Gasoline Prices, Transport Costs, and the U.S. Business Cycles

Hakan Yilmazkuday*

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Abstract

The effects of gasoline prices on the U.S. business cycles are investigated. In order to distinguish between gasoline supply and gasoline demand shocks, the price of gasoline is endogenously determined through a transportation sector that uses gasoline as an input of production. The model is estimated for the U.S. economy using five macroeconomic time series, including data on transport costs and gasoline prices. The results show that although standard shocks in the literature (e.g., technology shocks, monetary policy shocks) have significant effects on the U.S. business cycles in the long run, gasoline supply and demand shocks play an important role in the short run.

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*Department of Economics, Florida International University, Miami, FL 33199, USA. Phone:305-348-2316. E-mail: hakan.yilmazkuday@fiu.edu

1. Introduction

There is a close relationship between gasoline prices and the business cycles. One reason is that transportation of goods between producers and consumers is achieved by using gasoline as the main input. A second reason is that gasoline is by far the most important form of energy consumed in the United States; e.g., it accounts for 48.7% of all energy used by consumers.[1] A third reason is that gasoline prices reflect the developments in the global energy markets.[2] A fourth (and maybe the most important) reason is that gasoline is the form of energy with the most volatile price, which is important for any business cycle analysis.[3]

This paper investigates this relationship for the U.S. economy. In technical terms, the main innovation in this paper is to include a transportation sector (that uses gasoline as an input of production) between producers and consumers in an otherwise standard DSGE model. In the model, we can distinguish between demand and supply shocks by assuming a given (exogenous) endowment of gasoline, while letting the gasoline price to be determined in equilibrium. The optimization of households and firms results in an expression for the nominal price of gasoline depending on future nominal gasoline prices, future gasoline supply shocks, and nominal interest rates. The equilibrium real price of gasoline further depends on the global real economic activity together with the global endowment of gasoline.

In equilibrium, the effects of transport costs and gasoline prices are further summarized in an IS equation, a Phillips curve, a terms of trade expression, a monetary policy rule, and real prices of transportation and gasoline. Hence, in this paper, possible effects of gasoline supply and demand shocks on output, inflation, and transport costs can be investigated together with the effects of other shocks accepted as standard in the literature. We pursue such an approach to investigate the volatilities in gasoline prices and their effects on the U.S. business cycles. The results show that although standard shocks in the literature (e.g., technology shocks or monetary policy shocks) have significant effects on the U.S. business cycles in the long run, gasoline supply and demand shocks play an important role in the short run.[4]

Some earlier DSGE studies have also considered energy prices (mostly in the form of oil prices) and their effects on economic activity.[5] In the recent literature, Dhawan and Jeske (2008) have

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[1] See Kilian (2008); gasoline is followed by electricity with a share of 33.8% and natural gas with a share of 12.3%.

[2] For example, crude oil is the main input into gasoline production.

[3] A more detailed comparison between energy, oil, and gasoline prices has been provided in Kilian (2010)

[4] See Kilian (2008) and Edelstein and Kilian (2009) for discussions on mechanisms that explain how consumption expenditures may be directly affected by energy price changes.

[5] As earlier modeling approaches, see Hamilton (1988), Kim and Loungani (1992), Backus and Crucini (1992),

modeled (and calibrated) the energy consumption of households and firms; however, they have not endogenized the price of energy or estimated their model, hence they have not empirically distinguished between energy supply and energy demand shocks in the U.S. economy. Although Bodenstein et al. (2011) have endogenized energy prices and investigated (through calibrating) the role of financial risk sharing in a two-country DSGE model of the external adjustments caused by energy price shocks, they have not estimated their model and have not investigated the effects of energy shocks on the U.S. business cycles. Nakov and Pescatori (2010) have modeled and estimated energy-market specific demand shocks through considering energy consumption of firms, but they have not considered the demand shocks through energy consumption of final consumers or through the transportation sector. Balke et al. (2010) and Bodenstein and Guerrieri (2011) have modeled and estimated the energy consumption of households and firms; however, they have not considered the role of energy shocks through modeling a transportation sector, either. In contrast, this paper investigates all of these mentioned dimensions by modeling demand for and supply of gasoline which is by far the most important form of energy consumed in the United States.

The rest of the paper is organized as follows. Section 2 introduces the economic environment. Section 3 introduces the data and the estimation methodology. Section 4 depicts the estimation results and discusses the robustness of the analysis. Section 5 concludes. The log-linearized version of the model, together with its implications, is given in the Appendices.

2. Economic Environment

The two-country model is populated by a representative household, a continuum of production firms, a continuum of transportation firms taking care of the transportation of goods from producers to consumers, and a monetary authority.[6] It is a continuum of goods model in which all goods are tradable, the representative household holds assets, the production of goods requires labor input (subject to a production technology), and the production of transportation services requires gasoline input (subject to a transportation technology).

In terms of the notation, subscripts H and F stand for domestically and foreign-produced goods, respectively; superscript $*$ stands for the variables of the foreign country (i.e., rest of the world).[7]

Rotemberg and Woodford (1996), and Finn (2000).

[6]The model builds upon models such as Benigno and Benigno (2006) by introducing a transportation sector that uses gasoline as an input. The model also extends the model of Yilmazkuday (2009) by endogenizing the transport costs through considering endogenously determined gasoline prices.

[7]In order to give the reader a better understanding of the notation, for time t, φ_t stands for variable φ at

2.1. Households

The *representative* household in the domestic (i.e., home) country has the following intertemporal lifetime utility function:

$$E_t \left(\sum_{k=0}^{\infty} \beta^k \left\{ \log C_{t+k} - N_{t+k} \right\} \right) \tag{2.1}$$

where $\log C_t$ is the utility out of consuming a composite index of C_t, N_t is the disutility out of working N_t hours, and $0 < \beta < 1$ is a discount factor. The composite consumption index C_t is defined as:

$$C_t = (C_{H,t})^{1-\gamma}(C_{F,t})^{\gamma} \tag{2.2}$$

where $C_{H,t}$ and $C_{F,t}$ are consumption of home and foreign (i.e., imported) goods, respectively, and γ is the share of domestic consumption allocated to imported goods. These symmetric consumption sub-indexes are defined by:

$$C_{H,t} = \left(\int_0^1 C_{H,t}(j)^{(\theta_t-1)/\theta_t} dj \right)^{\theta_t/(\theta_t-1)} \quad \text{and} \quad C_{F,t} = \left(\int_0^1 C_{F,t}(j)^{(\theta_t-1)/\theta_t} dj \right)^{\theta_t/(\theta_t-1)} \tag{2.3}$$

where $C_{H,t}(j)$ and $C_{F,t}(j)$ represent domestic consumption of home and foreign good j, respectively, and $\theta_t > 1$ is the time-varying elasticity of substitution evolving according to:

$$\theta_t = (\theta)^{1-\rho_\theta} (\theta_{t-1})^{\rho_\theta} \exp\left(\varepsilon_t^\theta\right) \tag{2.4}$$

where θ is the steady-state level of θ_t, $\rho_\theta \in [0,1)$, and ε_t^θ is an i.i.d. *markup shock* (as will be evident, below) with zero mean and variance σ_θ^2.

The optimality conditions result in:

$$C_{H,t}(j) = \left(\frac{P_{H,t}(j)}{P_{H,t}} \right)^{-\theta_t} C_{H,t}$$

$$C_{F,t}(j) = \left(\frac{P_{F,t}(j)}{P_{F,t}} \right)^{-\theta_t} C_{F,t} \tag{2.5}$$

where $P_{H,t}(j)$ and $P_{F,t}(j)$ are prices of domestically consumed home and foreign good j, respectively, and $P_{H,t}$ and $P_{F,t}$ are price indexes of domestically consumed home and foreign goods, respectively, which are defined as:

$$P_{H,t} = \left(\int_0^1 ([P_{H,t}(j)])^{1-\theta_t} dj \right)^{1/(1-\theta_t)} \tag{2.6}$$

home, φ_t^* stands for variable φ in the foreign country, $\varphi_{H,t}$ stands for variable φ produced and consumed in the home country, $\varphi_{F,t}$ stands for variable φ produced in the foreign country but consumed in the home country, $\varphi_{H,t}^*$ stands for variable φ produced in the home country but consumed in the foreign country, $\varphi_{F,t}^*$ stands for variable φ produced and consumed in the foreign country. Accordingly, good level notation is implied: e.g., $\varphi_{F,t}^*(j)$ stands for variable φ produced and consumed in the foreign country in terms of good j.

and

$$P_{F,t} = \left(\int_0^1 ([P_{F,t}(j)])^{1-\theta_t} \, dj \right)^{1/(1-\theta_t)} \tag{2.7}$$

Similarly, the demand allocation of home and imported goods implies:

$$C_{H,t} = \frac{(1-\gamma) C_t P_t}{P_{H,t}} \tag{2.8}$$

and

$$C_{F,t} = \frac{\gamma P_t C_t}{P_{F,t}} \tag{2.9}$$

where $P_t = (P_{H,t})^{1-\gamma} (P_{F,t})^{\gamma}$ is the consumer price index (CPI).

