Lags in the response of gasoline prices to changes in crude oil prices: the role of short-term and long-term shocks

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Abstract

Using weekly data for the period March 1991 to August 2002, we estimate the response of retail gasoline prices to changes in crude oil and spot gasoline prices in the US allowing for a possibility of two types of cost shocks to the gasoline market: long-term and short-term shocks. Our conclusion is that theoretical models should be developed that allow more than one type of input price changes and the different effect of input price changes on output prices.

The empirical results support the conjecture of two types of cost shocks. As such, we find that lags in the response of retail gasoline prices to changes in crude oil prices may be due to the fact that approximately 97 % of changes in crude oil prices are viewed as short-term by the market participants. When two types of shocks are considered, there is large difference between the cumulative response function of gasoline prices to long-term and short-term shocks to crude oil prices. As such, this paper adds to our understanding of the price stickiness of gasoline prices.

Keywords: *gasoline prices, cost shocks, Markov-switching model*

JEL Classification Numbers: L7, C3

Introduction

The adjustment of market prices to input cost changes has been of interest to economists for a long time, and there is a substantial body of evidence indicating that prices respond to changes in input costs with substantial lags [1]. There have been a number of articles published on the transmission of crude oil price changes to retail gasoline prices, and the various stages in between. Most of the articles report finding long lags and asymmetric gasoline price responses. Borenstein et al. (1997) note that lags in the adjustment of price to input cost changes are not consistent with simple models of either competitive markets or monopoly. Theoretical explanations offered for long lags have pointed to costly inventory and production adjustments, menu costs, market power and search costs. Recently, Borenstein and Shephard (2002) argue that adjustment costs, inventory and production, and market power could be responsible for lags in price responses. Johnson (2002) argues that search cost influence the lag length suggesting that in markets with low search costs market prices respond faster than in markets with high search costs.

This paper aims to increase our understanding of gasoline price adjustments by pointing out to possible nonlinearities in gasoline prices and their implications for gasoline price adjustments. We conduct an empirical exploration of why gasoline prices may respond to changes in crude oil prices with lags by incorporating two types of crude oil price shocks into a model. A possibility of two types of cost changes gives rise to nonlinearities in retail gasoline prices. Our contention is that there are two types of crude oil shocks (long-term and short-term), where gasoline pricing responds different to these two types of shocks, and the uncertainty about the type of price shock being faced leads to lags in price adjustment. Intuitively, the idea of different regimes in changes of crude oil prices and gasoline prices may be seen from Figure 1. One may conjecture from this figure that crude oil prices and gasoline prices have been in two distinct regimes during the time periods of 1991:2 - 1998:5 and 1998:6 - 2003:3. We propose to use a Simultaneous Equation with hidden Markov chain model to examine the plausibility of two regimes in changes of crude oil prices, long-term and short-term, and how the responses of gasoline

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[1]See, for example, Johnson (2002) and Blinder et al. (1998).

prices might be affected by the possibility of different regimes in changes of crude oil prices.

The paper provides new evidence to bear on the issue of lag length in retail gasoline response. We show that retail gasoline prices seem to exhibit non-linear pricing behavior. The gasoline prices seem to adjust much faster to crude oil shocks viewed as long-term by market participants than to crude oil shocks viewed as short-term. Relative to the previous literature, an innovative contribution of the paper is the empirical approach adopted, one based on a hidden Markov chain model, and the introduction of two types of cost shocks.

The structure of the paper is as follows. In Section 1 we review the literature on lag adjustments focusing on the possible link between the lag in price responses and uncertainty whether input cost changes are long-term or short-term.

The econometric model and the estimation of gasoline price responses to crude oil price changes are explained in Section 2 and Section 3. In Section 4 we discuss data issues and present empirical results. We conclude in Section 5. The detailed description of an econometric techniques for the analysis, Simultaneous Equation model with hidden Markov chain, is in Appendix A.

1 Sticky gasoline prices

There is a substantial body of evidence in the literature indicating that gasoline prices typically respond to changes in crude oil prices not fully and with substantial lags. In recent work, Borenstein and Shephard (2002) analyze a problem of lags and incomplete adjustment of gasoline prices to changes in prices of crude oil. They find that a full adjustment of gasoline prices to changes in crude oil prices may take many weeks and argue that a lag in the response of gasoline prices to oil prices may be caused by the cost of adjusting gasoline production and level of inventories. Profit maximizing behavior dictates that refineries adjust the gasoline production to change both the supply of gasoline and the price of gasoline when the price of crude oil changes. Once the refineries change the gasoline price, they must also change the supply of gasoline by either changing the production level or the level of gasoline inventory. Both alternatives may be expensive to implement over short period of time, leading to long

lags in the adjustment of gasoline prices when crude oil prices change.

Borenstein and Shephard (2002) have argued supply adjustments in the form of changing gasoline production levels or changing inventory levels are costly for several reasons. The level of gasoline production for each refinery is determined using a complex algorithm, making it costly to adjust the level of production quickly after the change in crude oil prices and providing incentives to spread the adjustment of production over time to lower cost. However, gasoline prices should still adjust quickly and without any lags in response to crude oil price changes if firms can change supply of gasoline by costlessly changing the level of inventory. The authors have argued that the change in the level of inventory is limited by technical minimum requirements, the maximum inventory capacity and the cost associated with deviation from the preferred level of inventory. Therefore, there are costs of inventory adjustment, which may be the reason that the prices of gasoline do not respond immediately to the changes in oil prices.

Johnson (2002) notes that the assertion that the cost of changing inventory can lead to lags may be problematic because most outlets receive fuel shipments at least once a week and sometimes daily and therefore should not have high cost of changing inventory. Instead, Johnson (2002) posits that search costs explain the long lags in the response of retail gasoline prices to wholesale gasoline prices.

Pindyck (2001) suggested that cost shocks to commodity may be permanent and temporary. The author defines a permanent shock as a shock that is expected to persist for a long time and a temporary shock as a shock that is expected to persist for a short period of time. He analyzes the relationship among spot prices, futures prices and inventory levels of a commodity if a temporary shock, such as a temporary demand shock because of weather conditions, is realized and if a permanent shock, such as a sustained increase in the price volatility, is realized [2]. Pindyck (2001) develops a model to show that the dynamics of commodity prices, inventory levels and convenience yield for permanent shock to a commodity market is different from temporary shock to a commodity market. If the shock to the market is assumed to persist indefinitely, there will be a new equilibrium in which the spot price, the convenience

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[2]To illustrate his ideas, Pindyck (2001) uses the data not only for gasoline but also for heating oil and crude oil.

yield, and level of inventories are higher than they were at the outset. If the shock is assumed to be temporary, the equilibrium for the spot prices, convenience yield and the level of inventories will not change. We refer a reader to the paper of Pindyck for further details.

Similar to Pindyck (2001), we conjecture that changes in crude oil prices may be long-term, i.e. expected to persist indefinitely, or may be short-term, i.e. expected to persist for a short period of time. We call cost shocks long-term and short-term rather that permanent and temporary to avoid confusion with permanent and transitory shocks in the macroeconomic literature. In macroeconomics, a transitory shock has a temporary effect on the variable, and this effect goes to zero in the long run. In contrast, we assume that the effect of short-term crude oil shock should not die out in the long run. Rather, a short-term crude oil shock should lead to a slow adjustment of gasoline prices.

Since a short-term shock is a shock to the marginal cost of production that will prevail for a short period of time, we assume that it is not profitable for refineries to adjust the level of production and inventory and to change gasoline prices fully and immediately when facing a short-term shock. If refineries believe that a change in crude oil price is short-term, they may partially adjust gasoline prices and production to reflect the belief that crude oil prices will move in the opposite direction sometime soon in future. On the other hand, we assume that the long-term shock is a shock to marginal cost that will prevail indefinitely and requires an immediate change of production and inventory levels and a fast change of gasoline prices. If refineries believe that a crude oil shock is long-term, they fully and quickly adjust production and gasoline prices to reflect a belief that crude oil prices will not change in the opposite direction soon. Therefore, the lags in the adjustment of gasoline prices occur if the crude oil shocks are viewed as short-term by market participants and there should be no lags in the response of gasoline prices if the crude oil shocks are viewed as long-term shocks. If our conjecture that there are two types of shocks to crude oil prices is correct, then the observed lags in the response of gasoline prices may be due to the fact that many oil price changes are viewed as short-term by market participants but current analysis is based on the assumption that all the shocks to marginal cost are long-term (permanent).

Note that even if majority of crude oil shocks are indeed long-term, a possibility of two types of shocks along with the uncertainty as to which shock has realized may be enough to create lags in the response of gasoline prices. Since it is costly for refineries to change the level of production and to deviate from the optimal level of inventory if the oil shock is short-term, refineries may need time to decrease uncertainty about the nature of cost shock. If refineries do not immediately view the realized crude oil shock as long-term, it is not profitable to change the level of production and inventory in order to change the gasoline prices for a short-term period of time. Therefore, the existence of two types of shocks and uncertainty about shocks may explain why there are lags in response of gasoline prices to changes in crude oil prices.

The idea that there are some changes in crude oil price that affect gasoline prices and that there are some changes in crude oil price that do not affect gasoline prices can be also found in Godby et al. (2000). The authors use threshold autoregressive model (TAR), within an error correction framework, to test price asymmetries in the Canadian retail gasoline market. The motivation for use of TAR within an error correction framework is that price asymmetries can be triggered by minimum absolute increases in crude oil cost. The idea of minimum absolute increase in crude oil cost proposed by Godby et al. (2000) is similar to the idea of long-term and short-term shocks to crude oil cost prices proposed in our paper.

To summarize, we start with a conjecture that changes in oil prices may be viewed by market participants as long-term and short-term. A failure to recognize that there are two types of shocks to crude oil prices may be responsible for the observed lags in the response of gasoline prices. We then proceed to empirically test the conjecture of two types of cost shocks and show that it is empirically plausible.

2 Estimating the Response of Gasoline Prices to Oil Price Changes

The analysis of the response of gasoline prices to oil price changes can be done using the error correction model (ECM). This model can be reconfigured as in Johnson (2002) or Borenstein, Gilbert and Cameron (1997) to allow short-run adjustments to differ between crude oil price increases and decreases.

We follow Johnson (2002) and formulate the following model

$$
\begin{aligned}
\triangle R_t &= \sum_{i=0}^{n}(\beta_i^+ \triangle C_{t-i}^+ + \beta_i^- \triangle C_{t-i}^-) + \sum_{i=1}^{n}(\gamma_i^+ \triangle R_{t-i}^+ + \gamma_i^- \triangle R_{t-i}^-) \\
&+ \theta_1 \left[EC_{t-1}^+\right] + \theta_2 \left[EC_{t-1}^-\right] + u_t
\end{aligned}
\tag{1}
$$

where R is the retail price of gasoline per gallon, C is the price of crude oil per gallon, EC is the error correction term, $\triangle C_t = C_t - C_{t-1}$, $\triangle C_t^+ = max\{\triangle C_t, 0\}$, $\triangle C_t^- = min\{\triangle C_t, 0\}$, $EC_t^+ = max\{EC_t, 0\}$, $EC_t^- = min\{EC_t, 0\}$. The variables $\triangle R_t$, $\triangle R_t^+$ and $\triangle R_t^-$ are defined in the same way as $\triangle C_t$, $\triangle C_t^+$ and $\triangle C_t^-$. The error term u_t is assumed to be white noise. The difference in the coefficients β_i^+, β_i^-, γ_i^+, γ_i^- and θ_1 and θ_2 allows an asymmetric response of gasoline prices to changes in crude oil prices and the error correction term.

The error correction term EC_t is computed based on the following long-run equilibrium relationship between the retail gasoline price and the crude oil price

$$
R_t = \phi_0 + \phi_1 C_t + \phi_2 TIME + \epsilon_t
\tag{2}
$$

where ϵ_t is a white noise process. The error correction term in (1) is then defined as $EC_t = R_t - \hat{\phi}_0 - \hat{\phi}_1 C_t - \hat{\phi}_2 TIME$. The error-correction term allows for entry end exit in the market and gradually corrects deviations from a common long-run equilibrium. If prices deviate from the equilibrium values because of incomplete adjustment to past shocks or other market conditions, then the current supply changes should move them back toward the equilibrium. Therefore, we expect that the coefficients of error correction term, θ_1 and θ_2, are negative.

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In the regression model (1) the variables $\triangle C_t^+$ and $\triangle C_t^-$ are treated as endogenous. The model with endogenous variables can be estimated using 2SLS or Limited Information Bayesian Analysis. The instruments that we use to identify the parameters of the model (1) are the associated increase and decrease change variables created from four-month-ahead and three-month-ahead futures prices of crude oil. The four-month-ahead and three-month-ahead futures price of crude oil should be uncorrelated with demand shocks[3].

