Declining Effects of Oil Price Shocks*

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Abstract

In recent years, output responses to oil price shocks have not only been weaker, but have also reached their trough earlier. This paper builds a model that incorporates a realistic structure of US petroleum consumption and explores three possible explanations for the changes. The possible factors considered are (i) deregulation in the transportation industry, (ii) improved energy efficiency, and (iii) a lower degree of persistence of oil price shocks. Under realistic parameter values, the three factors play an important role quantitatively, accounting for half of the reduction in the largest impact on output of an oil price shock over time.

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1 Introduction

The 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 global economy in the 1970s. 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 US 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, 10 out of 11 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 relationship 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 2000s. A number 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 had reached a value more than three times as high as the average price in the 1990s. However, these large oil price hikes did not result in significant economic downturns until the subprime financial crisis occurred.

This paper starts by characterizing different responses of macroeconomic variables to oil price shocks in different time periods (before and after 1984), using VAR analysis. The VAR results reveal that the output responses to oil price shocks are quite different in the two subsamples. Moreover, not only output but also other macroeconomic variables display weaker responses to oil price shocks in the post-1984 period. This finding is very robust to different specifications. The biggest impact on output appears earlier in the post-1984 subsample. On average, the output response reaches its trough six quarters after the shock with a 1.52% decline compared with the unshocked path in the pre-1984 subsample, whereas in the post-1984 subsample, the largest deviation from the unshocked path occurs three quarters after the shock with only a

[1] These 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) are also skeptical about the role of oil price shocks in recessions in the 1970s.

0.38% drop. The size of the output trough changes by 75%, and the timing is shifted by three quarters.

This finding is in line with earlier studies.[2] In particular, Hooker (1999) finds that there is a structural break in the relationship between oil prices and the macroeconomy around 1980 in terms of Granger causality. Herrera and Pesavento (2009) find that the magnitude and the duration of the response of output and especially prices to oil price shocks have diminished during the Volcker–Greenspan era. Possibly, the only exception is Ramey and Vine (2011), who argue that responses of the economy to oil price shocks have been relatively stable, once they take into account the additional cost of shortages and rationing during the 1970s as part of the true cost of energy.

Building on the empirical findings in the VAR analysis, this paper explores possible explanations of why we expect to observe the weaker responses of macroeconomic variables to the same size oil price shock. Most earlier studies focus mainly on the 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, 2007; Cavallo and Wu, 2007) and do not address the issue of the weaker effects of oil price shocks. The paper most closely related to this one is Blanchard and Galí (2010), who ask a similar question. 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 that Blanchard and Galí (2010) consider, there are also other possible reasons that the effect of oil price shocks on economic activity has become weaker. In this paper, I will analyze in detail three possible explanations for the declining effect of oil price shocks. The first factor investigated is the effects of deregulation, especially in the US transportation industry. When we consider the macroeconomic consequences of oil price shocks, 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 1 shows petroleum consumption in the US economy from 1949 to 2005 obtained from the Energy Information Administration (EIA). Total petroleum consumption in the US economy has increased over time, except for large decreases in the late 1970s and the early 1980s. As US petroleum production peaked in 1970, this increasing demand for oil is met largely by imports from other countries, and the share of net imports

[2]Once the sample period is extended, Mork (1989) and Hooker (1996) find that the relationship between the oil price and macroeconomy is weakened. Davis and Haltiwanger (2001) also find evidence that the impact of oil price shocks on manufacturing employment growth is weaker in an extended sample including the late 1980s and the early 1990s.

follows a similar pattern to total petroleum consumption.[3] Examining each demand component reveals that, contrary to common treatment in the existing models, more than half of US petroleum consumption comes from the transportation sector. Furthermore, the recent increases in petroleum consumption are driven mainly by oil used in transportation. Thus, 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 to account for the effect of 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 1970s, 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 by 42%. This more efficient use of oil is apparent in terms of the oil expenditure share in value added. While the average oil expenditure share relative to GDP was 3.65% in the pre-1984 period, the average share declined in the post-1984 period to 2.75%. This point is similar to one of the factors considered in Blanchard and Galí (2010). As there exist two types of oil usage in the model, the 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 complementary to Blanchard and Galí (2010).

Finally, I also consider the role played by changes in the degree of persistence of oil price shocks. Small changes in the underlying shock process could alter the responses of macroeconomic variables. Figure 2 plots the real price of oil as measured by the PPI for crude petroleum divided by the GDP deflator. Judging from the data, it is clear that oil price behavior shows different patterns after the mid-1980s. In particular, it tends to be less persistent compared with the near-unit-root nature of the oil price we have observed until the mid-1980s. For whatever reason, if increases in the price of oil are expected to disappear relatively quickly, then there would be less of a need to react to the shock. Therefore, we would expect the same size shock to have a smaller impact. 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 output trough following the shock.

[3] In recent years, net imports have accounted for more than 50% of petroleum consumption, and about one-half is from OPEC countries.

The model is based on a standard sticky-price model with adjustment costs. I extend it to include the role of oil prices in 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.[4] It is assumed that all produced intermediate products must be delivered to customers by using transportation services. Including transportation firms amplifies the effects of oil price shocks, because, as will be described in Section 3, transportation firms had significant market power before deregulation.

In this paper, I will focus on oil price shocks that represent exogenous changes in the price of oil that could be triggered by shocks to oil supply conditions, global oil demand, and precautionary demand with increased uncertainty. In this paper, we are interested in any changes in the price of oil that are exogenous to the US economy. As argued by Kilian (2009), different sources of oil price increases could result in different responses of the economy, and changes in the composition of the shock could be an alternative explanation for the observed changes in the macroeconomic response to oil price shocks.

It should also be noted that, although there are empirical studies documenting possible asymmetric effects on economic activity (see, for example, Davis and Haltiwanger, 2001; Hamilton, 2003),[5] like other existing models, the structure of the model considered here implies that increases and decreases in the price of oil 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.[6]

The baseline specification of the model, which corresponds to the pre-1984 state of the economy, captures important aspects of the economy's response to oil price shocks well, under reasonable parameter values. In terms of accounting for the changes in the economy over time, each factor individually could account for about a 12–25% decline in the trough in aggregate value added. Combined together, the three factors result in a 52% reduction in the largest response and shift the timing of the trough by two quarters, compared with the baseline specification.

[4] This extension is related to recent papers that emphasize the important role played by distribution costs in the context of international business cycle models, such as Burstein, Neves, and Rebelo (2003) and Corsetti, Dedola, and Leduc (2008). The approach taken in this paper is similar to a study by Ravn and Mazzenga (2004), which introduces a transportation sector explicitly and find that a reduction in transportation costs has very large welfare effects.

[5] Although the asymmetric effects of oil price shocks are widely acknowledged, 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.

[6] However, taking the transportation industry into account may help resolve our inability to model asymmetric effects because a common practice in the industry is to include fuel surcharges on invoices, when the economy encounters rapid increases in fuel costs. Fuel surcharges accrue when oil prices increase, but are not applied when oil prices decrease. That is, potentially the structure of the industry itself is asymmetric in terms of responses to oil price shocks.

The rest of the paper is organized as follows. Section 2 characterizes different responses of the US economy to oil price shocks using VAR analysis. Section 3 provides some background information on regulation in the US transportation industry, as well as petroleum consumption of the transportation sector. Section 4 presents a model that we can use for assessing the three possible factors. The results are presented in Section 5, and Section 6 concludes.

2 Empirical Results

In this section, we will characterize some empirical facts about changes in the responses of the US economy to large increases in the oil price. To summarize the average dynamics of macroeconomic variables in response to oil price shocks, we estimate a VAR containing seven macroeconomic variables, together with an oil price shock variable. Following Hamilton (1996, 2003), we first use the net oil price increase (NOPI) over three years as a measure of oil price shocks; NOPI aims to capture exogenous movement in oil prices.[7]

The macroeconomic variables included are real GDP (GDPC1), real consumption (PCECC96), GDP deflator (GDPDEF), real investment (GPDIC1), real wage, labor productivity, and the interest rate (TB3MS). These variables are ordered in this way, preceded by NOPI. All of these variables are obtained from the FRED of the St. Louis Fed. Series IDs are reported in parentheses. For real wage, compensation per hour in the business sector (HCOMPBS) is deflated by the GDP deflator. Labor productivity is defined as output per hour per person. Here I use hours of all persons in the business sector (HOABS) divided by the civilian noninstitutional population (CNP16OV) in the end-of-quarter month to calculate hours worked per worker. The monthly three-month Treasury bill rate (TB3MS) is converted to a quarterly series by taking the quarterly average. Except for NOPI and the interest rate, all variables are logged. I include four lags in the VAR, and a Cholesky decomposition is used to identify oil price shocks. The specification employed here is similar to the one used in Christiano, Eichenbaum, and Evans (2005).

To examine potentially different responses to oil price shocks, I split the entire sample into two subsamples at 1984:Q1, following McConnell and Perez-Quiros (2000). The pre-1984 subsample starts from 1951:Q1 and ends at 1983:Q4 and the post-1984 subsample starts from 1984:Q1 and ends at 2007:Q3.[8] The results presented below are not sensitive to the exact timing of splitting the sample.

Figure 3 shows the behavior of the macroeconomic variables in response to a 10% increase in NOPI

[7] As in Hamilton (1996, 2003), I use the producer price index of crude petroleum, which can be downloaded from IHS Global Insight. Monthly series are converted to quarterly series using end-of-quarter observations.

[8] It is difficult to disentangle the contribution of oil price shocks and the subprime financial crisis in the last recession. To avoid a potential mess caused by the subprime financial crisis, the sample period ends before the 2007–09 recession starts. See Hamilton (2009) for a detailed analysis on the contribution of oil price increases to the 2007–09 recession.

in two different subsamples. These impulse response functions describe the average behavior following a 10% increase in oil prices above their previous three-year high (in terms of percentage deviations from the unshocked path). In the pre-1984 subsample, output, consumption, investment, real wage, and labor productivity decrease in response to an oil price shock, whereas inflation and the interest rate respond positively to the 10% increase in NOPI. Typically, it will take several quarters before the strongest reaction by the economy occurs. Except for the real wage, all variables show statistically significant responses to an oil price shock.

When I estimate the same specification with the data after 1984, I obtain totally different responses by the economy. In terms of point estimates, all variables show muted responses to the same 10% increase in NOPI. Furthermore, the largest impact is likely to take place much earlier in the post-1984 subsample than in the pre-1984 subsample. Another striking feature is that none of these responses is statistically significant.

On average, the most contractionary impact on output occurs at five quarters after an oil price shock hits the economy with a 1.52% decline compared with the unshocked path in the pre-1984 subsample. In the post-1984 subsample, however, output at most declines 0.38% from the unshocked path two quarters after the shock, meaning that the timing of the biggest impact occurs three quarters earlier. We can observe similar patterns in the other variables. This suggests that the effect of an oil price shock has weakened in terms of magnitudes and persistence.

