Is Oil Price Still Driving Inflation?

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ABSTRACT

In this paper, we empirically investigate the effects of oil price changes on inflation over the period 1991–2016 for eight industrial countries: the United States, Canada, Japan, Australia, Germany, France, Italy, and the UK. In doing so, we use an oil-augmented Phillips curve with unobserved components and we consider time-varying coefficients. The results show that even over a period of low and stable inflation, oil prices play a significant role in the dynamics of inflation. In all the countries except Germany, oil pass-through into inflation increased from the early 2000s up until the global financial crisis. In the United States it has nearly doubled in the last fifteen years. These findings suggest that central banks must continue to monitor oil prices closely.

Keywords: Energy and the economy, Oil price, Inflation, Phillips curve, Unobserved components models

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1. INTRODUCTION

The oil shocks and stagflation that characterized the 1970s led to a great deal of research on the effects of oil prices on the economy. Many empirical studies have shown that oil price shocks affect output and inflation. However, there is no consensus on the magnitude of the oil price effect in explaining recession episodes, and many studies have indicated that the relationship between oil price and the macroeconomy has changed over time. First, several studies (Mork, 1989; Mork et al. 1994; Hamilton and Herrera, 2004) support the position that the relationship between oil prices and macroeconomic aggregates broke down in the mid-1980s, the oil price collapse that occurred in 1986 having not produced an economic boom. Other authors, among them Kilian (2009), Blanchard and Gali (2007a), Hamilton (2009), Segal (2011), and Blanchard and Riggi (2011) point to a reduced impact of oil price shocks on macroeconomic aggregates over time. Indeed, since the late 1990s, the global economy has experienced two oil shocks comparable to those of the 1970s, but in contrast with the earlier shocks GDP growth and inflation remained relatively stable in much of the industrialized world until the financial crisis. Finally, authors including Bernanke et al. (1997), Barsky and Kilian (2004), Kilian and Lewis (2011), and Blinder and Rudd (2008) argue that oil price shocks have never been a major factor in macroeconomic cycles, even in the 1970s.

Some studies have focused exclusively on the issue of pass-through of oil prices into inflation, including for example Hooker (2002), LeBlanc and Chinn (2004), van den Noord and André (2007), De Gregorio al. (2007), Blanchard and Gali (2007a), Chen (2009a, 2009b), Clark and Terry (2010), and Fukač (2011). This issue is particularly important for the implementation of monetary policy, and remains relevant in a context of low oil prices. Indeed, it is now widely accepted that one

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of the main goals of monetary policy is the pursuit of price stability. To ensure this objective, those responsible for monetary policy must assess the impact of oil price changes on inflation and utilize the appropriate tools to control inflation. Understanding inflation dynamics is especially important today due to the very low inflation levels prevailing in many countries. When inflation is far below target, central banks' tolerance for further negative inflation impulses can be low. Furthermore, there may be a high risk that inflation expectations will fall as a result of the drop in oil prices. In a context of falling oil prices with a weak global growth environment and with nominal interest rates constrained by the zero lower bound in the advanced economies, monetary policy should react forcefully to stimulate economic activity, maintain the anchoring of inflation expectations, and prevent deflation risks.

In this paper we investigate the effects of oil price changes on inflation using an augmented Phillips curve framework. As widely suggested in the literature, the pass-through of oil prices into inflation has evolved over time and is still very much in a state of change. That is why, in line with Chen (2009a), we assume that the instability of the oil price pass-through may be gradual and we use a time-varying coefficients model which is particularly well adapted to take an on-going process into account. In addition, we implement an unobserved components model (Harvey, 2011; Stella and Stock, 2015) to take into account the persistence of inflation. We consider eight industrialized countries, namely the United States, Canada, Japan, Australia, Germany, France, Italy, and the United Kingdom over the period 1991–2016. This period is characterized by the adoption of inflation targeting by most central banks in the early 1990s, and by a low level of inflation. The aim of our work is to better understand the dynamics of inflation in a context of low inflation.

Our analysis differs from the existing literature on several points. First, the analysis is based on a new methodology using an unobserved components model in a state space framework. This allows a time-varying pass-through and avoids some difficulties in the specification of the Phillips curve, which involves a regression on unobserved variables, namely the output gap and inflation expectations. Second, our data set extends to 2016 and includes both the financial crisis and the falling oil prices initiated in June 2014, events that are not covered by previous studies. Third, because we employ a common methodology across countries and hold the sample period fixed, our results are directly comparable across countries, so we can assess both how the oil price pass-through evolves over time and what are the common features between the countries under study.

We establish that even in a low and stable inflation period, oil prices play a significant role in the dynamics of inflation. Furthermore, the results show evidence of significant time-varying oil pass-through, as well differences between countries. In all the countries, except Germany the oil pass-through into inflation increased from the early 2000s up until the global financial crisis, and in the last fifteen years it has nearly doubled in the United States.

The paper is organized as follows. Section 2 offers a literature review. Section 3 provides a brief description of the evolution of oil prices and inflation. Section 4 briefly reviews the theory and the empirical methodology. Section 5 reports and discusses the empirical results. The final section concludes.

2. LITERATURE REVIEW

The pass-through from oil prices to inflation is usually examined using a vector autoregression (VAR) or an augmented Phillips curve (APC) with oil prices. Whatever the model used, there is some evidence that the pass-through has sharply declined since the early 1980s. This evolution suggests that a linear, constant coefficient specification may not accurately capture the effects of oil price fluctuations on inflation. Consequently, time variation has to be allowed for in order to adequately model the pass-through from oil prices to inflation, and to explore how this relationship has evolved over time. Some authors have argued that this breakdown of the relationship reveals that the relationship between the variables is non-linear, and thus have proposed different specifications of it, particularly asymmetric ones. These specifications can be implemented either by introducing two separate variables for oil price increases and decreases, as in the models suggested by Mork (1989) and Mork et al. (1994), or by estimating Markov regime-switching models characterized by high and low inflation periods (Çatik and Önder, 2011), or even by using a quantile regression framework to estimate the marginal effect on inflation in the distribution (Chortareas et al., 2012). Other authors have suggested different ways to take time variation into account, either by splitting the sample into two sub-periods assuming a structural break in the early 1980s, by estimating regressions over rolling time windows, or by using time-varying parameters models. Table A1 in Appendix presents the key features of main studies carried out since the early 2000s.

As mentioned above, a broad consensus emerges regarding the decline of the pass-through from the mid-1980s. The structural break appears robust to a variety of specifications and for many industrialized countries. Hooker (2002) showed strong evidence of a structural break, the oil shocks having contributed substantially to core inflation (inflation excluding energy and food prices) until 1981, but the pass-through having become negligible since. LeBlanc and Chinn (2004) concluded that the sharp oil price increase experienced in the 1990s had a modest effect on inflation, although differences in the size of the effects exist across countries. Van den Noord and André (2007) and Clark and Terry (2010) showed that the effects of energy shocks on core‑inflation were sharply diminished in comparison with the 1970s and remain muted. De Gregorio et al. (2007) identified a drop in the average estimated pass-through for industrial economies and, to a lesser degree, for emerging economies. Blanchard and Gali (2007a) have reported much larger effects of oil price shocks on inflation in the first part of the sample, i.e. before 1984. Chen (2009a) found evidence of declining pass-through for almost all the countries considered. However, he noted that the percentage change in pass-through is negligible for some countries, especially in the United States and Australia. Fukač's results (2011) are consistent with previous studies: they pointed to the decline in the pass-through of oil prices to inflation after 1983.