Transportation of goods is subject to transport costs. Accordingly, the price of any domestically consumed home good j is given by:

$$P_{H,t}(j) = P_{H,t}^s(j)\tau_t(j) \tag{2.10}$$

where $P_{H,t}^s(j)$ is the price charged by the home producer at the source, and $\tau_t(j)$ represents good-specific multiplicative transport costs (between producers and consumers). Similarly, the price of any domestically consumed foreign good is given by:

$$P_{F,t}(j) = \Xi_t P_{F,t}^{s*}(j)\tau_t(j) \tag{2.11}$$

where Ξ_t is the nominal effective exchange rate, and $P_{F,t}^{s*}(j)$ is the price charged by the foreign producer at the source.

The household budget constraint is given by:

$$\int_0^1 [P_{H,t}(j)C_{H,t}(j) + P_{F,t}(j)C_{F,t}(j)] \, dj + E_t(F_{t,t+1}B_{t+1}) = W_t N_t + B_t + T_t \tag{2.12}$$

where $F_{t,t+1}$ is the stochastic discount factor, B_{t+1} is the nominal payoff in period $t+1$ of the portfolio held at the end of period t, W_t is the hourly wage, and T_t is the lump sum transfers (including profits coming from the firms); there are also complete international financial markets. By using the optimal demand functions, Equation (2.12) can be written in terms of the composite good as follows:

$$P_t C_t + E_t(F_{t,t+1}B_{t+1}) = W_t N_t + B_t + T_t \tag{2.13}$$

where $P_t C_t$ satisfies:

$$P_t C_t = P_{H,t} C_{H,t} + P_{F,t} C_{F,t} \tag{2.14}$$

where $P_{H,t}C_{H,t}$ and $P_{F,t}C_{F,t}$ further satisfy:

$$P_{H,t}C_{H,t} = \int_0^1 P_{H,t}(j)C_{H,t}(j)dj \tag{2.15}$$

4

and

$$P_{F,t}C_{F,t} = \int_0^1 P_{F,t}(j)C_{F,t}(j)dj \tag{2.16}$$

respectively.

The representative home agent's problem is to choose paths for consumption, portfolio, and the labor supply. Therefore, the representative consumer maximizes her expected utility (i.e., Equation (2.1)) subject to the budget constraint (i.e., Equation (2.13)). The standard first order conditions result in:

$$W_t = P_t C_t \tag{2.17}$$

and

$$\beta E_t \left(\frac{C_t P_t}{C_{t+1} P_{t+1}} \right) = \frac{1}{I_t} \tag{2.18}$$

where $I_t = 1/E_t [F_{t,t+1}]$ is the gross return on the portfolio.

The optimization problem is analogous for the rest of the world, which results in:

$$\beta E_t \left(\frac{C_t^* P_t^* \Xi_t}{C_{t+1}^* P_{t+1}^* \Xi_{t+1}} \right) = E_t (F_{t,t+1}) \tag{2.19}$$

Combining Equations (2.18) and (2.19), one can obtain (after iterating) that:

$$C_t = \tilde{c}C_t^* Q_t \tag{2.20}$$

where $\tilde{c} \left(= \frac{C_0 P_0}{C_0^* P_0^* \Xi_0} \right)$ is a constant representing the *ex ante* environment, and $Q_t = \Xi_t P_t^* / P_t$ is the real effective exchange rate.

2.2. Production Firms

The domestic production firm producing good j has the following production function:

$$Y_t(j) = Z_t N_t(j) \tag{2.21}$$

where N_t is labor input, and Z_t is an economy-wide exogenous productivity evolving according to:

$$Z_t = (Z_{t-1})^{\rho_z} \exp(\varepsilon_t^z) \tag{2.22}$$

where $\rho_z \in [0, 1)$, and ε_t^z is an i.i.d. *production technology shock* with zero mean and variance σ_z^2. Accordingly, the nominal marginal cost of production (that is common across producers) is given by:

$$MC_t^n = \frac{W_t}{Z_t} \tag{2.23}$$

5

For all differentiated goods, market clearing implies:

$$Y_t(j) = C_{H,t}(j) + C^*_{H,t}(j) \tag{2.24}$$

where $C^*_{H,t}(j)$ represents sales of the domestic production firm to foreign households. Using Equations (2.5) and 2.10, their symmetric versions for the rest of the world, and $\tau_t(j) = \tau_t$ for all j (to be shown during the optimization of transportation firms, below), this expression can be rewritten as follows:

$$Y_t(j) = \left(\frac{P_{H,t}(j)}{P_{H,t}} \right)^{-\theta_t} C^A_{H,t} \tag{2.25}$$

where $C^A_{H,t} = C_{H,t} + C^*_{H,t}$ is the aggregate world demand for the goods produced in the home country. The production firm takes this demand into account in its Calvo price-setting process. In particular, producers are assumed to change their prices only with probability $1 - \alpha$, independently of other producers and the time elapsed since the last adjustment. Accordingly, the objective function of the production firm can be written as follows:

$$\max_{\widetilde{P}_{H,t}} E_t \left(\sum_{k=0}^{\infty} \alpha^k F_{t,t+k} \left\{ Y_{t+k}(j) \left(\widetilde{P}_{H,t}(j) - MC^n_{t+k} \right) \right\} \right) \tag{2.26}$$

where α is the probability that producers maintain the same price of the previous period, and $\widetilde{P}_{H,t}$ is the new price chosen by the firm in period t (that satisfies $P^s_{H,t+k}(j) = \widetilde{P}_{H,t}$ with probability α^k for $k = 0, 1, 2, ...$). The production firm takes the transportation costs of $\tau_t(j)$ as given, and the first order necessary condition is obtained as follows:

$$E_t \left(\sum_{k=0}^{\infty} \alpha^k F_{t,t+k} \left\{ Y_{t+k}(j) \left(\widetilde{P}_{H,t}(j) - \zeta_t MC^n_{t+k} \right) \right\} \right) = 0 \tag{2.27}$$

where $\zeta_t \equiv \theta_t/(\theta_t - 1)$ is a markup shock as a result of market power that is received by home households as transfer payments.

2.3. Transportation Firms

Global transportation of each good j produced in both domestic and foreign countries is achieved by a global good-j-specific transportation firm. Since we would like to study the relation between gasoline prices and their effects on the transportation sector, we will consider the transportation firm using gasoline as the only input in the following production function:

$$Y^\tau_t(j) = Z^\tau_t G^\tau_t(j) \tag{2.28}$$

where $Y^\tau_t(j)$ is the transportation service produced to deliver good j to global (i.e., both home and foreign) consumers, Z^τ_t is an exogenous transportation productivity, and $G^\tau_t(j)$ is the amount of

6

gasoline used by transportation firm j. The exogenous productivity parameter evolves according to:

$$Z_t^\tau = \left(Z_{t-1}^\tau\right)^{\rho_z^\tau} \exp\left(\varepsilon_t^{z^\tau}\right) \tag{2.29}$$

where $\rho_z^\tau \in [0,1)$, and $\varepsilon_t^{z^\tau}$ is an i.i.d. *transportation technology shock* with zero mean and variance $\sigma_{z^\tau}^2$. Accordingly, after assuming that the price of gasoline P_t^G is the same for the transportation firm regardless of its location of use, the marginal cost of production in terms of the home currency is given by:

$$MC_t^\tau = \frac{P_t^G}{Z_t^\tau}$$

where the marginal cost is common across transportation firms.

