Inflation and Real Activity over the Business Cycle

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Abstract

We study the relation between inflation and real activity over the business cycle. We employ a Trend-Cycle VAR model to control for low-frequency movements in inflation, unemployment, and growth that are pervasive in the post-WWII period. We show that cyclical fluctuations of inflation are related to cyclical movements in real activity and unemployment, in line with what is implied by the New Keynesian framework. We then discuss the reasons for which our results relying on a Trend-Cycle VAR differ from the findings of previous studies based on VAR analysis. We explain empirically and theoretically how to reconcile these differences.

JEL: E31, E32, C32.
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1 Introduction

During the period of the Great Moderation, the evidence of an empirical relationship between real economic activity and inflation weakened, leading economists to rethink the foundations of New Keynesian models. Recent contributions offer explanations for the weakening of this empirical relationship (Del Negro et al., 2020 and references therein) or modifications to the New Keynesian model to improve its empirical fit (Gust et al., 2022). By contrast, other authors abandon the New Keynesian apparatus and develop business-cycle theories that abstract from discussing the implications for inflation (Beaudry et al., 2020; Basu et al., 2021) or in which shocks identified as the main drivers of business-cycle fluctuations are reminiscent of demand shocks but have no inflationary effects (Beaudry and Portier, 2013; Angeletos et al., 2018).

An important empirical justification for these alternative theoretical frameworks is offered by Angeletos et al. (2020). The authors consider the U.S. post-WWII period and find a disconnect between real activity and inflation at business cycle frequencies. In their clever empirical analysis, the authors follow an extensive empirical literature that uses vector autoregressions (VARs) as a "model free," but still structural approach to the data. The authors use a VAR to identify a "business-cycle" shock that explains the largest possible share of variation in real activity or unemployment at business-cycle frequencies. This single shock explains most of the business-cycle movements in various measures of real activity, but close to nothing of the business-cycle variation of inflation. The authors conclude that their results are at odds with the premise of the New Keynesian framework that features a tight link between inflation and output fluctuations.

As we argue next, the approach of using a VAR to identify shocks in the frequency domain has some limitations when the goal is to assess the business-cycle relationship between real and nominal variables over the U.S. post-WWII period. The main reason is that a standard fixed-coefficient VAR might be unable to correctly disentangle business-cycle and low-frequency movements in those variables over a relatively short period of time that features structural breaks (Clarida et al. (2000), Sims and Zha (2006), Bianchi (2013), Bianchi and Ilut (2017)). In a VAR, a single set of parameters and reduced-form shocks need to accommodate the variation at all frequencies observed over a relatively short period. As a result, a procedure that uses the estimated parameters and reduced-form shocks to identify variation at business-cycle frequency might be biased. The problem is particularly severe if one of the variables of interest shows significant variation at low frequency, as it is the case with inflation. Ultimately, the identified shock might fail to capture a business-cycle relationship between the two variables even when such a relation is in fact in the data. To remedy this limitation of the VAR for the specific question at hand, we adopt a more flexible model that explicitly extracts business-cycle movements in the variables of interest. Specifically, we argue that a Trend-Cycle VAR (TC-VAR) model is better suited to analyze the relation between inflation and real activity at business-cycle frequencies.

We start by presenting simple, but insightful, evidence that serves as motivation for our analysis. We consider a measure of inflation—the GDP deflator—and two measures of real economic activity—the level of real GDP per capita and the unemployment rate—over the period between 1960 and 2019. Using a bandpass filter, we extract movements in those measures at frequencies between 6 and 32 quarters—labeled "business-cycle frequencies"—and between 8 and 30 years—labeled "medium-cycle frequencies". After filtering out movements at high and low frequencies, the correlation of current inflation and real per-capita GDP (unemployment rate) over the business cycle is positive (negative) and roughly equal to about 0.2 (negative 0.4). The correlations become larger (in absolute value) when considering the relationship between current inflation and lagged measures of real economic activity, peaking at about 0.45 (negative 0.45) when considering real per-capita GDP (unemployment rate) lagged by four (two) quarters. In addition, over the medium cycle, these estimates can be up to nearly 50% larger (in absolute value) than those over the business cycle. This evidence is puzzling in light of the existing literature because it suggests that inflation is related to real activity at business cycle frequencies, at least to some extent.

Motivated by this analysis, we adopt a more rigorous empirical framework and estimate a multivariate Trend-Cycle VAR model building on the work of Watson (1986), Stock and Watson (1988, 2007), Villani (2009) and, Del Negro et al. (2017). We consider the sample between 1960 and 2019 using seven time series. The first four time series are commonly used in previous studies: GDP growth, unemployment, the federal funds rate (FFR), and inflation. We then include three additional time series. First, to better capture low-frequency movements in inflation, we add ten-year-ahead inflation expectations. Agents' long-term inflation expectations are informative about the *current* level of trend inflation, even if not necessarily good predictors of future inflation. Second, we use one-year-ahead inflation expectations as a variable that should respond to business cycle variation in inflation and be less affected by transitory shocks. Third, we include one-year-ahead expectations of unemployment to inform the estimates of the latent trend of unemployment.

Given that a TC-VAR already separates trends from cycles, we identify the shock that maximizes the variation of the latent cyclical component of the unemployment rate, and we study its contribution to the volatility of all cyclical components. A series of important results emerge from our analysis. First, under our baseline specification, the shock targeting the unemployment rate explains about 70% of the unemployment cycle and between 31% and 35% of the volatility of the inflation cycle. This is a relatively large share, suggesting that it is important to account for the low-frequency movements in real and nominal variables when studying their cyclical relationship. Second, the unemployment-identified shock explains about 49% of the inflation expectations cycle. This result provides further support for the notion that business-cycle movements in inflation are in fact related to real activity, given that expected inflation is obviously related to actual inflation, but less affected by high-frequency fluctuations. Furthermore, the result is in line with the New Keynesian framework, in which agents' inflation expectations depend on the state of the economy. In line with this reasoning, when we focus on frequencies that correspond to fluctuations in the cyclical component with duration of at least 1.5 years, the results become stronger. In this case, the shock identified targeting the rate of unemployment explains a higher percentage of the business-cycle volatility of all inflation measures compared to when all the frequencies are considered: 34% for realized inflation and 52% for inflation expectations.

Our results are robust to a number of alternative specifications. First, the results are very similar if we use GDP instead of unemployment to identify the real-activity shock. Second, the results are not sensitive to the choice of more conservative, though still realistic, priors on the standard deviation of shocks to the trend of the unemployment rate. Third, if we dogmatically model all latent trends as constant, rather than time-varying, we find evidence of a disconnect between nominal and real variables, thus recovering the results commonly found when adopting a standard VAR model (Giannone et al., 2019b; Angeletos et al., 2020). Crucially, this finding shows that the TC-VAR model is flexible enough to deliver results in line with the existing literature, but the data do not support this evidence, given that they present important trends that can confound the business-cycle analysis.

A TC-VAR has four clear advantages relative to the use of a VAR when identifying shocks in the frequency domain.[1] First, the inference exercise automatically separates the trends from the cycles. Second, cyclical variation is controlled by a different set of parameters with respect to low-frequency variation. Third, we do not need to take a stance on the

[1]The approach of identifying shocks in the frequency domain starting from a VAR was pioneered by Uhlig (2003). The approach has lately adopted by many others, including Giannone et al. (2019a), Angeletos et al. (2020) and Basu et al. (2021).

typical length of the business cycle. This is important in light of the fact that expansions have become progressively longer in the sample under consideration. Finally, by allowing for changes in trend growth, trend inflation, and variation in long-run unemployment, the model accommodates the notion that what matters for cyclical movements in inflation is the output (or unemployment) gap, while at the same time nesting a typical VAR specification if the data do not feature significant variation in the trend component.

A standard VAR model cannot easily capture the uncovered business-cycle relationship between nominal and real variables even if we choose priors and sample periods to account for low-frequency movements in the data. We borrow the framework of Angeletos et al. (2020) and fit a VAR on U.S. data. We consider their baseline VAR model with a Minnesota prior, as well as combining it with long-run priors *à la* Giannone et al. (2019a). For each specification, we identify a shock that targets the unemployment rate at business-cycle frequencies. In line with their results, the contribution of the shock to the variability of inflation at the same frequencies is very low, ranging from about 8% when using a Minnesota prior to about 11% when also assuming long-run priors.

We then lay out theoretical arguments for why the two methodological approaches reach such different conclusions. We demonstrate that a fixed-coefficient VAR estimated over a period of time that presents structural changes is misspecified, if the goal is trying to assess the comovement at business-cycle frequency. The misspecification problem associated with the use of a VAR model to describe a data generating process characterized by both low- and high-frequency movements cannot be resolved. An econometrician would need infinite data to reconstruct the VAR representation of a TC-VAR model. Even in that case, the reduced-form innovations that she would recover would map into the innovations affecting the latent persistent and stationary components *as well as* the error associated with the estimates of the latent components. In reality, these issues are exacerbated by the fact that the VAR parameters estimated over a finite sample would be distorted because a single set of parameters needs to account for both trend and cycle fluctuations.

We provide an illustration of these issues with a simple model of unemployment and inflation. We generate Monte Carlo simulations of the two series using a TC-VAR model. We then present four insights based on the estimation of a VAR on the simulated data and the subsequent identification of a shock targeting the unemployment rate at business-cycle frequencies. First, we consider a case in which we introduce a trend only in inflation and assume that the unemployment rate is stationary, persistent, and the *only driver* of cyclical movements in inflation. We show that the explanatory power of the unemployment-identified shock for business-cycle movements in inflation drops dramatically as the relevance of low-frequency movements in inflation rises. Second, even when we assume that inflation does not feature a trend and it is exclusively driven by cyclical variation in the unemployment rate, the identified shock explains small portions of the business-cycle movements in inflation if the unemployment rate features low-frequency movements. Third, in a case with trends in both inflation and unemployment, as well as a dependence of cyclical inflation on both its own lag and cyclical unemployment, it becomes even more challenging to successfully recover the underlying business-cycle relationship between the two series. Finally, if the model does not feature any relation between output and inflation, a TC-VAR would correctly uncover the absence of commovement.

Overall, our findings have implications for both the New Keynesian literature and the recent and growing literature that proposes alternative explanations for the sources of business-cycle fluctuations. For the former, the results support the evidence of a relationship between real and nominal variables over the business cycle, while highlighting the importance of accounting for low-frequency movements in real and nominal variables to properly quantify that relationship. For the latter, the results suggest that the alternative explanations for the drivers of business cycles should also propose transmission mechanisms which are consistent with the empirical evidence on the connection between movements in inflation and real economic activity.[2]

Our results are consistent with the findings of Hazell et al. (2022). These authors show that the relation between real activity and inflation, while tenuous, can be recovered from the data and has not undergone a structural change once controlling for long-term inflation expectations. Their evidence is based on a cross-sectional analysis of inflation across U.S. states, while we take a time-series approach. Ascari and Sbordone (2014) emphasize the importance of controlling for trend inflation when analyzing the conduct of monetary policy. Our findings also relate to the work of Hall and Kudlyak (2023) who suggest that the flat Phillips curve is an illusion caused by assuming that the natural rate of unemployment has little or no movement during recoveries. Finally, our analysis connects to Sargent and Sims (1977) that shows that two dynamic factors could explain a large fraction of the variance of a series of important macroeconomic variables, including output, employment, and prices. Two factors are in fact necessary to control for the low-frequency movements in nominal variables. The subsequent factor-analysis literature has repeatedly confirmed this key in-

[2]For an alternative theory that integrates Keynesian economics with general equilibrium theory without relying on nominal rigidities, refer to Farmer and Platonov (2019) and Farmer and Nicolò (2018, 2019).

sight (Giannone et al., 2006; Watson, 2004; Stock and Watson, 2011). Related branches of the literature use unobserved component models to measure long-run inflation (Stock and Watson, 2007; Mertens, 2016) and long-run interest rates (Laubach and Williams, 2003, 2015; Lubik and Matthes, 2015; Del Negro et al., 2017; Del Negro et al., 2019; Holston et al., 2017; Lewis and Vazquez-Grande, 2019; and Johannsen and Mertens, 2021).

Ascari and Fosso (2021) use a methodology similar to the one adopted in this paper to study the role of imported intermediate goods in explaining the lack of sensitivity of inflation to a business-cycle shock in the post-Millennial period. The contribution of the shock decreases from about 60% for the period starting in 1960 and ending in 1984 to nearly 30% for the period between 1985 and 2019. In line with our results, these estimates are about four and six times larger than the counterparts of 17% and 5% that Angeletos et al. (2020) find for the pre- and post-Volcker periods using a VAR and interpret as evidence of a disconnect. Our paper provides an explanation to reconcile these differences.

In addition, our findings support the evidence that a rise in unemployment during a recession is associated with a fall in inflation as highlighted by (Stock and Watson (2010) for the U.S., Smets (2010) for the Euro Area). Accounting for a relevant inflation-output relationship can improve inflation forecasts as shown in Stock and Watson (2008) for the U.S. and Smets (2010) and Giannone et al. (2014) for the Euro Area. Similar results hold also in data-rich environments (Bańbura et al., 2015; Crump et al., 2021).

2 Motivating evidence

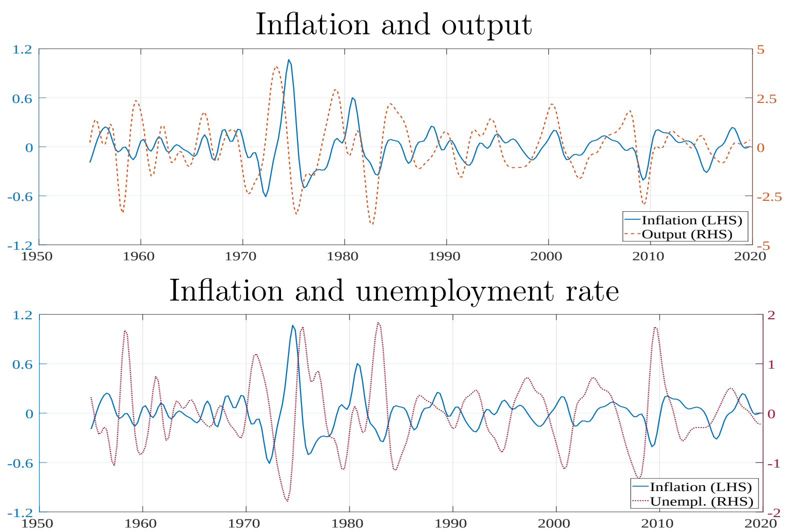
In this section, we provide motivating evidence for our subsequent empirical analysis. We aim to show that inflation and real activity are related over the business cycle once we control for their trends. We underscore the importance of adopting a unified empirical framework that distinguishes between business-cycle and low-frequency movements in these variables. Moreover, given that our goal is to study the relationship between inflation and real economic activity over the business cycle, we also want to control for higher-frequency movements. These are especially important for the dynamics of inflation. We then use a simple NK model to motivate the modeling choices adopted in Section 3.

2.1 Empirical evidence

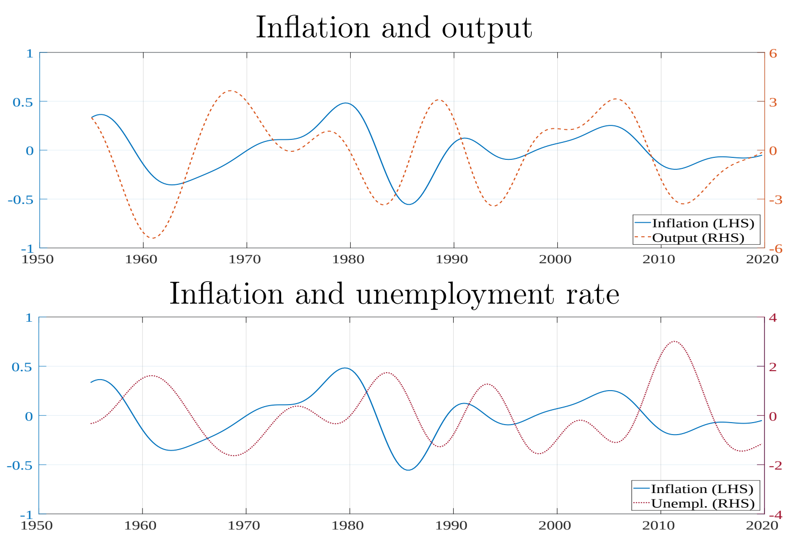
We consider the inflation rate—measured as the log difference in the GDP deflator—and two measures of real economic activity—the log level of real, per-capita GDP and the unemployment rate—over the period 1955:Q1-2019:Q4. Using a bandpass filter (Christiano

Figure 1: Inflation and real economic activity at business- and medium-cycle frequencies

(A) Business-cycle frequencies (6-32 quarters)



(B) Medium-cycle frequencies (8-30 years)



Notes: The inflation rate is defined as the log difference in the GDP deflator. For the two measures of real economic activity, we consider the log level of real, per-capita GDP and the unemployment rate. Data sample is from 1955:Q1 to 2019:Q4. Using the bandpass filter proposed by Christiano and Fitzgerald (2003), we extract the corresponding filtered time series over two frequency bands: the business cycle—defined as the period between 6 and 32 quarters—and the medium cycle—defined as the period between 8 and 30 years.

and Fitzgerald (2003)), we extract the corresponding filtered time series over two frequency bands: the business cycle—defined as fluctuations between 6 and 32 quarters—and the medium cycle—defined as fluctuations between 8 and 30 years.

