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RESEARCH ARTICLE



Estimating the natural real interest rate in lithuania: a semi-structural approach

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ABSTRACT

This paper estimates the natural real interest rate (r^*) for Lithuania over the period 2000–2025 and assesses the implied monetary policy conditions. The paper employs a semi-structural unobserved-components model tailored to a small, open, and converging economy by incorporating real effective exchange rate dynamics, while also enhancing output-gap identification and exploring the role of survey-based inflation expectations. The results indicate that Lithuania's r^* was relatively high in the early 2000s, declined markedly during the global financial crisis, remained persistently low thereafter, and returned to positive values in recent years. Following the euro's adoption, Lithuania's estimated r^* exhibits closer co-movement with the euro area's natural rate, consistent with deeper economic and financial integration. Estimates of the real interest rate gap suggest that monetary conditions have been predominantly accommodative historically and broadly neutral in recent periods.

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1. Introduction

Interest rates are the primary instrument through which central banks stabilize inflation and economic activity. A key challenge in the conduct of monetary policy is determining the appropriate level of policy rates over the medium term. The concept of the natural real interest rate (r^*), the real, risk-free rate consistent with stable inflation and output at potential in the absence of transitory shocks, provides a benchmark for assessing whether monetary policy is accommodative, restrictive, or neutral. Since its original formulation by Wicksell (1936) and its more recent interpretation within New Keynesian frameworks (Woodford, 2003), r^* has played a central role in both academic analysis and policy discussions. In applied work, Laubach and Williams (2003) operationalize this concept as the real interest rate consistent with output at potential and stable inflation over the medium term, a definition that closely aligns with standard monetary policy rules.

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Despite its conceptual appeal, the natural real interest rate is unobservable and must be inferred from data using empirical models that rely on strong assumptions. As highlighted in recent work, estimates of r^* are sensitive to model structure, data choices, and the economic mechanisms emphasized, leading to substantial uncertainty (Reis, 2025). These challenges are especially acute in the current environment, where central banks are transitioning away from restrictive policy settings as inflation returns closer to target, and where renewed attention has focused on the level at which policy rates may stabilize in the longer run.

While the behaviour of r^* has been extensively studied for large advanced economies such as the United States and the euro area as a whole, less is known about its evolution in small open economies that are undergoing structural transition and do not conduct an independent monetary policy. Heterogeneity across euro area member states suggests that estimates derived at the aggregate level may not adequately capture country-specific dynamics. This raises important questions about the interpretation of euro area-wide monetary policy for smaller, more open economies, such as Lithuania, which are particularly exposed to external shocks, capital flows, and demographic change.

Lithuania constitutes an especially interesting case. Since regaining independence in 1990, the economy has undergone rapid structural transformation, including accession to the European Union in 2004 and adoption of the euro in 2015. Over this period, Lithuania has experienced pronounced convergence dynamics, substantial real exchange rate appreciation, and significant demographic pressures. Understanding the evolution of r^* in such an environment is therefore crucial not only for assessing the domestic implications of common monetary policy but also for improving empirical approaches to estimating natural interest rates in small open and converging economies.

This paper contributes to the literature in several ways. First, it provides updated estimates of Lithuania's natural real interest rate over the period 2000–2025 and examines its evolution in response to domestic developments, global shocks, and institutional changes, including euro adoption. Second, by analysing the real interest rate gap, the paper assesses the monetary policy stance experienced by Lithuania within the euro area. Third, the paper extends existing semi-structural approaches by incorporating features that are particularly relevant for small open economies: real effective exchange rate dynamics, survey-based inflation expectations, and richer identification of cyclical conditions using consumption dynamics and labour market information. Finally, the analysis addresses the challenges posed by the COVID-19 pandemic by introducing a flexible outlier adjustment tailored to Lithuania's experience.

Methodologically, the paper builds on the semi-structural unobserved-components framework of Laubach and Williams (2003), adapted for open economies following Berger and Kempa (2014) and for converging economies following Kupkovič (2020). Relative to earlier applications for Lithuania (González-Astudillo & Vilán, 2025; International Monetary Fund, 2019; Reichenbachas et al., 2021), the framework employed here places greater emphasis on external adjustment channels, survey-based expectations, and the joint use of consumption and unemployment to improve the identification of latent trends and cyclical conditions. In so doing, the paper aims to deepen the empirical understanding of Lithuania's monetary environment and to inform broader discussions on the estimation and interpretation of natural interest rates in small open economies operating within a monetary union.

The remainder of the paper is organized as follows. Section 2 presents the empirical framework and outlines the Bayesian estimation approach. Section 3 describes the data used in the analysis. Section 4 reports the main results, compares them with alternative estimates, and examines robustness. Section 5 concludes. Additional results and supplementary material are provided in the Appendix.

2. Empirical framework

We employ a semi-structural model to estimate the natural real interest rate. Within this framework, macroeconomic variables are decomposed into a persistent component, modelled as an integrated process and denoted by the superscript (*), and a transitory component capturing business-cycle fluctuations, denoted by a tilde (~). For example, the real interest rate is decomposed as

$$r_t = r_t^* + \tilde{r}_t \quad (1)$$

We assume that the natural real interest rate consists of two components: potential output growth, g_t , and a latent structural factor, z_t , consistent with the semi-structural framework commonly used in the literature (Laubach & Williams, 2003).

$$r_t^* = cg_{t-1} + z_{t-1} \quad (2)$$

This formulation is consistent with neoclassical growth models in which the steady-state real interest rate equals the net marginal product of capital. In such settings, higher long-run productivity growth increases expected capital returns along the balanced growth path, leading to a higher equilibrium real interest rate, while weaker productivity or demographic headwinds exert downward pressure on r^* .

The latent component z_{t-1} captures additional structural forces affecting the natural rate that are not directly observable. These may include shifts in household preferences (such as risk aversion or intertemporal patience), changes in the supply of safe assets, global liquidity imbalances, inequality, and demographic trends (Brand et al., 2018). Importantly, the model does not attempt to decompose z_t into distinct structural drivers; instead, it remains agnostic with respect to their underlying sources.¹ The latent structural component evolves as a random walk:

$$z_t = z_{t-1} + \varepsilon_{z,t} \quad (3)$$

implying that such structural forces are highly persistent and change only gradually over time.

To model inflation dynamics, we follow Berger and Kempa (2014) and augment a hybrid Phillips curve with the real effective exchange rate. Domestic economic conditions affect inflation through the lagged output gap, $\tilde{y}_{t-1}$. External price pressures are captured by real-exchange-rate appreciation relative to its trend rate, $\Delta q_{t-1} - \mu_{t-2}$, where μ_t denotes the stochastic drift of the equilibrium real exchange rate. An appreciation above trend, $\Delta q_{t-1} - \mu_{t-2} > 0$, implies that imported goods become relatively cheaper, exerting downward pressure on inflation; this is reflected in a negative coefficient, $\beta_q < 0$.²

The anchored component of inflation, denoted by π_t^a , is modelled as a weighted average of lagged inflation, π_{t-1} , and trend inflation, π_t^* . The lagged-inflation term

captures backward-looking inflation inertia, including indexation and adaptive components in price setting, while trend inflation captures the long-run nominal anchor.

Unlike Laubach and Williams (2003), the Phillips curve is specified as non-accelerationist, reflecting the fact that for most of the sample period monetary conditions were largely determined by euro area monetary policy, where a credible inflation-stabilizing regime prevails.³ The resulting Phillips curve specification is given by

$$\pi_t = \beta_y \tilde{y}_{t-1} + \underbrace{\beta_\pi \pi_{t-1} + (1 - \beta_\pi) \pi_t^*}_{\pi_t^a} + \beta_q (\Delta q_{t-1} - \mu_{t-2}) + \varepsilon_{\pi,t} \quad (4)$$

Trend inflation, π_t^* , evolves as a random walk:

$$\pi_t^* = \pi_{t-1}^* + \varepsilon_{\pi^*,t} \quad (5)$$

To identify it, we use observed survey-based long-run inflation expectations as a noisy measurement, following Chan et al. (2018):

$$\pi_{obs,t}^* = \omega + \pi_t^* + \varepsilon_{\pi_{obs}^*,t} \quad (6)$$

The parameter ω captures time-invariant systematic bias in survey-based inflation expectations and may also reflect differences between the survey inflation concept and the model-implied measure of trend inflation.⁴

We specify a modified New Keynesian aggregate demand relationship in the form of an IS curve that relates the output gap to the real interest rate gap and the real effective exchange rate gap:

$$\tilde{y}_t = \alpha_{y,1} \tilde{y}_{t-1} + \alpha_{y,2} \tilde{y}_{t-2} + \alpha_{r,1} \tilde{r}_{t-1} + \alpha_{r,2} \tilde{r}_{t-2} + \alpha_q \tilde{q}_{t-1} + \varepsilon_{\tilde{y},t} \quad (7)$$

Two lags of the output gap are included to allow for richer cyclical dynamics (Harvey et al., 2007). A positive real interest rate gap is expected to dampen economic activity. Similarly, when the real exchange rate exceeds its equilibrium level, indicating an overvalued domestic currency, it tends to worsen external competitiveness and reduce net exports, thereby pushing output below potential. This implies a negative coefficient on the exchange rate gap ($\alpha_q < 0$). The level of potential output evolves according to

$$y_t^* = y_{t-1}^* + g_{t-1} + \varepsilon_{\tilde{y},t} + \varepsilon_{y^*,t} \quad (8)$$

where $\varepsilon_{\tilde{y},t}$ is common shock to potential output and consumption, $\varepsilon_{y^*,t}$ is the shock to potential output, and g_t denotes the stochastic trend growth rate of the economy. The evolution of potential growth is modelled as a random walk:

$$g_t = g_{t-1} + \varepsilon_{g,t} \quad (9)$$

To further improve identification, we enrich the model by incorporating private consumption. This addition is especially valuable in partially identified unobserved-components models, as consumption provides additional information about both long-run growth and cyclical economic conditions. Specifically, the inclusion of consumption helps to identify better the trend growth component g_t as well as the output gap $\tilde{y}_t$. We assume that long-run consumption shares a common stochastic trend with long-run output:

$$c_t^* = c_{t-1}^* + \phi_c g_{t-1} + \phi_c \varepsilon_{\tilde{y},t} + \varepsilon_{c^*,t} \quad (10)$$

where ϕ_c captures the sensitivity of trend consumption to potential output growth. Antolín-Díaz et al. (2024) show that such a specification improves the identification of latent long-run growth, which is crucial for explaining variation in the natural real interest rate.