Consistent with international trade studies using iceberg transport costs (e.g., see Anderson and van Wincoop, 2004), transport costs are assumed to be measured *per unit of source value transported*, and they are symmetric between home and foreign countries. Therefore, the global market clearing condition for transportation services of good j is obtained by considering the overall sales of domestic and foreign firms producing good j; it is given by:

$$Y_t^\tau(j) = \underbrace{P_{H,t}^s(j)\left(C_{H,t}(j) + C_{H,t}^*(j)\right)}_{\text{Sales of Domestic Firm}} + \underbrace{\Xi_t P_{F,t}^{s*}(j)\left(C_{F,t}(j) + C_{F,t}^*(j)\right)}_{\text{Sales of Foreign Firm}} \tag{2.30}$$

which is in domestic-currency terms for measurement purposes. Accordingly, the objective function of the production firm can be written as follows:

$$\max_{\tau_t(j)} E_t\left(\sum_{k=0}^\infty F_{t,t+k}\left\{Y_{t+k}^\tau(j)\left(\tau_{t+k}(j) - MC_{t+k}^\tau\right)\right\}\right) \tag{2.31}$$

subject to Equation 2.5, its symmetric version for the rest of the world, and Equation 2.30, where the transportation firm takes the pricing decision of the production firms (i.e., source prices of $P_{H,t}^s(j)$ and $P_{F,t}^{s*}(j)$) as given. Since transport costs are multiplicative according to Equations 2.10 and 2.11 (together with their symmetric versions for the rest of the world), the optimization results in the following pricing decision of the transportation firm:

$$\tau_t(j) = \zeta_t MC_t^\tau \tag{2.32}$$

where ζ_t is the same markup as production firms charge (so that there is no arbitrage opportunity between production and transportation firms in terms of markups), and it is assumed to be received by foreign households as transfer payments for simplicity. It is implied that $\tau_t(j) = \tau_t$ for all j; hence, we will drop the subscript j from $\tau_t(j)$ and consider τ_t as our measure of transport costs. According to Equations 2.6, 2.7, 2.10, and 2.11, it is implied that:

$$P_{H,t}^s = \frac{P_{H,t}}{\tau_t} = \left(\int_0^1 \left([P_{H,t}^s(j)]\right)^{1-\theta_t} dj\right)^{1/(1-\theta_t)} \tag{2.33}$$

and

$$P_{F,t}^{s*} = \frac{P_{F,t}}{\Xi_t \tau_t} = \left(\int_0^1 \left([P_{F,t}^{s*}(j)] \right)^{1-\theta_t} dj \right)^{1/(1-\theta_t)} \tag{2.34}$$

The total demand for gasoline in the world (coming from all transportation firms) is given by the summation of individual gasoline demand functions of transportation firms:

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\begin{aligned}
G_t^{\tau} &= \int_0^1 G_t^{\tau}(j) dj \\
&= \frac{1}{Z_t^{\tau}} \left\{ \int_0^1 P_{H,t}^s(j) \left(C_{H,t}(j) + C_{H,t}^*(j) \right) dj + \Xi_t \int_0^1 P_{F,t}^{s*}(j) \left(C_{F,t}(j) + C_{F,t}^*(j) \right) dj \right\}
\end{aligned}
$$

which can be rewritten using Equations 2.10, 2.11, 2.14, 2.15, 2.16, 2.20, and 2.32 as follows:

$$G_t^{\tau} = \frac{P_t C_t \Omega}{P_t^G \zeta_t} \tag{2.35}$$

where $\Omega = \frac{\tilde{c}+1}{\tilde{c}}$. Equation 2.35 depicts the relation between the demand for gasoline and the overall economic activity. In particular, as the overall economic activity (measured by C_t) increases or as the real price of gasoline (measured by P_t^G/P_t) decreases, the demand for gasoline goes up.

2.4. Gasoline Endowment

The world has a stock of gasoline Y_t^G in period t that is used only by the transportation sector; it further evolves according to:

$$Y_t^G = \left(Y_{t-1}^G \right)^{\rho_{yG}} \exp \left(\varepsilon_t^{yG} \right) \tag{2.36}$$

where $\rho_{yG} \in [0,1)$, and ε_t^{yG} is an i.i.d. *gasoline endowment shock* with zero mean and variance σ_{yG}^2. The income of gasoline is distributed among the foreign households through transfers in their budget constraints; this assumption is important in a country like the U.S. (that we will investigate, below) of which production of oil is fewer than its consumption. Accordingly, the market clearing condition in the gasoline market is given as follows:

$$Y_t^G = G_t^{\tau}$$

Combining this expression with the overall gasoline demand of the transportation sector (i.e., Equation 2.35) results in the following equilibrium real price of gasoline:

$$\frac{P_t^G}{P_t} = \frac{C_t \Omega}{Y_t^G \zeta_t} \tag{2.37}$$

which shows that the real price of gasoline (i.e., P_t^G/P_t in equilibrium) increases with economic activity (measured by C_t), and it decreases with the available stock of gasoline Y_t^G. If we further combine this expression with the intertemporal consumption decision of households given by Equation 2.18, we can obtain the following expression showing the dynamics of gasoline prices:

$$P_t^G = \frac{E_t\left(P_{t+1}^G Y_{t+1}^G \zeta_{t+1}\right)}{\beta Y_t^G \zeta_t I_t} \tag{2.38}$$

where the nominal price of gasoline depends on future nominal gasoline prices, future gasoline supply shocks, and nominal interest rates (as well as markup shocks).

2.5. Monetary Policy

A general/flexible monetary policy is considered according to the gross return on the portfolio satisfying:[8]

$$I_t = E_t\left(\frac{P_{t+1}}{P_t}\right)^{\chi_\pi} E_t\left(\frac{Y_{t+1}}{Y_t}\right)^{\chi_{\Delta y}} V_t^i \tag{2.39}$$

where Y_t is the production index in the domestic country connected to the production of individual production firms according to:

$$Y_t = \left(\int_0^1 Y_t(j)^{(\theta-1)/\theta} dj\right)^{\theta/(\theta-1)}$$

and V_t^i evolves according to:

$$V_t^i = \left(V_{t-1}^i\right)^{\rho_i} \exp\left(\varepsilon_t^i\right) \tag{2.40}$$

where ε_t^i is an i.i.d. *monetary policy shock* with zero mean and variance σ_i^2.

3. Data and Estimation Methodology

The log-linearized version of the model, which is depicted in the Appendix with the corresponding discussion on dynamics, is estimated using data for the quarterly period over 1974:Q1-2012:Q4, where the starting date has been selected because of the structural break in the relationship between U.S. real GDP and energy prices in late 1973 as shown by Alquist et al. (2011).

The introduction of large number of shocks allows us to estimate the full model using a large data set (with five series). We match the model with the seasonally-adjusted U.S. data on output growth, home CPI inflation, home nominal interest rates, real transport costs, and real gasoline prices. In particular, since labor is the only input in our production function, we use log difference

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[8]See Orphanides (2003) as another study considering output growth in the monetary policy rule.

of real value added scaled by 100 to measure quarter-to-quarter U.S. output growth. CPI inflation rates are defined as log difference of U.S. CPI multiplied by 400 to obtain annualized percentage rates. Annual Effective Federal Funds Rate (in percentage terms) is used for U.S. nominal interest rates. The transportation component of the U.S. CPI divided by U.S. CPI is used for the real transport costs. The gasoline (all types) component of the U.S. CPI divided by U.S. CPI is used for the real gasoline prices. All variables have been treated as deviations around the sample mean.

As in Smets and Wouters (2003, 2007), the estimation is achieved through a Bayesian approach which can be decomposed in two steps: (1) The mode of the posterior distribution is estimated by maximizing the log posterior function, which combines the prior information on the parameters with the likelihood of the data. (2) The Metropolis-Hastings algorithm is used to get a complete picture of the posterior distribution and to evaluate the marginal likelihood of the model. Accordingly, the choice of priors for the structural parameters plays an important role in the estimation. For parameters assumed to be between zero and one, we use the beta distribution; for the parameters representing the standard errors of shocks, we use the inverse gamma distribution; and for the remaining parameters assumed to be positive, we use the gamma distribution. One important detail is that the model is parameterized in terms of the steady-state real interest rate r, rather than the discount factor β, where r is annualized such that $\beta = \exp\left(-r/400\right)$.

