# Monetary Policy Responses to Oil Price Fluctuations*

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**Abstract**

The recent volatility in global commodity prices and in the price of oil, in particular, has created renewed interest in the question of how monetary policy makers should respond to oil price fluctuations. In this paper, we discuss why this question is ill-posed and has no general answer. The central message of our analysis is that the best central bank policy response to oil price fluctuations depends on why the price of crude oil has changed. For example, an unexpected oil supply disruption in the Middle East calls for a different policy response than an unexpected increase in Chinese productivity or oil intensity. This means that policy makers need to disentangle the structural shocks that are jointly driving the price of oil and the macroeconomy and tailor their response to the observed mix of shocks. We use a multi-country DSGE model to quantify the appropriate policy responses and to analyze the optimal responses from a welfare point of view. We also reexamine the welfare gains from global monetary policy coordination in a world with trade in oil.

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# 1 Introduction

The recent volatility in global commodity prices and in the price of oil, in particular, has created renewed interest in the question of how monetary policy makers should respond to oil price fluctuations. In this paper, we discuss why this question is ill-posed and has no general answer. The central message of our analysis is that the best central bank policy response to oil price fluctuations depends on why the price of crude oil has changed. For example, the appropriate U.S. interest rate response to a U.S. productivity shock driving up the real price of crude oil is quite different from the appropriate response to an unexpected increase in oil intensity in China raising the real price of oil by the same amount. Likewise, an unexpected oil supply disruption in the Middle East calls for a different policy response than an unexpected increase in Chinese productivity. This means that policy makers need to disentangle these demand and supply shocks and tailor their response to the observed mix of shocks.

This insight is not new. It was first discussed in Kilian (2009) who observed that policy makers should respond not to the price of oil (which is merely a symptom rather than a cause), but directly to the underlying demand and supply shocks that drive the real price of oil along with other macroeconomic variables. Nakov and Pescatori (2010a) reinforced this point by demonstrating - within the context of a stylized DSGE model with endogenous oil prices - that it is not welfare-maximizing for monetary policy makers to respond directly to oil price shocks. While the logic of this argument is unassailable, some policy makers have been slow to accept this conclusion. One reason may be that old habits, acquired during a time when macroeconomists thought of the real price of oil as being exogenous with respect to the economy, die hard. Another likely reason is that academic research on this question has not provided much constructive advice on how to respond to the oil demand and oil supply shocks in question. Although we know that responding to the price of oil is a bad idea, little is known to date about how a central bank such as the Federal Reserve Board should respond to specific oil demand or oil supply shocks. What analysis there is such as the work of Nakov and Pescatori (2010a) has been based on simplifying assumptions designed to make the model tractable with the intent of making a conceptual point rather than dispensing policy advice. Recent advances in constructing DSGE models of the global economy and of global oil markets allow us to be address this concern.

In this paper, we provide the first quantitative analysis of how U.S. monetary policy responses should differ depending on the source of the observed oil price fluctuations. Our model is considerably more realistic in several dimensions than previous models. An important feature of our analysis is that we rely on a global macroeconomic dynamic stochastic general equilibrium (DSGE) model with endogenous oil prices. Much of the existing analysis of appropriate monetary policy responses to oil price fluctuations has been conducted under the counterfactual premise that the real price of crude oil is exogenous with respect to the U.S. economy (see, e.g., Leduc and Sill 2004; Carlstrom and Fuerst 2006; Dhawan and Jeske 2007; Plante 2009a,b; Winkler 2009; Montoro 2010; Kormilitsina 2011; Natal 2012). Even those DSGE studies that have endogenized the real price of oil have made strong and unrealistic simplifying assumptions about the determination of the price of oil in global markets (see, e.g., Backus and Crucini 1998), have ignored monetary policy (see, e.g., Backus and Crucini 1998; Balke, Brown and Yücel 2010; Bodenstein, Erceg, and Guerrieri 2011; Nakov and Nuño 2011), or have ignored the open economy aspect of the transmission of oil price shocks (see, e.g., Bodenstein, Erceg, and Guerrieri 2008; Nakov and Pescatori 2010a,b). When studying the appropriate monetary policy responses to oil demand and oil supply shocks it is essential to work with a model that combines all three features.

Of special importance is the fact that the real price of oil is endogenously determined in global markets and that the transmission of the demand and supply shocks that drive the real price of oil has an international dimension. Kilian, Rebucci and Spatafora (2009) and Bodenstein, Erceg and Guerrieri (2011) recently have demonstrated empirically and theoretically that one cannot understand the global effects of oil demand and oil supply shocks without considering their effects on exchange rates, asset prices, oil and non-oil trade balances and capital accounts. Understanding the relationship between the economy and oil markets requires a multi-country DSGE model. Our analysis in this paper is based on the global model recently proposed by Bodenstein and Guerrieri (2011) which includes a net oil-importer (the United States) and a net oil exporter (the rest of the world).

Whereas Bodenstein and Guerrieri used this model to quantify the effects of oil demand and oil supply shocks on U.S. macroeconomic aggregates and on the real price of oil, our objective is to quantify the required policy responses within this framework under the premise that the Federal Reserve follows a standard interest rate policy rule under which the central bank responds to inflation and the output gap. We quantify the interest rate responses under two scenarios. In the first scenario, we employ policy rules with coefficients fixed at their estimated values. In the second scenario, we choose the coefficients of the U.S. policy rule to mazimize domestic welfare within the context of the model, taken the rest of the world as given. We also explore model solutions involving competitive Nash equilibria and the gains from international monetary policy cooperation. Our analysis deliberately abstracts from the presence of a zero lower bound following the financial crisis of 2008 nor do we model quantitative easing policies. Rather our focus is on characterizing the appropriate policy responses to shocks that shift the demand for oil or the supply of oil during normal times. The results are intended to provide a first benchmark for policy discussions. Extensions to nonlinear policy rules as well as further refinements of the global DSGE model are left for future research.[1]

Our analysis highlights that the distinction between oil demand shocks in particular and other structural shocks in the macroeconomy becomes moot, once it is recognized that all structural shocks in a DSGE model simultaneously cause fluctuations in domestic macroeconomic aggregates and in the real price oil. This fact has far-reaching implications for policy analysis. First, we demonstrate that no two structural shocks call for the same monetary policy response. Even after controlling for the magnitude of the impact effect on the real price of oil, the magnitude, shape and sign of the policy responses may differ, making it essential for policy makers to understand the causes of the observed oil price fluctuations. Our results contradict, for example, the popular notion in the literature that an increase in the real price of oil driven by Chinese demand from the point of view of other oil importers is just like an exogenous oil supply shock. Moreover, we illustrate that the appropriate monetary policy response may differ depending on why Chinese demand shifted. Second, we show that the optimal policy responses to a given structural shock differ substantially from the responses implied by the estimated policy rule based on historical data. We find that optimal monetary policy is well approximated by a policy rule that targets the output gap and attaches zero weight to inflation. Third, we find that oil trade greatly enhances the welfare gains from international monetary policy coordination.

The remainder of this paper is organized as follows. In section 2 we review the literature on the relationship between oil prices and monetary policy. Section 3 outlines the DSGE model on which our analysis is based. In section 4 we illustrate how optimal monetary policy responses to oil price fluctuations depend on the source of the oil price fluctuations. The concluding remarks are in section 5.

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[1] For a discussion of the implicications of a zero lower bound for the effects of exogenous oil price shocks the reader is referred to Bodenstein, Guerrieri and Gust (2010).

# 2 Oil Prices and Monetary Policy

The literature on the relationship between the real price of oil and monetary policy dates back to the 1980s. There is a consensus that causality in this relationship may run from events in oil markets to monetary policy as well as from shifts in monetary policy to the supply of oil and the demand for oil in global markets. Barsky and Kilian (2002), for example, discuss in the context of the experience of the 1970s and early 1980s how an exogenous shift in the global monetary policy regime may cause a shift in the demand for crude oil and hence in the real price of crude oil. Kilian (2010) and Erceg, Guerrieri, and Kamin (2011) explain why this explanation does not fit the more recent data, and indeed much of the literature since the 1990s has focused on the reverse direction of causality from oil prices to monetary policy. Notably, Bernanke, Gertler and Watson (1997) in an influential empirical paper attributed the severity of the 1974 and 1982 recessions to the Federal Reserve's direct response to the preceding oil price shocks. Recent research has shown their empirical analysis to be flawed and the theoretical premise of their analysis to be questionable (see, e.g., Kilian and Lewis (2011) and the references therein). There is no compelling evidence that the Federal Reserve was responding mechanically to oil price shocks beyond the response to the inflation and real output fluctuations associated with such shocks.

Bernanke, Gertler and Watson's (1997) empirical work, however, has stimulated a large DSGE model literature on the normative question of how monetary policy makers should respond to oil price shocks. Much of this optimal monetary policy literature has focused on models in which the policy maker follows a conventional interest rate policy rule within a closed economy. One of the key questions in this literature has been what inflation measure the central bank should focus on. Another key question has been whether there is a trade-off between stabilizing inflation and the welfare relevant output gap. For example, Bodenstein, Erceg and Guerrieri (2008) and Natal (2012) largely agree that dual mandate instrument rules based on core inflation measures come close to replicating welfare maximizing policies, as long as they are not overly aggressive in stabilizing core inflation. In related research, Plante (2009) finds that optimal monetary policy should stabilize a weighted average of core and nominal wage inflation. Winkler (2009) considers anticipated and unanticipated (deterministic) oil price shocks and also finds that optimal policy cannot stabilize at the same time prices, wages, and the welfare-relevant output gap; indeed, following an oil price shock, optimal policy requires a larger output drop than under a traditional Taylor rule.

The transmission channels and sources of oil price fluctuations in an open economy setting are potentially quite different. One reason is that the real price of oil is determined endogenously in global oil markets. It is immediately clear that the optimal response of monetary policy will be very different depending on the source of the oil price shock, even conditioning on the same magnitude of the initial oil price increase. We examine fifteen distinct structural shocks that shift oil demand or oil supply including, for example, shocks to the intensity of oil use at home and abroad, shocks to technology at home and abroad, shocks to the global production of crude oil at home and abroad as well as shocks to exogenous spending, markups, monetary policy, consumption preferences, and trade, among others.[2] The second reason why the open economy analysis is different is that, under incomplete markets, headline and core inflation are influenced by the different responses of the non-oil terms of trade for oil-importing and oil-exporting countries. Similarly, the effects on real output in the home country are affected by the trade channel. In addition, international financial integration can cushion

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[2] We do not consider speculative oil demand shocks, as discussed in Alquist and Kilian (2010) and Kilian and Murphy (2010) because there is no empirical evidence that speculation mattered for the fluctuations in the real price of oil between 2003 and 2010. This allows us to abstract from changes in crude oil inventories in the model.

the effects of shocks in oil markets. Hence, one needs to model the interaction of oil importers and oil exporters as well as the trade and asset market links between all countries to fully understand the implications of the shocks in question for the monetary policy maker. In this paper we focus on three main questions related to the global open economy model:

1. How do the different shocks underlying fluctuations in the real price of oil affect key U.S. macroeconomic aggregates such as inflation and real output in an open economy?
2. Taking the estimated policy rule as given, how does the source of the oil price shock affect the response of the monetary policy maker in the United States?
3. What is the optimal monetary policy response to these shocks from a welfare point of view, if we are free to choose the coefficients of the U.S. policy rule?
4. What are the welfare gains from international monetary policy coordination in a world with trade in crude oil compared with the competitive Nash equilibrium outcome?

# 3 Model Description

The model used in this paper is borrowed from Bodenstein and Guerrieri (2011). As in Backus and Crucini (1998), the model encompasses international trade in oil and nonoil goods. In addition, it incorporates the nominal and real rigidities that Smets and Wouters (2007) and Christiano, Eichenbaum and Evans (2005) have found to be empirically relevant in closed economy models.