Additional information from consumption dynamics can also enhance the identification of cyclical fluctuations. Jarociński and Lenza (2018) argue that incorporating variables that share common cyclical components with output can improve estimates of economic slack. Consumption, in particular, may reflect the Euler equation more closely than GDP, linking intertemporal choices to real interest rates.⁵ Accordingly, we specify a consumption gap equation that depends on the output gap, the real interest rate gap, and the real exchange rate gap:

$$\tilde{c}_t = \gamma_y^0(L)\tilde{y}_t + \gamma_r^1(L)\tilde{r}_t + \gamma_q^1(L)\tilde{q}_t + \varepsilon_{\tilde{c},t} \quad (11)$$

where $\gamma_x^k(L) = \sum_{j=k}^{k+p_x} \gamma_{x,j} L^j$ denotes a lag polynomial for $x \in \{y, r, q\}$. Labour market dynamics can also provide valuable information about the business cycle. In particular, we incorporate Okun's law, which links cyclical movements in unemployment to the output gap (Brand & Mazelis, 2019; Jarociński & Lenza, 2018). Periods of strong economic activity are typically associated with declining unemployment, a relationship captured by the following specification:

$$\tilde{u}_t = \alpha^0(L)\tilde{y}_t + \varepsilon_{\tilde{u},t}. \quad (12)$$

Structural changes in labour market conditions are reflected in movements of the unemployment trend, u_t^* , which evolves as a random walk:

$$u_t^* = u_{t-1}^* + \varepsilon_{u^*,t} \quad (13)$$

As previously motivated, for a small and open economy like Lithuania, the variation of the real effective exchange rate (REER) matters. To model the rate, we depart from the strict Purchasing Power Parity (PPP) assumption. While PPP implies a constant long-run real exchange rate, this framework is poorly suited for transition economies, where sustained real appreciation reflects structural convergence and productivity differentials. Persistent deviations from PPP are commonly attributed to productivity catch-up.

Following Égert et al. (2006) and Kupkovič (2020), we adopt a trend-adjusted framework that allows the equilibrium REER to evolve over time. The equilibrium real exchange rate follows a random walk with stochastic drift, capturing gradual trend appreciation during the convergence process:⁶

$$q_t^* = q_{t-1}^* + \mu_{t-1} + \varepsilon_{q^*,t}, \quad (14)$$

$$\mu_t = \mu_{t-1} + \varepsilon_{\mu,t}. \quad (15)$$

Short-run deviations from equilibrium are modelled as a stationary autoregressive process:

$$\tilde{q}_t = \theta_{q,1}\tilde{q}_{t-1} + \theta_{q,2}\tilde{q}_{t-2} + \varepsilon_{\tilde{q},t}, \quad (16)$$

allowing for temporary over- or undervaluation that gradually reverts to the trend.

The real exchange rate gap is linked to the real interest rate gap through the interest rate-exchange rate nexus, consistent with gap-based real interest parity (Berger & Kempa, 2014):

$$\tilde{r}_t = \gamma \tilde{q}_{t-1} + \kappa_{t-1}, \quad (17)$$

$$\kappa_t = \rho \kappa_{t-1} + \varepsilon_{\kappa,t}. \quad (18)$$

The latent component κ_t captures time-varying risk premiums, global financial shocks, and other distortions that affect international capital flows. Since both components in Equation (17) are assumed to be stationary, the real interest rate gap ($\tilde{r}_t$) is therefore characterized by purely transitory deviations.

Note that all disturbance terms $\varepsilon_{i,t}$ are assumed to be independent and identically distributed Gaussian white noise with constant standard deviations σ_i . While Gaussian shocks are standard in this class of models, we partially address fat-tail concerns via the COVID outlier block and robustness exercises.

2.1. Adjustment for COVID-19

The COVID-19 pandemic generated exceptionally large and transitory fluctuations in key macroeconomic variables, which can substantially distort parameter estimation and, in particular, estimates of the natural real interest rate. To mitigate this problem, we introduce an explicit outlier adjustment for output, consumption, and unemployment.

Following Holston et al. (2023), we assume that these variables are affected by a common disturbance during the pandemic period. This disturbance is captured by a pandemic-specific factor, o_t , which is exogenous to the remaining state equations of the model and absorbs extraordinary pandemic-related variation that would otherwise contaminate structural dynamics.

Observed macroeconomic variables are related to their latent counterparts as follows:

$$y_{obs,t} = y_t + \vartheta_y o_t / 100, \quad (19)$$

$$c_{obs,t} = c_t + \vartheta_c o_t / 100, \quad (20)$$

$$u_{obs,t} = u_t + (\vartheta_{u,0} o_t + \vartheta_{u,1} o_{t-1} + \vartheta_{u,2} o_{t-2}) / 100. \quad (21)$$

For unemployment, we allow the pandemic factor to enter with lags in order to capture richer dynamics. This specification reflects the delayed and more persistent labour market effects observed in Lithuania during the pandemic period.⁷

In contrast to Holston et al. (2023), who treat the common factor as observed and proxied by the Oxford Stringency Index (Hale et al., 2021), we allow the pandemic factor to be unobserved. We argue that treating the factor as directly observed may be overly restrictive, as pandemic-related economic disruptions are not fully captured by policy stringency measures alone. Instead, we infer o_t from the common component in macroeconomic fluctuations during the pandemic period.

Specifically, the pandemic factor is defined as

$$o_t = \begin{cases} \varepsilon_{o,t}, & t = 2020q1, \dots, 2022q4, \\ 0, & \text{otherwise,} \end{cases} \quad (22)$$

where $\varepsilon_{o,t} \sim \mathcal{N}(0, \sigma_o^2)$.

The adjustment window 2020Q1-2022Q4 is chosen based on the timing of pandemic-related emergency measures and the broad normalization of economic conditions in

Lithuania. The starting date corresponds to the introduction of the nationwide lockdown and state of emergency in March 2020, while the end date reflects the removal of most remaining restrictions by the end of 2022. This timing is also broadly consistent with the evolution of the Oxford Stringency Index for Lithuania, which remained elevated throughout this period.

For identification, we assume that the variance σ_o^2 is fixed and that the factor loadings on output and consumption, ϑ_y and ϑ_c , are negative. This sign restriction normalizes the factor so that a positive realization of o_t corresponds to a contractionary pandemic disturbance for output and consumption. Smoothed estimates of the pandemic factor are presented in Appendix [Figure A4](#), together with the Oxford Stringency Index. The estimates indicate that the largest pandemic-related outlier occurs in 2020Q2, coinciding with the peak of the initial economic disruption. To assess the sensitivity, Section 4.6 reports robustness checks based on alternative treatments of the COVID-19 period, including a specification that uses the Oxford Stringency Index as an observed proxy for the pandemic disturbance.

2.2. Bayesian estimation

We estimate the empirical model using Bayesian methods. The Bayesian framework is well suited to environments with limited data availability, such as transition economies like Lithuania, as it allows prior information to discipline the parameter space and improve inference when the likelihood is relatively weak (J. Fernández-Villaverde, 2010).

Prior specification reflects standard sign, support, and scale restrictions commonly adopted in semi-structural models. The complete set of priors is summarized in [Table A1](#). Most slope and dynamic parameters are assigned independent Normal priors centred at economically meaningful values, consistent with existing empirical evidence in the literature, and with sufficiently diffuse standard deviations to ensure that the data remain informative (Berger & Kempa, 2014; Brand & Mazelis, 2019; Jarociński & Lenza, 2018; Laubach & Williams, 2003). When economic theory implies restrictions, such as non-negativity or non-positivity, these Normal priors are appropriately truncated. Shock standard deviations are assigned Normal priors truncated to the positive domain, which guarantees admissibility while remaining only weakly informative. This choice contrasts with conjugate but inverse-Gamma priors, which are overly informative near zero values (Gelman, 2006; Kastner & Frühwirth-Schnatter, 2014). For parameters governing the COVID-related outlier adjustments, prior information is scarce; accordingly, Uniform priors are imposed over wide intervals.

Posterior inference is carried out using the Random-Walk Metropolis-Hastings algorithm. The model is cast in state-space form, with the likelihood evaluated using the Kalman filter, which accommodates missing observations in the data. To alleviate the inefficiency of the sampler, we run twelve parallel chains with dispersed initialisations, each with one million draws. After discarding an initial burn-in period, posterior moments are computed using 100000 retained draws per chain.

3. Data

[Table 1](#) summarizes the variables used in our analysis. The sample covers 2000q1 to 2025q3. All series are seasonally adjusted, and the model is estimated at a quarterly

Table 1. Variables used in the estimation.

Symbol	Name	Original series	Source
$y_{obs,t}$	Output	Real gross domestic product	Eurostat
π_t	Inflation	HICP excluding energy and food	Eurostat
r_t	Real interest rate	Constructed from 3-month euro OIS and Consensus next-year inflation projections	ECB; Consensus Economics
q_t	Exchange rate	Real effective exchange rate index Broad Basket	BIS
$u_{obs,t}$	Unemployment rate	Unemployment rate (Ages 15-74)	Eurostat
$c_{obs,t}$	Consumption	Private consumption	Eurostat
$\pi_{obs,t}^*$	Trend inflation	Long-term inflation expectations (6-10 years ahead); semiannual data from 2007 and quarterly from 2014	Consensus Economics

frequency. Variables available at higher frequencies are aggregated to quarterly observations using the average over the period.⁸

3.1. Real interest rate dilemma

Estimating the natural real rate of interest (r^*) is challenging because real interest rates are not directly observable. They must be inferred from nominal interest rates adjusted for realized or expected inflation. The choice of nominal rate and inflation measure can materially affect the estimated real rate. We highlight three key observations for constructing real interest rates for Lithuania.