It is possible that NOPI may not be a perfect measure for capturing exogenous movements in the price of oil. As a robustness check, I use a measure of exogenous oil supply shortfall constructed by Kilian (2008) as an alternative. As Kilian (2008)'s measure of exogenous disruption in the world oil supply (measured as a percentage share of world oil production) only starts from 1971:Q1, we will lose many observations in the pre-1984 period. This could underestimate the effect of the oil shock in the pre-1984 period because we will lose four recessions and episodes of oil price increases. Given a smaller sample, estimating the full system may be problematic. Thus, I will instead estimate a smaller system. The smaller system includes Kilian (2008)'s measure, a variable of interest (GDP, consumption, investment, real wage, or labor productivity), log of GDP deflator and the interest rate, in this order. The smaller system contains four lags. The pre-1984 sample contains 48 observations (after adjustment for lags) and there are 83 observations in the post-1984 sample.

Figure 4 presents impulse responses of the macroeconomic variables following a one percentage point reduction in oil supply in terms of world share. The responses of GDP, consumption, investment, real wage, and labor productivity are obtained separately from the smaller system. The responses of inflation and the interest rate are the ones obtained from estimating together with GDP. Unlike the impulse response functions obtained with NOPI, responses in the pre-1984 subsample are not significant, except for those of consumption and the interest rate. This may be because of the fact that there are not many observations in the pre-1984 subsample. As the oil shocks identified are different, it is difficult to obtain a direct comparison between the quantitative results in Figure 3 and Figure 4. Despite imprecise point estimates, the overall qualitative patterns of the pre- and post-1984 subsamples are similar, however.

Overall, these empirical results suggest that the impact of oil price shocks in the US economy changed after the mid-1980s.

3 Transportation Industry

This section provides background information about oil consumption, the deregulation that started in 1980, and responses to oil price shocks in the transportation industry.

3.1 Petroleum Consumption by Transportation Sector

As mentioned in the Introduction, the transportation sector is the largest consumer of petroleum in the US. One caveat is that the EIA's definition of the transportation sector includes supply-side petroleum consumption as well as household use of petroleum in automobiles. The EIA does not have data on use of petroleum in household vehicles except for selected years. Based on the information in the EIA's "Household Vehicles Energy Use: Latest Data & Trends,"[9] about 52% of petroleum is used by household vehicles in the transportation sector after the late 1980s. Therefore, even when we take account of household vehicle use, the transportation service industry itself consumes as much oil as all of the industrial sector.

Figure 5 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, therefore, needs to pay particular attention to the trucking industry.

3.2 Regulation in the Transportation Industry

The US transportation industry in the 1970s was regulated heavily by the Interstate Commerce Commission (ICC), which was established by the Interstate Commerce Act of 1887. The ICC regulated prices and

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

competition in interstate transportation. Starting with railroads, the control of the ICC was expanded to a variety of transportation modes, such as trucking, water transportation, oil pipelines, and freight forwarders. The trucking industry would be a good example of a perfectly competitive industry, if there were no regulation in the industry (Olson, 1972). Such a regulatory environment in the transportation industry imposed by the ICC 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 1980s, the control of the ICC had been diminishing. Ultimately, all regulations were removed in 1995 when the ICC was abolished.

Regulations by the ICC consisted primarily of restrictions on operating rights and a requirement to file price changes. The ICC controlled new entries by granting operating certificates, which specified the scope of operations, such as a list of routes, commodities, and areas that carriers may serve. A new certificate was issued if it could 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 protested against frequently by incumbent carriers. This procedure was also applicable to incumbents expanding their scope of operations, such as a larger 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 can be used as a measure of the monopolistic rents. In fact, these 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 30 days prior to the new rate becoming effective. For this 30-day period, the proposed new price was subject to objection from anyone, including the ICC itself and competitors (both those in the same transportation mode and those 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 operating under antitrust immunity since 1948 (the Reed–Bulwinkle Act). Although the ICC required rate bureaus to be open and democratic, investigations undertaken by the US 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). Because of limited ICC resources for reviewing proposed tariffs,[10] it was virtually the case that "[t]he carriers set their own rate" (U.S. Congress, Senate, 1980, p. 80).

The rate bureau system ensured that protesters 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 affected directly 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 a rate bureau. However, most rate bureaus required notice of the independent action before it could take effect, and other carriers had the option of whether to use 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 an 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 a mean of 52.2%) for railroads and those for trucking range from 26% to 49% (with a mean of 37.1%).

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 grant operating rights to any requesting firm that was 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 the new service, opponents were asked to provide evidence for why the new service was not beneficial. Furthermore, route restrictions were also eliminated. By 1986, the number of motor carriers holding ICC operating certificates was more than double 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 were within the ±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 found that there was sufficient competition to regulate

[10]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.

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 the importance of the rate bureau system.

Overall, the net effect of deregulation is higher efficiency and more competition, which lead 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 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 deregulation. They find that the estimated markup declined dramatically after deregulation. While the estimated markup rate using a 1977 sample is 35.5%, the estimate based on 1988 data is 1.9%.

If the deregulation in the transportation industry has a significant impact on the markup, we should expect to see a secular decline in the relative price.[11] For the US transportation industry, at least, there are two data sources available. One is the OECD STAN database, which contains price and quantity indices for different industries at an annual frequency. It contains both gross output and value-added measures. In terms of industry-level analysis, it is desirable to look at gross output as a measure of output. This is especially true for the analysis of oil price shocks because production of value added does not involve the use of materials and energy by definition. Thus, the supply-side effects of oil price shocks are likely to be underestimated by looking at value-added data. One drawback of the OECD STAN database is that while the value-added series starts in 1972 and ends at 2007, gross output data are only available from 1988. Another data set we can employ is the industry-level data set constructed by Jorgenson and his colleagues.[12] Jorgenson's data set also contains annual price and quantity indices based on gross output from 1960 to 2005.

Figure 6 plots two measures of the log of relative prices of the gross output and value added. Note that while the gross output price is deflated by the CPI, the value-added price is deflated by the GDP deflator. For the purpose of examining the effect of deregulation on the markup, we do not want relative prices affected significantly by changes in the oil price. As the production of gross output involves the use of oil, the gross output price reflects changes in the oil price. The CPI reflects changes in the oil price more than the GDP

[11] I thank an anonymous referee for pointing this out.

[12] It is available at http://hdl.handle.net/1902.1/10684. Details of his data set can be found in Jorgenson, Gollap, and Fraumeni (1987), Jorgenson (1990), and Jorgenson and Stiroh (2000).

deflator. This is why the gross output price is deflated by the CPI, rather than the GDP deflator used to deflate the value-added price.

Figure 6 shows that there is a downward trend in relative prices throughout the sample period. Prior to deregulation in 1980, relative prices did not change significantly. In 1981, the relative prices increase slightly, but they show a secular decline afterward. By 1985, relative prices based on gross output decline by 13.6% and that of value added drops by 7.8%, compared with the 1980 level. This reduction in relative prices around 1980 suggests that deregulation has changed the cost structure in the transportation industry. Of course, these reductions cannot be attributed solely to the markup change from deregulation. The increased competition in the industry increases the incentive to minimize the cost of operations and encourages the adaption of more energy-efficient production technology. Thus, the consequences of deregulation are (i) lower markup because of the more competitive environment and (ii) improved energy efficiency in the transportation industry (mainly via lifting route restrictions and reducing empty backhauls).

3.3 Effect of Oil Price Shocks in the Transportation Industry

Next, I will examine how the transportation sector responds to oil price shocks. It is important to examine the consequences of oil price shocks in the transportation industry, which usually draws little attention in terms of the effect of oil price shocks.

To illustrate how the transportation industry reacts to oil price shocks, I estimate a bivariate VAR including NOPI and either output growth or relative price inflation in that order. The transportation price is deflated by the GDP deflator. As before, the Cholesky decomposition is used to identify oil price shocks. The pre-1984 sample with gross output data from Jorgenson's data set starts from 1961 and ends at 1983 and the post-1984 sample ends at 2005. The pre-1984 sample with the value-added data from the OECD STAN data set starts from 1971 and ends at 1983 and the post-1984 sample ends at 2007. Because of this small sample size, this sector-level bivariate VAR just includes one lag to be parsimonious.

The top panels of Figure 7 depict the responses of output growth to a 10% increase in NOPI. Regardless of the measure of output (gross output or value added), output growth in the transportation industry is affected negatively by oil price shocks in the pre-1984 subsample. For gross output growth, the statistically significant negative impact persists even two years after the shock. Similarly, value-added growth is also depressed significantly one year after an oil price shock hits the industry. However, we do not see statistically significant responses of output growth in the post-1984 subsample, regardless of the measure of output we use. This observation is consistent with empirical findings at the aggregate level presented in Section 2.

The bottom panels of Figure 7 show the responses of relative price inflation. In the pre-1984 subsample, relative price inflation increases in response to a 10% increase in NOPI. In particular, in terms of point estimates, the results based on gross output show a relatively stronger response than that for value added. The responses of relative prices become much smaller in the post-1984 subsample. However, in both subsamples, the estimated responses of transportation inflation appear to be insignificant at the conventional level.

4 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.

There are two direct avenues whereby an increase in the price of oil can impact 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). As mentioned earlier, this is intended to capture the role of the industrial sector in US petroleum consumption. The other channel through which oil price shocks may have an effect on the economy is the direct impact on the cost of transportation. In the subsections below, we shall examine each sector in detail.

While intermediate-good firms produce distinct products and sell their output in monopolistically competitive markets, they act as price-takers 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 a factor input. 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 household consumption as well as being used as material inputs in the production process.

This roundabout production structure arising from inclusion of the raw materials helps amplify the effect of oil price shocks. Without this interdependence, oil price shocks only affect the costs of capital utilization and transportation. The inclusion of materials will create another indirect effect of oil price shocks through increased materials costs. In the absence of the roundabout production structure, the effect of oil price shocks would be smaller.

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 regions, products carried, and transportation modes.

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.

4.1 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-services 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 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 the 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.

4.2 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 carryover, the household receives a lump-sum transfer $\mathcal{T}_t(h)$ from the monetary authority at the beginning of each period. After the bonds have matured, the household also receives $B_{t-1}(h)$ additional units of money. During 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.

4.3 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 $T_t(i)$ to finalize its production process. I 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 the 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), I assume that the production of gross output involves the use of material inputs through 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 the 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 the firm itself. Here, I 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 product j. Notice that the CES technology is identical to the one that the final-good aggregator uses. Thus, it is equivalent to using the final good as a material input. 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 a materials input 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 a firm-specific capital stock according to the law 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 the time-varying depreciation rate. As is 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) and Leduc and Sill (2004), I assume that capital utilization is tied to 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 $\nu > 1$. For the 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 production technology (2) and (3), the optimality condition implies that

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

As 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. Firm i faces total demand 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 reflects 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 so 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-good firm chooses $P_t(i)$, $u_t(i)$, $K_{t+1}(i)$ and $N_t^I(i)$ 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). The real profits are given by

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

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

4.4 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 a competitive industry. However, because of the regulations described in Section 3, transportation firms are monopolistically competitive firms supplying distinctive services. For example, regional barriers in the industry are one of the sources of such distinctiveness.

