Declining Effects of Oil-price Shocks

Job Market Paper

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Abstract

Output responses to oil-price shocks not only tend to be weaker, but also to peak earlier recently. This paper builds a model that incorporates a realistic structure of US petroleum consumption and explores three possible explanations for the changes. The first is based on deregulation in the transportation sector, which has brought more competition and improved efficiency in the industry. The second is overall improvements in use of energy. The third is less persistence of the oil-price shock. Under realistic parameter values, it is demonstrated that all three factors play an important role quantitatively. These three factors together could account for a 51% reduction in the peak response of output to an oil-price shock.

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1 Introduction

Macroeconomic consequences of large increases in the price of oil have been of great concern among economists and policy makers, as well as the general public since two major oil-price shocks hit the economy in the 1970's. In recent years, however, it seems that the effect of oil-price shocks has been decreasing. For example, the Congressional Budget Office reports that:

> Contrary to general expectations, the large and persistent rise in energy prices that has occurred over the past two and a half years has not caused substantial problems for the overall U.S. economy. Although many households have had trouble adjusting to the higher prices, the effects on the nation's gross domestic product (GDP), employment, and inflation have thus far been moderate. (Congressional Budget Office, 2006, p.VII)

It is well known that, after World War II, nine out of ten recessions in the US economy were preceded by large increases in the oil price. A general perception is that oil-price increases may cause a prolonged and deep recession. In fact, a number of studies have tested the relation between economic activity and oil prices and have confirmed that it is not a statistical coincidence.[1] There have been substantial hikes in the oil price in the early 2000's. A couple of events, such as the civil unrest in Venezuela in 2002, the Iraq war of 2003, and Hurricanes Katrina and Rita in 2005, triggered increases in the oil price. During 2006, the nominal oil price has reached value more than three times as high as the average price in the 1990's. However, we have not observed any evidence of economic downturn yet, as of the writing of the paper.[2]

In order to see the possible changes in the US economy over time, Figure 1 plots different behavior of macroeconomics variables after a 10% increase in the net oil price increase

[1] Those studies include Hamilton (1983), Burbidge and Harrison (1984), Gisser and Goodwin (1986), Daniel (1997), Carruth, Hooker, and Oswald (1998), and Hamilton (2003). However, Bernanke, Gertler, and Watson (1997) argue that oil-price shocks were not a major cause of economic downturns. See also subsequent discussions in Hamilton and Herrera (2004) and Bernanke, Gertler, and Watson (2004). Barsky and Kilian (2002, 2004) also raise a skeptical view about the role of the oil-price shocks in recessions in the 1970's.

[2] The GDP-based recession probability index of Chauvet and Hamilton (2006) indicates 26.2% probability of recession as of the first quarter of 2007.

(NOPI) of Hamilton (1996, 2003). These impulse response functions describe average behavior following a 10% increase in oil prices above their previous 3-year high. Sample periods are split into two sub-samples at 1984, following McConnell and Perez-Quiros (2000). As can be seen clearly, we can observe different patterns in response to the oil-price shock, measured by an increase in the NOPI, in two sub-samples.[3] Not only output but also other variables display weaker responses to the oil-price shock in the post-1984 period. This is very robust to different specifications. Furthermore, the peak of the output responses appears earlier in the post-1984 sub-sample than the pre-1984 sub-sample. On average, the output responses peak at 5 quarters after the shock with a -1.76% decline compared to the unshocked path in the pre-1984 sub-sample, whereas, in the post-1984 periods, the responses peak at 2 quarters after the shock only with a -0.35% drop from the unshocked path. The peak response of output declines by 80% and the peak is shifted by 3 quarters. This suggests that there have been some changes in the economy.

This paper takes the evidence presented in Figure 1 seriously and explores possible explanations why we expect to observe the weaker responses of macroeconomic variables to the same size of the oil-price shock. Most of existing studies have focused mainly on recessionary consequences of oil-price shocks (e.g., Kim and Loungani, 1991; Rotemberg and Woodford, 1996; Finn, 2000; Leduc and Sill, 2004; Carlstrom and Fuerst, 2006; Aguiar-Conraria and Wen, 2005; Cavallo and Wu, 2007) and have not addressed the issue of weaker effects of oil-price shocks. The only exception is Blanchard and Galí (2007), who ask the same question as this paper does. In order to answer the question, they investigate four different hypotheses; (a) good luck (i.e., lack of concurrent adverse shocks), (b) smaller share of oil in production, (c) more flexible labor markets, and (d) improvements in monetary policy. They conclude that all four factors have played an important role in accounting for the mild effects on inflation and economic activity.

Besides the hypotheses Blanchard and Galí (2007) have considered, there are also other possibilities for the reason why we might expect the effect of the oil-price shock on economic activity has become weaker. In this paper, I will analyze three possible explanations for the

[3]Early studies, such as Mork (1989) and Hooker (1996), also document that, as the sample period is extended, the relation between oil prices and macroeconomy is weakened.

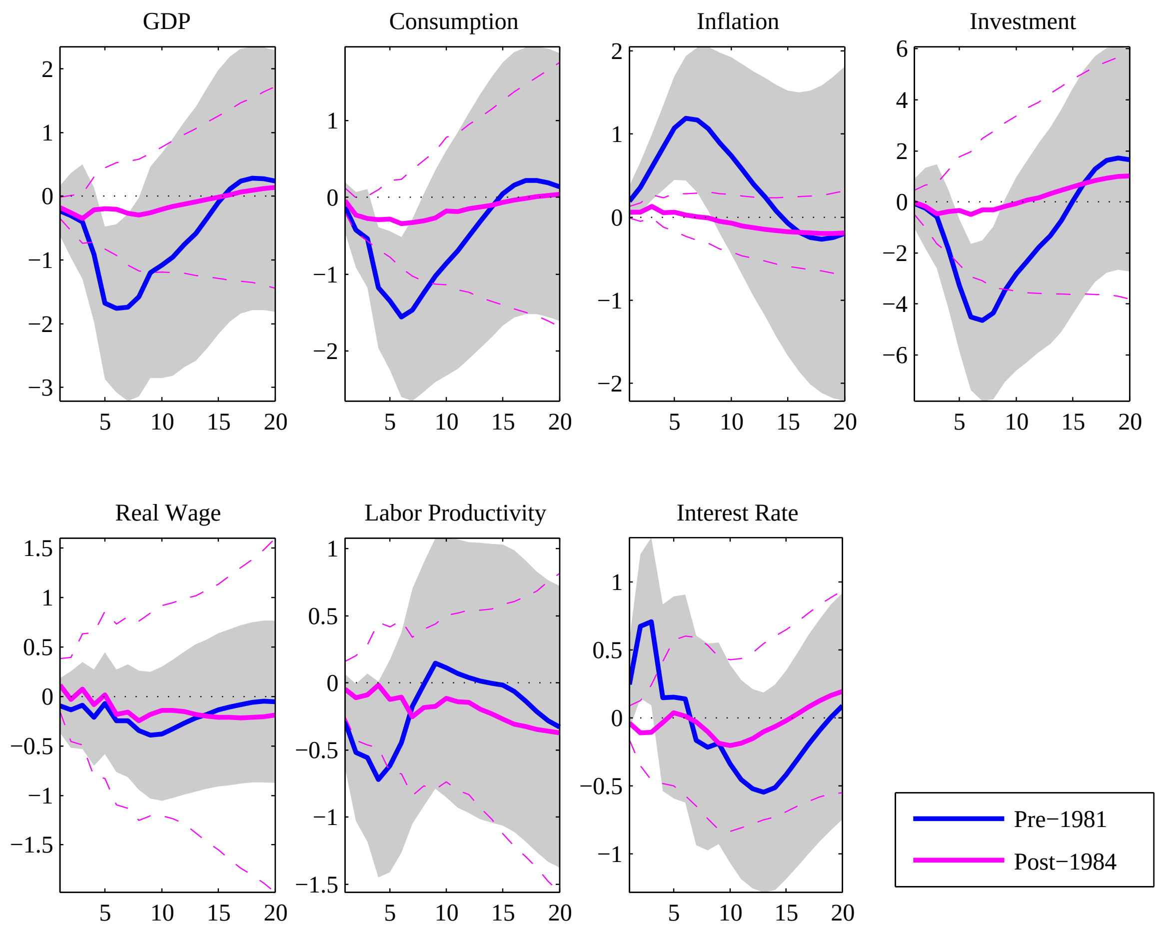

Figure 1: Different Responses to the Oil-price Shock: Before and After 1984

Note: Each panel plots responses to a 10% increase in NOPI. These impulse responses are obtained from 8-variable VAR with 4 lags, which is similar to the specification in Christiano, Eichenbaum, and Evans (2005). Variables included are NOPI, real GDP, real consumption, GDP deflator, real investment, real wage, labor productivity, and interest rate. A constant term is included as well. Data are quarterly. Except for NOPI, all variables are logged and retrieved from the FRED database of the FRB St. Louis. Horizontal axes indicate quarters and the vertical axes take percentage deviations from the unshocked path. Shaded areas represent 95% confidence bands for the Pre-1984 IRFs, while dashed lines show those for the Post-1984 IRFs.

declining effect of oil-price shocks in detail. The first factor investigated is the outcome of deregulation, especially in the US transportation industry. When we consider the macroeconomic consequences of an oil-price shock, we usually have the industrial/commercial sector in mind in terms of petroleum consumption. It is always helpful to look at data first to see how petroleum is used across sectors. Figure 2 shows petroleum consumption in the US economy from 1949 to 2005 obtained from the Energy Information Administration (EIA).

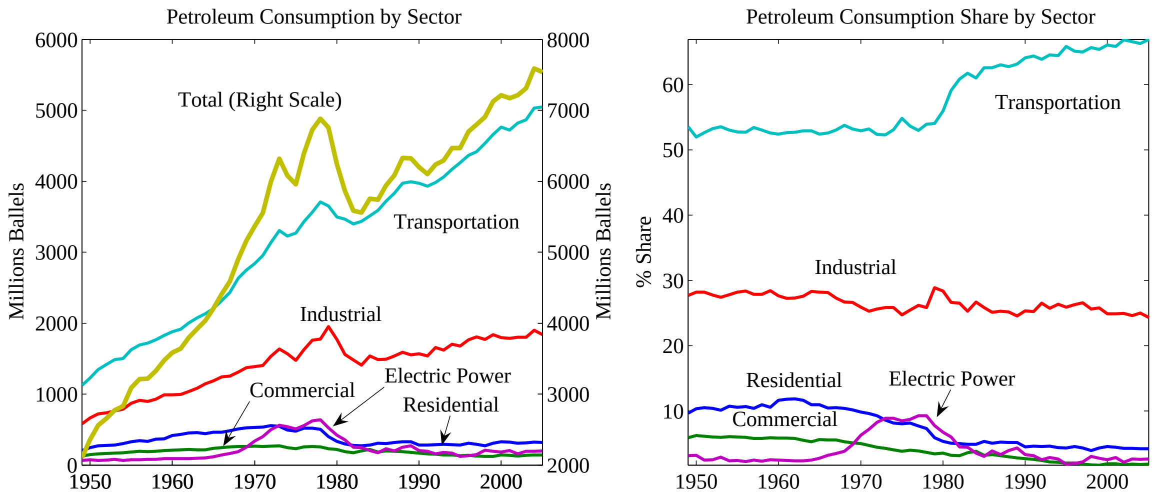

Figure 2: Petroleum Consumption by Sector 1949–2005
Sources: Department of Energy, Energy Information Administration (2006), *Annual Energy Review 2005*, Table 5.13a–5.13d.