3.1.1. Approximation of the Fisher equation

The commonly used linear approximation of the Fisher equation can generate non-negligible errors, particularly during periods of high macroeconomic volatility. In much of the applied literature, the real interest rate is approximated as

$$r_t \approx i_t - \pi_t^e, \quad (23)$$

for convenience, under the assumption that the resulting error is small.⁹ Strictly, the Fisher equation requires

$$r_t = \frac{1 + i_t}{1 + \pi_t^e} - 1. \quad (24)$$

When nominal rates or inflation expectations are volatile, the linear approximation introduces material discrepancies.

Quantifying the difference between the linear and exact calculations reveals errors up to 25 basis points during the Global Financial Crisis, around 5 basis points from 2010–2020, and nearly 60 basis points during the 2022 inflation surge (Figure 1). These deviations propagate into the estimated r^* and are economically significant for policy assessment.

3.1.2. Inflation expectations: forward vs. backward looking

The first panel of Figure 2(a) shows real interest rates calculated using the 3-month OIS rate, combined with forward- and backward-looking inflation expectations. Following Laubach and Williams (2003), backward-looking expectations are constructed as a four-quarter moving average of inflation, using either headline HICP or core HICP excluding

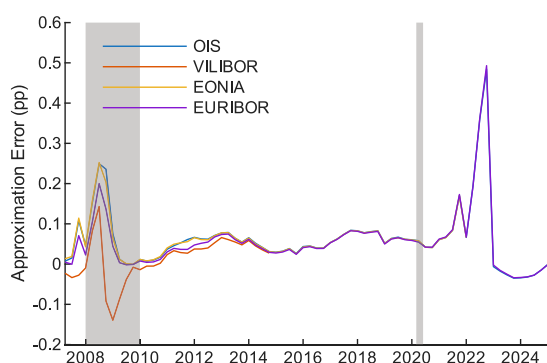


Figure 1. Fisher equation approximation error.

Note: The approximation error is calculated as the difference between the exact Fisher equation and its linear approximation using OIS, VILIBOR, EONIA, and EURIBOR nominal rates. Deviations are particularly pronounced during periods of high inflation volatility or financial stress. Shaded areas indicate crisis periods.

energy and food, $\sum_{i=0}^3 \pi_{t-i}$. Forward-looking expectations are based on one-year-ahead inflation forecasts averaged across professional forecasters.

Backward-looking measures yield more volatile real interest rates and are highly sensitive to the choice of inflation measure, whereas forward-looking expectations produce smoother and more stable series. Similar conclusions are reached by Lopez-Salido et al. (2020), who find that forward-looking expectations provide more precise estimates of the natural real interest rate. For these reasons, we rely on Consensus Economics' one-year-ahead inflation forecasts for Lithuania when constructing real interest rates.¹⁰

3.1.3. Nominal interest rate

The nominal interest rate must reflect the risk-free cost of funds and the monetary policy stance to accurately estimate the real rate. The literature typically recommends short-term interbank rates (Walsh, 2017), as these closely track monetary policy. For Lithuania, this corresponds to a 3-month VILIBOR until 2014 and a 3-month EURIBOR after the euro's adoption in 2015.

Interbank rates include credit and liquidity risk. During periods of financial stress, such as the late-1990s Russian crisis or the 2008 Global Financial Crisis, spreads widen substantially, reflecting credit risk rather than policy changes, as seen in the second panel of Figure 2(b).¹¹

A more robust alternative is the euro Overnight Indexed Swap (OIS) rate, which isolates the risk-free component of the rate. The OIS rate represents the fixed leg of a swap where one party pays a variable rate linked to the overnight unsecured interbank rate and receives a fixed payment. As Taylor and Williams (2009) note, the EURIBOR-OIS spread captures the credit and liquidity premium embedded in EURIBOR, making OIS the preferred measure of the short-term risk-free rate. This choice is consistent with the IMF's 2019 r-star assessment for Lithuania, which used EONIA (the predecessor of OIS) for all periods since 1996 (International Monetary Fund, 2019).

For those reasons, we use the 3-month OIS as the nominal rate and Consensus Economics' one-year-ahead inflation forecasts to construct a risk-free real interest rate series

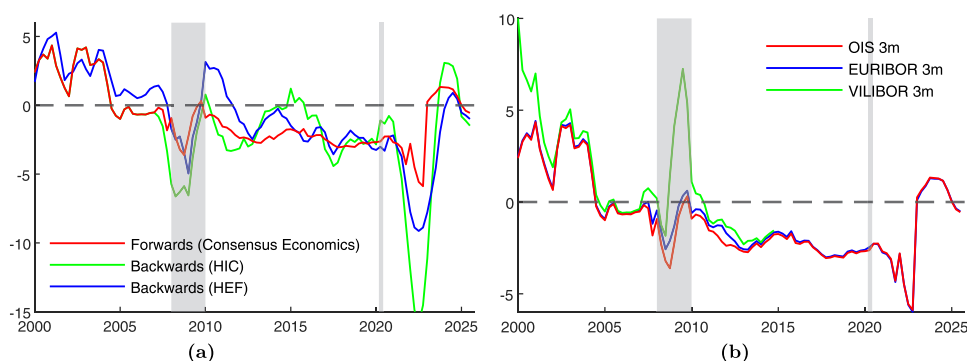


Figure 2. Real interest rate selection. (a) Forward vs backwards-looking real interest rates and (b) Real rates with forward-looking inflation expectations.

Note: Panel (a) Real interest rates are computed as the 3-month OIS rate minus inflation, using either backwards-looking headline HICP or HICP excluding energy and food, averages or forward-looking one-year-ahead forecasts from Consensus Economics (from 2007 onward; before 2007, HICP four-quarter averages are used). The figure highlights the sensitivity of real rate estimates to the choice of inflation measure and expectation horizon. Panel (b) compares real interest rates computed using forward-looking inflation expectations from Consensus Economics and alternative 3-month nominal rates (OIS, EURIBOR, and VILIBOR). Differences across series reflect variations in money market risk premia. The shaded areas reflect periods of economic downturn.

suitable for macroeconomic modelling in Lithuania. However, we also discuss robustness results in Section 4.5.

4. Results

This section presents the main empirical results. We first assess model validity using output gap estimate and discuss key features of the cyclical estimates. We then examine the level and dynamics of the natural real interest rate, compare it with alternative estimates, and assess the implied monetary policy conditions. Finally, we evaluate the contribution of the main model extensions and the robustness of the results across alternative specifications.

4.1. Output gap as a model validation check

Because the natural rate of interest is a model-based construct, and its level and dynamics are sensitive to model assumptions, data choices, and specification, it is important to assess the model's reliability by examining other estimated state variables. Such checks help ensure that the results reflect underlying macroeconomic conditions rather than model misspecification.

The output gap ($\tilde{y}_t$) provides a useful benchmark for this purpose. Like r^* , the output gap is unobservable and must be estimated. In our framework, it is estimated jointly within the same model and, as described in Section 2, plays a central role in identifying the natural rate. Comparing the model-implied output gap with external estimates, therefore, offers a natural way to evaluate the plausibility of the model.

Accordingly, we compare our output gap estimates with those published by Lietuvos bankas, the European Commission and the IMF. The results indicate that the model-implied output gap closely aligns with these institutions' estimates (Figure 3). This

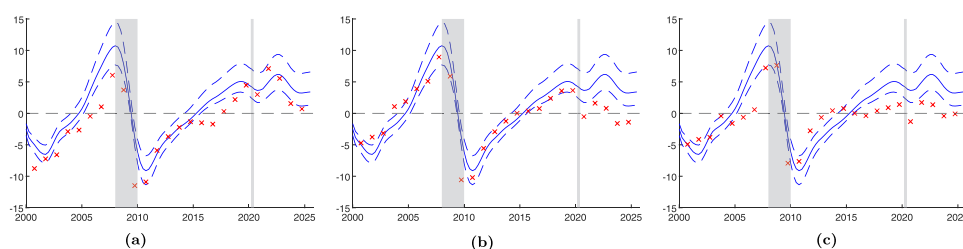


Figure 3. Model-based output gap compared with institutional estimates. (a) Model vs Lietuvos bankas. (b) Model vs. European Commission and (c) Model vs. IMF.

Note: Panel (a) compares the model-based output gap (blue line) with estimates produced by Lietuvos bankas (red markers). Panel (b) compares estimates produced by the European Commission, whereas Panel (c) compares estimates from the IMF in the World Economic Outlook. Output gap values are expressed as percentage-point deviations of actual output from potential output, measured over four-quarter averages. Dashed blue lines indicate the 90% credible bands, while the shaded grey areas denote periods of economic downturn.

alignment also suggests that the implied estimates of trend output (y_t^*) and potential growth (g_t) are broadly consistent with institutional assessments, as these latent components jointly underpin observed output dynamics (Note the identity: $y_t^* = y_t - \tilde{y}_t$).

This correspondence supports the plausibility of the model-implied cyclical dynamics and suggests that the estimated r^* evolves in line with the broader macroeconomic environment reflected in institutional assessments.¹²

4.2. Cyclical dynamics in Lithuania

We next provide an economic interpretation of the cyclical estimates and the corresponding parameters reported in Table A1. Two features are particularly relevant for Lithuania.

First, the model attributes a relatively large share of output fluctuations to movements in potential output rather than to the stationary output gap. The standard deviations of shocks to the output gap, potential growth, and the level of potential output are not directly comparable, as these shocks enter different state equations and have different dynamic implications. In particular, potential-output level shocks capture persistent shifts in potential output without necessarily implying permanent changes in trend growth. Such movements are plausible for a small, open, and converging economy exposed to external shocks, migration dynamics, and structural transformation.