Many arguments have been put forward to explain the decline in pass-through since the mid-1980s (see Chen, 2009a). However, more recent studies, based upon up-to-date data, suggest that oil prices have been playing a larger role in the inflation process since the late 2000s. Fukač (2011) showed that the pass-through exhibits a structural break before the great recession of 2007, and has increased over the period 2000–2010 in the United States. Although the pass-through is still low compared with its level in the 1970s and 1980s, its increase since the early 2000s is statistically significant, and it has almost doubled over the last ten years. Fukač offers various explanations in explaining these patterns. First, the share of consumer spending on oil and petroleum products, which fell in the 1990s, has increased to levels last observed in the 1970s in the United States. Second, the "financialization" of commodity markets may have contributed to the increase in oil pass-through. Since the early 2000s, non-energy commodity prices have become increasingly correlated with oil prices. Fukač noted that this situation is similar to the 1970s and early 1980s when non-energy commodity prices rose in tandem with oil prices. Third, he pointed out that the very accommodative stance of monetary policy during the global financial crisis, by stimulating inflation expectations, has probably contributed to a greater pass-through. Paradiso and Rao (2012) showed that the pass-through of oil prices into inflation exhibits an upward trend in the United States and Australia. The pass-through became significant from 1992 in the United States and from 2001 in Australia. Millard and Shakir (2013) found that the impact of oil shocks has increased since the mid-2000s in the UK, they emphasized that this upward movement coincided with the United Kingdom's transition from being a net exporter to a net importer of oil. Oinonen and Paloviita (2014) also highlighted the growing impact of oil prices on inflation in the Euro area over the period 1991–2014.

3. BACKGROUND ON THE RELATIONSHIP BETWEEN OIL PRICES AND INFLATION

This section provides a brief overview of the evolution of oil prices and domestic inflation. This review of the facts should help better understand the relationship between oil prices and inflation over the period 1991–2016 in the eight countries studied.

3.1 The evolution of oil prices over the period 1991–2016

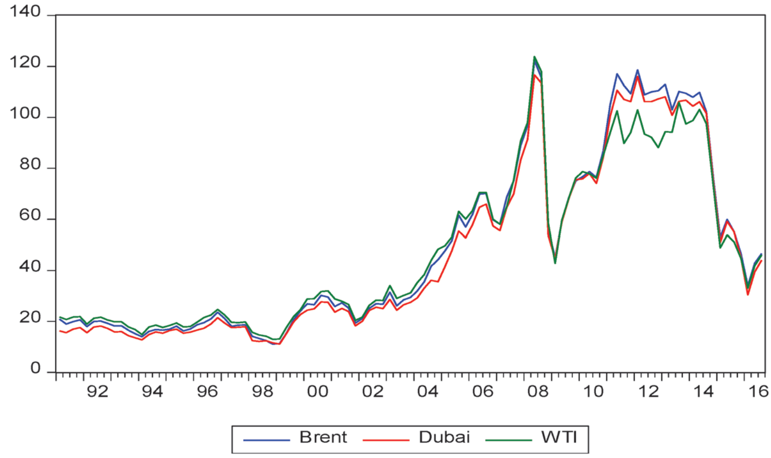
We use the crude oil spot price as the nominal price of oil and we consider the most appropriate crude oil price for each geographical area: Brent for European countries, West Texas Intermediate (WTI) for North American countries, and Dubai Fateh for the countries of the Asia-Oceania region. Figure 1 plots oil prices from 1991:Q1 to 2016:Q2, quarterly oil prices are calculated from an average of monthly crude oil prices, taken from the World Bank Commodity Price Data.

Differences in the prices of these various crude oils are related to quality features,[1] transportation costs from production areas to refineries, and regional and global supply and demand conditions, including refinery utilization. We observe that prices track each other very closely and remain within a fairly tight range until the end of 2010, with small occasional jumps outside of this band. For years, the WTI price has been slightly higher than the Brent and Dubai prices due to the steadily growing crude oil consumption in the United States in conjunction with declining domestic production, which has made the United States increasingly dependent on foreign oil imports from the 1990s until 2010. But by the end of 2010 this longstanding condition had changed: WTI became cheaper than Brent and Dubai, the spread reaching up to $23 per barrel in the third quarter of 2011. US oil production has experienced a revolution since 2009 due to the exploitation of vast shale oil deposits, which has enabled US crude oil production to reach levels not seen since the early 1990s. At the same time, the war in Libya and the gradual decline in production from the North Sea fields has created price pressure.

Like all commodities, the oil price is volatile. But it is particularly prone to episodes of sharp rises or falls related to the geopolitical situation and the decisions of "Organization of Petroleum Exporting Countries (OPEC)". Oil prices showed relative stability during the 90s, until the Asian crisis of 1998 and 1999, when global oil demand slowed in relation to supply. A significant increase in excess capacity in oil production then pushed down oil prices to around 10 US dollars. The period 2000–2003 was marked by relative stability of prices within a band of variation (25–35 dollars per barrel), as targeted by OPEC following the collapse of prices in 1998. The years 2004–2008 are characterized by an explosion in oil demand driven by strong global economic growth, both in emerging countries and in the United States: prices soar to 100 US dollars. The period 2008–2009 was marked by three successive phases: oil prices reached a peak of more than 120 dollars in the second quarter of 2008; then a downwards spike from the effects of the economic crisis in 2008; and prices increased at the end of 2009, reaching 75 dollars per barrel. In the second quarter of 2011, a

1. For example, API gravity (density) or sulfur content. WTI, Brent, and Dubai, have an API gravity respectively of 39.6, 38.3, and 31 degrees and contain respectively 0.24%, 0.37%, and 2% sulfur.

Figure 1: Oil prices in US dollars per barrel



barrel of Brent or Dubai exceeded 110 dollars. At the time, this upward trend was explained by an increase in production costs affecting the entire energy sector. Several phenomena combined: global oil consumption increased sharply again after 2010, driven by demand from emerging countries. But because of production quotas, supply did not follow. Political unrest in North Africa and the Middle East also had an effect, and speculation amplified the movement. Oil prices remained anchored over the period 2011–2013, up until June 2014, in the range of $100–120 per barrel. Through much of 2012 and 2013 the impact of softening global demand on oil markets was offset by concerns about geopolitical risks and pricing policies implemented by OPEC. The geopolitical context, which was regularly strained, helped keep the price at a high level—Arab revolutions, tensions with Iran, the Russia-Ukraine conflict, the advances of Daesh in Iraq. The sharp fall in oil prices since June 2014 could be explained by the combination of several factors: moderate economic growth, the rise in the dollar exchange rate, excess supply, and a change in OPEC policy. The cause of the abundant supply is no mystery: this is American LTO ("Light tight oil"), that is to say the shale oils whose annual growth has continued to accelerate since 2010. The OPEC decision in November 2014 not to change its quotas, and thus to allow the market to rebalance by price, removed the last barrier to the plummeting oil prices. Prices continued to fall during 2015, hitting $30 per barrel at the beginning of 2016, representing a decrease of 70% compared to June 2014. Then crude oil prices rose slightly, reaching up to $40 per barrel in the second quarter of 2016.

3.2 The relationship between inflation and oil prices

It is widely accepted that changes in oil prices are partially passed through to inflation. Historically, oil price fluctuations and inflation have been positively correlated, even though this relationship has varied widely over time and from country to country.

Rising oil prices affect inflation through several transmission channels. First, oil prices increases have a direct effect on the prices of refined products. Assuming that other prices are downwardly rigid, an external inflationary shock increases the domestic price level. Secondly, the rising oil price has an indirect impact on consumer prices through producer prices. Because oil is an input for firms, companies may adjust the prices of final goods and services in accord with changes in energy prices, which leads to inflation. There may also be medium-term repercussions on headline inflation if oil price increases translate into higher inflation expectations. The second-round effects of higher oil prices occur when consumers are not willing to accept lower real income caused by the first round effects and demand higher wages. Oil price increases may therefore trigger a wage-price spiral. It is only in this second round that core inflation, excluding the prices of petroleum products, is significantly affected. Fluctuations in oil prices ought therefore to be transmitted to the domestic price level.