It reveals that contrary to common treatment in the existing models, more than a half of the US petroleum consumption is coming from the transportation sector. Thus, it suggests that it is important to pay more attention to the role of petroleum consumption in transportation. Commercial transportation had been one of the most regulated industries in the US economy. This regulatory environment had created inefficiencies and economic rents, and deregulation resulted in lower costs and a more competitive environment. In this paper, in addition to the typical industrial sector, I explicitly model the role of the transportation industry in order to account for the effect of the deregulation in the transportation industry that began in 1980.

Another possibility I will examine is the effect of improvements in energy efficiency and hence less dependence of the US economy on petroleum as a source of energy. After the two oil-price shocks in the 1970's, technological advances enabled us to utilize petroleum more efficiently. For example, vehicles' miles per gallon improved dramatically. According to the Energy Information Administration (2006), from 1973 to 1991, miles per gallon (all motor vehicles) improved 42%. This more efficient use of oil is apparent in terms of the oil expenditure share in value added. While average oil expenditure share relative to GDP was 3.65% in the pre-1984 periods, the average share declines in the post-1984 periods to 2.75%. This point is similar to one of factors considered in Blanchard and Galí (2007). Since there

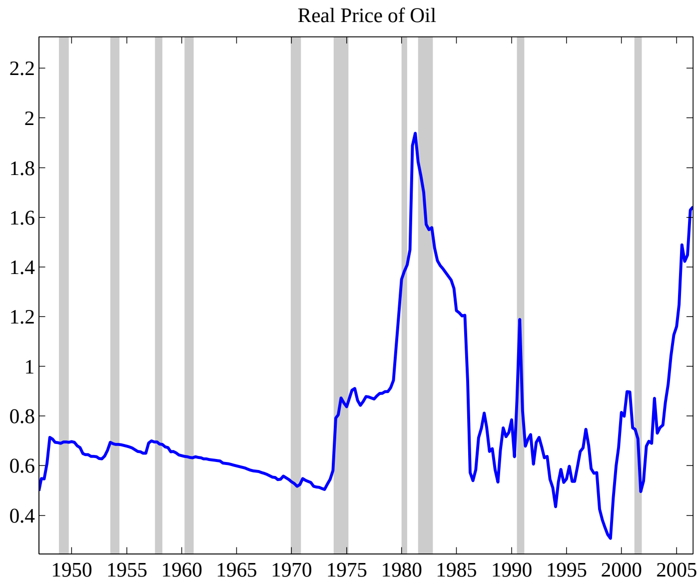

Figure 3: Real Price of Oil

exist two types of oil usage in the model, industrial sector and transportation sector, it is possible to analyze the consequence of improved energy efficiency in more detail. In this sense, this paper is complimentary to Blanchard and Galí (2007).

Lastly, I also consider a possible effect of changes in persistence of the oil-price shock. Small changes in the underlying shocks process could alter the responses of macroeconomic variables. Figure 3 plots real price of oil measures by the PPI of crude petroleum deflated by GDP deflator. Judging from data, it is clear that the oil-price behavior shows different patterns after the mid 1980's. Particularly, it tends to be less persistent compared to the near-unit-root nature of the oil price we have observed up until the mid 1980's. The goal of the paper is to investigate the role of these three factors in accounting for the two changes observed in the time series data, that is, weaker responses of output and the earlier timing of the peak.

The model is based on a standard model with price and nominal wage adjustment costs. I extend the standard sticky-price model to include the role of oil prices into the economy in two ways. As in Finn (2000), variable capital utilization tied to petroleum consumption is introduced in the intermediate-good production process. Another extension is to include a transportation sector as an additional sector in the economy. It is assumed that all produced intermediate products must be delivered to customers by using transportation services. Including transportation firms amplifies the effects of the oil-price shock, because, as will be described in Section 2, transportation firms had significant market power before the deregulation. It should be noted that, although there are empirical studies documenting possible asymmetric effects on the economic activity (see, for example, Davis and Haltiwanger, 2001; Hamilton, 2003)[4], like other existing models, the structure of the model considered here implies that increases and decreases in the price of oil would have symmetric effects. However, the focus of this paper is on the recessionary consequences following a large increase in the price of oil and on accounting for the changes in the economy over time.

The baseline specification of the model, which corresponds to the pre-1984 state of the economy, well captures important aspects of the economy's response to the oil-price shock, under reasonable parameter values. In terms of accounting for the changes in the economy overtime, each factor individually could account for about a 20-25% decline in the peak response of aggregate value added. Combined together, the three factors result in a 51% reduction in the peak response and shift the timing of the peak by 2 quarters, compared with the baseline specification.

The rest of the paper is organized as follows. Section 2 provides some background information on regulation in the US transportation industry, as well as petroleum consumption of the transportation sector. Section 3 presents a model that we can use for assessing the three possible factors. Results are in Section 4 and Section 5 concludes.

2 Transportation Industry Background

2.1 Petroleum Consumption for Transportation

As mentioned in the Introduction, most of US petroleum consumption comes from the transportation sector. One caveat is that the EIA's definition of the transportation sector includes the supply-side petroleum consumption as well as petroleum use of households for driving automobiles. The EIA does not have data on how much petroleum can be attributed to fuel of household vehicles except for selected years. Based on the information in the EIA's

[4]Although the asymmetric effects of oil-price shocks are widely believed, Kilian (2007) summarizes supporting evidence for the symmetric responses of monthly real consumption expenditure based on formal statistical tests and suggests that nonresidential investment could be a source of the asymmetry.

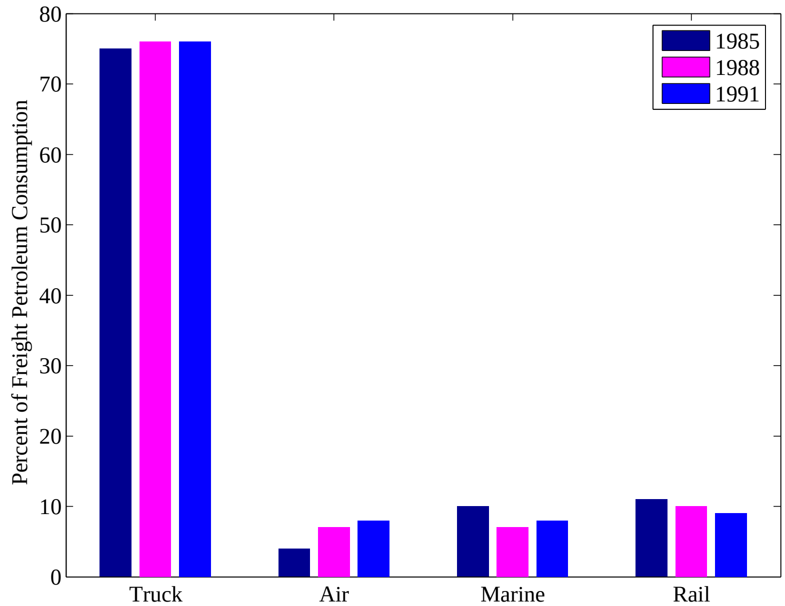

Figure 4: Petroleum Consumption in the Transportation Industry by Mode

Source: Department of Energy, Energy Information Administration (1995), *Measuring Energy Efficiency In The United States' Economy: A Beginning*, Figure 5.17

"*Household Vehicles Energy Use: Latest Data & Trends*" [5], about 52% of petroleum is used by household vehicles in the transportation sector after the late 1980's. Therefore, even when we take account of household vehicle use, the transportation service industry itself consumes as much oil as the whole industrial sector does.

Figure 4 displays the share of oil consumption in the transportation sector by mode. As can be seen clearly, within the transportation industry, the trucking industry is a major source of oil consumption. Any investigation of the recessionary consequences of oil-price shocks needs to pay particular attention to the trucking industry.

2.2 Regulation in the Transportation Industry

The U.S. transportation industry in the 1970's was heavily regulated by the Interstate Commerce Commission (ICC), which was established by the Interstate Commerce Act of 1887. The ICC regulated prices and competition in interstate transportation. Starting from railroads, the control of the ICC was expanded to a variety of transportation modes, such as

[5] Available at http://www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/.

trucking, water transportation, oil pipeline, and freight forwarders. The trucking industry is likely to be a good example of a perfectly competitive industry, if there is no regulation in the industry (Olson, 1972). Such a regulatory environment in the transportation industry imposed by the ICC had reduced competition and created significant inefficiency. However, the regulatory environment came to an end in 1980. The Motor Carriers Act of 1980 and the Staggers Rail Act of 1980 triggered deregulation in the transportation industry. Throughout the 1980's, the control of the ICC had been diminishing. Ultimately, all of regulations were removed in 1995 when the ICC was abolished.

Regulations by the ICC primarily consisted of restrictions on operating rights and a requirement of filing price changes. The ICC controlled new entries by granting operating certificates, which specified a scope of operation, such as a list of routes, commodities, and areas that carriers may serve. A new certificate was issued if it can be proven that the new service contributed to the public convenience and necessity and that incumbent carriers were unable to provide the service. New applications were frequently protested by incumbent carriers. This procedure was also applicable to incumbents expanding their scope of operations, such as more variety of commodities and operation routes. Such a difficulty led many firms to purchase the operating authorities of other carriers. The market value of those operating rights could be a measure of the monopolistic rents. In fact, those operating rights were listed as assets on regulated firms' books. Snow and Sobotka (1977) report that the market value of the operating rights amounted to 15-20% of gross annual revenues. The ICC's control of operating rights created not only market power, but also inefficiencies. Restrictions on routes and products often resulted in empty backhauls. For example, based on the 1976 ICC study, Wright (1983) argues that about 38% of interstate and 71% of intrastate backhauls were empty.

In addition to the entry control, regulated carriers were required to file all changes in their rates with the ICC, thirty days prior to the new rate becoming effective. Within thirty days, the proposal of a new price was subject to objections from anyone, including the ICC itself and competitors (both those in the same transportation mode and from different types of carriers). Once the proposal was protested, the ICC would investigate its reasonableness. Ratemaking and filing to the ICC were usually done in a collective manner, via regionally distributed rate bureaus. Those rate bureaus approved by the ICC had been operated under antitrust immunity since 1948 (the Reed-Bulwinkle Act). Although the ICC required rate bureaus to be open and democratic, investigations done by the U.S. congress and the ICC revealed that "these rate bureaus are, for most part, dominated by small groups of large carriers" (U.S. Congress, Senate, 1980, p. 60). Due to limited resources of the ICC reviewing proposed tariffs,[6] virtually it was the case that "[t]he carriers set their own rate" (U.S. Congress, Senate, 1980, p. 80).

The rate bureau system ensured that protestants could impose substantial costs on applicants trying to underprice other carriers, and hence created an incentive not to lower prices. An individual carrier could propose selective rate changes. Such proposals were usually forwarded to the standing rate committee, which set up a public hearing on the proposal. Any interested parties could participate, regardless of whether they were directly affected by the proposal. Frequently, those proposals were opposed by other carriers, sometimes causing the ICC to investigate the proposed rate, and making rate changes extremely time-consuming and difficult. The ICC might then suspend the rate and call for a formal investigation of its legality. It was possible for an individual carrier to file an independent action to the ICC without going through the review at the rate bureau. However, most of rate bureaus required the independent action to be informed before taking effect and other carriers had an option of whether to join in the new rate or not. Thus, the rate bureau system under the ICC regime created an incentive not to lower prices and discouraged competitive pricing in the industry.