Panel (A) of Figure 1 plots business-cycle fluctuations for inflation and real per-capita GDP as well as for inflation and unemployment. Panel (B) of Figure 1 plots the corresponding medium-cycle fluctuations. The plots offer two main empirical facts. First, inflation appears correlated with both measures of real economic activity at both business-cycle and medium-cycle frequencies. As expected, inflation is positively correlated with real per-capita GDP and negatively correlated with unemployment. Second, movements in both measures of real economic activity lead changes in the inflation dynamics at business-cycle and medium-cycle frequencies. High (low) levels of real per-capita GDP (unemployment) are associated with subsequent high levels of inflation, and vice versa.

To formalize the notion that cyclical fluctuations in inflation comove with real activity, Table 1 reports the correlations between current (filtered) inflation and current and lagged (filtered) levels of real per-capita GDP and unemployment rate at time $(t-j)$ for $j = \{0, 2, 6, 8\}$. We consider both business-cycle and medium-cycle frequencies. Over the business cycle, the positive (negative) correlation of inflation peaks with real per-capita GDP (unemployment rate) lagged by four (two) quarters at about 0.45 (negative 0.45). Over the medium cycle, the correlation of inflation with real per-capita GDP (unemployment rate) lagged by eight quarters peaks at about 0.65 (negative 0.55). These correlations are larger (in absolute value) than the counterparts with real per-capita GDP and the rate of unemployment lagged by four quarters over the business cycle.

The empirical evidence presented in this section motivates us to adopt a dynamic, multivariate framework that allows to study the relationship between inflation and real economic activity over the business cycle while controlling for low-frequency variation in those variables. We discuss the adopted framework in the next section.

2.2 A simple theoretical framework

In this subsection, we discuss a simple NK model with three goals in mind. First, to explain why low frequency movements in inflation can act as confounding effects for the relation between inflation and real activity. Second, to provide a theoretical motivation for the more flexible model used in our empirical analysis. Third, to clarify that while the NK framework does not predict perfect positive commovement between inflation and real activity at business-cycle frequencies, its theoretical appeal is nevertheless rooted in the

Table 1: Correlations of inflation with lagged measures of real economic activity

Business-cycle frequencies (6-32 quarters)					
	$j=8$	$j=6$	$j=4$	$j=2$	$j=0$
Output	0.15	0.36	0.47	0.42	0.22
Unemployment rate	0.09	-0.13	-0.34	-0.44	-0.36
Medium-cycle frequencies (8-30 years)					
	$j=8$	$j=6$	$j=4$	$j=2$	$j=0$
Output	0.64	0.61	0.54	0.45	0.33
Unemployment rate	-0.54	-0.50	-0.44	-0.36	-0.25

Notes: The inflation rate is defined as the log difference in the GDP deflator. For the two measures of real economic activity, we consider the log level of real, per-capita GDP and the unemployment rate. Data sample is from 1955:Q1 to 2019:Q4. Using the bandpass filter proposed by Christiano and Fitzgerald (2003), we extract the corresponding filtered time series over two frequency bands: the business cycle—defined as the period between 6 and 32 quarters—and the medium cycle—defined as the period between 8 and 30 years. We provide the correlations between current (filtered) inflation and current and lagged (filtered) levels of real per-capita GDP and unemployment rate at time $(t-j)$ for $j = \{0, 2, 6, 8\}$.

connection between the two sides of the economy. For example, it is through real activity, that central banks can lower or lift inflation.

The model features a balanced growth path. Technology is described by the process

$$\gamma_{a,t} \equiv \ln\left(A_t/A_{t-1}\right) = (1-\rho_a)\gamma + \rho_a\gamma_{a,t-1} + \eta_{a,t}, \qquad \eta_{a,t} \sim \mathcal{N}(0, \sigma_a).$$

Thus, if we define detrended output as $y_t \equiv \ln(Y_t/A_t)$, output growth evolves as

$$dy_t = \ln\left(Y_t/Y_{t-1}\right) = \gamma + \gamma_{a,t} + \left(y_t - y_{t-1}\right).$$

With respect to a textbook NK model, we allow for time-varying trend inflation, following a unit-root process $\pi_t^\tau = \pi_{t-1}^\tau + \eta_{\pi^\tau,t}$, and assume full indexation to trend inflation:

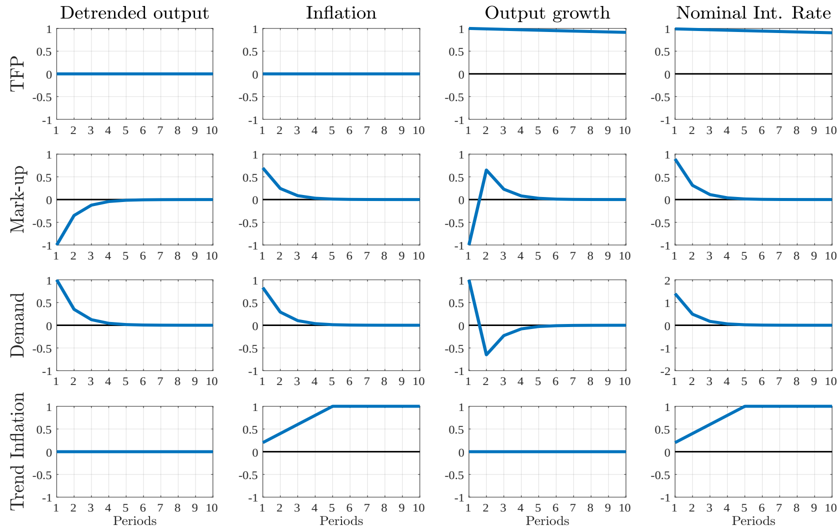
$$y_t = E_t(y_{t+1}) - \left[R_t - (r_t^n + E_t(\pi_{t+1}))\right] + \left[z_{b,t} - E_t(z_{b,t+1})\right], \quad (1)$$

$$\pi_t - \pi_t^\tau = \beta E_t(\pi_{t+1} - \pi_{t+1}^\tau) + \kappa\, y_t + z_{p,t}, \quad (2)$$

$$R_t = (r_t^n + \pi_{t+1}^\tau) + \phi_\pi(\pi_t - \pi_t^\tau) + \phi_y y_t, \quad (3)$$

where π_t is inflation and R_t is the nominal interest rate. The model implies long-run mone-

Figure 2: Selected impulse responses



Notes: The figure plots the impulse responses to shocks to TFP (η_a), mark-up (η_p), household preferences (η_b), and the inflation target (η_{π^τ}). The standard deviation of the TFP, mark-up, and demand shocks is calibrated to induce a one-percent change (in absolute value) of output growth. For the inflation target shock, we assume 5 consecutive shocks (of 0.2 percentage points each) starting in period 1. The y-axes are expressed in percentages.

tary neutrality and it is similar to a case provided in Chapter 4 of Woodford (2003), except that indexation is with respect to trend inflation as opposed to lagged inflation (see also Hazell et al. (2022)). We do not discuss the origins of fluctuations in trend inflation or the possibility of asymmetric information between agents and the central bank (Bianchi et al. (2021)). Price markup shocks ($z_{p,t}$) and preference shocks ($z_{b,t}$) follow an autoregressive process $z_{i,t} = \rho_i z_{i,t} + \eta_{i,t}$ where $\eta_{i,t} \sim \mathcal{N}(0, \sigma_i)$ for $i = \{p, b\}$. In addition, potential output—defined as the level of output prevailing under flexible prices and in absence of markup shocks—coincides with the level of output along the balanced growth path. Therefore, y_t also denotes the output gap. Finally, the natural rate of interest ($r_t^n \equiv \rho_a \gamma_{a,t}$) responds to highly persistent productivity shocks that the central bank accommodates.

We calibrate the model to conventional values in the literature. We set the discount factor (β) and the Calvo probability of keeping prices unchanged to 0.99 and 0.6 respectively and assume a unitary Frisch elasticity. The central bank's responses to inflation and output gap are 1.5 and 0.15, respectively. We assume that productivity shock is highly persistent by setting ρ_a to 0.99. To introduce a slight degree of inertia in the model, we set the autoregressive coefficients of markup shocks (ρ_p) and preference shocks (ρ_b) to 0.35.

Figure 2 reports the responses of output, inflation, and output growth to the four shocks.

The standard deviations of the TFP, mark-up, and demand shocks are normalized to induce a one-percent change (in absolute value) of output growth. For trend inflation, we assume five consecutive shocks of 0.2 percentage points each. A productivity shock generates a persistent increase in output growth, while cyclical output and inflation do not respond, as the movements in natural rate of interest completely offset the effects of the shock. As shown in the second row, a price markup shock induces negative commovement between detrended output and inflation. After the contemporaneous one-percent decrease, output growth turns positive as the economy goes back to its long-term trend. In contrast, the responses to the preference shock—reported in the third row—indicate a positive comovement between the cycles of output and inflation. Finally, a change in trend-inflation (last row) moves inflation but not real activity.

This model, while clearly stylized, provides some key insights that are useful to interpret the flexible TC-VAR used in our empirical analysis below. First, the focus should be on the possibility of commovement between inflation and the cyclical component of output, as opposed to the cyclical component of output growth. Second, cyclical movements of output and inflation are unaffected by persistent productivity shocks that instead generate low frequency movements in output growth. Third, shocks to trend inflation generate low-frequency movements in nominal variables, with no effects on the real economy. Third, agents' long-term inflation expectations are informative about the *current* level of trend inflation, even if not necessarily good predictors of future inflation. Finally, the model can account for both positive and negative commovement between detrended output and inflation because markup shocks push output and inflation in opposite directions. However, the preliminary evidence presented in Subsection 2.1 suggests a positive commovement between cyclical inflation and output, and a dominant role of demand-size fluctuations.

3 The Trend-Cycle VAR model

In this section, we present the TC-VAR used to model the joint dynamics of GDP, unemployment, the FFR, and inflation, as well as three expectations measures: the one-year-ahead unemployment expectations and the one- and ten-year-ahead inflation expectations.

Our baseline specification has four trends and six cycles. Unemployment u_t evolves as

$$u_t = \tau_{u,t} + c_{u,t}, \tag{4}$$

where $\tau_{u,t}$ and $c_{u,t}$ are the trend and cyclical components, respectively.

In line with the typical approach employed in structural macroeconomic models, we assume that real per-capita GDP follows a process of the form $Y_t = \bar{Y}_t \exp(c_{y,t})$, where $c_{y,t}$ represents the cyclical movements of real GDP around a stochastic trend $\bar{Y}_t$. As a result, real per-capita GDP growth, $g_t \equiv log\,(Y_t/Y_{t-1})$, can be expressed as

$$g_t = \tau_{g,t} + (c_{y,t} - c_{y,t-1})\,, \tag{5}$$

where $\tau_{g,t} \equiv log\left(\bar{Y}_t/\bar{Y}_{t-1}\right)$ is the trend component of GDP growth. It is worth emphasizing that we model the cycle in real GDP, as opposed to GDP growth, because what matters for inflation and unemployment dynamics is the output gap, not output growth.

Additionally, one-year-ahead unemployment expectations share a common trend with the realized unemployment rate, while also following a separate cyclical component

$$u_t^{e,1y} = \tau_{u,t} + c_{u,t}^{e,1y}. \tag{6}$$

Assuming the Fisher relation holds in the long run, the FFR evolves as

$$f_t = (\tau_{r,t} + \tau_{\pi,t}) + c_{f,t}, \tag{7}$$

where $\tau_{r,t}$ and $\tau_{\pi,t}$ are the trend of the real interest rate and inflation, respectively. Realized inflation and the one- and ten-year-ahead inflation expectations are decomposed as

$$\pi_t = \tau_{\pi,t} + c_{\pi,t} + (\eta_{\pi,t} - \eta_{\pi,t-1})\,, \tag{8.1}$$

$$\pi_t^{e,1y} = \tau_{\pi,t} + c_{\pi,t}^{e}, \tag{8.2}$$

$$\pi_t^{e,10y} = \tau_{\pi,t} + \delta c_{\pi,t}^{e} + \eta_{\pi,t}^{e,10y}, \tag{8.3}$$

thus sharing a common trend $\tau_{\pi,t}$. We assume that the cyclical component for expected inflation, $c_{\pi,t}^{e}$, is shared across the one- and ten-year-ahead inflation expectation surveys. Because the ten-year inflation expectation $\pi_t^{e,10y}$ is fairly stable over time, we estimate its loading with the belief that it is less than one $\delta < 1$. This parameterization is consistent with the definitions of one-year-ahead and ten-year-ahead inflation expectations that measure expected average inflation over the respective horizons. We allow for idiosyncratic errors in the ten-year-ahead inflation expectations, $\eta_{\pi,t}^{e,10y}$. Finally, we allow for an i.i.d. measurement error in the log-level of the GDP deflator, $\eta_{\pi,t}$, which implies that, after taking log difference, realized inflation features a negative moving average measurement error component. Below, we show that the results are robust to pervasive changes in these modeling assumptions.

For ease of exposition, we collect observables and state variables in vectors

$$z_t = \left\{g_t, u_t, u_t^{e,1y}, f_t, \pi_t, \pi_t^{e,1y}, \pi_t^{e,10y}\right\}', \ \tau_t = \left\{\tau_{g,t}, \tau_{u,t}, \tau_{r,t}, \tau_{\pi,t}\right\}', \ c_t = \left\{c_{y,t}, c_{u,t}, c_{u,t}^{e,1y}, c_{f,t}, c_{\pi,t}, c_{\pi,t}^{e}\right\}',$$
$$\eta_t = \left\{\eta_{\pi,t}, \eta_{\pi,t}^{e,10y}\right\}', \ \varepsilon_{\tau,t} = \left\{\varepsilon_{\tau,g,t}, \varepsilon_{\tau,u,t}, \varepsilon_{\tau,r,t}, \varepsilon_{\tau,\pi,t}\right\}', \ \varepsilon_{c,t} = \left\{\varepsilon_{c,y,t}, \varepsilon_{c,u,t}, \varepsilon_{c,u,t}^{e,1y}, \varepsilon_{c,f,t}, \varepsilon_{c,\pi,t}, \varepsilon_{c,\pi,t}^{e}\right\}'.$$

The dynamics of the trend τ_t and cyclical component c_t are given as[3]

$$\tau_t = \tau_{t-1} + \varepsilon_{\tau,t}, \tag{9.1}$$
$$c_t = \Phi_1 c_{t-1} + \Phi_2 c_{t-2} + \ldots + \Phi_p c_{t-p} + \varepsilon_{c,t}. \tag{9.2}$$

We assume $\eta_t = \varepsilon_{\eta,t}$ and that shocks are independent and identically distributed as

$$\varepsilon_t = \begin{bmatrix} \varepsilon_{\tau,t} \\ \varepsilon_{c,t} \\ \varepsilon_{\eta,t} \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}, \begin{bmatrix} \Sigma_\tau & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Sigma_c & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \Sigma_\eta \end{bmatrix} \right),$$

where the matrices Σ_τ, Σ_c, and Σ_η are conforming positive definite matrices, $\Sigma_s = E\left(Q_s Q_s'\right)$ for $s = \tau, c, \eta$, and $\mathcal{N}(\cdot,\cdot)$ denotes the multivariate Gaussian distribution. We do not restrict covariance matrix Σ_τ to be diagonal. This implies that while the trends follow random walks, they are not assumed to be independent of each other.

The model can be recast into a state-space representation.[4] Using generic notation, let us begin with n observables which can be decomposed into n_τ trends and n_c cycles, where $0 < n_\tau \leq n$ and $0 < n_c \leq n$.

Measurement equation. Allowing for a vector of observation errors η_t, the vector of observables z_t can be expressed as

$$z_t = \Lambda x_t = \Lambda_\tau x_{\tau,t} + \Lambda_c x_{c,t} + \Lambda_\eta x_{\eta,t}, \tag{10}$$

where $x_t = \{x_{\tau,t}, x_{c,t}, x_{\eta,t}\}'$, $x_{\tau,t} = \tau_t$, $x_{c,t} = \left\{c_t, c_{t-1}, \ldots, c_{t-(p-1)}\right\}'$, $x_{\eta,t} = \{\eta_t, \eta_{t-1}\}'$ and p denotes the lags of the stationary cyclical components. The $n \times n_\tau$ matrix Λ_τ captures $(n - n_\tau)$ cointegrating relationships, while $\Lambda_c = [\Lambda_{c,0}, \ldots, \Lambda_{c,p-1}]$ and $\Lambda_\eta = [\Lambda_{\eta,0}, \Lambda_{\eta,1}]$.

State-transition equation. The vector of states x_t evolves as

$$x_t = \Phi x_{t-1} + \mathcal{R}\varepsilon_t, \tag{11}$$

[3] In his pioneering work, Watson (1986) emphasizes that models with stochastic, rather than deterministic, trends are more flexible and apt for most economic time series. Moreover, casting a detrending problem using a latent trend allows for the use of state-of-the-art methods such as the Kalman filter described in Durbin and Koopman (2001) and the backward smoothing algorithm of Carter and Kohn (1994).