Here, we sketch the key features of the model, and the determinants of oil demand and supply in particular. We refer the reader to Bodenstein and Guerrieri (2011) for a more detailed description of the model. There are two countries, country 1, the home country, and country 2, the foreign country. We estimate the model using U.S. data for the home country and aggregate data for the principal trading partners of the United States for the foreign bloc. Because the structure of the country blocs is symmetric, we focus on the home country in describing the model. Country specific values for the parameters allow for differences in population size, oil shares in production and consumption, oil endowments, expenditures shares, and in nonoil and oil trade flows. While asset markets are complete at the country level, asset markets are incomplete internationally. The assumption of incomplete asset markets across countries is a key ingredient in generating country-specific wealth effects in reaction to shocks that affect the price of oil.

In each country, a continuum of firms produces differentiated varieties of an intermediate good under monopolistic competition. Each firm utilizes capital, labor, and oil and acts in perfectly competitive factor markets. The production technology is characterized by a nested constant-elasticity of substitution specification. Since capital is owned by households and rented out to firms, the cost minimization problem of firm $i$ that intends to produce overall output $Y_{1,t}(i)$ can be written as:

$$\min_{\substack{K_{1,t}(i),L_{1,t}(i),\\ O^{y}_{1,t}(i),V_{1,t}(i)}} R^{k}_{1,t}K_{1,t}\left(i\right)+W_{1,t}L_{1,t}\left(i\right)+P^{o}_{1,t}O^{y}_{1,t}\left(i\right) \tag{1}$$

$$s.t.$$

$$Y_{1,t}\left(i\right)=\left(\left(\omega^{vy}_{1}\right)^{\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}}\left(V_{1,t}\left(i\right)\right)^{\frac{1}{1+\rho^{o}_{1}}}+\left(\omega^{oy}_{1}\right)^{\frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}}\left(\mu^{t}_{zo}Z^{o}_{1,t}O^{y}_{1,t}\left(i\right)\right)^{\frac{1}{1+\rho^{o}_{1}}}\right)^{1+\rho^{o}_{1}} \tag{2}$$

$$V_{1,t}\left(i\right)=\left(\left(\omega^{k}_{1}\right)^{\frac{\rho^{v}_{1}}{1+\rho^{v}_{1}}}\left(K_{1,t}\left(i\right)\right)^{\frac{1}{1+\rho^{v}_{1}}}+\left(\omega^{l}_{1}\right)^{\frac{\rho^{v}_{1}}{1+\rho^{v}_{1}}}\left(\mu^{t}_{z}Z_{1,t}L_{1,t}\left(i\right)\right)^{\frac{1}{1+\rho^{v}_{1}}}\right)^{1+\rho^{v}_{1}}. \tag{3}$$

Utilizing capital $K_{1,t}(i)$ and labor services $L_{1,t}(i)$, the firm produces a "value-added' input $V_{1,t}(i)$, which is then combined with oil $O^{y}_{1,t}(i)$ to produce variety $i$ of the domestic nonoil good, $Y_{1,t}(i)$. The rental rates of capital, labor, and oil are, respectively: $R^{k}_{1,t}$, $W_{1,t}$, and $P^{o}_{1,t}$.

The quasi-share parameter $\omega^{oy}_{1}$ determines the importance of oil purchases in the output of firms, and the parameter $\rho_1^o$ determines the price elasticity of demand for oil. The term $Z_{1,t}$ represents a stochastic process for the evolution of technology while $\mu_z$ denotes constant labor augmenting technological progress. The term $Z_{1,t}^o$ represents a stochastic process that influences the oil intensity of production, while the term $\mu_{zo}^t$ can capture a secular decline in oil intensity.

Goods prices are determined by Calvo-Yun staggered contracts. Trade occurs at the level of intermediate goods and within each country the varieties are aggregated into a (nonoil) consumption and an investment good. Households consume oil, the nonoil consumption good, save and invest, and supply differentiated labor services under monopolistic competition. Wages are determined by Calvo-Yun staggered contracts.

The consumption basket $C_{1,t}$ that enters the households utility is produced by perfectly competitive consumption distributors whose production function mirrors the preferences of households over home and foreign nonoil goods and oil.[3] The cost minimization problem of a representative distributor that produces the consumption good $C_{1,t}$ can be written as:

$$\min_{\substack{C_{1,t}^d, M_{1,t}^c \\ C_{1,t}^{ne}, O_{1,t}^c}} P_{1,t}^d C_{1,t}^d + P_{1,t}^m M_{1,t}^c + P_{1,t}^o O_{1,t}^c \qquad \textit{subject to}$$

$$C_{1,t} = \left( \left(\omega_1^{cc}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(C_{1,t}^{ne}\right)^{\frac{1}{1+\rho_1^o}} + \left(\omega_1^{oc}\right)^{\frac{\rho_1^o}{1+\rho_1^o}} \left(\mu_{zo}^t Z_{1,t}^o O_{1,t}^c\right)^{\frac{1}{1+\rho_1^o}} \right)^{1+\rho_1^o} \tag{4}$$

$$C_{1,t}^{ne} = \left( \left(\omega_1^{c}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(C_{1,t}^{d}\right)^{\frac{1}{1+\rho_1^c}} + \left(\omega_1^{mc}\right)^{\frac{\rho_1^c}{1+\rho_1^c}} \left(Z_{1,t}^m M_{1,t}^c\right)^{\frac{1}{1+\rho_1^c}} \right)^{1+\rho_1^c}. \tag{5}$$

The representative distribution firm produces a nonoil aggregate $C_{1,t}^{ne}$ from the home and foreign intermediate consumption aggregates $C_{1,t}^d$ and $M_{1,t}^c$, which is then combined with oil $O_{1,t}^c$ to produce the final consumption good in the home country $C_{1,t}$.

The parameter $\omega_1^{oc}$ determines the ratio of oil purchases to the output of the firm. The price elasticity of oil demand $\rho_1^o$ in the consumption aggregate (4)

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[3] For convenience, we suppress firm-specific indices as all the distributors behave identically in equilibrium.

coincides with the one in the production function (2). The same shock $Z_{1,t}^{o}$ that affects oil intensity in production also affects the oil intensity of consumption. $\mu_{zo}^{t}$ denotes a constant rate of oil efficiency gains. The quasi-share $\omega_1^{mc}$ determines the importance of nonoil imports in the nonoil aggregate. The elasticity of substitution between the home and foreign intermediate good is denoted by $\rho_1^c$. The term $Z_{1,t}^{m}$ captures an import preference shock. In our estimation, this shock accounts for the volatility of nonoil goods trade that is not explained by the remaining shocks.

The distributors sell the consumption aggregate at the price $P_{1,t}^{c}$ under perfect competition. Thus, $P_{1,t}^{c}$ coincides with the Lagrange multiplier on equation (4) in the cost minimization problem of a distributor. The price of the nonoil consumption good $C_{1,t}^{ne}$ is referred to as the "core" price level $P_{1,t}^{ne}$.

Each period the home and foreign countries are endowed with exogenous supplies of oil $Y_{1,t}^{o}$ and $Y_{2,t}^{o}$, respectively. The two endowments are governed by distinct stochastic processes. With both domestic and foreign oil supply determined exogenously, the oil price $P_{1,t}^{o}$ adjusts endogenously to clear the world oil market:

$$Y_{1,t}^{o} + \frac{1}{\zeta_1} Y_{2,t}^{o} = O_{1,t} + \frac{1}{\zeta_1} O_{2,t}, \tag{6}$$

where $O_{i,t} = O_{i,t}^{y} + O_{i,t}^{c}$. For the oil market to clear, the sum of home and foreign oil production must equal the sum of home and foreign oil consumption by firms and households. [4]

Our model of the oil market focuses on the demand side of the market, while keeping the supply side deliberately simple. This approach is in line with overwhelming empirical evidence in recent years that the large fluctuations in the real price of oil have been driven by demand shocks (see, e.g., Bodenstein and Guerrieri 2011; Kilian 2009; Kilian and Hicks 2011; Kilian and Murphy 2010,

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[4] Because all variables are expressed in per capita terms, foreign variables are scaled by the relative population size of the home country $\frac{1}{\zeta_1}$.

2011). It also facilitates a direct comparison with the analysis in Backus and Crucini (1998). A number of recent DSGE studies have imposed more structure on the supply side of the crude oil market, often focusing on models of imperfect competition (see, e.g., Nakov and Pescatori 2010; Balke, Brown and Yücel 2010; Nakov and Nuño 2011). Finding direct empirical evidence in favor of such models is difficult, given the paucity of relevant data (see, e.g., Smith 2005; Almoguera, Douglas, and Herrera 2011). Although it is not difficult to design elaborate models of endogenous oil production decisions, without reliable data on reserves, exploration, drilling, and other investment activities that could be used to pin down the parameters of this process, it is difficult to estimate the parameters of such models reliably. Given the lack of a consensus on how to model the supply side of the global crude oil market, we treat oil production as exogenous. Given how smoothly oil production has evolved over our sample period, this simplification is not likely to affect the results much.

Monetary policy follows a modified version of the interest rate reaction function suggested by Taylor (1993):

$$\begin{aligned} i_{1,t} &= \bar{i}_1 + \gamma_1^i (i_{1,t-1} - \bar{i}_1) \\ &\quad + (1-\gamma_1^i)\left[(\pi_{1,t}^{core} - \bar{\pi}_1^{core}) + \gamma_1^{\pi}(\pi_{1,t}^{core} - \bar{\pi}_1^{core}) + \gamma_1^y y_{1,t}^{gap}\right] + \epsilon_{1,t}^i. \qquad (7) \end{aligned}$$

The terms $\bar{i}_1$ and $\bar{\pi}_1^{core}$ are the steady-state values for the nominal interest rate and inflation, respectively. The inflation rate $\pi_{1,t}^{core}$ is expressed as the logarithmic percentage change of the core price level, i.e., inflation in nonoil consumer prices $\pi_{1,t}^{core} = log(P_{1,t}^{ne}/P_{1,t-1}^{ne})$. The term $y_{1,t}^{gap}$ denotes the log deviation of gross output from the value of gross output in a model that excludes nominal rigidities, but is otherwise identical to the one described. The parameter $\gamma_1^i$ allows for interest rate smoothing. The term $\epsilon_{1,t}^i$ may reflect a time varying inflation target or any other stochastic innovation to the monetary policy rule.

The preferences of the representative household are given by:

$$E_t \sum_{j=0}^{\infty} \beta_1^j \left\{ \frac{Z_{1,t}^c}{1-\sigma_1} \left( Z_{1,t}^c C_{1,t+j} - \kappa_1 C_{1,t+j-1}^A \right)^{1-\sigma_1} + \frac{\chi_{0,1}}{1-\chi_1} \left(1 - L_{1,t+j}\right)^{1-\chi_1} \right\}. \quad (8)$$

$E_t$ denotes the expectations conditional on information available at time $t$. The variables $C_{1,t}$ and $L_{1,t}$ represent consumption and hours worked, respectively. The parameter $\sigma_1$ is used to determine the intertemporal elasticity of substitution, $\chi_1$ the Frisch elasticity of labor supply, $\chi_{0,1}$ the steady-state number of hours worked. The term $Z_{1,t+j}^c$ models a preference shock to consumption. In addition, a household's utility from consumption is affected by the presence of external consumption habits, parameterized by $\kappa_1$. $C_{1,t-1}^A$ is the per capita aggregate consumption level. In every period $t$, household $h$ maximizes the utility functional (8) with respect to consumption, labor supply, investment, end-of-period capital stock, and holdings of domestic and foreign bonds, subject the budget constraint, and the law of motion for capital. In doing so, prices, wages, and net transfers are taken as given.