Transportation services are produced by combining value added and oil with 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 requires capital and labor and 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

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

where $u_t^T(n)$ is the variable utilization rate of $A_t(n)$, which represents transportation firm n's beginning-of-period stock of transportation equipment, $N_t^T(n)$ is labor input, $a \in (0,1)$, 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 a 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 because of the fact that operating transportation equipment requires a certain amount of labor. I have also experimented with a typical Cobb–Douglas value-added production function, but the quantitative results for accounting for changes in the economy over time are not significantly different.

Each transportation firm accumulates a stock of transportation equipment following the law of motion

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

where δ_t^A is the variable depreciation rate of $A_t(n)$ and $I_t^A(n)$ is transportation firm n's investment. It is assumed that

$$\delta_t^A(n) = \delta^A + b\frac{u_t^T(n)^{1+\zeta} - 1}{1+\zeta}, \tag{16}$$

where δ^A is the steady-state rate of depreciation, $b > 0$, and $\zeta > 0$ controls the elasticity of marginal depreciation. This specification of the variable depreciation function is adapted from Baxter and Farr (2005) and maintains standard characteristics used in the literature. Similar to intermediate-good producers, each transportation firm is subject to capital adjustment costs, given by

$$AC_t^A(n) = \frac{\phi_A}{2}\left(\frac{A_{t+1}(n)}{A_t(n)} - 1\right)^2 A_t(n), \tag{17}$$

with $\phi_A > 0$.

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

$$T_t(n) = \left(\frac{P_t^T(n)}{P_t^T}\right)^{-\theta_T} T_t, \tag{18}$$

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) – (18), 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

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

4.5 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 the 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 the model's equilibrium unique, even under the pre-1979 estimates.

4.6 Real Price of Oil

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

$$\log(p_t^E) = (1 - \rho_{p^E}) \log(p_s^E) + \rho_{p^E} \log(p_{t-1}^E) + \varepsilon_{p^E,t}, \tag{19}$$

where $p_t^E = P_t^E/P_t$, p_s^E represents the steady-state real price of oil, and $|\rho_{p^E}| < 1$. This process represents agents' perception about how oil prices change over time.

However, as argued by Barsky and Kilian (2002), there might be a problem in treating the real price of oil as exogenous, especially after 1973. In fact, some recent studies (such as, Balke, Brown, and Yücel, 2008; Nakov and Pescatori, 2010) incorporate an oil-producing sector in the economy to allow for endogenous oil price determination. However, such an approach will complicate the analysis and thus we focus mainly on how the oil-importing US economy would react to exogenous changes in the price of oil.

4.7 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 $B_t = B_{t-1} = 0$, must also hold.

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

$$Y_t - p_t^E(E_t^I + E_t^T) = C_t + I_t + I_t^A + AC_t^W + AC_t^K + AC_t^Y + AC_t^A. \tag{20}$$

Equation (20) states that the sum of consumption, total investment, and total adjustment costs equal real value added, which is the value of the 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.[13]

5 Results

This section presents the quantitative results and discusses how the model presented in Section 4 responds to an oil price shock. To obtain the solution to the system, I log-linearize the equilibrium conditions of the model around its steady state and apply the standard solution method. Before showing the quantitative results, I describe the calibration procedure in the following subsection.

5.1 Calibration

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

The parameter values drawn from the pre-1979 estimates of Ireland (2001) are the 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 the annualized interest rate is 6.3%.

The capital adjustment cost parameter is assumed to be 10 for both intermediate-good firms and transportation firms. This is the value imposed in Ireland (2001). The pre-1979 estimates of Ireland (2001)

[13] A complete description of the system is summarized in the Appendix, which is available from the author upon request.

adopted here are all based on this capital adjustment cost parameter and we will use the same values to maintain consistency. The wage adjustment cost parameter is 58.[14] The demand elasticity parameter for the final good, θ, equals 6, which implies that in the steady state, the price markup becomes 20%. This is the value widely used in the literature as well as the one used in Ireland (2001). I also set the labor demand elasticity, θ_N, to be 6.

The Frisch labor supply elasticity is set to 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 a different specification.[15] 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 one for transportation firms δ^A are both set equal to 0.025. The steady-state rate of utilization in the transportation sector u^T is set equal to 1. We set the value of ζ equal to 1, which is the same as the value used in Baxter and Farr (2005) and is based on a point estimate from Basu and Kimball (1997). I have experimented with different values of ζ, such as $\zeta \to \infty$ (i.e., constant depreciation) or $\zeta = 0.001$ (i.e., less costly utilization). My experiments suggest that the results remain the same qualitatively regardless of the choice of ζ.

For parameter values related to transportation technology, I set the demand elasticity parameter θ_T equal to 3.8169 for the baseline specification, such that the implied markup is 35.5%. I set the value after the deregulation in the transportation industry equal 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 Jorgenson's industry-level data set, 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.[16] 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%.[17] Thus, I set $\chi_Y = 0.0386$.

I 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 by estimating (19) using the pre-1984 data on the log-real price of oil, which is measured as the log of PPI for crude petroleum deflated by the GDP deflator.

[14] 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 the wage adjustment cost parameter corresponds roughly to about 20% of households being able to reoptimize their wages in each period, given other parameter values used in the baseline specification.

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

[16] 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 values for the share of materials, this is primarily because they take into account the energy cost as well.

[17] Details on this calculation are given in the Appendix, which is available from the author upon request.

In terms of the percentage deviations of the aggregate value added from the steady-state value, the oil expenditure share in aggregate value added plays 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 St. Louis Fed, the average share of oil consumption in value added from 1949 to 1983 was 3.65%, and the average share after 1983 was 2.75%. According to the EIA's data, the average value of the ratio E^I/E^T was 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 the other parameter values, these calibrating targets for the 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

$$\omega = \frac{(1 + s_1 + s_2)\left(1 + \frac{s_1}{s_2}\right)\chi_Y p_s^E}{(s_1 + s_2)\{1 - \chi_Q(1 - \chi_Y)\}}. \tag{21}$$

The values of ν and κ are determined jointly by solving the following nonlinear system of equations

$$\frac{s_1}{s_2} = \frac{(u_s)^\nu}{\nu}\left\{\frac{1}{\beta} - (1 - \delta_s) + p_s^E \frac{(u_s)^\nu}{\nu}\right\}^{-1} \frac{\Xi_s^Y}{\Lambda_s}(1 - \chi_Q(1 - \chi_Y))\frac{\alpha\chi_V\omega}{\chi_Y}, \tag{22}$$

$$\frac{1}{\beta} - 1 = (u_s)^\kappa\left(1 - \frac{1}{\kappa}\right) + p_s^E(u_s)^\nu\left(1 - \frac{1}{\nu}\right), \tag{23}$$

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 $\kappa = 1.06$. By imposing the steady-state value $u^T = 1$, the value of b is given by $b = \frac{1}{\beta} - \delta^A$, which equals 0.0276.

5.2 Baseline Results

First, we consider the baseline specification, which corresponds to the pre-1984 state of the economy. Figure 8 shows the dynamic responses of variables to a 10% increase in the real price of oil.

The aggregate value added, which corresponds to real GDP, shows a hump-shaped response and achieves its trough five quarters after the shock. The near-unit-root nature of the oil shock results in strong persistence in the IRFs. Other variables, except for inflation, show a hump-shaped response as well, because of price stickiness. Among the macroeconomic variables, investment is affected most severely, as pointed out by Aguiar-Conraria and Wen (2007). 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 because of the fact that the income effect dominates the substitution effect slightly, and then decline. Under the monetary policy rule assumed, the Fed increases the interest rate 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 oil price shocks can affect the economy. The first one is via capital utilization tied with the use of oil. Oil price shocks result in a higher cost of utilizing the 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.

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

$$\widehat{mc}_t = \frac{1}{mc_s}\left\{(1-\chi_Q)(1-\chi_Y)mc_s^V\widehat{mc}_t^V + \chi_Y p_s^T \widehat{p}_t^T\right\}, \tag{24}$$

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 in the real price of oil affects both $\widehat{mc}_t^V$ via capital utilization and $\widehat{p}_t^T$ through transportation costs. 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 the reasons we expect the lower markup on transportation services to contribute to the weaker response to the same size oil price shock.

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

5.3 Changes in the Economy Over Time

To understand the declining effects of oil price shocks, we will consider three different factors individually and a combination of those. First, we will consider the consequence of a more competitive environment in the transportation industry triggered by the deregulation after 1980. Second, we will consider the effect of improved energy efficiency in the economy. Lastly, we will consider the consequences of the less persistent oil price shock. Table 2 provides a summary of changes in the largest response of aggregate value added under each scenario, and the associated IRFs are shown in Figure 9 and Figure 10.

Case 1: Increased Competition among Transportation Firms

The main impact of deregulation in the transportation industry is the increased competition among transportation firms. To see the effect of the deregulation, I 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).[18] Other parameter values are left unchanged.

As shown in Figure 9 under the label "Deregulation," all variables show weaker responses to the same size oil price shock. The largest steady-state deviation of aggregate value added is reduced by 11.79%. Quantitatively speaking, this reduction is nontrivial, given the very small share of the transportation industry. However, there are no changes in the timing of the largest impact.

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 a new steady state with a higher level of output and a lower aggregate price level. To produce the higher level of output, all factor inputs will be used 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 (24) tell us that a decline in p_s^T induces deviations in the real marginal cost by putting less weight on deviations of the price of transportation firms. In turn, it results in smaller deviations in other real variables.

Case 2: Improved Energy Efficiency in the Economy

Another factor that could contribute to the weaker responses of the macroeconomic variables is improvements in the efficiency of petroleum use. It is quite intuitive that improved energy efficiency might be a candidate for the declining effects of oil price shocks. 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, and other studies also consider this possibility, such as Blanchard and Galí (2010) and Nakov and Pescatori (2010).

More efficient use of oil could originate from transportation and/or capital utilization in the present model. Unlike the putty-clay model of Atkeson and Kehoe (1999), which can generate an endogenous increase in energy efficiency, the model does not have an endogenous mechanism to improve energy efficiency. Thus,

[18]Another consequence of deregulation is the improved energy efficiency in the transportation firms. However, we do not have an explicit estimate for the contribution of deregulation to the improved transportation efficiency. Thus, we will restrict our attention to the lower markup.

I will change ω and ν, which govern energy efficiency directly in the transportation and industrial sectors, respectively.

Changes in ω can arise from improvements in transportation technology, such as more fuel-efficient vehicles. Even though it is very difficult to provide quantitative measures, it is also important to point out that deregulation reduces the amount of energy that is necessary to provide one unit of transportation services. A significant number of empty backhauls existed under the regulatory environment, and the restriction on routes also reduced the energy efficiency of the transportation industry. For the intermediate-good firms, changes in energy efficiency via ν affect the energy–capital complementarity for a given level of utilization.