[4] Appendix A details the construction of the state-space representation for our baseline specification.

or equivalently,

$$\begin{bmatrix} x_{\tau,t} \\ x_{c,t} \\ x_{\eta,t} \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Phi_c & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \Phi_\eta \end{bmatrix} \begin{bmatrix} x_{\tau,t-1} \\ x_{c,t-1} \\ x_{\eta,t-1} \end{bmatrix} + \begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathcal{R}_c & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathcal{R}_\eta \end{bmatrix} \begin{bmatrix} \varepsilon_{\tau,t} \\ \varepsilon_{c,t} \\ \varepsilon_{\eta,t} \end{bmatrix},$$

where

$$\Phi_c = \begin{bmatrix} \Phi_1 & \Phi_2 & & \dots & \Phi_p \\ \mathbf{I} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{I} & \mathbf{0} \end{bmatrix}, \quad \mathcal{R}_c = \begin{bmatrix} \mathbf{I} \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}, \quad \Phi_\eta = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{I} & \mathbf{0} \end{bmatrix}, \quad \mathcal{R}_\eta = \begin{bmatrix} \mathbf{I} \\ \mathbf{0} \end{bmatrix}.$$

The initial conditions are distributed as

$$x_{\tau,0} \sim \mathcal{N}\left(\underline{\tau}, \underline{V_\tau}\right), \quad x_{c,0} \sim \mathcal{N}\left(0, \underline{V_c}\right), \tag{12}$$

where $\underline{V_\tau}$ is an identity matrix, and $\underline{V_c}$ is the unconditional variance of c_0 consistent with (11) and thus a function of the VAR coefficients $\varphi = \{\Phi_1, \dots, \Phi_p\}'$ and variance Σ_c.

4 Inference

In this section, we describe the data, the priors, and the methodology employed in our empirical analysis.

4.1 Data

We estimate the TC-VAR model using the following seven quarterly time series which are expressed at annualized rates: i) the growth rate of real, per-capita GDP g_t; ii) the unemployment rate u_t; iii) the median four-quarter-ahead unemployment rate expectations, $u_t^{e,1y}$, from the SPF; iv) the FFR f_t by treating observations at the zero lower bound (ZLB) as missing following Del Negro et al. (2017); v) the inflation rate π_t, measured as the log difference in GDP deflator (PGDP); vi) the median four-quarter-ahead average PGDP inflation expectations, $\pi_t^{e,1y}$, from the SPF; vii) a measure of average ten-year-ahead inflation expectations, $\pi_t^{e,10y}$, which, following Del Negro and Schorfheide (2013), we construct by combining survey expectations on average ten-year-ahead CPI inflation from the SPF and Blue Chip Economic Indicators survey, and adjusting it for the historical difference between CPI and PGDP inflation. We use the period between 1955:Q1 and

1959:Q4 as pre-sample and estimate the TC-VAR model over the period from 1960:Q1 to 2019:Q4. Appendix B provides the definitions, data sources and transformations.

4.2 Priors and initial conditions

For the assumptions about initial conditions and prior distributions, we mainly follow the approach of Del Negro et al. (2017). We consider standard priors for covariance matrices Σ_τ and Σ_c and for the VAR coefficients $\varphi = \{\Phi_1, \dots, \Phi_p\}'$

$$p(\Sigma_\tau) \quad = \mathcal{IW}\left(\kappa_\tau, (\kappa_\tau + n_\tau + 1)\underline{\Sigma_\tau}\right), \tag{13.1}$$

$$p(\Sigma_c) \quad = \mathcal{IW}\left(\kappa_c, (\kappa_c + n_c + 1)\underline{\Sigma_c}\right), \tag{13.2}$$

$$p(\phi|\Sigma_c) = \mathcal{N}\left(\underline{\phi}, \Sigma_c \otimes \underline{\Omega}\right)\mathcal{I}(\phi), \tag{13.3}$$

where $\phi = vec(\varphi)$, $\underline{\phi} = vec\left(\underline{\varphi}\right)$, and $\mathcal{IW} = (\kappa(\kappa + n + 1)\underline{\Sigma})$ corresponds to the inverse Wishart distribution with mode $\underline{\Sigma}$ and k degrees of freedom, and $\mathcal{I}(\phi)$ is an indicator function that equals 0 if the VAR in (11) is explosive and 1 otherwise.

We center the prior distribution for the initial conditions of the trends τ_0 in (12) to the pre-sample mean of the corresponding variables. The priors for the initial conditions of the annualized trend of real GDP growth and of unemployment are set to 1% and 5%, respectively. For the trend of the real interest rate and inflation, the priors for the initial condition are centered at 0.1% and 2.5%.

To specify the prior for the covariance matrix of the shocks to the trends Σ_τ in (13.1), we assume that those shocks are *a priori* uncorrelated. We then set the standard deviation for the expected change in the annualized trend of real GDP growth to 1% over a time period of 40 years. For all the remaining variables, we assume a 1% standard deviation for the expected change in their trends over 20 years. As in Del Negro et al. (2020), we assume a tight prior by setting κ_τ to 100.

The shocks to the cyclical components Σ_c in (13.2) are also assumed to be uncorrelated *a priori*. We calibrate the standard deviation of the shocks affecting the stationary component of the (annualized) real, per-capita GDP growth and the unemployment rate to 5% and 1.1%, reflecting their pre-sample standard deviations. The standard deviation of the shocks affecting the cycle of the nominal interest rate and inflation are also set to their pre-sample standard deviations of 0.8% and 1.5% respectively. We also need to specify assumptions for the priors on the standard deviation of the cyclical component of the one-year-ahead unemployment rate expectations and the cyclical component that is common for the two inflation expectations measures. Because these surveys are not available for the pre-sample period, we assume the standard deviations of the one-year-ahead unemployment rate expectation to be 0.9%, thus smaller than the pre-sample counterpart of 1.1% of realized unemployment rate. Similarly, we set the prior for the standard deviation of the common cyclical component of inflation expectations to 1.2%, therefore smaller than the pre-sample counterpart of 1.5% for realized inflation. As in Kadiyala and Karlsson (1997) and Giannone et al. (2015), we set $\kappa_c = n_c + 2$.

For the prior of the VAR coefficients ϕ in (13.3), we assume a conventional Minnesota prior with hyperparameter for the overall tightness equal to 0.2 in line with Giannone et al. (2015). Because the cyclical component in (9.2) is assumed to be stationary, we then center the prior for each variable's own lag to 0, rather than 1, as in Del Negro et al. (2017). We report additional details on the Bayesian inference in Appendix C.

4.3 Identifying shocks that drive business-cycle fluctuations

As discussed in the Introduction, the TC-VAR model delivers a decomposition between trends and cycles. Given that the cyclical components are already cleaned of movements at frequencies other than business cycles, we do not need to remove the low-frequency variation by using spectral analysis. Instead, we look for the combination of reduced-form shocks that explains the largest possible share of unemployment or output *cycles*, without having to take a stance on which frequencies correspond to the business cycle. In our baseline analysis, we ask how much the unemployment-identified or output-identified shock contributes to the volatility of the cyclical component of the other variables, with a special focus on inflation and inflation expectations. As a robustness check, we also ask if the results are sensitive to further removing high-frequency movements in the cycles. In this second case, we ask how much the unemployment-identified shock contributes to the volatility of the cyclical component of the other variables at frequencies that correspond to fluctuations with duration of at least 1.5 years. Thus, in this second methodology we take into account that the cyclical component of the variables could present some residual high-frequency movements that are not related to the business cycle.

5 Results

In this section, we present the main results of the paper. We first present the decomposition of the variables in trends and cycles. We then proceed to analyze how much the unemployment-identified shocks can explain of the cyclical variation of inflation and inflation expectations and how it propagates through real and nominal variables.

5.1 Estimated latent trends and cycles

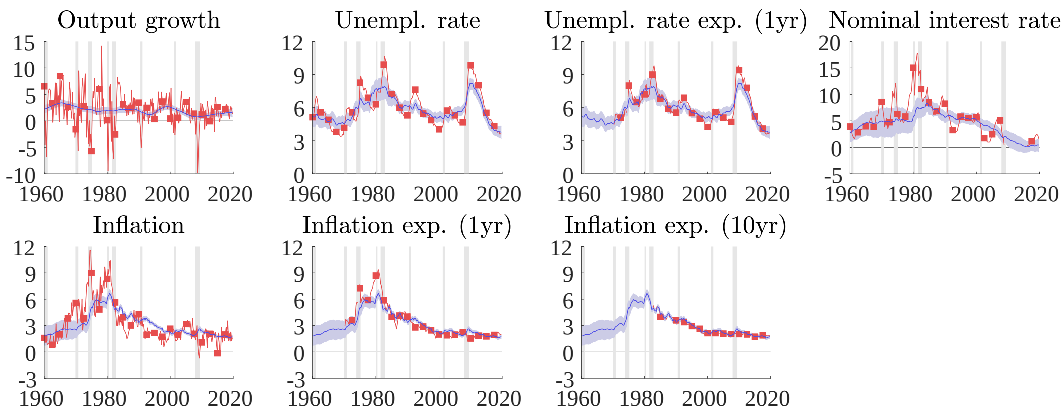
Panel (A) of Figure 3 plots the data (red lines) used for the estimation of the VAR with common trends over the 1960-2019 period as well as the posterior median of their latent trends (blue lines) and the corresponding 90-percent posterior-coverage intervals (shaded blue area). Panel (B) of Figure 3 plots the posterior median of the latent cycles (blue lines) and the corresponding 90-percent posterior-coverage intervals (shaded blue area).

The results confirm some stylized facts about the US economy that are commonly accepted. First, in the 1960s and 1970s the U.S. economy experienced an increase in trend inflation. This was possibly caused by the attempt of policymakers to counteract a break in productivity that manifested itself with an increase in the natural rate of unemployment or to partially accommodate the inflationary pressure resulting from a large increase in spending that occurred starting from the mid-1960s. These two stylized facts are captured by an increase in the trend components of inflation and unemployment rate during those years. The appointment of Volcker marked a change in the conduct of monetary policy. Trend inflation declined, and so did the long-term inflation expectations. Note that even if we do not impose any restriction on the mapping from the trend component of inflation to long-term inflation expectations, the two variables largely coincide. Thus, including long-term inflation expectations helps in separating trend and cycle fluctuations. In addition, the trend unemployment rate rose during the Great Financial Crisis to levels consistent with estimates of the natural rate of unemployment reported by Hall and Kudlyak (2023) and based on the New Keynesian model of Galí et al. (2011). Instead, trend inflation remained roughly unchanged over that period because of anchored long-term inflation expectations.

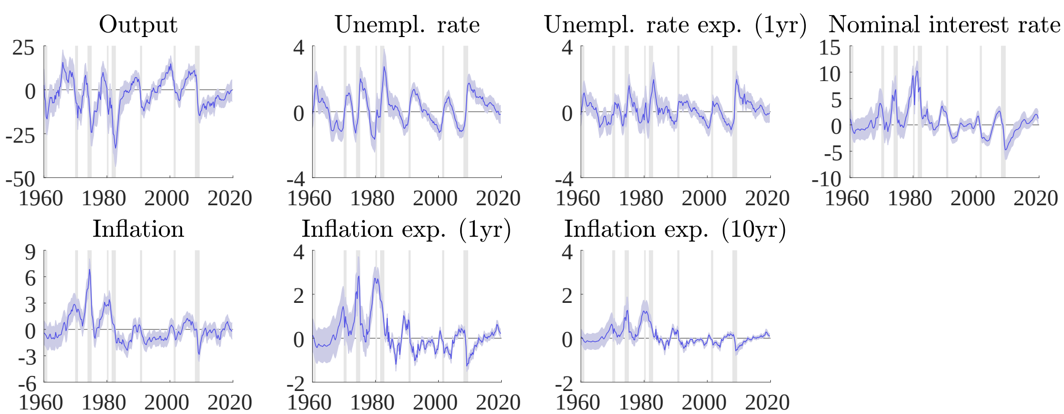
The behavior of the cycles is reported in panel (B) of Figure 3. From this figure, a clear pattern emerges, consistent with our understanding of how the economy behaves over the business cycle. The unemployment rate increases during recessions and smoothly declines over time as the economy recovers. Based on a cursory look at the cycles, inflation seems to behave as the New Keynesian framework would suggest: Declining during a recession, when the unemployment rate is high, and increasing during an expansion when the unemployment rate is low. This is especially visible when focusing on inflation expectations at the one-year horizon: its cyclical component behaves very much like inflation, but it is smoother.

Figure 3: Data, trends and cycles

(A) Trends



(B) Cycles



Notes: The figure plots the data (red lines) used for the estimation of the TC-VAR model over 1960-2019 period as well as the posterior median of their latent trends (blue lines) in panel (A) and latent cycles (blue lines) in panel (B) and the corresponding 90-percent posterior-coverage intervals (shaded blue areas). NBER recessions are denoted by shaded grey areas.

5.2 Inflation and unemployment over the business cycle

We now move to formally study the relation between the real economy and inflation over the business cycle. We use the estimated TC-VAR to identify the unemployment cycle shock using the method described in Subsection 4.3. Specifically, the shock is identified by maximizing its contribution to the volatility of the cyclical component of unemployment. As explained above, we consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case

Table 2: Variance contributions of unemployment shock

All frequencies ($0 - \infty$ quarters)

Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
71.8	58.2	68.6	63.6	30.7	49.2
[60.0,84.5]	[47.6,70.1]	[56.0,80.3]	[39.4,78.9]	[11.8,50.5]	[24.8,70.0]

All-but-short-run frequencies ($6 - \infty$ quarters)

Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
72.8	57.8	71.7	64.4	34.4	52.3
[60.7,86.1]	[46.9,70.3]	[58.7,85.1]	[39.4,79.9]	[13.2,55.3]	[27.2,74.1]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of realized unemployment rate. We consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case we exclude frequencies that imply cycles less than 1.5 years. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequencies.

we exclude frequencies that imply cycles less than 1.5 years.

The top panel of Table 2 reports the median and the 68% posterior-coverage interval for the contribution of the identified shock to the variance of the *cycle* of all the other variables. In the second panel, we repeat the exercise by excluding frequencies that imply cycles less than 1.5 years. Not surprisingly, the shock can explain a large share of the fluctuations of the unemployment cycle. However, the shock can also explain a sizable fraction of the cyclical component of inflation. In the baseline scenario, the unemployment-identified shock can explain around 30% of the inflation cycle. When excluding cycles shorter than 1.5 years, the unemployment-identified shock explains nearly 35% of inflation variability. These are large shares when considering that the unemployment shock explains around 72%, rather than the entirety, of unemployment fluctuations.

The results are even stronger when focusing on the cyclical component of inflation expectations: approximately 49% in the baseline scenario—or 52%, in the alternative scenario—of the business-cycle variability of underlying inflation is explained by the unemployment-identified shock. Given that the cycle of inflation expectations appears to be a smoother version of the cycle of realized inflation, this result corroborates the finding that inflation moves in a way consistent with the New Keynesian framework over the business cycle.

Table 3: Variance contributions of GDP-identified business cycle shock

All frequencies ($0 - \infty$ quarters)

Output	Unempl.	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
65.1	63.6	60.5	43.1	31.5	42.3
[57.6,75.9]	[46.2,76.7]	[43.1,73.3]	[11.3,83.6]	[10.3,62.1]	[12.0,79.9]

All-but-short-run frequencies ($6 - \infty$ quarters)

Output	Unempl.	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
65.4	63.0	61.7	44.9	35.9	49.0
[57.7,76.9]	[45.9,77.7]	[44.1,76.3]	[11.3,85.0]	[11.1,66.6]	[13.6,84.0]

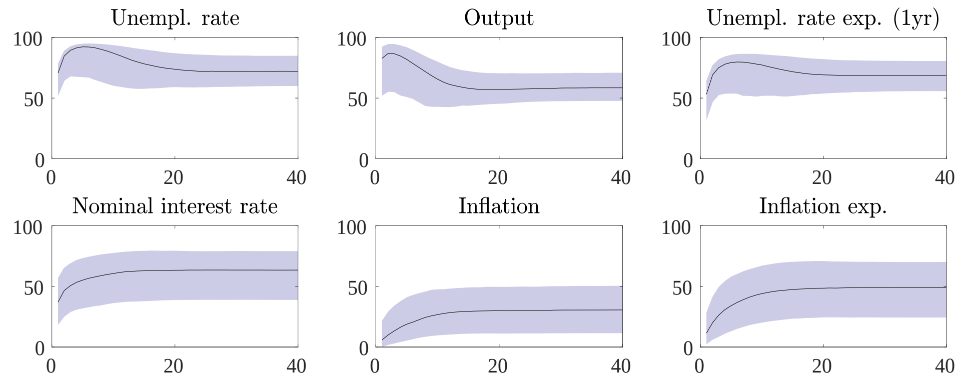
Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of real GDP (in loglevels). We consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case we exclude frequencies that imply cycles less than 1.5 years. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequencies.

When comparing the results of the baseline and alternative cases, we find that the contribution for inflation and inflation expectations goes visibly up when removing the short cycles. This implies that there is likely to be some residual high-frequency variation in these variables that it is not related to the business cycle. In addition, the shock explains about 64% of the volatility of cyclical nominal interest rate over both frequency bands. Combined with the previous two findings, this result implies that the shock also explains the volatility of the cyclical component of the real interest rate, defined as the difference between the FFR and expected inflation.

Finally, the identified shock explains a large portion of the volatility of cyclical real GDP over all frequencies and also when excluding frequencies associated with the first 6 quarters of the cycles. The shock also explains a share of the volatility of the cyclical component of expected unemployment rate similar to the corresponding share for realized unemployment. All these findings support the evidence that the identified shock is the main driver of the U.S. real business-cycle.