To compare the response of gasoline prices to crude oil increases and decreases, we construct a cumulative adjustment function. For one-time, one percent[4] increase in the crude oil prices, the cumulative distributed lag adjustment is given by:

$$
\begin{aligned}
B_0^+ &= \beta_0^+ \\[2mm]
B_1^+ &= B_0^+ + \beta_1^+ + \theta_1(B_0 - \phi_1) + \gamma_1^+ max(0, B_0) + \gamma_1^- min(0, B_0) \\[2mm]
B_2^+ &= B_1^+ + \beta_2^+ + \theta_1(B_1 - \phi_1) + \gamma_1^+ max(0, B_1 - B_0) + \gamma_1^- min(0, B_1 - B_0) \\[2mm]
&+ \gamma_2^+ max(0, B_0) + \gamma_2^- min(0, B_0) \\[4mm]
&\qquad . \qquad\qquad . \\[2mm]
&\qquad . \qquad\qquad . \\[4mm]
B_k^+ &= B_{k-1}^+ + \beta_k^+ + \theta_1(B_{k-1} - \phi_1) \\
&+ \sum_{i=1}^{k} \left(\gamma_i^+ max[0, (B_{k-i} - B_{k-i-1})] + \gamma_i^- min[0, (B_{k-i} - B_{k-i-1})] \right)
\end{aligned}
$$

(3)

The cumulative adjustment function for one-time one percent decrease in crude oil prices is constructed in the same way.

However, our interests lie in estimating the effect of long-term and short-term shocks on the gasoline

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[3]We also checked the results using twelve-month-ahead futures prices and six-month-ahead futures prices as instruments. The results seem not to be sensitive to the choice of instruments.

[4]If the variables in the model are in levels and changes of levels, then the change in crude oil is in absolute terms. Since, we primary use the data in logs, the change in crude oil is in percentage terms.

pricing. We have assumed that when the realized shock to crude oil price is viewed as long-term, the speed of adjustment of retail gasoline price is faster than when the realized shock is short-term. To allow a possibility of different speed of adjustment of retail prices to changes in the price of crude oil, we assume that parameters (β_i^+, β_i^-), $i = 0, ..., n$, may take on different values depending on the value of unobserved state variable S. Therefore, our empirical procedure allows us to identify the two regimes ex-post[5].

We suppose that the state variable S takes on two values. The state variable S takes on a value one if the realized shock is viewed as long-term, and S takes on a value two if the realized shock is viewed as short-term.

Pindyck (2001) explains how prices, rates of production and inventory are determined via equilibrium in two interconnected markets: a cash market for spot purchases and sales of the commodity and a market for storage of the commodity. He argues that producers must determine the production levels and inventory levels jointly with the expected inventory drawdowns and buildups. One of the factors that affects production and inventory decisions is the spot price of gasoline. Pindyck (2001) formulates inverse net demand function which stipulates that price of a commodity is a function of a change in inventory level of a commodity, net demand, and some other factors. Based on the arguments of Pindyck (2001), we add change in gasoline inventory levels to the equation (1).

Therefore, the model that we analyze is written as follows:

$$
\begin{aligned}
\triangle R_t &= k_1 + k_2 \triangle J_t + \beta_0^+(S_t)\triangle C_t^+ + \beta_0^-(S_t)\triangle C_t^- + \sum_{i=1}^{n}[\beta_i^+(S_t)\triangle C_{t-i}^+ + \beta_i^-(S_t)\triangle C_{t-i}^-] \\
&+ \sum_{i=1}^{n}(\gamma_i^+ R_{t-i}^+ + \gamma_i^- \triangle R_{t-i}^-) + \theta_1 \left[EC_{t-1}^+\right] + \theta_2 \left[EC_{t-1}^-\right] + u_t
\end{aligned}
\tag{4}
$$

where S_t may take values one and two and J_t denotes the level of gasoline inventory.

Once the model (4) is estimated, we construct four sets of gasoline cumulative responses $\{f_h^{l+}\}_{h=1}^{H}$, $\{f_h^{l-}\}_{h=1}^{H}$, $\{f_h^{s+}\}_{h=1}^{H}$, $\{f_h^{s-}\}_{h=1}^{H}$, where $\{f_h^{l+}\}_{h=1}^{H}$ is the cumulative response of gasoline prices to the

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[5]Noel (2002) analyzes retail pricing patterns in Canadian cities using a Markov switching model but he does not embed it within a error correction model.

long-term increase in crude oil prices and $\{f_h^{s-}\}_{h=1}^H$ is the cumulative response of gasoline price to the short-term decrease in crude oil prices and so on. To test whether cumulative response functions to long-term increases and decreases in crude oil prices are different from those to short-term increases and decreases in crude oil prices we estimate and construct the following two difference functions:

$$
\begin{aligned}
df_h^+ &= f_h^{l+} - f_h^{s+}, \quad h = 1, ..., H \\
df_h^- &= f_h^{l-} - f_h^{s-}, \quad h = 1, ..., H
\end{aligned}
$$

If the confidence intervals around these difference functions do not include zero for some periods h, then our conjecture that there are two types of cost shocks is supported by empirical evidence. Since it means that gasoline prices respond to long-term changes differently than to short-term changes.

The analysis of the model (4) is similar in spirit to the analysis of threshold autoregressive model (TAR) within an error-correction model analysed by Godby et al. (2000). The TAR model can be expressed as follows:

$$
y_t = x_t'\beta_1 + e_t, \ q_t \leq \gamma \tag{5}
$$

$$
y_t = x_t'\beta_2 + e_t, \ q_t > \gamma \tag{6}
$$

where y_t and q_t are observations on the dependent variable and the threshold variable that splits sample into different groups, x_t is a $p \times 1$ vector of independent variables. The TAR model can be written in a single equation form, by defining the dummy variable $d_t(\gamma) = I(q_t \leq \gamma)$, where $I(.)$ denotes an indicator function. Then equations (5) - (6) can be written as:

$$
y_t = x_t'\beta + x_t(\gamma)'\theta + e_t \tag{7}
$$

where $x_t(\gamma) = x_t d_t(\gamma)$, $\beta = \beta_2$ and $\theta = \beta_1 - \beta_2$. The TAR model in (7) is similar to the hidden Markov chain model in (4). However, we believe that the hidden Markov chain model in (4) is more flexible than TAR in (7) for the analysis of gasoline responses to crude oil price changes because we do not

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have to choose a threshold variable. It will be useful to conduct a formal hypothesis testing of a hidden Markov chain formulation of the model against a TAR alternative, but to our knowledge this test has not been developed yet[6].

The analysis of model (4) raises an econometric problem. Model in equation (4) has not only a group of exogenous variables that follow hidden Markov chain but also endogenous variables that follow hidden Markov chain. Therefore our estimation techniques should address both issues: endogeneity of the variables and time-varying parameters of the variables.

We develop Limited Information Bayesian Analysis (LIBA) for estimation of Simultaneous Equations with Hidden Markov chain to estimate model (4). The Bayesian Analysis of Simultaneous Equation Model has advantage in analysis of this problem relative to other econometric methods because it allows a straightforward derivation of standard deviation of the parameters of the model and estimated cumulative responses of gasoline prices to changes in crude oil prices. Since the parameters (β_i^+, β_i^-) in the model are not linear and since cumulative responses of gasoline prices to increase and decrease in oil prices are very non-linear functions of the parameters of the model, the statistical inference using alternative methods is complicated [7]. In the next section we explain how model (4) can be estimated using LIBA of Simultaneous Equation with Hidden Markov chain model.

3   The Econometric Model and Choice of prior distribution

To analyze model (4) we devide variables in the model into three groups of variables. The first group of variables, denoted as C_1, consists of endogenous variables with time-varying parameters that follow Markov chain. The second group of variables, denoted C_2, consists of exogenous variables with time-varying parameters. The third group of variables, denoted X_1, consists of exogenous variables with constant parameters.

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[6]Hansen (2000) suggests a bootstrap procedure in classical framework to test the above null hypothesis of a linear formulation of the model against a TAR alternative.

[7]To our knowledge, there is no analysis of the Simultaneous Equation with Hidden Markov chain model proposed in the classical framework.

Let us explain the econometric model that we formulate and the estimation procedure that we propose for the general model first and then we show how this procedure can be used to analyze the gasoline industry.

Model in (4) can be analyzed using the Limited Information Bayesian Analysis of the Simultaneous Equation Model (SEM) of the following form:

$$y_{1t} = C_{1t}\zeta_1(S_t) + C_{2t}\zeta_2(S_t) + X_{1t}\gamma_1 + u_{1t} \quad t = 1, ..., T \tag{8}$$

$$C_{1t} = C_{2t}\gamma_2 + X_{1t}\gamma_3 + X_{2t}\gamma_4 + V_{1t} \tag{9}$$

where y_{1t} is a 1×1 vector, C_{1t} is a $1 \times m_1$ vector of endogenous variables on the right hand side of the equation of interest, C_{2t} is a $1 \times m_2$ vector of exogenous variables with time-varying parameters, $m = m_1 + m_2$, X_{1t} is $1 \times k_1$ a matrix of exogenous variables, X_{2t} is a $1 \times k_2$ matrix of exogenous variables excluded from the equation of interest. A vector $\zeta_1(S_t)$ is an $m_1 \times 1$ vector and a vector $\zeta_2(S_t)$ is a $m_2 \times 1$, $S_t = 1, ..., q$.

The order condition for identification requires that $k_2 \geq m_1$, which me explicitly make. We also assume that the $rk(\gamma_4) = m_1$, so that the rank condition for identification is satisfied.

We assume that the error term $[u_{1t}, V_{1t}]$ is distributed as $N(0, \Omega)$ and Ω can be partitioned as follows:

$$\Omega = \begin{bmatrix} \sigma_1^2 & \delta' \\ \delta & \Omega_{22} \end{bmatrix} \tag{10}$$

where σ^2 is a scalar, δ is an $m_1 \times 1$ vector, Ω_{22} is a $m_1 \times m_1$ matrix.

The parameters ζ_1 and ζ_2 vary over time and are determined by an unobserved state variable S. The unobserved state takes on a finite number of values $j = 1, ..., q$ and follows a Markov chain with a transition probability matrix P, so that

$$P[S_t = i | S_{t-1} = j] = p_{ij} \tag{11}$$

Since some of the parameters of the simultaneous equation model (8) - (9) follow hidden Markov

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chain, we call this model Simultaneous Equation with Hidden Markov Chain model[8].

In the analysis of the gasoline market we set $y_1 = \triangle R_t$, $C_1 = [\triangle C_t^+, \triangle C_t^-]$, $X_2 = [\triangle F_t^+, \triangle F_t^-]$, $X_1 = [\triangle C_{t-1}^+, ..., \triangle C_{t-n}^+, \triangle C_{t-1}^-, ..., \triangle C_{t-n}^+, \triangle R_{t-1}^+, ..., \triangle R_{t-n}^+, \triangle R_{t-1}^-, ..., \triangle R_{t-n}^+, EC_{t-1}^+, EC_{t-1}^-, \triangle J_t]$, where F_t^+ and F_t^- are the increase and decrease change variables created from four-month-ahead and three-month-ahead futures price of crude oil and which are used as instruments. We assume that there are two regimes in Markov switching model. The oil price change is viewed as long-term by the market participants in regime 1, $S_t = 1$. The oil price change is viewed as short-term in regime 2, $S_t = 2$. We further assume that in the analysis of gasoline pricing there are no exogenous variables with time-varying parameters in model (4) which implies that $C_2 = 0$ and $\zeta_2(S) = 0$, $S = 1, 2$. Note that in the notation of model (4) $\zeta_1(S_t = 1) = [\beta_0^+(S_t = 1), \beta_0^-(S_t = 1)]'$, $\zeta_1(S_t = 2) = [\beta_0^+(S_t = 2), \beta_0^-(S_t = 2)]'$.

3.1 Choice of the prior distribution

To simplify the notation, let $\zeta_1^1 = \zeta_1(S = 1)$ and $\zeta_i^j = \zeta_i(S = j)$, $i = 1, 2$, $j = 1, ..., q$, $\zeta^j = [\zeta_1^{'j}, \zeta_2^{'j}]'$, an $m \times 1$ vector, $\zeta(S) = [\zeta^1, \zeta^2, ..., \zeta^q]$, an $m \times q$ matrix, $\gamma = [\gamma_1, \gamma_2, \gamma_3, \gamma_4]$, $\phi(S) = [\zeta(S), \gamma, \Omega, P]$.