Table 1 provides information on prior distributions for all parameters that have been carefully selected as consistent with the existing literature. Following Smets and Wouters (2007), the standard errors of the innovations are assumed to have a mean of 0.1 and two degrees of freedom, which corresponds to a rather loose prior; the persistence of the AR(1) processes is assumed to have a mean of 0.5 and standard deviation 0.1. The prior mean of steady-state interest rate r has been chosen to be 2.5 as in Lubik and Schorfheide (2007). The parameters describing the monetary policy rule are based on a general/flexible monetary policy rule where the mean priors for reaction on future inflation χ_π and output growth $\chi_{\Delta y}$ are set as 1.5 and 0.25, similar to Smets and Wouters (2007) and Lubik and Schorfheide (2007). The prior mean for price stickiness α is set at 0.75 which is consistent with the price stickiness observed by Nakamura and Steinsson (2008) within the U.S. using micro-level producer prices. The prior mean of openness γ is set to 0.25 which is consistent with the long-run imports/GDP ratio of the U.S. excluding the service sector. The prior mean of steady-state elasticity of substitution θ has been selected as 1.5. It is important to emphasize that we tested the stability of these priors using the sensitivity analysis of prior distributions provided in Ratto (2008); we found that all parameter values in the specified ranges give unique saddle-path solution. Nevertheless, for robustness, we also consider alternative

priors in the estimation process, as we discuss in more details, below.

4. Estimation Results

4.1. Posterior Estimates of the Parameters

The Bayesian estimates of the structural parameters are given in Table 1. In addition to 90% posterior probability intervals, we report posterior means as point estimates. The estimates are in line with the existing literature and statistically significant according to the 90% posterior probability intervals. The steady-state real interest rate is estimated as 2.16 which corresponds to a β value of 0.99. The reactions of the monetary policy to the future inflation χ_π and output growth $\chi_{\Delta y}$ are measured by coefficient estimates of 1.21 and 0.09, respectively. For robustness, we also considered alternative prior means of 0.50 and 2.50 for χ_π and of 0.01 and 0.50 for $\chi_{\Delta y}$; in all cases, as is evident in Table 2, the odds ratio tests have rejected these priors (i.e., the benchmark prior means have been selected) according to our data.[9]

The parameter of price stickiness α is estimated about 0.80 that implies a price change in about every 5 quarters on average. The parameter of openness γ is estimated about 0.19 which is slightly below the long-term imports/GDP ratio of the U.S. when services are excluded. The steady-state elasticity of substitution θ is significantly estimated as 1.49; for robustness, we also considered two alternative prior means for θ, namely 1.09 and 2.00.[10] Nevertheless, both cases have been rejected by data (i.e., the benchmark prior means have been selected) according to the odds ratio tests of which results are given in Table 2.[11]

The production technology, interest rates, and gasoline endowment are estimated to be the most persistent, with AR(1) coefficients of 0.95, 0.95, and 0.93, respectively. These high persistencies imply that, at long horizons, most of the forecast error variance of our real variables will be explained by these shocks, which we discuss in details in the following subsection.

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[9]We also considered prior means for χ_π ($\chi_{\Delta y}$) even lower than 0.50 (0.01) and higher than 2.50 (0.50); the results were the same (i.e., the benchmark prior means were selected).

[10]For example, Yilmazkuday (2012) estimates the elasticity of substitution across goods as 1.09 using interstate trade data within the U.S.

[11]We also considered prior means for θ even lower than 1.09 and higher than 2.00; the results were the same (i.e., the benchmark prior means were selected).

4.2. Driving Forces of the Endogenous Variables

In this subsection, we address the following questions: (1) What are the main driving forces of the endogenous variables for which we have used data from the U.S.? (2) What are the effects of gasoline demand and gasoline supply shocks on the gasoline prices and the U.S. business cycles?

The forecast error variance decompositions of the U.S. endogenous variables evaluated at different horizons are given in Table 3. As is evident, the U.S. output volatility is governed mostly by technology and gasoline endowment shocks, followed by monetary policy shocks. Although transportation technology shocks and gasoline endowment shocks are effective in the short run, production technology shocks and monetary policy shocks are more effective in the long run; therefore, gasoline supply and demand shocks have played an important role in historical U.S. business cycles, especially in the short run.

The volatility in U.S. CPI inflation is governed mostly by monetary policy shocks, followed by transportation technology shocks and gasoline endowment shocks; the effects are stable across different horizons. The volatility in real transport costs are affected mostly by monetary policy shocks and gasoline endowment shocks, followed by technology shocks and markup shocks. As expected, the volatility in real gasoline prices are mostly governed by gasoline endowment shocks and transportation technology shocks (i.e., gasoline supply and demand shocks). Finally, the volatility in interest rates are mostly governed by transportation technology shocks, followed by monetary policy shocks and gasoline endowment shocks.

In order to further understand how the model works, we also depict the impulse responses of several endogenous variables in Figure 1, where the responses are to one standard deviation structural shocks of transportation technology and gasoline endowment, which are the key factors in this paper. As is evident, positive transportation technology shocks have positive effects on the economic activity measured by the output. The model works through the partial removal of a friction in the U.S. economy, leading to relatively higher demand for goods (i.e., *discretionary income effect*, just like the removal of a consumption tax) that increases both prices and output in equilibrium. Such increases in output also lead to higher demand for transportation services, increasing both nominal transportation costs and nominal gasoline prices (due to the increase in gasoline demand). Since the positive response of CPI is higher (lower) than the positive response of nominal transportation costs (nominal gasoline prices), real transportation costs (real gasoline prices) go down (up), where the difference between the responses of transportation costs and gasoline prices are mostly governed by transportation technology shocks. In sum, positive transportation technology shocks reduce real transportation costs, and they increase real gasoline

prices, working as only gasoline demand shocks (i.e., there is no change in gasoline supply in this process).

Positive gasoline endowment shocks have almost similar effects, except for the response of real gasoline prices. It is straightforward to follow the chain of logic to understand the nuance: An increase in gasoline endowment (i.e., a gasoline supply shock, by definition) leads to a reduction in gasoline prices, which, in turn, reduces transportation costs. Accordingly, as in the previous paragraph, the discretionary income effects come into picture to increase output and prices, which, in turn, increase the demand for transportation services and thus gasoline. Therefore, both supply and demand for gasoline are affected in this process, where the effects of gasoline demand dominate, and nominal gasoline prices increase. Nevertheless, the positive response of nominal gasoline prices is lower than the positive response of CPI, implying that real gasoline prices decline. In sum, positive gasoline endowment shocks reduce both real transportation costs and real gasoline prices. This result, together with the last sentence of the previous paragraph, is the key in understanding the contribution of this paper, where we distinguish between the effects of gasoline demand and gasoline supply shocks.

4.3. Robustness: Discussion on Shocks

The empirical results above should be qualified with respect to the shocks defined/employed; therefore, it is useful to consider possible caveats regarding them.

Since we have used data on both transport costs and gasoline prices, according to Equation 2.32, the transportation technology shocks might have captured any part of transport costs that cannot be explained by the changes in gasoline prices, since this is the only expression that includes transportation technology shocks. Therefore, if transport costs have deviated from gasoline prices at any time (e.g., slow pass-through of gasoline costs in transportation service production), such deviations might have been captured by the transportation technology shocks.

Although we have a monetary policy shock that affects the consumption side, the production sector uses only labor in the model. Therefore, (both production and transportation) technology shocks may be reflecting the effects of any monetary policy shock on the production side. Furthermore, if we remove the assumption of complete international financial markets, Euler equations for home and foreign countries (i.e., Equations 2.18 and 2.19) will not have the same right hand sides anymore; instead, the gross returns on the portfolios will be different from each other between the two countries. Such a financial friction (if any) would further appear in the uncovered interest parity and the terms of trade expressions and thus in our monetary policy shocks and/or gasoline

(supply and demand) shocks.