The results are similar when using GDP to identify the business cycle shock. Table 3 reports the median contribution—and the corresponding 68-percent posterior-coverage interval—of the shock identified targeting the cycle of real GDP to the variance of the

Figure 4: Forecast error variances of unemployment shock

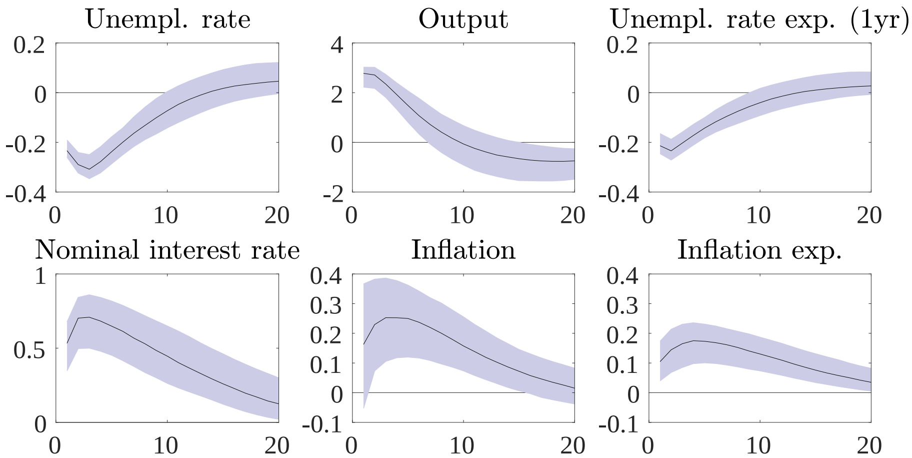


Notes: The figure shows the contribution of the unemployment-identified shock to the forecast error variance of the cyclical component of all the variables at different time horizons. The figure plots the posterior median (blue lines) and the corresponding 68-percent posterior-coverage intervals (shaded blue area).

cycles of all the variables. As before, we consider two cases. In the first case, we identify the shock and compute its contributions based on all frequencies of the cycles. In the second case, we consider frequencies that imply fluctuations of at least 1.5 years. As in the case of unemployment, the shock can explain a large share of the cyclical fluctuations of real GDP. In line with the results for the unemployment-identified shock in Table 2, the shock also explains a sizable fraction of the cyclical component of realized and expected inflation as well as realized and expected unemployment rate. Additionally, the contribution of the output-identified shock for the variability of the realized and expected inflation increases noticeably when movements at frequencies shorter than 1.5 years are excluded. Given that the results are similar across the two specifications, in the rest of the paper we focus on the unemployment-identified shock.

In Figure 4, we show the contribution of the unemployment-identified shock to the forecast error variance of the cyclical component of all the variables at different time horizons. The explanatory power of the shock reaches about 80% and 90% of the cyclical movements in unemployment and output after the first five years and about 70% of the movements in the nominal interest rate at any horizon. Moreover, the shock explains a large portion of the movements in inflation, reaching about 30% after five years. The result for inflation and inflation expectations is consistent with the motivating evidence of Section 2.1 that shows that inflation cycles lag output cycles. This percentage rises to about 50% after the first few years for inflation expectations. These results are in line with the shock's contributions reported in Table 2 and clearly point to the large explanatory power of the unemployment-identified shock for the business-cycle movements in all inflation measures.

Figure 5: Impulse responses to unemployment shock



Notes: The figure shows the response to the unemployment-identified shock of the cyclical component of all the variables over a period of 20 quarters. The figure plots the posterior median (blue lines) and the corresponding 68-percent posterior-coverage intervals (shaded blue area).

Finally, Figure 5 plots the median response—and corresponding 68-percent posterior-coverage intervals—of each cyclical component to the unemployment-identified shock over a period of 20 quarters. The resulting interpretation of the unemployment-identified shock is in line with a demand shock in a canonical New-Keynesian model. The unemployment rate decreases about 2% percent on impact and subsequently returns to its initial level after about 2.5 years. The response of the one-year-ahead unemployment rate expectations is quantitatively and qualitatively similar to that of the unemployment rate. Considering real GDP (in loglevels), the shock causes an increase by nearly 3% on impact, and its effect gradually vanishes after about 2 years. When considering the nominal variables, the shock leads to a contemporaneous increase of about 0.2% (0.1%) in the cyclical component of realized (expected) inflation and a subsequent decline to the initial level of inflation after about 4 (5) years. In response to the identified shock that boosts real economic activity and increases realized and expected inflation, the nominal interest rate peaks at nearly .7% after about a year and gradually returns to its initial value thereafter.

To summarize, the responses of the real side of the economy are consistent with the findings of Angeletos et al. (2020) who point to the presence of a main shock driving the fluctuations of real economic activity over the business cycle. However, differently from their findings, the unemployment shock that we identify has significant effects also on the nominal side of the economy.

5.3 Robustness checks

We briefly discuss the results of a wide range of robustness checks detailed in Appendix D. All variations show compelling evidence that the main results are robust.

Bivariate specification. Appendix D.1 documents that our main findings do not depend on the richness of our baseline specification. We explore two versions of a simple bivariate system that rely on baseline data concerning realized and one-year-ahead average expected inflation. The difference lies in one version incorporating the unemployment rate alongside its one-year-ahead survey expectation, while the other version is based on data related to real GDP growth. For each version, we make three sets of assumptions about measurement errors and combine these with six sets of priors with varying tightness concerning the standard deviation of shocks to inflation trends and either the unemployment rate or real GDP growth. Overall, the results corroborate the evidence that real activity and inflation are strongly related over the business cycle and that the richness of our baseline specification solely improves the quantitative assessment of this nexus.

Baseline specification. In Appendix D.2, we consider three robustness checks that validate our results based on the baseline specification. First, we highlight the importance of properly capturing low-frequency movements in real and nominal variables for the question at hand. Considering a constrained specification of our baseline model in which all trends are assumed constant, the shock's contribution to the volatility of inflation is well within the range of estimates provided in Angeletos et al. (2020), about 9% of the volatility of the realized inflation cycle and about 7% of the volatility of expected inflation. Second, the exclusion of the negative MA component as measurement error for realized inflation does not undermine our findings. Third, our baseline results are not sensitive to the choice of two sets of alternative priors that reduce, to a different degree, the standard deviation of the shock to the trend unemployment rate.

Alternative specifications. We also consider three alternative specifications to model expectations, while leaving unchanged the decomposition assumed for the other variables. In Appendix D.3, we provide the details and discuss the results for these three alternative specifications. The main results are robust to all considered alternative specifications. Here, we briefly explain how these specifications differ from our baseline.

First, we consider a specification that is more parsimonious than our baseline specification. We assume that realized unemployment and one-year-ahead unemployment expectations share a common cyclical component $c_{u,t}$. Similarly, inflation and one-year-ahead inflation expectations share one common cyclical component, $c_{\pi,t}$. Because ten-year-ahead inflation expectations are fairly stable over time, we treat them as a proxy for trend inflation. Lastly, we allow for idiosyncratic errors for both inflation expectations. This alternative specification is more parsimonious than the baseline one because, while considering the same number of trends, it allows for four, rather than six, cyclical components.

In contrast to the first alternative specification, the second specification is more flexible than the baseline. Under this alternative specification, the decompositions of unemployment in (4) and one-year-ahead unemployment rate expectations in (6) are identical to those assumed under the baseline case. However, we consider a more flexible decomposition for the two inflation expectations measures. Specifically, the two measures follow separate, idiosyncratic cyclical components, while both sharing a common inflation trend with realized inflation decomposed as under the baseline in (8.1). As a result, this specification allows for seven, rather than six, cyclical components, one for each observable.

The third and final alternative specification verifies the robustness of the results to the use of the one-year-ahead unemployment rate expectations for the estimation of the TC-VAR model by excluding measurement equation (6) for unemployment expectations.

6 VARs and the link between inflation and real activity

In this section, we show that the use of a standard VAR, as opposed to a TC-VAR, can lead to very different conclusions about the link between real activity and inflation over the business cycle. This is because the VAR parameters need to account at the same time for the low-frequency and business-cycle frequency variation observed in the data with a finite number of observations. We check whether this discrepancy disappears when imposing alternative priors or when considering a sample that presents less low-frequency variation. We find that while these extensions help, the results are still quite different from our baseline analysis based on the TC-VAR.

We proceed to estimate a VAR model with two lags using Bayesian methods. We consider two sets of priors. In one case, we follow Angeletos et al. (2020) and use a Minnesota prior. In the other case, we combine a long-run prior *à la* Giannone et al. (2019a) with the Minnesota prior. The cointegrating relationships that we assume in this second case are in line with those of Giannone et al. (2019a) and are described in Appendix E.1. We allow for separate shrinkage for each active row of the matrix that captures the cointegrating relationship among the variables. Hyperparameters for the priors are optimized following Giannone et al. (2019a). We then identify the business cycle unemployment shock in

Table 4: Variance contributions of unemployment shock: 1955-2019

	Unemployment	Output	Investment	Consumption	Hours
Minnesota	91.9	71.4	74.4	47.3	75.1
	[88.3, 94.5]	[66.9, 77.5]	[69.4, 79.5]	[37.9, 54.4]	[70.7, 78.8]
Minnesota	92.4	72.8	74.6	49.7	75.9
+ Long-run	[88.7, 94.7]	[68.6, 76.1]	[70.7, 77.6]	[44.2, 58.4]	[73.1, 79.4]

	TFP	Labor share	Inflation	FFR
Minnesota	19.2	15.1	7.6	36.3
	[11.3, 28.1]	[9.8, 22.7]	[3.9, 17.9]	[26.5, 45.4]
Minnesota	18.5	14.9	11.5	38.2
+ Long-run	[10.2, 24.4]	[11.0, 21.6]	[5.9, 17.8]	[32.2, 45.9]

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of all the variables over the same frequencies.

the frequency domain using the method described in Subsection 4.3. Table 4 reports the contribution of the shock for each of the variables of the VAR over the same frequencies.

Alternative priors. We first revisit the results obtained by Angeletos et al. (2020) by allowing for different priors. We extend the estimation sample by two years so that the periods match those of our baseline analysis, 1955:Q1-2019:Q4. As detailed in Section I of their paper, the data consist of quarterly observations on unemployment, real GDP, investment, consumption, hours worked per person, utilization-adjusted total factor productivity (TFP), the labor share, inflation, and the FFR.[5]

The results in Table 4 indicate that, even when combining the Minnesota and long-run priors, we still recover the evidence of a disconnect between real and nominal variables. While the identified shock explains nearly 8% of the volatility of inflation over the business-cycle when only using Minnesota priors, its contribution slightly increases to about 11% when those priors are combined with long-run priors *à la* Giannone et al. (2019a). These results are in line with those obtained from a vast variety of specifications that Angeletos et al. (2020) consider, including vector error correction models.

Alternative samples. We now consider a sample that is arguably less affected by time-

[5] We drop labor productivity because it can be measured by the ratio between output and hours worked.

Table 5: Variance contributions of unemployment shock: 1984-2008

	Unemployment	Output	Investment	Consumption	Hours
Minnesota	92.8	54.3	55.3	34.9	69.4
	[85.5, 95.6]	[43.2, 67.7]	[44.8, 67.9]	[21.0, 49.5]	[61.3, 79.5]
Minnesota	92.8	52.7	55.9	33.1	69.6
+ Long-run	[87.7, 95.3]	[42.2, 66.6]	[45.8, 66.1]	[21.3, 53.4]	[61.7, 78.1]

	TFP	Labor share	Inflation	FFR
Minnesota	9.4	11.6	15.8	63.2
	[3.5, 22.1]	[3.7, 21.3]	[7.3, 39.3]	[56.9, 73.9]
Minnesota	9.6	9.9	16.3	63.5
+ Long-run	[3.4, 21.5]	[3.1, 17.5]	[7.7, 29.1]	[54.9, 72.3]

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median contribution and the corresponding 68-percent posterior-coverage interval of the shock to the variance of all variables over the same frequencies.

varying trends: 1984:Q1-2008:Q4. We once again consider the two alternative assumptions about the priors. As expected, the results in Table 5 show that restricting the sample to the period of the Great Moderation improves the contribution of the identified shock on inflation. However, such contribution is still small (about 16%) regardless of the priors.

Dogmatic priors. As a final check, we explore whether dogmatic priors combined with the 1984-2008 sample can help in recovering results more similar to our baseline analysis. The objective is to understand whether the discrepancy can be narrowed with the help of specific priors. We consider several different combinations of hyperparameters such that the two Minnesota and long-run priors can be either not imposed, optimized, or set dogmatically. For this exercise, it is important to notice that we are imposing the same degree of shrinkage for each active row of the matrix that captures the cointegrating relationships.

Table 6 reports the contribution of the unemployment-identified shock on inflation at business-cycle frequencies. The results are straightforward to understand. When only dogmatic Minnesota priors are imposed (see lower left corner of Table 6), the inflation variance contribution of the unemployment shock is nearly zero. It is not exactly zero because the shocks are correlated even when the individual series follow a random-walk process. However, the opposite case of dogmatic long-run priors (see upper right corner of Table 6) leads to a contribution of the unemployment shock to inflation volatility of about

Table 6: Inflation variance contribution of unemployment shock: 1984-2008

	No long-run	Optimized long-run	Dogmatic long-run
No Minnesota	25.2	26.2	33.1
	[9.2, 42.6]	[13.3, 52.4]	[11.0, 49.0]
Optimized Minnesota	20.1	26.2	33.1
	[11.0, 31.5]	[13.3, 52.4]	[11.0, 49.0]
Dogmatic Minnesota	2.0	26.2	–
	[0.4, 5.6]	[13.3, 52.4]	

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median contribution and the corresponding 68-percent posterior-coverage interval of the shock to the variance of all variables over the same frequencies. For long-run priors, we are imposing same degree of shrinkage for each active row of the matrix that captures the cointegrating relationship among the variables.

33%.[6] This is an interesting finding. It suggests that a VAR might recover results similar to the TC-VAR if (1) tight priors are chosen to reflect the long-run relationships suggested by economic theory and (2) a sample not subject to sever low-frequency variation is chosen. Not properly accounting for those features in the data could lead to imprecise conclusions about how real activity and inflation are connected over the business cycle.

Using the same data as in the TC-VAR. As a final exercise, we bring our attention back to the data used in Section 5 and described in Subsection 4.1. We focus on the period of the Great Moderation between 1984 and 2008 and examine the extent to which the estimated VAR model can reproduce empirical evidence provided by our baseline TC-VAR model.[7] We estimate the model using only a Minnesota prior ("Minnesota") or combining it with long-run priors ("Minnesota+Long-run").[8] The cointegrating relationships that we impose across variables are reported in Appendix E.2. We report the results in Table 7. Even in this case, the evidence suggests the need of going beyond the VAR dynamics to examine the relation between real activity and inflation over the business cycle.

[6]The number 26.2% in the middle of Table 6 does not coincide with 16.3% in Table 5 is because we are imposing the same degree of shrinkage for each active row of the matrix that captures the cointegrating relationship among the variables in Table 6 but not in Table 5 which allows for separate shrinkage.

[7]Relative to the baseline specification, we drop the ten-year-ahead inflation expectations as it is not straightforward to impose long-run relationships across two inflation expectations series.

[8]The application of recent techniques—such as those proposed by Demetrescu and Salish (2023)—may furtherhelp in aligning the results based on VAR models with those from our approach.

Table 7: Variance contributions of unemployment shock: 1984-2008

	Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.(1y)
Minnesota	86.8	57.2	71.4	70.8	15.3	23.6
	[79.0, 93.0]	[45.9, 73.1]	[61.0, 81.6]	[61.8, 78.8]	[5.2, 26.2]	[13.4, 35.1]
Minnesota	84.1	64.3	72.2	72.2	16.6	26.9
+ Long-run	[80.1, 90.4]	[49.9, 74.2]	[59.4, 81.6]	[64.7, 78.2]	[5.3, 27.9]	[13.5, 47.1]

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median contribution and the corresponding 68-percent posterior-coverage interval of the shock to the variance of all variables over the same frequencies.

7 Reconciling VAR and TC-VAR Results

In this section, we provide theoretical arguments that motivate the adoption of a TC-VAR model, rather than a standard VAR model, for the results presented in Section 5. In Subsection 7.1, we show that a fixed-coefficient VAR model estimated over a period of time that presents structural changes is misspecified, if the goal is trying to assess the comovement at business-cycle frequency. The misspecification problem associated with the use of a VAR model to describe a data generating process characterized by both low- and high-frequency movements cannot be easily resolved.[9] Even if an econometrician could correctly reconstruct the VAR representation of the TC-VAR model, the parameter estimates of the misspecified model would confound low-frequency movements associated with the trend with those at business-cycle frequencies related to the cycle. Moreover, the reduced-form innovations that she would recover would not only map into the innovations affecting the latent persistent and stationary components. By contrast, the reduced-form innovations would also capture the error associated with the estimates of the latent components. Of course, in reality, these issues would be exacerbated by the fact that the VAR parameters estimated over a finite sample would be distorted because a single set of parameters would need to account for both trend and cycle fluctuations.