These regulations and controls by the ICC had created oligopolistic environment in the transportation industry. For example, Winston (1981) estimates the markup over marginal cost for various commodity categories. Among regulated commodities, the estimated markup rates range from 29% to 64% (with the mean of 52.2%) for railroads and those for trucking range from 26% to 49% (with the mean of 37.1%).

The deregulation resulted in freer entries and more flexible expansions of the scope of business. The Motor Carriers Act of 1980 eliminated entry barriers. It required the ICC to

[6] For example, according to the report from U.S. Congress, Senate (1980), 278,039 tariff publications were filed to the ICC in 1978. On average, 5,000 pages of tariffs are filed daily. However, there were only 60 employees at the ICC who were in charge of checking those tariffs.

grant operating rights to any requesting firm that is able to provide the service. The burden of proof was reversed. Although, prior to the Motor Carriers Act of 1980, new entrants had been required to prove the necessity of new service, opponents were asked to provide evidence why the new service was not beneficial. Furthermore, route restrictions were eliminated as well. By 1986, the number of motor carriers holding ICC operating certificates was more than doubled compared with 1980 (Winston, Corsi, Grimm, and Evans, 1990, p.12).

The Motor Carriers Act of 1980 also increased price flexibility. It guaranteed individual motor carriers and freight forwarders complete freedom to change rates as long as price changes are within the $\pm 10\%$ range compared with the level one year prior to a specified point of reference. The ICC could increase the range up to 15% for rate increases in any year that it finds that there is sufficient competition to regulate rates, and that the carriers, shippers and the public would derive a benefit from the increased flexibility. The law prohibited the use of the rate bureau for single-line rate making. Although the rate bureaus themselves were not abolished, expanded independent actions increased pricing flexibility and reduced importance of the rate bureau system.

Overall, the net effect of the deregulation can be summarized as higher efficiency and more competition, which led to lower average costs. Ying and Keeler (1991) estimate the effect of deregulation on rates charged by motor carriers, controlling for various factors, such as changes in primary factor prices and fuel costs. They find that, on average, prices decreased by 15-20% within three years after the deregulation and that prices further dropped by 25-35% by 1985. Nebesky, McMullen, and Lee (1995) estimate and compare the markup rate of the less-than-truckload segment of the trucking industry before and after the deregulation. They find that the estimated markup has declined dramatically after the deregulation. While the estimated markup rate using a 1977 sample is 35.5%, the estimate based on 1988 data is 1.9%.

In terms of the changes in the economy over time, I will interpret the consequences of the deregulation as (i) lower markup due to the more competitive environment and (ii) improved energy efficiency in the transportation industry. The following section will present the model which incorporates the role of transportation in the economy.

3 The Model

The economy consists of continuums of households, intermediate-good firms, and transportation firms, which are indexed by $h \in [0,1]$, $i \in [0,1]$, and $n \in [0,1]$, respectively, as well as the monetary authority and the aggregator of final-good and labor services.

Each household supplies different types of labor services, which are imperfect substitutes, in a monopolistically competitive market. There exist nominal wage rigidities in the form of quadratic wage adjustment costs.

While intermediate-good firms produce distinct products and sell their output in monopolistically competitive markets, they act as a price-taker in factor markets. Production of intermediate goods requires two additional inputs, other than capital and labor. First, I assume that all produced goods must be delivered to consumers and intermediate-good producers incur the cost of transportation services. Second, the firms also use raw materials as one of factor inputs. The raw materials are assumed to be composed of all intermediate goods. That is, produced intermediate goods will be used to assemble the final good for households' consumption as well as used as materials inputs for the production process.

Transportation firms supply distinct transportation services to intermediate-good firms in monopolistically competitive markets. Their services are distinct in the sense that there exist segmentations in the US transportation industry, such as operating region, products carried, and transportation modes.

There are two direct avenues whereby an increase in the price of oil could have impact on the economic activity. One is variable capital utilization tied with use of energy, as in Finn (2000), Leduc and Sill (2004), and Cavallo and Wu (2007). This is intended here to capture the role of the industrial sector in US petroleum consumption mentioned earlier. The other channel through which the oil-price shock may have an effect in the economy is direct impact on the cost of transportation. In the subsections below, we shall see the details on each sector.

3.1 Aggregators

There are two types of aggregators in the economy. The final-good aggregator purchases differentiated goods from intermediate-good firms and assembles the final good, which is sold to households for consumption in a competitive market. The labor-service aggregator hires differentiated labor services from households and transforms them into the composite labor input, which is demanded by both intermediate-good firms and transportation firms in a competitive market.

Both aggregation technologies are based on a typical constant returns to scale CES technology. The final good and the composite labor are produced by

$$Y_t = \left[\int_0^1 Y_t(i)^{(\theta-1)/\theta} di\right]^{\theta/(\theta-1)},$$

$$N_t = \left[\int_0^1 N_t(h)^{(\theta_N-1)/\theta_N} dh\right]^{\theta_N/(\theta_N-1)},$$

respectively, where $Y_t(i)$ represents the gross output of intermediate-good firm i, $N_t(h)$ is the labor service of household h, and $\theta > 1$ and $\theta_N > 1$ are the elasticity of substitution between the different inputs.

Taking the price of inputs as given, the aggregators minimize total costs. The first-order conditions give us constant-elasticity inverse demand functions for intermediate products and labor services

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\theta} Y_t,$$

$$N_t(h) = \left(\frac{w_t(h)}{w_t}\right)^{-\theta_N} N_t,$$

respectively, where $P_t(i)$ is the price of intermediate good i, $w_t(h)$ is real wage for labor services supplied by household h, and $P_t = \left[\int_0^1 P_t(i)^{1-\theta} di\right]^{1/(1-\theta)}$ and $w_t = \left[\int_0^1 w_t(h)^{1-\theta_N} dh\right]^{1/(1-\theta_N)}$ are the aggregate price index and the aggregate wage index, respectively.

3.2 Households

There is a continuum of households indexed by $h \in [0,1]$. Households are identical except for the heterogeneity of labor. Each household maximizes the expected utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log\left(C_t(h)\right) + \frac{(M_t(h)/P_t)^{1-\sigma}}{1-\sigma} - \frac{N_t(h)^{1+\varphi}}{1+\varphi} \right\},$$

where $0 < \beta < 1$ is the subjective discount factor, $C_t(h)$ is consumption of final goods, $M_t(h)/P_t$ is real money balances, and $N_t(h)$ is hours worked.

Each household carries $M_{t-1}(h)$ units of money and $B_{t-1}(h)$ bonds into period t. In addition to the carry-over, the household receives a lump-sum transfer $\mathcal{T}_t(h)$ from the monetary authority at the beginning of each period. After the maturity of bonds, the household also receives $B_{t-1}(h)$ additional units of money. During the period t, the household provides labor in exchange for labor income. The household also receives nominal dividends from intermediate-good producers and transportation firms, denoted by Π_t and Π_t^T, respectively.

In addition, each household is a monopolistic supplier of differentiated labor services $N_t(h)$ and faces a downward-sloping labor demand curve. Each household sets its own nominal wage subject to quadratic wage adjustment costs, as in Kim (2000). The wage adjustment cost function takes the form

$$AC_t^W(h) = \frac{\phi_W}{2}\left(\frac{W_t(h)}{W_{t-1}(h)} - \pi_s\right)^2 \frac{W_t(h)}{P_t},$$

where $\phi_W > 0$ is a wage adjustment cost parameter, $W_t(h)$ is household h's nominal wage, π_s is the steady-state rate of inflation, and P_t is the general price index. Thus, household h faces the following budget constraint:

$$\frac{M_{t-1}(h) + \mathcal{T}_t(h) + B_{t-1}(h) + W_t(h)N_t(h) + \Pi_t(h) + \Pi_t^T(h)}{P_t} = C_t(h) + \frac{B_t(h)/r_t + M_t(h)}{P_t} + AC_t^W(h), \quad (1)$$

where r_t is the gross nominal interest rate.

3.3 Intermediate-good Firms

There is a continuum of intermediate-good producers indexed by $i \in [0,1]$. Each intermediate firm produces a distinct product $\widetilde{Y}_t(i)$ and sells it in a monopolistically competitive market. Unlike typical models, I assume that all goods produced must be delivered to customers and each firm incurs transportation costs. Specifically, each intermediate-good producer must purchase transportation services $T_t(i)$ in order to finalize its production process. We assume that the whole production process is described by

$$\widetilde{Y}_t(i) = \min\left[\frac{Q_t(i)}{1-\chi_Y}, \frac{T_t(i)}{\chi_Y}\right], \tag{2}$$

where $\chi_Y \in (0,1)$ is a technology parameter which determines complementarity of transportation services, $Q_t(i)$ is firm i's gross output, and $T_t(i)$ is firm i's demand for transportation services, which will be defined below.

Following Rotemberg and Woodford (1995) and Basu (1996), we assume that production of gross output involves use of material inputs through the fixed-coefficient technology between value added $V_t(i)$ and material inputs $X_t(i)$, given by

$$Q_t(i) = \min\left[\frac{V_t(i)}{1-\chi_Q}, \frac{X_t(i)}{\chi_Q}\right], \tag{3}$$

where $\chi_Q \in (0,1)$ is a share of materials cost in the value of gross output. Each firm produces its value added $V_t(i)$ by using capital services $u_t(i)K_t(i)$ and labor input $N_t^I(i)$ with a typical Cobb-Douglas production technology

$$V_t(i) = [u_t(i)K_t(i)]^{\alpha}[N_t^I(i)]^{1-\alpha}, \tag{4}$$

where $u_t(i)$ is capital utilization and $K_t(i)$ is firm i's beginning-of-period stock of capital.

The material inputs $X_t(i)$ are the CES aggregate of output produced by all intermediate firms, including itself. Here, we assume that $X_t(i)$ is defined by

$$X_t(i) = \left[\int_0^1 X_t(i,j)^{(\theta-1)/\theta} dj\right]^{\theta/(\theta-1)},$$

where $X_t(i,j)$ is firm i's demand for the product j. Notice that the CES technology is exactly the same as the final-good aggregator uses. Thus, it is equivalent to use the final good as material inputs. The first-order condition for the cost-minimization problem of total material costs implies that firm i's inverse conditional demand function for intermediate product j is given by

$$X_t(i,j) = \left(\frac{P_t^X(j)}{P_t^X}\right)^{-\theta} X_t(i),$$

where $P_t^X(j)$ is the price of intermediate product j and $P_t^X = \left[\int_0^1 P_t(j)^{1-\theta} dj\right]^{1/(1-\theta)}$. The aggregate demand for firm j's product as materials inputs is then given by

$$X_t(j) = \int_0^1 X_t(i,j)di = \left(\frac{P_t^X(j)}{P_t^X}\right)^{-\theta} X_t,$$

where $X_t = \int_0^1 X_t(i)di$.

Similarly, $T_t(i)$ is the CES aggregate of transportation services supplied by all transportation firms, that is,

$$T_t(i) = \left[\int_0^1 T_t(i,j)^{(\theta_T-1)/\theta_T} dj\right]^{\theta_T/(\theta_T-1)},$$

where $T_t(i,j)$ is firm i's demand for type-j transportation services and $\theta_T > 1$.