Unfortunately, we do not have reliable data on how energy efficiency has been improved in the economy. We do know that the average oil expenditure share has dropped from 3.65% in the pre-1984 period to 2.75% in the post-1984 period. We can also observe changes in petroleum consumption in the industrial and transportation sectors. In particular, 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 (21), I can infer a new value of ω, which is consistent with the post-1984 characteristics of US petroleum consumption, by using the above information. As a result, ω increases from 3.0334 to 3.6752. According to (13), this means that the energy efficiency in terms of the amount of transportation services produced given one unit of energy (e.g., miles per gallon) improves by more than 20%. Alternatively, the amount of energy necessary to provide one unit of transportation services ($1/\omega$) decreases. Given the value of ω, ν is changed via (22) such that the resulting steady-state oil expenditure share equals 2.75%. As a result, ν changes from 1.7373 to 1.8864.

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, an increase in ω results in smaller deviations of the transportation price as follows:

$$\widehat{p}_t^T = \frac{mc_s^T}{mc_s^T + p_s^E/\omega}\widehat{mc}_t^T + \frac{p_s^E/\omega}{mc_s^T + p_s^E/\omega}\widehat{p}_t^E. \tag{25}$$

In turn, this makes deviations in the marginal cost smaller.

An increase in ν results in the smaller value of the steady-state marginal cost of producing intermediate-good firms' value added mc_s^V and also $\widehat{mc}_t^V$ becomes smaller, given the same size oil price shock. Improved energy efficiency through ω and ν affects $\widehat{mc}_t$ through different channels.

Given the same size shock, the IRFs in Figure 9 labeled "Energy Efficiency" also show weaker responses of all variables. As a result, the largest deviation of aggregate value added becomes smaller by 24.75% compared with the baseline specification.

Case 3: Lower Degree of Persistence of the Shock

It is not difficult to imagine that the shape of the IRFs would be affected by a small change in the underlying shock process, and thus one might suspect that it could explain why we observe the weaker response of macroeconomic variables to oil price shocks. 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 the GDP deflator, suggests that it falls from 0.99 to 0.92. Thus, I change the persistence parameter ρ_{p^E} from 0.99 to 0.92.

It should be noted that changes in the persistence parameter represent adjustments in the agents' perception of the nature of oil price shocks. If agents believe that increases in the price of oil will die out relatively quickly, then there would be less need to react to the shock. As a result, we would expect to see more muted responses from the economy to oil price shocks.

The IRFs shown in Figure 10 labeled "Less Persistence" are the resulting responses. In terms of the largest response, as expected, a small change in the persistence parameter contributes to a large reduction in the trough, 26.38%. Although there are no changes in the timing of the largest deviations in output under the other factors considered, less persistence in the oil price process shifts the timing of the trough by two quarters.

Case 4: Post-1984

Finally, the IRFs in Figure 9 labeled "Post-84" show the responses of the economy to an oil price shock when all factors considered so far are combined together. This illustrates how much the model could explain changes in the economy over time in response to an oil price shock. As can be clearly seen, all factors together result in much smaller responses to the same size oil price shock. In terms of the changes in the largest impact on aggregate value added, it suggests that the most contractionary impact is reduced by 51.55% as a whole and the timing of the trough is shifted by two quarters because of the less persistent oil price process.

5.4 Discussion

The effect of deregulation through the lower markup results in nearly a 12% reduction in the output trough. If we combine the effect of improved transportation efficiency, about a 20% drop in the output response can be attributed to the transportation industry. Despite the fact that it has a small share in the economy, this contribution of the transportation sector is quite comparable to other factors considered in the paper. The overall effect of more efficient use of oil in the US economy weakens the largest deviations of value added by 25%. A less persistent oil price shock accounts for a 26% reduction in the output trough. Overall, all factors play an important role in accounting for the declining effects of oil price shocks and are equally important quantitatively. Combining them together, all factors together account for about a 52% reduction of the value added response to an oil price shock.

If one believes the VAR results presented in Section 2 are a good representation of changes in the economy over time, then the factors considered in this paper could account for a majority of the declining effects of oil price shocks. It should be noted, however, that these results do not suggest that the factors considered here are the only sources of changes in the economy over time. The unexplained changes in the responses to an oil price shock must be attributed to some other factors that are not considered in the paper.

The model is successful in explaining changes in the output responses. However, there are some aspects of the economy that the model fails to account for. For example, empirically, the behavior of the real wage stays relatively unchanged in both periods, but the factors considered are not sufficient for explaining the real wage behavior. Changes in the wage adjustment cost toward more flexible wages can mitigate the problem to some extent. However, my experiment suggests that, even with zero wage adjustment costs, it is not sufficient to keep the real wage dynamics relatively unchanged.

One might argue that the economy is shifting toward more flexible prices.[19] Regarding reduced price stickiness, it would contribute to shifting the timing of the trough and help keep the real wage dynamics unchanged, but other aspects of the economy's response deteriorate. However, because price stickiness has dampening effects on the dynamic response of model variables, a more flexible price (lower value of ϕ_Y) would result in stronger responses of aggregate value added and other variables in this framework.

The post-1984 IRFs suggest that the interest rate does not respond to an oil price shock. Such muted responses of the interest rate are not fully captured by those factors considered in the model, suggesting the contributions of monetary policy are also important, such as changes in the systematic reaction of monetary

[19] It has been believed widely that the average frequency of price changes is about one year (for example, Taylor, 1999). However, Bils and Klenow (2004) document that in the mid-1990s, the average frequency of price changes is greater than typically believed.

policy, which is examined in Herrera and Pesavento (2009).

This paper treats different causes of the oil price increases equally and focuses on the structural explanation about the changes in the economy over time. However, this does not necessarily exclude other possibilities. For example, Kilian (2009) argues that distinguishing the underlying causes of the oil price increases is very important because different types of shocks can result in different dynamic responses of the economy. His result supports a claim that recent oil price hikes are driven primarily by global demand shocks. He argues that changes in the composition of the underlying shocks help explain the different behavior of the economy. This is a plausible idea, and it should be explored further in the future. To correctly assess and disentangle the role played by structural changes in the economy or the different composition of underlying shocks affecting the oil price, we need to build and estimate a more sophisticated structural model that incorporates endogenous oil price determination.

Hamilton (2009) also argues that the oil price run-up of 2007–08 was driven by strong demand, together with stagnant world oil production. He demonstrates that despite the different causes, there are negative effects on consumption spending and auto sales, which appear to be very similar to the previous oil price shock episodes. This leads him to conclude that the 2007–08 recession should be included in the list of US recessions, where oil prices appear to have made a material contribution. His conclusions do not contradict the finding in this paper that, given the same size oil price shock, the effect on the US economy would be smaller than before. It is not surprising that the 2007–08 oil price shock has made a significant contribution to the last recession, given the relatively large oil price shocks observed in 2007 and 2008. He acknowledges that the manufacturing industry share has declined, implying that the impact of oil price shocks has lessened, and that there was a critical contribution of the subprime financial crisis in the last recession. A combination of the subprime problem and oil price shocks is the likely cause of the 2007–08 recession, and thus accurate evaluation of the contribution of oil price shocks is difficult.

In the model of Nakov and Pescatori (2010), the oil price, oil supply, and oil demand are all endogenous. This is quite different from typical approaches that treat the oil price as exogenous. They consider the diminished reliance on oil as one of the potential factors contributing to the Great Moderation and find that it can account for an 18% reduction in GDP growth volatility. Similarly, Balke, Brown, and Yücel (2008) share the same motivation as the current paper and examine the effects of oil supply shocks and oil demand shocks arising domestically or from the rest of the world. They find that the poor economic performance in the 1970s and early 1980s can be attributed to the confluence of negative technology shocks and negative labor supply shocks, rather than the oil supply shocks.

Unlike the current paper, a common feature in these papers is that oil is introduced as one of the inputs into production and there is no mechanism to amplify the impact of the increased oil price (such as variable capital utilization or a roundabout production structure in this model). In general, such an approach is expected to produce a weak contractionary effect of oil-related shocks. If the underlying model has difficulty generating a large contractionary effect, it is possible that changes in the economy triggered by oil-related shocks are attributable to some other factors. Thus, this different role for oil along with variable utilization capital and transportation in the economy could potentially lead to different quantitative and qualitative implications, and further investigation is necessary.[20]

Dhawan, Jeske, and Silos (2010) find that there was a negative spillover effect from energy prices to total factor productivity (TFP) before 1982 and argue that the spillover effect that has disappeared since 1982 accounts for the reduced volatility in TFP, which in turn is considered to be the cause of the Great Moderation. However, they do not offer a good explanation for the origin of the spillover effect or its disappearance after 1982. According to the construction of their TFP measure, changes in the rate of capital utilization are not accounted for. Thus, it is highly likely that their TFP measure captures unobserved variable capital utilization and this could potentially explain the spillover effect.

6 Conclusion

We have developed a model that is more realistic in terms of US petroleum consumption, to explore the possible explanations for 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 adequately captures important aspects of the economy's response to oil price shocks. Price stickiness accounts for the hump-shaped responses of output measures, which are consistent with what we see in the 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 equally important quantitatively. It is worth noting that in spite of its small share, the contribution of the transportation industry triggered by deregulation is nontrivial. If the US economy becomes less dependent on transportation, we would expect a further contribution from the transportation sector. Combining all factors, the model predicts a 52% reduction in the largest impact on aggregate value added and the trough comes two quarters earlier.

We can draw one implication from this study. Deregulation in the transportation industry has led to

[20]For example, in my experiment, less reliance on oil per se can result in about a 28% reduction in output volatility.

a more competitive environment and less reliance on petroleum. Furthermore, technological advancement resulted in 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 the view that large increases in the price of oil trigger a deep recession. However, we expect that, given a same size oil price shock, the large recessionary consequences of oil price shocks that we observed in the 1970s will not be seen again.

References

Aguiar-Conraria, L., and Y. Wen (2007): "Understanding the Large Negative Impact of Oil Shocks," *Journal of Money, Credit and Banking*, 39(4), 925–944.

Atkeson, A., and P. J. Kehoe (1999): "Models of Energy Use: Putty-Putty versus Putty-Clay," *American Economic Review*, 89(4), 1028–1043.

Balke, N. S., S. P. A. Brown, and M. K. Yücel (2008): "An International Perspective on Oil Price Shocks and U.S. Economic Activity," Globalization and Monetary Policy Institute Working Paper 20, Federal Reserve Bank of Dallas.

Barsky, R. B., and L. Kilian (2002): "Do We Really Know that Oil Caused the Great Stagflation? A Monetary Alternative," in *NBER Macroeconomics Annual 2001*, ed. by B. Bernanke, and K. Rogoff, vol. 2001, pp. 115–134. MIT Press, Cambridge, MA.