In Subsection 7.2, we generate data from a Monte Carlo simulation of a bivariate TC-VAR model and show that a VAR model does not succeed in capturing the assumed cyclical relationship between the two variables, even with a long data sample. Finally, we consider an

[9] Watson (1986) discusses the equivalence between an unobserved component model and its autoregressive, integrated, moving average (ARIMA) representation, thus pointing to the misspecification problem characterizing a VAR representation of a TC-VAR model.

univariate trend-cycle autoregressive (TC-AR) model of U.S. inflation based on Stock and Watson (2007) and derive analytically its infinite-order autoregressive (AR) representation.

7.1 Trend-Cycle models and their VAR(∞) representation

Our goal is to map the state-space representation in (14) introduced in Section 3 into a VAR model. In doing so, we follow the approach proposed in Fernández-Villaverde et al. (2007). For convenience, we report the state representation in (10) and (11) here:

$$z_t = \Lambda x_t, \tag{14.1}$$

$$x_t = \Phi x_{t-1} + \mathcal{R}\varepsilon_t, \tag{14.2}$$

where $\varepsilon_t = Qw_t$, $E(w_t w_t') = \mathcal{I}$, and $E(\varepsilon_t \varepsilon_t') = \Sigma$. For all the specifications considered in our analysis, the overall number of shocks of the TC-VAR model is strictly larger than the number of observables. Equivalently, $dim(w_t) = (n_\tau + n_c + n_\eta) > n = dim(z_t)$. As a result, the *'poor man's invertibility condition'* proposed in Fernández-Villaverde et al. (2007) cannot be tested because it requires the number of shocks and observables to coincide. We therefore seek to find the *'innovations representation'* of (14).

Because the innovations representation results from the application of the Kalman filter to the state-space representation, we first ensure the suitability of the filter for our purpose and more specifically its asymptotic stability and convergence. Clearly, these properties of the filter depend on the properties of (14) and should not be taken for granted in our setup: In the transition equation (14.2), the cyclical components are assumed to be stationary, while trends follow unit-root processes. However, we follow Anderson and Moore (1979) who suggest to verify two conditions: i) the pair $(\Phi, \mathcal{R}Q)$ is stabilizable; ii) the pair (Φ, Λ') is detectable—or equivalently, the pair (Φ', Λ') is stabilizable.[10] For all the specifications of the TC-VAR model that we consider in Section 3, both conditions are satisfied for each draw obtained from the model estimation.

Having verified the suitability of the Kalman filter, we follow Fernández-Villaverde et al. (2007) to derive the innovations representation. We express the representation in (14) as

$$x_{t+1} = Ax_t + Bw_{t+1}, \tag{15.1}$$

$$z_{t+1} = Cx_t + Dw_{t+1}, \tag{15.2}$$

[10] We provide the definition of stabilizability in Appendix F.1. For further details, refer to Burridge and Wallis (1983), Sargent (1988), Anderson et al. (1996) and Hansen and Sargent (2008, 2013) among others. We refer the reader to pp. 76-82 and Appendix C in Anderson and Moore (1979) for the details on the conditions mentioned here and the definition of stabilizability.

where $A = \Phi$, $B = \mathcal{R}Q$, $C = \Lambda A$, $D = \Lambda B$ and $E(w_t w_t') = \mathcal{I}$. Defining the linear projection of x_t on $z^t \equiv \{z_j\}_{j=1}^{t}$ as $\hat{x}_t \equiv E(x_t|z^t)$, the one-step-ahead error associated with the forecast of z_{t+1} as $\hat{D}_{t+1}\nu_{t+1}$ and the term updating the estimator of the state for the next period $\hat{x}_{t+1}$ as $\hat{B}_{t+1}\nu_{t+1}$, the application of the Kalman filter to (15) delivers the innovations representation

$$\hat{x}_{t+1} = A\hat{x}_t + \hat{B}_{t+1}\nu_{t+1}, \tag{16.1}$$

$$z_{t+1} = C\hat{x}_t + \hat{D}_{t+1}\nu_{t+1}, \tag{16.2}$$

where $x_0 \sim (\hat{x}_0, \Omega_0)$, the covariance matrix Ω_0 is positive semi-definite, and ν_t is a vector of mean-zero, normal and uncorrelated white-noise innovations such that $E(\nu_t \nu_t') = \mathcal{I}$. Notably, under this representation, the number of shocks and observables coincide. Also, because the innovation ν_t is fundamental for z_t by definition, it is uncorrelated with z_{t-s} and ultimately ν_{t-s} for any $s \geq 0$.

The innovations representation in (16) shows that, with a finite sample $\{z_t\}_{t=1}^{T}$ where $T < \infty$, it is *not* possible to derive a VAR representation because the matrices $\hat{B}_t$ and $\hat{D}_t$ depend on time t. As a result, we consider the limit case for T approaching infinity. Because the asymptotic stability and convergence of the Kalman filter hold, the matrices $\hat{B}_t$ and $\hat{D}_t$ also converge to their time-invariant counterparts $\hat{B}$ and $\hat{D}$.[11] Therefore, we derive the infinite-order VAR representation by solving (16.2) for ν_{t+1} and combining with (16.1)

$$\left[\mathcal{I} - \left(A - \hat{B}\hat{D}^{-1}C\right)L\right]\hat{x}_{t+1} = \hat{B}\hat{D}^{-1}z_{t+1}, \tag{17}$$

where L denotes the lag operator. The asymptotic properties of the Kalman filter also guarantee that all the eigenvalues of the matrix $\left(A - \hat{B}\hat{D}^{-1}C\right)$ are all strictly inside the unite circle in modulus (Anderson and Moore, 1979). Therefore, we solve equation (17) for $\hat{x}_{t+1}$ and plug the solution in the time-invariant version of equation (16.2) to obtain the following VAR(∞) representation

$$\begin{aligned} z_{t+1} &= C\left[\mathcal{I} - \left(A - \hat{B}\hat{D}^{-1}C\right)L\right]^{-1}\hat{B}\hat{D}^{-1}z_t + \hat{D}\nu_{t+1} \\ &= \sum_{s=0}^{\infty} C\left(A - \hat{B}\hat{D}^{-1}C\right)^{s}\hat{B}\hat{D}^{-1}z_{t-s} + \hat{D}\nu_{t+1}, \end{aligned} \tag{18}$$

where we have used the fact that the inverted matrix in square brackets in the first equation is a square summable polynomial in L.

[11] Appendix F.2 provides the details on the equations for matrices $\hat{B}$ and $\hat{D}$.

Equation (18) allows us to reach three important conclusions. First, the state-space representation of the TC-VAR model in (14) maps into the infinite-order VAR representation in (18) under the assumption that infinite data are available. As a result, a finite-order VAR with finite data cannot capture the dynamics described by the decomposition of the observables z_t into trends and cycles. Second, even if infinite data were available, equation (18) clarifies that estimates of the autoregressive parameters associated with the VAR(∞) representation confound movements of z_{t+1} that are driven by both the trend and cycle. Equivalently, the VAR(∞) representation cannot disentangle movements of z_{t+1} at low frequencies from those at cyclical frequencies. Finally, as shown in Fernández-Villaverde et al. (2007), the innovations associated with the VAR(∞) representation, $\hat{D}\nu_{t+1}$, capture not only the shocks to the latent trends and cycles, Dw_{t+1}, but also the error associated with the estimate of those latent components, $C(x_t - \hat{x}_t)$. In Appendix F.3, we provide a simple analytical example based on an unobserved components model of U.S. inflation by Stock and Watson (2007) to show the intuition for these results.

These results are not meant to establish the unconditional superiority of a TC-VAR over a VAR. Over the past four decades, economists have used VARs as extremely flexible econometric models capable of uncovering a variety of enlightening empirical results. However, for the specific question of assessing the strength of the relation between inflation and real activity over the business cycle, a TC-VAR appears to be a more effective tool.

7.2 Monte Carlo simulations of a bivariate TC-VAR model

To provide some examples for the theoretical results in Subsection 7.1, let us assume that the data generating process for unemployment and inflation, $z_t = \{u_t, \pi_t\}'$, is described by the measurement equation $z_t = \tau_t + c_t$, where the dynamics of the trend τ_t and cyclical component c_t can be modeled as:

$$\tau_t = \tau_{t-1} + \varepsilon_{\tau,t}, \tag{19.1}$$

$$c_t = \Phi_1 c_{t-1} + \varepsilon_{c,t}, \tag{19.2}$$

where $\tau_t = \{\tau_{u,t}, \tau_{\pi,t}\}'$, $c_t = \{c_{u,t}, c_{\pi,t}\}'$, $\varepsilon_{\tau,t} = \{\varepsilon_{\tau,u,t}, \varepsilon_{\tau,\pi,t}\}'$ and $\varepsilon_{c,t} = \{\varepsilon_{c,u,t}, \varepsilon_{c,\pi,t}\}'$. In this example, we assume that (19.2) is

$$\begin{bmatrix} c_{u,t} \\ c_{\pi,t} \end{bmatrix} = \begin{bmatrix} \rho_{uu} & 0 \\ -(1-\rho_{\pi\pi})\kappa & \rho_{\pi\pi} \end{bmatrix} \begin{bmatrix} c_{u,t-1} \\ c_{\pi,t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{c,u,t} \\ \varepsilon_{c,\pi,t} \end{bmatrix}$$

implying that, while the cyclical component of unemployment only depends on its lag, the cyclical component of inflation depends on its lag as well as on the lagged cyclical component of unemployment. We assume that the shocks are *iid*:

$$\varepsilon_t = \begin{bmatrix} \varepsilon_{\tau,t} \\ \varepsilon_{c,t} \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \end{bmatrix}, \begin{bmatrix} \Sigma_\tau & \mathbf{0} \\ \mathbf{0} & \Sigma_c \end{bmatrix} \right), \quad \Sigma_\tau = \begin{bmatrix} \sigma_{\tau,u} & \mathbf{0} \\ \mathbf{0} & \sigma_{\tau,\pi} \end{bmatrix}, \quad \Sigma_c = \begin{bmatrix} \sigma_{c,u} & \mathbf{0} \\ \mathbf{0} & \sigma_{c,\pi} \end{bmatrix}.$$

Within this framework, we consider four cases of interest. In the first case, unemployment does not feature low-frequency variation and it is only driven by its business-cycle movements, while inflation also features changes in the trend. We consider different degrees of low-frequency variation for inflation, while always maintaining the assumption that its cycle is affected by cyclical movements in unemployment. Specifically, for unemployment, we set the autoregressive parameter ρ_{uu} to 0.95 and normalize the standard deviation of the shock to the cycle $\sigma_{c,u}$ to 1. Because we assume that unemployment is not subject to low-frequency movements, we turn off the shocks to its trend ($\sigma_{\tau,u}$=0). Focusing on inflation, we assume that its cyclical movements are only driven by the corresponding movements of unemployment, thus assuming $\rho_{\pi\pi} = 0$, $\kappa = 1$, and $\sigma_{c,\pi} = 0$. However, to capture the degree to which the low-frequency movements drive inflation dynamics, we consider three values for the standard deviation of the shock to the inflation trend ($\sigma_{\tau,\pi}$). Relative to the normalized standard deviation of the shock to the cyclical component of the unemployment rate, the standard deviation of the shock to inflation trend is one order of magnitude smaller ($\sigma_{\tau,\pi} = 0.1$), equivalent ($\sigma_{\tau,\pi}$=1) or twice as large ($\sigma_{\tau,\pi}$=2). For each calibration, we produce several, long Monte Carlo simulations that we use to estimate a VAR model, identify the shock targeting the unemployment rate at business-cycle frequencies, and ultimately compute the median contribution of the identified shock to the variance of both series over the same frequencies.[12]

For each calibration of the standard deviation of the shock to inflation trend, Table 8 reports the median and 68% posterior-coverage intervals of the median contributions of the identified shock. As expected, the identified shock fully explains the cyclical movements of the unemployment rate regardless of the chosen calibration. However, the explanatory power of the unemployment-identified shock for inflation depends on the importance of the low-frequency variation in inflation. The higher the low-frequency variation, the lower the

[12] We generate 500 Monte Carlo simulation of 50,000 observations of which we keep the last 1,000 for each simulation. We choose the lags with the lowest Bayesian Information Criterion (BIC), use a Minnesota prior as in Angeletos et al. (2020), and keep the last 1,000 of 50,000 draws to identify the shock.

Table 8: Variance contribution of unemployment shock (data simulated with $\sigma_{\tau,u} = 0$)

	Unemployment	Inflation
$\sigma_{\tau,\pi} = 0.1$	100.0	98.8
	$[100.0, 100.0]$	$[98.7, 98.9]$
$\sigma_{\tau,\pi} = 1$	100.0	17.9
	$[100.0, 100.0]$	$[15.3, 20.4]$
$\sigma_{\tau,\pi} = 2$	100.0	4.5
	$[100.0, 100.0]$	$[3.3, 6.1]$

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median and the corresponding 68-percent posterior-coverage interval of the median contributions of the shock to the variance of all variables over the same frequencies. To simulate the data, we use the following calibrations. For the unemployment rate, we set $\rho_{uu} = 0.95$, $\sigma_{c,u} = 1$ and $\sigma_{\tau,u} = 0$. For the inflation rate, we set $\rho_{\pi\pi} = 0$, $\kappa = 1$, and $\sigma_{c,\pi} = 0$ and $\sigma_{\tau,\pi} = \{0.1, 1, 2\}$.

degree to which the unemployment-identified shock explains business-cycle movements in inflation. This conclusion holds even with long data samples and in presence of strong assumptions about the cyclical relationship between the unemployment rate and inflation. In line with our results above, the identification of the shock at business-cycle frequencies does not succeed in extracting the cyclical relationship between unemployment and inflation because the fixed-coefficient VAR fails to separate cycle and trend innovations in inflation.

For brevity, the results of the other three cases are briefly presented here, while the details are discussed in Appendix F.4. In the second case, we introduce low-frequency movements in the unemployment rate, while the inflation rate only follows the cyclical component of the unemployment rate. In the third case, the underlying true data generating process features trends in both inflation and unemployment. The results for these two cases confirm the importance of explicitly controlling for low-frequency movements in both inflation and unemployment rate to appropriately extract their business-cycle relationship. In the fourth and last case, output and inflation cycles are assumed to be unrelated, and we ask whether the TC-VAR would correctly recover the truth. To this end, we simulate a model with independent persistent processes for inflation and output and then fit the TC-VAR on the simulated data. We find that a bivariate TC-VAR model correctly recovers the disconnect between the two simulated series. Thus, the fact that the model has the flexibility of separating trends from cycles does not mean that it would automatically try to recover commovement between the two.

8 Conclusions

In recent years, a series of papers have called into question the validity of the New Keynesian framework. One important argument is the observation that inflation seems to be disconnected from business-cycle movements in real activity. In this paper, we used a Trend-Cycle VAR model to study the relation between inflation and the real economy over the business cycle. The Trend-Cycle VAR model has the virtue of removing low-frequency movements in inflation and real activity that can contaminate inference about the VAR parameters and innovations. We show that at business-cycle frequencies, fluctuations of inflation are in fact related to movements in real activity, in line with what implied by the New Keynesian framework. We explain why evidence based on VARs can be misleading. We see three distinct directions for future research: first, to investigate the drivers of low-frequency movements in the macroeconomy; second, to allow for the possibility of multiple shocks at business-cycle frequencies to separate demand-driven and supply-driven fluctuations; third, to apply the same methods to study the cyclical behavior of other key macroeconomic variables that feature a strong trend component, such as the employment-to-population ratio (Fukui et al. (2023)) and the share of employment in middle-skilled jobs (Jaimovich and Siu (2020)).