The model encompasses an unusually rich stochastic structure. The shocks included arise from fifteen separate sources: U.S. and foreign productivity, U.S. and foreign oil supply, U.S. and foreign oil intensity, U.S. autonomous spending, U.S. and foreign consumption preferences, U.S. and foreign import preferences, U.S. investment specific technology, the U.S. price markup, U.S. labor supply, and the U.S. inflation target.

# 4 Model Results

The model is estimated by the method of maximum likelihood based on quarterly data for 1984.I through 2008.III. For details of the estimates and estimation method the reader is referred to Bodenstein and Guerrieri (2011).

## 4.1 The Channels of Transmission to Inflation and Output in the Net Oil Importing Economy

A key question in recent years has been how U.S. monetary policy makers should respond to an increase in the real price of oil driven by increased demand for oil from emerging Asia in particular. A number of recent studies using a variety of methods have shown that positive foreign oil intensity shocks are one of the key determinants of the surge in the real price of oil between 2003 and mid-2008 (see, e.g., Kilian 2009; Kilian and Murphy 2010; Bodenstein and Guerrieri 2011). For example, Kilian (2009) noted that the global demand for oil depends not only on the pace of overall growth, but also on how efficiently oil is used in producing domestic real output. Dollar for dollar, Chinese economic growth tends to require more oil consumption than the same economic growth in OECD economies, consistent with the fact that Chinese oil consumption accelerated even faster than its economic growth. Thus models concerned with changes in real GDP or in aggregate productivity alone, will be unable to explain the extent of the surge in the real price of oil between 2003 and mid-2008.

Given the empirical importance of foreign oil intensity shocks, in section 4.2 we examine in detail how these shocks are transmitted to U.S. real activity and inflation, and what determines the appropriate U.S monetary policy response. We offer a novel decomposition of the domestic marginal cost of production that highlights the role of each factor input in the evolution of domestic inflation. While it is not possible (and indeed not necessary) to analyze each of the fifteen structural shock in our model in the same detail, in section 4.3, we provide a systematic comparison of how the dynamic response of the real price of oil and of the U.S. interest rate differs for each of the fifteen structural shocks in the model. We show that not only the pattern and magnitude, but even the sign of the monetary policy response will differ depending on the origin of the oil price fluctuations.

## 4.2 The Effects of a Foreign Oil Intensity Shock

Figure 1 illustrates the effects of a one-standard deviation shock that pushes up foreign oil intensity through a change in $Z^{o}_{2,t}$.[5] As foreign oil demand expands, the real price of oil in US. consumption units increases. Upon impact, the price rises 15%. The half life of the response is close to 5 years. Home oil demand contracts as both households and firms substitute away from the more expensive oil input. Since the oil price elasticity of demand in the model is estimated close to -0.4, the decline in demand is also approximately 40% of the price increase.[6]

Eventually, lower oil use leads to a fall in the current and future marginal product of capital, causing investment, consumption, and gross output to fall. However, in the short run, the shock does not unequivocally lead to a fall in output. Real rigidities prevent both consumption and investment from adjusting immediately, as can be inferred from the response of domestic absorption. Furthermore, the response of net nonoil exports, as well as the role of nominal rigidities and monetary policy need to be taken into account.

Focusing on trade, for a net oil importer such as the United States with a demand elasticity well below unity, an oil price increase results in a marked deterioration of the oil trade balance. With incomplete international financial markets, the deterioration in the oil trade balance is linked to substantial differences in wealth effects across countries. Because the negative wealth effect is relatively larger for the oil importer, the home nonoil terms of trade worsen and

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[5] When the oil substitution elasticity is less than 1, an increase in foreign oil intensity is brought about through a decline in $Z^{o}_{2,t}$.

[6] It is still widely believed that the short-run price elasticity of oil demand is close to zero. This consensus is based on reduced-form regression estimates that are known to be biased toward zero. These traditional estimates are invalid. Recently, a number of studies have provided for the properly identified estimates of the short-run price elasticity of oil demand from structural econometric models. The latter studies, regardless of methododolgy, yield much higher elasticity estimates that are similar in magnitude to our estimate in this paper (see, e.g., Kilian and Murphy (2010) and the references therein).

induce an expansion in nonoil net exports.

Apart from net exports, nominal rigidities and monetary policy also play an important role in shaping the short-term response. In Figure 1, realized output expands whereas potential output contracts. The differences in the responses of the realized real interest rate and the potential real interest rate are stark. In the presence of pronounced real rigidities that make the economy relative insensitive to movements in the real interest rate in the short run, very large swings in the real interest rate occur in the potential economy in order to curb domestic absorption. Consequently, potential absorption drops more substantially than realized absorption. By contrast, the smoothing component of the estimated historical monetary policy rule generates a gradual increase in real rates that ends up overshooting the increase in potential rates after a couple of quarters. The relative movements of realized and potential output mirror those of the interest rate movements. After a couple of quarters, as potential real rates fall more sharply than realized rates, potential output recovers more quickly and "leapfrogs" realized output. The figure also reveals that the initial expansion in realized output is associated with an expansion in hours worked. By contrast, the demand for oil and capital falls uniformly.

### 4.2.1 Inflation Dynamics

The systematic response of monetary policy to inflation associated with unexpected oil price movements has been the subject of intense scrutiny. One hypothesis advanced by Bruno and Sachs (1985) points to interactions between wages and prices that could lead to persistent inflation increases as a possible mechanism for why monetary policy could deepen the effects of shocks that drive the price of oil upwards. Other papers deemed those interactions implausible on account of evidence of falling real wages in response to higher oil prices (see, e.g., Rotemberg and Woodford 1996). Our model is a reminder that falling real wages cannot be taken as a sufficient statistic for the absence of inflationary pressures from the labor market.

The structure of the model helps us disentangle these various hypotheses. Figure 1 highlights that a quantitatively important channel for the initial increase in core inflation is the deterioration of the terms of trade. The presence of imported intermediate goods in the final consumption good accounts for the prominent wedge between core inflation and domestic goods inflation.

When it comes to domestic good inflation, the standard New-Keynesian Phillips curve implicit in our model provides a familiar framework to understand the propagation channels of movements in the price of oil. Given that the estimate for the parameter governing lagged indexation, $\iota^p$, is 0 and abstracting from the mark-up shock $\hat{\theta}_{1,t}$, one can express domestic inflation $\hat{\pi}_{1,t}$ as:

$$\hat{\pi}_{1,t} = \sum_{s=0}^{\infty} \beta_1^s \frac{\left(1-\xi_1^p \beta_1\right)\left(1-\xi_1^p\right)}{\xi_1^p} E_t \widehat{mc}_{1,t+s}, \tag{9}$$

where the term $\widehat{mc}_{1,t+s}$ is the marginal cost of production in log deviation from its level along the balanced growth path, $1-\xi^p$ is the Calvo probability of renewing the price contract, and $\beta$ is the discount factor. In words, to a first-order approximation, current inflation can be thought of as the discounted sum of current and expected marginal cost of production. The only departure from the familiar formulation estimated in Galí and Gertler (2000) is that marginal cost depends on oil as an additional factor input and can be expressed as:

$$\begin{aligned} \widehat{mc}_{1,t} &= +\omega_1^{oy}\left[\hat{p}_{1,t}^o - \widehat{mpo}_{1,t}\right] \\ &\quad +\omega_1^{vy}\phi_1\left[\hat{r}_{1,t}^k - \widehat{mpk}_{1,t}\right] + \omega_1^{vy}\left(1-\phi_1\right)\left[\hat{w}_{1,t} - \widehat{mpl}_{1,t}\right], \end{aligned} \tag{10}$$

where $\widehat{mpo}_{1,t}$, $\widehat{mpk}_{1,t}$, $\widehat{mpl}_{1,t}$ are the marginal products of oil, capital, and labor inputs, respectively, all in log deviation from their values along the balanced growth path. $\phi_1$ is a constant related to the share of capital in value added.[7]

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[7] The term $\phi_1$ satisfies $\phi_1 = \omega_1^k \left(\frac{1}{\omega_1^k \mu_z}\frac{K_{1,0}^*}{V_{1,0}^*}\right)^{\frac{1}{1+\rho^v}}$, with $K_{1,0}^*/V_{1,0}^*$ denoting the ratio of capital to value added along the balanced growth path.

Accordingly, domestic goods inflation is related to appropriately weighted gaps between the rental rate and the marginal product of each factor input. When nominal rigidities are absent, these gaps never open up and the real marginal cost is constant. But with nominal price rigidities, even abstracting from sticky wages, these gaps can be sizable.

Figure 2 considers the reaction of each factor input to the same shock to oil intensity discussed thus far. The fall in the oil input in reaction to higher prices pushes up the marginal product of oil, but exerts downward pressure on the marginal product of the other factor inputs. As monetary policy does not push up the real rate aggressively enough, aggregate demand only contracts gradually and the demand for oil remains so elevated that the rental rate overshoots the marginal product. However, when weighted by the appropriate share, this gap only makes a small contribution to the rise in marginal cost and inflation.[8]

No such drastic reduction in magnitude occurs for the gap associated with labor inputs, since they have the largest share in production. As firms shift away from using more expensive oil, they push up the relative demand for other factor inputs. The labor input is the only factor that can be adjusted immediately, so hours worked increase. Notice that the contraction of the marginal product of labor is partly linked to the increase in the labor input and partly to the fall in oil input. Sticky nominal wages ward off a large immediate rise in the rental rate for labor, but they also hinder subsequent downward adjustment towards the marginal product. The resulting persistent gap between the real wage and the marginal product of labor is the key contributor to the rise in marginal cost and domestic price inflation.

Finally, capital is predetermined in its first period and there are sizable adjustment costs for investment. As agents are forward-looking in planning investment

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[8] Notice also that oil adjustment costs would induce a larger gap between the rental rate and the marginal product of oil inputs, but would reduce the gaps for capital and labor.

and aggregate demand is predicted to fall, capital inputs fall uniformly. On impact, the higher demand for all factor inputs leads to a substantial rise in the rental rate for capital, but that gap quickly closes up. The overall contribution to marginal costs remains modest relative to that of labor inputs.

Based on the response of capital inputs, it is easy to see that without nominal wage rigidities, the real wage would also jump up on impact. Accordingly, sticky wages restrain the contribution of labor to the rise in marginal cost. Over time, however, sticky wages also contribute to impart persistence on the increase in marginal cost and inflation. Importantly, the simulation results act as a reminder that falling real wages are no sufficient statistic of lower cost pressures on inflation. Rather the labor input can make a contribution to the increase in marginal cost and inflation even with a falling real wage, simply because the reduction in other factor inputs depresses the marginal product of labor persistently.

## 4.3 What Difference the Source of the Oil Price Fluctuations Makes

The discussion so far has focused on an a foreign oil intensity shock. While that shock is estimated to be the most prominent driver of recent oil price fluctuations, it is by no means the only source of variation in oil prices. In this section, we illustrate differences in the magnitude, pattern and sign of the policy responses to different structural shocks. It is important to bear in mind that every structural shock in the model has implications for either the demand for oil or the supply of oil and hence sets in motion adjustments in both the real price of oil and in domestic and foreign macroeconomic aggregates. We focus on one shock at a time. It is understood that policy makers in real life may face several oil demand and oil supply shocks at the same time, the response to which will be a weighted average of the responses shown.

It may seem that the same type of shock taking place in a different part of the world, should have similar effects on the real price of oil and on U.S. monetary policy. This is not the case. In section 4.3.1, we illustrate this point for the example of domestic and foreign oil intensity shocks. When comparing the magnitude of the responses to domestic and foreign oil intensity shocks, we control for the magnitude of the oil price increase implied by these shocks. This approach facilitates the comparison, but may require considering shocks far greater than are likely to prevail in practice. In section 4.3.2, we therefore illustrate the differences in the responses across all structural shocks in the model, with each structural shock normalized to represent a one-standard deviation shock. We show that no two structural shocks are alike in that each shock requires a different monetary policy response in the U.S. The policy responses implied by the estimated policy rule differ not only in their magnitude and shape, but even their sign may differ, demonstrating that responses to oil price fluctuations without regard to the origin of these fluctuations are misguided.