——— (2004): "Oil and the Macroeconomy since the 1970s," *Journal of Economic Perspectives*, 18(4), 115–134.

Basu, S. (1996): "Procyclical Productivity: Increasing Returns or Cyclical Utilization," *Quarterly Journal of Economics*, 111(3), 719–751.

Basu, S., and M. S. Kimball (1997): "Cyclical Productivity with Unobserved Input Variation," *NBER Working Paper*, No. 5915.

Baxter, M., and D. D. Farr (2005): "Variable capital utilization and international business cycles," *Journal of International Economics*, 65(2), 335–347.

Bernanke, B. S., M. Gertler, and M. Watson (1997): "Systematic Monetary Policy and the Effects of Oil Price Shocks," *Brookings Papers on Economic Activity*, 1997(1), 91–142.

Bernanke, B. S., M. Gertler, and M. W. Watson (2004): "Oil Shocks and Aggregate Macroeconomic Behavior: The Role of Monetary Policy. A Reply," *Journal of Money, Credit and Banking*, 36(2), 287–291.

Bils, M., and P. J. Klenow (2004): "Some Evidence on the Importance of Sticky Prices," *Journal of Political Economy*, 112(5), 947–985.

Blanchard, O. J., and J. Galí (2010): "The Macroeconomic Effects of Oil Price Shocks: Why Are the 2000s so Different from the 1970s?," in *International Dimensions of Monetary Policy*, ed. by J. Galí, and M. J. Gertler, pp. 373–421. University of Chicago Press.

Burbidge, J., and A. Harrison (1984): "Testing for the Effects of Oil-Price Rises using Vector Autoregressions," *International Economic Review*, 25(2), 459–484.

Burnside, C., and M. Eichenbaum (1996): "Factor-Hording and the Propagation of Business-Cycle Shocks," *American Economic Review*, 86(5), 1154–1174.

Burstein, A. T., J. C. Neves, and S. Rebelo (2003): "Distribution Costs and Real Exchange Rate Dynamics during Exchange-rate-based Stabilizations," *Journal of Monetary Economics*, 50(6), 1189–1214.

Carlstrom, C. T., and T. S. Fuerst (2006): "Oil Prices, Monetary Policy, and Counterfactual Experiments," *Journal of Money, Credit and Banking*, 38(7), 1945–1958.

Carruth, A. A., M. A. Hooker, and A. J. Oswald (1998): "Unemployment Equilibria and Input Prices: Theory and Evidence from the United States," *Review of Economics and Statistics*, 80(4), 621–628.

Cavallo, M., and T. Wu (2007): "Measuring Oil-price Shocks Using Market-based Information," *Federal Reserve Bank of San Francisco Working Paper.*

Christiano, L. J., M. Eichenbaum, and C. L. Evans (2005): "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*, 113(1), 1–45.

Clarida, R., J. Galí, and M. Gertler (2000): "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory," *Quarterly Journal of Economics*, 115(1), 147–180.

Congressional Budget Office (2006): "The Economic Effects Recent Increases in Energy Prices," A CBO Paper.

Corsetti, G., L. Dedola, and S. Leduc (2008): "International Risk Sharing and the Transmission of Productivity Shocks," *Review of Economic Studies*, 75(2), 443–473.

Daniel, B. C. (1997): "International interdependence of national growth rates: A structural trends analysis;," *Journal of Monetary Economics*, 40(1), 73–96.

Davis, S. J., and J. Haltiwanger (2001): "Sectoral Job Creation and Destruction Responses to Oil Price Changes," *Journal of Monetary Economics*, 48, 465–512.

Department of Energy, Energy Information Administration (1995): "Measuring Energy Efficiency In The United States' Economy: A Beginning," U.S. Government Printing Office.

——— (2006): "Annual Energy Review 2005," U.S. Government Printing Office.

Dhawan, R., K. Jeske, and P. Silos (2010): "Productivity, Energy Prices and the Great Moderation: A New Link," *Review of Economic Dynamics*, 13(3), 715 – 724.

Dotsey, M., and R. G. King (2006): "Pricing, Production, and Persistence," *Journal of European Economic Association*, 4(5), 893–928.

Finn, M. G. (2000): "Perfect Competition and the Effects of Energy Price Increases on Economics Activity," *Journal of Money, Credit and Banking*, 32(3), 400–416.

Gisser, M., and T. H. Goodwin (1986): "Crude Oil and the Macroeconomy: Tests of Some Popular Notions: Note," *Journal of Money, Credit and Banking*, 18(1), 95–103.

Greenwood, J., Z. Hercowitz, and G. W. Huffman (1988): "Investment, Capacity Utilization, and the Real Business Cycle," *American Economic Review*, 78(3), 402–417.

Hamilton, J. D. (1983): "Oil and the Macroeconomy since World War II," *Journal of Political Economy*, 91(2), 228–248.

——— (1996): "This is what happened to the oil price-macroeconomy relationship;," *Journal of Monetary Economics*, 38(2), 215–220.

——— (2003): "What is an oil shock?," *Journal of Econometrics*, 113(2), 363–398.

——— (2009): "Causes and Consequences of the Oil Shock of 2007–08," *Brookings Papers on Economic Activity*, 1, 215–261.

Hamilton, J. D., and A. M. Herrera (2004): "Oil Shocks and Aggregate Macroeconomic Behavior: The Role of Monetary Policy: A Comment," *Journal of Money, Credit and Banking*, 36(2), 265–286.

Herrera, A. M., and E. Pesavento (2009): "Oil Price Shocks, Systematic Monetary Policy, and the "Great Moderation"," *Macroeconomic Dynamics*, 13, 107–137.

Hooker, M. A. (1996): "What happened to the oil price-macroeconomy relationship?;," *Journal of Monetary Economics*, 38(2), 195–213.

——— (1999): "Oil and the Macroeconomy Revisited," Finance and Economics Discussion Series 1999-43, Board of Governors of the Federal Reserve System.

Huang, K. X., and Z. Liu (2004): "Input-output Structure and Nominal Rigidity: The Persistence Problem Revisited," *Macroeconomic Dynamics*, 8, 188–206.

Ireland, P. N. (2001): "Sticky-price Models of the Business Cycle: Specification and Stability," *Journal of Monetary Economics*, 47, 3–18.

Jorgenson, D. W. (1990): "Productivity and Economic Growth," in *Fifty Years of Economic Measurement*, ed. by E. R. Berndt, and J. E. Triplett, vol. 54 of *Studies in Income and Wealth*, chap. 3, pp. 19–118. University of Chicago Press.

Jorgenson, D. W., F. M. Gollap, and B. M. Fraumeni (1987): *Productivity and U.S. Economic Growth*. Harvard University Press, Cambridge.

Jorgenson, D. W., and K. J. Stiroh (2000): "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity*, 2000(1), 125–211.

Kilian, L. (2007): "The Economic Effects of Energy Price Shocks," Working paper, University of Michigan.

——— (2008): "Exogenous Oil Supply Shocks: How Big Are They and How Much Do They Matter for the U.S. Economy?," *Review of Economics and Statistics*, 90(2), 216–240.

——— (2009): "Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market," *American Economic Review*, 99(3), 1053–1069.

Kim, I.-M., and P. Loungani (1991): "The Role of Energy in Real Business Cycle Models," *Journal of Monetary Economics*, 29, 173–189.

Kim, J. (2000): "Constructing and Estimating a Realistic Optimizing Model of Monetary Policy," *Journal of Monetary Economics*, 45, 329–359.

Leduc, S., and K. Sill (2004): "A Quantitative Analysis of Oil-price Shocks, Systematic Monetary Policy, and Economic Downturns," *Journal of Monetary Economics*, 51, 781–808.

Levin, A. T., A. Onatski, J. C. Williams, and N. Williams (2006): "Monetary Policy Under Uncertainty in Micro-Founded Macroeconometric Models," in *NBER Macroeconomics Annual 2005*, ed. by M. Gertler, and K. Rogoff, pp. 229–287. MIT Press.

McConnell, M. M., and G. Perez-Quiros (2000): "Output Fluctuations in the United States: What Has Changed Since the Early 1980's?," *American Economic Review*, 90(5), 1464–1476.

Mork, K. A. (1989): "Oil and the Macroeconomy When Prices Go Up and Down: An Extension of Hamilton's Results," *Journal of Political Economy*, 97(3), 740–744.

Nakov, A., and A. Pescatori (2010): "Oil and the Great Moderation," *The Economic Journal*, 120(543), 131–156.

Nebesky, W., B. S. McMullen, and M.-K. Lee (1995): "Testing for Market Power in the U.S. Motor Carrier Industry," *Review of Industrial Organization*, 10, 559–576.

Olson, J. E. (1972): "Price Discrimination by Regulated Motor Carriers," *The American Economic Review*, 62(3), 395–402.

Ramey, V. A., and D. J. Vine (2011): "Oil, Automobiles, and the U.S. Economy: How Much Have Things Really Changed?," in *NBER Macroeconomics Annual 2010*, ed. by D. Acemoglu, and M. Woodford, vol. 25. University of Chicago Press.

Ravn, M. O., and E. Mazzenga (2004): "International Business Cycles: the Quantitative Role of Transportation Costs," *Journal of International Money and Finance*, 23(4), 645–671.

Rotemberg, J. J., and M. Woodford (1995): "Dynamic General Equilibrium Models with Imperfectly Competitive Product Markets," in *Frontiers of Business Cycle Research*, ed. by T. F. Cooley, pp. 243–293. Princeton University Press.

——— (1996): "Imperfect Competition and the Effects of Energy Price Increases on Economic Activity," *Journal of Money, Credit and Banking*, 28(4), 549–577.

Snow, J. W., and S. Sobotka (1977): "Certificate Values," in *Regulation of Entry and Pricing in Truck Transportation*, ed. by P. W. MacAvoy, and J. W. Snow, chap. 6, pp. 153–156. American Enterprise Institute for Public Policy Research.

Taylor, J. B. (1993): "Discretion versus policy rules in practice," *Carnegie-Rochester Conference Series on Public Policy*, 39, 195–214.

——— (1999): "Staggered Price and Wage Setting in Macroeconomics," in *Handbook of Macroeconomics*, ed. by J. B. Taylor, and M. Woodford, vol. 1B. Elsevier.

U.S. Congress, Senate (1980): *Federal Restraints on Competition in the Trucking Industry: Antitrust Immunity and Economic Regulation: Report of the Committee on Judiciary*, vol. 96th Congress, 2nd Session. U.S. Government Printing Office, Washington.

Winston, C. (1981): "The Welfare Effects of ICC Rate Regulation Revisited," *Bell Journal of Economics*, 12(1), 232–244.

Winston, C., T. M. Corsi, C. M. Grimm, and C. A. Evans (1990): *The Economic Effects of Surface Freight Deregulation*. Brookings Institution Press.