Each intermediate-good firm accumulates firm-specific capital stock according to the low of motion

$$K_{t+1}(i) = (1-\delta_t(i))K_t(i) + I_t(i), \tag{5}$$

where $I_t(i)$ is firm i's investment at time t and $\delta_t(i)$ is time-varying depreciation rate. As standard in the variable capital utilization literature (for example, Greenwood, Hercowitz, and Huffman, 1988; Burnside and Eichenbaum, 1996), the capital depreciation rate $\delta_t(i)$ depends on the rate of capital utilization through

$$\delta_t(i) = \frac{(u_t(i))^\kappa}{\kappa}, \tag{6}$$

with $\kappa > 1$. As in Finn (2000), Leduc and Sill (2004), and Cavallo and Wu (2007), we assume that capital utilization is tied with use of energy. Higher capital utilization must be accompanied by more petroleum consumption per unit of capital, at an increasing rate. The relationship is specified as

$$\frac{E_t^I(i)}{K_t(i)} = \frac{(u_t(i))^\nu}{\nu}, \tag{7}$$

where $E_t^I(i)$ represents firm i's oil consumption for capital utilization and $\nu > 1$. In order for capital stock to be productive, each firm must purchase the necessary amount of petroleum from the oil producer at the nominal price of P_t^E.

With the production technology (2) and (3), the optimality condition implies that

$$\widetilde{Y}_t(i) = \frac{Q_t(i)}{1-\chi_Y} = \frac{T_t(i)}{\chi_Y} \qquad \text{and} \qquad Q_t(i) = \frac{V_t(i)}{1-\chi_Q} = \frac{X_t(i)}{\chi_Q}. \tag{8}$$

Since each intermediate firm sells its distinct product to the final-good aggregator and other intermediate-good firms, it faces its own downward-sloping demand curve. The total demand firm i faces is given by

$$Y_t(i) + X_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\theta} Y_t + \left(\frac{P_t^X(i)}{P_t^X}\right)^{-\theta} X_t = \left(\frac{P_t(i)}{P_t}\right)^{-\theta} (Y_t + X_t) \tag{9}$$

The last equality is due to the fact that there are no distinctions between outputs sold to the final-good aggregator and those to intermediate-good firms as materials inputs, so that $P_t(i) = P_t^X(i)$ for all $i \in [0,1]$ and hence $P_t = P_t^X$. Each firm will make a decision such that it can meet the total demand from the final-good aggregator and other intermediate-good firms.

As in Ireland (2001), each intermediate-good firm is subject to two types of quadratic adjustment costs for price and capital, which are respectively given by

$$AC_t^Y(i) = \frac{\phi_Y}{2}\left(\frac{P_t(i)}{\pi_s P_{t-1}(i)} - 1\right)^2 Y_t, \tag{10}$$

$$AC_t^K(i) = \frac{\phi_K}{2}\left(\frac{K_{t+1}(i)}{K_t(i)} - 1\right)^2 K_t(i), \tag{11}$$

where $\phi_Y > 0$ and $\phi_K > 0$ are adjustment cost parameters and π_s is the steady-state rate of inflation.

Given (4)–(11), each intermediate firm chooses $P_t(i)$, $u_t(i)$, $K_{t+1}(i)$ and $N_t^I(i)$ in order to maximize its discounted market value defined as

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\Lambda_t}{P_t} \Pi_t(i),$$

where Λ_t is the Lagrange multiplier associated with the household budget constraint (1),

$$\frac{\Pi_t}{P_t} = \frac{P_t(i)}{P_t}\widetilde{Y}_t(i) - w_t N_t^I(i) - \frac{P_t^E}{P_t} E_t^I(i) - X_t(i) - \frac{P_t^T}{P_t} T_t(i) - I_t(i) - AC_t^K(i) - AC_t^Y(i),$$

P_t^E is the nominal price of oil, and P_t^T is the nominal price of transportation services.

3.4 Transportation Firms

There is a continuum of transportation firms indexed by $n \in [0, 1]$. Each transportation firm provides distinct transportation services $T_t(n)$ in a monopolistically competitive market. If there were no regulations, the transportation industry could be considered as a good example of competitive industry. However, due to the regulations described in Section 2, transportation firms are monopolistically competitive firms supplying distinctive services. For example, we can think of regional barriers in the industry as one of the sources for creating the distinctiveness.

Transportation services are produced by combining value added, which requires capital and labor, and oil with a fixed-coefficient technology

$$T_t(n) = \min\left[V_t^T(n), \omega E_t^T(n)\right], \tag{12}$$

where $V_t^T(n)$ is transportation firm n's value added, which will be defined below, $E_t^T(n)$ is petroleum used for transportation, and $\omega > 0$ is a transportation energy efficiency parameter. Given (12), the optimality condition implies that

$$T_t(n) = V_t^T(n) = \omega E_t^T(n) \tag{13}$$

The value-added production function of transportation firm n is assumed to be

$$V_t^T(n) = \left[aA_t(n)^{(\gamma-1)/\gamma} + (1-a)N_t^T(n)^{(\gamma-1)/\gamma}\right]^{\gamma/(\gamma-1)}, \tag{14}$$

where $A_t(n)$ is transportation firm n's beginning-of-period stock of transportation equipment, $N_t^T(n)$ is labor inputs, $a \in (0,1)$, and γ is the elasticity of substitution between capital and labor. Unlike the value-added production function of intermediate-good firms, that of transportation firms takes the form of the CES production function. It is intended to take account of the possibility that transportation equipment and labor are more complements in value-added production of transportation with $\gamma < 1$, compared with that of intermediate-good firms. Such complementarity can arise due to the fact that operating transportation equipment requires certain amount of labor. I have also experimented with a typical Cobb-Douglas value-added production, but the quantitative results on accounting for the changes in the economy overtime are not significantly different.

Each transportation firm accumulates stock of transportation equipment following the low of motion

$$A_{t+1}(n) = (1-\delta_A)A_t + I_t^A(n), \tag{15}$$

where δ_A is the time-invariant depreciation rate of $A_t(n)$ and $I_t^A(n)$ is transportation firm n's investment. Like intermediate-good producers, each transportation firm is subject to capital adjustment costs, given by

$$AC_t^A(n) = \frac{\phi_A}{2}\left(\frac{A_{t+1}(n)}{A_t(n)} - 1\right)^2 A_t(n), \tag{16}$$

with $\phi_A > 0$.

Transportation firm n faces its own downward-sloping demand curve, which is given by

$$T_t(n) = \left(\frac{P_t^T(n)}{P_t^T}\right)^{-\theta_T} T_t, \tag{17}$$

where $P_t^T(n)$ is the price of $T_t(n)$, $P_t^T = \left[\int_0^1 P_t^T(n)^{1-\theta_T} dn\right]^{1/(1-\theta_T)}$ and $T_t = \int_0^1 T_t(n)dn$.

Subject to (14) – (17), each transportation firm chooses $P_t^T(n)$, $N_t^T(n)$, and $A_{t+1}(n)$ to maximize its discounted market value

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\Lambda_t}{P_t} \Pi_t^T(n),$$

where

$$\frac{\Pi_t^T(n)}{P_t} = \frac{P_t^T(n)}{P_t} T_t(n) - w_t N_t^T(n) - \frac{P_t^E}{P_t} E_t^T(n) - I_t^A(n) - AC_t^A(n).$$

3.5 The Monetary Authority

Following Ireland (2001), it is assumed that the monetary authority will set short-term interest rate r_t following a Taylor-type policy rule

$$\log(r_t/r_s) = \rho_y \log(Y_t/Y_s) + \rho_\pi \log(\pi_t/\pi_s) + \rho_\mu \log(\mu_t/\mu_s) + \varepsilon_{r,t}$$

where $\mu_t = \frac{M_t}{M_{t-1}}$ and those variables with s-subscripts indicate the associated steady-state values. Unlike the original policy rule proposed by Taylor (1993), this policy rule allows monetary policy to respond to changes in money growth as well. Although it is well known that the variant of the original Taylor rule estimated using pre-1979 data results in indeterminacy (e.g., Clarida, Galí, and Gertler, 2000), Ireland (2001) notes that this specification makes model's equilibrium unique, even under the pre-1979 estimates.

3.6 Real Price of Oil

The log real price of oil follows an exogenous AR(1) process:

$$\log(p_t^E) = (1 - \rho_{p^E}) \log(p_s^E) + \rho_{p^E} \log(p_{t-1}^E) + \varepsilon_{p^E,t}, \tag{18}$$

where $p_t^E = P_t^E / P_t$, p_s^E represents the steady-state value the real price of oil, and $|\rho_{p^E}| < 1$.

3.7 Symmetric Equilibrium

In a symmetric equilibrium, all agents in each sector make the same decision. The corresponding values are denoted by variables without indices h, i, and n. For example, $N_t^I(n) = N_t^I$ and $N_t^T(n) = N_t^T$ for all $i \in [0,1]$, $n \in [0,1]$, and t. The market-clearing condition of the labor market implies that $N_t = N_t^I + N_t^T$. The market-clearing conditions for money and bonds, $M_t = M_{t-1} + \mathcal{T}_t$ and $B_t = B_{t-1} = 0$, have to hold as well.

In the symmetric equilibrium, the household budget constraint (1) can be expressed as

$$Y_t - p_t^E(E_t^I + E_t^T) = C_t + I_t + I_t^A + AC_t^W + AC_t^K + AC_t^Y + AC_t^A. \tag{19}$$

The equation (19) states that the sum of consumption, total investment, and total adjustment costs equal to real value added, which is the value of output produced net of all costs (including energy costs), except for primary-factor payments. Thus, an appropriate measure of output in the model economy that corresponds to real GDP is real value added $Y_t - p_t^E(E_t^I + E_t^T)$, rather than Y_t.

The system of difference equations that characterize the symmetric equilibrium consists of the first-order conditions for the households, the intermediate-good firms, and the transportation firms, the laws of motion for capital, the monetary policy rule, and the oil-price process. A complete description of the system is summarized in the Appendix.

4 Results

This section presents the quantitative results and discusses how the model presented in Section 3 responds to an oil-price shock. In order to obtain the solution to the system, I log-linearize the equilibrium conditions of the model around its steady state and use the generalized Schur decomposition described by Klein (2000) and Sims (2002).[7] Before tuning to showing the quantitative results, I describe the calibration procedure in the following subsection.

[7] This is implemented in DYNARE.

Table 1: Summary of Parameter Values in the Baseline Specification

Parameter		Values
β	Discount factor	0.9974*
χ_Q	Materials cost share	0.47324
χ_Y	Transportation share	0.0386
σ	Money utility parameter	10
φ	Frisch labor supply elasticity	1
α	Capital share (intermediate-good firms)	0.36
a	Capital share (transportation firms)	0.36
γ	Transportation firms' elasticity of substitution between capital and labor	0.1
δ_A	Depreciation rate for transportation firms	0.025
ϕ_A	Capital adjustment cost parameter (transportation firms)	10
ϕ_K	Capital adjustment cost parameter (intermediate-good firms)	10
ϕ_W	Wage adjustment cost parameter	58
ϕ_Y	Price adjustment cost parameter	72.01*
θ	Demand elasticity for consumption goods	6
θ_N	Demand elasticity for labor	6
θ_T	Demand elasticity for transportation services	3.8169
ρ_{p^E}	Persistence parameter of the oil price process	0.99
ρ_π	Monetary policy coefficient on inflation rate	0.8617*
ρ_y	Monetary policy coefficient on output	0.0499*
ρ_μ	Monetary policy coefficient on money growth	0.7351*
p_s^E	Steady-state real price of oil	1
π_s	Steady-state inflation rate	1.0129*
δ_s	Steady-state depreciation rate for intermediate-good firms	0.025
s_1	Steady-state value-added expenditure share of oil used for capital utilization	0.0123
s_2	Steady-state value-added expenditure share of oil used for transportation	0.0242
ω	Energy efficiency parameter for transportation	3.0334
ν	Energy efficiency parameter for capital utilization	1.7373
κ	Elasticity of depreciation	1.06

Note: Parameter values with asterisks are those based on the pre-1979 estimates of Ireland (2001).