The data series for the consumer price index (CPI) and the bilateral exchange rates with the US dollar are extracted from the OECD Database. The inflation rate is calculated as the annualized quarterly change of the consumer price index: $\pi_t = 400 \times Ln(CPI_t / CPI_{t-1})$. On the basis of the bilateral exchange rate with the US dollar, oil prices are expressed in domestic currency to account for potentially offsetting exchange rate movements. Finally, they are divided by the consumer price index (CPI) to obtain the real price of oil.[2] Summary descriptive statistics relative to real oil price growth rate and inflation rate are reported in Table 1. The average inflation rate ranges from 0.31% in Japan to 2.62 % in Italy, while the average real oil price growth rate ranges from 0.28 % in the US to 0.82 % in Japan. The coefficient of variation indicates a high real oil price growth rate dispersion over the period 1991–2016. The highest dispersion is recorded in Japan for the inflation rate and in the US for the real oil price growth rate.

Figure 2 plots real oil price growth rate and inflation rate for each country. The graphs show that the Great Recession related to the US financial crisis led to a dramatic collapse in oil price in late 2008, which resulted in a sharp drop in inflation. The magnitude of the effect on inflation depends on the country, but is particularly marked in North American countries, especially in the United States. However, we observe that the oil prices-inflation relationship is not always so clear-cut. Some national events strongly affect the inflation rate.[3]

Table 1: Descriptive statistics

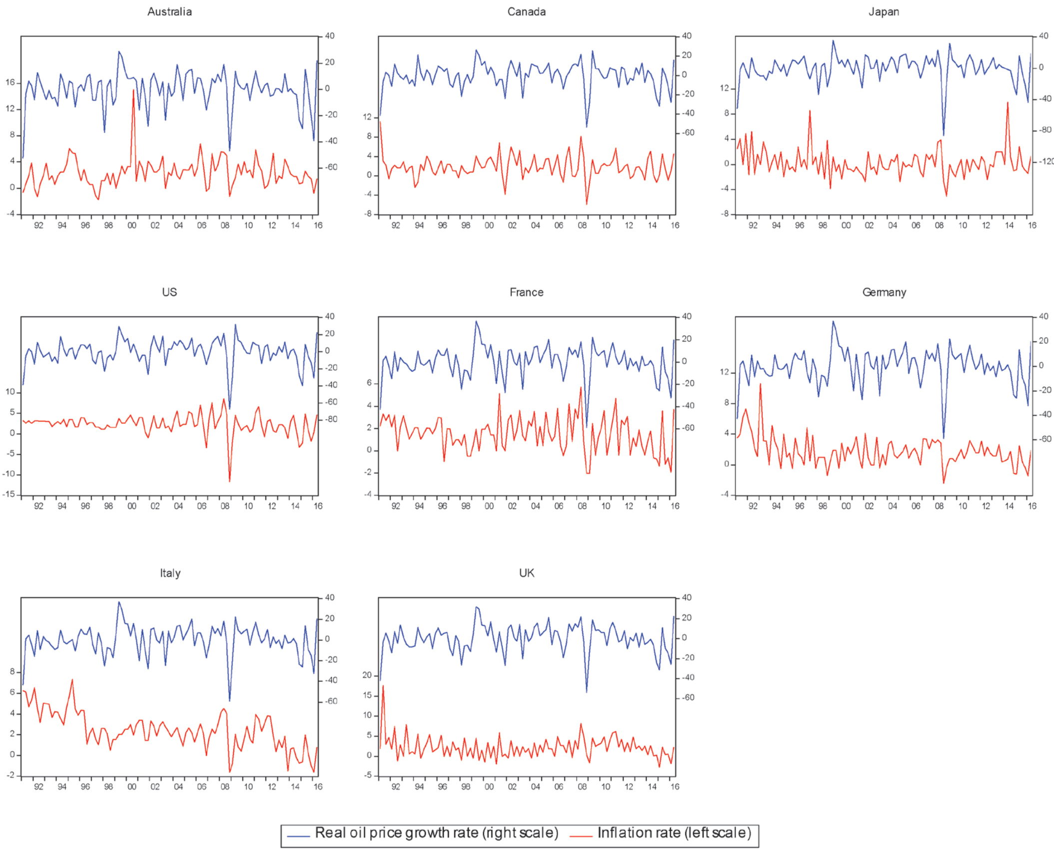
	Inflation rate (%)					Real oil price growth rate (%)				
	Mean	Max	Min	Std. Dev.	CV (%)	Mean	Max	Min	Std. Dev	CV (%).
Canada	1.88	11.32	–5.95	2.34	124.47	0.38	26.62	–53.64	12.51	3292.10
US	2.37	8.54	–11.70	2.42	102.11	0.28	31.84	–67.31	13.88	4957.14
Australia	2.46	15.03	–1.73	2.20	89.43	0.32	28.94	–52.54	12.78	3993.75
Japan	0.31	9.93	–5.11	2.27	732.26	0.82	35.53	–85.52	15.54	1895.12
UK	2.32	17.59	–1.96	2.69	115.95	0.52	31.98	–53.92	13.22	2542.30
France	1.58	5.71	–2.04	1.48	93.67	0.59	36.99	–58.98	13.59	2303.39
Italy	2.62	7.36	–1.63	1.70	64.89	0.33	36.96	–59.08	13.70	4151.51
Germany	1.86	10.62	–2.42	1.90	102.15	0.52	37.00	–58.88	13.64	2623.08

Note: Our calculations on OECD and World Bank Commodity Price Data. CV denotes the coefficient of variation (%).

2. This variable is defined as it is used in the oil-augmented Phillips curve thereafter.

3. In Australia, the rise in consumer prices accelerated sharply in the third quarter of 2000, due to the July 1 replacement of the wholesale sales tax by a tax on goods and services whose base is much wider. In Japan, the increase in VAT from 3% to 5% in April 1997 and from 5% to 8% in April 2014 caused an increase in prices. German reunification resulted in inflationary pressures over the period 1990–1993. In May 2001, the annual rate of inflation peaked in France, with the prices of unprocessed food products being the main factor behind the rise. The increase in prices of these products was driven primarily by health concerns related to the occurrence of cases of bovine spongiform encephalopathy (BSE) in several countries in the Euro area. France was the most impacted by the "food crisis".

Figure 2: Oil prices and inflation over the period 1991:Q1-2016:Q2



4. THEORY AND EMPIRICAL METHODOLOGY

Since the works of Hooker (2002), Leblanc and Chinn (2004), De Gregorio et al. (2007), and Chen (2009a), the usual framework for studying the relationship between inflation and crude oil price has been the oil-augmented Phillips curve. In the traditional Phillips curve, inflation is related to the output gap and lagged values of inflation. The lagged variables are designed to capture inflation persistence. In the oil-augmented Phillips curve, the exogenous crude oil prices are added into the specification, as a measure of supply shocks. The innovative aspect of our approach is to estimate an oil-augmented Phillips curve with, firstly, an unobserved components model to take into account the persistence of inflation, and, secondly, with coefficients assumed to vary over time to allow for asymmetry and structural breaks which may exist in the relationship.

4.1 The oil-augmented Phillips curve

The New Keynesian Phillips curve (NKPC) has become the canonical model of inflation in the academic community. It can be view as a structural model because it has theoretical microeconomic foundations that explain nominal price rigidities in the economy.[4] The NKPC suggests

4. The New Keynesian Phillips Curve (NKPC) is derived from the Calvo model (1983), which combines staggered price-setting by imperfectly competitive firms and the use of rational expectations by private sector agents.

that current inflation depends on expected inflation and a proxy for real economic activity, such as marginal cost or output gap (Rotemberg, 1982; Calvo, 1983). The NKPC curve can be formulated as follows:

$$\pi_t = \alpha\, E_t\,(\pi_{t+1}) + \beta\, y_t^{gap} + \varepsilon_t, \varepsilon_t \sim NID\,(0, \sigma_\varepsilon^2),\;\; t = 1, \ldots, T \quad (1)$$

where π_t is the rate of inflation, $E_t(\pi_{t+1})$ is the unobservable expected rate of inflation for period $t + 1$ conditional on information available at time t, y_t^{gap} is a measure of the output gap.

