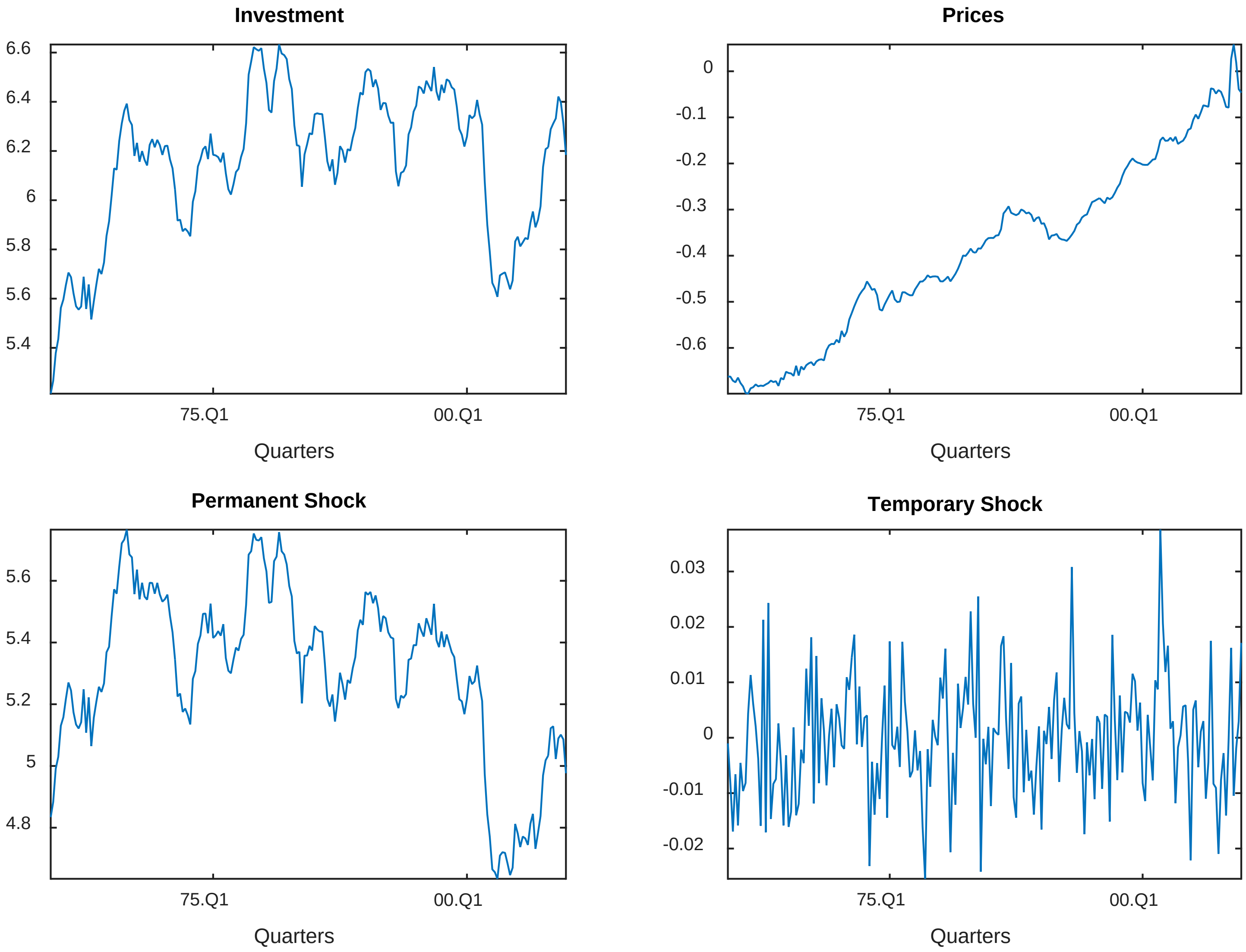


FIGURE 4.2. INVESTMENT PRICES AND INVESTMENT SUPPLY SHOCKS, MANUFACTURING STRUCTURES



APPENDIX 4.A

ARIMA(1,1,1) REPRESENTATION OF UC-ARMA(1,0) MODEL

The unobserved components model in equations (2)–(4) is also known as a UC-ARMA(1,0) model, in other words it is the sum of a stochastic trend, a random walk with drift in this case, and a stationary ARMA(1,0) process. In this appendix, we derive the univariate ARIMA representation for this model. Using equation (2) and rearranging terms we can write

$$x_t^m - \rho^m x_{t-1}^m = \left(x_t^{m,perm} - \rho^m x_{t-1}^{m,perm}\right) + \left(x_t^{m,trans} - \rho^m x_{t-1}^{m,trans}\right). \tag{1}$$

Iterating backwards one period we obtain

$$x_{t-1}^m - \rho^m x_{t-2}^m = \left(x_{t-1}^{m,perm} - \rho^m x_{t-2}^{m,perm}\right) + \left(x_{t-1}^{m,trans} - \rho^m x_{t-2}^{m,trans}\right). \tag{2}$$

Subtracting (2) from (1), applying the difference operator on the left-hand side and rearranging yields

$$\begin{aligned}\Delta x_t^m - \rho^m \Delta x_{t-1}^m = &\left(x_t^{m,perm} - x_{t-1}^{m,perm}\right) - \rho^m \left(x_{t-1}^{m,perm} - x_{t-2}^{m,perm}\right) + \\ &+ \left(x_t^{m,trans} - \rho^m x_{t-1}^{m,trans}\right) - \left(x_{t-1}^{m,trans} - \rho^m x_{t-2}^{m,trans}\right)\end{aligned}. \tag{3}$$

We substitute in equations (3) and (4) to simplify expression (3) and we obtain

$$\Delta x_t^m - \rho^m \Delta x_{t-1}^m = \left(\mu^m + \varepsilon_t^{m,perm}\right) - \rho^m \left(\mu^m + \varepsilon_{t-1}^{m,perm}\right) + \varepsilon_t^{m,trans} - \varepsilon_{t-1}^{m,trans}. \tag{4}$$

The composite innovation on the right hand side has non-zero autocorrelations only up to one lag, so it admits an MA(1) representation. This implies that the unobserved components model corresponds to a univariate (reduced-form) ARIMA(1,1,1) process

$$\Delta x_t^m = \mu^m \left(1 - \rho^m\right) + \rho^m \Delta x_{t-1}^m + e_t + \theta^m e_{t-1} \tag{5}$$

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