4.1 Calibration

In order to analyze changes in the economy over time, I need to set the baseline specification such that the model economy corresponds approximately to the state of the pre-1984 period. In order to do so, I use pre-1984 values for some of share parameters, such as the value-added oil expenditure shares. Furthermore, if available, I will utilize some of pre-1979 estimates for parameter values from Ireland (2001) as an approximation. Parameter values assigned in the baseline specification are summarized in Table 1.

Those parameter values drawn from the pre-1979 estimates of Ireland (2001) are a discount factor β, the steady-state rate of inflation π_s, the price adjustment cost parameter ϕ_Y and coefficients on the monetary policy rule, ρ_y, ρ_π, and ρ_μ. β is set equal to 0.9974.

With the steady-state quarterly inflation rate $\pi_s = 1.0129$, the value of β implies that annualized interest rate is 6.3%.

Frisch labor supply elasticity is set to be unity. The value of σ is assumed to be 10, which is broadly consistent with various estimates presented in Christiano, Eichenbaum, and Evans (2005) with different specification.[8] Capital share parameters α and a are set equal to 0.36. The steady-state depreciation rate for intermediate-good firms δ_s and the time-invariant depreciation rate for transportation firms δ_A are both equal to 0.025. Capital adjustment cost parameter is assumed to be 10 for both intermediate-good firms and transportation firms. The wage adjustment cost parameter is 58.[9] Demand elasticity parameters for the final good and for the index of labor services, θ and θ_N, respectively, equal to 6, which implies in the steady-state, price and wage markup rates are 20%.

For parameter values related to transportation firms, I set the demand elasticity parameter θ_T to be 3.8169 for the baseline specification, such that the implied markup is 35.5% and for the value after the deregulation in the transportation industry, I set it to 53.632, so that the implied markup becomes 1.9%. The markup rate is consistent with the estimates of Nebesky, McMullen, and Lee (1995).

Based on the industry-level data compiled by Dale Jorgenson and his colleagues,[10] the average share of materials cost (excluding energy cost) in the value of gross output from 1958 to 1983 is 47.3%, and hence, the materials cost share χ_Q is set equal to 0.473.[11] The value of χ_Y can be pinned down by the steady-state share of the transportation industry in the total aggregate gross output from the optimality condition (8). The pre-1984 average share of the transportation industry in Jorgenson's data is 3.86%.[12] Thus, I set $\chi_Y = 0.0386$.

[8] Levin, Onatski, Williams, and Williams (2006) also have a similar estimate with Bayesian approach. Although their estimate is about 11. This difference in the value of σ does not alter the results presented below.

[9] Wage rigidities introduced by the quadratic wage adjustment cost will have the same log-linearized wage Phillips curve as Calvo-type wage stickiness. This value of wage adjustment cost parameter roughly corresponds to about 20% of households being able to reoptimize their wages in each period, given other parameter values used in the baseline specification.

[10] Data were downloaded from http://post.economics.harvard.edu/faculty/jorgenson/data/35klem.html. Description of the data set is found in Jorgenson, Gollap, and Fraumeni (1987), Jorgenson and Stiroh (2000), and Jorgenson (1990).

[11] This number is close to the materials share used in Dotsey and King (2006). Although other authors such as Rotemberg and Woodford (1996), and Huang and Liu (2004), use larger value for the share of materials, this is primarily because they take account of the energy cost as well.

[12] Details on this calculation are given in Appendix.

We set the steady-state value of the relative price of oil $p_s^E = 1$ and the AR(1) coefficient for the oil price process $\rho_{p^E} = 0.99$. This is obtained from estimating (18) using the pre-1984 data on log-real price of oil, which is measured as log of PPI for crude petroleum deflated by GDP deflator.

In terms of percentage deviations of the aggregate value added from the steady-state value, the oil expenditure shares in aggregate value added play an important role. According to the petroleum consumption data of the EIA and time series data on the price of West-Texas Intermediate from FRED of the FRB St. Louis, the average share of oil consumption in value added from 1949 to 1983 is 3.65%, and the average share after 1983 is 2.75%. According to the EIA's data, the average value of the ratio E^I/E^T is 0.51 in the pre-1984 period and 0.39 after 1984. Therefore, I set $s_1 = p_s^E E_s^I / \{Y_s - p_s^E(E_s^I + E_s^T)\} = 0.0123$ and $s_2 = p_s^E E_s^T / \{Y_s - p_s^E(E_s^I + E_s^T)\} = 0.0242$ for the baseline specification.

Together with other parameter values, these calibrating targets on oil expenditure shares are used to determine the remaining parameter values, which are related to energy efficiency in the model economy, ω, ν, and κ. From the steady-state relation, the value of ω is given by

$$\omega = \frac{(1 + s_1 + s_2)\left(1 + \frac{s_1}{s_2}\right)\chi_Y p_s^E}{(s_1 + s_2)\{1 - \chi_Q(1 - \chi_Y)\}}. \tag{20}$$

The values of ν and κ are jointly determined by solving the following non-linear system of equations:

$$\frac{s_1}{s_2} = \frac{(u_s)^\nu}{\nu}\left\{\frac{1}{\beta} - (1 - \delta_s) + p_s^E\frac{(u_s)^\nu}{\nu}\right\}^{-1}\frac{\Xi_s^Y}{\Lambda_s}(1 - \chi_Q(1 - \chi_Y))\frac{\alpha\chi_V\omega}{\chi_Y}, \tag{21}$$

$$\frac{1}{\beta} - 1 = (u_s)^\kappa\left(1 - \frac{1}{\kappa}\right) + p_s^E(u_s)^\nu\left(1 - \frac{1}{\nu}\right), \tag{22}$$

where $u_s = (\kappa\delta_s)^{1/\kappa}$, $\frac{\Xi_s^Y}{\Lambda_s}$ is the real marginal cost of producing an additional unit of V, and $\chi_V = \frac{(1-\chi_Q)(1-\chi_Y)}{1-\chi_Q(1-\chi_Y)}$. Under the baseline specification, $\omega = 3.0334$, $\nu = 1.7373$, and $\kappa = 1.06$.

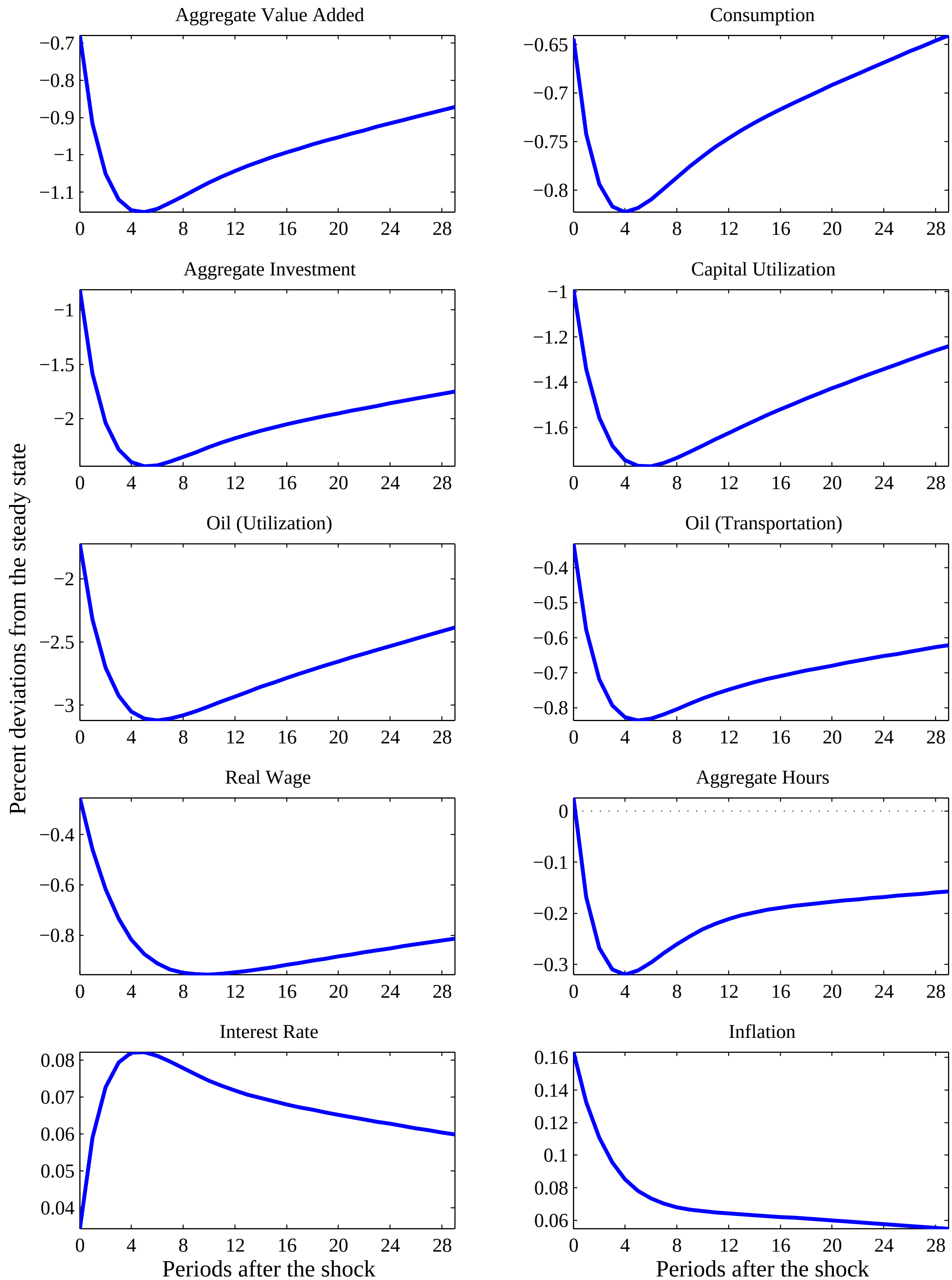

Figure 5: Impulse Responses to a 10% Increases in the Oil Price: Baseline Results

4.2 Baseline Results

First, we will look at the baseline specification, which corresponds to the pre-1984 state of the economy. Figure 5 shows dynamic responses of variables to a 10% increase in the real price of oil.

Aggregate value added, which corresponds to real GDP in data, shows a hump-shaped response and peaks at 5 quarters after the shock. The near-unit-root nature of the oil shock results in strong persistence in IRFs. Other variables, except for inflation, show hump-shaped response as well, due to the price stickiness. Among macroeconomic variables, investment is most severely affected, as pointed out by Aguiar-Conraria and Wen (2005). Two types of oil consumption show different patterns in terms of magnitude. Oil consumption for capital utilization is more price elastic compared with oil used for transportation. Aggregate hours worked have a positive response in the first period due to the fact that the income effect slightly dominates the substitution effect, and then decline. Under the monetary policy rule assumed, the Fed increases interest rate in order to fight against inflation triggered by increases in the oil price. Inflation dynamics look like a mirror image of the oil-price process because there are no mechanisms that generate the hump-shaped response of inflation, such as backward indexation or price adjustment costs for inflation.