### 4.3.1 How the Same Type of Shock Has Different Effects Depending on Where in the World it Originates From

Figure 3 compares the effects of positive domestic and foreign oil intensity shocks. For ease of comparison, the solid lines show again the responses to the one-standard deviation increase in foreign oil intensity discussed above. The dashed line shows responses to an increase in U.S. oil intensity. To make the initial price increase comparable across shocks, at the cost of realism, the magnitude of the U.S. oil intensity shock had to be magnified to approximately 12 standard deviations. Not surprisingly, controlling for the initial price increase, the domestic intensity shock has greatly magnified effects on the domestic activity. What may appear surprising, however is that controlling for the oil price increase, the response of domestic price inflation is substantially larger in the case of the domestic oil intensity shock. The decomposition of marginal cost in Equation 10 is again a useful framework to investigate the differences. Equally strikingly, the gap between the real oil price and the marginal product of the oil input remains small. Log-linearizing the marginal product of the oil input offers some useful clues:

$$\frac{\partial \hat{Y}_{1,t}}{\partial O^{y}_{1,t}} = \frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}\left(\hat{Y}_{1,t} - \hat{O}^{y}_{1,t}\right) + (1 - \frac{\rho^{o}_{1}}{1+\rho^{o}_{1}})Z^{o}_{1,t} \tag{11}$$

Observe that oil substitution elasticity (in absolute value) is $\frac{1+\rho^{o}_{1}}{\rho^{o}_{1}}$. In our case that elasticity is estimated at 0.42. Moreover, the term $(1 - \frac{\rho^{o}_{1}}{1+\rho^{o}_{1}})$ is approximately -1.4 and, thus, the decline in $Z^{o}_{1,t}$ that brings about the increase in domestic oil demand also increases the marginal product of oil. The increase in the marginal product of oil, in conjunction with the relatively small share of oil in production, explains why the contribution of the oil gap to marginal cost in equation (10) remains small, even in the case of this domestic shock.

As shown in Figure 4, once again, the gap that opens up between the marginal product of labor and the rental rate of labor makes the largest contribution to the increase in marginal cost and domestic price inflation. To understand why the marginal product of labor declines substantially more in the case of the domestic oil intensity shock, relative to when the shock has foreign origin, it is useful to consider, the log-approximation to the marginal product of labor, given by:

$$\frac{\partial \hat{Y}_{1,t}}{\partial L_{1,t}} = \frac{\rho^{o}_{1}}{1+\rho^{o}_{1}}\left(\hat{Y}_{1,t} - \hat{V}_{1,t}\right) + \hat{Z}_{1,t} + \frac{\rho^{v}_{1}}{1+\rho^{v}_{1}}\left(\hat{V}_{1,t} - \hat{Z}_{1,t} - L_{1,t}\right). \tag{12}$$

In the case of the domestic oil intensity shock, using Equation (2), one can see that the term $Y_{1,t}$, present in the equation for the marginal produc of labor above, takes a direct hit from the shock $Z^{o}_{1,t}$. This impact substantially magnifies the decline in the marginal product of labor and consequently the increase in the marginal cost of production and domestic price inflation.

In the economy without price and wage rigidities, the gap between the marginal product of labor and the real wage never opens up. In the absence of nominal rigidities, the real wage decline, in line with the larger decline in the marginal product of labor, results in a bigger reduction in labor supply and in production. Hence, the direct impact of the domestic oil intensity shock on the marginal product of labor is also connected to the larger initial output gap and initial greater increase in the Federal Funds rate shown in Figure 3.

### 4.3.2 No Two Shocks Induce the Same Policy Response

It is sometimes claimed that the origin of an oil price shock do not matter, as long as the source of the oil price shock is abroad. For example, Blanchard and Galí (2010) suggest that "if the price of oil rises as a result of, say, higher Chinese demand, this is just like an exogenous oil supply shock for the remaining countries." Figure 5 demonstrates that this conjecture is not correct. Not only is the response of the real price of oil different, but so is the interest rate response under the estimated policy rule. For example, the interest rate response to a negative foreign supply shock turns positive after 20 quarters, whereas the response to a positive foreign intensity shock remains negative for 32 quarters. Even more strikingly, if Chinese demand arises from a Chinese technology shock, as shown in Figure 6, then the interest rate is positive except on impact, whereas it is negative except for the first few quarters when the same oil price increase is driven by increased Chinese oil intensity.

Figures 5 and 6 include many more examples of the interest rate response depending on the origin of the oil price increase. In fact, no two structural shocks induce the same responses, regardless of the scale of the structural shocks. More generally, the responses can be classified as follows. Positive foreign consumption preference shocks and positive U.S. technology shocks call for unambiguously higher interest rates. Positive U.S. consumption preference shocks and U.S. price markup shocks call for unambiguously lower interest rates. Positive U.S. investment shocks, U.S. and foreign oil supply shocks, U.S. and foreign oil intensity shocks, U.S. trade shocks and foreign trade shocks, U.S. monetary policy shocks and U.S. spending shocks involve interest rate responses that vary in sign over time.

We conclude this section with a historical decomposition of the cumulative effects of oil supply shocks and oil-intensity shocks on the U.S. federal funds rate. These two shocks would not be included in standard global DSGE models, making it important to assess their ability to explain variation in the policy instrument in our context. Although these two shocks explain much of the variation in the real price of oil since the mid-1980s in our model, as documented in Bodenstein and Guerrieri (2010), Figure 7 shows that they explain little of the evolution of the U.S. federal funds rate. Instead, much of the historical variation in the federal funds rate is explained by the remaining shocks in the model (including spending shocks, monetary policy shocks, technology shocks, price markup shocks, trade shocks, investment shocks, and consumption preference shocks both in the U.S. and abroad). This is indirect evidence that oil supply and foreign oil intensity shocks have had little impact on monetary policy in the U.S., to the extent that our policy rule is an adequate characterization of U.S. monetary policy. This empirical finding is also consistent with independent evidence based on the VAR analysis in Kilian and Lewis (2011).

## 4.4 Optimal Monetary Policy Responses in the Oil Importing Economy

So far, we have focused on the responses to shocks derived under the estimated monetary policy rule. As seen above, that rule implies substantial inertia in the response of the real rate relative to the potential economy, suggesting that an optimal rule would behave quite differently. In this section we depart from the estimated model by optimizing the coefficients in the monetary policy rule with respect to a social welfare criterion. We focus on two classes of rules. The first class follows the benchmark form reported in equation (7) above. Rules in the second class respond to headline inflation instead of core inflation. As above, headline inflation is the log change in the price of the consumption basket $P^c_{1,t}$. In the optimization exercise, we choose the coefficients of the monetary policy rule that govern the degree of interest rate smoothing, the strength of the responses to the deviation of inflation from target and to the output gap, respectively $\gamma^i_1$, $\gamma^\pi_1$ and $\gamma^y_1$. Those coefficients are chosen so as to maximize, in expectation, the utility of the representative agent, defined in equation (8). In this section, we take monetary policy in the rest of the world as given. Nash and cooperative equilibria are considered in the next section.

Whether the rule responds to headline or core inflation, the optimized coefficients $\gamma^i_1$, $\gamma^\pi_1$ are equal to 0, while the optimized coefficient $\gamma^y_1$, equal to $9.95 * 10^5$, is large enough to prevent the output gap from opening. This finding is in line with previous results in Bodenstein, Erceg, and Guerrieri (2008). For a stylized model, they showed that the optimal policy is well approximated by rules that target the output gap. Our results confirm that their previous analysis translates to instrument rules and applies to a large-scale empirically-validated model.

The welfare losses in Table 1 relate to the changes in expected welfare relative to the optimized rule, expressed in terms of the equivalent change in permanent consumption, as a percentage of steady state consumption.[9] The table also shows the standard deviations of core inflation, wage inflation, and the output gap. Relative to the estimated rule, the optimized rule drives the standard deviation of the output gap to zero and reduces both the standard deviation of core inflation and of wage inflation. The latter, in particular, drops drastically from 6.24 percent to 0.98 percent.

One of the striking results in Table 1 is the size of the welfare gains. Table

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[9] In the table, the welfare changes are scaled by the term $100\frac{U_C C_1}{1-\beta_1}$, where $U_C$ represents the marginal utility of consumption evaluated at the non-stochastic steady state.

1 also includes some sensitivity analysis that points to the features of the model responsible for the large welfare gains from optimization. As above, we compare the estimated and the optimized rule. We re-optimize the benchmark rule that responds to lagged interest rates, core inflation, and the output gap, as we vary key elements of the model. The first change considered is a reduction in the duration of price stickiness and wage stickiness such that the Calvo coefficients imply four-quarter contracts. This change alone more than halves the welfare gain from optimization, which drops from 2.99 to 1.39 percent of steady state consumption. However, the latter change in permanent consumption remains an order of magnitude larger than the losses typically reported.[10]

To understand this result recall that the volatility of wage and price inflation is tightly linked to two features of the model – the average duration of the Calvo contracts and the size of the wage and price markup shocks. From the decomposition of the population variance at business cycle frequencies, price markup shocks and wage markup shocks (or labor supply shocks) account for 50% of the variation in output in our model. Especially when the Frisch labor supply elasticity is estimated to be close to zero, departures from the labor supply schedule implied by wage rigidities, can have a large impact on welfare, as derived in Bodenstein, Erceg, and Guerrieri (2008).[11]

Table 2 shows that when we shut off wage and price markup shocks, the welfare gain of switching to the optimized rule falls to 0.11 percent of steady state consumption, a number in the same order of magnitude as the gains typically reported by studies that characterize optimal monetary policy in a general equilibrium context.

Table 1 also allows us to assess the impact of the explicit treatment of the

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[10] Another study that finds large losses from the estimated policy relative to the optimal rule is Levin et al. (2006). For a closed economy model of the United States, they find that the estimated policy has a welfare cost equal to 0.56 of steady-state consumption.

[11] See equation (20) in their paper.

oil market on the optimized policy. When the oil supply shocks and oil intensity shocks in the U.S. and abroad are excluded from the model, the gains from adopting the optimized rule change little nor does the optimal policy rule change noticeably. Virtually all the weight in the policy rule remains on the output gap. When these two shocks are the only source of variation in the data, in contrast, the welfare losses are all but eliminated. The optimized coefficients are $\gamma_1^i = 0$, $\gamma_1^\pi = 0.45$ and $\gamma_1^y = 1.74$, which still implies a very high weight on the output gap.[12]

It is sometimes difficult to compare policy rules solely based on a summary statistic such as the welfare measure reported in Table 1. Figures 8 and 9 provide some complementary evidence. They show the nominal interest rate responses for selected shocks under the estimated and the optimized policy rule. Each structural shock has been rescaled to induce a 1 percent increase on impact in the real price of oil under the estimated rule. Figures 8 and 9 reveal not only that the responses greatly depend on the type of shock, but they show substantial differences in the path of the policy instrument variable in response to the same shock, depending on whether the estimated or the optimized rule is used. The latter difference in magnitude may easily be as high as a factor of 10.

It can be shown that, in general, under the optimized policy rule, the implied response of the real interest rate is closer to the real interest rate path in the "potential economy", defined as an economy without nominal rigidities. Figure 10 illustrates this point for the example of a foreign oil intensity shock. For ease of comparison with earlier figures the shock is resized to one standard deviation. The figure shows that in line with the information in Tables 1 and 2, the output gap does not open up. The immediate drop in consumption is more

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[12] The monetary policy rule in equation (7) is expressed for quarterly policy rates and inflation. Annualizing the interest rate rule, implies multiplying the coefficient on the output gap by 4 and leaving the other coefficients unchanged.

pronounced under the optimized rule, while the real interest rate, after increasing more sharply initially, comes down more quickly. Furthermore, core inflation is uniformly positive and wage inflation uniformly negative. The optimized rule avoids the overshooting typical of rules with interest rate smoothing because the weight on the lagged interest rate is essentially zero.