Wright, C. L. (1983): "Issues in Freight Transportation Regulation: Comment," *American Journal of Agricultural Economics*, 65(1), 162–166.

Ying, J. S., and T. E. Keeler (1991): "Pricing in a Deregulated Environment: The Motor Carrier Experience," *RAND Journal of Economics*, 22(2), 264–273.

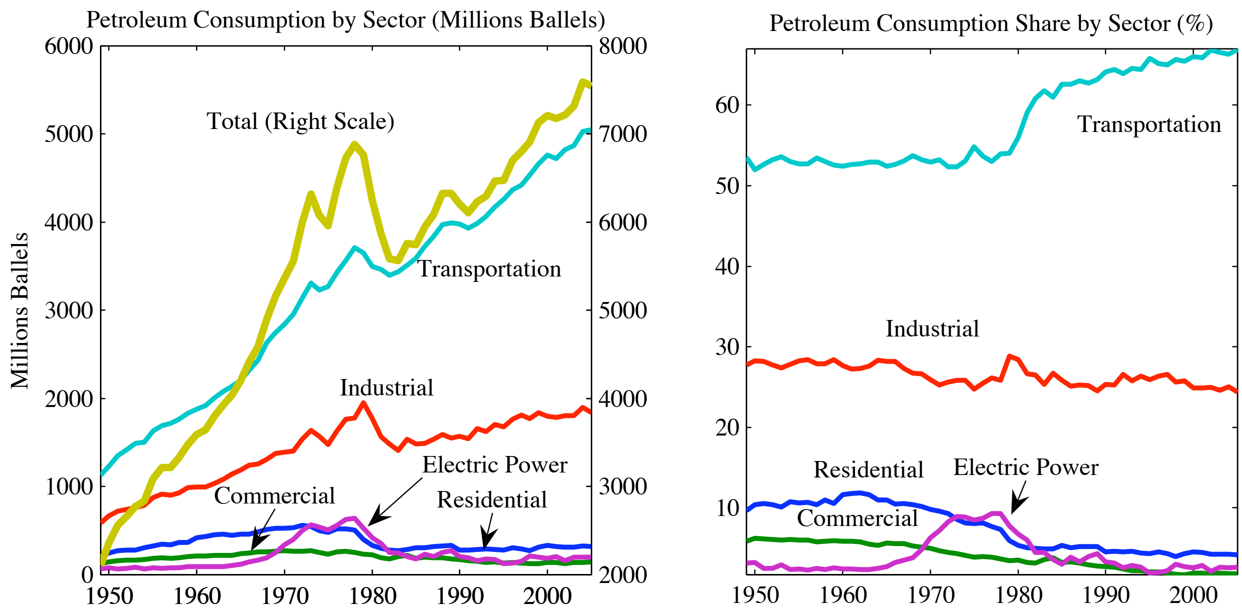

Figure 1: Petroleum Consumption by Sector 1949–2005

Sources: Department of Energy, Energy Information Administration (2006), *Annual Energy Review 2005*, Table 5.13a–5.13d.

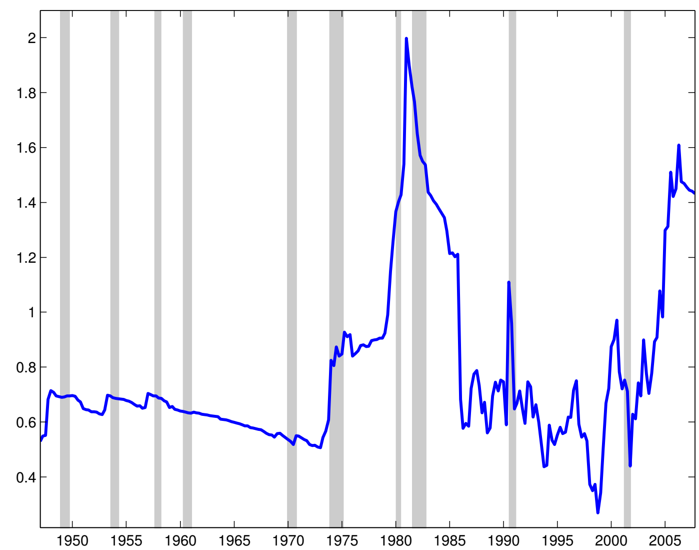

Figure 2: Real Price of Oil

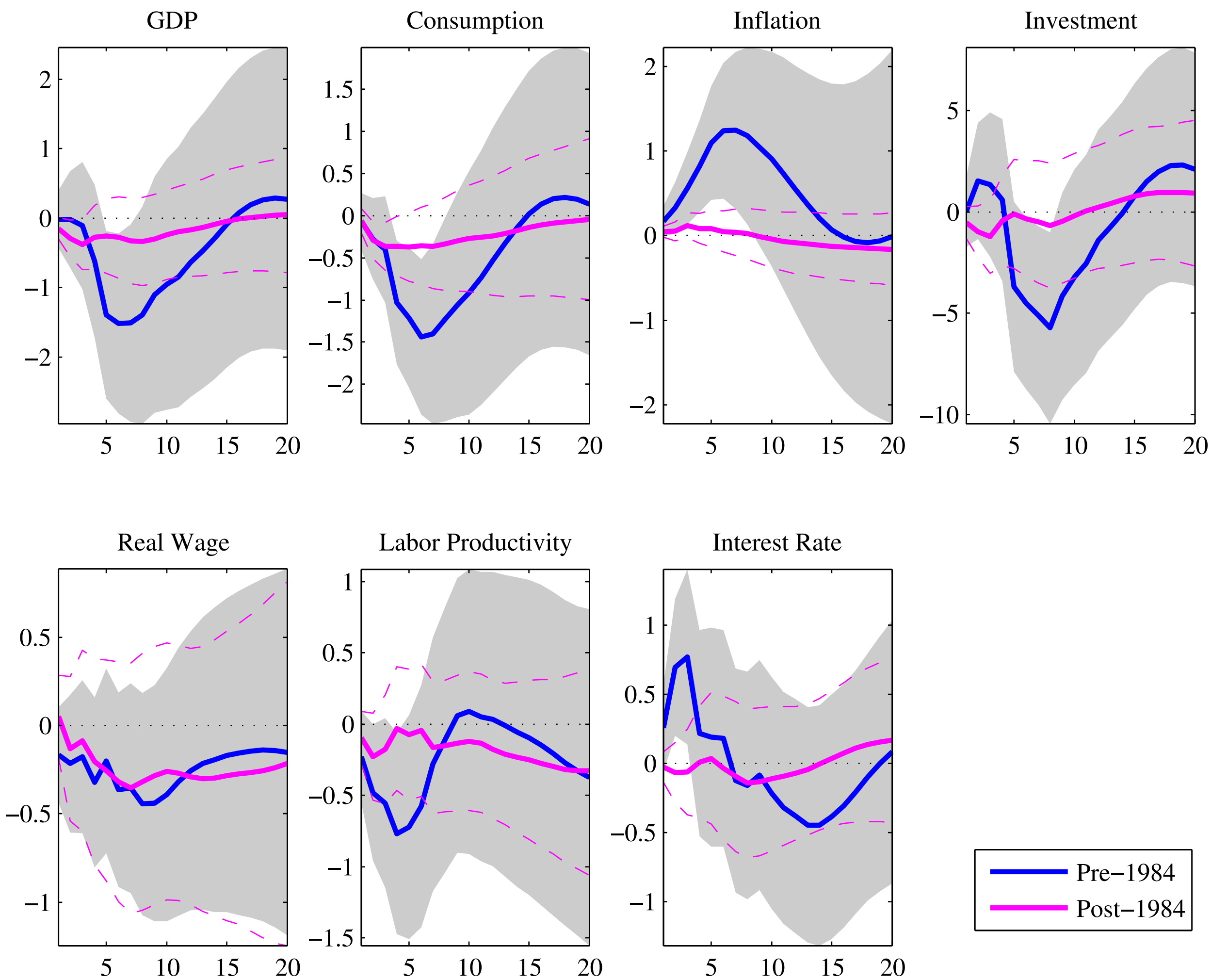

Figure 3: Different Responses to an Oil Price Shock with NOPI

Note: Each panel plots responses to a 10% increase in NOPI. The horizontal axes indicate quarters and the vertical axes measure percentage deviations from the unshocked path. The shaded areas represent two standard error bands for the pre-1984 impulse response functions (IRFs), while the dashed lines show those for the post-1984 IRFs. The error band is obtained from 1000 Monte Carlo repetitions.