There are two channels through which the oil-price shocks can affect the economy. The first one is via capital utilization tied with use of oil. The oil-price shock results in a higher cost utilization of capital stock, and hence a lower rate of capital utilization. This in turn reduces the level of output produced. The second channel is a direct impact on the cost of delivering goods produced.

Intermediate firms' real marginal cost of producing an additional unit of output in terms of log-deviations from the steady state is given by

$$\widehat{mc}_t = \frac{1}{mc_s} \left\{ (1-\chi_Q)(1-\chi_Y) mc_s^V \widehat{mc}_t^V + \chi_Y p_s^T \widehat{p}_t^T \right\}, \tag{23}$$

where $mc_s^V = \frac{\Xi_s^Y}{\Lambda_s}$ represents the steady-state real marginal cost of producing an additional unit of their value added, p_s^T is the real price of transportation services, and hat-variables represent log-deviations from the steady state. Holding everything else constant, an increase

Table 2: Summary of Changes in the Peak Response of Aggregate Value Added

		% Change in Peak Responses	Changes in the Timing
Case 1	Lower Markup	−11.41%	±0
Case 2	Transportation Industry	−19.73%	±0
Case 3	Improved Energy Efficiency	−24.72%	±0
Case 4	Less Persistent Shock	−26.52%	−2
Case 5	Post-1984	−51.38%	−2

in the real price of oil affects both $\widehat{mc}_t^V$ via capital utilization and $\widehat{p}_t^T$ through transportation costs. Therefore, although the value of its share parameter χ_Y is small, we expect that including transportation services makes the effect of the oil-price shock stronger than otherwise. In addition, transportation firms' markup plays a role in terms of amplifying the responses of macroeconomic variables. The higher the markup, the more expensive the steady-state price of transportation services. This is one of reasons why we expect the lower markup on transportation services can contribute to the weaker response to the same size of the oil-price shock.

The above equation (23) also highlights the importance of taking account of materials inputs. As the cost share of materials inputs χ_Q becomes smaller, the relative importance of $\widehat{p}_t^T$ becomes smaller. Although the price-stickiness usually dampens the effect of exogenous shocks, materials inputs together with inclusion of transportation firms contributes to sizable responses of macroeconomic variables to the oil-price shock.

Now, we turn to analyze factors that contribute to the observed weaker responses of macroeconomic variables to the oil-price shock.

4.3 Changes in the Economy Over Time

In order to understand the declining effects of the oil-price shocks, we will consider three different factors individually and some combinations of those. First, we will look at the consequence of more competitive environment in the transportation industry triggered by the deregulation after 1980. Second, we will see the effect of improved energy efficiency in the economy. Lastly, we will look at the consequence of the less persistent oil-price shock. Table 2 reports summary of changes in the peak response of aggregate value added under each scenario and associated IRFs are shown in Figure 6 – Figure 8.

Case 1: Increased Competition among Transportation Firms

In order to see the outcome of the increased competition in the transportation industry, we will only change the value of θ_T from 3.8169 to 53.632 such that the implied steady-state markup of transportation firms changes from 35.5% to 1.9%, which is based on Nebesky, McMullen, and Lee (1995). Other parameter values are left unchanged.

As shown in Figure 6 with the label of *Lower Markup*, all variables show weaker responses to the same size of the oil-price shock. The peak response of aggregate value added is reduced by 11.41%. However, there are no changes in the peak response.

Holding other things constant, the immediate effect of the lower markup is a reduction in the steady-state price of transportation services p_s^T. This induces a downward shift in the marginal cost curve of intermediate-good firms. As a result, the economy moves to the new steady state with the higher level of output and the lower level of the general price index. To meet with the higher level of output, all factor inputs will be utilized more than before.

Although the lower markup does not change the dynamics of $\widehat{p}_t^T$, the log-deviations of the real marginal cost (23) tells us that a decline in p_s^T induces in the deviations in the real marginal cost, by putting less weight on deviations on the price of transportation firms. In turn, it results in smaller deviations in other real variables.

We can observe another effect of lowring the markup on the inflation dynamics. The intermediate-firms' first-order condition with respect to their prices in the symmetric equilibrium is given by

$$\begin{aligned} 0 = (1-\theta)Y_t + \theta\left\{\chi_Q(1-\chi_Y) + \chi_Y p_t^T\right\}Y_t - \phi_Y\left(\frac{\pi_t}{\pi_s} - 1\right)\frac{\pi_t}{\pi_s}\left(1 - \chi_Q(1-\chi_Y)\right)Y_t \\ + \theta\frac{\Xi_t^Y}{\Lambda_t}(1-\chi_Q)(1-\chi_Y)Y_t + \beta\mathbb{E}_t\left[\frac{\Lambda_{t+1}}{\Lambda_t}\phi_Y\left(\frac{\pi_{t+1}}{\pi_s} - 1\right)\frac{\pi_{t+1}}{\pi_s}\left(1 - \chi_Q(1-\chi_Y)\right)Y_{t+1}\right] \end{aligned} \tag{24}$$

Log-linearizing the above equation gives us the New-Keynesian-Phillips-curve type relation:

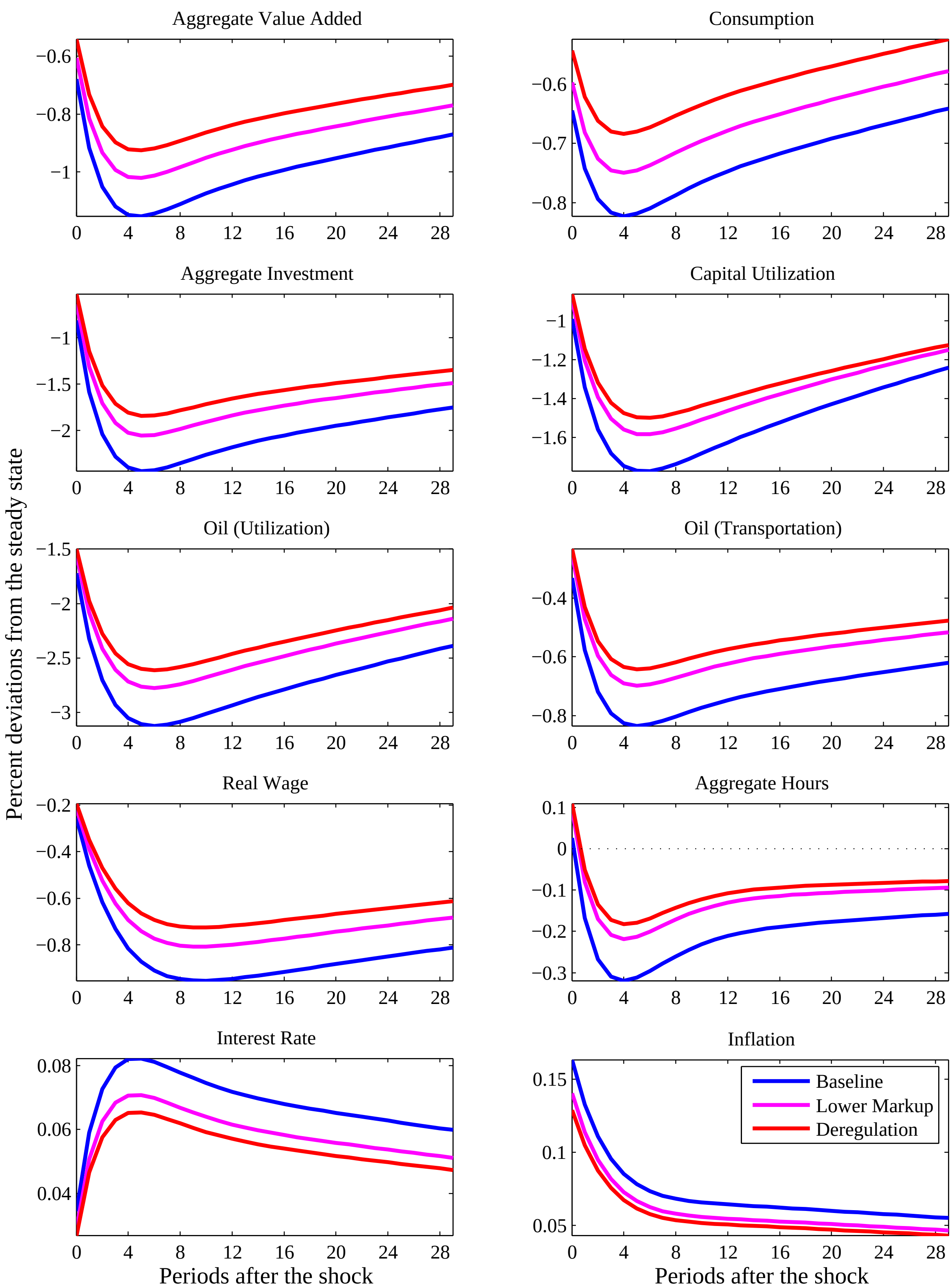

Figure 6: Comparison of IRFs to a 10% Increase in the Oil Price: Case 1 and Case 2

$$\widehat{\pi}_t = \frac{\theta}{\phi_Y} \left\{ \frac{(1-\chi_Q)(1-\chi_Y) mc_s^V}{1-\chi_Q(1-\chi_Y)} \widehat{mc}_t^V + \frac{\chi_Y p_s^T}{1-\chi_Q(1-\chi_Y)} \widehat{p}_t^T \right\} + \beta \mathbb{E}_t[\widehat{\pi}_{t+1}]. \tag{25}$$

Thus, immediately from the above equation, a reduction in p_s^T induces smaller deviations in inflation.

Case 2: Transportation Industry (Deregulation)

As described in Section 2, another consequence of the deregulation is that it has contributed to improve efficiency in the transportation industry. It is important to consider this contribution of the transportation industry as a whole because it accounts for the majority of US petroleum consumption. Here we will consider the contribution of the transportation industry, by taking account of the lower markup and the improved energy efficiency in the industry.

Unfortunately, we do not have reliable data on how energy efficiency has been improved in the transportation industry. One thing we know is that the the average oil expenditure share has dropped from 3.65% in the pre-1984 period to 2.75% in the post-1984 period. Another thing we can observe is changes in petroleum consumption in industrial and transportation sectors. Particularly, the ratio s_1/s_2 has decreased from 0.51 to 0.39 in the post-1984 period. Holding other parameter values fixed and using (20), I can infer a new value of ω, which is consistent with the post-1984 characteristic of the US petroleum consumption, by using the above information. As a result, ω increases from 3.0334 to 3.6752.

In order to see the consequence of the deregulation, I will change both θ_T and ω from the values used in the baseline specification. Since improved energy efficiency in the industry could be because of the deregulation and/or advanced transportation technology, such as higher miles per gallon, this specification does not represent the exact outcome of the deregulation. I sill believe that it is a good proxy for the consequence of the deregulation, however. If there still existed restrictions on entry/exit in the industry, then there would be no entrants that are more efficient and there would be less incentive for incumbents to improve efficiency by adopting more fuel efficient technology.

IRFs presented in Figure 6 labeled *Deregulation* report the contribution originated from the transportation sector of the economy. All variables show weaker responses to the same size of the shock than the baseline specification. In terms of changes in the aggregate value-added peak responses, the consequence of the deregulation accounts for a 19.73% reduction, compared to the baseline specification.