Finally, since we have used U.S. Federal Funds Rate as a measure of nominal interest rates, the monetary policy shocks might have captured any frictions in the transmission mechanism of monetary policy as well. This may shed more light on the contribution of monetary policy shocks on the U.S. business cycles in this paper.[12]

5. Concluding Remarks

This paper has investigated the role of gasoline shocks on the historical U.S. business cycles by introducing and estimating an open-economy DSGE model. The main innovation has been to distinguish between the effects of gasoline demand and supply shocks, where the former is attached to a transportation sector that uses/demands gasoline as an input, and the latter is attached to exogenously determined gasoline endowment (consistent with the U.S. economy that is a net oil importer). According to the forecast error variance decomposition calculated at different horizons, although standard shocks in the literature (e.g., technology shocks, monetary policy shocks) have significant effects on the U.S. business cycles in the long run, it is the gasoline supply and demand shocks that play an important role in the short run. Therefore, the optimal policy depends on the horizon considered in the U.S. economy. The results are mostly driven by discretionary income effects of transportation costs (and thus gasoline prices) which are important for a country like the U.S., which is a net oil importer.

The results of this paper should be qualified with respect to the structural model employed as it may be misspecified. Therefore, the results are subject to improvement; endogenizing the production of gasoline, introducing capital accumulation, intermediate input trade, and internationally incomplete asset markets would generate richer model dynamics. These are possible topics of future research. Nevertheless, the results of this paper would be similar if gasoline were modeled as a factor of production for production firms; because, if the final good is defined as the good consumed by the consumer, transportation is just a part of the final good production.

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[12]Since the model has no zero lower bound (ZLB) for the policy rate during the period of 2009-2012, the ZLB would show up as tightening shocks.

References

[1] Alquist, R., Kilian, L, and Vigfusson, R., (2011), "Forecasting the Price of Oil" the Handbook of Economic Forecasting.

[2] Anderson, J.E., and Wincoop, E.V., (2004), "Trade Costs", Journal of Economic Literature, 42: 691-751.

[3] Balke, N.S., S.P.A. Brown, and M.K. Yücel (2010), "Oil Price Shocks and U.S. Economic Activity: An International Perspective," mimeo, Federal Reserve Bank of Dallas.

[4] Benigno, G., Benigno, P., (2006). "Designing targeting rules for international monetary policy cooperation." Journal of Monetary Economics 53 (3), 473–506.

[5] Bodenstein, M. and Guerrieri, L. (2011). Oil Efficiency, Demand, and Prices: a Tale of Ups and Downs, *mimeo*.

[6] Bodenstein, M., Erceg, C.J. , and Guerrieri, L. (2011). Oil Shocks and External Adjustment. Journal of International Economics 83, 168–184.

[7] Edelstein, P. and Kilian, L. (2009), How Sensitive are Consumer Expenditures to Retail Energy Prices?, Journal of Monetary Economics, 56(6), 766-779.

[8] Finn, M.G. (2000), "Perfect Competition and the Effects of Energy Price Increases on Economic Activity," Journal of Money, Credit, and Banking, 32, pp. 400-416.

[9] Hamilton, J.D. (1988) "A Neoclassical Model of Unemployment and the Business Cycle." Journal of Political Economy, 96: 593-617.

[10] Hamilton, J.D. (2005), "Oil and the Macroeconomy," in S. Durlauf and L. Blume (eds), The New Palgrave Dictionary of Economics, 2nd ed., Palgrave MacMillan Ltd.

[11] Hamilton, J.D. (2011), "Nonlinearities and the Macroeconomic Effects of Oil Prices," Macroeconomic Dynamics, 15, 364-378.

[12] Kerr, W., and King, R.G., (1996), "Limits on interest rate rules in the IS model", Federal Reserve Bank of Richmond Economic Quarterly 82: 47-75.

[13] Kilian, L. (2008), The Economic Effects of Energy Price Shocks, Journal of Economic Literature, 46(4), December 2008, 871-909.

[14] Kilian, L. (2010), Explaining Fluctuations in Gasoline Prices: A Joint Model of the Global Crude Oil Market and the U.S. Retail Gasoline Market, Energy Journal, 31(2), 87-104.

[15] Kim, In-Moo, and Loungani, P. (1992), "The Role of Energy in Real Business Cycle Models," Journal of Monetary Economics, 29, no. 2, pp. 173-189.

[16] King, R.G., (2000), "The New IS-LM Model: Language, Logic and Limits", Federal Reserve Bank of Richmond Economic Quarterly Volume 86/3.

[17] Lubik, T.A. and Schorfheide, F., (2007), "Do Central Banks Respond to Exchange Rate Movements: A Structural Investigation", Journal of Monetary Economics, 54: 1069-1087.

[18] Nakamura, E. and Steinsson, J. (2008). Five Facts About Prices: A Reevaluation of Menu Cost Models. Quarterly Journal of Economics, 123(4): 1415-1464.

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

[20] Orphanides, A. (2003). Historical monetary policy analysis and the Taylor rule. Journal of Monetary Economics 50: 983-1022.

[21] Ratto, M. (2008). Analysing dsge models with global sensitivity analysis. Computational Economics, 31:115–139.

[22] Rotemberg, JJ., and Woodford, M. (1996), "Imperfect Competition and the Effects of Energy Price Increases," Journal of Money, Credit, and Banking, 28 (part 1), pp. 549-577.

[23] Smets, F. and Wouters, R., (2003). "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," Journal of the European Economic Association, 1(5): 1123-1175

[24] Smets, F. and Wouters, R., (2007). "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," American Economic Review, 97(3): 586-606.

[25] Yilmazkuday, H. (2009), "Is there a Role for International Trade Costs in Explaining the Central Bank Behavior", MPRA Working Paper No 15951.

[26] Yilmazkuday, H. (2012), "Understanding Interstate Trade Patterns", Journal of International Economics, 86: 158-166.

6. Appendix A: Log-Linearization of the Model

Loglinearization is achieved around the steady state where domestic terms of trade P_H/P_F is normalized to unity. In terms of the notation, lower case variables with a time subscript or Greek variables with a cap (e.g., p_t or $\widehat{\theta}_t$) represent percentage deviations from their steady states, and upper case variables or Greek variables without a time subscript (e.g., P or θ) represent their steady-state values.

6.1. Households

The log-linearized version of CPI can be written as:

$$p_t \equiv (1-\gamma)p_{H,t} + \gamma p_{F,t} \tag{6.1}$$

where $p_{H,t}$ and $p_{F,t}$ satisfy the log-linearized versions of Equations 2.33 and 2.34:

$$p_{H,t} = p_{H,t}^s + \widehat{\tau}_t \tag{6.2}$$

and

$$p_{F,t} = e_t + p_{F,t}^{s*} + \widehat{\tau}_t \tag{6.3}$$

where $p_{H,t}$ is the price index of domestic goods at the destination (i.e., the price paid by consumers), $p_{H,t}^s$ is the price index of domestic goods at the source (i.e., the price received by producers), $p_{F,t}$ is the price index of imported goods at home (i.e., destination) country, $p_{F,t}^{s*}$ is the (log) price index of imported goods at foreign (source) country, e_t is the nominal effective exchange rate, and $\widehat{\tau}_t$ is the gross transport cost per unit of source value transported that can be thought as either a shipping cost or the cost of a visit to the source, and it is assumed to be the same for domestic and international transportation.

The effective terms of trade is defined as $s_t \equiv p_{F,t} - p_{H,t}$, which can be combined with Equations 6.2 and 6.3 to have an alternative expression:

$$s_t \equiv e_t + p_{F,t}^{s*} - p_{H,t}^s \tag{6.4}$$

The formula of CPI inflation is implied as follows:

$$
\begin{aligned}
\pi_t &= \pi_{H,t}^s + \gamma\left(s_t - s_{t-1}\right) + \Delta\widehat{\tau}_t \tag{6.5}\\
\\
&= \pi_{H,t} + \gamma\left(s_t - s_{t-1}\right)
\end{aligned}
$$

where $\pi_t = p_t - p_{t-1}$ is the domestic CPI inflation for consumers, $\pi^s_{H,t} = p^s_{H,t} - p^s_{H,t-1}$ is the domestic PPI inflation for producers, and $\pi_{H,t}$ is the inflation of home-produced products faced by consumers. Combining Equations 6.4 and (6.5) results in an alternative expression of CPI inflation:

$$\pi_t = (1 - \gamma) \pi^s_{H,t} + \gamma \left(\Delta e_t + \pi^{s*}_{F,t} \right) + \Delta \widehat{\tau}_t \tag{6.6}$$

which suggests that domestic CPI inflation is a weighted sum of domestic PPI inflation, foreign PPI inflation, growth in exchange rate, and growth in transport costs. Hence, transport costs play an important role in the determination of CPI inflation.