For completeness we also include some results for other specifications of the interest rate rule. Table 2, allows a comparison of the welfare loss implied by the estimated rules and by other rules often considered in the literature. A policy rule that responds to core inflation and excludes interest rate smoothing fares better than the estimated rule, i.e., the welfare gain of switching to the optimized rule is smaller.[13] Furthermore, rules that respond to core inflation fare better than rules that respond to headline inflation.[14]

We conclude that based on the domestic welfare criterion, there is no trade-off between optimizing monetary policy in a closed-economy setting and in a global economy with oil markets. This conclusion, of course, relies on taking the rest of the world as given. We relax that assumption next.

## 4.5 Competitive Factors in Monetary Policy and the Gains from Cooperation

The last column of Table 1 reports the welfare change in the foreign bloc when optimizing the coefficients governing the monetary policy rule in the U.S. bloc, taking the rest of the world as given. A general pattern is that gains in the U.S. bloc imply non-trivial losses in welfare in the foreign bloc, when the foreign bloc does not re-optimize its own policy rule. Next, we allow the foreign bloc to respond to the optimization in the U.S. bloc. We focus on Nash and cooperative

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[13] We assigned parameters in line with Taylor (1993). Accordingly, $\gamma_1^i = 0$, $\gamma_1^\pi = 0.5$ and $\gamma_1^y = 0.125$.

[14] The rules that respond to inflation only have the following coefficients: $\gamma_1^i = 0$, $\gamma_1^\pi = 2$ and $\gamma_1^y = 0$. The welfare losses associated with this kind of rule can be magnified by increasing the value of $\gamma_1^\pi$.

equilibria for the same simple monetary policy rules considered above.

A comprehensive review of the literature on optimal monetary policy in open economies is offered by Corsetti, Dedola, and Leduc (2011). Following Obstfeld and Rogoff (2002), we characterize the Nash and cooperative equilibrium in terms of the coefficients governing the monetary policy reaction functions in the two country blocs. However, we depart from their setup by considering an inherently asymmetric configuration – the U.S. is an oil importer, the foreign bloc an oil exporter. Furthermore, like Coenen et al. (2010), our exercise focuses on an empirically validated model that includes a wide range of sources of fluctuations in both country blocs.[15]

Intuitively, allowing for the foreign bloc to choose its own best response, cuts into the domestic gains from optimization. In the benchmark configuration, keeping the foreign bloc at the estimated rule, the gain from optimization for the United States was found to be 2.99 percent of steady state consumption, relative to the estimated rule. With the Nash game, the analogous gain reduces to 2.94 percent of steady state consumption.

A typical result in the literature on optimal monetary policy in open economies is that the gain from cooperation is small when compared to the competitive outcomes under a Nash equilibrium. For instance, Coenen et al. (2010) find that the gain from cooperation amounts to 0.0021 percent of steady state consumption for the United States. Table 3 reports joint welfare losses implied by the competitive Nash equilibrium relative to the cooperative equilibrium. The joint welfare of departing from the cooperative outcome amounts to 0.11 percent of U.S. steady state consumption, a nontrivial amount, especially when compared to the typical results in the literature.

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[15] Coenen et al. (2010) does not include oil as a factor input. The optimization of feedback rules for monetary policy is not the principal focus of their analysis, but is considered to allow comparisons with other studies.

One of the features of our model that sets it apart relative to other models is the explicit treatment of oil as a globally traded commodity. To ascertain the role of this feature of the model, we consider an alternative calibration that zeros out the oil endowments in each country and sets the parameters that govern the oil shares in production and consumption to zero in both country blocs. We confirm that in that variant of the model, the gains from cooperation are reduced by an order of magnitude from 0.11 percent of U.S. steady-state consumption to 0.02 percent of U.S. steady-state consumption.

# 5 Conclusion

Even large and relatively closed economies like the United States and the euro area import a sizable fraction of the oil they consume. That fraction is close to half for the United States, while local production is close to nil in the euro area. Nonetheless, most of the existing analysis on the optimal design of monetary policy in the face of fluctuations in oil prices posits an autarkic environment and a simplistic stochastic structure, especially in modeling the demand side of the global crude oil market.

Using an estimated two-country dynamic stochastic general equilibrium (DSGE) model that encompasses trade in oil and nonoil goods, we showed how the evolution of inflation and real output and hence the conduct of monetary policy is influenced by a large variety of structural shocks that move both the real price of oil and the domestic economy. The model is borrowed from Bodenstein and Guerrieri (2011). Oil is used both as a factor of production, along with capital and labor, and as a direct input in the consumption basket of households. This setup allows us to capture key differences between headline and core inflation. Shocks that influence oil prices lead to nonoil trade movements that affect the nonoil terms of trade and spill over to both headline and core inflation. Focusing on the domestic part of inflation – the price inflation for domestic goods – we offered a novel decomposition that highlights the propagation channels of different types of shocks reflected in oil price fluctuations.

In our New Keynesian model, as is standard, domestic inflation depends on the discounted sum of current and expected marginal production costs. We showed that the marginal cost of production can in turn be expressed as the appropriately weighted sum of the gap between the relative price and the marginal product for each factor input. When nominal rigidities are absent, these gaps never open and the real marginal cost remains constant. In contrast, in the presence of nominal rigidities, even abstracting from sticky wages, these gaps can become large.

In the presence of price and wage rigidities, we showed that the labor market provides a key contribution to the persistence of inflation in the face of the shocks that drive oil price fluctuations. Focusing on an estimated interest rate policy rule, we illustrated, first, that the response of policy rates is vastly different depending on the source of the shock, even conditioning on the same observable change in real price of oil. This result also applies when the policy rule coefficients are chosen optimally to maximize welfare in the U.S. bloc, as well as when considering Nash and cooperative equilibria over the choice of policy rules.

Second, we showed that the monetary policy rule estimated for the United States puts a larger weight on interest rate smoothing and on inflation than the optimal rule. Under a policy rule that is optimal in that its coefficients have been estimated to maximize social welfare, policy makers must respond aggressively to the output gap. Responding aggressively to the output gap not only increases social welfare, but it also reduces the volatility of price and wage inflation relative to the estimated rule.

Third, one of the striking results in the earlier literature on the interaction of monetary policy across countries is that the gains from cooperation are small relative to the allocations in a Nash competitive equilibrium. We showed that the gains from cooperation in our benchmark model, while still modest, are an order of magnitude larger than the gains obtained in a model without oil trade.

The model used in this paper can be viewed as a stylized representation of the key players in global oil markets in recent years. Our analysis can undoubtedly be refined further. Some dimensions in which the model may be lacking, include the specification of oil production decisions, the absence of valuation effects and the absence of speculative elements in the real price of oil. One also might break down the rest of the world further into distinct blocks of countries such as OPEC, OECD (other than the U.S.) and the emerging economies. Moreover, it would be useful to extend our model to focus more directly on monetary policy decisions in oil-exporting countries. This extension is likely to require a more careful modeling of fiscal policy, however. Despite these potential limitations, our analysis constitutes the first formal study of monetary policy responses to oil price fluctuations in an open economy with endogenous oil prices. It also provides a benchmark for more refined models for policy analysis to be developed in the future.

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Table 1: An Assessment of Alternative Monetary Policy Rules: Sensitivity Analysis*

| Rule | U.S. Welfare Loss (change from optimized) | U.S. Core Inflation Std. Dev. | U.S. Wage Inflation Std. Dev. | U.S. Output Gap Std. Dev. | Foreign Welfare Loss (change from optimized) |
|---|---|---|---|---|---|
| Benchmark Model | | | | | |
| Estimated | 2.99 | 3.41 | 6.24 | 1.15 | -0.07 |
| Optimized | 0 | 2.67 | 0.98 | 0 | 0 |
| 4-quarter Calvo Contracts | | | | | |
| Estimated | 1.39 | 3.87 | 11.85 | 0.69 | -0.03 |
| Optimized | 0 | 2.91 | 3.12 | 0 | 0 |
| No Price and Wage Markup Shocks | | | | | |
| Estimated | 0.11 | 3.13 | 4.93 | 0.87 | 0.01 |
| Optimized | 0 | 1.93 | 0.53 | 0 | 0 |
| 4-quarter Calvo Contracts and No Price and Wage Markup Shocks | | | | | |
| Estimated | 0.12 | 3.58 | 7.91 | 0.50 | 0.01 |
| Optimized | 0 | 1.94 | 0.99 | 0 | 0 |
| No Oil Supply and No Oil Intensity Shocks | | | | | |
| Estimated | 2.99 | 3.36 | 6.16 | 1.13 | -0.04 |
| Optimized | 0 | 2.60 | 0.76 | 0 | 0 |
| Oil Supply and Oil Intensity Shocks Only | | | | | |
| Estimated | 0.0012 | 0.51 | 1.11 | 0.28 | -0.0033 |
| Optimized | 0 | 0.46 | 0.39 | 0.08 | 0 |

* The losses reported are expressed as a percent of steady state consumption. The inflation measures are annualized.

Table 2: An Assessment of Alternative Monetary Policy Rules*

| Rule | U.S. Welfare Loss (rel. to optimized) | U.S. Core Inflation Std. Dev. | U.S. Wage Inflation Std. Dev. | U.S. Output Gap Std. Dev. | Foreign Welfare Loss (rel. to optimized) |
|---|---|---|---|---|---|
| Estimated | 2.99 | 3.41 | 6.24 | 1.15 | -0.07 |
| Optimized | 0 | 2.67 | 0.98 | 0 | 0 |
| Taylor with Core | 2.45 | 2.75 | 3.95 | 0.75 | -0.07 |
| Core Infl. Only | 2.44 | 1.59 | 4.72 | 1.14 | -0.07 |
| Taylor with Headline | 2.50 | 2.77 | 3.95 | 0.75 | -0.06 |
| Headline Infl. Only | 2.52 | 1.68 | 4.90 | 1.22 | -0.05 |

* The losses reported are expressed as a percent of steady state consumption. The inflation measures are annualized.

Table 3: Cooperative and Competitive Equilibria

| Rule | Joint Welfare Loss (rel. to cooperative) | U.S. Core Inflation Std. Dev. | U.S. Wage Inflation Std. Dev. | U.S. Output Gap Std. Dev. |
|---|---|---|---|---|
| Benchmark Model | | | | |
| Nash | 0.11 | 2.67 | 0.97 | 0 |
| Cooperative | 0 | 2.87 | 0.98 | 0 |
| Model Without Oil Inputs | | | | |
| Nash | 0.02 | 2.60 | 0.75 | 0 |
| Cooperative | 0 | 2.65 | 0.76 | 0 |

[*] The joint welfare loss is expressed as a percent of U.S. steady state consumption.
The inflation measures are annualized.