Improved energy efficiency in the transportation sector, that is, an increase in ω has two effects. First, it reduces the steady-state price of transportation services, which has the same effects as the lower markup. Under this specification, the steady-state price of transportation services decreases by 31%, which is consistent with the empirical finding of Ying and Keeler (1991). Second, it makes deviations of the transportation price smaller.

$$\widehat{p}_t^T = \frac{1}{p_s^T}\left\{mc_s^T \widehat{mc}_t^T + \frac{p_s^E}{\omega}\widehat{p}_t^E\right\} \tag{26}$$

It is clear that an increase in ω makes $\widehat{p}_t^T$ smaller than before. In turn, it makes deviations in the marginal cost smaller.

A 20% increase in ω used in this specification is much smaller than the 42% improvements in the average MPG of all vehicles mentioned in the Introduction. This is particularly because of the fact that the US economy is more dependent on transportation, which is apparent in a large drop in the ratio s_1/s_2. If the ratio stayed the same, which is equivalent to less reliance on transportation, we would expect a bigger contribution from the transportation industry.

Case 3: Improved Energy Efficiency in the Economy

Another factor that could contribute to the weaker responses of macroeconomic variables is improvements in efficiency of petroleum use. It is quite intuitive that improved energy efficiency might be a candidate for the declining effects of the oil-price shock. As energy efficiency improves, the economy needs to rely less on petroleum and becomes less vulnerable to an increase in the oil price. This is apparent in the smaller oil expenditure share.

More efficient use of oil could originate from capital utilization and/or transportation.

Thus, here I will change both ω and ν, which govern energy efficiency in both transportation and industrial sectors, respectively. Given the value of ω used in Case 2 and other parameter values fixed, ν is changed such that the resulting steady-state oil expenditure share equals to 2.75%. As a result, ν changes from 1.7373 to 1.8864.

Given the same size of shock, IRFs in Figure 7 labeled *Energy Efficiency* also show weaker responses of all variables. As a result, the peak response of aggregate value added becomes smaller by 24.72%, compared with the baseline specification.

An increase in ν has an effect similar to an increase in ω. It results in the smaller value of steady-state marginal cost of producing intermediate-good fimrs' value added mc_s^V and also $\widehat{mc}_t^V$ becomes smaller given the same size of shock in the oil price.

Case 4: Less Persistence of the Shock

It is not hard to imagine that the shape of IRFs would be affected by a small change in the underlying shock process, and thus one might suspect that it could be the whole story why we observe the weaker response of macroeconomic variables to the oil-price shock. Less persistence in the oil price is easily observed. In the post-1984 period, the estimated AR(1) coefficient on the log-real price, measured as log of PPI for crude petroleum deflated by GDP deflator, suggests that it is dropped from 0.99 to 0.92. Thus, I change the persistence parameter ρ_{p^E} from 0.99 to 0.92.

IRFs shown in Figure 7 labeled *Less Persistence* are the resulting responses. In terms of the peak response, as expected, a small change in the persistence parameter contributes to a large reduction in the peak response, 26.52%. Although there are no changes in the timing of the peak under other factors considered, less persistence in the oil-price process shifts the timing of the peak by 2 quarters.

Case 5: Post-1984

Finally, I combine all factors considered in this paper together, in order to see how much the model could explain changes in the economy over time in response to the oil-price shock. Figure 8 compares resulting IRFs with those from the baseline specification. As can be seen clearly, all factors together result in much smaller responses to the same size of the

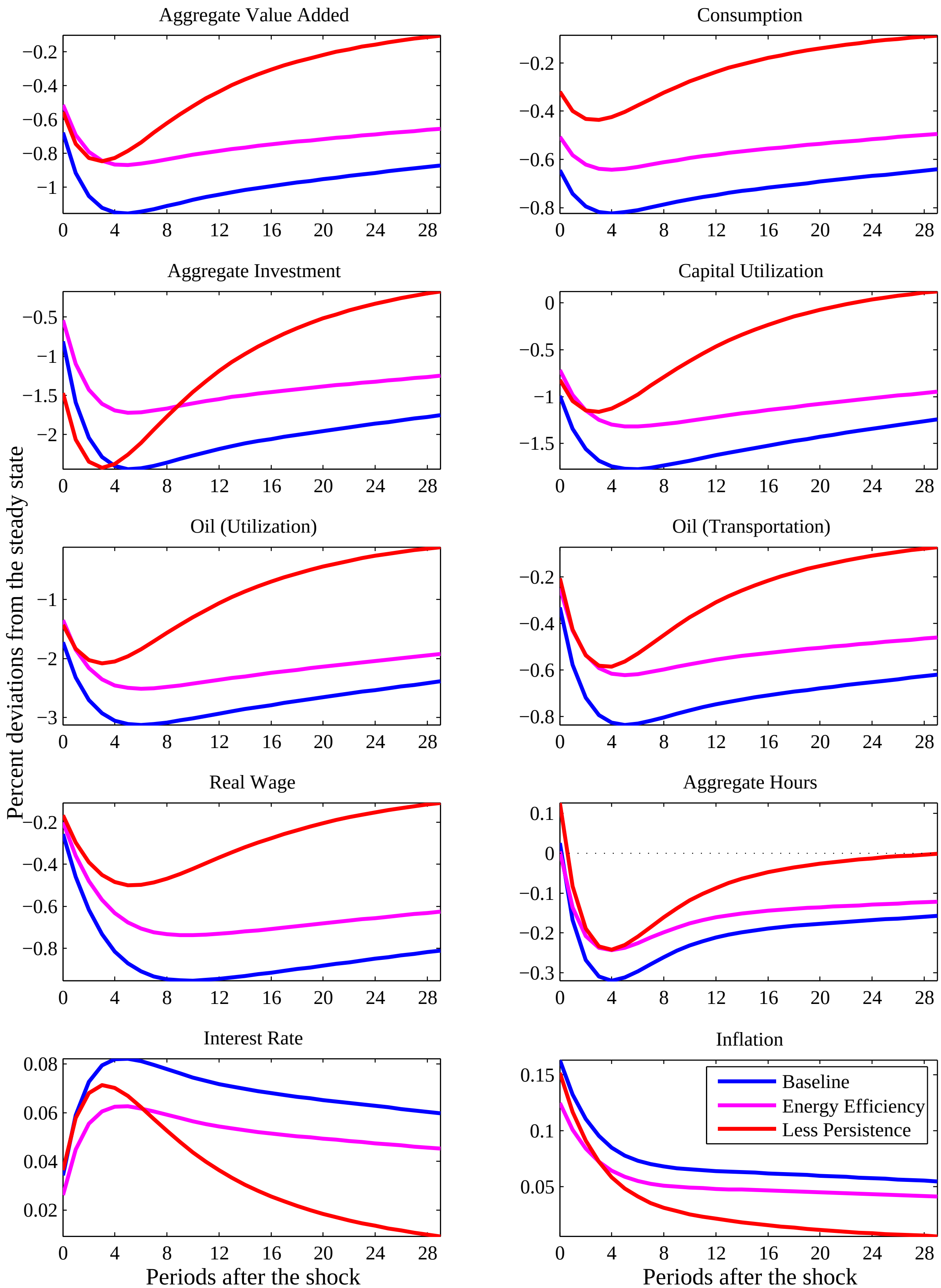

Figure 7: Comparison of IRFs to a 10% Increase in the Oil Price: Case 3 and Case 4

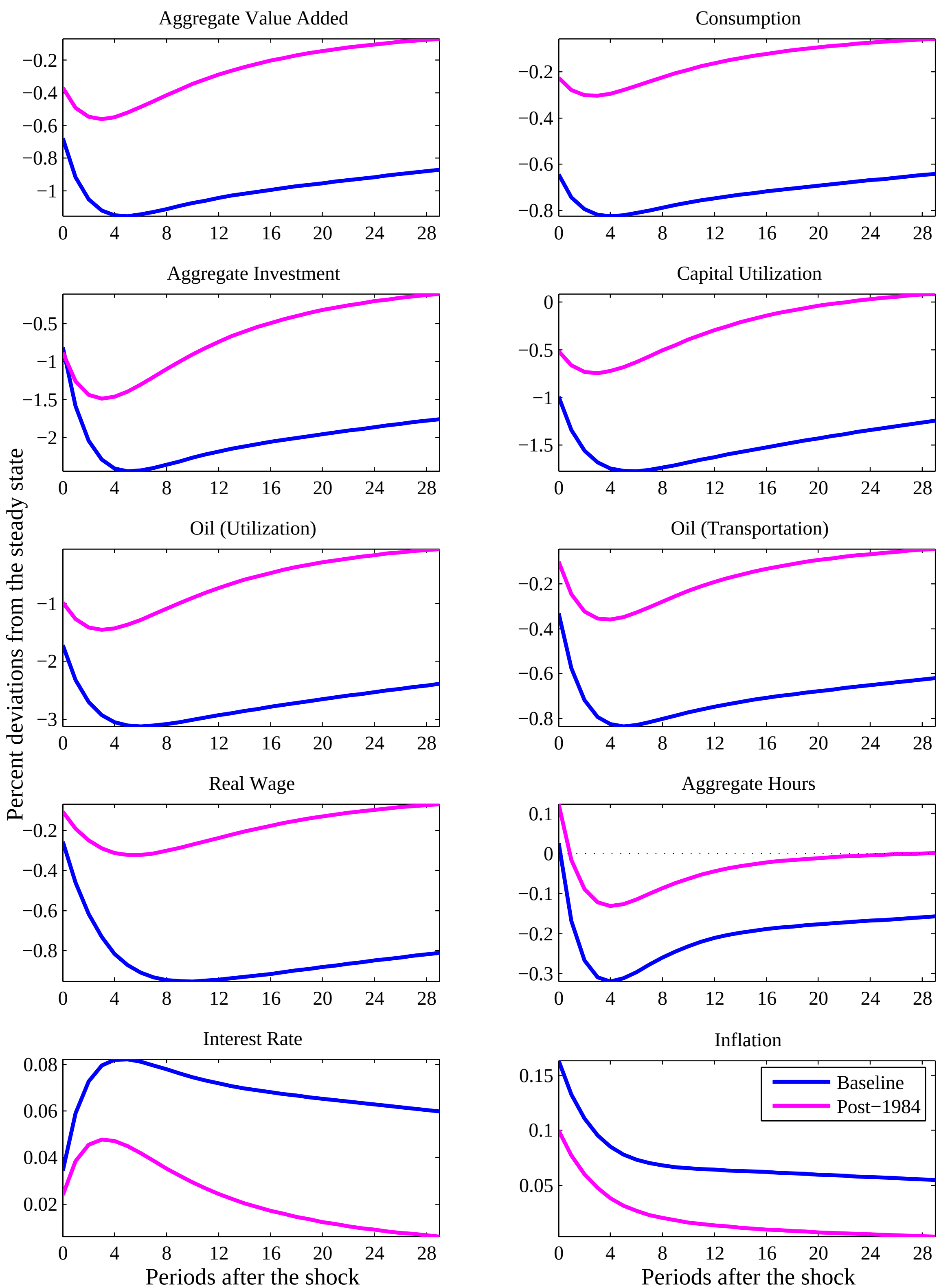

Figure 8: Comparison of IRFs to a 10% Increase in the Oil Price: Before and After 1984

oil-price shock. In terms of the changes in the peak response of aggregate value added, it suggests that the peak response is reduced by 51.38% as a whole and the timing of the peak is shifted by 2 quarters due to the less persistent oil-price process.

If one believes the VAR results presented in the Introduction are a good representation of changes in the economy over time, then these factors considered in this paper could account for a majority of the declining effects of the oil-price shock. It should be noted that, however, these results do not suggest that the factors considered here are the only source of changes in the economy over time, or that all changes have made the effects smaller. For example, in the presence of the trade-off between output and inflation stabilization, a strong anti-inflation stance of the monetary authority, which is widely documented, then it would even contribute to much stronger responses of output. However, increased credibility of the Fed could stabilize the output response as demonstrated in Blanchard and Galí (2007).