We need to formulate our subjective beliefs about the parameters of the model in form of prior distribution in Bayesian analysis. We assume that parameters of the model are distributed as follows:

$$\pi(\zeta_i^j) = N(\mu_i^j, \tau_i^{2(j)}), \ j = 1, ..., q, \ i = 1, 2 \tag{12}$$

$$\pi(\gamma) \propto c \tag{13}$$

$$\pi(\Omega) \propto |\Omega|^{-\frac{1}{2}(m_1 + 2)} \tag{14}$$

$$\pi(P_{\cdot i}) = D_k(\alpha_1, ..., \alpha_q), \ i = 1, ..., q \tag{15}$$

where $P_{\cdot i}$ denotes column i of a matrix P, D_k denotes Dirichlet distribution with parameters $\alpha_1, ..., \alpha_q$.

We think that it is reasonable to assume that a little information is known about the parameters of the lags of increase and decrease in crude oil prices, gasoline prices and changes in inventory level.

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[8]The Limited Information Bayesian analysis of a SEM with white noise error term and with an autocorrelated error term was developed by Radchenko and Tsurumi (2002).

Economic theory suggests that the parameter on error correction term θ_1, θ_2 should be negative. This belief can be incorporated into the construction of prior but we have decided to leave the sign of θ_1 and θ_2 unrestricted. We use the estimated sign of θ_1, θ_2 as an indirect check of plausibility of the estimated results. Therefore, we assume a diffuse prior in (13) for the parameters γ. Diffuse prior is commonly assumed to represent a high level of uncertainty about the parameters.

We also assume that no prior information is available about the variance-covariance matrix of the model. As a result, we specify diffuse prior in (14) as a prior for the variance-covariance matrix.

We assume a proper prior for the parameters ζ_i^j, $j = 1, ..., q$ and $i = 1, 2$. There are several reasons for doing that. For identification of the parameters we need to formulate a prior density with an explicit assumption that $\zeta_i^j > \zeta_i^{(j+1)}$, $j = 1, ..., q-1, i = 1, 2$. We set prior parameters $\mu_i^j, j = 1, ..., q, i = 1, 2$ such that $\mu_i^j > \mu_i^{(j+1)}$ for all j.

Another reason for the use of proper prior is that this prior can incorporate the prior belief about the possibility of two types of oil price shocks. When the realized shock to crude oil price is viewed as long-term, we expect that the speed of adjustment of gasoline prices is faster than when the realized shock is short-term. Therefore, we have the following prior expectations:

$$\beta_0^{1+} > \beta_0^{2+} \tag{16}$$

$$\beta_0^{1-} > \beta_0^{2-} \tag{17}$$

Recall that $\zeta_1^j = [\beta_0^{j+}, \beta_0^{j-}]'$, $j = 1, 2$. Thus, setting $\zeta_i^j > \zeta_i^{(j+1)}$ not only insures identification of the model parameters but also incorporates the prior beliefs about the speed of adjustment of gasoline prices in (16) - (17).

When we use logs of the variables, we set $\mu_1^{1+} = \mu_1^{1-} = 0.9$, which reflects our beliefs that when a realized shock is believed to be long-term, the adjustment of gasoline prices to changes in crude oil prices is almost immediate and symmetric. We set $\mu_1^{2+} = \mu_1^{2-} = 0.7$ which reflects the idea that when a realized shock is believed to be short-term, the adjustment of gasoline prices is not immediate but still symmetric. Note that we could introduce asymmetric responses in the prior distribution of ζ_i^j, $j = 1, 2$ and $i = 1, 2$, by relaxing an assumption that $\mu_1^{j+} = \mu_1^{j-}$.

To formulate a prior for a transition matrix P, we need to set values of hyperparameters of Dirichlet distribution $\alpha_1, ..., \alpha_q$. To make a prior uninformative we set $\alpha_1 = \alpha_2 = ... = \alpha_q$.

We further assume that all the parameters in model (8) - (9) are conditionally independent so that

$$\pi(\phi(S)) = \pi(\zeta(S))\pi(\gamma)\pi(\Omega)\pi(P) \tag{18}$$

where $\pi(\zeta(S)) = \prod_{j=1}^{q} \prod_{i=1}^{2} \pi(\zeta_i^j)$

The estimation of the model using Limited Information Bayesian Analysis is presented in Appendix A.

4   Data and Results

Data on gasoline inventory, spot and retail gasoline prices and crude oil price have been obtained from US Department of Energy [9]. The data sets include daily and weekly observations on regular gasoline prices, West Texas Intermediate crude oil prices, and four-month-ahead and three-month-ahead futures prices of oil for the time period from March 1991 to February 2003, the time period for which weekly data are available from the US Department of Energy. The Department's US average weekly retail gasoline prices are for Monday of each week, [10] while the average weekly gasoline inventory level is for Thursday of each week.

Retail prices include taxes which potentially may raise a problem if there were any significant gasoline tax changes over the time period of the analysis. We have checked the state average gasoline taxes and find no significant changes in state average taxes[11]. Federal tax rates on gasoline increased from 14.1 cents per gallon to 18.4 cents per gallon on October 1, 1993[12]. To check whether this increase has any

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[9]The data can be accessed on Internet via the link http://www.eia.doe.gov/neic/historic/hpetroleum2.htm#Gasoline.

[10]Johnson (2002) used the data of US Department of Energy and the data for 15 cities obtained from private vendors to analyze the long lags in response of gasoline and diesel. He finds that the results for separate cities and for the data from US Department of Energy are very similar. Peltzman (2000) uses monthly national averages from Bureau of Labor Statistics in the analysis of asymmetric response.

[11]One may check state motor-fuel tax rates at the following webpage http://www.fhwa.dot.gov/ohim/hs00/mf205.htm.

[12]One may check federal tax rates on motor fuels at the following webpage

significant effect on the parameter estimates we have included a dummy variable into our regression model. The dummy variable takes on a value zero before October 1, 1993 and a value one otherwise. The dummy variable turned out to be insignificant and we omit it from the model estimation. The inflation rate for the period from March 1991 to August 2002 was quite low, ranging from 1.54 % to 3.58 % and the estimated results should not be effected by the problem of inflation.

The model estimation was performed using logs and changes in logs, implying a simple percent mark-up rule for margins. This, in turn, implies that crude-gasoline margins increase with the price of crude oil. To test the robustness of our estimates to a change in functional form[13], we also estimated the model using levels and changes in levels of the variables. The results using levels and changes in levels of the variables are similar to the results using logs and changes in logs of the variables. Therefore, we present only the results using logs of the variables.

We analyze the transmission of crude oil shocks and shocks in spot prices to retail gasoline prices. In the first model, denoted Retail Gasoline - Crude Oil, we estimate the responses of retail gasoline prices to changes in crude oil prices. In the second model, denoted Retail Gasoline - Spot Gasoline, the responses of retail gasoline prices to changes in spot gasoline prices.

Because the long-run effect of 1% change differs across different models, we follow Johnson (2002) and divide cumulative response function by corresponding ϕ_1 from equation (2). Therefore, the cumulative adjustment functions reported are proportional measures and are expected to approach unity over time.

We use 10000 replications in MCMC algorithm. We discard first 2000 draws of the chain and use the remaining 8000 observation to find posterior means of the parameters, highest posterior density intervals (HPDI) of the parameters and other quantities of interest. Based on the draws of the model parameters we construct different cumulative response functions of gasoline prices and estimate confidence intervals around them.

Note also that we use four instruments in the model while there are only two endogenous variables.

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http://www.fhwa.dot.gov/ohim/hs00/fe101a.htm.

[13]Borenstein, Cameron and Gilbert (1997) and Johnson (2002) argue that a use of data in levels in estimation of long-run equilibrium relationship between crude oil and gasoline price is more appropriate.

Therefore, the model is overidentified of order two and the posterior mean of the parameters should be finite [14]. Based on the AIC, we set lag length on lags of crude oil price and own lags of gasoline in model (4) equal to two.

In all the cases, the coefficients on the error correction term, θ_1 and θ_2, were negative as is required for stability and significant. This may serve as an indirect evidence that the estimated results are plausible. The coefficients θ_1, θ_2 are small suggesting sluggish response to long-run equilibrium deviations. To check whether the small estimates of parameters θ_1, θ_2 are a consequence of the hidden Markov chain model, we estimate the linear model of Borenstein et al. (1997) and TAR of Godby et al. (2000) and find similar estimates of θ_1 and θ_2. In linear model the estimates are -0.042 (0.013) and -0.063 (0.015) for θ_1 and θ_2 respectively while in TAR these estimates are -0.047 (0.010) and -0.066 (0.012). This leads us to conclude that small estimates of θ_1, θ_2 are not specific to our model but may be a result of high frequency data that we use. We would also like to point out that small estimates of the effect of error correction term, deviations from the long-run equilibrium, do not imply the small response of gasoline prices to long-term crude oil price changes. The deviations from the long-run equilibrium capture the incomplete adjustment of gasoline prices to past shocks while long-term shocks to crude oil imply that current changes in crude oil prices are expected to persist indefinitely. As such, long-term crude oil price shocks and the error correction term measure different phenomena.

The estimates of the parameters of the contemporaneous effect of crude oil prices are all positive and significant as is expected. We expect that the estimate of the inventory parameter is negative. In his examination of inventories and prices, Pindyck (2001) shows that there is a negative relationship between the inventory level of a commodity and the price when the shock to the market is temporary (Figure 5 in Pindyck (2001)). In contrast, when the shock to the market is permanent (long-term), the price of a commodity may change without affecting the level of inventory initially. As the market moves to the new equilibrium, there is a negative relationship between the price of a commodity and the inventory level (Figure 6 in Pindyck (2001)). Therefore, we expect to find a negative relationship

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[14]Chao and Phillips (1998), Chao and Phillips (2002) analyze the properties of the posterior densities of the parameters for the analysis of SEM using diffuse and Jeffreys prior analysis.

between a change in inventory and a change in the retail price of gasoline. The estimate of the inventory parameter in Table 4 is negative and significant which confirms our expectations. The similar result of the inventory effect was obtained by Radchenko and Tsurumi (2002).

To have a sense of how our model performs we measure the quality of regime classification using the regime classification measure (RCM) proposed proposed by Ang and Bekaert (2002), defined for two states as:

$$RCM = 400 \times \frac{1}{T} \sum_{t=1}^{T} p_t (1 - p_t) \qquad (19)$$

where p_t is the estimated probability to be in state one at period t. This statistic is between 0 and 100. Good regime classification is associated with low RCM values. In particular, a value of 0 means perfect regime classification and a value of 100 implies that no information about the regime is revealed. The RCM values for two models that we analyze are presented in Table 1. As one can see the regime classification is quite good suggesting a presence of two different types of shocks from crude oil prices and spot gasoline prices to retail gasoline prices. We have checked R^2, the in-sample measure of model performance, for the hidden Markov chain model, the linear model of Borenstein et al. (1997) and the TAR model of Godby et al. (2000). The coefficient of determination R^2 is 0.58 for the linear model, 0.57 for the TAR model and 0.68 for the hidden Markov chain model. Therefore, based on the coefficient of determination one can see that the hidden Markov chain model compares favorably to other alternatives. Unfortunately, since estimation of our model in Bayesian framework is computationally expensive we can not compare root mean squared forecast error, the out-of-sample performance, of hidden Markov chain model relative to the linear model and the TAR model.

We present the estimates of the transition probabilities in Table 2. The estimated transition probabilities confirm our expectations that long-term shocks are not persistent while transitory shocks are persistent. The probability to have a long-term shock in two consecutive periods is 0.20 while the probability of a short-term shock in two consecutive periods is 0.94. We present the filtered and smoothed probabilities that a shock from the crude oil price to the retail gasoline price in Figure 2(a) - (b). One

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can see that most of the long-term shocks from crude oil prices to retail gasoline prices occurred since the Winter of 1998, the period of high volatility in gasoline prices and increased cooperation among OPEC members. The fact that majority of long-term shocks occurred in the end of the time period is not surprising and confirms our expectations from the levels of retail gasoline prices and crude oil prices in Figure 1. We present the estimates of periods with long-term shocks and the corresponding description of oil relevant events and production behaviour in Table 3. A short description of the oil related events is based on the papers by Adelman (2002) and Kohl (2002) and the world oil price chronology published by the Energy Information Administration [15].

The results on the estimates of the long-term shocks are interesting and may give some insights about the effectiveness and credibility of OPEC oil production policy. There were several attempts of OPEC to increase oil prices in 1998. OPEC and several non-OPEC countries reached an agreement in March 1998 on a production decrease of 1.245 million barrels/day and an additional 1.36 million barrels/day in June. Our estimates of long-term shock probabilities in Figure 2 suggest that these agreements were not viewed as credible, persist for a long period of time, by the market. The probability that changes in oil prices were long-term is low in 1998 indicating that market participants did not believe in long-term devotion to cut oil production by OPEC members. This is verified by Kohl (2002) who indicates that the compliance of these agreements was shaky and Iraq, China and Russia have increased the production in 1998. In March 1999, a new agreement between OPEC and several non-OPEC countries was reached. The compliance of this agreement was strong and we may conclude from Figure 2 that market participants did view the increased cooperation among OPEC countries to increase oil prices as credible and long-term. It is interesting to note that our estimates indicate that market participants did not trust the ability of OPEC members to increase production after September 2000 meeting of OPEC. This result coincides with Kohl (2002) who points out that the market participants were concerned about OPEC's lack of spare capacity at that period of time. It is also interesting to note that the estimated long-term shocks are all price increases and there is no a single period with long-term oil

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[15]The webpage for the chronology of the Energy Information Administration is http://eia.doe.gov/emeu/cabs/chron.html.

price decrease.