The effective real exchange rate is log-linearized as follows:

$$q_t = e_t + p^*_t - p_t \tag{6.7}$$

By using Equations (6.1), (6.3) and (6.4), together with the symmetric versions of Equations (6.1) and (6.3) for the rest of the world, we can rewrite Equation (6.7) as follows:

$$q_t = (1 - \gamma - \gamma^*)s_t \tag{6.8}$$

where γ^* is the share of foreign consumption allocated to goods imported from the home country.

Under the assumption of complete international financial markets, by combining log-linearized version of Equations (2.18), (2.19) and (2.20), together with Equation (6.7), the uncovered interest parity condition is obtained as:

$$i_t = i^*_t + E_t \left(e_{t+1} \right) - e_t \tag{6.9}$$

where $i_t = \log \left(I_t \right) = \log \left(1 / \left(E_t \left(F_{t,t+1} \right) \right) \right)$ is the home interest rate and $i^*_t = \log \left(\Xi_t / \left(E_t \left(F_{t,t+1} \Xi_{t+1} \right) \right) \right)$ is the effective foreign interest rate. This uncovered interest parity condition relates the movements of the interest rate differentials to the expected variations in the effective nominal exchange rate. Since $s_t \equiv e_t + p^{s*}_{F,t} - p^s_{H,t}$ according to Equation (6.4), we can rewrite Equation (6.9) as follows:

$$s_t = \left(i^*_t - E_t \left(\pi^{s*}_{F,t+1} \right) \right) - \left(i_t - E_t \left(\pi^s_{H,t+1} \right) \right) + E_t \left(s_{t+1} \right) \tag{6.10}$$

Equation (6.10) shows the terms of trade between the home country and the rest of the world as a function of current interest rate differentials, expected future home inflation differentials and its own expectation for the next period.

6.2. Production Firms

Using Equation (2.18), we can rewrite Equation (2.27) as follows:

$$E_t \left[\sum_{k=0}^{\infty} (\beta\alpha)^k \frac{Y_{t+k}}{C_{t+k}} \frac{P^s_{H,t-1}}{P_{t+k}} \left\{ \frac{\widetilde{P}_{H,t}}{P^s_{H,t-1}} - \zeta_t \Pi^{sH}_{t-1,t+k} MC_{t+k} \right\} \right] = 0 \tag{6.11}$$

18

where $\Pi^{sH}_{t-1,t+k} = \frac{P^s_{H,t+k}}{P^s_{H,t-1}}$ and $MC_{t+k} = \frac{MC^n_{t+k}}{P^s_{H,t+k}}$. Log-linearizing Equation (6.11) around the steady-state CPI inflation $\overline{\Pi} = 1$ (i.e., zero inflation) and balanced trade results in:

$$\widetilde{p}_{H,t} = \overline{\pi} + p^s_{H,t-1} + E_t \left(\sum_{k=0}^{\infty} (\beta\alpha)^k \pi^s_{H,t+k} \right) + (1 - \beta\alpha) E_t \left(\sum_{k=0}^{\infty} (\beta\alpha)^k \widehat{mc}_{t+k} \right) \quad (6.12)$$
$$+ (1 - \beta\alpha) E_t \left(\sum_{k=0}^{\infty} (\beta\alpha)^k \widehat{\zeta}_{t+k} \right)$$

where $\overline{\pi} = \log\overline{\Pi} = 0$; $\widehat{mc}_t = mc_t - mc$ is the log deviation of real marginal cost from its steady state value, $mc = -\log\zeta$, and $\widehat{\zeta}_t = \log\left(\theta_t/(\theta_t - 1)\right) - \log\zeta$ is the log deviation of markup from its steady state value, $\log\zeta = \log\left(\theta/(\theta - 1)\right)$. Equation (6.12) can be rewritten as:

$$\widetilde{p}_{H,t} - p^s_{H,t-1} = \beta\alpha E_t \left(\widetilde{p}_{H,t+1} - p^s_{H,t} \right) + \pi^s_{H,t} + (1 - \beta\alpha) \widehat{mc}_t - \left(\frac{1 - \beta\alpha}{\theta - 1} \right) \widehat{\theta}_t \quad (6.13)$$

where $\widehat{\theta}_t$ is further given by the log-linearized version of Equation 2.4:

$$\widehat{\theta}_t = \rho_\theta \widehat{\theta}_{t-1} + \varepsilon^\theta_t$$

where $\rho_\theta \in [0, 1)$, and ε^θ_t is an i.i.d. *markup shock* with zero mean and variance σ^2_θ.

In equilibrium, each producer that chooses a new price in period t will choose the same price and the same level of output. Then the (aggregate) price of domestic goods will obey:

$$P^s_{H,t} = \left(\alpha \left(P^s_{H,t-1} \right)^{1-\theta_t} + (1 - \alpha) \left(\widetilde{P}_{H,t} \right)^{1-\theta_t} \right)^{1/(1-\theta_t)} \quad (6.14)$$

which can be log-linearized as follows:

$$\pi^s_{H,t} = (1 - \alpha) \left(\widetilde{p}_{H,t} - p^s_{H,t-1} \right) \quad (6.15)$$

Finally, by combining Equations (6.13) and (6.15), we can obtain a version of the New-Keynesian Phillips curve with PPI inflation as follows:

$$\pi^s_{H,t} = \beta E_t \left(\pi^s_{H,t+1} \right) + \lambda_x \widehat{mc}_t - \lambda_m \widehat{\theta}_t$$

and a version with the CPI inflation as follows:

$$\pi_{H,t} = \beta E_t \left(\pi_{H,t+1} - \Delta\widehat{\tau}_{t+1} \right) + \lambda_x \widehat{mc}_t - \lambda_m \widehat{\theta}_t + \Delta\widehat{\tau}_t \quad (6.16)$$

where $\lambda_x = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}$, $\lambda_m = \frac{\lambda_x}{\theta-1}$.

6.3. Equilibrium Dynamics

Using Equation (2.8) and the symmetric version of Equation (2.9) for the rest of the world, Equation (2.25) can be rewritten as follows:

$$Y_t(j) = \left(\frac{P_{H,t}(j)}{P_{H,t}}\right)^{-\theta_t} \left((1-\gamma)\frac{P_t C_t}{P_{H,t}} + \gamma^* \frac{P_t^* C_t^*}{P_{H,t}^*}\right) \tag{6.17}$$

Further using $Y_t = \left(\int_0^1 Y_t(j)^{(\theta_t-1)/\theta_t} dj\right)^{\theta_t/(\theta_t-1)}$, one can write:

$$\begin{aligned} Y_t &= \left((1-\gamma)\frac{P_t C_t}{P_{H,t}} + \gamma^* \frac{P_t^* C_t^*}{P_{H,t}^*}\right) \\ &= \left(\frac{P_t}{P_{H,t}}\right) C_t \left((1-\gamma) + \gamma^* \left(\frac{P_t^* P_{H,t}}{P_t P_{H,t}^*}\right) Q_t^{-1}\right) \end{aligned} \tag{6.18}$$

which implies that Equation (6.17) can be rewritten as follows:

$$Y_t(j) = \left(\frac{P_{H,t}(j)}{P_{H,t}}\right)^{-\theta_t} Y_t \tag{6.19}$$

Log-linearizing Equation (6.18) around the steady-state, together with using $s_t \equiv p_{F,t} - p_{H,t}$ and Equation (6.8), will transform it to the following expression:

$$y_t = c_t + \gamma s_t \tag{6.20}$$

Also using Equation (6.5) and the log-linearized version of Equation (2.18) (i.e., Euler), Equation (6.20) can be rewritten as follows:

$$\begin{aligned} y_t &= E_t\left(y_{t+1}\right) - \left(i_t - E_t\left(\pi_{H,t+1}^s\right)\right) + E_t\left(\Delta\widehat{\tau}_{t+1}\right) \\ \\ &= E_t\left(y_{t+1}\right) - \left(i_t - E_t\left(\pi_{H,t+1}\right)\right) \end{aligned} \tag{6.21}$$

which represents an IS curve that considers the effect of transport costs on output when PPI inflation is used (in the first line). When the version with the CPI inflation (in the second line) is considered, Equation (6.21) represents an IS curve that relates the expected change in (log) output (i.e., $E_t\left(y_{t+1}\right) - y_t$) to the difference between the interest rate, and the expected future domestic inflation (i.e., an approximate measure of real interest rate that becomes an exact measure of real interest rate when the terms of trade are constant across periods).[13] An increase in the difference between the expected inflation and the nominal interest rate decreases the expected change in the

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[13]See Kerr and King (1996), and King (2000) for discussions on incorporating the role for future output gap in the IS curve with a unit coefficient.

output gap, with a unit coefficient. When the version with PPI inflation is used, an expected increase in the transport costs leads to a decrease in the expected change in (log) output, which is due to the intertemporal substitution of consumption.