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A The State-space Representation

Section 3 presents the state-state representation in (10) and (11) and reported below in (20)

$$z_t = \Lambda_\tau x_{\tau,t} + \Lambda_c x_{c,t} + \Lambda_\eta x_{\eta,t}, \tag{20.1}$$
$$x_t = \Phi x_{t-1} + \mathcal{R}\varepsilon_t, \tag{20.2}$$

where $\Lambda = [\Lambda_\tau, \Lambda_c, \Lambda_\eta]$, $\Lambda_c = [\Lambda_{c,0}, \ldots, \Lambda_{c,p-1}]$ and $\Lambda_\eta = [\Lambda_{\eta,0}, \Lambda_{\eta,1}]$. For our baseline specification, these matrices are constructed as

$$\Phi = \begin{bmatrix} \mathbf{I}_{4\times4} & \mathbf{0}_{4\times6} & \mathbf{0}_{4\times6} & \mathbf{0}_{4\times2} & \mathbf{0}_{2\times2} \\ \mathbf{0}_{6\times4} & \Phi_1 & \Phi_2 & \mathbf{0}_{6\times2} & \mathbf{0}_{2\times2} \\ \mathbf{0}_{6\times4} & \mathbf{I}_{6\times6} & \mathbf{0}_{6\times6} & \mathbf{0}_{6\times2} & \mathbf{0}_{2\times2} \\ \mathbf{0}_{2\times4} & \mathbf{0}_{2\times6} & \mathbf{0}_{2\times6} & \mathbf{0}_{2\times2} & \mathbf{0}_{2\times2} \\ \mathbf{0}_{2\times4} & \mathbf{0}_{2\times6} & \mathbf{0}_{2\times6} & \mathbf{I}_{2\times2} & \mathbf{0}_{2\times2} \end{bmatrix}, \quad \mathcal{R} = \begin{bmatrix} \mathbf{I}_{4\times4} & \mathbf{0}_{4\times6} & \mathbf{0}_{4\times2} \\ \mathbf{0}_{6\times4} & \mathbf{I}_{6\times6} & \mathbf{0}_{6\times2} \\ \mathbf{0}_{6\times4} & \mathbf{0}_{6\times6} & \mathbf{0}_{6\times2} \\ \mathbf{0}_{2\times4} & \mathbf{0}_{2\times6} & \mathbf{I}_{2\times2} \\ \mathbf{0}_{2\times4} & \mathbf{0}_{2\times6} & \mathbf{0}_{2\times2} \end{bmatrix},$$

$$\varepsilon_t = \begin{bmatrix} \varepsilon_{\tau,t} \\ \varepsilon_{c,t} \\ \varepsilon_{\eta,t} \end{bmatrix}, \quad \Sigma = \begin{bmatrix} \Sigma_\tau & \mathbf{0}_{4\times6} & \mathbf{0}_{4\times2} \\ \mathbf{0}_{6\times4} & \Sigma_c & \mathbf{0}_{6\times2} \\ \mathbf{0}_{2\times4} & \mathbf{0}_{2\times6} & \Sigma_\eta \end{bmatrix},$$

$$\Lambda = \begin{bmatrix} \Lambda_{\tau,0} & \Lambda_{c,0} & \Lambda_{c,1} & \Lambda_{\eta,0} & \Lambda_{\eta,1} \end{bmatrix},$$

$$\Lambda_{\tau,0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Lambda_{c,0} = \begin{bmatrix} \mathbf{I}_{5\times5} & \mathbf{0}_{5\times1} \\ 0 & 1 \\ 0 & \delta \end{bmatrix}, \quad \Lambda_{c,1} = \begin{bmatrix} -1 & \mathbf{0}_{1\times5} \\ \mathbf{0}_{6\times1} & \mathbf{0}_{6\times5} \end{bmatrix},$$

$$\Lambda_{\eta,0} = \begin{bmatrix} \mathbf{0}_{4\times1} & \mathbf{0}_{4\times1} \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad \Lambda_{\eta,1} = \begin{bmatrix} \mathbf{0}_{4\times1} & \mathbf{0}_{4\times1} \\ -1 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

B Data

The following data series are from the Federal Reserve Economic Database (FRED) maintained by the Federal Reserve Bank of St. Louis:

- Real GDP per capita, A939RX0Q048SBEA, quarterly frequency. We transform the series by taking quarterly growth rates at annual rate and express these rates in percentages.
- Unemployment rate, UNRATE, monthly frequency. We transform the series by taking quarterly averages.
- Inflation, GDPDEF, quarterly frequency. We transform the series for the GDP price index by taking quarterly growth rates at annual rate and express these rates in percentages.
- Effective federal funds rate, FEDFUNDS, monthly frequency. Because the series is already expressed at annual rate, we take quarterly averages.

The following data series are available from the Real-Time Data Research Center maintained by the Federal Reserve Bank of Philadelphia:[13]

- One-year-ahead inflation expectations, INFPGDP1YR, quarterly frequency. The series corresponds to the median forecast for one-year-ahead annual average inflation measured by the GDP price index. The series starts in 1970:Q2.
- Ten-year-ahead inflation expectations. We follow Del Negro and Schorfheide (2013) to construct this time series. Specifically, we combine longer-run inflation expectations from the SPF and the Blue Chip Economic Indicators survey. We use the ten-year-ahead Consumer Price Index (CPI) inflation expectations from the Blue Chip survey—from 1979:Q4 to 1991:Q3 and available twice a year—and those from

[13]The data may contain missing observations. More details are available at the webpage: https://www.philadelphiafed.org/surveys-and-data/real-time-data-research/inflation-forecasts.

the SPF (INFCPI10YR)—available each quarter starting from 1991:Q4. To combine the measures, we subtract from the ten-year-ahead CPI inflation expectations the historical average difference between CPI and GDP annualized inflation over the estimation period.

- One-year-ahead unemployment rate expectations, UNEMP6 , quarterly frequency. The series corresponds to the median forecast for one-year-ahead unemployment rate. The series starts in 1968:Q4.

C Estimation Details

C.1 Settings

For all the considered specifications, we assume that the cyclical components evolve according to a VAR model with two lags ($p = 2$) following the baseline approach of Angeletos et al. (2020). For each estimation, we adopt the Gibbs sampler described in Appendix C.2. We use 50,000 draws to estimate the TC-VAR model. We then discard the first 25,000 draws and keep one in every 25 draws, thus leaving 1,000 draws, to use for the identification of the shocks.

C.2 Gibbs Sampler

We assume that some element of Σ_η is known. We collect parameters that need to be estimated in

$$\Theta_\tau = \{\Sigma_\tau\}, \quad \Theta_c = \{\Phi_1, \Phi_2, \Sigma_c\}, \quad \Theta_e = \{\delta, \Sigma_\eta\}.$$

We use the Gibbs sampler to estimate the model unknowns. We rely on the state-space representation of (10) and (11). For the jth iteration,

- Run Kalman smoother to generate $\tau^j_{1:T}$ and $c^j_{0:T}$ conditional on $\Theta^j_\tau, \Theta^j_c$: This is explained in Subsection C.2.1.

- Obtain posterior estimates of $\Theta^{j+1}_\tau, \Theta^{j+1}_c, \Theta^{j+1}_e$ from the MNIW conditional on $\tau^j_{1:T}$ and $c^j_{0:T}$: This is explained in Subsection C.2.2.

C.2.1 Kalman smoother

We rely on the state-space representation in equations (10) and (11). Conditional on the jth draw of $\Theta_\tau^j, \Theta_c^j$, we apply the standard Kalman filter as described in Durbin and Koopman (2001). Suppose that the distribution of

$$x_{t-1}|\{z_{1:t-1}, \Theta_\tau^j, \Theta_c^j\} \sim N(x_{t-1|t-1}, P_{t-1|t-1}).$$

Then, the Kalman filter forecasting and updating equations take the form

$$\begin{aligned} x_{t|t-1} &= \Phi x_{t-1|t-1} \\ P_{t|t-1} &= \Phi P_{t-1|t-1}\Phi' + \mathcal{R}\Sigma\mathcal{R}' \\ x_{t|t} &= x_{t|t-1} + (\Lambda P_{t|t-1})'(\Lambda P_{t|t-1}\Lambda')^{-1}\left(z_t - \Lambda x_{t|t-1}\right) \\ P_{t|t} &= P_{t|t-1} - (\Lambda P_{t|t-1})'(\Lambda P_{t|t-1}\Lambda')^{-1}(\Lambda P_{t|t-1}). \end{aligned}$$

In turn,

$$x_t|\{z_{1:t}, \Theta_\tau^j, \Theta_c^j\} \sim N(x_{t|t}, P_{t|t}).$$

Next, the backward smoothing algorithm developed by Carter and Kohn (1994) is applied to recursively generate draws from the distributions $x_t|(X_{t+1:T}, Z_{1:T}, \Theta_\tau^j, \Theta_c^j)$ for $t = T-1, T-2, \ldots, 1$. The last element of the Kalman filter recursion provides the initialization for the simulation smoother:

$$\begin{aligned} x_{t|t+1} &= x_{t|t} + P_{t|t}\Phi' P_{t+1|t}^{-1}\left(x_{t+1} - \Phi x_{t|t}\right) \\ P_{t|t+1} &= P_{t|t} - P_{t|t}\Phi' P_{t+1|t}^{-1}\Phi P_{t|t} \\ x_t^j &\sim N(x_{t|t+1}, P_{t|t+1}), \quad t = T-1, T-2, \ldots, 1. \end{aligned} \tag{21}$$

In sum, we obtain smoothed estimates of $\tau_{1:T}^j$ and $c_{0:T}^j$.

C.2.2 Posterior draw

We treat the smoothed estimates of $\tau_{1:T}^j$ and $c_{0:T}^j$ as data points. The objective is to draw Θ_τ^{j+1} and Θ_c^{j+1}.

VAR coefficients. For ease of exposition, we omit the superscript j below. For $t \in$

$\{2, ..., T\}$, we express the VAR as

$$c_t' = \underbrace{\begin{bmatrix} c_{t-1}' & c_{t-2}' \end{bmatrix}}_{w_t'} \underbrace{\begin{bmatrix} \Phi_1' \\ \Phi_2' \end{bmatrix}}_{\beta} + \epsilon_{c,t}', \quad \epsilon_{c,t} \sim N(\mathbf{0}, \Sigma_c). \tag{22}$$

Define $X = [c_2, ...c_T]'$, $W = [w_2, ..., w_T]'$, and $\epsilon_c = [\epsilon_{c,2}, ..., \epsilon_{c,T}]'$ conditional on the initial observations. If the prior distributions for β and Σ_c are

$$\beta|\Sigma \sim MN\big(\underline{\beta}, \Sigma \otimes (\underline{V}_\beta \xi)\big), \quad \Sigma_c \sim IW(\underline{\Psi}, \underline{d}), \tag{23}$$

then because of the conjugacy the posterior distributions can be expressed as

$$\beta|\Sigma \sim MN\big(\overline{\beta}, \Sigma \otimes \overline{V}_\beta\big), \quad \Sigma_c \sim IW(\overline{\Psi}, \overline{d}) \tag{24}$$

where

$$\begin{aligned} \overline{\beta} &= \big(W'W + (\underline{V}_\beta \xi)^{-1}\big)^{-1}\big(W'X + (\underline{V}_\beta \xi)^{-1}\underline{\beta}\big), \\ \overline{V}_\beta &= \big(W'W + (\underline{V}_\beta \xi)^{-1}\big)^{-1}, \\ \overline{\Psi} &= (X - W\overline{\beta})'(X - W\overline{\beta}) + (\overline{\beta} - \underline{\beta})'(\underline{V}_\beta \xi)^{-1}(\overline{\beta} - \underline{\beta}) + \underline{\Psi}, \\ \overline{d} &= T - 2 + \underline{d}. \end{aligned} \tag{25}$$

We follow the exposition in Giannone et al. (2015) in which ξ is a scalar parameter controlling the tightness of the prior information in (23). For instance, prior becomes more informative when $\xi \to 0$. In contrast, when $\xi = \infty$, then it is easy to see that $\overline{\beta} = \hat{\beta}$, i.e., an OLS estimate.

In sum, we draw β^{j+1} and Σ^{j+1} from (24). Hence, we obtain $\Theta_c^{j+1} = \{\Phi_1^{j+1}, \Phi_2^{j+1}, \Sigma_c^{j+1}\}$.

Trend component variances. Conditional on $\tau_{1:T}^j$, the objective is to draw $\Theta_\tau^{j+1} = \{\Sigma_\tau^{j+1}\}$. For ease of exposition, we omit the superscript j below. Define $X = [\tau_2, ..., \tau_T]'$ and $W = [\tau_1, ..., \tau_{T-1}]'$. Similarly as before we draw from

$$\Sigma_\tau \sim IW(\overline{\Psi}, \overline{d}), \quad \overline{\Psi} = (X - W)'(X - W) + \underline{\Psi}, \quad \overline{d} = T - 1 + \underline{d}. \tag{26}$$

Parameters for survey expectations. Conditional on $\tau_{1:T}^j$ and $c_{1:T}^j$, the objective is to draw $\Theta_e^{j+1} = \{\delta^{j+1}, \Sigma_\eta^{j+1}\}$. For ease of exposition, we omit the superscript j below. Define

$X = [\pi_1^{e,10y} - \tau_{\pi,1}, ..., \pi_T^{e,10y} - \tau_{\pi,T}]'$ and $W = [c_{\pi,1}^e, ..., c_{\pi,T}^e]'$. We draw δ^{j+1} and Σ_η^{j+1} from posterior distributions expressed in (24).

D Robustness Checks

This appendix provides more details on the robustness checks presented in Subsection 5.3.

D.1 Robustness checks via bivariate specification

This appendix documents that our main finding does not depend on the richness of our baseline specification. To this end, we explore two versions of a simple bivariate system. Both versions rely on baseline data concerning realized and one-year-ahead average expected inflation. The difference lies in one version incorporating the unemployment rate alongside its one-year-ahead survey expectation, while the other version is based on data related to real GDP growth. Realized and expected data for nominal or real variables share a common trend and a common cycle—while accounting for model-consistent expectations.[14] As in our baseline, the trends follow unit-root processes and the cycles a VAR(2) model. For both versions, we make three sets of assumptions about measurement errors. We consider the case in which only survey expectations have measurement errors, the case when also realized inflation is subject to those errors, and ultimately a case with measurement errors for all series. We estimate each bivariate model using six sets of priors, varying in the tightness concerning the standard deviation of shocks to inflation trends and either the unemployment rate or real GDP growth.

A bivariate TC-VAR model. Let us denote inflation by π and a real variable—either unemployment rate or real GDP growth—by s. We assume that trends and cycles evolve as

$$\begin{bmatrix} \tau_{s,t} \\ \tau_{\pi,t} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \tau_{s,t-1} \\ \tau_{\pi,t-1} \end{bmatrix} + \begin{bmatrix} \epsilon_{\tau,s,t} \\ \epsilon_{\tau,\pi,t} \end{bmatrix}, \quad \epsilon_{\tau,t} \sim N(0, \Sigma_\tau), \tag{27}$$

$$\begin{bmatrix} c_{s,t} \\ c_{\pi,t} \end{bmatrix} = \begin{bmatrix} \rho_{ss}^1 & \rho_{s\pi}^1 \\ \rho_{\pi s}^1 & \rho_{\pi\pi}^1 \end{bmatrix} \begin{bmatrix} c_{s,t-1} \\ c_{\pi,t-1} \end{bmatrix} + \begin{bmatrix} \rho_{ss}^2 & \rho_{s\pi}^2 \\ \rho_{\pi s}^2 & \rho_{\pi\pi}^2 \end{bmatrix} \begin{bmatrix} c_{s,t-2} \\ c_{\pi,t-2} \end{bmatrix} + \begin{bmatrix} \epsilon_{c,s,t} \\ \epsilon_{c,\pi,t} \end{bmatrix}, \quad \epsilon_{c,t} \sim N(0, \Sigma_c).$$

[14] We have chosen this approach to maintain parsimony, avoiding the introduction of additional independent components for survey expectations.

More compactly,

$$\begin{bmatrix} \tau_t \\ c_t \\ c_{t-1} \\ \eta_t \\ \eta_{t-1} \end{bmatrix} = \begin{bmatrix} I & 0 & 0 & 0 & 0 \\ 0 & \rho^1 & \rho^2 & 0 & 0 \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 \end{bmatrix} \begin{bmatrix} \tau_{t-1} \\ c_{t-1} \\ c_{t-2} \\ \eta_{t-1} \\ \eta_{t-2} \end{bmatrix} + \begin{bmatrix} \epsilon_{\tau,t} \\ \epsilon_{c,t} \\ 0 \\ \varepsilon_{\eta,t} \\ 0 \end{bmatrix}. \tag{28}$$

For convenience, denote

$$\gamma_t = \rho\gamma_{t-1} + \varepsilon_{c,t} \tag{29}$$

where

$$\gamma_t = \begin{bmatrix} c_t \\ c_{t-1} \end{bmatrix}, \quad \rho = \begin{bmatrix} \rho^1 & \rho^2 \\ I & 0 \end{bmatrix}, \quad \varepsilon_{c,t} = \begin{bmatrix} \epsilon_{c,t} \\ 0 \end{bmatrix}. \tag{30}$$

The state-transition equation becomes

$$\begin{bmatrix} \tau_t \\ \gamma_t \\ \eta_t \\ \eta_{t-1} \end{bmatrix} = \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & \rho & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & I & 0 \end{bmatrix} \begin{bmatrix} \tau_{t-1} \\ \gamma_{t-1} \\ \eta_{t-1} \\ \eta_{t-2} \end{bmatrix} + \begin{bmatrix} \epsilon_{\tau,t} \\ \varepsilon_{c,t} \\ \varepsilon_{\eta,t} \\ 0 \end{bmatrix}, \quad \varepsilon_{\eta,t} \sim N(0, \Sigma_\eta). \tag{31}$$

The measurement equation is

$$z_t = \begin{bmatrix} \Lambda_\tau & \Lambda_\gamma & \Lambda_{\eta,0} & \Lambda_{\eta,1} \end{bmatrix} x_t. \tag{32}$$

Specifications. We explore two scenarios: one where we incorporate the unemployment rate and inflation into the estimation, and another where we utilize real GDP growth and inflation. In both cases, we enhance the model by including their respective 4-quarter-ahead survey expectations:

- Unemployment and inflation: $z_t = (u_t^e, \pi_t^e, u_t, \pi_t)'$; define $e_s' = [1, 0, 0, 0]$ and $e_\pi' = [0, 1, 0, 0]$.
- GDP growth and inflation: $z_t = (g_t^e, \pi_t^e, g_t, \pi_t)'$; define $e_s' = [1, 0, -1, 0]$ and $e_\pi' = [0, 1, 0, 0]$.