The cumulative response functions of retail gasoline price to changes in crude oil price are presented in Figure 3. Figure 3(a) depicts the response of retail gasoline price to long-term crude oil shocks, Figure 3(b) depicts the response of retail gasoline prices to short-term crude oil shocks and Figure 3(c) depicts the cumulative response of retail price to changes in crude oil prices from the linear model of Borenstein et al. (1997). We can see from Figure 3(a) - (b) that dynamics of the gasoline response to short-term crude oil shocks in hidden Markov chain model looks similar to the dynamics of the gasoline response from the linear model in which all oil price changes are long-term. This can be explained by the fact that 97% of oil prices in hidden Markov chain model are indeed short-term and only 3% are long-term.

Each time period on a graph of the cumulative gasoline response denotes one week. For example, the results at first period in panel (a) of Figure 3(a) say that a 1 % increase in the price of crude oil leads proportionally to 1.5 % increase in retail gasoline prices in the first week if a crude oil price change is viewed as long-term. At the same time, a 1 % decrease in the price of crude oil leads to proportionally 0.3 % decrease in retail gasoline price in the first week if a crude oil price change is viewed as long-term.

The adjustment of retail gasoline prices is completed withing a week for the long-term oil price increase and within five weeks for the long-term oil price decrease. The results in Figure 3 confirm long lags in the response of retail gasoline prices occur if changes in crude oil prices are viewed as short-term. For short-term crude oil price increases and decreases the adjustment of retail gasoline prices is completed in approximately twenty weeks. This can be seen in Figure 3(a) - (b). More than that, the retail gasoline price overadjusts to a long-term increase in the crude oil price. By the end of the fifth week, the retail gasoline prices increase by 2.5% as a result of 1% long-term increase in the crude price. This increase is more than two times as high as is expected in the long-run. The cumulative response function peaks after five-six weeks, 2.5%, and then gradually decreases to 1%. When the crude oil shocks are viewed as short-term the retail gasoline price increase only 0.7% in five weeks since short-term oil increase and 0.8% in seven weeks since long-term oil increase.

The difference in response of retail gasoline price to changes in crude oil prices is statistically sig-

nificant. This can be seen from the graph presented in Figure 4. Figure 4(a) presents the difference between the cumulative response of retail gasoline prices to long-term and short-term increases. Figure 4(b) depicts the difference in the gasoline response to long-term and short-term decreases in crude oil prices. The confidence interval in Figure 4(a) does not contain zero for the first fourteen weeks after the crude oil price increase. This means that there is statistically significant difference in the response of gasoline prices to long-term and short-term crude oil price increases. However, the situation is different for the long-term and short-term decreases in crude oil price. The confidence interval in Figure 4(b) contains zero which means that there is no difference in the response of retail gasoline prices to long-term and short-term crude oil prices decreases.

As expected the response of gasoline prices to long-term and short-term changes in crude oil prices is the same in the long-run. The cumulative adjustment functions of gasoline prices converge to unity because of the presence of error correction terms, EC^+ and EC^-, which push gasoline prices to long-run equilibrium. According to our model, the error correction terms have the same effect for both long-term and short-term changes in crude oil prices. We have estimated the model in which the coefficients of error correction terms, θ_1 and θ_2, depend on the unobserved state variable S_t so that the effect of error correction terms may be different across long-term and short-term shocks. The cumulative adjustment functions of gasoline prices for this model are similar to presented adjustment functions and we do not report them. Another alternative is to allow the long-run equilibrium relation between retail gasoline prices and crude oil prices be different for long-term and short-term crude oil price changes. In this case, the parameters in equation (2) depend on the unobserved state variable S_t and one should estimate simultaneously equations (2) and (4). Because of econometric issues[16], we leave the investigation of this possibility for future research.

In the next step, we test the relationship between retail gasoline prices and spot gasoline prices. The results are presented in Table 6 and Figure 6. The estimates of transition probability matrix are presented in Table 5 which are similar to the estimates of transition probability matrix in Table 2.

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[16]We can no longer use the limited information Bayesian analysis to estimate equations (2) - (4).

Overall, the results for Retail Gasoline - Spot Gasoline model are similar to the results for Retail Gasoline - Crude Oil model. One can observe a relatively fast adjustment of gasoline prices to long-term changes in spot gasoline prices. The response of gasoline prices to long-term increases in spot gasoline prices is completed within two weeks while the response of retail prices to long-term decrease in spot prices is completed within five weeks. The response of retail prices to short-term increases and decreases in spot prices is completed in twenty weeks.

The policy implication of the finding that there are two regimes in the response of retail gasoline prices to crude oil prices is that theoretical models should be developed that allow more than one type of input price changes and the different effect of input prices changes on output prices.

5   Concluding Remarks

In the paper we have empirically investigated the question of lags in the response of gasoline prices to changes in crude oil prices and how they can be explained by the possibility of nonlinearities in gasoline and oil prices. We have conjectured that lags in the response of gasoline prices to crude oil price shocks may be a result of the existence of two types of oil shocks, long-term and short-term. We have posited that when the oil shock is viewed by the market as long-term, gasoline prices should adjust without lags. In contrast, when the oil shock is short-term gasoline prices should adjust with a lag.

To conduct the empirical estimates, we developed the Metropolis-Hasting algorithm to estimate a simultaneous equation model with hidden Markov Chain, which may be used in future microeconomic applications. The empirical results confirm that there are two types of crude oil shocks and that lags in the response of gasoline prices are a result of short-term shocks to crude oil prices. We have shown that if changes in crude oil prices are viewed as long-term retail gasoline prices adjust much faster than when changes in crude oil prices are short-term. There is a big difference between the cumulative response function of gasoline prices to long-term and short-term shocks to crude oil prices.

Long lags in the response of retail gasoline prices to changes in crude oil prices or spot gasoline prices found by previous researchers using linear model may be due to the fact that estimated 97% of changes

in crude oil prices are viewed as short-term and only 3% of changes are long-term.

Appendix A: estimation of Simultaneous Equation with Hidden Markov Chain Model

In the appendix we explain how one can conduct a Limited information Bayesian analysis of a Simultaneous Equation with hidden Markov chain model:

$$y_{1t} = C_{1t}\zeta_1(S_t) + C_{2t}\zeta_2(S_t) + X_{1t}\gamma_1 + u_{1t} \quad t = 1, ..., T \tag{A-1}$$

$$C_{1t} = C_{2t}\gamma_2 + X_{1t}\gamma_3 + X_{2t}\gamma_4 + V_{1t} \tag{A-2}$$

where the error term $[u_{1t}, V_{1t}]$ is distributed as $N(0, \Omega)$ and Ω is partitioned as follows:

$$\Omega = \begin{bmatrix} \sigma_1^2 & \delta' \\ \delta & \Omega_{22} \end{bmatrix} \tag{A-3}$$

where σ^2 is a scalar, δ is an $m_1 \times 1$ vector, Ω_{22} is a $m_1 \times m_1$ matrix.

The analysis of the model is done using Markov Chain Monte Carlo (MCMC) approaches, Metropolis-Hastings (MH) algorithm and Gibbs sampling where appropriate.

We follow Chib (1996) and Kim and Nelson (1998) and analyze the model (A-1) - (A-2) treating the chain of state variable $\{S_t\}_{t=1}^T$ as an unknown parameter and simulate it along side the other parameters.

Given a transition matrix P and a chain of state variables $\{S_t\}_{t=1}^T$, the posterior density function for the model (A-1) - (A-2) can be written as

$$f(\phi(S)|d) \propto \pi(\zeta(S))|\Omega|^{-\frac{T+m_1+2}{2}} exptr\left[-\frac{1}{2}(W - Z\Pi)'(W - Z\Pi)\Omega^{-1} \right] \tag{A-4}$$

where $\phi(S) = (\zeta(S), \Pi, \sigma_1^2, \delta, \Omega_{22})$, $W = [y_1 - \sum_{j=1}^q A^j C\zeta^j, C_1]$, $C = [C_1, C_2]$, $\zeta^j = [\zeta_1^{j'}, \zeta_2^{j'}]'$, $Z = [C_2, X_1, X_2]$, $exptr(A) = exp(trace(A))$, A^j is a $T \times T$ diagonal matrix such that $A_{tt}^j = 1$ if $S_t = j$, $t = 1, ..., T$, and all other elements of A^j are zeros; Π is defined as follows:

$$\Pi = \begin{bmatrix} \Pi_1 & \Pi_2 \end{bmatrix} = \begin{bmatrix} 0 & \gamma_2 \\ \gamma_1 & \gamma_3 \\ 0 & \gamma_4 \end{bmatrix} \tag{A-5}$$

Using a well-known decomposition

$$\Omega^{-1} = \begin{bmatrix} 1 & 0 \\ -\Omega_{22}^{-1}\delta & I_{m_1} \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_1^{-2} & 0 \\ 0 & \Omega_{22}^{-1} \end{bmatrix} \begin{bmatrix} 1 & -\delta'\Omega_{22}^{-1} \\ 0 & I_{m_1} \end{bmatrix} \tag{A-6}$$

where

$$\tilde{\sigma}_1^2 = \sigma_1^2(1 - \rho^2) \tag{A-7}$$

Using the decomposition in (A-6), the posterior density function (A-4) can be transformed into

$$
\begin{aligned}
f(\tilde{\phi}(S)|d) \quad \propto \quad & |J|\pi(\zeta(S))(\tilde{\sigma}_1^2)^{-\frac{T+m_1+2}{2}}|\Omega_{22}|^{-\frac{T+m_1+2}{2}} exptr\left(-\frac{1}{2}(C_1 - Z\Pi_2)'(C_1 - Z\Pi_2)\Omega_{22}^{-1}\right) \\
\times \quad & exp\left(-\frac{1}{2\tilde{\sigma}_1^2}(y_1 - \sum_{j=1}^{q} A^j C\zeta^j - X_1\gamma_1 - V_1\theta)'(y_1 - \sum_{j=1}^{q} A^j C\zeta^j - X_1\gamma_1 - V_1\theta)\right) \text{(A-8)}
\end{aligned}
$$

where $\tilde{\phi}(S) = (\zeta(S), \Pi, \tilde{\sigma}_1^2, \theta, \Omega_{22})$, $\theta = \Omega_{22}^{-1}\delta$, J is Jacobian of transformation from the parameters $\phi(S)$ to $\tilde{\phi}(S)$.

To transform the parameters $\phi(S)$ into the parameters $\tilde{\phi}(S)$, we need to compute Jacobian of transformation in (A-8). The relevant part in transformation is transformation of parameters from (σ_1^2, δ) into the parameters $(\tilde{\sigma}_1^2, \theta)$, which gives the Jacobian of transformation $|\Omega_{22}|$.

The posterior density in (A-8) can be analyzed using the MCMC algorithms to draw the parameters of the model from (A-8). However, to derive the posterior density in (A-8) we have assumed that a transition matrix P and a chain of state variables $\{S_t\}_{t=1}^{T}$ are given. Therefore, the analysis of the model (A-1)-(A-2) using MCMC algorithm consists of several steps:

- Find filtered and smoothed distribution for the states $\{S_t\}_{t=1}^{T}$. Make a draw of the chain $\{S_t\}_{t=1}^{T}$ using smoothed distributions

- Make a draw of the parameters γ_1, θ

- Make a draw of the parameters ζ_i^j, $i = 1, 2$ and $j = 1, ..., q$.

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- Make a draw of the parameters $\tilde{\sigma}_1^2$, Π_2, Ω_{22}

- Make a draw of the transition matrix P

Suppose that we are given a draw of the parameters $\tilde{\phi}^i(S) = (\{S_t^i\}_t, \zeta^i(S), \gamma^i, \theta^i, \Pi_2^i, P^i, \Omega_{22}^i, \tilde{\sigma}_1^{2(i)})$.
We need to make a draw of the parameters $\tilde{\phi}^{i+1}$.