Figure 1: The Effects of a One-Standard Deviation Increase in Foreign Oil Intensity: Deviations from the Balanced Growth Path

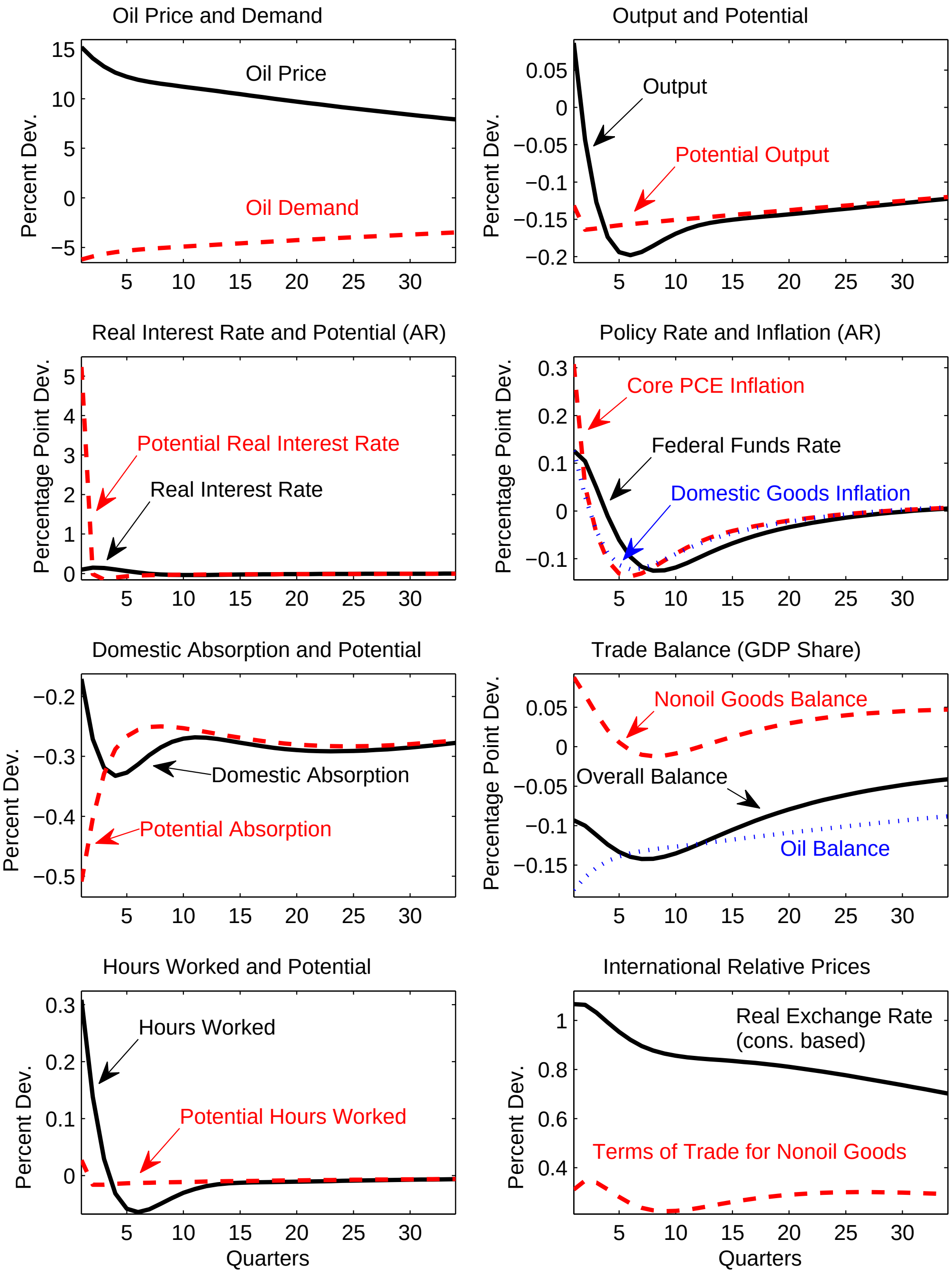


Figure 2: The Effects of a One-Standard Deviation Increase in Foreign Oil Intensity on Factor Inputs: Deviations from the Balanced Growth Path

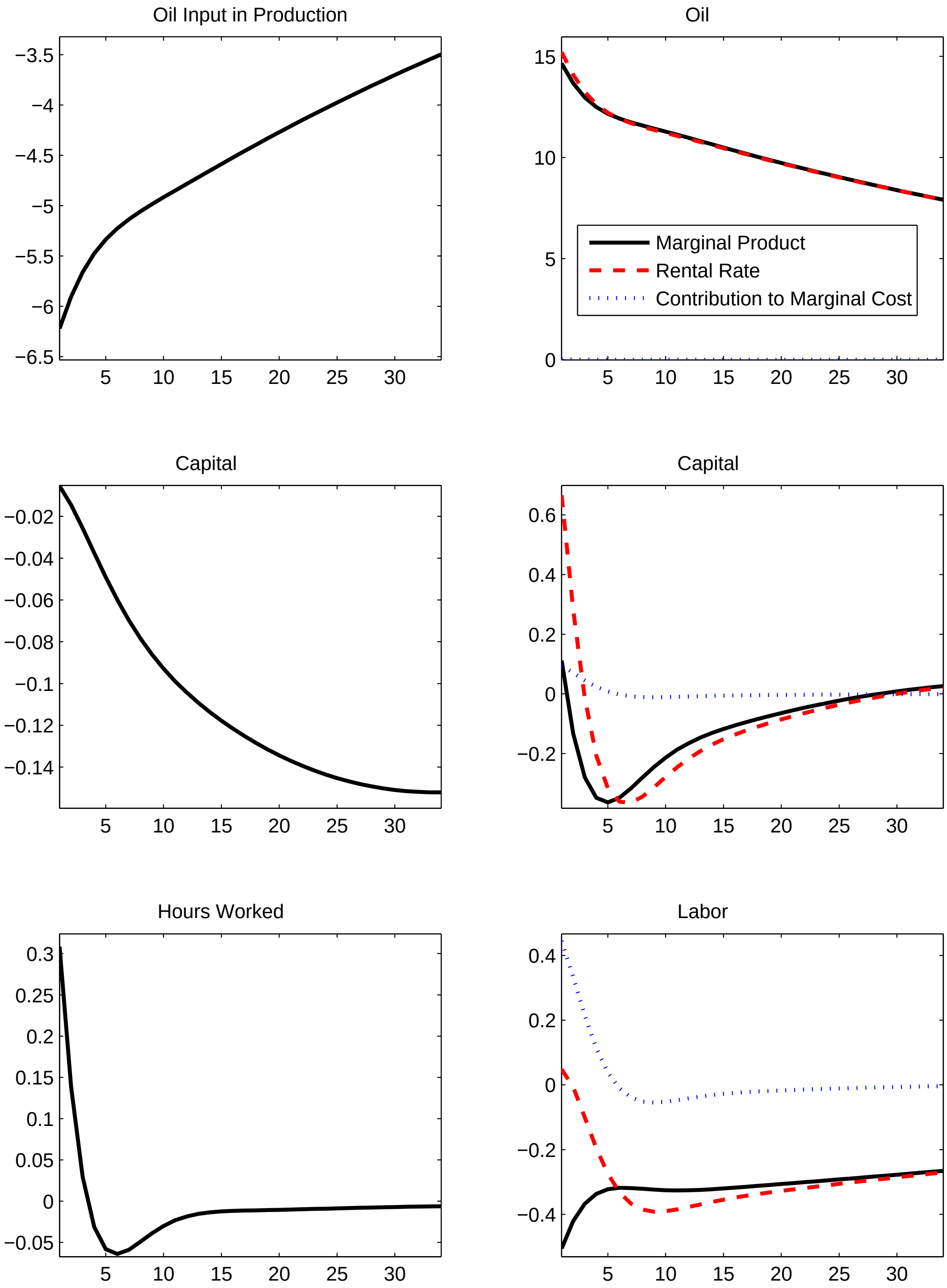


Figure 3: A Comparison of Foreign and Domestic Oil Intensity Shocks

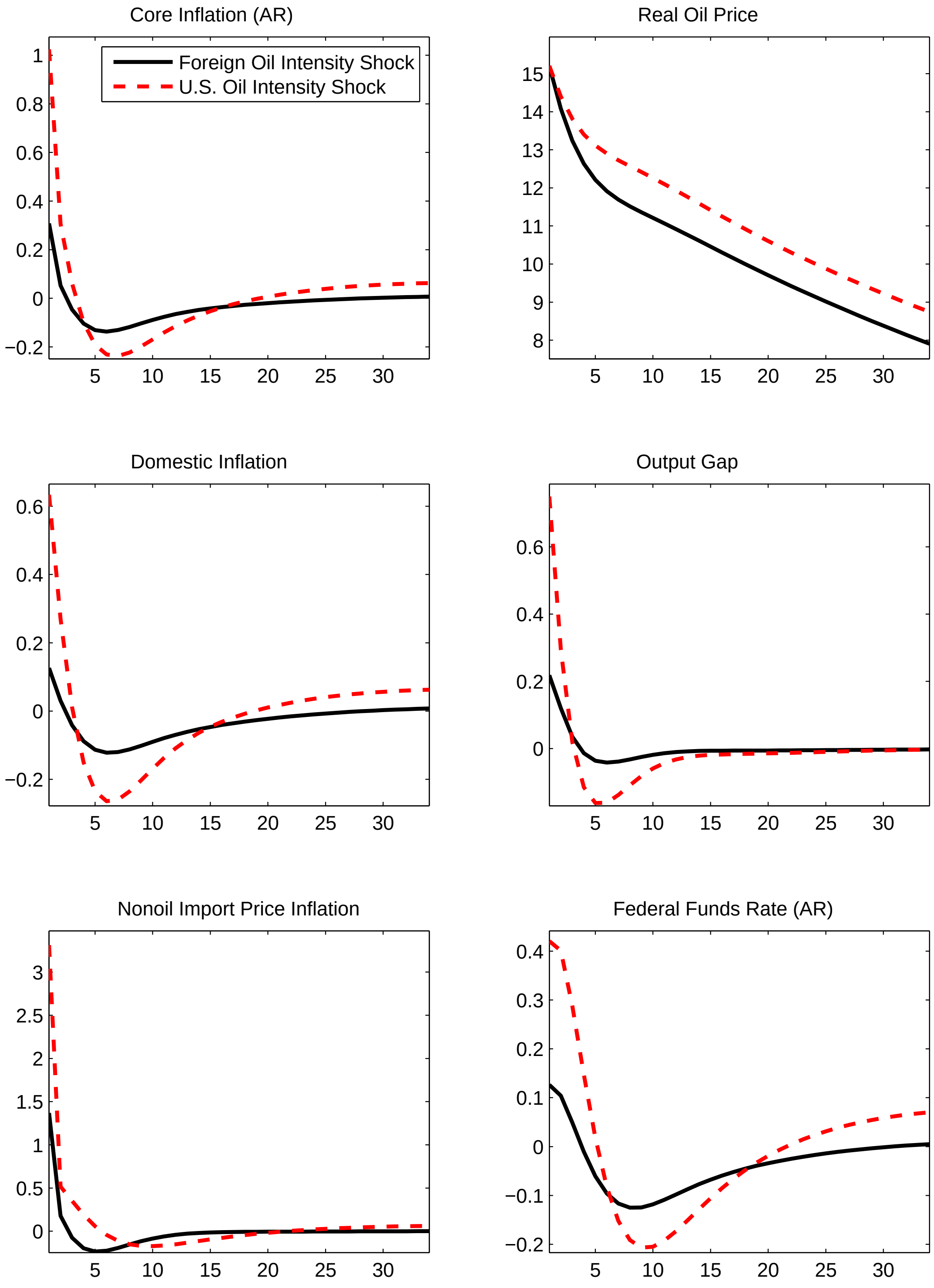


Figure 4: The Effects of a One-Standard Deviation Increase in U.S. Oil Intensity on Factor Inputs: Deviations from the Balanced Growth Path