We impose

$$\Lambda_\tau = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \Lambda_\gamma = \begin{bmatrix} e_s'\rho^4 \\ \frac{1}{4}e_\pi'(\rho^4+\rho^3+\rho^2+\rho^1) \\ e_s' \\ e_\pi' \end{bmatrix}, \tag{33}$$

and consider the following three cases for Λ_η:

(M1) Measurement errors for survey expectations

$$\Lambda_{\eta,0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \Lambda_{\eta,1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \tag{34}$$

(M2) Measurement errors for survey expectations and inflation

$$\Lambda_{\eta,0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Lambda_{\eta,1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \tag{35}$$

(M3) Measurement errors for all series

- Unemployment and inflation

$$\Lambda_{\eta,0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Lambda_{\eta,1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \tag{36}$$

- GDP growth and inflation

$$\Lambda_{\eta,0} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Lambda_{\eta,1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \tag{37}$$

Priors. We consider six sets of priors for (27)

$$p(\Sigma_\tau) = IW(\kappa_\tau, (\kappa_\tau + n_\tau + 1)\underline{\Sigma}_\tau). \tag{38}$$

Specifically, with respect to (38), we set κ_τ to 100 and vary

(P1) $diag(\underline{\Sigma}_\tau) = [1/120, 1/120]$;

(P2) $diag(\underline{\Sigma}_\tau) = [1/80, 1/80]$;

(P3) $diag(\underline{\Sigma}_\tau) = [1/40, 1/40]$;

(P4) $diag(\underline{\Sigma}_\tau) = [1/120, 1/60]$;

(P5) $diag(\underline{\Sigma}_\tau) = [1/80, 1/40]$;

(P6) $diag(\underline{\Sigma}_\tau) = [1/60, 1/40]$.

We set the measurement error variance priors as follows: $\kappa_\tau = 100$ as before, and we impose $diag(\bar{\Sigma}_\eta) = [3.0, 3.0, 3.0, 3.0]$.

Results. For each estimated specification, we identify the shock with the largest contribution to the volatility of the cyclical component of realized unemployment rate or real GDP. Table 9 reports the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle over all the frequencies of the cycle. Out of the 36 estimated specifications, the median contribution of the identified shocks ranges between 33.6% and 95.3%. These results corroborate the evidence of a strong empirical nexus between real activity and inflation over the business cycle. The richness of our baseline specification solely improves the quantitative assessment of this nexus.

D.2 Robustness checks within baseline specification

In this appendix, we check the robustness of our results based on the baseline specification.

Table 9: Variance contributions of the unemployment/GDP shock to inflation

	Unemployment shock			GDP shock		
	(M1)	(M2)	(M3)	(M1)	(M2)	(M3)
(P1)	83.35	95.04	53.34	33.56	72.18	41.80
	[66.35, 90.93]	[89.81, 97.04]	[20.97, 76.97]	[20.58, 48.37]	[56.04, 87.50]	[27.57, 61.63]
(P2)	82.06	92.83	42.30	50.29	65.13	66.08
	[68.34, 92.57]	[85.31, 97.01]	[10.79, 70.28]	[33.64, 71.81]	[48.96, 82.47]	[41.18, 83.11]
(P3)	76.04	91.70	33.89	54.06	62.91	65.42
	[38.16, 93.96]	[81.07, 96.87]	[11.24, 66.22]	[35.36, 72.04]	[44.74, 81.81]	[46.40, 82.23]
(P4)	87.67	90.47	58.09	43.78	53.95	53.80
	[66.75, 93.74]	[74.04, 95.61]	[19.74, 84.58]	[26.21, 60.75]	[33.83, 73.27]	[40.04, 72.82]
(P5)	85.99	95.27	46.03	42.87	53.55	55.84
	[66.16, 93.02]	[88.42, 97.93]	[5.53, 81.01]	[27.01, 61.19]	[33.73, 71.16]	[41.48, 70.77]
(P6)	81.67	94.24	41.40	45.86	57.86	53.79
	[57.04, 91.56]	[85.08, 97.83]	[16.19, 75.41]	[33.31, 65.21]	[43.56, 77.81]	[38.24, 73.09]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of realized unemployment rate or real GDP. The shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of inflation over the corresponding frequencies.

D.2.1 Importance of time-varying trends

Our main results highlight the importance of properly capturing low-frequency movements in real and nominal variables. By treating the latent trends as time-varying objects, our model is able to assess the relationship between those variables at business-cycle frequencies. To elucidate this point, we consider a constrained specification in which all trends are assumed constant. Specifically, we leave unchanged all other assumptions about priors and initial conditions and simply set the standard deviation of shocks to the trends to zero. Table 10 reports the contributions of the identified shock to the volatility of the cyclical components of the unemployment rate as well as the remaining variables over the same frequencies. Note that now the shock only explains about 9% of the volatility of the realized inflation cycle and about 7% of the volatility of expected inflation. The estimate of the shock's contribution to the volatility of inflation is well within the range of estimates

Table 10: Variance contributions of unemployment shock: When trends are constant

Business-cycle frequencies ($6-32$ quarters)					
Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
89.7	46.6	92.5	44.7	9.2	7.3
[86.7,92.4]	[39.9,54.5]	[89.5,94.6]	[37.0,53.2]	[4.9,14.9]	[3.4,12.5]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of realized unemployment rate over business-cycle frequencies (6-32 quarters). We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the same frequencies.

provided in Angeletos et al. (2020). The similarity of our findings under this scenario to those of Angeletos et al. (2020) is not surprising. Once the latent trends are assumed to be constant, our model collapses to a VAR model, with the only distinction that output is modeled in deviations from a linear trend and the other variables are demeaned.

D.2.2 No measurement errors for inflation

Our baseline specification includes a negative MA component as measurement error for realized inflation. This modelling choice aims at capturing and purging our results from some of the high-frequency movements of inflation due to energy prices. In this subsection, we verify that the exclusion of measurement errors for realized inflation does not undermine our findings. In contrast, we show that the main results carry over, supporting the inclusion of those measurement errors to sharpen the empirical evaluation of the business-cycle relationship between nominal and real variables.

Relative to our baseline specification, we consider a specification that removes the MA component of the measurement error for realized inflation. We estimate the model with the priors specified in Section 4.2 and identify the shock by targeting the cyclical component of the unemployment rate over all the frequencies of the cycle. Panel (A) of Table 11 reports the median—and the 68% posterior-coverage interval—for the contribution of the identified shock to the variance of the cycle of all variables. Not surprisingly, the shock can explain a large share of the fluctuations of the unemployment-rate cycle. However, the shock can also explain a sizable fraction of the cyclical component of realized inflation. The unemployment-identified shock can explain around 43% and nearly 69% of the cyclical movements of realized and expected inflation, respectively. If we identify the shock by

Table 11: Robustness checks within baseline specification

All frequencies ($0 - \infty$ quarters)

	Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.
A. No measurement errors for inflation						
	74.8	80.0	79.5	20.7	43.7	68.8
	[66.1,83.9]	[64.9,88.9]	[68.7,88.0]	[5.7,48.1]	[19.5,68.4]	[29.1,92.9]
B. Alternative priors						
Conservative	68.6	59.3	66.0	57.2	30.5	45.3
priors	[58.6, 81.3]	[46.9, 74.2]	[54.8, 79.3]	[26.3, 81.7]	[10.6, 55.6]	[15.3, 76.2]
Tight	67.0	62.6	65.0	48.0	28.4	38.7
priors	[57.6, 78.1]	[45.9, 79.2]	[55.1, 77.8]	[12.8, 79.7]	[9.9, 61.4]	[9.4, 78.4]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of realized unemployment rate over all the frequencies of the cycle. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequency.

targeting the cyclical component of the real GDP or we exclude frequencies that imply cycles less than 1.5 years, the results suggest a slightly stronger empirical relationship.

D.2.3 Alternative priors

We now show that our baseline results with time-varying trends are not sensitive to the choice of alternative priors for the standard deviation of the shock to the trend unemployment rate. In our baseline specification, we set the standard deviation for the expected change in the trend unemployment rate to 1% over a time period of 20 years. We now consider two alternative priors: a "Conservative" prior which sets that standard deviation to 1% over a period of 30 years and a "Tight" prior which assumes the same standard deviation but over a period of 40 years. Panel (B) of Table 11 reports the median contributions—and the associated 68-percent posterior-coverage intervals—of the unemployment-identified shock to the variability of each cyclical component under the two alternative priors. Setting an increasingly tighter prior on the standard deviation of the shock to the trend unemployment rate does not affect the results. The shock explains between about 60 - 70% of the cyclical components of the real variables. Similarly, the shock's contributions on the variability of the cyclical components of the nominal variables are also robust to the choice of either prior. We also obtain slightly stronger results for the case in which the shock is identified over all frequencies of the cycle excluding those that imply cycles less than 1.5 years.

D.3 Alternative specifications

In this appendix, we present details on the three alternative specifications considered in Subsection 5.3 and, for each alternative, we describe the assumptions about initial conditions and priors used for the model estimation, and report the corresponding results.

D.3.1 Parsimonious specification

Specification and priors. In this alternative, we consider a more parsimonious specification than the baseline. We assume that realized unemployment rate and one-year-ahead unemployment rate expectations evolve as

$$u_t = \tau_{u,t} + c_{u,t}, \tag{39.1}$$

$$u_t^{e,1y} = \tau_{u,t} + c_{u,t} + \eta_{u,t}^{e,1y}, \tag{39.2}$$

thus sharing the common cyclical component $c_{u,t}$. We allow for observation error on the one-year-ahead unemployment expectations. We decompose the inflation measures as

$$\pi_t = \tau_{\pi,t} + c_{\pi,t} + \eta_{\pi,t} - \eta_{\pi,t-1}, \tag{40.1}$$

$$\pi_t^{e,1y} = \tau_{\pi,t} + c_{\pi,t} + \eta_{\pi,t}^{e,1y}, \tag{40.2}$$

$$\pi_t^{e,10y} = \tau_{\pi,t} + \eta_{\pi,t}^{e,10y}. \tag{40.3}$$

Therefore, we assume one common cyclical component for inflation, $c_{\pi,t}$, which is shared across realized inflation and the one-year-ahead inflation expectation. We assume that ten-year-ahead inflation expectations proxy for the trend component but does not include any cyclical component. Lastly, we allow for idiosyncratic errors for both inflation expectations.

In this case, the vectors of observables, trends and shocks to the trends are unchanged relative to the baseline, while we re-define the other vectors as

$$c_t = \{c_{y,t}, c_{u,t}, c_{f,t}, c_{\pi,t}\}', \;\; \eta_t = \left\{\eta_{\pi,t}, \eta_{\pi,t}^{e,1y}, \eta_{\pi,t}^{e,10y}\right\}', \;\; \varepsilon_{c,t} = \{\varepsilon_{c,y,t}, \varepsilon_{c,u,t}, \varepsilon_{c,f,t}, \varepsilon_{c,\pi,t}\}'.$$

Evidently, this alternative specification is more parsimonious than the baseline because, while considering the same number of trends, it allows for four, rather than six, cyclical components.

Table 12: Parsimonious specification: Variance contributions of unemployment shock

All frequencies ($0-\infty$ quarters)

Unempl.	Output	FFR	Inflation
74.7	81.6	44.7	39.2
[64.0,85.6]	[70.2,90.2]	[19.2,73.6]	[24.3,54.2]

All-but-short-run frequencies ($6-\infty$ quarters)

Unempl.	Output	FFR	Inflation
75.8	82.7	44.6	44.9
[64.9,86.3]	[71.1,90.9]	[19.6,72.3]	[28.0,59.8]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical common component of the unemployment rate. We consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case we exclude frequencies that imply cycles less than 1.5 years. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequencies.

Initial conditions and priors. Under this alternative specification, we leave unchanged the assumptions on the initial conditions of the trends and the prior for the standard deviation of the shocks to the trend components. As a result, the prior covariance matrix of the shocks to the trends is diagonal with the following elements on the main diagonal $diag\left(\underline{\Sigma_{\tau}}\right) = [1/40, 1/20, 1/20, 1/20]$. Finally, we need to set the prior for the standard deviation of the shocks affecting the four cyclical components. For real GDP and nominal interest rate, we keep the same priors as under the baseline. For the common cyclical components of unemployment rate and inflation, we set those priors to the pre-sample standard deviations of the respective realized measures of unemployment rate and inflation. Therefore, the prior covariance matrix of the shocks to the cycles is diagonal and such that the value on the main diagonal approximately correspond to $diag\left(\underline{\Sigma_{c}}\right) = [25, 1.3, 0.6, 2.2]$.

Results. We estimate the alternative specification of the TC-VAR model using the state-space representation in (10) and (11) and subsequently identify the shock targeting the common cyclical component of unemployment rate. We report in Table 12 the contributions of the identified shock to the volatility of each cyclical components. Even in this case, the results are in line with those of the baseline specification. When the shock is identified over all frequencies, it accounts for about 39% of the cyclical volatility of the cyclical common component of inflation. When we identify the shock excluding frequencies that imply cycles less than 1.5 years, the same contribution of the shock rises to nearly 45%.

D.3.2 Flexible specification

Specification and priors. Under this alternative specification, the decompositions of realized unemployment rate in (4) and one-year-ahead unemployment rate expectations in (6) are identical to those assumed under the baseline. However, we consider the following more flexible decomposition for the two inflation expectations measures

$$\pi_t^{e,1y} = \tau_{\pi,t} + c_{\pi,t}^{e,1y}, \tag{41.1}$$

$$\pi_t^{e,10y} = \tau_{\pi,t} + c_{\pi,t}^{e,10y}. \tag{41.2}$$

Hence, the two inflation expectation measures follow separate, idiosyncratic cyclical components, while both sharing a common inflation trend with realized inflation decomposed in (8.1). For this alternative specification, the vectors of observables, measurement error, trends and shocks to the trends are unchanged relative to the baseline. However, the vectors of the cyclical components and the associated disturbances are re-written as

$$c_t = \left\{c_{y,t}, c_{u,t}, c_{u,t}^{e,1y}, c_{f,t}, c_{\pi,t}, c_{\pi,t}^{e,1y}, c_{\pi,t}^{e,10y}\right\}', \;\; \varepsilon_{c,t} = \left\{\varepsilon_{c,y,t}, \varepsilon_{c,u,t}, \varepsilon_{c,u,t}^{e,1y}, \varepsilon_{c,f,t}, \varepsilon_{c,\pi,t}, \varepsilon_{c,\pi,t}^{e,1y}, \varepsilon_{c,\pi,t}^{e,10y}\right\}',$$

therefore allowing for seven, rather than six, idiosyncratic cyclical components.

Initial conditions and priors. Under this alternative specification, we keep the same assumptions on the initial conditions of the trends and the standard deviation of the shocks to the trends as under the baseline, that is $diag\left(\underline{\Sigma_\tau}\right) = [1/40, 1/20, 1/20, 1/20]$.

For the shocks to the cyclical components, we assume the same priors as under the baseline for real GDP growth, realized and expected unemployment rate, nominal interest rate and inflation. Because the measures of one- and ten-year-ahead inflation expectations are not available for the pre-sample period, we set the standard deviations of the shocks to those cyclical components to about 1.2% and 1% respectively, thus smaller than the pre-sample counterpart of 1.5% for realized inflation. As a result of these assumptions, the prior covariance matrix of the shocks to the cycles is diagonal and such that the values on the main diagonal approximately correspond to $diag\left(\underline{\Sigma_c}\right) = [25, 1.3, 0.8, 0.6, 2.2, 1.4, 1.0]$.

Results. We estimate the proposed alternative specification of the TC-VAR model and identify the shock targeting the cyclical component of realized unemployment rate. In Table 13, we report the shock's contributions to the volatility of the cyclical components of all variables. The results show that the findings under the baseline specification carry over.

Table 13: Flexible specification: Variance contributions of unemployment shock

All frequencies ($0-\infty$ quarters)

Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.(1y)	Inflation exp.(10y)
67.6	60.1	65.5	51.2	17.5	33.8	12.3
[58.2,78.6]	[49.0,71.6]	[54.8,76.7]	[27.3,71.7]	[7.6,33.7]	[16.5,54.7]	[4.8,26.9]

All-but-short-run frequencies ($6-\infty$ quarters)

Unempl.	Output	Unempl. exp.(1y)	FFR	Inflation	Inflation exp.(1y)	Inflation exp.(10y)
68.6	60.0	68.8	51.8	20.2	38.9	18.4
[58.8,80.0]	[48.5,71.9]	[57.2,80.5]	[26.4,73.0]	[8.4,38.0]	[19.2,62.0]	[7.3,40.3]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of realized unemployment rate. We consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case we exclude frequencies that imply cycles less than 1.5 years. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequencies.

In fact, the shock explains nearly 34% of the volatility of the cyclical component of one-year-ahead inflation expectations which we consider as a measure of underlying inflation. When excluding movements in cyclical components at frequencies higher than 1.5 years, the results point to an increase to about 39% in the explanatory power of the identified shock for the cyclical component of underlying inflation.

D.3.3 Specification with no unemployment rate expectations

Specification and priors. Under the third and final alternative specification, we exclude the measurement equation (6) for the expectations of the one-year-ahead unemployment rate, while leaving all the other decompositions as under the baseline. As a result, only the vectors of observables, cyclical components and the associated disturbances are modified as follows

$$z_t = \left\{g_t, u_t, f_t, \pi_t, \pi_t^{e,1y}, \pi_t^{e,10y}\right\}', \; c_t = \left\{c_{y,t}, c_{u,t}, c_{f,t}, c_{\pi,t}, c^e_{\pi,t}\right\}', \; \varepsilon_{c,t} = \left\{\varepsilon_{c,y,t}, \varepsilon_{c,u,t}, \varepsilon_{c,f,t}, \varepsilon_{c,\pi,t}, \varepsilon^e_{c,\pi,t}\right\}'.$$

Initial conditions and priors. Even under this alternative specification, we keep the same assumptions on the initial conditions of the trends and the standard deviation of the shocks to the trends as under the baseline, that is $diag\left(\underline{\Sigma_\tau}\right) = [1/40, 1/20, 1/20, 1/20]$.