Second, the estimated consumption gap is more volatile than the output gap, as illustrated in Figure 4. Although this differs from the standard consumption-smoothing benchmark, it is consistent with evidence for small open and emerging economies, where consumption can be more volatile than output (Aguilar & Gopinath, 2004). One explanation is Lithuania's volatile import-intensive consumption: fluctuations in imported consumption affect measured private consumption but do not translate one-for-one into domestic output, since imports are deducted in the GDP identity. In addition, a relatively large share of hand-to-mouth households may limit aggregate consumption smoothing (Bielskis et al., 2025).

4.3. Estimated natural rate and historical interpretation

Figure 5 presents the baseline estimate of the natural real interest rate, r^* , together with its decomposition into a growth-related component, g_t , and a residual component, z_t . The

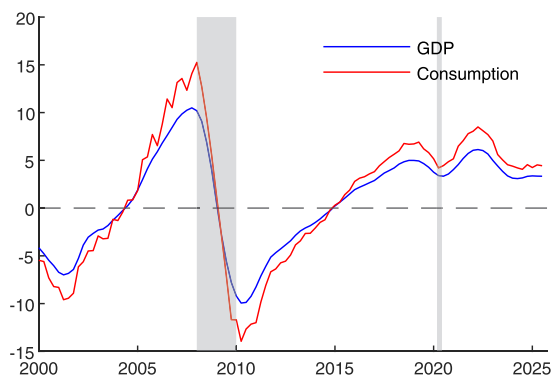


Figure 4. Estimated GDP and consumption gaps.

Note: The figure presents posterior median estimates of the GDP and consumption gaps for Lithuania. The blue line denotes the GDP gap and the red line denotes the consumption gap.

estimates suggest substantial time variation in Lithuania's equilibrium real interest rate over the sample period. Within this model-implied decomposition, most of the variation in r^* is attributed to changes in potential output growth.

The decomposition should be interpreted cautiously. Within the semi-structural Laubach–Williams framework, the residual component z_t captures all persistent movements in r^* not explained by trend growth and therefore does not admit a structural interpretation on its own. More generally, semi-structural models with latent states are known to face identification challenges, particularly in short samples and small open economies (Buncic, 2024). The discussion below, therefore, provides a descriptive interpretation of the estimates.

In the early 2000s, the estimated natural real interest rate fluctuated around 2 percent, supported by strong estimated potential growth during the convergence period preceding the global financial crisis. The crisis marked a sharp turning point, with r^* falling to substantially negative levels alongside weaker growth prospects and deteriorating

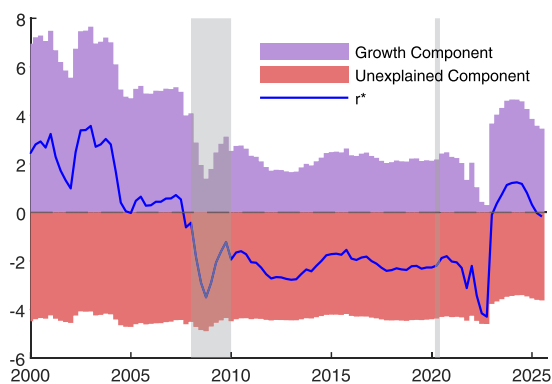


Figure 5. Natural real interest rate and its decomposition.

Note: The blue line denotes the posterior median estimate of the natural real interest rate for Lithuania. The natural real interest rate is decomposed into a growth-related component (cg) and a residual component (z).

global financial conditions. Domestic factors, such as EU accession-related capital inflows, migration dynamics, and financial convergence, may also have contributed.

After the crisis, the estimated natural rate remained persistently below its pre-crisis level. This pattern is broadly consistent with evidence for advanced economies, where equilibrium real interest rates declined because of weaker productivity growth, demographic developments, high global savings, and financial integration (Brand et al., 2018; Seim, 2024).

Between 2013 and 2015, r^* increased modestly while remaining in negative territory. This period coincides with structural reforms related to the adoption of the euro, as suggested by Reichenbachas et al. (2021), and a decline in inflation expectations. Following the COVID-19 pandemic, higher inflation and elevated short-term inflation expectations coincided with a renewed decline in the estimated natural real interest rate, which again fell to levels around -4 percent.

Around 2023, the estimated natural real interest rate temporarily returned to positive territory before declining again toward the end of the sample. Recent literature has linked the recent increase in equilibrium real interest rates in advanced economies to higher long-term inflation expectations, changes in safe-asset demand, balance sheet normalization, and expansionary fiscal policies (J. M. Fernández-Villaverde et al., 2024; Schnabel, 2025). For Lithuania, one possible explanation for the stronger estimated potential growth is the sharp change in demographic dynamics since 2022, associated with the inflow of Ukrainian refugees and returning residents.¹³ Nevertheless, the recent increase in estimated potential growth should be interpreted cautiously, as end-of-sample estimates in semi-structural models are often subject to substantial revision.

By 2025q3, the posterior median estimate of Lithuania's natural real interest rate is close to zero.

4.3.1. Comparison with other estimates for Lithuania and the Euro area

Figure 6 compares our model-based estimates of the natural real interest rate for Lithuania with those reported by Reichenbachas et al. (2021), International Monetary Fund (2019), and González-Astudillo and Vilán (2025), and also contrasts them with our corresponding estimates for the euro area, as detailed in Section 2. Estimates of Lithuania's natural real interest rate differ markedly across studies.

Notably, similar to our approach, International Monetary Fund (2019) and González-Astudillo and Vilán (2025) employ modified semi-structural Laubach–Williams-type frameworks. Despite these similarities, the resulting estimates diverge substantially.¹⁴ IMF estimates point to a positive and gradually increasing natural real interest rate, whereas González-Astudillo and Vilán (2025) report a persistently negative and declining trend over the same period. These differences suggest that variation in estimated natural rates reflects not only differences in modelling frameworks, but also alternative assumptions, data choices, and sample periods.

In comparison to earlier studies, our analysis emphasizes the role of survey-based inflation expectations, introduces a more comprehensive modelling structure to enhance the identification of latent variables, and evaluates the consistency of the resulting estimates with institutional assessment. Together, these elements constitute the main contributions of this study.

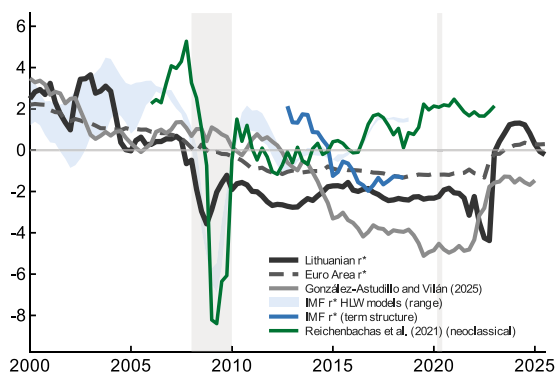


Figure 6. Comparison of natural real interest rate estimates for Lithuania.

Note: The Lithuanian and euro area r^* series shown in the figure are model-based estimates derived from various empirical frameworks. The estimates reported by González-Astudillo and Vilán (2025) and International Monetary Fund (2019) are based on semi-structural models, while the series from Reichenbachas et al. (2021) corresponds to their neoclassical estimate. The IMF term-structure model, following Negro et al. (2017), provides an additional alternative estimate of Lithuania's natural real interest rate.

Nevertheless, modelling uncertainty is not specific to Lithuania. It is also a prominent feature of natural real interest rate estimates for the euro area and the United States (Benigno et al., 2024; Brand et al., 2025).

Compared with the euro area, Lithuania's natural real interest rate is more volatile, reflecting the greater sensitivity of a small, converging open economy to macroeconomic shocks. At the beginning of the sample, Lithuania's r^* was broadly aligned with that of the euro area. Following the global financial crisis, Lithuania's r^* fell below the euro area level and remained lower until around 2022. This pattern reflects a combination of domestic and global factors, including prolonged low nominal interest rates in the euro area following the ECB's accommodative monetary policy stance from 2013 onward, alongside relatively elevated long-term inflation expectations in Lithuania (around 2.25 percent), resulting in lower real rates. Consistent with these findings, González-Astudillo and Vilán (2025) documents that many euro area countries that joined after 1999 experienced natural real interest rates below the euro area average in the post-crisis, pre-pandemic period.

Lithuania's and the euro area's natural real interest rates exhibit broadly similar dynamics during periods of macroeconomic stability, suggesting increasing economic and financial integration, particularly after 2015. Following the COVID-19 pandemic, Lithuania's r^* declined more sharply, coinciding with the increase in inflation and inflation expectations, before subsequently rising as domestic demand prospects recovered. By 2025q2, estimates of the natural real interest rate for Lithuania and the euro area had converged to similar levels.

Given that the natural real interest rate is unobservable, it is difficult to assess which estimate is 'correct.' Differences across models and wide uncertainty bands imply that r^* should be interpreted with caution.

4.4. Monetary policy conditions

The analysis of the natural real interest rate can be complemented by examining the real interest rate gap ($\tilde{r}_t$). The real interest rate gap, defined as the difference between the

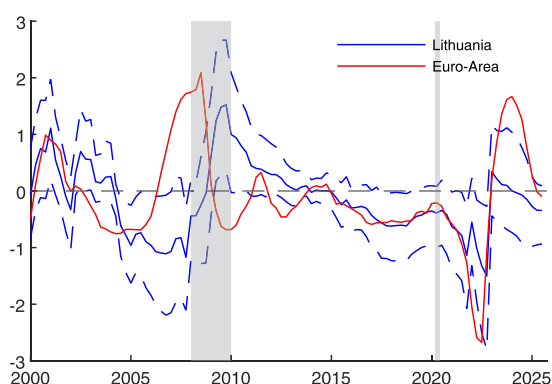


Figure 7. Real interest rate gap: Lithuania and the Euro area.

Note: The figure presents the estimated real interest rate gap for Lithuania and the euro area. Shaded areas denote recession periods in Lithuania. Solid lines denote posterior medians, and dashed lines denote 90% credible bands.

observed real interest rate and the natural real interest rate, is an indicator of the monetary policy stance. A positive real interest rate gap indicates that real interest rates exceed the natural rate, implying a restrictive monetary policy stance. In contrast, a negative gap is associated with an accommodative stance.