In order to introduce some persistence in the purely forward-looking model, Fuhrer and Moore (1995) introduced lagged inflation in the Phillips curve. This is commonly referred to as the hybrid New-Keynesian Phillips curve:

$$\pi_t = \gamma\, \pi_{t-1} + \alpha\, E_t\,(\pi_{t+1}) + \beta\, y_t^{gap} + \varepsilon_t, \varepsilon_t \sim NID\,(0, \sigma_\varepsilon^2),\;\; t = 1, \ldots, T \quad (2)$$ [5]

Blanchard and Gali (2007b) structurally embedded, in addition to the driving variable, the change in real price of a non-produced good in the economy, representing an observable equivalent of a supply shock term. This term may empirically capture effects such as commodity prices changes or other supply side factors (Dufour et al. 2010a, 2010b). To answer to the research question that is raised in the present study, we added the price of crude oil in the specification, as a measure of supply shock (Hooker, 2002; Leblanc and Chinn, 2004; De Gregorio et al., 2007, and Chen, 2009a). Then the oil-augmented Phillips curve can be written as follows:

$$\pi_t = \gamma\, \pi_{t-1} + \alpha\, E_t\,(\pi_{t+1}) + \beta\, y_t^{gap} + \varphi\, \Delta oil_t + \varepsilon_t, \varepsilon_t \sim NID\,(0, \sigma_\varepsilon^2), t = 1, \ldots, T \quad (3)$$

where Δoil_t is the quarterly percentage change in crude oil prices.

4.2 Modelling the oil-augmented Phillips curve with unobserved components

Crucial as they are, however, the output gap and inflation expectations cannot be observed, so they must be estimated. As far as inflation expectations are concerned, different empirical approaches are usually used[6]. All these approaches can be implemented using the Generalized Method of Moments (Hansen, 1982). Many authors, including Jondeau and Le Bihan (2005), Mavroeidis et al. (2014), highlighted difficulties in estimating equations (1) to (3) and emphasized that relatively innocuous changes in instruments used, as well as in vintage of data and in model selection, significantly affect the results.

These difficulties, incurred by estimation of unobservable variables, can be overcome by using structural time series models (Harvey and Koopman, 1997). These models are explicitly based on the stochastic properties of the data. They are formulated directly in terms of unobserved components time series models and have a natural state-space representation (Harvey, 1989). The key feature of this class of models is the decomposition of a time series into trend, seasonal, cycle, and irregular components, which have a direct interpretation. Each component is formulated as a stochastically evolving process over time. The estimates of trend and cyclical components in real GDP are particularly suitable for measuring the output gap (Clark, 1987; Harvey and Jaeger, 1993, Har-

5. This specification can be generalized by introducing additional lags and leads of inflation (Taylor, 1980; Fuhrer and Moore, 1995; Fuhrer, 1997).

6. Mavroeidis et al. (2014) classify them as follows: the first uses instrumental variables to compute a proxy for inflation expectations, the second derives expectations from a particular reduced-form model as a VAR, and the latter uses survey measures.

vey and Koopman, 1997). Recent literature (including Stock and Watson, 2007; Cogley and Sbordone, 2008; Cogley et al., 2010; Harvey, 2011, and Stella and Stock, 2015) supports the view that the trend component of inflation can be considered as a target inflation, as a latent random walk.[7]

In line with the seminal work of Harvey (2011), we use an unobserved components decomposition of the real GDP to estimate the output gap and consider a model in which lagged inflation is replaced by an unobserved random walk component. The role of the random walk component is to capture the underlying level of inflation. Since the output gap and the percentage change in crude oil prices are stationary, the long-run forecast is the current expected value of the random walk. This is usually considered as a definition of core inflation. Eckstein (1981) defines core inflation as the expected inflation variable in a Phillips curve equation relating headline inflation to expected inflation, the output gap, and aggregate supply shocks.[8] Furthermore, we estimate time-varying coefficients using the state-space method with Kalman filtering techniques (Harvey, 1989; Hamilton, 1994; Durbin and Koopman, 2001). This method is better suited than rolling regressions, because it uses available information more efficiently and avoids the need to choose an estimation window.[9]

Following Harvey (2011), a simple version of the oil-augmented Phillips curve with unobserved components can be specified as:

$$\pi_t = \mu_t + \gamma_t + \psi_t + \beta y_t^{gap} + \varphi\, \Delta oil_t + \varepsilon_t, \varepsilon_t \sim NID\,(0, \sigma_\varepsilon^2),\ \ t = 1, \ldots, \mathrm{T} \tag{4}$$

where μ_t is a random walk, γ_t is the seasonal component, ψ_t is the cycle component, and ε_t is the irregular component.

Equation (4) can be extended to a model with time-varying parameters:

$$\pi_t = \mu_t + \gamma_t + \psi_t + \beta_t y_t^{gap} + \varphi_t\, \Delta oil_t + \varepsilon_t, \varepsilon_t \sim NID\,(0, \sigma_\varepsilon^2), t = 1, \ldots, \mathrm{T} \tag{5}$$

The coefficients β_t and φ_t are assumed to vary over time according to a random walk process:

$$\beta_t = \beta_{t-1} + u_t, u_t \sim NID\,(0, \sigma_u^2),\ \ t = 1, \ldots, \mathrm{T} \tag{6a}$$

$$\varphi_t = \varphi_{t-1} + v_t, v_t \sim NID\,(0, \sigma_v^2),\ \ t = 1, \ldots, \mathrm{T} \tag{6b}$$

Although this model has a simple form, it is not an artificial special case; it provides a basis for analysis of important problems in actual practice time series.

The additional parameters σ_u^2 and σ_v^2 will be estimated simultaneously with the other parameters. Details on the unobserved components models specification are reported in Appendix. These models belonging to the class of state-space models (Harvey, 1989), and can be estimated by using the Kalman filter.

5. RESULTS AND DISCUSSION

Quarterly data are used for the eight countries over the period 1991 to 2016. The series for the consumer price index (CPI), the gross domestic product GDP, the GDP deflator, and the bilateral exchange rates with the US dollar are extracted from the OECD Database. Oil prices are taken

7. Nason and Smith (2013) point out that “the trend-cycle model with unobserved components is consistent with numerous studies of US inflation history and is of interest partly because the trend may be viewed as the Fed’s evolving inflation target or long-horizon expected inflation”.