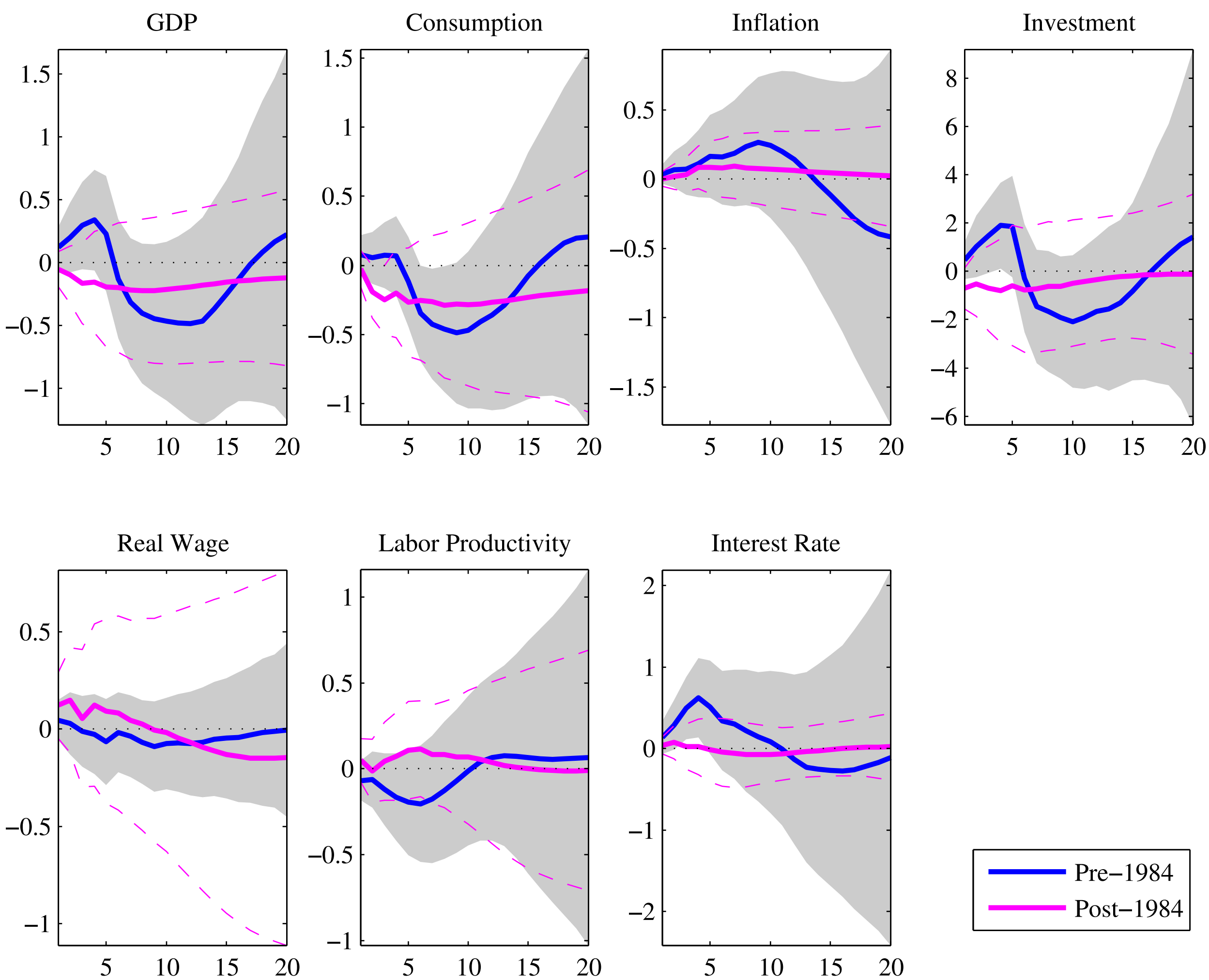

Figure 4: Different Responses to an Oil Price Shock with Kilian's Measure

Note: Each panel plots the responses to a one percentage point reduction in Kilian's measure. The horizontal axes indicate quarters and the vertical axes measure percentage deviations from the unshocked path. The responses of GDP, consumption, investment, real wage, and labor productivity are obtained from the smaller VAR system containing Kilian's measure, inflation, and the interest rate. The responses of inflation and the interest rate are those obtained together with output. The shaded areas represent the two standard error bands for the pre-1984 IRFs, while the dashed lines show those for the post-1984 IRFs. The error band is obtained from 1000 Monte Carlo repetitions.

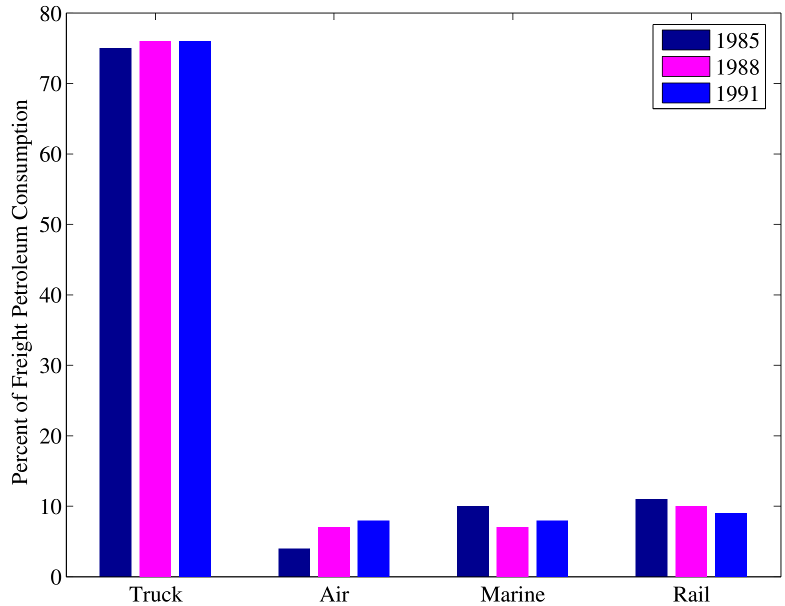

Figure 5: Petroleum Consumption in the Transportation Industry by Mode

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

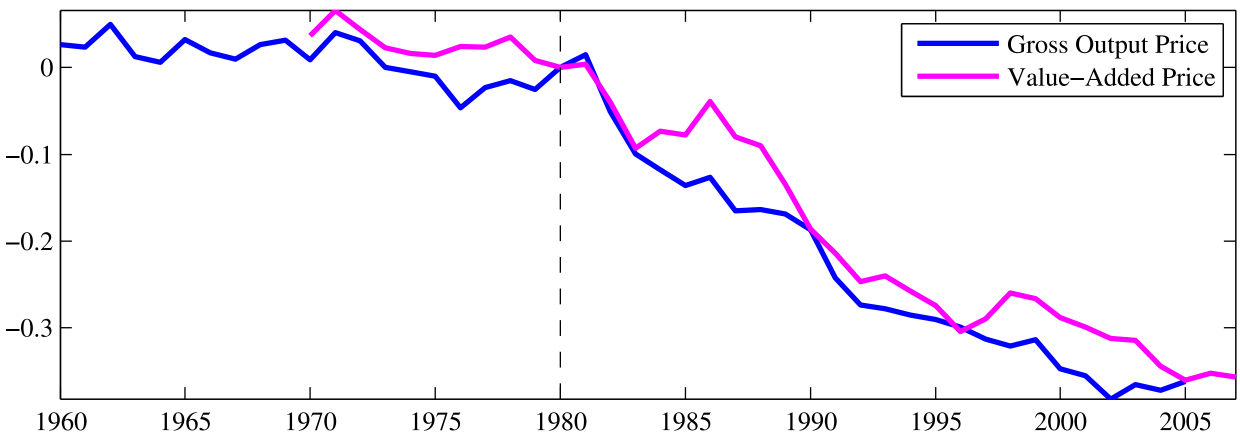

Figure 6: Log Relative Prices of Transportation (1980 = 0)

Note: Relative prices are normalized such that 1980 = 0 in logs. The gross output price is deflated by the CPI, whereas the value-added price is deflated by the GDP deflator.

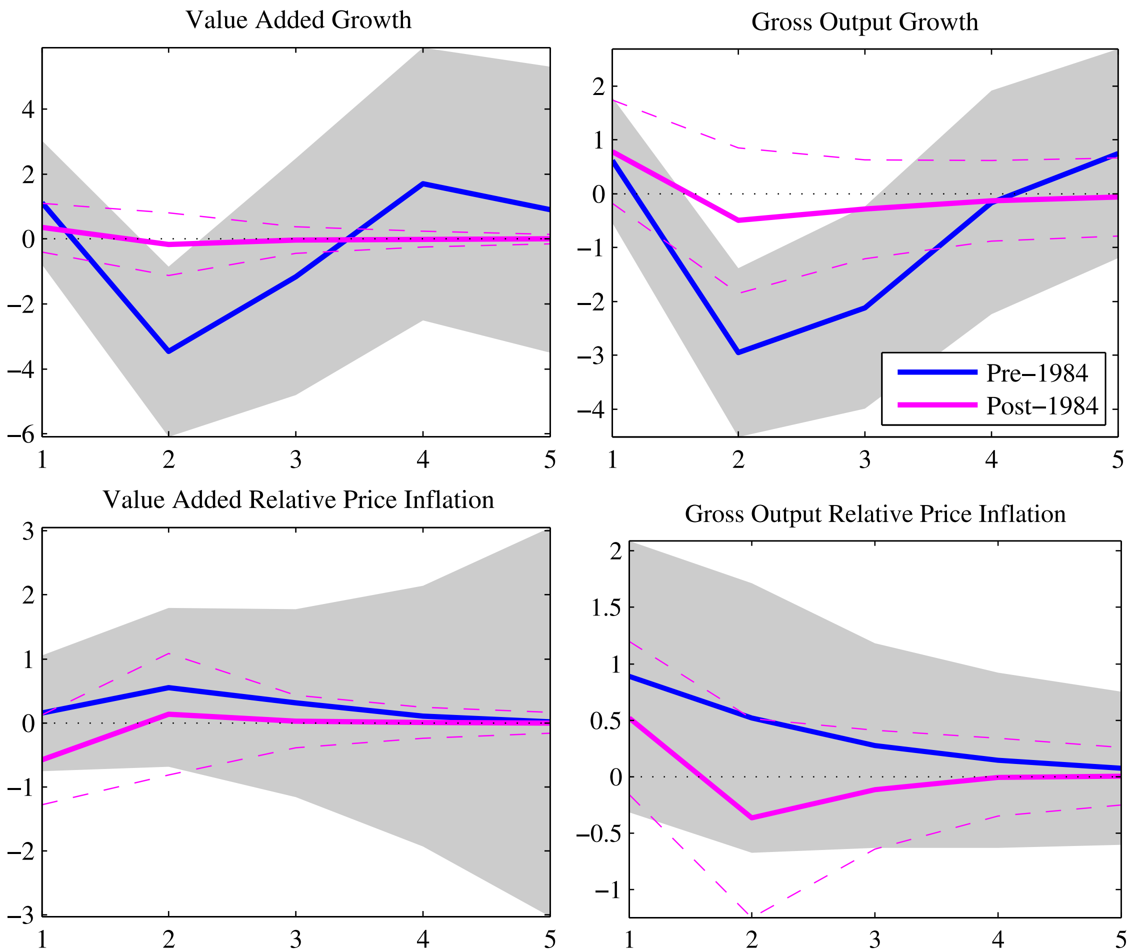

Figure 7: Responses of Transportation Industry to an Oil Price Shock

Note: Each panel plots the response to a 10% increase in NOPI. The horizontal axes indicate years and the vertical axes measure the responses in percentages. The shaded areas indicate the two standard error bands for the pre-1984 IRFs, while the dashed lines show those for the post-1984 IRFs. The error bands are obtained from 1000 Monte Carlo repetitions.