Figure 7 presents estimates of the real interest rate gap for Lithuania and the euro area over the period 2000–2025. Prior to the global financial crisis, Lithuania's real interest rate gap was markedly more negative than that of the euro area, indicating a highly accommodative monetary policy stance that plausibly contributed to economic overheating and a sharper subsequent adjustment during the crisis. At the height of the crisis, monetary conditions in Lithuania became more restrictive relative to the euro area, reflecting a pronounced deterioration in domestic long-term growth prospects and a sharper decline in the estimated natural real interest rate.

Following the euro's adoption, real interest rate gaps in Lithuania and the euro area moved closer together, reflecting deeper economic integration into the common monetary policy framework. During and after the COVID-19 period, divergences re-emerged as inflation and inflation expectations increased across the euro area, with a particularly strong response in Lithuania. As of 2025q3, the estimated real interest rate gap for Lithuania suggests a broadly neutral monetary policy stance.

While the real interest rate gap provides useful information on monetary conditions, it should be interpreted alongside other indicators. The literature indicates several notable limitations. First, the real interest rate gap does not capture the effects of unconventional monetary policy instruments on overall financial conditions. Second, it does not represent an optimal policy benchmark, but rather a descriptive measure of the stance relative to the estimated natural rate. Third, the gap reflects the influence of short-run shocks, without distinguishing whether monetary policy should respond to all such disturbances, particularly temporary supply shocks that may involve policy trade-offs. Finally, substantial modelling and statistical uncertainty complicates the use of real-time estimates of the real interest rate gap for policy assessment.¹⁵

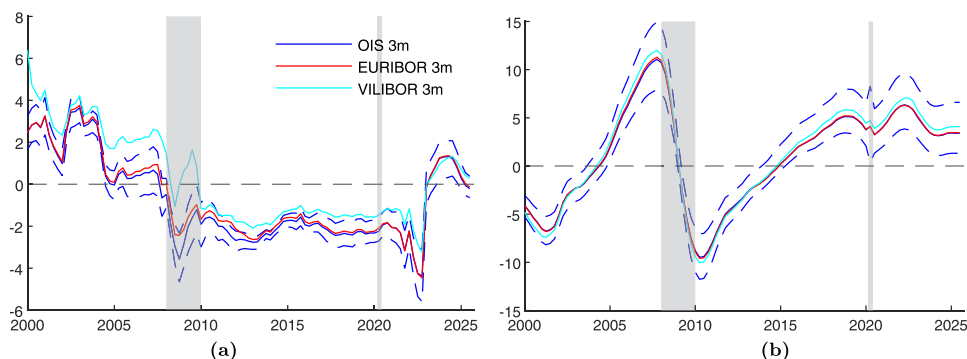


Figure 8. Natural real interest rate and output gap estimates under alternative nominal interest rates. (a) Natural Real Interest Rate and (b) Output Gap

Note: Both panels report baseline estimates (blue solid and dashed lines denote the posterior median and 90% credible intervals, respectively) and compare them with alternative specifications using the 3-month EURIBOR (red line) and the 3-month VILIBOR (cyan line) to construct ex-ante real interest rates. Panel (a) presents estimates of the natural real interest rate, while panel (b) reports output gap estimates. Shaded grey areas indicate periods of economic downturn.

4.5. Estimates under alternative nominal interest rates

Following Section 3.1, we examine whether the choice of nominal interest rate used to construct the real rate affects the estimates. Figure 8 compares the baseline specification (blue solid and dashed lines denote the posterior median and 90% credible intervals, respectively) with alternatives using the 3-month EURIBOR (red line) and the 3-month VILIBOR (cyan line).

The most significant differences arise when VILIBOR is used prior to Lithuania's entry into the euro area. In this specification, the observed real interest rate lies persistently above the baseline, reflecting Lithuania-specific credit and liquidity premia embedded in the domestic interbank rate. The spread relative to the OIS-based specification narrows over time, consistent with Lithuania's gradual financial convergence.

Appendix Figure A7 further decomposes the difference between the VILIBOR- and OIS-based estimates. Most of the additional variation associated with VILIBOR is absorbed by the residual component, z_t , rather than the potential-growth component. Moreover, the VILIBOR–OIS contribution to z_t declines over time. This pattern is consistent with the gradual compression of Lithuania-specific financial premia during the convergence process.

The largest deviations occur around the global financial crisis, when these premia increased sharply. This illustrates the trade-off in choosing the interest-rate benchmark. VILIBOR captures Lithuania-specific financial conditions and their convergence toward euro-area levels, but it also incorporates temporary premia that can rise sharply during periods of financial stress. As a result, the VILIBOR-based specification may transmit short-lived financial disturbances into the estimated long-run natural rate. We therefore retain OIS as our baseline measure, while using VILIBOR as a complementary specification to examine Lithuania-specific financial conditions and their convergence over time.

By contrast, output gap estimates are largely unaffected by the choice of nominal interest rate, with differences that are neither economically nor statistically significant.

4.6. Exploring robustness to COVID-19 period

The COVID-19 pandemic induced unprecedented but highly transitory fluctuations in key macroeconomic variables, potentially distorting parameter estimates and, in particular, the inferred path of the natural real interest rate. To account for these effects, the baseline specification incorporates an explicit outlier adjustment for output, consumption, and unemployment, as detailed in Section 2.1.

Figure 9 compares the baseline results with several alternative specifications. The blue solid line reports the posterior median of the baseline estimate, while the blue dashed lines denote the corresponding 90% credible interval. The red line shows estimates obtained from the full sample without the COVID-19 outlier adjustment, that is, imposing $\vartheta_i = 0$ for all i . The cyan line reports estimates based on a sample ending in 2019Q4. Finally, the magenta line shows estimates from a specification in which the observed common factor is measured using the Oxford Stringency Index.

The estimated natural real interest rate is virtually unchanged across the baseline, the unadjusted full-sample specification, and the pre-pandemic sample (Panel (a)). The output

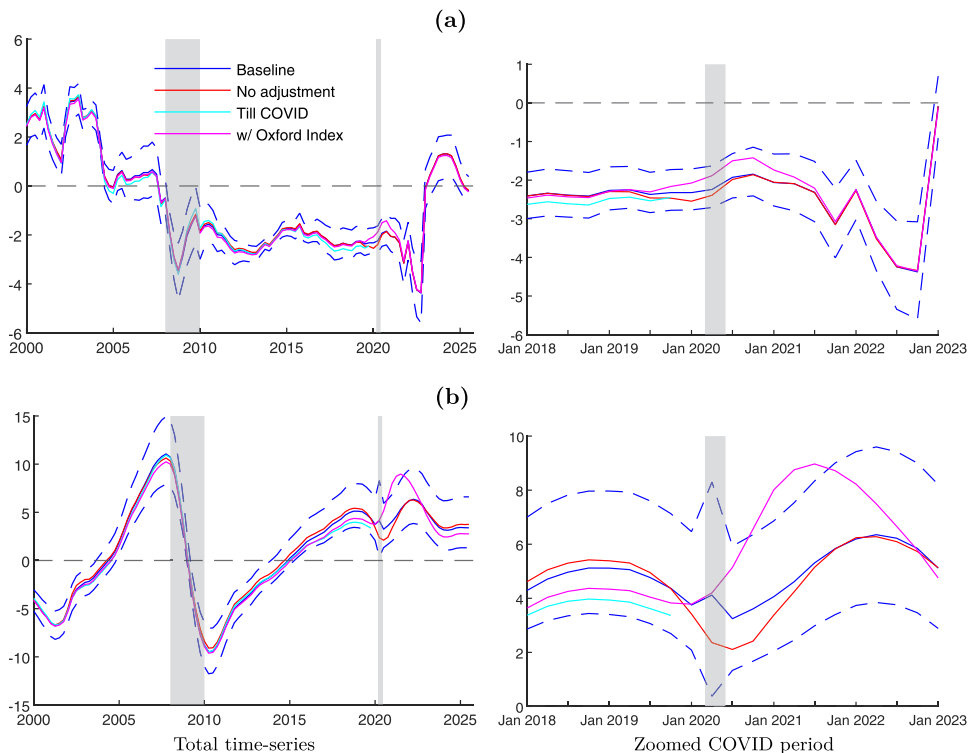


Figure 9. Robustness to the COVID-19 period. (a) Natural Real Interest Rate and (b) Output Gap

Note: Both panels report the baseline estimates and compare them with alternative specifications. The blue solid line denotes the posterior median of the baseline estimate, while the blue dashed lines denote the corresponding 90% credible interval. The red line shows estimates obtained using the full sample without the COVID-19 outlier adjustment, that is, imposing $\vartheta_i = 0$ for all i . The cyan line reports estimates based on a sample ending in 2019Q4. The magenta line shows estimates from a specification in which the observed common factor is measured using the Oxford Stringency Index. Panel (a) presents estimates of the natural real interest rate, and Panel (b) reports output gap estimates. Figures on the left show the full sample, while figures on the right focus on the COVID-19 period. Shaded grey areas indicate periods of economic downturn.

gap estimates are also broadly similar across these specifications. Although omitting the COVID-19 outlier adjustment implies somewhat larger slack during the pandemic, the differences are neither economically large nor statistically significant (Panel (b)). Consistent with this evidence, posterior parameter estimates remain broadly stable across specifications. We also estimate a specification in which the pandemic factor is allowed to affect only 2020Q2, the quarter associated with the largest estimated pandemic outlier. The resulting estimates of r^* and the output gap are very close to the baseline; the corresponding results are reported in Appendix [Figure A8](#).

The main difference arises when the Oxford Stringency Index is used as the observed common factor. Under this specification, the output gap is estimated to be more positive from the onset of the COVID-19 disruption. However, this alternative treatment has minor effect on the estimated path of the natural real interest rate.