Using log-linearized versions of Equations 2.17, 2.23, 6.20 together with price definitions and $\widehat{mc}_t = \widehat{mc}_t^n - p_{H,t}^s$, we can also obtain an alternative expression for the New-Keynesian Phillips curve (given by Equation 6.16):

$$\pi_{H,t} = \beta E_t \left(\pi_{H,t+1} - \Delta\widehat{\tau}_{t+1} \right) + \lambda_x \left(y_t - z_t + \widehat{\tau}_t \right) - \lambda_m \widehat{\theta}_t + \Delta\widehat{\tau}_t \tag{6.22}$$

where z_t evolves according to the log-linearized version of Equation 2.22:

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z$$

where $\rho_z \in [0, 1)$, and ε_t^z is an i.i.d. *production technology shock* with zero mean and variance σ_z^2.

6.4. Transportation Firms

The optimal decision of the non-profit transportation firm (i.e., Equation 2.32) is log-linearized according to the following expression:

$$\widehat{\tau}_t = p_t^G - z_t^\tau - \frac{\widehat{\theta}_t}{\theta - 1} \tag{6.23}$$

where p_t^G is the price of gasoline in terms of home currency, and z_t^τ is the transportation-sector-specific technology (in real terms) evolving according to:

$$z_t^\tau = \rho_{z^\tau} z_{t-1}^\tau + \varepsilon_t^{z^\tau}$$

where $\rho_{z^\tau} \in [0, 1)$, and $\varepsilon_t^{z^\tau}$ is an i.i.d. *transportation technology shock* with zero mean and variance $\sigma_{z^\tau}^2$.

6.5. Gasoline Endowment

The market clearing condition in the gasoline market (i.e., Equation 2.37) is combined with Equation 2.18 to obtain Equation 2.38, which can be log-linearized as follows:

$$p_t^G = E_t \left(p_{t+1}^G \right) + E_t \left(\Delta y_{t+1}^G \right) - i_t - \frac{\Delta\widehat{\theta}_{t+1}}{\theta - 1} \tag{6.24}$$

where $E_t \left[p_{t+1}^G \right]$ is the expected future price of gasoline, $E_t \left[\Delta y_{t+1}^G \right]$ is the expected change in gasoline endowment y_t^G that evolves according to:

$$y_t^G = \rho_{y^G} y_{t-1}^G + \varepsilon_t^{y^G}$$

where $\rho_{y^G} \in [0,1)$, and $\varepsilon_t^{y^G}$ is an i.i.d. *gasoline endowment shock* with zero mean and variance $\sigma_{y^G}^2$. Since Equation 6.24 is the key innovation in this paper, it requires further explanation. According to Equation 6.24, the price of gasoline depends on not only the developments in the gasoline market, but also the domestic nominal interest rate. For instance, if interest rates increase today, households consume less to save more, which, in turn, results in lower demand for gasoline and thus lower gasoline prices today.

6.6. Monetary Policy

The home nominal interest rates determined by a general/flexible monetary policy rule (i.e., Equation 2.39) is log-linearized as follows:

$$i_t = \chi_\pi E_t\left(\pi_{t+1}\right) + \chi_{\Delta y} E_t\left(\Delta y_{t+1}\right) + v_t^i \tag{6.25}$$

where v_t^i evolves according to:

$$v_t^i = \rho_i v_{t-1}^i + \varepsilon_t^i$$

where ε_t^i is an i.i.d. *monetary policy shock* with zero mean and variance σ_i^2.

In the absence of a monetary authority for the rest of the world, we simply assume that foreign interest rates are determined according to $i_t^* = E_t\left(\pi_{F,t+1}^{s*}\right)$. Implications of this assumption are further discussed on the robustness section of the text.

7. Appendix B: Equations Entering the Estimation

We estimate the model by matching the U.S. data on output growth (Δy_t), CPI inflation (π_t), interest rates (i_t), real gasoline prices ($\overline{p_t^G} = p_t^G - p_t$), and real transport costs ($\overline{\widehat{\tau}_t} = \widehat{\tau}_t - p_t$). Accordingly, in this section, we depict how we connect the model to the data by modifying the equations used in the estimation.

The IS curve given by Equation 6.21 can be rewritten using Equation 6.5 as follows:

$$E_t\left(\Delta y_{t+1}\right) - i_t + E_t\left(\pi_{t+1} - \gamma\Delta s_{t+1}\right) = 0$$

The New-Keynesian Phillips Curve given by Equation 6.22 can be rewritten using Equation 6.5 and $\overline{\widehat{\tau}_t} = \widehat{\tau}_t - p_t$ as follows:

$$\beta E_t\left(\gamma\Delta s_{t+1} + \Delta\overline{\widehat{\tau}_{t+1}}\right) - \lambda_x\left(y_t - z_t + \widehat{\tau}_t\right) + \lambda_m\widehat{\theta}_t - \Delta\overline{\widehat{\tau}_t} - \gamma\Delta s_t = 0$$

$\lambda_x = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}$, $\lambda_m = \frac{\lambda_x}{\theta-1}$, and z_t and $\widehat{\theta}_t$ evolve according to:

$$z_t = \rho_z z_{t-1} + \varepsilon_t^z$$

and

$$\widehat{\theta}_t = \rho_\theta \widehat{\theta}_{t-1} + \varepsilon_t^\theta$$

Using Equation 6.23, an expression for the real transport costs $\overline{\widehat{\tau}}_t$ can be obtained as follows:

$$\overline{\widehat{\tau}}_t - \overline{p_t^G} + z_t^\tau + \frac{\widehat{\theta}_t}{\theta - 1} = 0$$

where $\overline{p_t^G}$ is the real gasoline price which is further given (according to Equation 6.24) as follows:

$$E_t \left(\Delta \overline{p_{t+1}^G} \right) + E_t \left(\pi_{t+1} \right) + E_t \left(\Delta y_{t+1}^G \right) - i_t - \frac{\Delta \widehat{\theta}_{t+1}}{\theta - 1} = 0 \tag{7.1}$$

where z_t^τ and y_t^G evolve according to:

$$z_t^\tau = \rho_{z^\tau} z_{t-1}^\tau + \varepsilon_t^{z^\tau}$$

and

$$y_t^G = \rho_{y^G} y_{t-1}^G + \varepsilon_t^{y^G}$$

The terms-of-trade expression can be rewritten using Equations 6.5 and 6.10, together with $\overline{\widehat{\tau}}_t = \widehat{\tau}_t - p_t$ and $i_t^* = E_t \left(\pi_{F,t+1}^{s*} \right)$, as follows:

$$(1 - \gamma) E_t \left(\Delta s_{t+1} \right) - i_t - E_t \left(\Delta \overline{\widehat{\tau}_{t+1}} \right) = 0 \tag{7.2}$$

Finally, the model is closed by the monetary policy rule which is given by Equation 6.25:

$$i_t - \chi_\pi E_t \left(\pi_{t+1} \right) - \chi_{\Delta y} E_t \left(\Delta y_{t+1} \right) - v_t^i = 0 \tag{7.3}$$

where v_t^i evolves according to:

$$v_t^i = \rho_i v_{t-1}^i + \varepsilon_t^i$$

It is important to emphasize that, since we match the data on Δy_t and $\overline{\widehat{\tau}}_t$ in the estimation of the model, y_t and $\widehat{\tau}_t$ are treated as latent variables, and the Kalman filter is used to infer these variables based on the observables as in the literature (e.g., see Lubik and Schorfheide, 2007).