Alternatively, one might argue that the economy is shifting toward more flexible prices.[13] Regarding reduced price stickiness, it would contribute to shifting the timing of the peak. The more flexible the price is, the earlier peak we would expect. Since price stickiness has dampening effects on dynamic response of variables, more flexible price would result in stronger responses of aggregate value added, however. Mechanically, less habit persistence, if any, could work in the same way as flexible prices. As argued in Blanchard and Galí (2007), it could be also true that wage rigidities have become smaller over time.

To sum up, by comparing Case 1 and Case 2, we can see that two factors affecting the contribution of the transportation industry, namely more competition and more efficient use of oil in the industry, are equally important. The effect of the deregulation in the transportation industry results in a 20% reduction in the peak response of aggregate value added. It should be noted that in spite of its small share in the economy, the contribution of the transportation industry is non-negligible. The overall effect of more efficient use of oil in the US economy weakens the peak responses of value added by 25%. The results suggest that the industrial sector (intermediate-good firms) has a slightly larger impact on the

[13]It has been widely believed that the average frequency of price change is about one year (for example, Taylor, 1999). But Bils and Klenow (2004) document that in the mid-1990's the average frequency of price change is much more frequent than what typically believed.

weaker response than the transportation sector does, since improved energy efficiency in the transportation industry roughly accounts for about a 10% reduction in the peak response. A less persistent oil-price shock accounts for a 27% reduction in the peak response. Overall, all factors play an important role in accounting for the declining effects of the oil-price shock and are equally important quantitatively.

5 Conclusion

We have developed a model that is more realistic in terms of the US petroleum consumption, in order to explore possible explanations for the weaker responses of macroeconomic variables to oil-price shocks. Under the baseline specification, which corresponds to the pre-1984 state of the economy, the model well captures important aspects of the economy's response to the oil-price shock. Price stickiness accounts for hump-shaped responses of output measures, which are consistent with what we see in data.

We have explored three developments that may have affected the response of output to an oil-price shock, namely the effect of deregulation in the transportation industry, improved energy efficiency, and less persistent oil-price shocks. All factors are important quantitatively. It is worth noting that in spite of its small share, the contribution of the transportation industry triggered by the deregulation is nontrivial. If the US economy becomes less dependent on transportation, we would expect further contribution of the transportation sector. Combining all factors together, the model predicts a 51% reduction in the peak response of aggregate value added and the peak comes 2-quarter earlier.

We can draw one implication from this study. Deregulation in the transportation industry has led to more competitive environment and less reliance on petroleum. Also, technological advancement enables us more efficient use of petroleum overall. Both factors should make the economy less vulnerable to oil-price shocks in the future. From past experience, the general public as well as policy makers might still hold a view that large increases in the price of oil trigger a deep recession. However, we expect that large recessionary consequences of oil-price shocks we observed in the 1970's will not be seen again.

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Appendix

A Calculating the Ratio of T/Y

We can use Jorgenson's data set to obtain the ratio T/Y. In Jorgenson's data set, we have annual data on price and quantity indices of output for all industries from 1958 to 1996.

Let $P_{i,t}$ and $Y_{i,t}$ denote price and quantity indices of gross output of industry i in year t, respectively. Then the total value of gross output in the economy, which correspond to $P\widetilde{Y}$ in the model economy, is given by

$$P_t \widetilde{Y}_t = \sum_{i=1}^{N} P_{i,t} Y_{i,t}, \tag{27}$$

where N is the number of industries in the economy.

Deflating it by P_t, we will obtain a quantity index of the aggregate gross output. Since the data set itself contains the quantity index of the transportation industry, it is easy to obtain an estimate of T_t/Y_t.

Define a Divisia price index for the aggregate gross output as:

$$\frac{dP_t}{P_t} = \sum_{i=1}^{N} s_{i,t} \frac{dP_{i,t}}{P_{i,t}}, \tag{28}$$

where $s_{i,t}$ is the expenditure share of the i^{th} industry.

A discrete approximation of the above index (= Törnquist index) is then given by:

$$\Delta \log P_t = \sum_{i=1}^{N} \bar{s}_{i,t} \Delta \log P_{i,t}, \tag{29}$$

where

$$\bar{s}_{i,t} = \frac{1}{2} \left\{ \frac{P_{i,t} Y_{i,t}}{P_t Y_t} + \frac{P_{i,t-1} Y_{i,t-1}}{P_{t-1} Y_{t-1}} \right\}. \tag{30}$$

With the normalization that $P_{1992} = 1$, which is a convention in Jorgenson's data set, we can recover a sequence of $\{P_t\}$.

As a result, we obtain the pre-1984 average of T_t/Y_t is 0.0386 and the post-1984 average is 0.0397.

B Characterizing Equilibrium

Let Ξ^Y and Ξ^T denote the Lagrange multipliers associated with (4) and (14), respectively. The symmetric equilibrium is characterized by the following system of equations.

$$
\begin{aligned}
\frac{1}{C_t} &= \Lambda_t \\
\theta_N \frac{N_t^{1+\varphi}}{w_t} &= \Lambda_t \left[\phi_W \left(\frac{\pi_t w_t}{w_{t-1}} - \pi \right) \frac{\pi_t w_t}{w_{t-1}} + \frac{\phi_W}{2} \left(\frac{\pi_t w_t}{w_{t-1}} - \pi \right)^2 - (1-\theta_N) N_t \right] \\
&\quad - \beta \mathbb{E}_t \left[\Lambda_{t+1} \phi_W \left(\frac{\pi_{t+1} w_{t+1}}{w_t} - \pi \right) \left(\frac{w_{t+1}}{w_t} \right)^2 \pi_{t+1} \right] \\
m_t^{-\sigma} &= \Lambda_t - \beta \mathbb{E}_t \left[\frac{\Lambda_{t+1}}{\pi_{t+1}} \right] \\
\Lambda_t &= \beta r_t \mathbb{E}_t \left[\frac{\Lambda_{t+1}}{\pi_{t+1}} \right] \\
Y_t - p_t^E (E_t^I + E_t^T) &= C_t + I_t + I_t^A \\
&\quad + \frac{\phi_W}{2} \left(\frac{\pi_t w_t}{w_{t-1}} - \pi \right)^2 w_t + \frac{\phi_K}{2} \left(\frac{K_{t+1}}{g K_t} - 1 \right)^2 K_t \\
&\quad + \frac{\phi_Y}{2} \left(\frac{\pi_t}{\pi_s} - 1 \right)^2 Y_t + \frac{\phi_A}{2} \left(\frac{A_{t+1}}{g A_t} - 1 \right)^2 A_t \\
0 &= \Lambda_t \Big[(1-\theta) Y_t + \theta \big\{ \chi_Q (1-\chi_Y) + \chi_Y p_t^T \big\} Y_t \\
&\quad - \phi_Y \left(\frac{\pi_t}{\pi} - 1 \right) \frac{\pi_t}{\pi} \left(1 - \chi_Q (1-\chi_Y) \right) Y_t \Big] \\
&\quad + \theta \Xi_t^Y (1-\chi_Q)(1-\chi_Y) Y_t \\
&\quad + \beta \mathbb{E}_t \left[\Lambda_{t+1} \phi_Y \left(\frac{\pi_{t+1}}{\pi} - 1 \right) \frac{\pi_{t+1}}{\pi} \left(1 - \chi_Q (1-\chi_Y) \right) Y_{t+1} \right] \\
\Lambda_t w_t &= \Xi_t^Y \frac{(1-\alpha)(1-\chi_Q)(1-\chi_Y)}{1-\chi_Q(1-\chi_Y)} \frac{Y_t}{N_t^I} \\
\Lambda_t \left\{ 1 + \phi_K \left(\frac{K_{t+1}}{K_t} - 1 \right) \right\} &= \beta \mathbb{E}_t \Bigg[\Lambda_{t+1} \Big\{ (1-\delta_{t+1}) - p_{t+1}^E \frac{(u_{t+1})^\nu}{\nu} \\
&\quad + \phi_K \left(\frac{K_{t+2}}{K_{t+1}} - 1 \right) \left(\frac{K_{t+2}}{K_{t+1}} \right) - \frac{\phi_K}{2} \left(\frac{K_{t+2}}{K_{t+1}} - 1 \right)^2 \Big\} \\
&\quad + \Xi_{t+1}^Y \frac{\alpha (1-\chi_Q)(1-\chi_Y)}{1-\chi_Q(1-\chi_Y)} \frac{Y_{t+1}}{K_{t+1}} \Bigg] \\
\Xi_t^Y \frac{\alpha(1-\chi_Q)(1-\chi_Y)}{1-\chi_Q(1-\chi_Y)} \frac{Y_t}{u_t} &= \Lambda_t \left\{ (u_t)^{\kappa-1} K_t + p_t^E (u_t)^{\nu-1} K_t \right\} \\
\frac{(1-\chi_Q)(1-\chi_Y)}{1-\chi_Q(1-\chi_Y)} Y_t &= [u_t K_t]^\alpha [N_t^I]^{1-\alpha} \\
K_{t+1} &= (1-\delta_t) K_t + I_t \\
\delta_t &= \frac{(u_t)^\kappa}{\kappa}
\end{aligned}
$$

$$
\begin{aligned}
\frac{E_t^I}{K_t} &= \frac{(u_t)^\nu}{\nu} \\
T_t &= \frac{\chi_Y}{1-\chi_Q(1-\chi_Y)} Y_t \\
p_t^T &= \frac{\theta_T}{(\theta_T - 1)} \left\{ \frac{\Xi_t^T}{\Lambda_t} + \frac{p_t^E}{\omega} \right\} \\
w_t &= \frac{\Xi_t^T}{\Lambda_t} (T_t)^{1/\gamma} (1-a) (N_t^T)^{-1/\gamma} \\
\Lambda_t \left\{ 1 + \phi_A \left(\frac{A_{t+1}}{A_t} - 1 \right) \right\} &= \beta \mathbb{E}_t \Bigg[\Lambda_{t+1} \left\{ (1-\delta_A) + \phi_A \left(\frac{A_{t+2}}{A_{t+1}} - 1 \right) \left(\frac{A_{t+2}}{A_{t+1}} \right) - \frac{\phi_A}{2} \left(\frac{A_{t+2}}{A_{t+1}} - 1 \right)^2 \right\} \\
&\quad + \Xi_{t+1}^T (T_{t+1})^{1/\gamma} a (A_{t+1})^{-1/\gamma} \Bigg] \\
T_t &= \left[a A_t^{(\gamma-1)/\gamma} + (1-a) N_t^{T(\gamma-1)/\gamma} \right]^{\gamma/(\gamma-1)} \\
T_t &= \omega E_t^T \\
A_{t+1} &= (1-\delta_A) A_t + I_t^A \\
\log(r_t/r_s) &= \rho_y \log(Y_t/Y_s) + \rho_\pi \log(\pi_t/\pi_s) + \rho_\mu \log(\mu_t/\mu_s) + \varepsilon_{r,t} \\
\log(p_t^E) &= (1-\rho_{p^E}) \log(p^E) + \rho_{p^E} \log(p_{t-1}^E) + \varepsilon_{p^E,t} \\
N_t &= N_t^I + N_t^T \\
\mu_t &= \left(\frac{m_t}{m_{t-1}} \right) \pi_t
\end{aligned}
$$