Pitfalls in Estimating Asymmetric Effects of Energy Price Shocks

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The Literature on Oil Prices and the U.S. Economy

● Since the 1970s oil price shocks have been one of the leading candidates for explaining U.S. postwar recessions.

**Problem:** Finding an oil price shock measure that “works” in a VAR context is not straightforward (BGW 1997):

→ “anomalous” macroeconomic outcomes relative to the conventional wisdom.
→ “unstable” relationship with macroeconomic outcomes, as the sample is lengthened.

● Search for increasingly complicated specifications of the “true” relationship between oil prices and the U.S. economy, when linear and symmetric models failed to produce the desired results.
Asymmetric Models of the Transmission of Oil Price Shocks

Censored regression models seem to deliver larger and more stable responses:

- 1\textsuperscript{st} Generation (Mork 1989)

\textit{Oil price increase:}

\[ \Delta p_t^+ = \begin{cases} \Delta p_t & \text{if } \Delta p_t > 0 \\ 0 & \text{if } \Delta p_t \leq 0 \end{cases} \]

- 2\textsuperscript{nd} Generation (Hamilton 1996, 2003)

\textit{Net oil price increase:}

\[ \Delta p_t^+ = \max[0, p_t - p_t^*], \]

where \( p_t^* \) is the highest oil price in the preceding 12 (or 36) months.
Two Types of Studies in the Literature


2. Studies that estimate the dynamic response of macroeconomic aggregates to percent increases or net percent increases in the price of oil. Examples:

Hooker (JME 1996); Bernanke, Gertler and Watson (BPEA 1997); Davis and Haltiwanger (JME 2001); Lee and Ni (JME 2002); Hamilton (JoE 2003); Leduc and Sill (JME 2004); Hamilton and Herrera (JMCB 2004).

Prototypical recursively identified VAR model:

\[
\left( \frac{\Delta p_t^+}{\Delta gdp_t} \right) \sim VAR(p) \quad \text{or} \quad \left( \frac{\Delta p_t^{+,net}}{\Delta gdp_t} \right) \sim VAR(p)
\]

Remark: Similar issues arise in studying the transmission of crude oil price shocks to retail energy prices (e.g., Borenstein, Cameron, and Gilbert QJE 1997; Bachmeier and Griffin 2003).
Consensus in the Macroeconomic Literature

The “evidence for asymmetric responses to oil price ups and downs is well established” (Davis and Haltiwanger 2001).

Why?

● Tests on slope parameters sometimes reject symmetry.

● More stable results?

● Censoring produces “better looking” VAR impulse responses (BGW 1997).

● Nicely complements some theoretical models of the transmission of oil price shocks (Bernanke 1983; Hamilton 1988; Pindyck 1991). We need these models to explain large effects of energy price shocks.
Limitations of Existing Estimates of Asymmetric Responses from Censored VAR Models

1. The VAR models in question are fundamentally misspecified. In fact, the asymmetric DGP cannot be represented as a VAR model of any kind. As a result, the parameter estimates are inconsistent.

2. The implied impulse responses have been computed incorrectly.

3. Whether asymmetric responses differ from responses based on linear symmetric models has not been tested properly. Existing tests are inadequate for this purpose.
A Stylized Static Model: Symmetric Case

Static Symmetric DGP Model:

\[ x_t = \alpha_1 + \varepsilon_{1,t} \]
\[ y_t = \alpha_2 + x_t \beta + \varepsilon_{2,t} \]  \hspace{1cm} (1)

where \( \varepsilon_{1,t} \) and \( \varepsilon_{2,t} \) are mean zero iid Gaussian with variances \( \sigma_1^2 \) and \( \sigma_2^2 \).