In contrast to results reported for several advanced economies (Holston et al., 2023), the explicit adjustment for COVID-19 effects appears to be of limited importance for Lithuania, reflecting the robustness of the estimated natural real interest rate to alternative treatments of the pandemic period. One possible explanation is that the pandemic-related contraction in Lithuania led to macroeconomic aggregates declining by magnitudes comparable to those observed during the global financial crisis. As a result, these observations may not be perceived by the model as exceptional. By contrast, in several Western economies, the decline in economic activity during the pandemic was unprecedented, necessitating explicit adjustments to account for extreme events and time-varying volatility that would otherwise be difficult to reconcile within models assuming homoscedastic shocks.

4.7. Model extensions and fit

Relative to the standard Laubach–Williams framework, our specification additionally incorporates the real exchange rate, private consumption, and unemployment. As discussed in Section 2, these extensions are motivated by previous studies and are intended to better capture the dynamics of a small open economy such as Lithuania but also help with the identification of latent states.

To assess their contribution to model fit, we compare the baseline model with nested specifications that sequentially exclude these extensions. [Table 2](#) reports differences in

Table 2. Marginal data density relative to the baseline specification.

Excluded from baseline	Laplace	Modified Harmonic Mean
Unemployment ^a	−40.619	−39.398
Consumption ^b	−21.639	−22.409
Consumption and unemployment	−45.241	−46.255
Real exchange rate ^c	−6.227	−5.041
Real exchange rate and consumption	−27.373	−27.191
Real exchange rate and unemployment	−45.012	−43.159
Real exchange rate, consumption, and unemployment	−48.587	−49.004

Note: The table reports differences in log marginal data density between each restricted specification and the baseline model. Negative values indicate greater support for the baseline specification. Results are reported using the Laplace approximation and the modified harmonic mean estimator. ^a The unemployment block is excluded by setting the coefficients in Equation (12) to zero. ^b The consumption-gap equation, Equation (11), is excluded. ^c The real-exchange-rate channels are excluded by setting β_{q^*} , α_{q^*} , $\gamma_{q^*}^1$, and γ to zero.

log marginal data density between each restricted specification and the baseline model. The restricted models are obtained by setting the parameters associated with the corresponding extension to zero, as detailed in the table notes. Negative values, therefore, indicate greater support for the full baseline specification.

The results provide clear support for the extensions. Excluding either unemployment or consumption substantially reduces the marginal data density, with a larger deterioration when both are excluded. Excluding the real-exchange-rate channels also reduces the marginal data density, although to a lesser extent. Both marginal-likelihood estimators lead to the same conclusion. Overall, the results favour the full specification, with consumption and unemployment contributing the largest improvements in model fit.

4.8. Robustness to alternative measures of economic slack

We consider three alternative specifications to assess the robustness of our baseline estimates and to better capture features of a small open economy such as Lithuania.¹⁶ The results are summarized in Figure 10.

First, following Bulir (2024), we explicitly account for external demand conditions by including the euro area output gap in the IS curve. The euro area output gap, $\tilde{y}_{EA,t}$, is estimated separately using the same framework as our baseline model (see Appendix Section 2). We then include the estimated euro area output gap in both the output-gap and consumption-gap equations:

$$\begin{aligned}\tilde{y}_t &= \alpha_{y,1}\tilde{y}_{t-1} + \alpha_{y,2}\tilde{y}_{t-2} + \alpha_{r,1}\tilde{r}_{t-1} + \alpha_{r,2}\tilde{r}_{t-2} + \alpha_q\tilde{q}_{t-1} + \alpha_{EA,1}\tilde{y}_{EA,t-1} + \alpha_{EA,2}\tilde{y}_{EA,t-2} + \varepsilon_{\tilde{y},t} \\ \tilde{c}_t &= \gamma_y^0(L)\tilde{y}_t + \gamma_r^1(L)\tilde{r}_t + \gamma_q^1(L)\tilde{q}_t + \gamma_{EA,1}\tilde{y}_{EA,t-1} + \gamma_{EA,2}\tilde{y}_{EA,t-2} + \varepsilon_{\tilde{c},t}\end{aligned}$$

The resulting estimates are virtually unchanged relative to the baseline, indicating that explicitly incorporating euro area cyclical conditions has only a limited effect on the estimated output gap and r^* for Lithuania.

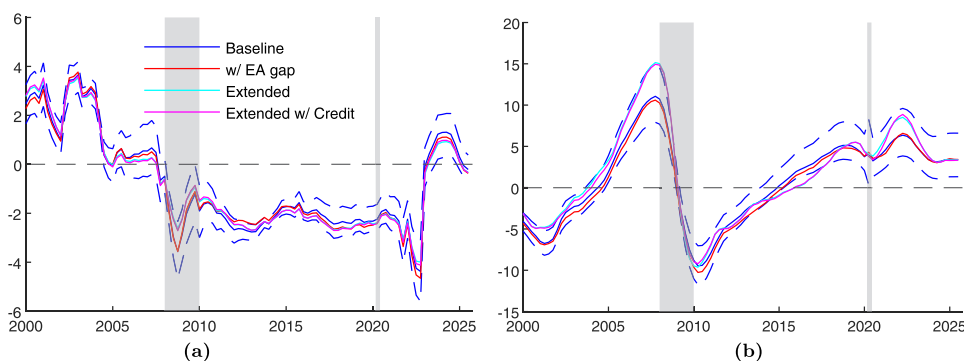


Figure 10. Natural real interest rate and output gap under alternative slack specifications. (a) Natural Real Interest Rate and (b) Output Gap

Note: The figure compares baseline estimates with three alternative specifications. The first incorporates the euro area output gap into the IS and consumption equations. The second augments the set of indicators used to identify economic slack with investment, trade, and sentiment variables. The third further includes credit aggregates. Panel (a) reports estimates of the natural real interest rate, while panel (b) reports output gap estimates. Blue solid and dashed lines denote the posterior median and 90% credible intervals of the baseline specification. Shaded grey areas indicate periods of economic downturn.

Second, we augment the set of indicators used to identify the common slack factor, $\tilde{y}_t$. In addition to real GDP, private consumption, and unemployment, we include real gross capital formation, real imports, real exports, and the Economic Sentiment Indicator. Trade variables capture external demand conditions, while investment and sentiment indicators may provide early signals of cyclical turning points. The specification follows Jarociński and Lenza (2018).

The extended specification produces somewhat smoother estimates of the natural real interest rate, although the differences relative to the baseline are neither economically nor statistically significant. The effect is more pronounced for the output gap, with estimates indicating a stronger degree of overheating prior to the global financial crisis and during the post-pandemic inflation surge.

Third, we examine the role of credit indicators. Motivated by Borio et al. (2017), who emphasize the importance of financial cycles for assessing economic conditions, we augment the extended specification with aggregate loans to households and non-financial corporations. Controlling for the financial cycle may be particularly relevant for Lithuania, given the rapid credit expansion preceding the global financial crisis (Constantinescu & Nguyen, 2017). Nevertheless, the inclusion of credit indicators results in only minor changes in the estimated output gap and the natural real interest rate.

Overall, the results suggest that the baseline estimates are robust to the inclusion of additional external, financial, and macroeconomic information.

5. Discussion and concluding remarks

This paper provides model-based estimates of the natural real interest rate for Lithuania using a semi-structural framework. The results indicate that Lithuania's r^* was relatively high in the early 2000s, then declined sharply over most of the sample period, and returned to positive values in recent years. Following the euro's adoption, Lithuania's estimated natural real interest rate exhibits closer co-movement with the euro area natural rate, consistent with increasing economic and financial integration. Based on the estimated real interest rate gap, monetary conditions in Lithuania appear broadly consistent with a neutral stance at the end of the sample.

Within the model-implied decomposition, most of the variation in Lithuania's r^* is attributed to changes in potential growth, consistent with the strong growth dynamics accompanying economic convergence. This should not, however, be interpreted as evidence that potential growth was necessarily the dominant structural driver of r^* . Other forces, including financial integration, demographic developments, and global factors, are not separately identified within the framework. In particular, the alternative specification using VILIBOR suggests that Lithuania-specific financial premia may account for part of the residual component of r^* during the convergence period. A natural avenue for future research is therefore to identify these structural determinants more explicitly and quantify their relative importance.

These findings also illustrate that common monetary conditions may have different domestic implications in converging economies, particularly when country-specific equilibrium rates and inflation dynamics differ from those of the currency union as a whole. More generally, the results highlight the value of adapting natural-rate frameworks to

the characteristics of small, open, and converging economies, while recognizing the limits of structural interpretation in semi-structural models.

Differences relative to existing studies underscore the considerable uncertainty surrounding estimates of r^* and their sensitivity to modelling assumptions. Nevertheless, country-specific estimates provide a useful analytical benchmark for assessing monetary and macroeconomic conditions. While they should not be interpreted mechanically or used in isolation, they can complement other macroeconomic and financial indicators and contribute useful information to the broader policy toolkit.

Notes

1. The objective of the model is not to provide a structural decomposition of the natural rate into specific economic mechanisms but to capture persistent, low-frequency movements in r^* in a parsimonious manner.
2. This adjustment prevents the Phillips curve from introducing an additional stochastic trend into inflation through the real-exchange-rate block. In the model, the stochastic trend in inflation is intended to be captured by π_t^* .
3. Laubach and Williams (2003) treats a two to four quarter average of core inflation, $\frac{1}{3} \sum_{i=2}^4 \pi_{t-i}$, as a precise observation of trend inflation.
4. Consensus Economics, the provider of the expectations data, does not specify whether forecasters report expectations for Harmonized Index of Consumer Prices (HICP) inflation or for the national consumer price index.; We treat ω as time invariant because the available Lithuanian long-term expectations series is short and does not allow us to separately identify a time-varying wedge. The parameter should therefore be interpreted as an average wedge over the sample.
5. In richer structural models with household optimization, the Euler equation is typically defined in terms of consumption. Semi-structural models often approximate this relationship using output, implicitly assuming that consumption equals output in small-scale models that abstract from investment and government spending.
6. Figure A1 presents the time-series for the real effective exchange rate that is clearly trending.
7. We do not adjust the core inflation series for additional outliers. Figure A1 shows no COVID-related outlier or post-pandemic spike outside plausible historical variation. Trend inflation is further disciplined by long-term Consensus inflation expectations as determined by Equation (6).
8. The observed data is plotted in appendix Figure A1.
9. This approximation is reasonable when nominal rates and inflation expectations are low and stable but becomes less accurate during periods of rapid monetary or price fluctuations.
10. Ideally, one- or four-quarter-ahead inflation expectations would be used. However, these series are not available to us at the time of writing.
11. In Slovakia, Kupkovič (2020) addressed this by using the central bank's policy rate during stressed periods; in Lithuania, this option is not available because Lietuvos Bankas did not maintain an official policy rate.
12. We do not use external output gap estimates as observables in the estimation. Such estimates are themselves subject to statistical and measurement uncertainty, and using them without explicitly modelling this uncertainty could create a false sense of precision.
13. In a canonical Ramsey model, population growth is one determinant of potential growth and the natural real interest rate. Following the discussion in Brand et al. (2018), higher population growth can one-to-one increase potential growth and, through this channel, r^* . Figure A5 compares estimated annualized potential growth with year-on-year population growth. The figure shows that the recent increase in potential growth coincides with a notable improvement in population dynamics.