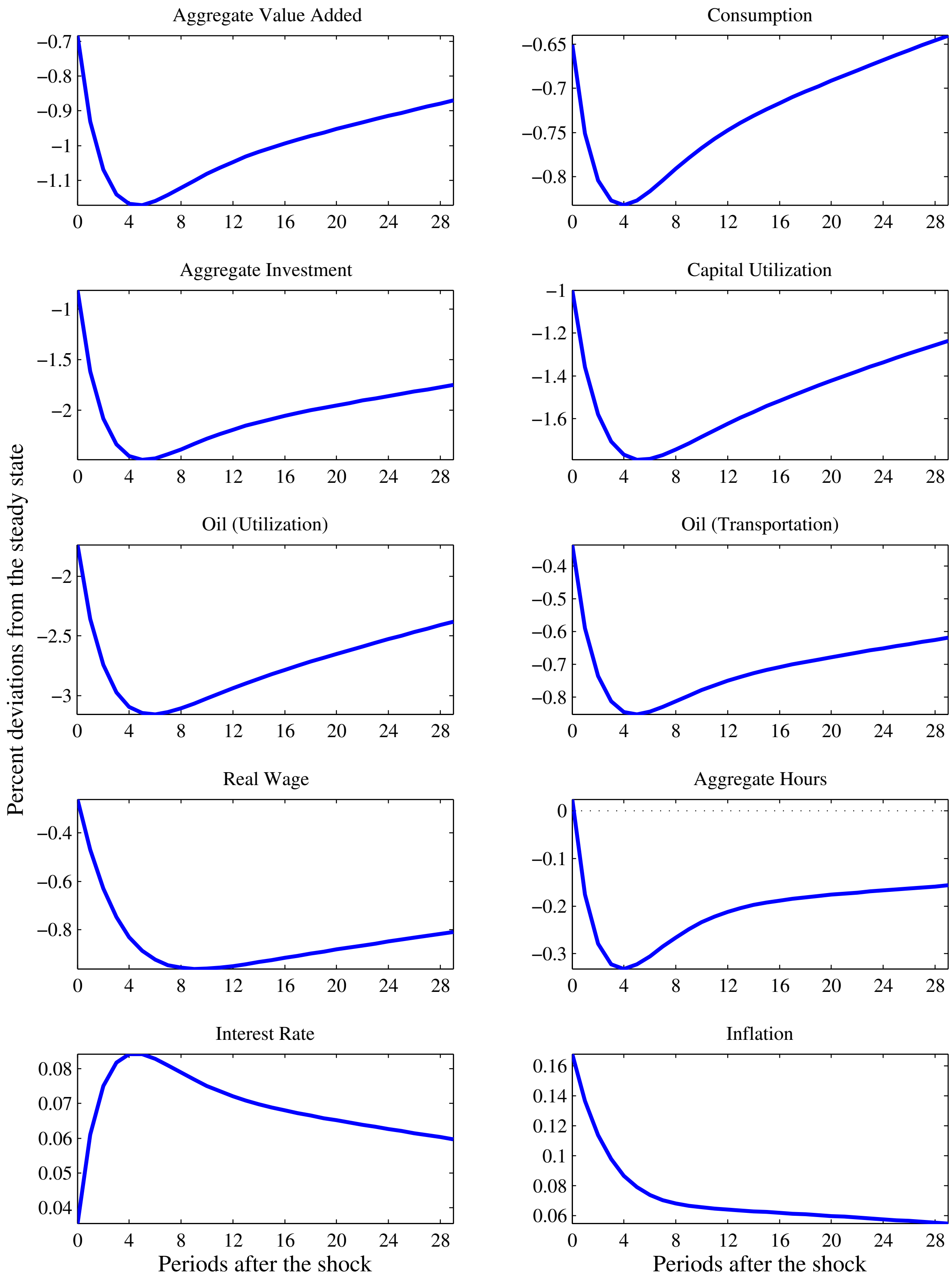

Figure 8: Impulse Responses to a 10% Increase in the Oil Price: Baseline Results

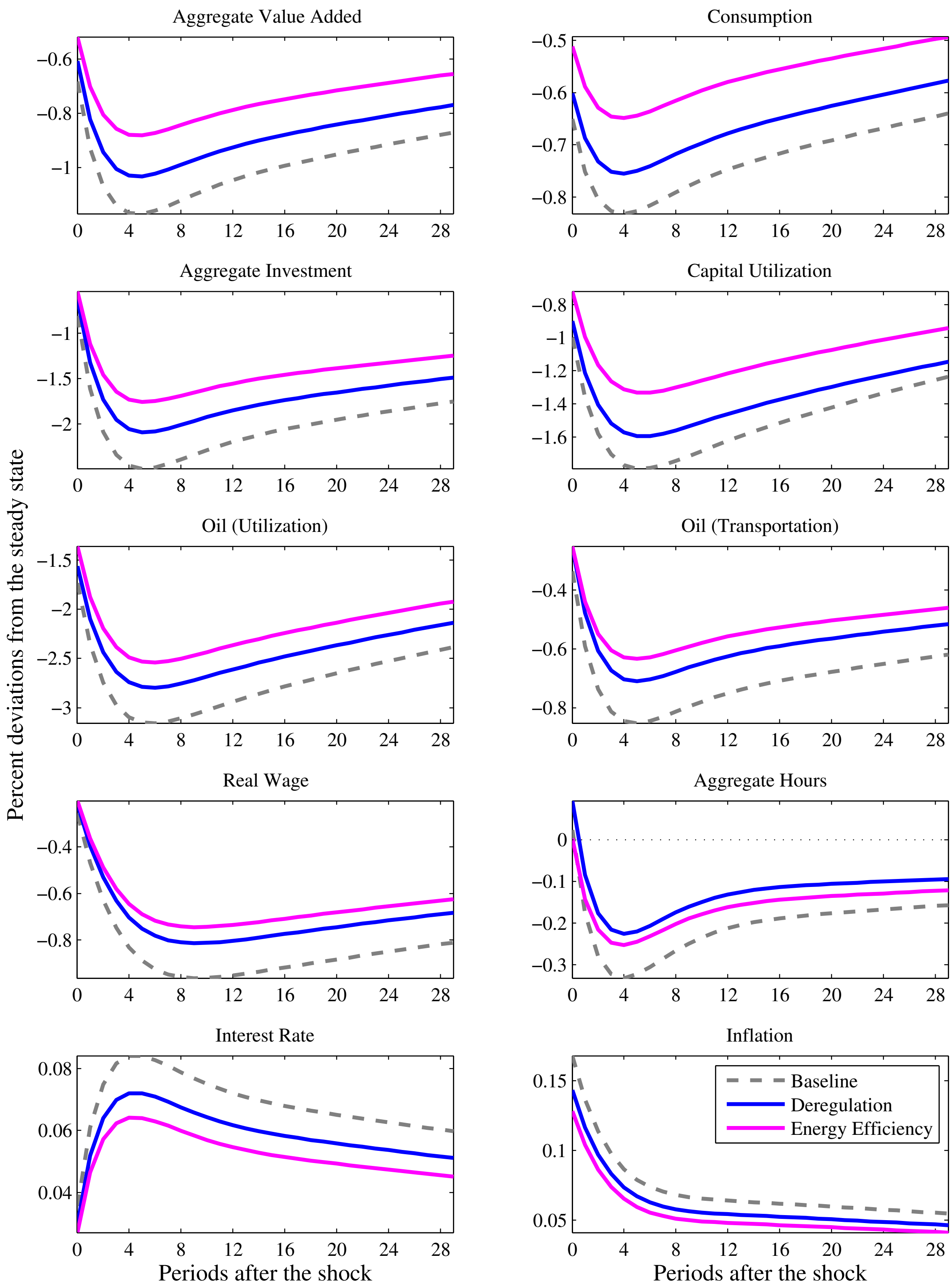

Figure 9: Comparison of the IRFs to a 10% Increase in the Oil Price: Case 1 and Case 2

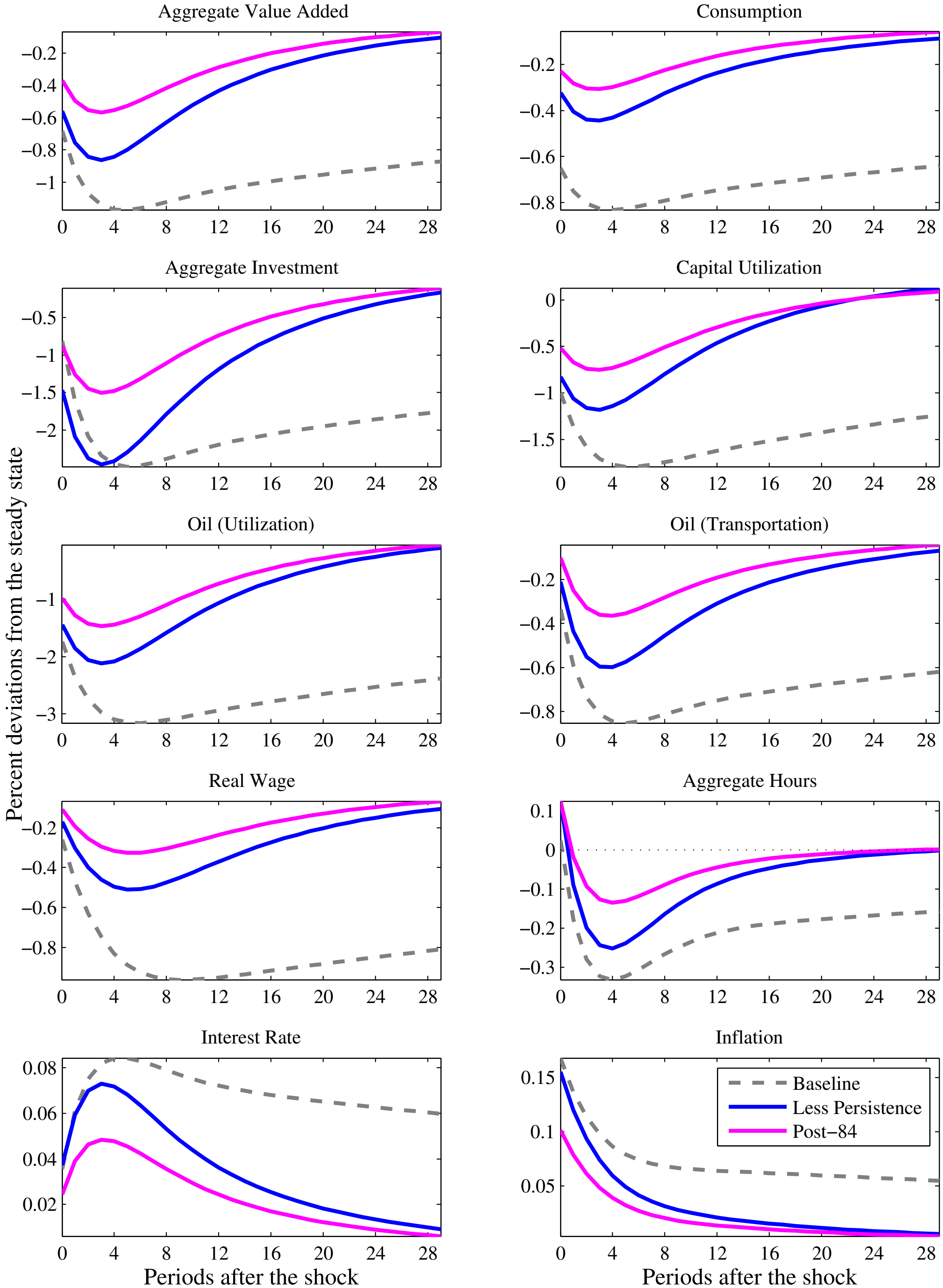

Figure 10: Comparison of the IRFs to a 10% Increase in the Oil Price: Case 3 and Case 4

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	0.1
δ^A	Depreciation rate for transportation firms	0.025
ζ	Marginal depreciation cost parameter for transportation firms	1
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 oil expenditure share for capital utilization	0.0123
s_2	Steady-state value-added oil expenditure share 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
b	Slope parameter in the transportation depreciation function	0.0276

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

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

		% Changes in largest responses	Changes in the timing
Case 1	Deregulation	−11.79%	±0
Case 2	Improved energy efficiency	−24.75%	±0
Case 3	Less persistent shock	−26.38%	−2
Case 4	Post-1984	−51.55%	−2