Standard Regression Model:

\[ y_t = a + x_t b + u_t \quad \Rightarrow \hat{b} \text{ is consistent for } \beta \]

Censored Regressor Model:

\[ y_t = a + x_t^+ b + u_t \text{ where } x_t^+ = \begin{cases} x_t & \text{if } x_t > 0 \\ 0 & \text{if } x_t \leq 0 \end{cases} \]
\[ \Rightarrow \hat{b} \text{ is inconsistent for } \beta \text{ (upward bias)} \]
The Effect of Censoring Negative Values of the Regressor
How Big Is the Asymptotic Bias?

● Suppose $\alpha = 0$ and $x_t$ has a symmetric distribution with mean zero and variance 1. Also suppose $\varepsilon_{1,t}$ and $\varepsilon_{2,t}$ are uncorrelated. Then:

$$\hat{b} \xrightarrow{p} -\beta \frac{0.5\mu}{1 - 0.4\mu^2} \text{ where } \mu \equiv E(x_t \mid x_t > 0).$$

● If $x_t \sim NID(0,1)$, we obtain:

$$\hat{b} \xrightarrow{p} 1.47\beta$$
A Stylized Static Model: Asymmetric Case

Static Asymmetric DGP Model:

\[ x_t = \alpha_1 + \varepsilon_{1,t} \]
\[ y_t = \alpha_2 + x_t \beta + x_t^+ \gamma + \varepsilon_{2,t} \tag{2} \]

where \(\varepsilon_{1,t}\) and \(\varepsilon_{2,t}\) are mean zero iid Gaussian with variances \(\sigma_1^2\) and \(\sigma_2^2\).

Censored Regressor Model:

\[ y_t = a + x_t^+ b + u_t \quad \Rightarrow \hat{b} \text{ is inconsistent for } \beta + \gamma \text{ unless } \beta = 0 \]

(upward bias)
Asymptotic Bias from Censoring in the Static Asymmetric Model

<table>
<thead>
<tr>
<th>Population slope parameters</th>
<th>Average estimated slope $\hat{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
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<tr>
<td>0.7</td>
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<tr>
<td>1.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>1.5</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

Notes: Asymmetric DGP: $\alpha_1 = \alpha_2 = 0, \sigma_1 = \sigma_2 = 1$. Average results for 2000 samples of 100,000 observations each.
Extensions to Dynamic Models

Standard approach:

\[
\begin{pmatrix}
  x_t^+ \\
  y_t
\end{pmatrix} \sim VAR(p)
\]

**BGW (BPEA 1997, p. 103):**

“Mork provided evidence that only positive changes in the relative price of oil have important effects on output. Accordingly, in our VARs we employ an indicator that equals the log-difference of the relative price of oil when that change is positive and otherwise is zero.”

**Leduc & Sill (JME 2004, p. 790):**

“To get an empirical estimate of the output response to positive oil-price shocks, we run a VAR using ... oil-price increases [...] constructed by taking the first difference of the log of oil prices, then setting negative values to zero. Thus, only oil-price increases affect the other variables in the system.”
What if the DGP is a Linear Symmetric VAR?


\[
\begin{pmatrix}
    x_t \\
    y_t
\end{pmatrix} \sim \text{VAR}(6)
\]

- Regression model: Recursively identified censored VAR

\[
\begin{pmatrix}
    x_t^+ \\
    y_t
\end{pmatrix} \sim \text{VAR}(6)
\]

where \( x_t \) and \( y_t \) are expressed in growth rates and \( y_t \) denotes the macroeconomic aggregate of interest.

Remark: In the empirical literature, impulse responses from this model have routinely been computed exactly as in linear VAR models. For now, we will follow that practice, so we can assess the empirical results in the literature.
Inconsistency of the Estimated Effect of Energy Price Increases
Symmetric VAR DGP

Censored VAR

Symmetric VAR

Notes: T=100,000.
What if the DGP is an Asymmetric Dynamic Model?

- A censored VAR will generate realizations $x_t^+ < 0$ with positive probability.

The source of this problem is that the regression model is an incomplete description of the DGP.