5.1 Draw of the states $\{S_t\}_{t=1}^T$

Suppose we are given a draw of parameters of the model $(\phi(S), P)$ and suppose that we are given
$p(S_t|Y_t, \phi(S), P) = p(S_t|Y_t, \cdot)$, the probability density function of S_t given data, Y_t, up to period t and
P. We will use a forward recursion to find a filtered estimate of $p(S_{t+1}|Y_{t+1}, \phi(S), P)$ first, and then we
use a backward recursion to find a smoothed estimate $p(S_{t+1}|Y_T, \phi(S), P)$.

We use the following observation:

$$f(y_{t+1}, S_{t+1} = i, S_t = j|Y_t, \cdot) = p(S_t = j|Y_t, \cdot) \times p(S_{t+1} = i|S_t = j) \times f(y_{t+1}|Y_t, \phi(S_t = j), \cdot) \quad \text{(A-9)}$$

Since we have assumed that $p(S_t = j|Y_t, \cdot)$ and P are given, we can compute the expression in (A-9).
But then we can compute

$$p(y_{t+1}|Y_t, \phi(S), P) = \sum_{i=1}^{q}\sum_{j=1}^{q} f(y_{t+1}, S_{t+1} = i, S_t = j|Y_t, \cdot) \quad \text{(A-10)}$$

$$p(S_{t+1} = j|Y_{t+1}, \phi(S), P) = \frac{\sum_{j=1}^{q} p(y_{t+1}, S_{t+1}, S_t = j|Y_t, \cdot)}{p(y_{t+1}|Y_t, \cdot)} \quad \text{(A-11)}$$

To start the recursions we need an unconditional distribution of S_1, $p(S_1)$. We follow the suggestion
of Sims and find it as the right eigenvector of P associated with its unit eigenvector:

$$P\bar{p} = \bar{p} \quad \text{(A-12)}$$

To start the backward recursions for computation of the smoothed distribution of states, we assume
that we have computed the filtered distribution of states $\{p(S_t|Y_t)\}_{t=1}^T$. We want to find the distribution
$p(S_t|Y_T)$. This can be done using the following recursions

$$p(S_{t+1} = i, S_t = j|Y_T, \cdot) \quad = \quad p(S_{t+1} = i|Y_T, \cdot) \times p(S_t = j|S_{t+1} = j, Y_T, \cdot) \tag{A-13}$$

$$= \quad p(S_{t+1} = i|Y_T)\frac{p(S_{t+1} = i|S_t = j)p(S_t = j|Y_t)}{\sum_j p(S_{t+1} = i|S_t = j)p(S_t = j|Y_t)}$$

where we use the fact that $P(S_t = j|S_{t+1} = i, Y_T, \cdot) = p(S_t = j|S_{t+1} = i, Y_t, \cdot)$.

The smoothed distribution $p(S_t|Y_T)$ then is found as

$$p(S_t|Y_T) = \sum_{i=1}^{q} p(S_{t+1} = i, S_t = j|Y_T) \tag{A-14}$$

To start the backward recursions for smoothed probabilities we use the filtered distribution for the final period $p(S_T|Y_T)$.

We draw the chain $\{S_t\}_{t=1}^{T}$ from the computed smoothed distributions $\{p(S_t|Y_T)\}_{t=1}^{T}$.

5.2 Draw of the parameters ζ^j

Given the parameters $(\{S_t^{i+1}\}_t, \gamma^i, \theta^i, \Pi_2^i, P^i, \Omega_{22}^i, \tilde{\sigma}_1^{2(i)})$ and the residuals V_1^i, the posterior function becomes

$$
\begin{aligned}
f(\tilde{\phi}(S)|d) \quad &\propto \quad \pi(\zeta(S)) \prod_{j=1}^{q} (\tilde{\sigma}_1^2)^{-\frac{T+m_1+2}{2}} exp\left(-\frac{1}{2\tilde{\sigma}_1^2}(\tilde{y}_1^j - \tilde{C}^j\zeta^j)'(\tilde{y}_1^j - \tilde{C}^j\zeta^j)\right) \\
&\propto \quad (\tilde{\sigma}_1^2)^{-\frac{T+m_1+2}{2}} \prod_{j=1}^{q} exp\left(-\frac{1}{2\tilde{\sigma}_1^2}[(\tilde{y}_1^j - \tilde{C}^j\zeta^j)'(\tilde{y}_1^j - \tilde{C}^j\zeta^j)]\right) \\
&\times \quad \prod_{j=1}^{q} (\tau_j^2)^{-\frac{m}{2}} exp\left(-\frac{1}{2\tau^{2(j)}}[(\zeta^j - \mu^j)'(\zeta^j - \mu^j)]\right) \\
&\propto \quad (\tilde{\sigma}_1^2)^{-\frac{n}{2}} \prod_{j=1}^{q} exp\left(-\frac{1}{2}(\zeta^j - \tilde{\zeta}^j)\tilde{\Sigma}^{-1(j)}(\zeta^j - \tilde{\zeta}^j)\right)
\end{aligned}
\tag{A-15}
$$

where $\tilde{y}_1^j = A^j(y_1 - X_1\gamma - V_1\theta)$ and $C^j = A^jC$, where A^j is a $T \times T$ diagonal matrix such that $A_{tt}^j = 1$ if $S_t = j$ and $t = 1, ..., T$. The parameters $\tilde{\zeta}^j$ and $\tilde{\Sigma}^j$ are defined as follows

$$\tilde{\zeta}^j = (\tilde{\sigma}_1^{-2}(\tilde{C}'^j\tilde{C}^j) + \tau^{-2(j)}I_{m_1})^{-1}(\tilde{\sigma}_1^{-2}(\tilde{C}'^j\tilde{C}^j)\hat{\zeta}^j + \tau^{-2(j)}I_{m_1}\mu^j) \quad j = 1, .., q$$

$$\tilde{\Sigma}^j = (\tilde{\sigma}_1^{-2}(\tilde{C}'^j\tilde{C}^j) + \tau^{-2(j)}I_{m_1})^{-1} \quad j = 1, .., q$$

where $\hat{\zeta}^j = (\tilde{C}^{j'}\tilde{C}^j)^{-1}\tilde{C}^{j'}\tilde{y}_1^j$.

Then the conditional distribution of ζ^j is as follows:

$$f(\zeta^j|\cdot) = N(\tilde{\zeta}^j, \tilde{\Sigma}^{(j)}) \tag{A-16}$$

5.3   Draw of the parameters γ_1 and θ

Given the parameters $(\{S_t^{i+1}\}_t, \zeta^{(i+1)}(S), \Pi_2^i, P^i, \Omega_{22}^i, \tilde{\sigma}_1^{2(i)})$ and the residuals V_1^i, the posterior function becomes

$$\begin{aligned} f(\tilde{\phi}(S)|d) &\propto (\tilde{\sigma}_1^{2(i)})^{-\frac{T+m_1+2}{2}} exp\left(-\frac{1}{2\tilde{\sigma}_1^{2(i)}}(\bar{y}_1 - \bar{Z}\xi)'(\bar{y}_1 - \bar{Z}\xi)\right) \\ &\propto (\tilde{\sigma}_1^{2(i)})^{-\frac{T+m_1+2}{2}} exp\left(-\frac{1}{2\tilde{\sigma}_1^2}[\bar{s}^2 + (\hat{\xi} - \xi)'\bar{Z}'\bar{Z}(\hat{\xi} - \xi)]\right) \end{aligned}$$

where $\bar{y}_1 = y_1 - \sum_{j=1}^q A^j C\zeta^j$, $\bar{Z} = [X_1, V^i]$, $\xi = [\gamma_1, \theta]$, $\bar{s}^2 = (\bar{y}_1 - \bar{Z}\hat{\xi})'(\bar{y}_1 - \bar{Z}\hat{\xi})$, $\hat{\xi} = (\bar{Z}'\bar{Z})^{-1}\bar{Z}'\bar{y}_1$.

Then the conditional distribution of ξ is as follows

$$f(\xi|\cdot) = N(\hat{\xi}, \tilde{\sigma}_1^{2(i)}(\bar{Z}'\bar{Z})^{-1}) \tag{A-17}$$

5.4   Draw of the parameter $\tilde{\sigma}_1^2$

Given the parameters $(\gamma^{i+1}, , \theta^{i+1}, \zeta^{i+1}(S), \{S_t^{i+1}\}_t, \Pi_2^i, P^i, \Omega_{22}^i)$ and the residuals V_1^i, the posterior function becomes

$$f(\tilde{\phi}(S)|d \propto (\tilde{\sigma}_1^2)^{-\frac{T+m_1+2}{2}} exp\left(-\frac{1}{2\tilde{\sigma}_1^2}s^2\right)$$

where $s^2 = (y_1 - \sum_{j=1}^{q} A^j C \zeta^j - X_1 \gamma_1^{i+1} - V_1^i \theta^{i+1})'(y_1 - \sum_{j=1}^{q} A^j C \zeta^j - X_1 \gamma_1^{i+1} - V_1 \theta^{i+1})$.

Then the conditional distribution of $\tilde{\sigma}_1^2$ is as follows:

$$f(\beta_j|\cdot) = IW(s^2, T + m_1 + 1) \tag{A-18}$$

5.5 Draw of the parameters Π_2

Given the parameters $(\tilde{\sigma}_1^{2(i+1)}, \gamma^{i+1}, \theta^{i+1}, \zeta^{i+1}(S), \{S_t^{i+1}\}_t, P^i, \Omega_{22}^i)$ and the residuals V_1^i, the posterior function becomes

$$
\begin{aligned}
f(\tilde{\phi}(S)|d) \quad &\propto \quad |\Omega_{22}|^{-\frac{T+m_1+2}{2}(i)} exptr\left(-\frac{1}{2}(C_1 - Z\Pi_2)(C_1 - Z\Pi_2)'\Omega_{22}^{-1}\right) \tag{A-19} \\
&\propto \quad |\Omega_{22}|^{-\frac{T+m_1+2}{2}(i)} exptr\left(-\frac{1}{2}[SSR * \Omega^{-1(i)} + (\hat{\Pi}_2 - \Pi_2)Z'Z(\hat{\Pi}_2 - \Pi_2)\Omega_{22}^{-1(i)}\right)
\end{aligned}
$$

where $SSR = (C_1 - Z\hat{\Pi}_2)(C_1 - Z\hat{\Pi}_2)'$, $\hat{\Pi}_2 = (Z'Z)^{-1}Z'C_1$.

The conditional distribution of Π_2 is as follows:

$$f(vec(\Pi_2)|\cdot) = N(vec(\hat{\Pi}_2), \Omega_{22}^i \otimes (Z'Z)^{-1}) \tag{A-20}$$

Once we generate a draw Π_2^{i+1} we update residuals $V_1^{i+1} = C_1 - X\Pi_2^{i+1}$.

5.6 Draw of the parameters Ω_{22}

Given the parameters $(\Pi_2^{i+1}, \tilde{\sigma}_1^{2(i+1)}, \gamma^{i+1}, \theta^{i+1}, \zeta^{i+1}(S), \{S_t^{i+1}\}_t, P^i)$ and the residuals V_1^i, the posterior function becomes

$$
\begin{aligned}
f(\tilde{\phi}(S)|d) \quad &\propto \quad |\Omega_{22}|^{-\frac{T+m_1+2}{2}} exptr\left(-\frac{1}{2}(C_1 - X\Pi_2^{i+1})(C_1 - X\Pi_2^{i+1})'\Omega_{22}^{-1}\right) \\
&\propto \quad |\Omega_{22}|^{-\frac{T+m_1+2}{2}}(exptr\left(-\frac{1}{2}[SSR^{i+1}\Omega_{22}^{-1}\right) \tag{A-21}
\end{aligned}
$$

where $SSR^{i+1} = (C_1 - X\Pi_2^{i+1})(C_1 - X\Pi_2^{i+1})'$.

The conditional distribution of Ω_{22} is as follows:

$$f(\Omega_{22}|\cdot) = IW(SSR^{i+1}, T+1) \tag{A-22}$$

5.7 Draw of the parameters P

Given the parameters $(\Omega_{22}^{i+1}, \Pi_2^{i+1}, \tilde{\sigma}_1^{2(i+1)}, \gamma^{i+1}, \theta^{i+1}, \beta^{i+1}(S), \{S_t^{i+1}\}_t)$ and the residuals V_1^i, the posterior density becomes

$$f(\tilde{\phi}(S)|\cdot) \propto p(S_1) \prod_{i=1}^{q} \prod_{j=1}^{q} p_{ij}^{n(i,j)} \tag{A-23}$$

where $n(i,j)$ is the number of dates t, $2 \geq t \geq T$, at which $S_{t-1} = i$ and $S_t = j$. The expression $\prod_{i=1}^{q} \prod_{j=1}^{q} h_{ij}^{n(i,j)}$ has the form of the product of m independent $Dirichlet(n(1,j) + 1, n(2,j) + 1, ..., n(q,j) + 1)$ density functions for $j = 1, ..., q$. However, when we add the distribution for the first state the posterior distribution has a non-standard form. We devise a Metropolis-Hastings algorithm to sample the parameters in P.