14. Reichenbachas et al. (2021) also discuss semi-structural estimates for Lithuania, but this specification has been discontinued by the authors, as more recent estimates exhibit increased volatility and are no longer considered informative for assessing underlying economic developments. The series reported in Figure 6 therefore corresponds to their neoclassical estimate.
15. In semi-structural models with latent states, end-of-sample estimates are often subject to sizeable revisions because smoothed estimates use limited future information (Orphanides & van Norden, 2002) and trend-cycle decompositions are weakly identified, especially in short samples. Regarding similar arguments when estimating r -star, Brand et al. (2025) presents a valuable and recent discussion.
16. We thank two anonymous referees for suggesting these extensions.

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Author contributions

CRediT: **Žymantas Budrys**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; **Giedrė Krotovaitė**: Conceptualization, Data curation, Visualization, Writing – original draft.

Disclaimer

the views expressed in this paper are those of the authors, and do not necessarily reflect those of Lietuvos bankas.

Data availability statement

This study uses a combination of publicly available and non-public data. Public macroeconomic and financial time series—including price indices, real activity measures, labour market indicators, interest rates, and exchange rate variables—are sourced from Eurostat, the European Central Bank, and the Bank for International Settlements, and are available via a public data repository (https://zymantasbudrys.com/bk16_naturalrate_data/). Certain inputs used, such as expectations, seasonally adjusted variables, projections, output gaps, and other internally constructed or confidential series, are not publicly available and therefore cannot be shared.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Declaration of generative AI use

The authors used ChatGPT, version 5.6, solely for minor editorial assistance. The authors reviewed and edited all AI-assisted output and take full responsibility for the manuscript's content.

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Appendices

Appendix 1. Data plots

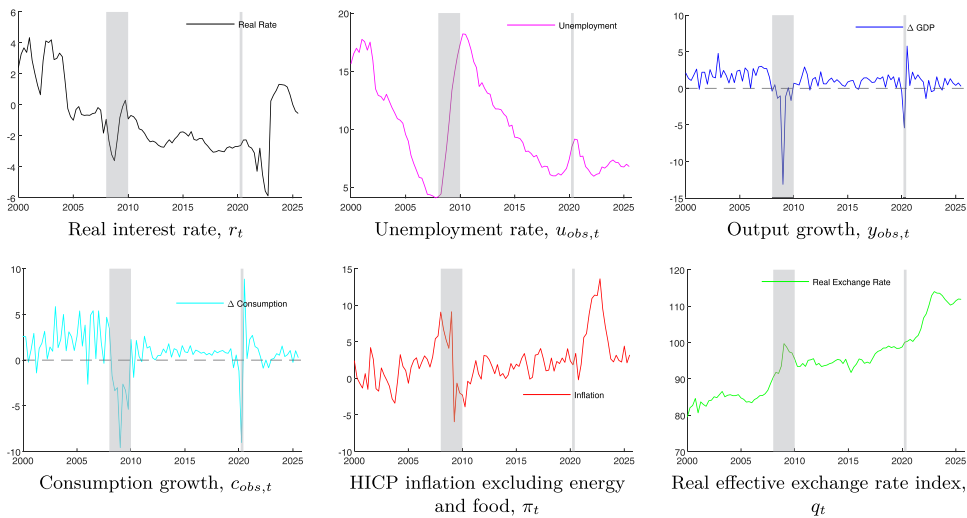


Figure A1. Observed data series used in the estimation.

Note: The figure reports the observed macroeconomic series used in the baseline estimation. The sample covers 2000Q1 to 2025Q3. All series are seasonally adjusted and are used at a quarterly frequency. Series available at higher frequencies are aggregated to quarterly observations using period averages. Output and consumption correspond to real gross domestic product and private consumption, respectively. The real interest rate is constructed from the 3-month euro OIS rate and Consensus Economics next-year inflation projections. Sources: Eurostat, ECB, BIS, and authors' calculations.

Appendix 2. Model adjustment for the euro area

Figure A2 compares the real natural real rate estimated using our model with the range of estimates published by the ECB. In the most recent period, our estimates are broadly consistent with alternative measures, although they tend to lie somewhat below the ECB range during the 2008–2015 period.

The estimation of the euro area natural rate using our framework is presented primarily for completeness and to assess the consistency of the model. We do not claim that our estimates are superior to existing ECB measures. Our model is designed for a small, open economy and places particular emphasis on real exchange rate dynamics, which may be less applicable to the euro area as a whole. In the euro area context, additional structural features, notably an endogenous monetary policy reaction function, may play a more important role, as emphasized by Brand et al. (2018).

Nevertheless, several adjustments are made to adapt the model to euro area conditions. While the core structure remains unchanged, we introduce modifications to better reflect EA-specific characteristics and data availability. Compared with the LT model, which seeks to capture economic convergence, the EA specification adopts a simpler representation of equilibrium real exchange rate dynamics. In particular, the EA REER equation does not have a stochastic drift, and is specified as a random walk:

$$q_t^* = q_{t-1}^* + \varepsilon_{q^*,t} \quad (\text{A1})$$

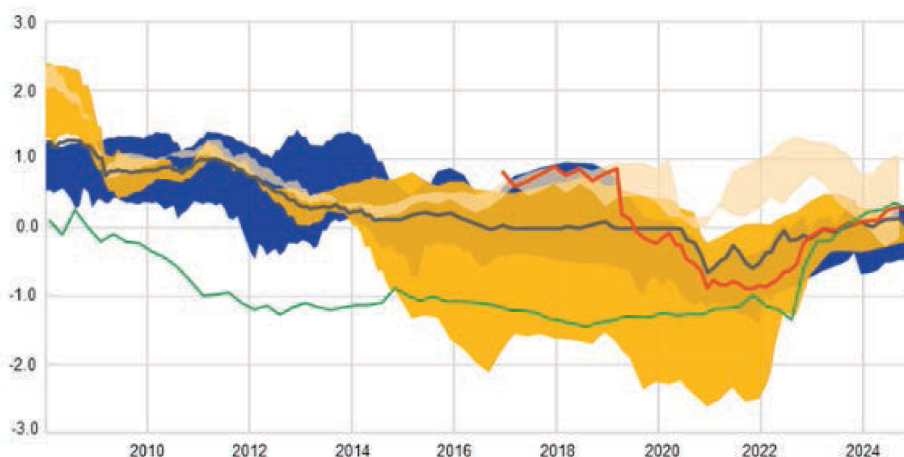


Figure A2. Model estimated r-star compared with ECB published estimates.

Note: The figure shows the model-estimated real natural rate for the Euro Area (*green line*) alongside ECB-published estimates. The *blue shaded range* corresponds to term-structure-based estimates; the *orange shaded range* shows semi-structural estimates excluding HLW-based measures; the *light yellow shaded range* includes semi-structural HLW-based estimates only; the *green line* represents the median across all estimates; and the *red line* denotes the median of survey-based estimates. The latest observation is 2024Q4. Sources: Authors' calculations; ECB; Eurosystem; Federal Reserve Bank of New York; and Consensus Economics.

Consequently, the EA Phillips curve is adjusted and specified as:

$$\pi_t = \beta_y \tilde{y}_{t-1} + \underbrace{\beta_\pi \pi_{t-1} + (1 - \beta_\pi) \pi_t^*}_{\pi_t^c} + \beta_q \Delta q_{t-1} + \varepsilon_{\pi,t} \quad (\text{A2})$$

The trend inflation is identified using two measures of long-term inflation expectations: 6–10 year Consensus Economics forecasts and 5-year expectations from the ECB's Survey of Professional Forecasters (SPF). Accordingly, the EA trend inflation component is linked to two observable measure:

$$\pi_{spf,t} = \pi_t^* + \varepsilon_{spf,t}, \quad (\text{A3})$$

$$\pi_{cons,t} = \ell_2 + \rho_{\pi,2} \pi_t^* + \varepsilon_{cons,t} \quad (\text{A4})$$

The use of two expectation measures allows us to extend the sample and exploit the information content of a broader set of expectation measures. The euro area sample is larger and begins in 1990Q2. For the construction of the real interest rate, we use four-quarter-ahead inflation expectations from the SPF. In addition, prior distributions are recalibrated for the euro area.

Appendix 3. Prior and posterior estimates

Table D1. Prior and posterior estimates.

Parameter	Prior mean	Posterior mean	90% HPD interval		Prior	Prior s.d.
			Lower	Upper		
$\sum_{i=0}^1 \alpha_{y,i}$	0.844	0.8588	0.7792	0.9373	norm	0.0872
$\alpha_{y,1}$	−0.508	−0.4518	−0.7096	−0.2070	norm	0.2154
$\alpha_{r,1}$	−0.250	−0.0714	−0.4050	0.2456	norm	0.2500
α_q	−0.250	−0.3839	−0.6591	−0.1111	norm	0.5000
ϑ_y	−50.000	−18.6136	−30.0973	−7.1499	unif	28.8675

(Continued)

Table D1. Continued.