- It is tempting to deal with this problem by censoring realizations with the wrong sign.

In that case, the same type of asymptotic bias from censoring arises, as for the linear symmetric VAR-DGP.
Inconsistency of the Estimated Effect of Energy Price Increases
Censored VAR DGP with Censored Regressors
Proposal for a Fully Specified Asymmetric DGP

- Strictly asymmetric structural DGP:

  \[ x_t = \sum_{i=1}^{p} b_{11,i} x_{t-i} + \sum_{i=1}^{p} b_{12,i} y_{t-i} + \varepsilon_{1,t} \]  

  \[ y_t = \sum_{i=0}^{p} b_{21,i} x_{t-i} + \sum_{i=1}^{p} b_{22,i} y_{t-i} + \varepsilon_{2,t} \]  

  where the structural shocks \( \varepsilon_{1,t} \) and \( \varepsilon_{2,t} \) are uncorrelated. Although the slope parameters can be estimated consistently by OLS, the resulting residuals will not be uncorrelated. To impose that restriction, we need a restricted MLE.

- Regression:

  \[ x_t^+ = \sum_{i=1}^{p} b_{11,i} x_{t-i}^+ + \sum_{i=1}^{p} b_{12,i} y_{t-i} + \varepsilon_{1,t} \]  

  \[ y_t = \sum_{i=1}^{p} b_{21,i} x_{t-i}^+ + \sum_{i=1}^{p} b_{22,i} y_{t-i} + \varepsilon_{2,t} \]  

  Unlike in the static model, the censored VAR will be inconsistent even if \( x_t \) has zero coefficients \( \forall t \) in the second equation of the DGP!
Inconsistency of Estimated Effect of Oil Price Increase on GDP
Strictly Asymmetric Structural DGP
Fitting Censored VAR
Inconsistency of Estimated Effect of Oil Price Increase on Oil Price
Strictly Asymmetric Structural DGP
Fitting Censored VAR
A General Model of the Oil Price-Economy Link

If we do not know whether there is an asymmetry, we face a dilemma. Which model should we fit to the data?

Proposal:

\[ x_t = \sum_{i=1}^{p} b_{11,i} x_{t-i} + \sum_{i=1}^{p} b_{12,i} y_{t-i} + \varepsilon_{1,t} \]

\[ y_t = \sum_{i=0}^{p} b_{21,i} x_{t-i} + \sum_{i=1}^{p} b_{22,i} y_{t-i} + \sum_{i=0}^{p} g_{21,i} x_{t-i}^+ + \varepsilon_{2,t} \]  

By construction, the OLS residuals of model (4) will be mutually uncorrelated.

Estimates of this model will always be consistent. This eliminates the asymptotic bias at the price of being possibly inefficient.

This model allows for nonzero effects from energy price decreases, consistent with economic theory.
Correct Approach to Estimating the Effect of Energy Price Increases
Symmetric VAR DGP

NOTES: T=1,000,000
Correct Approach to Estimating the Effect of Energy Price Increases

Strictly Asymmetric Structural DGP

NOTES: T=1,000,000
Computing Asymmetric Impulse Responses Properly

- The standard approach to constructing impulse responses is misleading since it ignores the path dependence of the future values of $y_t$ and their dependence on the magnitude of the shock.

For that reason, the asymmetric responses to energy price shocks typically reported in the literature would be suspect, even if a correctly specified model and consistent estimation methods had been used.

- The computation of impulse responses for nonlinear multivariate reduced form models is discussed in Koop et al. (1996).

**Problem:** 1. Shock is not uniquely defined because reduced form innovations are mutually correlated.
2. Shock is not structural.

**Solution:** In the context of our structural asymmetric model, in contrast, the errors are mutually uncorrelated, so we can compute economically meaningful responses by drawing from the marginal distribution of structural shocks.
Computing Nonlinear Responses to
Unanticipated Energy Price Increases

Having estimated the asymmetric model as discussed earlier, proceed as follows:

Step 1: Take a block of $p$ consecutive values of $x_t$ and $y_t$. This defines a history $\Omega^i$.