We make a draw of a matrix P^{s+1} from Dirichlet distribution and accept the draw $(s+1)$ with probability $\rho(P^s, P^{s+1})$ which is defined as follows

$$\rho(P^s, P^{s+1}) = \frac{p(S_1)^{s+1} \prod_{i=1}^{q} \prod_{j=1}^{q} p_{ij}^{n(i,j)(s+1)}}{p(S_1)^s \prod_{i=1}^{q} \prod_{j=1}^{q} p_{ij}^{n(i,j)(s)}} \times \frac{\prod_{i=1}^{q} \prod_{j=1}^{q} p_{ij}^{(\alpha_{ij}-1)(s+1)}}{\prod_{i=1}^{q} \prod_{j=1}^{q} p_{ij}^{(\alpha_{ij}-1)(s)}} \tag{A-24}$$

where α_{ij} are hyperparameters in the prior distribution (15).

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Table 1: RCM statistics

Model	Value
Retail Gasoline price - Crude Oil price	21.17
Retail Gasoline price - Spot Gasoline price	19.67

Table 2: Estimates of transition matrix
H: Retail Gasoline - Crude Oil

	$S_{t-1} = 1$	$S_{t-1} = 2$
$S_t = 1$	0.203	0.059
	(0.04, 0.385)	(0.03, 0.09)
$S_t = 2$	0.797	0.941
	(0.61, 0.96)	(0.91, 0.97)

Table 3: Estimates of the periods with long-term shocks

Date	Price change	Oil market events
10/04/1993	+	
03/15/1999 03/29/1999	+ +	The meeting in Vienna on March 23, the OPEC 10 (excluding Iraq) pledged to cut production from previous quotas by 1.716 mln. barrels/day.
03/06/2000	+	OPEC oil ministers agree on an increase in oil production of 1.452 million barrels per day by its members, excluding Iran and Iraq.
05/08/2000	+	
06/12/2000	+	
09/05/2000	+	At a meeting in Vienna, OPEC agrees to raise production quotas by 800,000 barrels per day in an attempt to decrease price under $28 per barrel. The quota increases become effective October 1.
10/16/2000	+	
04/09/2001 04/16/2001	+ +	A ministerial conference on March 16-17, OPEC agreed to cut production by 1 mln. barrels/day as of 04/01/2001. Later estimates showed that OPEC discipline weakened in the opening months of 2001 and OPEC was overproducing by about 600,000 barrels/day in spring (Kohl (2002)).
03/11/2002	+	Ordinary conference in Vienna on March 15, OPEC members emphasized firm committment to their Agreements of November and December of 2001 to reduce production level by 1.5 mln. barrels/day.*
02/03/2003 02/10/2003	+ +	Venezuela crude oil production dropped from 2.9 million barrels per day in November 2002 to about 600,000 barrels per day in January 2003.

* The OPEC Conference on November 14 decided to reduce production by 1.5 mln. barrels/day, effective 1 January 2002, "subject to a firm commitment from non-OPEC oil producers to cut their production by a volume of 500,000 barrels/day simultaneously". Only when non-OPEC members finally made such a commitment by March of 2002, to the tune of 426,000 barrels/day, OPEC implemented its agreement of November 2001.

Table 4: Estimates of the Parameters: Retail Gasoline - Crude Oil

	Parameter Estimates	Highest Posterior Density Interval
$\triangle Crude^+_{t,1}$ [a]	0.590	(0.50, 0.68)
$\triangle Crude^+_{t,2}$ [b]	0.025	(0.01, 0.05)
$\triangle Crude^-_{t,1}$ [c]	0.150	(0.02, 0.32)
$\triangle Crude^-_{t,2}$ [d]	0.037	(0.01, 0.06)
$\triangle Crude^+_{t-1}$	0.096	(0.07, 0.12)
$\triangle Crude^-_{t-1}$	0.056	(-0.03, 0.02)
$\triangle Crude^+_{t-2}$	-0.003	(-0.02, 0.02)
$\triangle Crude^-_{t-2}$	-0.002	(-0.07, 0.04)
$\triangle Gasoline^+_{t-1}$	0.349	(0.26, 0.44)
$\triangle Gasoline^-_{t-1}$	0.449	(0.31, 0.59)
$\triangle Gasoline^+_{t-2}$	0.102	(0.02, 0.18)
$\triangle Gasoline^-_{t-2}$	0.289	(0.15, 0.42)
$Error\ Correction\ Term^+_{t-1}$	-0.043	(-0.07, -0.02)
$Error\ Correction\ Term^-_{t-1}$	-0.060	(-0.08, -0.03)
$\triangle Inventory$	-0.068	(-0.12, -0.02)

[a] $\triangle Crude^+_{t,1}$ - the effect of a permanent increase in crude oil price

[b] $\triangle Crude^+_{t,2}$ - the effect of a transitory increase in crude oil price

[c] $\triangle Crude^-_{t,1}$ - the effect of a permanent decrease in crude oil price

[d] $\triangle Crude^-_{t,2}$ - the effect of a transitory decrease in crude oil price

Table 5: Estimates of transition matrix P: Retail Gasoline - Spot Gasoline

	$S_{t-1} = 1$	$S_{t-1} = 2$
$S_t = 1$	0.319	0.066
	(0.07, 0.58)	(0.03, 0.11)
$S_t = 2$	0.681	0.934
	(0.41, 0.93)	(0.89, 0.97)

Table 6: Estimates of the Parameters: Retail Gasoline - Spot Gasoline

|	Parameter Estimates	Highest Posterior Density Interval
$\triangle Spot\ Gasoline_{t,1}^{+}$ [a]	0.293	(0.25, 0.34)
$\triangle Spot\ Gasoline_{t,2}^{+}$ [b]	0.019	(-0.01, 0.05)
$\triangle Spot\ Gasoline_{t,1}^{-}$ [c]	0.122	(0.34, 0.22)
$\triangle Spot\ Gasoline_{t,2}^{-}$ [d]	0.039	(0.01, 0.06)
$\triangle Spot\ Gasoline_{t-1}^{+}$	0.126	(0.10, 0.15)
$\triangle Spot\ Gasoline_{t-1}^{-}$	0.061	(0.04, 0.08)
$\triangle Spot\ Gasoline_{t-2}^{+}$	0.005	(-0.02, 0.03)
$\triangle Spot\ Gasoline_{t-2}^{-}$	0.027	(0.01, 0.05)
$\triangle Retail\ Gasoline_{t-1}^{+}$	0.258	(0.17, 0.34)
$\triangle Retail\ Gasoline_{t-1}^{-}$	0.347	(0.21, 0.48)
$\triangle Retail\ Gasoline_{t-2}^{+}$	0.106	(0.03, 0.18)
$\triangle Retail\ Gasoline_{t-2}^{-}$	0.336	(0.21, 0.46)
$Error\ Correction\ Term_{t-1}^{+}$	-0.029	(-0.054, -0.00)
$Error\ Correction\ Term_{t-1}^{-}$	-0.060	(-0.09, -0.03)
$\triangle Inventory$	-0.009	(-0.05, 0.04)

[a] $\triangle Spot\ Gasoline_{t,1}^{+}$ - the effect of a permanent increase in spot gasoline price

[b] $\triangle Spot\ Gasoline_{t,2}^{+}$ - the effect of a transitory increase in spot gasoline price

[c] $\triangle Spot\ Gasoline_{t,1}^{-}$ - the effect of a permanent decrease in spot gasoline price

[d] $\triangle Spot\ Gasoline_{t,2}^{-}$ - the effect of a transitory decrease in spot gasoline price
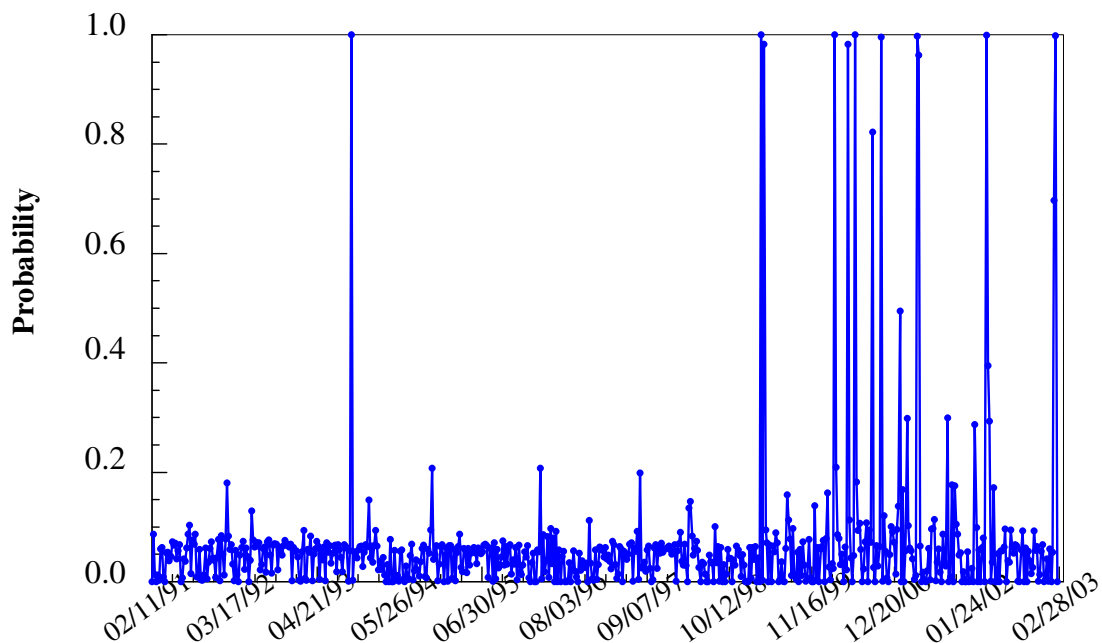
Regular retail gasoline prices, cents/gallon
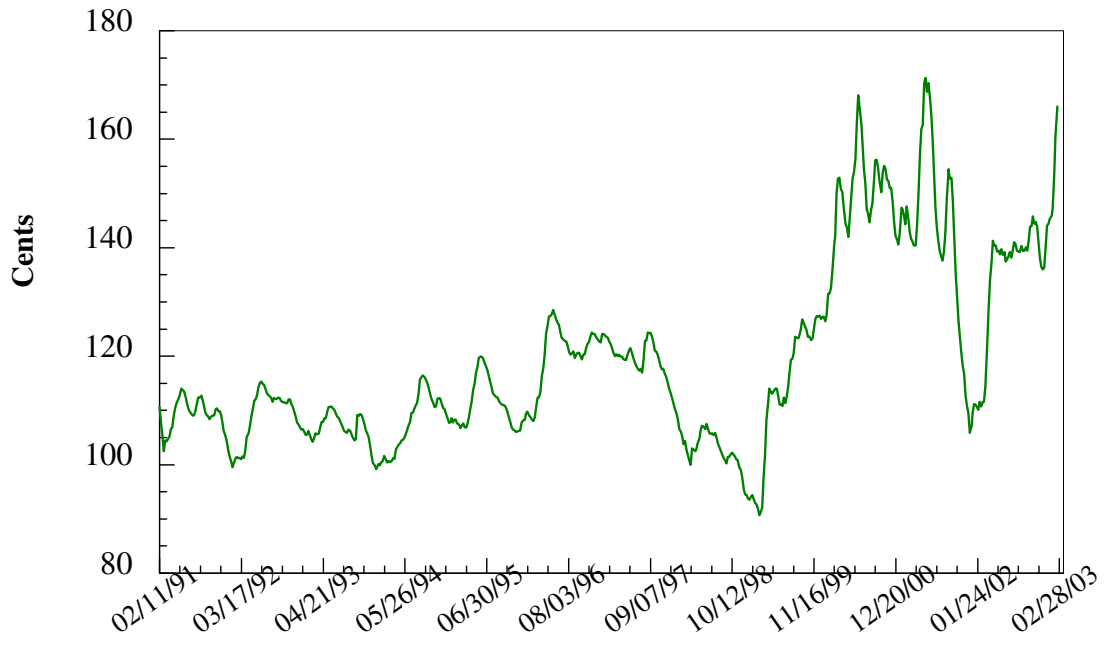
Crude oil prices, $/barrel

Figure 1: The levels of regular retail gasoline prices and crude oil prices.