Table 1 - Prior Distributions and Parameter Estimation Results

Parameter	Domain	Density	Prior Mean	Prior Standard Deviation	Posterior Mean	Posterior 90% Interval
r	$\mathfrak{R}^+$	Gamma	2.50	1.00	2.16	[0.78, 3.40]
χ_π	$\mathfrak{R}^+$	Gamma	1.50	0.05	1.21	[1.20, 1.22]
$\chi_{\Delta y}$	$\mathfrak{R}^+$	Gamma	0.25	0.05	0.09	[0.07, 0.12]
α	$[0,1)$	Beta	0.75	0.01	0.80	[0.79, 0.81]
γ	$[0,1)$	Beta	0.25	0.01	0.19	[0.19, 0.20]
θ	$\mathfrak{R}^+$	Gamma	1.50	0.05	1.49	[1.41, 1.57]
ρ_i	$[0,1)$	Beta	0.50	0.10	0.95	[0.95, 0.95]
ρ_z	$[0,1)$	Beta	0.50	0.10	0.95	[0.95, 0.95]
ρ_{z^τ}	$[0,1)$	Beta	0.50	0.10	0.13	[0.07, 0.17]
ρ_{y^G}	$[0,1)$	Beta	0.50	0.10	0.93	[0.91, 0.94]
ρ_θ	$[0,1)$	Beta	0.50	0.10	0.86	[0.81, 0.90]
σ_i	$\mathfrak{R}^+$	InvGamma	0.10	2.00	0.10	[0.09, 0.11]
σ_z	$\mathfrak{R}^+$	InvGamma	0.10	2.00	5.23	[4.71, 5.73]
σ_{z^τ}	$\mathfrak{R}^+$	InvGamma	0.10	2.00	1.15	[1.01, 1.28]
σ_{y^G}	$\mathfrak{R}^+$	InvGamma	0.10	2.00	1.56	[1.39, 1.72]
σ_θ	$\mathfrak{R}^+$	InvGamma	0.10	2.00	0.27	[0.21, 0.32]

Notes: The posterior mean of parameters have been computed using four independent Markov chains Monte Carlo (MCMC) trials with 1,000,000 draws in each chain (after discarding the first 25%). The procedure has been tuned so that the acceptance rate in the MCMC trials averaged approximately 30%.

Table 2 - Posterior Marginal Data Densities

Case	Prior Mean of: θ	χ_π	$\chi_{\Delta y}$	Marginal Density	Posterior Odds
Benchmark	1.50	1.50	0.25	-1603.63	1.00
Alternative #1	1.09			-1623.40	2.59×10^{-9}
Alternative #2	2.00			-1613.72	4.15×10^{-5}
Alternative #3		0.50		-1731.55	2.79×10^{-56}
Alternative #4		2.50		-1722.08	3.61×10^{-52}
Alternative #5			0.01	-1791.81	1.88×10^{-82}
Alternative #6			0.50	-1645.45	6.88×10^{-19}

Notes: Empty cells mean that such prior means have been kept the same as in the benchmark case. Prior standard errors are the same as in Table 1. The reported posterior odds test the hypothesis of the benchmark case representing the true model, assuming that the prior odds are one.

Table 3 - Forecast Error Variance Decomposition

Accounted for by:	Horizon	Output	CPI Inflation	Real Transport Costs	Real Gasoline Prices	Interest Rates
				Variance of:		
Production Technology Shocks	4	32.06	2.80	9.64	8.62	1.92
	12	46.57	2.81	11.70	8.64	2.18
	20	48.72	2.85	12.34	8.77	2.51
	∞	49.86	2.89	12.90	8.88	2.80
Gasoline Endowment Shocks	4	41.58	20.23	27.93	41.78	16.64
	12	20.04	20.34	28.04	42.00	17.41
	20	15.51	20.32	26.64	41.89	17.38
	∞	13.00	20.30	24.66	41.79	17.33
Transportation Technology Shocks	4	18.85	21.15	7.47	44.12	60.68
	12	8.34	20.95	2.76	43.69	58.77
	20	6.41	20.92	2.14	43.58	58.49
	∞	5.36	20.90	1.83	43.48	58.27
Monetary Policy Shocks	4	7.30	55.79	44.29	5.41	20.75
	12	24.86	55.89	51.92	5.60	21.63
	20	29.19	55.89	54.44	5.69	21.61
	∞	31.64	55.88	56.81	5.78	21.58
Markup Shocks	4	0.21	0.02	10.67	0.06	0.01
	12	0.19	0.02	5.58	0.07	0.02
	20	0.16	0.02	4.44	0.07	0.02
	∞	0.13	0.02	3.81	0.07	0.02

Figure 1 - Impulse Responses
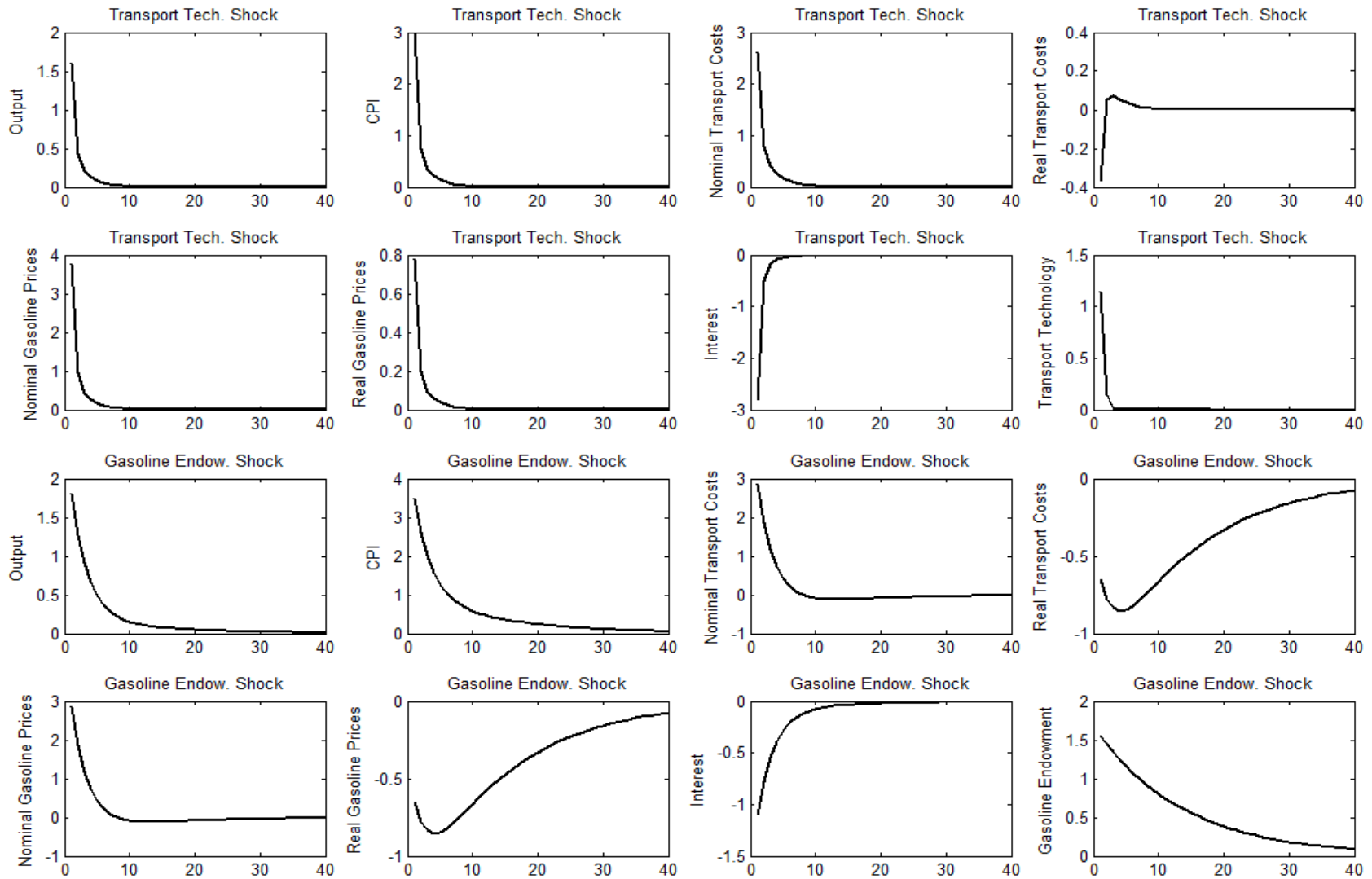
Notes: Figure depicts impulse responses to one-standard deviation structural shocks up to forty quarters.