Step 2. Given $\Omega^i$, simulate two time paths for $x_{t+i}$ and $y_{t+i}$, $i = 0,1,...,h$. In generating
the first time path, the value of $\varepsilon_{1,t}$ is equal to a prespecified value $\delta$. In generating
the other time path, the value of $\varepsilon_{1,t}$ is drawn from the marginal empirical distribution
of $\varepsilon_{1,t}$. The values of all subsequent shocks $\varepsilon_{1,t+i}$ and the value of $\varepsilon_{2,t+i}$, $i = 0,1,2,...,h,$
are drawn from their respective marginal distributions. In practice, we treat these
draws as independent.

Step 3: Calculate the difference between the time paths for $y_{t+i}$, $i = 0,1,...,h$.

Step 4: Average this difference across $m=10,000$ repetitions of Steps 2 and 3.
• This average is the response of $y_{t+i}$ to a shock of magnitude $\delta$ conditional on $\Omega^i$:

$$I_y(h, \delta, \Omega^i)$$

is the relevant statistic for forecasting and policy work.

• The corresponding unconditional response

$$I_y(h, \delta) = \int I_y(h, \delta, \Omega^i) d\Omega^i$$

is a measure of the general importance of oil price shocks.

• In contrast, the counterfactual response

$$I_y(h, \delta, 0)$$

conditions on a hypothetical initial condition, in which all variables equal zero.
• The response typically used in existing empirical work is

$$I_y^*(h, \delta, 0)$$

where rather than integrating over possible shock paths, we impose that all future shocks are equal to zero, and the initial shock is 0 under one path and 1 under the other.

Problems:
1. Koop et al. (1996) show that this traditional impulse response may not converge to zero, even when the stochastic process is stationary.


3. Why is this specific history interesting?
How Different is the Traditional Response from the Correctly Computed Unconditional Response?

Notes: Response of GDP to a positive oil price shock. $I_y(h, \sigma)$ is computed by Monte Carlo integration over 300 histories with 10,000 paths each. The responses have been scaled for compatibility. $h$ denotes the horizon.
Testing for Symmetry in the Impulse Responses

● The **traditional approach** to testing for symmetry in the transmission of energy price shocks involves tests on the symmetry of slope coefficients in regressions of \( y_t \) on lagged \( x_t^+ \) and \( x_t^- \) (e.g., Mork 1989).

This is equivalent to testing \( H_0 : g_{21,1} = ... = g_{21,p} = 0 \) in model (4).

● Model (4) suggests that Mork’s (1989) reduced form test fails to impose all restrictions. A test of all symmetry restrictions on the slopes involves:

\[
H_0 : g_{21,0} = ... = g_{21,p} = 0
\]

We will examine this new test below.
Empirical Results: Slope-Based Symmetry Tests
Baseline Model Model with 6 Lags

<table>
<thead>
<tr>
<th>Variable</th>
<th>The Proposed Test of Symmetric Slope Coefficients</th>
<th>Marginal Significance Level</th>
<th>Mork’s Test of Symmetric Slope Coefficients</th>
<th>Marginal Significance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unemployment</td>
<td>7.722</td>
<td>0.358</td>
<td>3.132</td>
<td>0.792</td>
</tr>
<tr>
<td>Gasoline Consumption</td>
<td>11.376</td>
<td>0.123</td>
<td>9.237</td>
<td>0.161</td>
</tr>
<tr>
<td>Real GDP</td>
<td>10.472</td>
<td>0.163</td>
<td>9.757</td>
<td>0.135</td>
</tr>
</tbody>
</table>
Limitations of Slope-Based Symmetry Tests

1. The previous example illustrates that even 1% rejection of symmetry based on slopes does not guarantee large degree of asymmetry in the impulse responses.