(a) Filtered probability that a shock is long-term:
crude oil - retail price

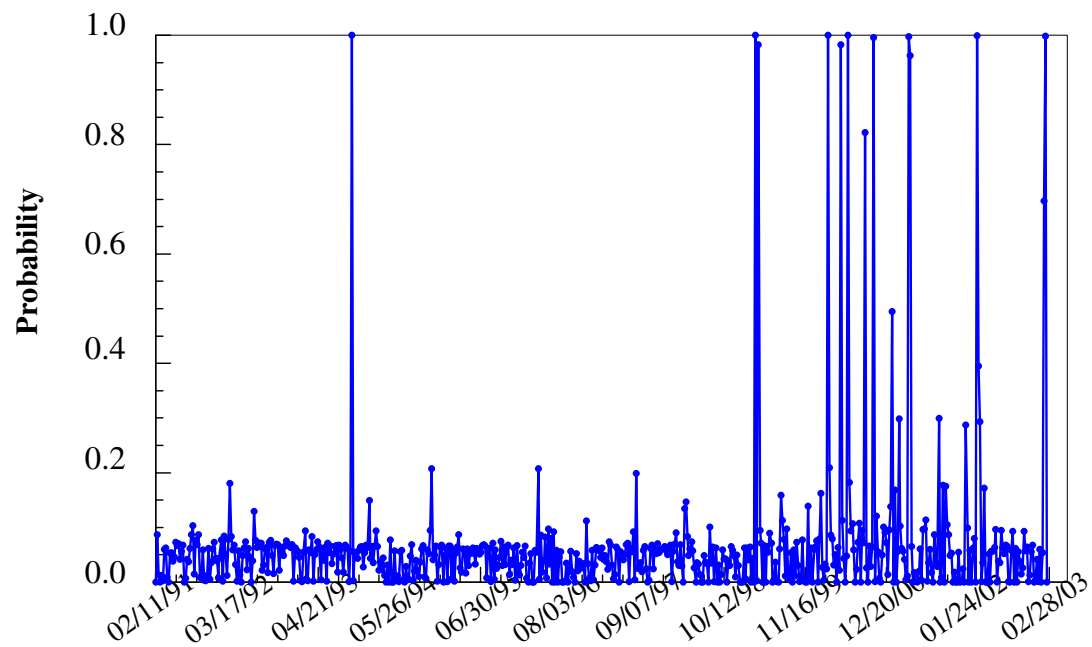(b) Smoothed probability that a shock is long-term:
crude oil - retail price

Figure 2: Estimates of filtered and smoothed probability that a shock from crude oil price to retail gasoline price is long-term.
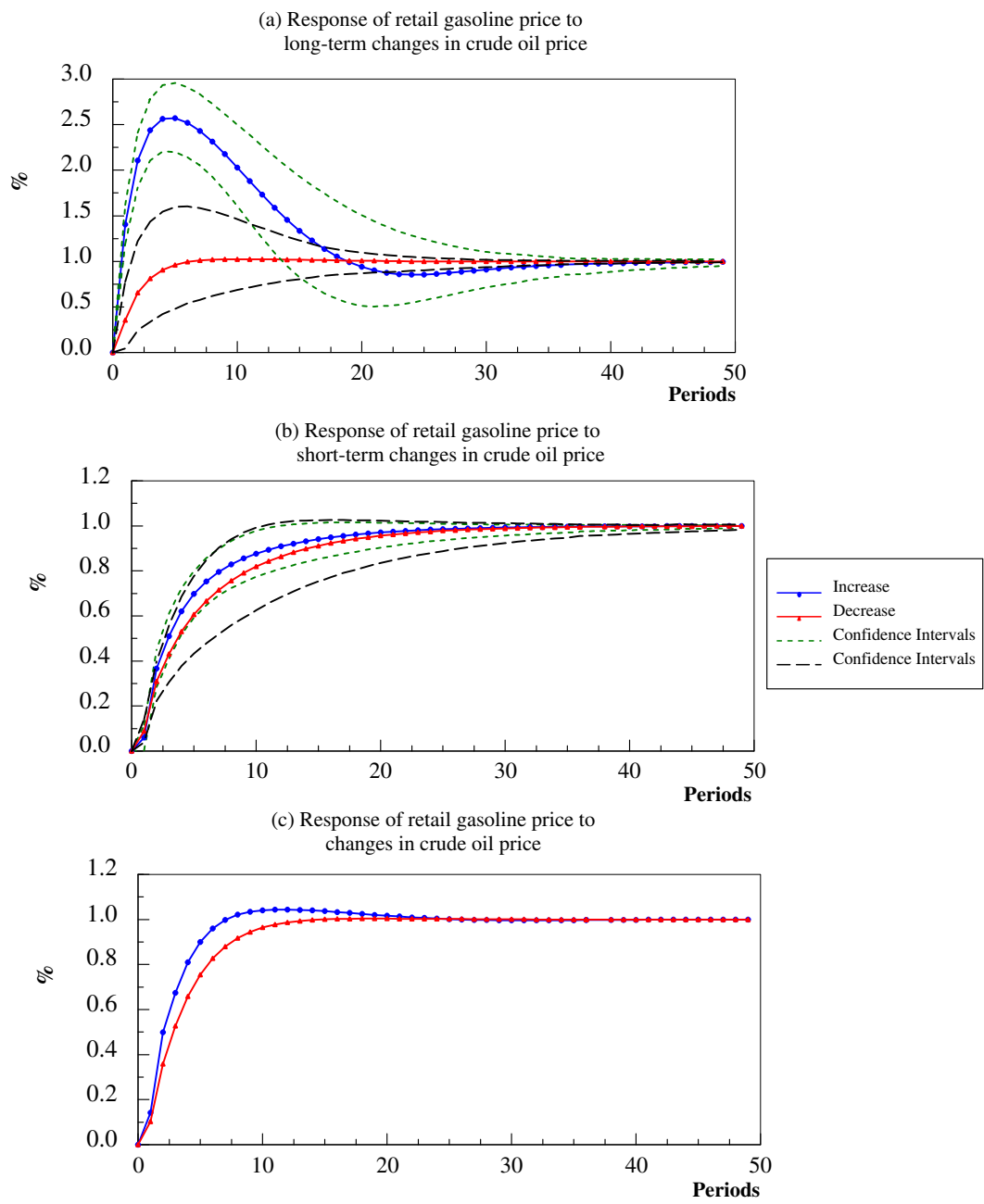
(a) Response of retail gasoline price to
long-term changes in crude oil price

(b) Response of retail gasoline price to
short-term changes in crude oil price

(c) Response of retail gasoline price to
changes in crude oil price

Figure 3: Cumulative response function of retail gasoline price to a 1 % increase and decrease in crude oil price.

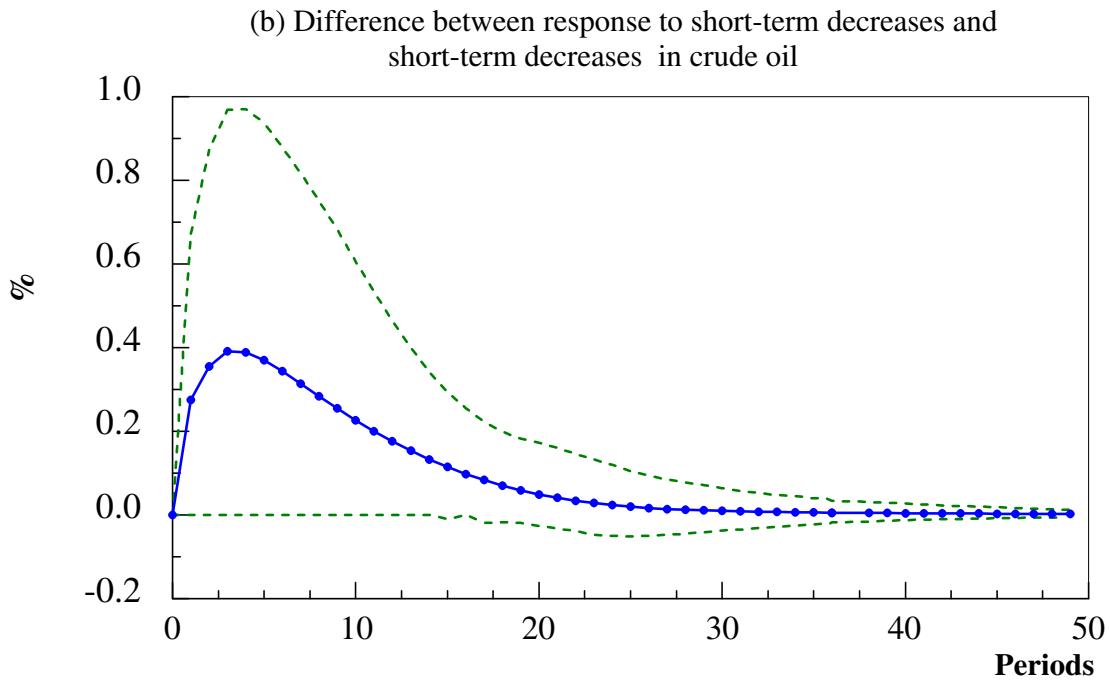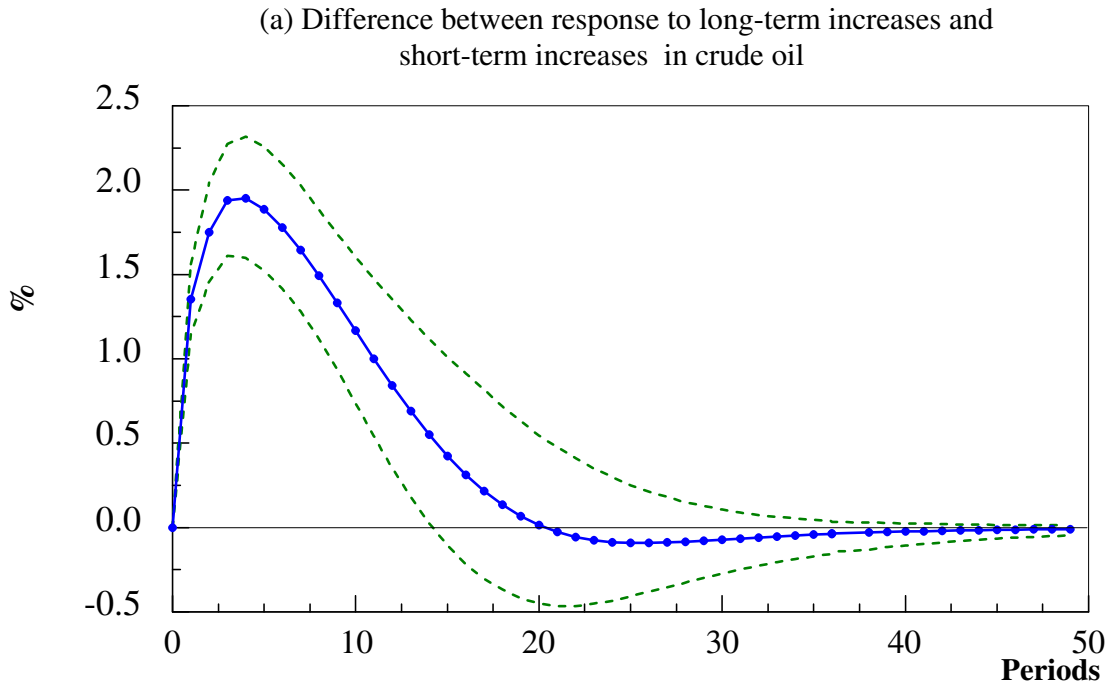(a) Difference between response to long-term increases and short-term increases in crude oil

(b) Difference between response to short-term decreases and short-term decreases in crude oil
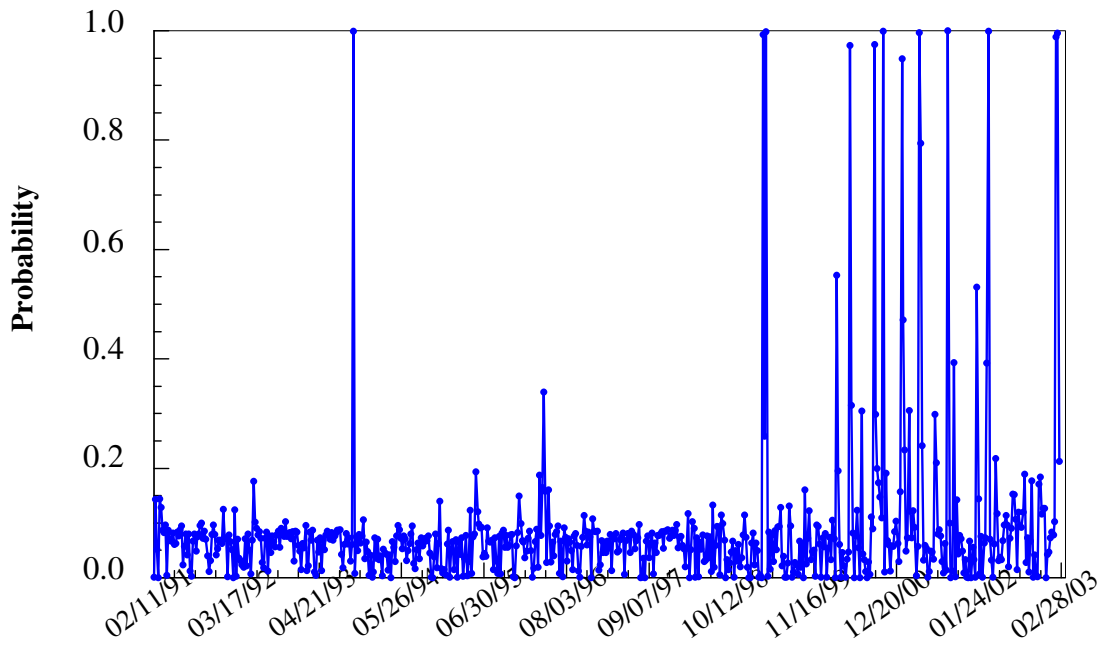
Figure 4: Asymmetry in the response of retail gasoline prices to long-term and short-term changes in crude oil price.