8. See also Bryan and Ceccheti (1994) and Cogley (2002).

9. With this approach, model parameters can be updated optimally for every period, which is to allow for all Phillips curve parameters to change simultaneously in response to new information and structural changes.

from World Bank Commodity Price Data. The starting date of the estimation period is determined by the availability of the data for almost all countries concerned, except for Japan for which GDP is available from 1994. The inflation rate is calculated as indicated above (see 3.2). Output is measured by the logarithm of quarterly real GDP, the latter being calculated using the GDP deflator. We use the bilateral exchange rate with the US dollar and the consumer price index (CPI) to determine the real spot price for crude oil expressed in domestic currency. In the traditional Phillips curve, supply shocks are usually associated with changes in the relative imports prices or international commodity prices, for example oil prices. It is therefore relevant to consider the real oil price (Mehra, 2004; Hooker, 2002; Van den Noord and André, 2007; Gordon, 2013). Moreover, as advocated by many authors, including De Gregorio et al. (2007), Van den Noord and André (2007), Oinonen and Paloviita (2014) and Baffes et al. (2015), the price of oil is measured in domestic currency.[10]

5.1 Estimating constant coefficients models

The model in equation (4) was estimated using the STAMP software by Koopman et al. (2009). Including the cycles gives a better fit and improves diagnostic tests only in the case of the UK, so for other countries we have not included the cycles. For Australia, the seasonal component was not significant in a two-tailed test at the 5% level, so the component is not included.[11]

In order to get the best fit, the output gap and the oil price can be lagged. We tested different structures by introducing up to four lags. The output gap of lag one seems to give the best fit for Canada, the United States, Germany, and Japan; a lag of three quarters provides the best fit in the case of Australia. For the other three countries, a contemporaneous output gap provides a good fit. Concerning oil price, the contemporaneous effects are the most relevant, this means that there is a rapid transmission of oil price changes to headline inflation. Autoregressive distributed lag models are often used but the estimates are erratic and difficult to interpret (Harvey, 2011), and that is why we selected models with only one lag (from 0 to 4) for each variable. According Koopman et al. (2009, p36), since the estimation procedure converges and the diagnostics appear satisfactory, we can be reasonably confident that we have estimated a sensible model. Some dummy variables are used to take account of outlying observations, related to national events which strongly affect the inflation rate. These variables take the value one at the time of the outlier and zero elsewhere, insuring normality. We have introduced the following dummy variables: D2000Q3 in Australia, D1997Q2 and D2014Q2 in Japan, D2000Q3 in France, D2008Q4 in the United States, and D1991Q4, D1993Q1 and D1999Q1 in Germany (see 3.2).

Table 2 reports the estimation of the model in Equation (4). The diagnostic tests are generally very satisfactory, except the heteroskedasticity test for the United States. Furthermore, as endogeneity of the output gap is largely supported by most empirical work published on the NKPC, we checked that results are not affected by potential endogeneity. We found no statistically significant relationship between residuals of the unobserved components models and the output gap. Moreover, we estimated bivariate unobservable components models, where inflation and GDP are modelled jointly (Harvey, 2011). We observed that single equation (the augmented Philipps curve) and bivariate models deliver similar results for all countries concerning both the unobserved components and the oil price coefficients. This result has already been underlined by Harvey for the US. So outcomes

10. One implication of this is that exchange rate changes affect inflationary pressures arising from oil price increases. For example, if a currency appreciates relative to the dollar, the corresponding increases in exchange rates dampen the price increases in local currency of oil resulting from the rise in the dollar price of oil.

11. Results are found to be robust to different specifications.

Table 2: Augmented Philips-curve estimation with fixed coefficients

	Canada	US	Australia	Japan	UK	France	Italy	Germany
μ	0.017	0.014	0.018	0.004	0.005	0.005	–0.008	0.007
	(0.00)	(0.00)	(0.00)	(0.23)	(0.45)	(0.23)	(0.07)	(0.11)
y^{gap}	0.348	0.603	0.651	0.302	0.386	0.416	0.496	0.265
	(0.04)	(0.00)	(0.06)	(0.00)	(0.05)	(0.00)	(0.00)	(0.00)
Δoil	0.086	0.072	0.039	0.021	0.050	0.058	0.028	0.065
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
D1		–0.077	0.118	0.066		0.021		0.058
		(0.00)	(0.00)	(0.00)		(0.00)		(0.00)
D2				0.082				0.052
				(0.00)				(0.00)
D3								–0.022
								(0.00)
T	101	102	99	89	102	102	102	101
PEV	2.21E–04	1.55E–04	2.38E–04	1.5E–04	2.46E–04	6.83E–05	7.78E–05	7.86E–05
R^2	0.64	0.78	0.44	0.74	0.58	0.73	0.45	0.82
N	4.26	5.56*	0.49	3.57	0.64	2.44	4.03	1.00
H	0.47	2.19**	0.84	0.95	0.94	0.84	0.99	0.40
Q	10.63	17.97*	6.56	6.44	7.43	10.67	11.48	6.51

Notes: The coefficients μ are those estimated in the final state, that is to say for the second quarter of 2016. P-values are in brackets.
PEV is the predictive error variance. N is the Bownan-Shenton normality test statistic having a χ^2 distribution with 2 degrees of freedom when the model is correctly specified. H is the heteroskedasticity test statistic calculated on the first h residuals when h is set to the closest integer of T/3. It has an F distribution with (h,h) degrees of freedom. Q is the Box-Ljung statistic based on the p first autocorrelations, and should be tested against a χ^2 distribution with q degrees of freedom, q is set equal to $p + 1$ minus the number of parameters. For these three statistics, the asterisks ***, **, and * denote the rejection of the null hypothesis at the 1%, 5%, and 10% levels respectively.

appear robust to different specifications and provide some confidence that endogeneity does not affect results.

Several findings can be highlighted. Core inflation is very low but differs widely across countries, ranging from –0.08% in Italy to 1.8% in Australia for the second quarter of 2016; we observe that the final state coefficients are only significant at the 5% level in Canada, the US and Australia. The path of the level component μ, representing core inflation, is plotted with a 95% confidence interval in Figure A1 in the appendix. The evolution of core inflation differs widely from country to country. In Japan, core inflation is not significant at the 5% level over the whole period 1996–2016. Japan has experienced 15 years of deflation since the mid-1990s. For other countries, core inflation is mostly significantly positive at the 5% level. But, it stands at a low level at the end of the period in European countries, close to 1%. In Canada, the US and Australia, the final state coefficients remain close to the 2 per cent inflation target, suggesting a better anchoring of inflation expectations in these countries. The output gap coefficient estimates are significant in a two-tailed test at the 5% level, except for Australia, where it is significant at the 10% level. All of the estimated coefficient are positive, suggesting that the output gap continue to drive inflation, consistent with the standard Phillips curve intuition. Coefficients range from 0.265 for Germany to 0.651 for Australia. This means that an output gap of 1% above trend is associated with an annual inflation rate that is 0.27% above core inflation for Germany and 0.65% for Australia. It appears that in Australia and in the United States, prices rise more strongly in response to demand pressure. We observe that oil prices play a significant role in inflation dynamics over the period in all countries, but the inflationary effect of oil price varies across countries: from 0.021 for Japan to 0.086 for Canada. That is, a 10% increase in the oil price leads to an increase in headline inflation of 0.21% in Japan and of 0.86% in Canada.

These findings provide empirical evidence that the Phillips curve is alive and oil prices still influence the dynamics of inflation. Results point out that the pass-through is significant over the period 1991–2016. They are consistent with those of Fukač (2011), Paradiso and Rao (2012) and Millard and Shakir (2013), who highlight that oil price is still a significant driver of inflation and show that the pass-through has increased since the mid-2000s. It therefore seems important to deepen the analysis by studying the evolution of the pass-through over the study period.