2. Likewise, statistically insignificant departures from symmetric slopes may translate to a large and/or statistically significant degree of asymmetry in impulse responses.

3. Slope-based tests ignore that the extent to which the responses in the symmetric linear model provide a good approximation depends on the magnitude of the shock we consider.

This suggests that we test symmetry directly on the object of interest.
A New Test of the Symmetry of Impulse Responses

- Estimate the nonlinear model (4) and compute the impulse responses to a positive and a negative energy price shock, as discussed earlier.

- Construct a Wald test of $H_0 : I_y(h, \delta) = -I_y(h, -\delta)$ for $h = 0, \ldots, H$.

- The test statistic has an asymptotic $\chi^2_{H+1}$ distribution.

Remarks:
The variance-covariance matrix of the vector sum of response coefficients can be estimated by bootstrap simulation.
## Size of the 5% Test of Symmetric Responses

<table>
<thead>
<tr>
<th>$H$</th>
<th>Unemployment 1 std dev</th>
<th>Unemployment 2 std dev</th>
<th>Gas Consumption 1 std dev</th>
<th>Gas Consumption 2 std dev</th>
<th>Real GDP 1 std dev</th>
<th>Real GDP 2 std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>0.08</td>
<td>0.05</td>
<td>0.08</td>
<td>0.06</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>8</td>
<td>0.09</td>
<td>0.07</td>
<td>0.10</td>
<td>0.07</td>
<td>0.09</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Notes: Based on average of 90 histories and 20,000 draws under the null.
Empirical Results of Tests for Symmetric Responses

$p$-Values for Test of $H_0 : I_y(h, \delta) = -I_y(h, -\delta)$ for $h = 0, \ldots, H$.

<table>
<thead>
<tr>
<th>$H$</th>
<th>Gas Consumption</th>
<th>GDP</th>
<th>Unemployment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Std. Deviation</td>
<td>2 Std. Deviation</td>
<td>1 Std. Deviation</td>
</tr>
<tr>
<td>0</td>
<td>0.45</td>
<td>0.47</td>
<td>0.40</td>
</tr>
<tr>
<td>1</td>
<td>0.13</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.15</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.25</td>
<td>0.56</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>0.21</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td><strong>0.04</strong></td>
<td>0.15</td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>0.06</td>
<td>0.18</td>
<td>0.48</td>
</tr>
<tr>
<td>7</td>
<td>0.09</td>
<td>0.26</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Notes: Based on 20,000 simulations of Model (4). $p$-values based on the $\chi^2_{H+1}$-distribution.
Gasoline Consumption Example:
How Different are the Response Estimates?
Baseline Model with 6 Lags
Testing Models of Net Energy Price Increases

- Existing evidence against the linear symmetric VAR model does not justify:

\[
\begin{pmatrix}
  x_{t}^{+,\text{net}} \\
  y_t
\end{pmatrix} \sim VAR(p)
\]

That model is misspecified and its impulse responses have been routinely computed incorrectly (also see Balke et al. 2002).

- Existing tests of the net increase model are based on one-step ahead single-equation predictive models:

\[
y_t = \sum_{i=1}^{p} \beta_i y_{t-i} + \sum_{i=1}^{p} \gamma_i x_{t-i} + \sum_{i=1}^{p} \delta_i x_{t-i}^{+,\text{net}} + u_t \quad \text{Balke et al. (2002)}
\]

\[
y_t = \sum_{i=1}^{p} \beta_i y_{t-i} + \sum_{i=1}^{p} \delta_i x_{t-i}^{+,\text{net}} + u_t \quad \text{Hamilton (2003)}
\]