Table 14: No unemployment rate expectations: Variance contributions of unemployment shock

All frequencies ($0-\infty$ quarters)				
Unempl.	Output	FFR	Inflation	Inflation exp.
71.2	80.4	56.2	44.5	51.5
[61.2,81.5]	[69.4,88.1]	[21.8,81.9]	[29.8,57.7]	[25.3,71.2]

All-but-short-run frequencies ($6-\infty$ quarters)				
Unempl.	Output	FFR	Inflation	Inflation exp.
72.2	81.2	55.7	49.8	57.4
[62.2,82.4]	[70.5,88.7]	[21.9,81.6]	[34.1,62.7]	[28.5,77.6]

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of the unemployment rate. We consider two cases. In the first case, the shock is chosen to maximize the fraction of the volatility over all the frequencies of the cycle, while in the second case we exclude frequencies that imply cycles less than 1.5 years. We report the median contribution and the corresponding 68-percent posterior-coverage interval of the identified shock to the variance of the cycle of all variables over the corresponding frequencies.

For the shocks to the cyclical components, we simply drop the assumption on the standard deviation for the cyclical component of the one-year-ahead unemployment rate expectations, while keeping the other assumptions as under the baseline. The resulting prior covariance matrix of the shocks to the cycles is $diag\left(\underline{\Sigma_c}\right) = [25, 1.3, 0.6, 2.2, 1.4]$.

Results. After estimating the TC-VAR model under the assumptions of the proposed alternative specification, we identify the shock targeting the cyclical component of realized unemployment rate. Table 14 reports the contributions of the identified shock to the volatility of the cyclical components of all variables. The results verify the robustness of our main findings to the exclusion of the one-year-ahead unemployment rate expectations for the estimation of the TC-VAR model. In fact, the shock explains about 44% and 51% of the volatility of the cyclical component of realized inflation and one-year-ahead inflation expectations respectively. Excluding movements in cyclical components at frequencies higher than 1.5 years, the contribution of the shock to the cyclical components of realized and expected inflation reaches about 51% and 57% respectively.

E Details on Long-run Priors

E.1 Long-run priors for Angeletos et al. (2020)

As detailed in Section I of Angeletos et al. (2020), their data consist of quarterly observations on the following macroeconomic variables: real, per-capita levels of GDP (Y_t), investment (I_t), consumption (C_t); unemployment rate (u_t); hours worked per person (h_t); the level of utilization-adjusted total factor productivity (TFP_t); the labor share ($w_t h_t / Y_t$); the inflation rate (π_t), as measured by the rate of change in the GDP deflator; and the nominal interest rate (R_t), as measured by the FFR. When estimating the VAR model using the long-run priors, we consider the arbitrary ordering of the observables $z_t = \{Y_t, I_t, C_t, u_t, h_t, TFP_t, w_t h_t / Y_t, \pi_t, R_t\}'$. We assume that the following matrix H captures the cointegrating relationships in the long run

$$H = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}.$$

E.2 Long-run priors for VAR model in Section 6

When estimating the VAR model on our data and using the long-run priors, we consider the arbitrary ordering of the observables $z_t = \left\{g_t, u_t, f_t, \pi_t, \pi_t^{e,1y}, u_t^{e,1y}\right\}'$. We assume that the following matrix H captures the cointegrating relationships in the long run

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 \end{bmatrix}. \quad (42)$$

F Supplementary Material to Section 7

F.1 Definition of stabilizability

Definition 1 *The pair (A, B) is stabilizable if any of the following conditions holds:*

- *There exists no left eigenvector of A associated with an eigenvalue having nonnegative real part that is orthogonal to the columns of B;*

$$\begin{cases} \nu^* A = \lambda \nu \quad (Re[\lambda(A)] \geq 0) \\ \nu^* B = 0 \end{cases} \Rightarrow \nu = 0.$$

- *rank* $[\lambda I - A \quad B] = dim(A)$ *for all* $Re[\lambda(A)] \geq 0$.

F.2 Matrices for time-invariant innovations representation

As shown in Fernández-Villaverde et al. (2007), the time-invariant matrices $\hat{B}$ and $\hat{D}$ satisfy the following equations:

$$\Omega = A\Omega A' + BB' - (A\Omega C' + BD')(C\Omega C' + DD')^{-1}(A\Omega C' + BD')', \quad (43.1)$$

$$K = (A\Omega C' + BD')(C\Omega C' + DD')^{-1}, \quad (43.2)$$

$$\hat{D}\hat{D}' = DD' + C\Omega C', \quad (43.3)$$

$$\hat{B} = K\hat{D}. \quad (43.4)$$

F.3 The AR representation of a univariate TC-AR model

In this appendix, we provide an intuitive, analytical example that considers the unobserved components model used by Stock and Watson (2007) to test whether the U.S. inflation process experienced a structural change since the beginning of the Great Moderation. Inflation is described by the following state-space representation

$$\pi_t = \Lambda_\tau \tau_{\pi,t} + \Lambda_\eta \eta_{\pi,t}, \tag{44.1}$$

$$\tau_{\pi,t} = \Phi_\tau \tau_{\pi,t-1} + \mathcal{R}\varepsilon_{\tau,\pi,t}, \tag{44.2}$$

where

$$\Phi_\tau = 1, \quad \mathcal{R} = 1, \quad \Lambda_\tau = 1, \quad \Lambda_\eta = 1,$$

and $\varepsilon_{\tau,\pi,t} = Qw_{\tau,\pi,t}$, $Q = \sigma_\tau$, $\eta_{\pi,t} = \sigma_\eta w_{\eta,\pi,t}$ such that $E(w_t w_t') = \mathcal{I}$ where $w_t = \{w_{\tau,\pi,t}, w_{\eta,\pi,t}\}'$. Defining $z_t = \pi_t$ and $x_t = \tau_t$, the representation in (44) coincides with (10) and (11) where, following the notation in Anderson and Moore (1979), we appended the measurement error $\eta_{\pi,t}$ directly in (10) as opposed to redundantly defining it in the transition equation (11). Thus, we verify two conditions: i) the pair $(\Phi_\tau, \mathcal{R}Q)$ is stabilizable; ii) the pair $(\Phi_\tau', \Lambda_\tau')$ is stabilizable. Because Φ_τ has only one (unit-root) eigenvalue, then

$$rank\,[I - \Phi_\tau \quad \mathcal{R}Q] = rank\,[0 \quad \sigma_\tau] = 1,$$

and

$$rank\,[I - \Phi_\tau' \quad \Lambda_\tau'] = rank\,[0 \quad 1] = 1.$$

Therefore, the asymptotic properties of the Kalman filter hold, and we can derive the AR(∞) representation of (44). In particular, we write (44) as in (15) where

$$A = 1, \quad B = \begin{bmatrix} \sigma_\tau & 0 \end{bmatrix}, \quad C = 1, \quad D = \begin{bmatrix} \sigma_\tau & \sigma_\eta \end{bmatrix},$$

assuming that the shock to the trend is $\varepsilon_{\tau,\pi,t} = \sigma_\tau w_{\tau,\pi,t}$ and the measurement error is $\eta_{\pi,t} = \sigma_\eta w_{\eta,\pi,t}$ and $E(w_t w_t') = \mathcal{I}$ where $w_t = \{w_{\tau,\pi,t}, w_{\eta,\pi,t}\}'$. Defining $\sigma_{\widehat{\tau}} \equiv \Omega$ as the variance of the error associated with the estimate of the trend, $(\tau_{\pi,t} - \widehat{\tau}_{\pi,t})$, we can use the equation (43) in Appendix F.2 to derive the time-invariant matrices $\hat{B}$ and $\hat{D}$ as

$$\sigma_{\widehat{\tau}}^2 = \frac{1}{2}\left(-\sigma_\tau^2 + \sqrt{\sigma_\tau^4 + 4\sigma_\tau^2\sigma_\eta^2}\right) > 0, \tag{45.1}$$

$$K = 1 - \delta, \tag{45.2}$$

$$\hat{D}\hat{D}' = \left(\sigma_{\widehat{\tau}}^2 + \sigma_\tau^2 + \sigma_\eta^2\right), \tag{45.3}$$

$$\hat{B} = (1-\delta)\left(\sigma_{\widehat{\tau}}^2 + \sigma_\tau^2 + \sigma_\eta^2\right)^{1/2}, \tag{45.4}$$

Table 15: Variance contribution of unemployment shock (data simulated with $\sigma_{\tau,\pi} = 0$)

	Unemployment	Inflation
$\sigma_{\tau,u} = 0.1$	100.0	98.8
	$[99.9, 100.0]$	$[98.7, 98.9]$
$\sigma_{\tau,u} = 1$	99.3	14.3
	$[98.7, 99.7]$	$[11.9, 16.8]$
$\sigma_{\tau,u} = 2$	99.6	3.2
	$[99.0, 99.9]$	$[2.2, 4.4]$

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median and the corresponding 68-percent posterior-coverage interval of the median contributions of the shock to the variance of all variables over the same frequencies. To simulate the data, we use the following calibrations. For the unemployment rate, we set $\rho_{uu} = 0.95$, $\sigma_{c,u} = 1$ and $\sigma_{\tau,u} = \{0.1, 1, 2\}$. For the inflation rate, we set $\rho_{\pi\pi} = 0$, $\kappa = 1$, and $\sigma_{c,\pi} = 0$ and $\sigma_{\tau,\pi} = 0$.

where $\delta = \sigma_\eta^2 / \left(\sigma_{\hat{\tau}}^2 + \sigma_\tau^2 + \sigma_\eta^2\right) < 1$. Finally, using (18) and (45), we map the state-space representation in (44) into the infinite-order autoregression, AR(∞),

$$\begin{aligned} \pi_{t+1} &= \sum_{s=0}^{\infty} C\left(A - \hat{B}\hat{D}^{-1}C\right)^s \hat{B}\hat{D}^{-1}\pi_{t-s} + \hat{D}\nu_{t+1} \\ &= \sum_{s=0}^{\infty} C\left(A - KC\right)^s K\pi_{t-s} + \hat{D}\nu_{t+1}, \\ &= (1-\delta)\sum_{s=0}^{\infty} \delta^s \pi_{t-s} + \left(\sigma_{\hat{\tau}}^2 + \sigma_\tau^2 + \sigma_\eta^2\right)^{1/2} \nu_{t+1}, \end{aligned} \tag{46}$$

where $\nu_t \sim \mathcal{N}(0,1)$. Equation (46) shows that, even with infinite data, the estimation of the AR(∞) representation leads to parameter estimates and VAR residuals that confound the standard deviation of both the measurement error σ_η and the innovations to the trend σ_τ with the standard deviation $\sigma_{\hat{\tau}}$ resulting from the error associated with the estimate of the trend, $(\tau_{\pi,t} - \widehat{\tau}_{\pi,t})$.

F.4 Bivariate TC-VAR model: An alternative case

In this appendix, we provide details for the three alternative cases discussed in Subsection 7.2. In the first case of this appendix, we introduce low-frequency movements in the unemployment rate, while the inflation rate only follows the cyclical component of the unemployment rate. The unemployment-rate cycle evolves as in the previous case—that

Table 16: Variance contribution of unemployment shock

Unemployment	Inflation
100.0	2.2
$[99.9, 100.0]$	$[1.1, 3.7]$

Notes: The shock is identified by maximizing its contribution to the volatility of the unemployment rate over business-cycle frequencies (6-32 quarters). We report the median and the corresponding 68-percent posterior-coverage interval of the median contributions of the shock to the variance of all variables over the same frequencies. To simulate the data, we use the following calibration. For the unemployment rate, we set $\rho_{uu} = 0.95$, $\sigma_{c,u} = 1$ and $\sigma_{\tau,u} = 1$. For the inflation rate, we set $\rho_{\pi\pi} = 0.5$, $\kappa = 1$, $\sigma_{c,\pi} = 0$, and $\sigma_{\tau,\pi} = 1$.

is $\rho_{uu} = 0.95$ and $\sigma_{c,u} = 1$. However, we also allow shocks to the trend unemployment rate and consider three calibrations for its standard deviation $\sigma_{\tau,u} = \{0.1, 1, 2\}$. For the inflation rate, we assume that its process is fully explained by the cyclical component of the unemployment rate. This assumption is evidently unrealistic but is chosen to ensure that the innovations to the *cyclical component of the unemployment rate* are the only source of fluctuations for *inflation*. Implementing this assumption requires turning off the shocks to both the trend and cyclical components of inflation—that is, $\sigma_{\tau,\pi} = \sigma_{c,\pi} = 0$—and setting the autoregressive parameter $\rho_{\pi\pi}$ to zero and $\kappa = 1$. As a result, the simulated inflation rate evolves as $\pi_t = -c_{u,t-1}$.

Table 15 reports the median and 68% posterior-coverage intervals of the median contributions of the identified shock. The unemployment-identified shock explains nearly the entirety of the business-cycle movements in unemployment for all calibrations, but smaller portions of movements in inflation as the unemployment rate is increasingly driven by low-frequency movements. Thus, the shocks that are recovered by the procedure do not coincide with the structural shocks produced by the true data generating process. By construction, the identified shocks explain a large fraction of unemployment variation at business cycle frequency, but this assessment is based on the VAR parameter estimates, not the true parameters of the TC-VAR generating the data.

In the second case, we introduce trends in both inflation and unemployment and assume that cyclical inflation is persistent and not exclusively driven by cyclical unemployment rate. Specifically, for the unemployment rate, we set $\rho_\pi = 0.95$ and $\sigma_{c,u} = 1$ for its cyclical component and $\sigma_{\tau,u} = 1$ for its trend component, implying the presence of low-frequency movements. For inflation, we set $\rho_\pi = 0.5$, $\kappa = 1$, and $\sigma_{c,\pi} = 0$, resulting in a cyclical component of inflation that is driven by its lag and cyclical unemployment rate.

Table 17: Variance contribution of unemployment shock (with TC-VAR model)

Unemployment	Inflation
98.8	5.7
$[96.9, 99.5]$	$[3.2, 20.2]$

Notes: The shock is identified by maximizing its contribution to the volatility of the cyclical component of the unemployment rate over all frequencies (0-∞ quarters). We report the median and the corresponding 68-percent posterior-coverage interval of the median contributions of the shock to the variance of all variables over the same frequencies. To simulate the data, we use the following calibration. For the unemployment rate, we set $\rho_{uu} = 0.95$, $\sigma_{c,u} = 1$ and $\sigma_{\tau,u} = 0$. For the inflation rate, we set $\rho_{\pi\pi} = 0.95$, $\kappa = 0$, $\sigma_{c,\pi} = 1$ and $\sigma_{\tau,\pi} = 0$.

Additionally, $\sigma_{\tau,\pi} = 1$, thus introducing an inflation trend.

Table 16 reports the median—and the corresponding 68-percent posterior-coverage interval—of the median contributions of the identified shock to the variance of all variables over business-cycle frequencies. The contribution of the unemployment-rate shock to inflation at business-cycle frequencies is only 2.2%. Intuitively, under this alternative calibration, the inflation rate depends not only on its trend and the persistence of its cyclical component but also on the business-cycle and low-frequency movements in unemployment rate. Consequently, the estimated VAR confounds all these effects, implying no explanatory power of the unemployment-identified shock on inflation at business-cycle frequencies. To conclude, even if the long simulations were generated under the assumption that the cyclical components of unemployment rate and inflation were related, the identified shock does not capture this feature of the simulated data.

In the last case, we show that, if the data are generated by a model in line with the findings of Angeletos et al. (2020), the flexible TC-VAR model does not produce a counterfactual relationship between nominal and real variables. We assume that the unemployment rate and inflation follow two independent ($\kappa = 0$), highly persistent ($\rho_{uu} = \rho_{\pi\pi} = 0.95$) processes whose shocks are uncorrelated. Trends are absent in this specification. For each simulation, we estimate the TC-VAR model and evaluate the contribution of the unemployment-identified shock to the variability of the cyclical components of the model.[15]

[15] To speed up the estimation of the TC-VAR model on all the simulated data, we consider 100 (rather than 500) Monte Carlo simulation of $50,000$ observations of which we keep the last 500 (rather than $1,000$) for each simulation. To estimate each TC-VAR model, we use the first 100 observations as pre-sample to define both the initial conditions for the trend components and the diagonal elements of the prior covariance matrix of the shocks to the cycles. We set the two diagonal elements of the prior covariance matrix of the shocks to the trends to $1/40$. This prior is the most flexible among those for the bivariate specification in Appendix D.1. As in our baseline, we assume two lags of the VAR describing the evolution of the cyclical

Table 17 reports the median and the corresponding 68-percent posterior-coverage interval of the median contributions of the identified shock to the variance of the cyclical components of the unemployment rate and inflation over all frequencies. Although the simulated unemployment rate and inflation are highly persistent, the TC-VAR model points to a disconnect between nominal and real variables over the business cycle. While flexible, our model does not induce counterfactual relationships.

components. For each simulation, we identify the shock by targeting the cyclical unemployment rate.