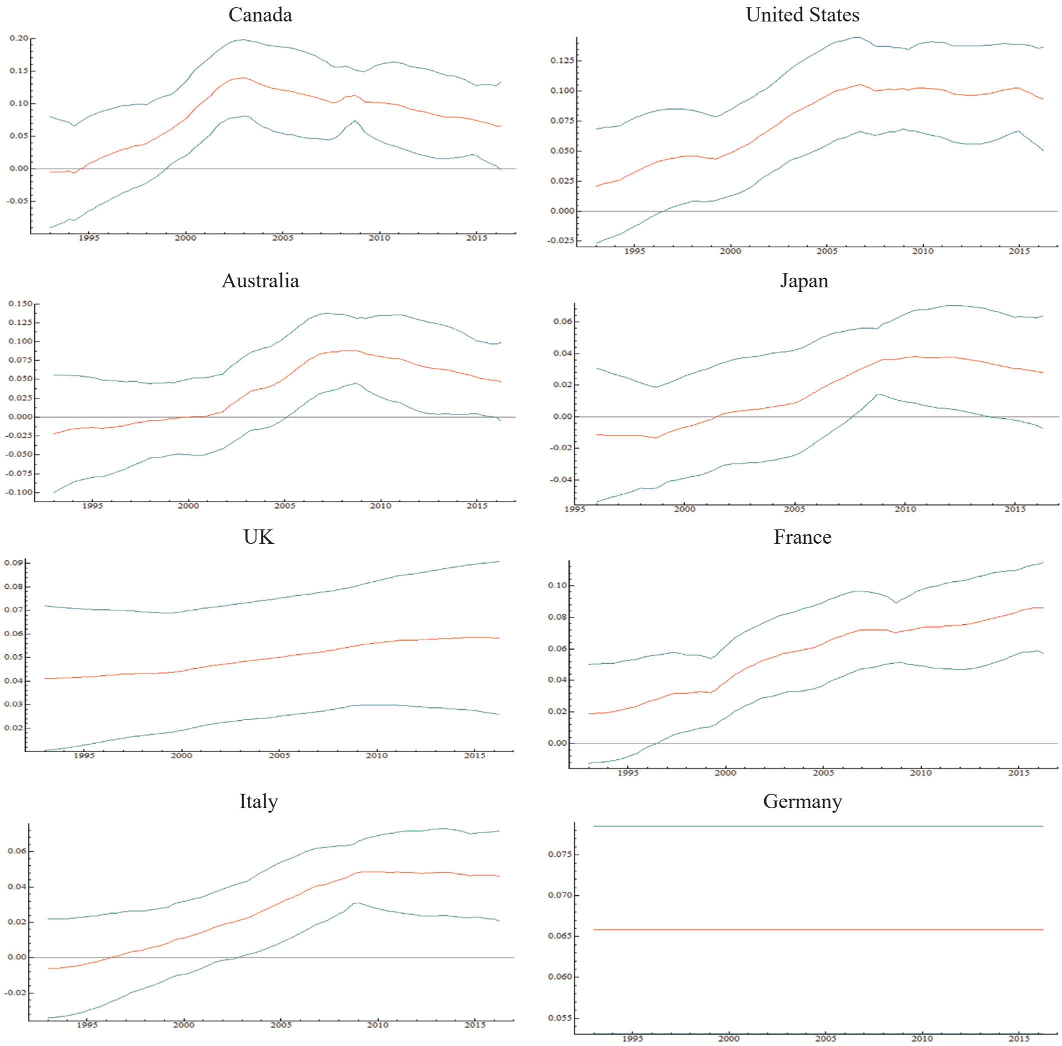
5.2 Estimating time-varying coefficients models

We estimated an augmented Phillips curve with time-varying coefficients according to the equations (5) and (6). The estimators of maximum likelihood parameters of states obtained by applying the Kalman filter technique allow us to track the temporal evolution of the coefficients β_t and φ_t, as well as that of the level component μ_t. The study is carried out from the graphical analysis of these parameters. With a graphical examination of the temporal evolution of these coefficients, we are able to examine whether the coefficients change over time and in particular if the oil pass-through is declining. We initially assumed a time-varying process for both coefficients associated with the output gap (β) and with the variation of oil price (φ); but when it turned out that one coefficient does not vary in time, we re-estimated the specifications by imposing the constancy of the coefficient. We checked that results are robust to different specifications.

As the scope of this research is to investigate the effects of oil price change on inflation, we focus mainly on the temporal evolution of the oil pass-through.[12] The time varying paths of the oil pass-through coefficient φ are plotted with a 95% confidence interval in Figure 3. The graphs reveal that, despite some differences between countries, oil pass-through overall shows an upward trend over the whole period in almost all countries. These findings are in line with those of Paradiso and Rao (2012) and Oinonen and Paloviita (2014). We note that the oil pass-through coefficient is significant at the 5% level over all the period in Germany and the UK, while it became significant at the 5% level at the end of the 1990s in the US, Canada and France and rather later (around 2005) in Italy, Australia and Japan. With the exception of Japan, the oil pass-through coefficient remains significant until the end of the period. Highlighting the growing impact of oil prices on inflation since the 2000s, our results corroborate those obtained by Fukač (2011), Paradiso and Rao (2012), Millard and Shakir (2013) and Oinonen and Paloviita (2014), and extend them to other countries. Indeed, except in Germany where the pass-through is constant, in other countries it has evolved throughout the period. The sustained rise in oil prices during the period 2003–2008 resulted in a strong increase of the pass-through in all countries, except in Canada. Then, the pass-through evolves differently in each country. Thus it peaked at 0.11 in the United States, at 0.09 in Australia, at 0.025 in Japan, and at 0.045 in Italy in 2008. Then it stabilized in some countries, namely in Italy and in the United States and started to decline from around 2009 in Japan and Australia. By contrast, the oil pass-through continues to increase at the end of the period in France and in the UK and peaks at 0.085 and 0.06 respectively. That is, a 10% increase in the oil price leads to an increase in headline inflation of 0.85% in France and of 0.6% in the UK. Our results are very close to the values estimated by

12. The results relating to the coefficients associated with the level component (μ) and the output gap (β) are reported in figures A1 and A2 in appendix. The temporal evolutions of the level component are similar to those obtained with constant coefficient models. We find deep changes in the relationship between the output gap and inflation over the period considered. The output gap continued to drive the inflation rate in most countries, but the magnitude of the effect varies widely over time and from country to country.

Figure 3: Time varying paths of the oil pass-through coefficient φ with 95% confidence interval



Oinonen and Paloviita (2014) over the period 1990–2014 for the euro area, ranging from 0.025 in 1990 to 0.08 in 2014.

The inflationary effect of oil price varies across countries, ranging from 0.03 in Japan to 0.1 in the United States in 2016. These disparities stem from structural differences between countries, such as their dependence on oil, the energy intensity, or the degree of nominal rigidities in their respective economies. Our results indicate that the estimated impact of oil price changes on consumer price inflation is particularly marked in North American countries.

It has doubled over the last fifteen years in the United States—this result is also found by Fukač (2011)—rising from 0.05 in 2000 to almost 0.10 in 2016. That means that a 10% increase in the oil price passes through to an increase of 1% in inflation in the United States in 2016. In Canada, the oil pass-through has been above 0.08 since 2000 and reached a record level in 2003, a year in which it stood at 0.14. These findings confirm that changes in oil prices have a greater effect on domestic inflation in countries most heavily dependent on oil. A lower pass-through in European countries and in Japan can be explained by the lower oil intensity of the economy and the higher proportion of taxes in oil prices in these countries. The higher the fuel tax wedge, the smaller the proportional impact on prices of a given rise in oil prices.

Overall, our results provide strong evidence in favor of time-varying oil pass-through, and emphasize that oil price movements remain an important component of headline inflation over the period 1991–2016. Oil prices exert strong deflation pressure in all countries over the recent period.

Furthermore, the results obtained using unobserved components model and time-varying specifications, suggest that oil-augmented Phillips curve model is still relevant for tracking short-run inflation dynamics and making monetary policy. In the NKPC framework, oil price shocks can affect inflation from the supply side. Since these shocks are transitory and volatile,[13] they do not impact the underlying inflation rate and do not trigger monetary policy responses. When confronted with oil price fluctuations, central banks favour a medium or long-run approach to price stability by avoiding second-round effects but by letting first-round effects on prices play out (Natal, 2012). For example, the Fed explicitly targets core inflation, the ECB targets headline inflation, but only over medium term, so that transitory fluctuations are ignored.