Such models do not allow the construction of impulse responses since they omit the equation determining \(x_t\). They also omit the contemporaneous regressor. Their implications for impulse response analysis are unclear.
Testing Symmetry in Models of Net Energy Price Increases

\[ x_t = \sum_{i=1}^{p} b_{11,i} x_{t-i} + \sum_{i=1}^{p} b_{12,i} y_{t-i} + \varepsilon_{1,t} \]

\[ y_t = \sum_{i=0}^{p} b_{21,i} x_{t-i} + \sum_{i=1}^{p} b_{22,i} y_{t-i} + \sum_{i=0}^{p} g_{21,i} x_{t-i}^{+\text{net}} + \varepsilon_{2,t} \]  

(5)

Slope-based test: \[ H_0 : g_{21,0} = \ldots = g_{21,p} = 0 \]

Impulse-response based test: \[ H_0 : I_y(h, \delta) = -I_y(h, -\delta) \text{ for } h = 0, \ldots, H. \]
Slope-Based Test of the Linear Symmetric VAR Model against the 3-Year Net Increase VAR Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>3-Year Net Increase Test of Linear Symmetric Model</th>
<th>Marginal Significance Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unemployment</td>
<td>9.6332</td>
<td>0.210</td>
</tr>
<tr>
<td>Gasoline Consumption</td>
<td>14.5307</td>
<td><strong>0.043</strong></td>
</tr>
<tr>
<td>Real GDP</td>
<td>14.2965</td>
<td><strong>0.046</strong></td>
</tr>
</tbody>
</table>

NOTES: *p*-values based on $\chi^2_{H+1}$ distribution.
Empirical Responses to 1- and 2-Std. Deviation Positive and Negative Energy Price Shocks 3-Year Net Increase Model

GDP

One Standard Deviation Shock

Two Standard Deviation Shock

Unemployment

One Standard Deviation Shock

Two Standard Deviation Shock

Gas Consumption

One Standard Deviation Shock

Two Standard Deviation Shock
$p$-Values of Tests of $H_0 : I_y(h, \delta) = -I_y(h, -\delta)$ for $h = 0,\ldots, H$

3-Year Net Increase Model

<table>
<thead>
<tr>
<th>$H$</th>
<th>Gas Consumption</th>
<th></th>
<th></th>
<th>GDP</th>
<th></th>
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<th>Unemployment</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1 Std. Deviation Shock</td>
<td>2 Std. Deviation Shock</td>
<td>1 Std. Deviation Shock</td>
<td>2 Std. Deviation Shock</td>
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<td>2 Std. Deviation Shock</td>
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<td></td>
<td></td>
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<tr>
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<td>0.98</td>
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<td>0.95</td>
<td>0.13</td>
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</table>

NOTES: $p$-Values based on $\chi^2_{H+1}$ distribution. Bootstrap variance estimates using 20,000 replications of model (5).
Implications for the Literature on the Transmission of Oil Price Shocks

- Davis and Haltiwanger (2001) considered “the evidence for asymmetric responses to oil price ups and downs as well established”.

Our analysis suggests that this evidence has been overstated. There is no compelling evidence of asymmetry in these responses.

- Theoretical models of sectoral reallocations or of delayed investment are inconsistent with our test results. These are precisely the models required to explain potentially large effects of oil price shocks on U.S. output.

- In contrast, traditional models of cost-push and aggregate demand reduction are consistent with the lack of asymmetry. These models do not predict large fluctuations in U.S. output in response to oil price shocks.
Conclusions

1. Asymmetric responses should be estimated and tested using the econometric methods outlined in this paper. Earlier methods are invalid.

2. There is no statistically significant evidence of asymmetric responses to energy price shocks:

   → There is no compelling reason to abandon the use of linear symmetric models in empirical work on the transmission of energy price shocks (or the use of linear approximations to the steady state in theoretical work).

   → Theoretical models of the transmission of energy price shocks that imply asymmetries are not consistent with the U.S. data.

3. Key empirical studies that have shaped our thinking about how monetary policy has responded to oil price shocks are invalid.

Much of the evidence on plant level and sectoral effects of oil price shocks will also have to be reexamined.