(a) Filtered probability that a shock is long-term:
spot gasoline price - retail gasoline price

(b) Smoothed probability that a shock is long-term:
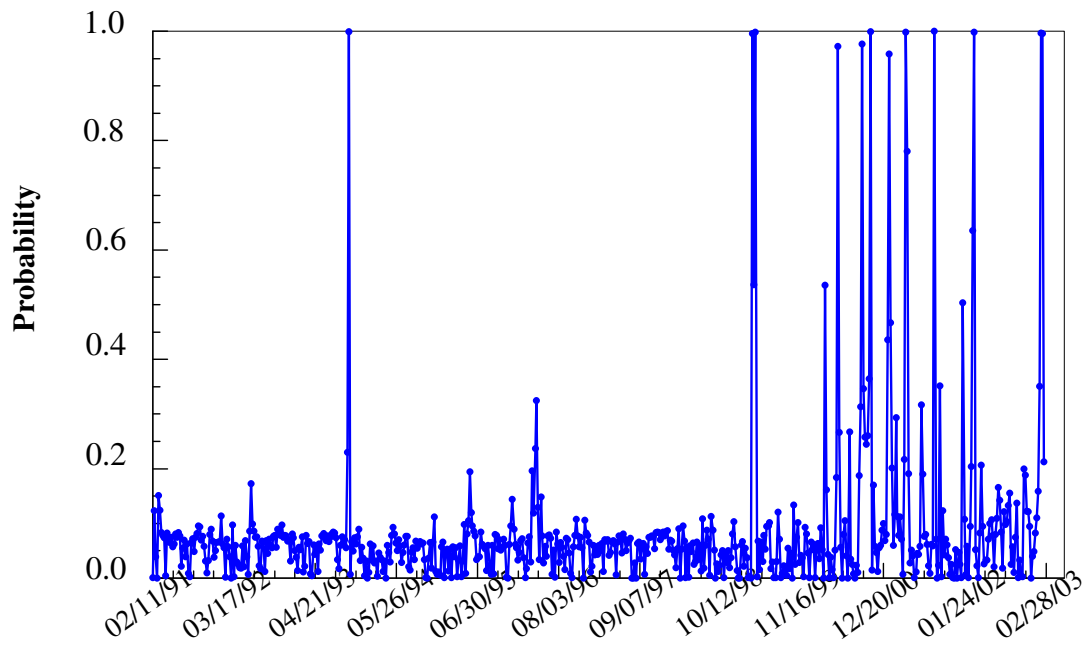spot gasoline price - retail gasoline price

Figure 5: Estimates of filtered and smoothed probability that a shock from spot price to retail gasoline price is long-term.
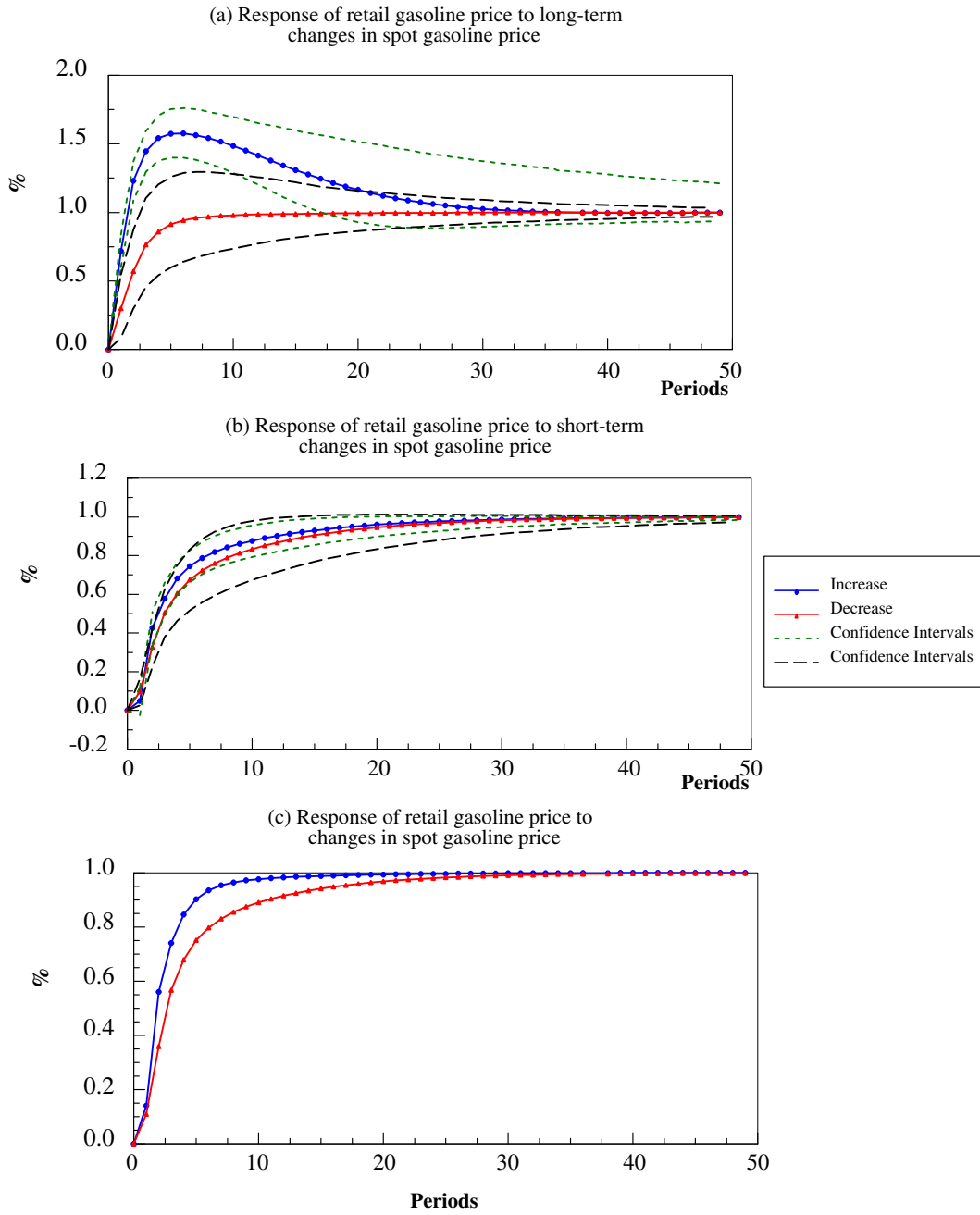
(a) Response of retail gasoline price to long-term
changes in spot gasoline price

(b) Response of retail gasoline price to short-term
changes in spot gasoline price

(c) Response of retail gasoline price to
changes in spot gasoline price

Figure 6: Cumulative response function of retail gasoline price to a 1 % increase and decrease in spot gasoline price.

(a) Difference between response to long-term increases and short-term increases in spot gasoline

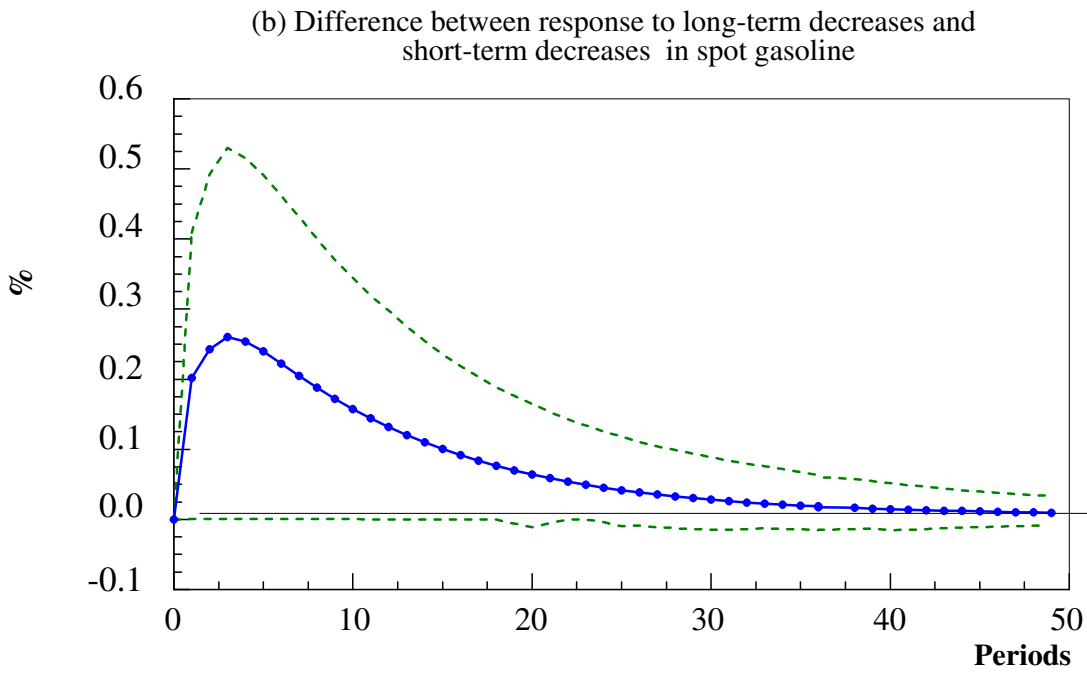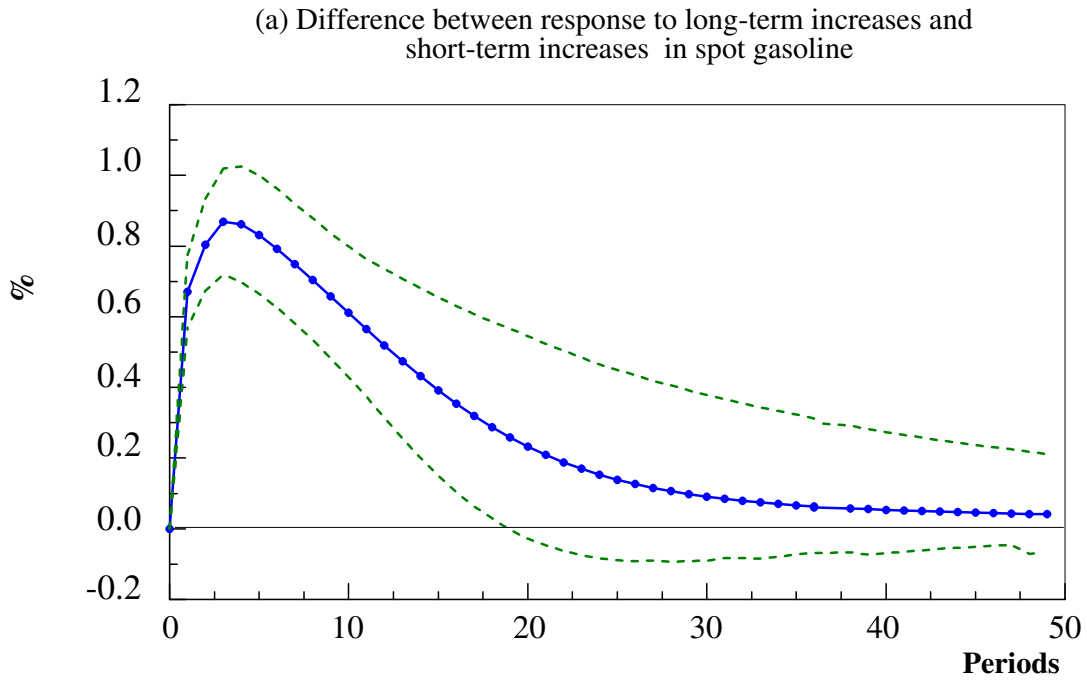(b) Difference between response to long-term decreases and short-term decreases in spot gasoline

Figure 7: Asymmetry in the response of retail gasoline prices to long-term and short-term changes in spot gasoline price.