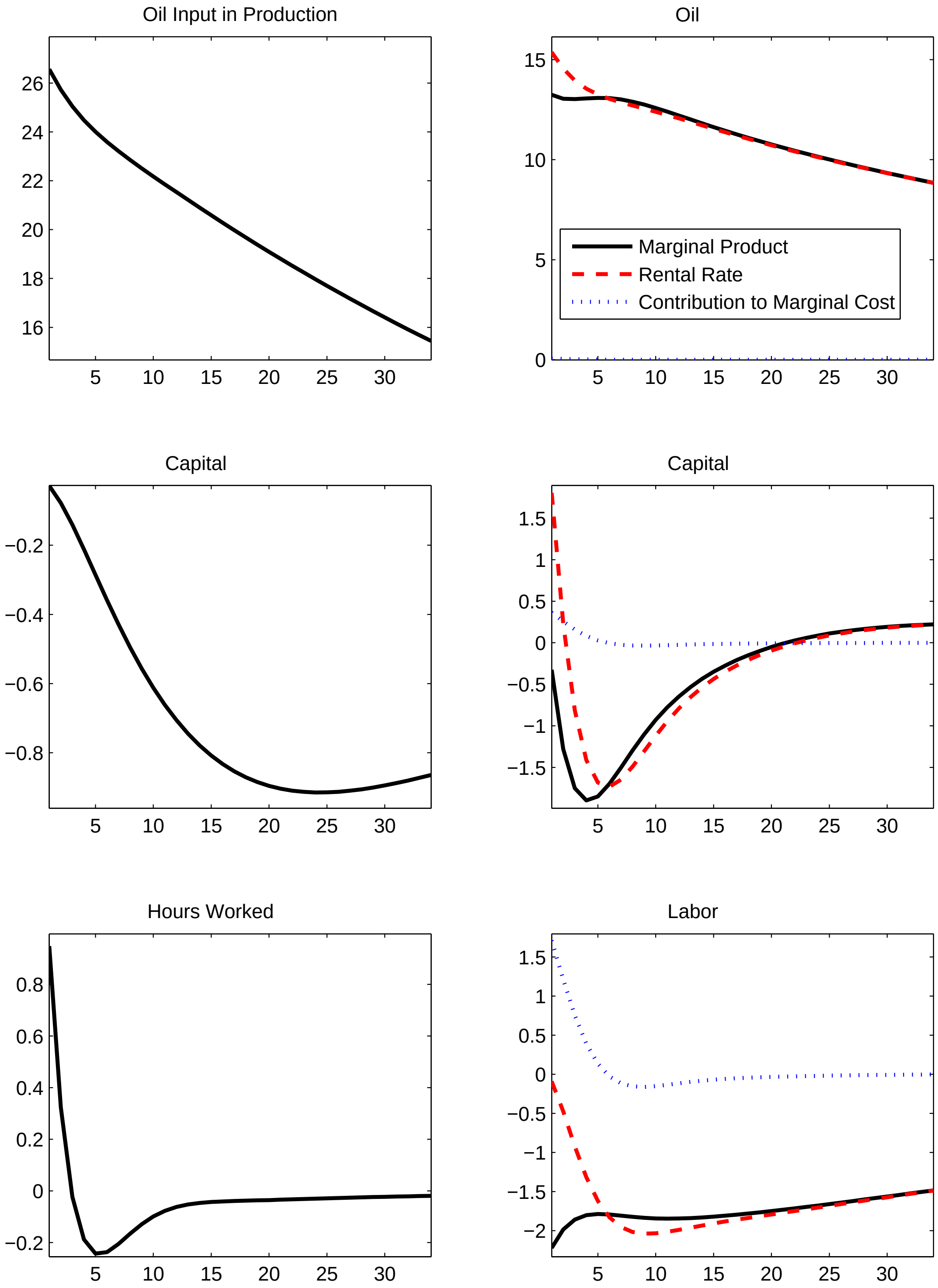


Figure 5: The Effects of Different Shocks on the Real Dollar Price of Oil and U.S. Interest Rates (the shocks are sized at 1 standard deviation)

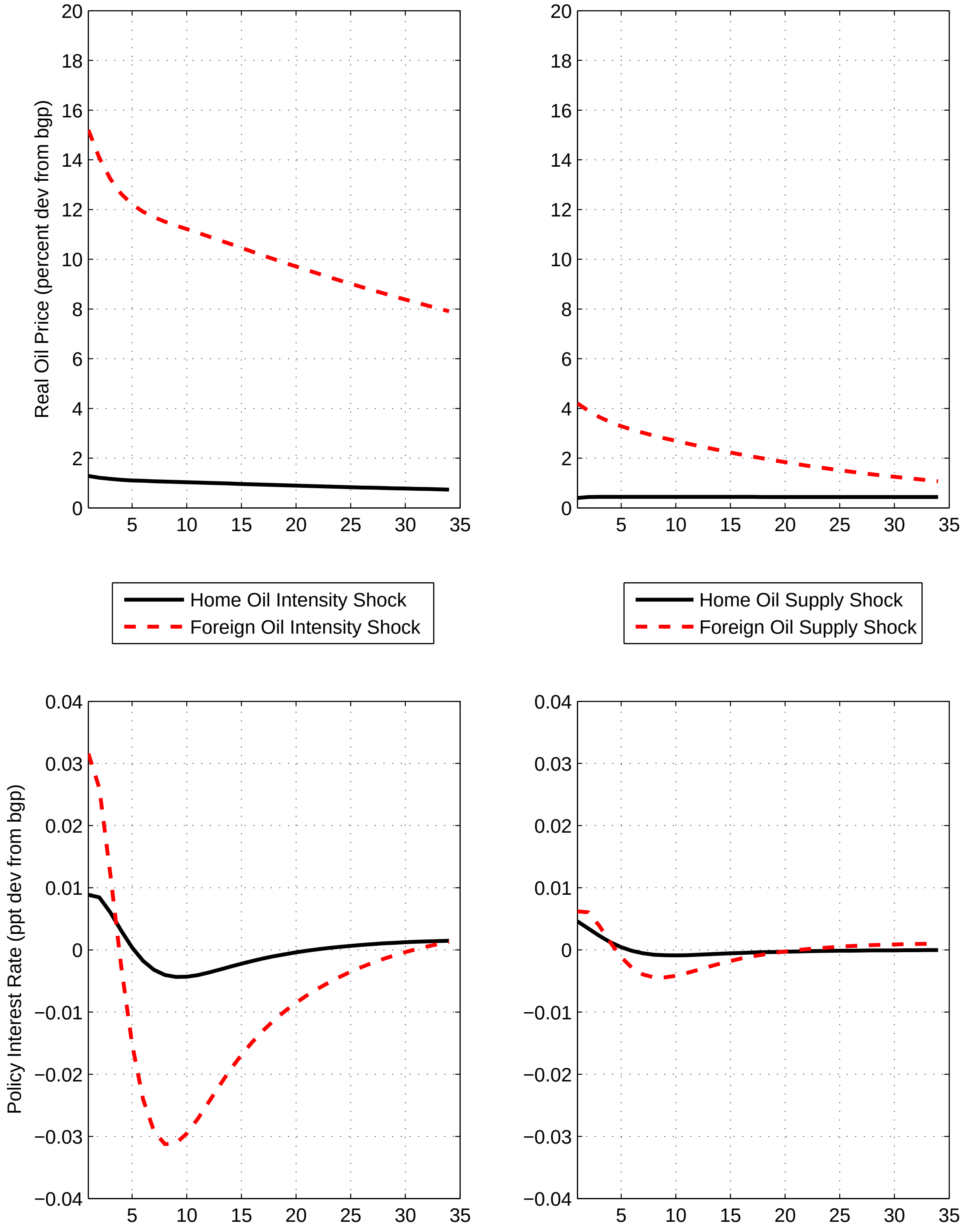


Figure 6: The Effects of Different Shocks on the Real Dollar Price of Oil and on U.S. Interest Rates (the shocks are sized at 1 standard deviation)

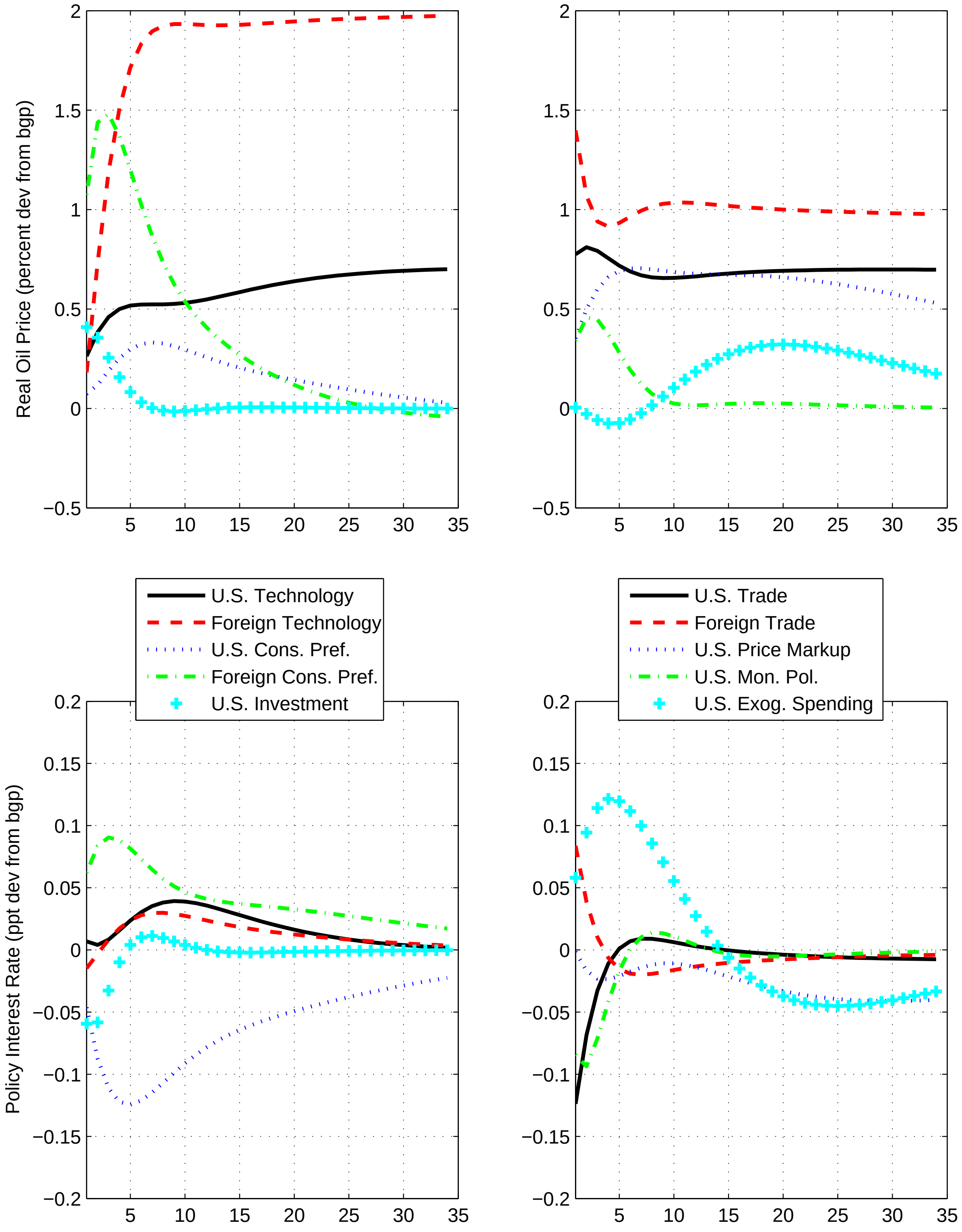


Figure 7: Variation in the U.S. Federal Funds Rate Explained by Different Subsets of Shocks