What is more, the response of monetary policy can vary greatly depending on the nature of the oil shocks (supply-driven or demand-driven) and their impact on aggregate demand (Kilian, 2009; Kilian and Lewis, 2011). These differences may explain some of the changes in the oil pass-through over time.[14] Nevertheless, if the oil shocks are persistent, they can lead to a second-round effect, through the price-wage loop, that can impact inflation expectations and therefore require central banks to intervene. In this case, they may respond to oil price fluctuations by changing short-term interest rates (Bernanke et al., 1997). Over the medium and long term, it is therefore essential that policymakers adjust the stance of monetary policy in order to maintain stable inflation expectations. Once an inflationary/deflationary spiral is underway, it can be difficult and costly to reverse.

The long period of sharp drop in oil prices initiated in June 2014 has led to a decrease in inflation rates and has prompted policymakers to become worried about potential second-round effects. In a context of falling oil prices with a weak global growth environment and with nominal interest rates constrained by the zero lower bound in the advanced economies, monetary policy may have to react forcefully to stimulate economic activity, maintain the anchoring of inflation expectations, and prevent deflation risks.

Figure A1 in the appendix shows that, in all countries except in Canada, core inflation has been steadily declining since mid-2014. It stands at a low level and remaining significantly positive with a few exceptions. These results suggest that inflation expectations certainly helped to drag the inflation rate down, but not so far as to bring it into a deflation regime. The credibility of monetary policy and the anchoring of inflation expectations at low levels have so far avoided the risk of deflation. Market participants continue to believe in the ability of central banks to bring inflation back to its target. In most countries, the commitment of central banks to a 2% inflation target has kept expected inflation close to 2%, which in turn has prevented actual inflation from falling very far below that level. The sluggish economic environment following the financial crisis led central banks to implement unconventional policies known as "quantitative easing". These consist of massive purchases of securities by central banks to stimulate the economy by injecting liquidity and thus curbing deflationary pressures when interest rates are close to zero. The use of unconventional

13. Using micro-data, Dhyne et al. (2006) highlighted a marked heterogeneity in the frequency of price adjustment. In particular, energy prices change considerably more frequently than those of other goods and services.

14. "Disentangling cause and effect in the relationship between oil prices and economy requires structural models of the global economy including the oil market" (Kilian, 2009). But this topic goes well beyond the scope of our study.

monetary policies has prevented unanchored inflation expectations. Following the drop in inflation expectations in Japan and in the European countries (see Figure A1 in the appendix), coinciding with the downturn in oil prices in mid-2014, central banks have greatly loosen monetary policy providing forward guidance to fend-off medium-term deflation risks (Baffes et al., 2015; Kuroda, 2015).[15] However, inflation expectations are found to be more firmly anchored in the US, Canada and Australia.

6. CONCLUSIONS AND POLICY IMPLICATIONS

Understanding inflation dynamics is especially important today due to the very low inflation levels prevailing in many countries. The aim of this paper was to investigate the oil pass-through into inflation for eight industrialized countries over the period 1991–2016. This issue is of increasing interest for policymakers in a low inflation environment coupled with a sustained fall in oil prices. Indeed, monetary authorities need to understand the impact of oil price changes on inflation to prevent the risk of deflation and to implement appropriate policies.

In order to estimate the impact of oil prices on headline inflation, we used an oil-augmented Phillips curve with unobserved components. These models are based on modelling the observed structure of the data. This framework allows us to avoid the usual problems of measuring output gap and inflation expectations arising from the estimation of an augmented Phillips curve. Moreover, we consider time-varying coefficients models which are particularly well suited to account for behavioral changes.

Our results have important implications for the implementation of monetary policy. First, they give a clear indication that the Philips curve coefficients have changed over time, suggesting that central banks ought not rely on a stable Phillips curve for setting monetary policy. Secondly, although low, core inflation remains positive even at the end of the period, except in Italy in the first half of 2016, suggesting that the credibility of monetary policy and the anchoring of inflation expectations at low levels have so far avoided the risk of deflation. The use of unconventional monetary policies has prevented unanchored inflation expectations. However, inflation expectations are found to be more firmly anchored in the US, Canada and Australia. Thirdly, inflation reacts strongly in response to demand pressure in the United States and Australia. For other countries, the relationship between inflation and the output gap is much more tenuous, implying that an accommodative monetary policy is less likely to trigger the upward drive in prices necessary to compensate for falling inflation expectations, even in situations where monetary policy has been successful in stimulating economic activity. Fourthly, the oil pass-through into inflation is highly significant for all the countries over the period 1991–2016. This is evidence that even over a low and stable inflation period, oil prices continuing to play a significant role in the dynamics of inflation. Fifthly, despite some differences between countries, the oil pass-through has shown an upward trend over the period in almost all countries. We observe an increasing effect of oil prices on inflation since the early 2000s until the global financial crisis in all the countries except Germany; then it stabilizes and even starts to decline in the United States, Italy, Australia, and Japan. This break may result from the accommodative monetary policies put in place during the global financial crisis. Our results show that the pass-through is particularly high in North American countries, it has nearly doubled in the United States over the last fifteen years.

15. According to Kuroda (2015), "This decision was not made to respond to the decline in crude oil prices itself. It was made out of concern over a risk that the decline in crude oil prices affects inflation expectations through sluggish growth in the inflation rates, thereby delaying conversion of the deflationary mindset".

Our results suggest that central banks must continue to monitor oil prices fluctuations closely, especially when they are prolonged over time. Over the period 2014–2016, the persistence of low oil prices complicates the conduct of monetary policy. If the drop in oil prices persists over a long period, there is a risk that lower oil prices could add to deflationary pressures; inflation expectations could be de-anchored and could lead to a deflationary spiral. The situation could be more problematic in Europe and Japan, where slow economic growth and low inflation rates are combined with nominal interest rates constrained by the zero bound. Furthermore, in these countries inflation responds weakly to demand pressure. Monetary policy should react more forcefully to stimulate economic activity, to maintain the anchoring of inflation expectations, and prevent deflation risks.

Undoubtedly, oil pass-through into inflation will continue to interest both academics and policy makers for a long time. In future research it would be relevant to extend the analysis to oil-exporting countries. The decline in oil prices has clearly negative impacts on oil-exporting emerging economies. Some of these countries, which have relied on high oil prices to balance their budgets, could face serious financial difficulties. Central banks would have to balance the need to support growth against the need to maintain stable inflation and investor confidence in the currency.

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APPENDIX

Table A1: Some previous studies on oil pass-through into inflation

Authors	Period	Countries	Specification
Hooker (2002)	1962:Q1to 2000:Q1	US	APC with nonlinearities and structural breaks
Le Blanc and Chinn (2004)	1980:Q1 to 2001:Q4	US, UK, France, Germany, Japan	APC with asymmetric and non linear effects
Van den Noord and André (2007)	1971:Q2 to 2006:Q3	US, Euro area	Asymmetric APC
De Gregorio et al. (2007)	1962:Q1 to 2006:Q2	34 countries 12 countries	- APC with structural breaks - Rolling VAR
Blanchard and Gali (2007a)	1970:Q1 to 2005:Q4	US, UK, France, Germany, Italy, Japan	- VAR with a break in the mid-1980s - Rolling bivariate VAR
Chen (2009a)	1970:Q1 to 2006:Q4	19 industrialized countries	APC with time-varying parameters
Clark and Terry (2010)	1965:Q1 to 2008:Q2	US	Bayesian VAR
Fukač (2011)	1970:Q1 to 2010:Q4	US	Rolling VAR
Paradiso and Rao (2012)	1978Q1 to 2010Q3	US, Australia	APC with unobserved components
Millard and Shakir (2013)	1965:Q2 to 2011:Q1	UK	Time-varying parameter structural VAR
Oinonen and Paloviita (2014)	1990:Q1 to 2014:Q2	Euro area	APC with time-varying parameters

THE UNOBSERVED COMPONENTS MODEL

First, it is necessary to estimate the output gap; then the unobserved components model specified by equations (4) or (5) can be estimated.

Specification of the output gap

y^{gap} is obtained through an univariate trend-cycle decomposition.

A trend-cycle decomposition model is given by:

$$y_t = \mu_t + \psi_t + w_t,\ w_t \sim NID\,(0, \sigma_w^2),\quad t = 1, \ldots, \mathrm{T} \tag{7}$$

where μ_t represents the trend, ψ_t is a stochastic cycle, and w_t is white noise.

The stochastic trend component is specified as:

$$\mu_t = \mu_{t-1} + b_{t-1} + \eta_t,\ \eta_t \sim NID\,(0, \sigma_\eta^2),\quad t = 1, \ldots, \mathrm{T} \tag{8}$$

$$b_t = b_{t-1} + \zeta_t,\ \zeta_t \sim NID\,(0, \sigma_\zeta^2),\quad t = 1, \ldots, \mathrm{T} \tag{9}$$

where b_t is the slope. The irregular w_t, the level disturbance η_t, and the slope disturbance ζ_t are serially and mutually uncorrelated.

The statistical specification of a cycle, ψ_t, is as follows:

$$\begin{bmatrix} \psi_t \\ \psi_t^* \end{bmatrix} = \rho \begin{bmatrix} \cos\lambda_c & \sin\lambda_c \\ -\sin\lambda_c & \cos\lambda_c \end{bmatrix} \begin{bmatrix} \psi_{t-1} \\ \psi_{t-1}^* \end{bmatrix} + \begin{bmatrix} \kappa_t \\ \kappa_t^* \end{bmatrix},\quad t = 1, \ldots, \mathrm{T} \tag{10}$$

where ψ_t^* is an auxiliary variable of the cyclic component, it is necessary to write the cyclical term in a recursive form but has no special interpretation, λ_c is the frequency, in radians, in the range $0 < \lambda_c < \pi$, κ_t and κ_t^* are two mutually uncorrelated NID disturbances with zero means and common variance σ_κ^2, and ρ is a damping factor.[16] The disturbances w_t, ζ_t, κ_t, and κ_t^* are serially and mutually uncorrelated with variances σ_w^2 and σ_ζ^2 for the irregular and slope.

The statistical treatment can be performed with the Kalman filter, which is a recursive procedure which, combined with the Maximum-Likelihood method, provides an optimal estimate of the unobservable components. The smoothed estimate of the cycle is used as a measure of the output gap.

Model specification

The components of equations (4) and (5) can be specified as follows.

First, the component μ_t is specified as a random-walk-plus-noise model:

$$\mu_t = \mu_{t-1} + \eta_t, \eta_t \sim NID\,(0, \sigma_\eta^2),\quad t = 1, \ldots, \mathrm{T} \tag{11}$$

where the disturbances ε_t and η_t are serially and mutually uncorrelated.

Secondly, the seasonal component has the trigonometric seasonal form and is given by

16. Note that the period is $2\pi/\lambda_c$. The stochastic cycle becomes a first-order autoregressive process if λ_c is 0 or π (Koopman et al., 2009).

$$\gamma_t = \sum_{j=1}^{[s/2]} \gamma_{j,t} \tag{12}$$

$$\begin{bmatrix} \gamma_{j,t} \\ \gamma^*_{j,t} \end{bmatrix} = \begin{bmatrix} \cos\lambda_j & \sin\lambda_j \\ -\sin\lambda_j & \cos\lambda_j \end{bmatrix} \begin{bmatrix} \lambda_{j,t-1} \\ \gamma^*_{j,t-1} \end{bmatrix} + \begin{bmatrix} \omega_{j,t} \\ \omega^*_{j,t} \end{bmatrix}, \; j=1,\dots,[s/2];\; t=1,\dots,\mathrm{T} \tag{13}$$

where $\lambda_j = 2\pi/s$ is the frequency, in radians, and the seasonal disturbances ω_t and ω_t^* are two mutually uncorrelated NID disturbances with zero mean and common variance σ^2_ω. Note that the component $\gamma^*_{j,t}$ is not included in $\gamma_t$directly but is used as auxiliary variable to write seasonal term in recursive form.

Finally, the stochastic cycle ψ_t is as in equation (10).

The disturbances associated to each of the components are mutually uncorrelated.

Figure A1: Time varying paths of the level component μ with 95% confidence interval

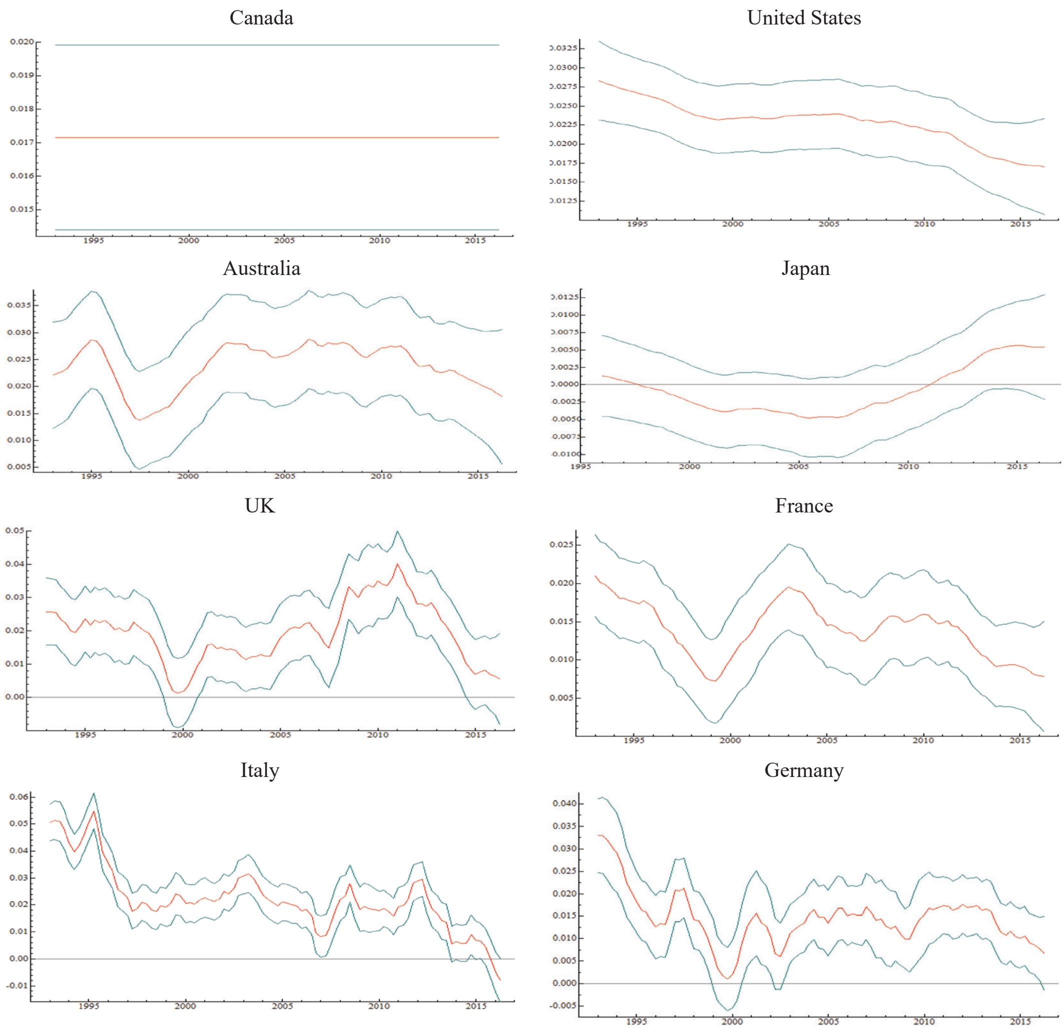

Figure A2: Time varying paths of the output gap coefficient β with 95% confidence interval