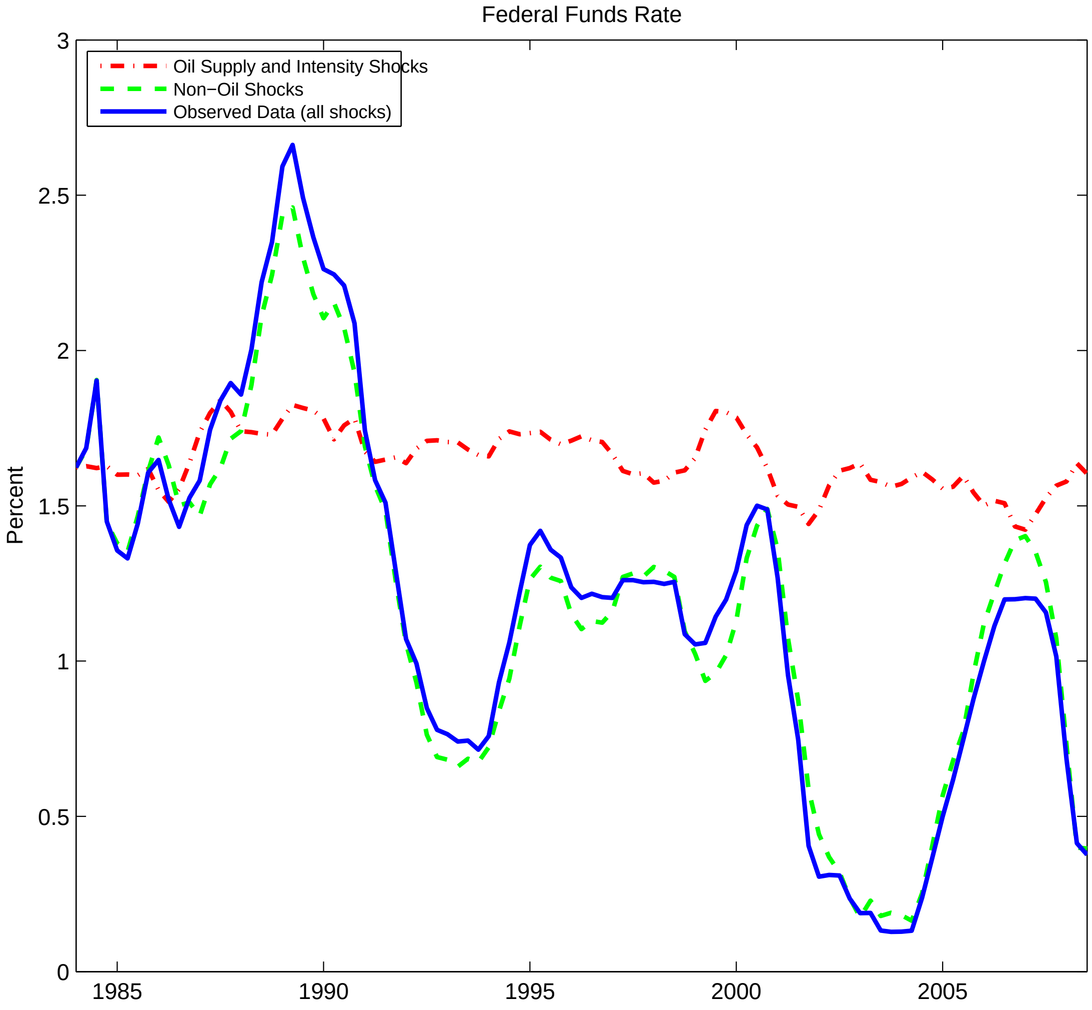
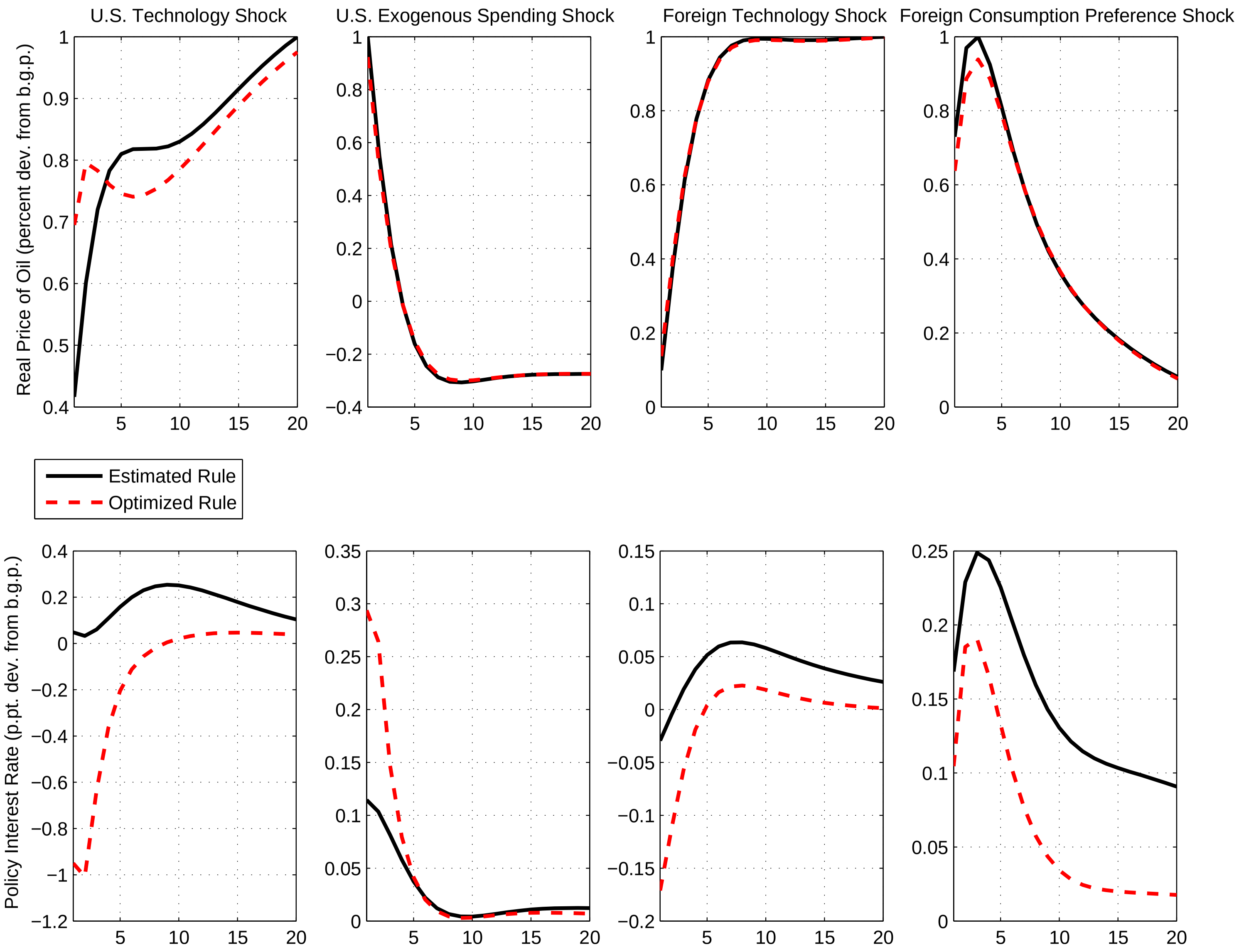
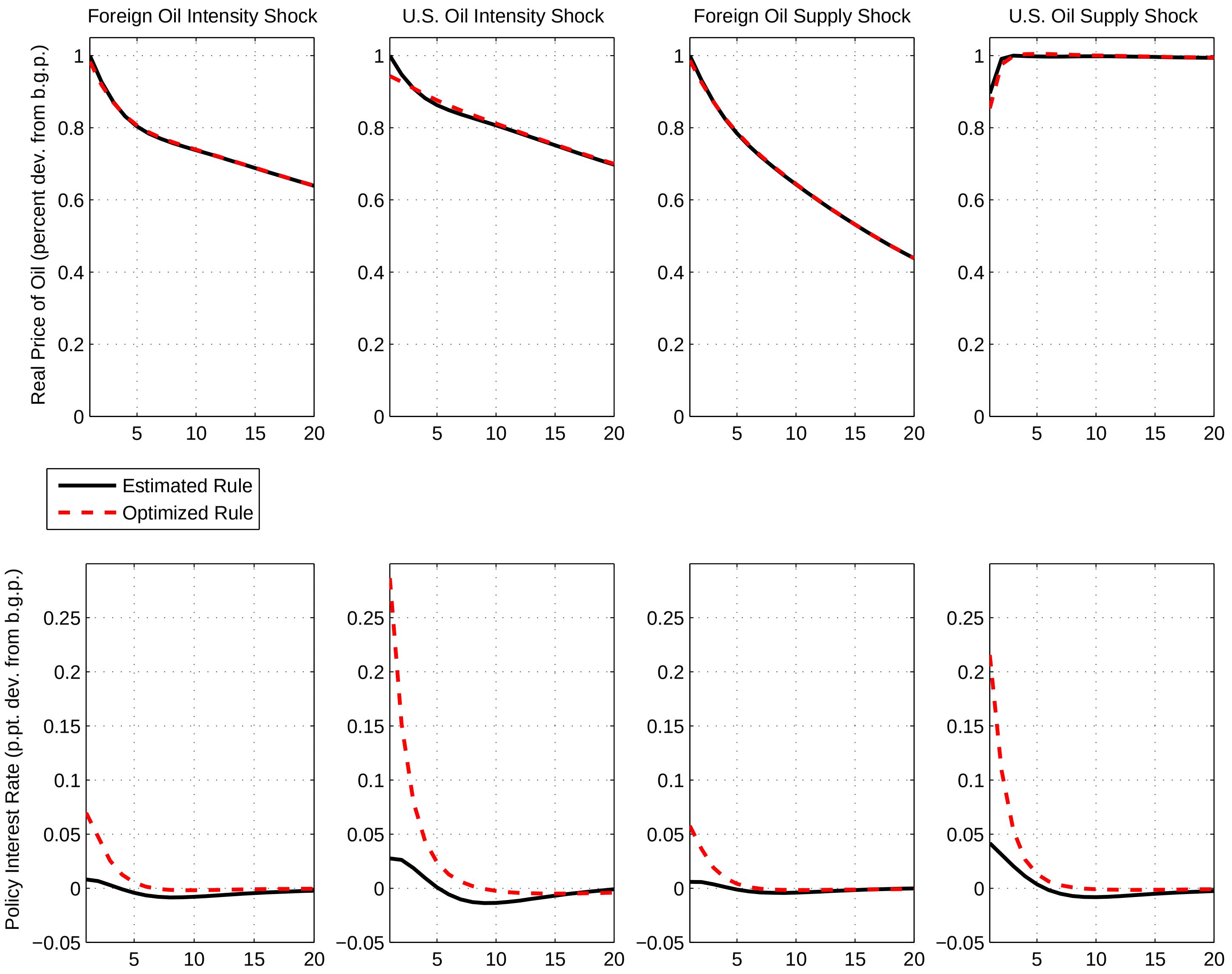


Figure 8: A Comparison of the Effects of Key Shocks Affecting Oil Prices under Alternative Policy Rules* (the shocks are scaled to induce a one percent increase in real price of oil at peak)



* The scale of the U.S. technology shock is 1.5632 standard deviations The scale of the U.S. autonomous spending shock is 2.0453 standard deviations. The scale of the foreign technology shock is 0.51361 standard deviation. The scale of the foreign consumption preference shock is 0.66794 standard deviation.

Figure 9: A Comparison of the Effects of Key Shocks Affecting Oil Prices under Alternative Policy Rules* (the shocks are scaled to induce a one percent increase in the real price of oil at peak)



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* The scale of the foreign oil intensity shock is 0.06584 standard deviation. The scale of the U.S. oil intensity shock is 0.78125 standard deviation. The scale of the foreign oil supply shock is 0.23862 standard deviation. The scale of the U.S. oil supply shock is 2.264 standard deviations.

Figure 10: The Effects of a One-Standard Deviation Increase in Foreign Oil Intensity: Deviations from the Balanced Growth Path Under Alternative Policy Rules and in the Potential Economy