Parameter	Prior mean	Posterior mean	90% HPD interval		Prior	Prior s.d.
			Lower	Upper		
$\vartheta_{u,0}$	10.000	2.9939	0.0054	5.5818	unif	5.7735
$\vartheta_{u,1}$	5.000	4.3247	0.4912	8.1326	unif	8.6603
$\vartheta_{u,2}$	5.000	4.2169	0.6650	7.6822	unif	8.6603
ϑ_c	-50.000	-29.4600	-46.4504	-12.2133	unif	28.8675
β_y	0.250	0.1512	0.0470	0.2520	norm	1.2145
β_π	0.400	0.5853	0.4397	0.7395	norm	0.2500
β_q	-0.250	-0.1718	-0.4831	0.1424	norm	1.2638
ω	0.000	0.0043	-0.1573	0.1707	norm	0.1000
c	4.000	4.3244	3.5883	5.0711	norm	0.5000
γ	0.000	0.2901	-0.0129	0.5974	norm	0.5000
ρ	0.500	0.5927	0.2834	0.9122	norm	0.2500
$\theta_{q,0}$	0.800	0.9407	0.8949	0.9895	norm	0.5000
$\theta_{q,1}$	-0.700	-0.6393	-0.9032	-0.3656	norm	0.5000
α_0	-0.500	-0.6890	-0.8739	-0.4993	norm	0.4282
ϕ_c	1.000	0.9902	0.7907	1.1878	norm	0.4078
$\gamma_{r,1}$	-0.250	-0.2442	-0.6162	0.1181	norm	0.2500
γ_q	-0.250	0.0964	-0.3798	0.5846	norm	0.5000
$\gamma_{y,0}$	0.900	1.3680	1.0613	1.6794	norm	1.3573
ε_{y^*}	0.750	0.8773	0.6201	1.1323	norm	0.3616
ε_g	0.082	0.1484	0.1022	0.1940	norm	0.0393
$\varepsilon_{\tilde{y}}$	0.267	0.2482	0.0824	0.4106	norm	0.1288
ε_π	1.242	2.1532	1.9112	2.3935	norm	0.5991
ε_{π^*}	0.169	0.1878	0.1184	0.2577	norm	0.0815
ε_z	0.286	0.2894	0.0588	0.5067	norm	0.1381
ε_κ	0.371	0.3880	0.1316	0.6485	norm	0.1790
ε_{q^*}	1.183	1.1446	0.9752	1.3166	norm	0.5705
ε_μ	0.075	0.0613	0.0001	0.1221	norm	0.0722
$\varepsilon_{\tilde{q}}$	0.836	0.4335	0.1916	0.6778	norm	0.4034
ε_{u^*}	0.556	0.3535	0.2151	0.4909	norm	0.2683
$\varepsilon_{\tilde{u}}$	0.393	0.1509	0.0327	0.2568	norm	0.1897
ε_{c^*}	1.169	0.7189	0.2702	1.1589	norm	0.5637
$\varepsilon_{\tilde{c}}$	1.169	0.7141	0.4697	0.9666	norm	0.5637
$\varepsilon_{\tilde{y}}$	0.750	1.0708	0.8314	1.3121	norm	0.3616
$\varepsilon_{\pi_{obs}^*}$	0.000	0.0893	0.0000	0.1658	norm	0.100

Notes: The table reports prior and posterior parameter estimates obtained from Bayesian estimation. Prior mean and Prior s.d. denote the mean and standard deviation of the assumed prior distribution, while Prior indicates the functional form of the prior (normal or uniform). The Posterior mean is the mean of the posterior distribution generated by the Markov Chain Monte Carlo (MCMC) algorithm. The 90% HPD interval corresponds to the highest posterior density interval, defined by the lower and upper bounds that contain 90% of the posterior probability mass.

Appendix 4. Relevant results

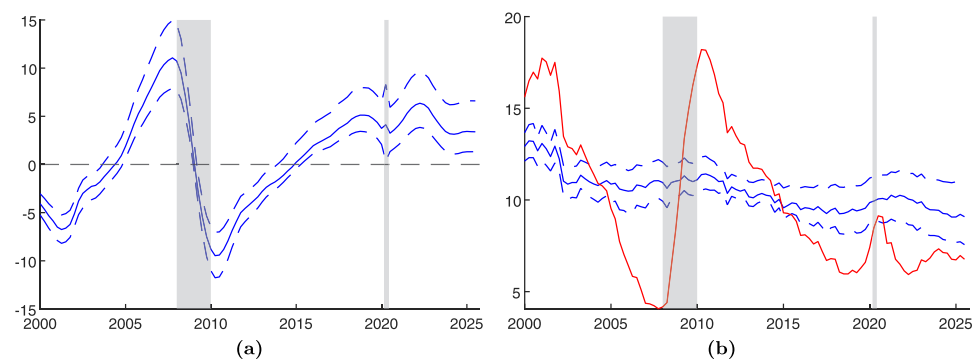


Figure A3. Model-based estimates of quarterly the output gap and long-term unemployment.

Note: Panel (a) presents a model-based quarterly output gap. Solid and dashed blue lines indicate the posterior median and 90% credible bands, respectively. The values are expressed as percentage-point deviations of actual output from potential output. Panel (b) compares the model-based long-term unemployment gap (blue line) with the observed unemployment (red line). Dashed blue lines indicate the 90% credible bands, while the shaded grey areas denote periods of economic downturn.

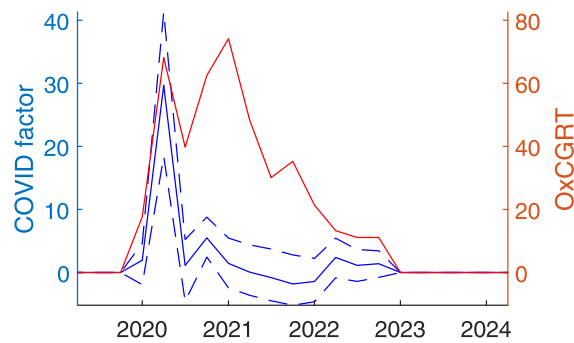


Figure A4. Estimated COVID-19 outlier compared with the Oxford Stringency Index.

Note: The figure compares the estimated COVID-19 outlier with the Oxford Stringency Index used by Holston et al. (2023). The blue solid line and dashed lines denote the posterior median and 90% credible intervals, respectively. The orange line shows the Oxford Stringency Index, measured on the right-hand axis.

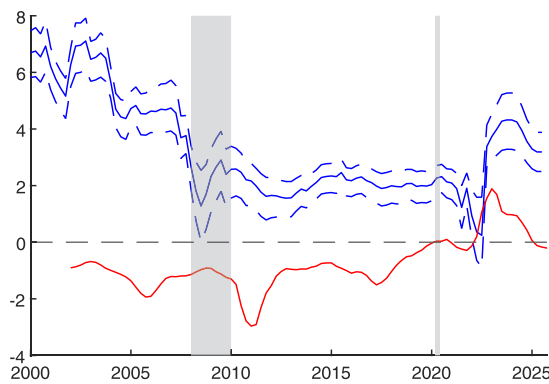


Figure A5. Estimated annualized potential growth and population growth in Lithuania.

Note: The figure compares the model-implied annualized potential growth rate (blue line) with year-on-year population growth in Lithuania (red line).

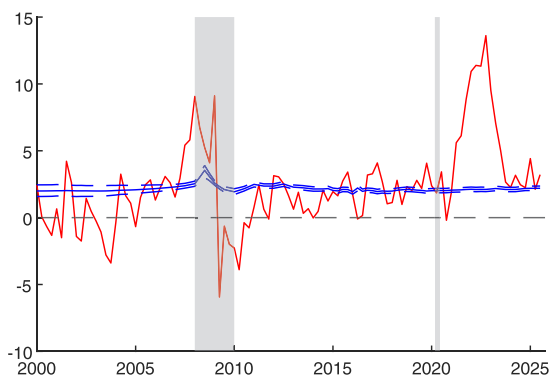


Figure A6. Smoothed estimates of trend inflation, π_t^* .

Note: The figure shows smoothed estimates of trend inflation, π_t^* , together with observed inflation (red line). The blue solid line denotes the posterior median, while the dashed lines indicate the 90% credible interval.

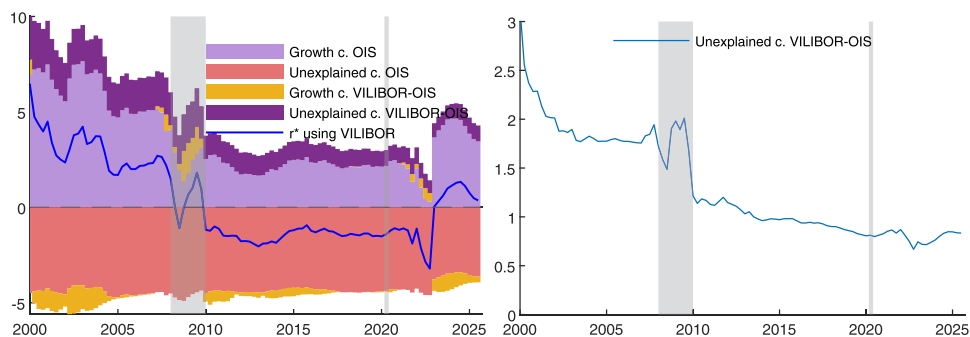


Figure A7. Natural real interest rate under VILIBOR and decomposition of the VILIBOR–OIS difference.

Note: The left panel presents the posterior median estimate of Lithuania's natural real interest rate when VILIBOR is used to construct the observed real interest rate prior to 2015. The estimate is decomposed into the growth-related and residual (z) components obtained under the baseline OIS specification, together with the additional contributions arising from replacing OIS with VILIBOR. These additional contributions are calculated as the differences between the corresponding growth and residual components under the VILIBOR and OIS specifications. The right panel isolates the VILIBOR–OIS difference in the residual component.

A.1. Further COVID robustness checks

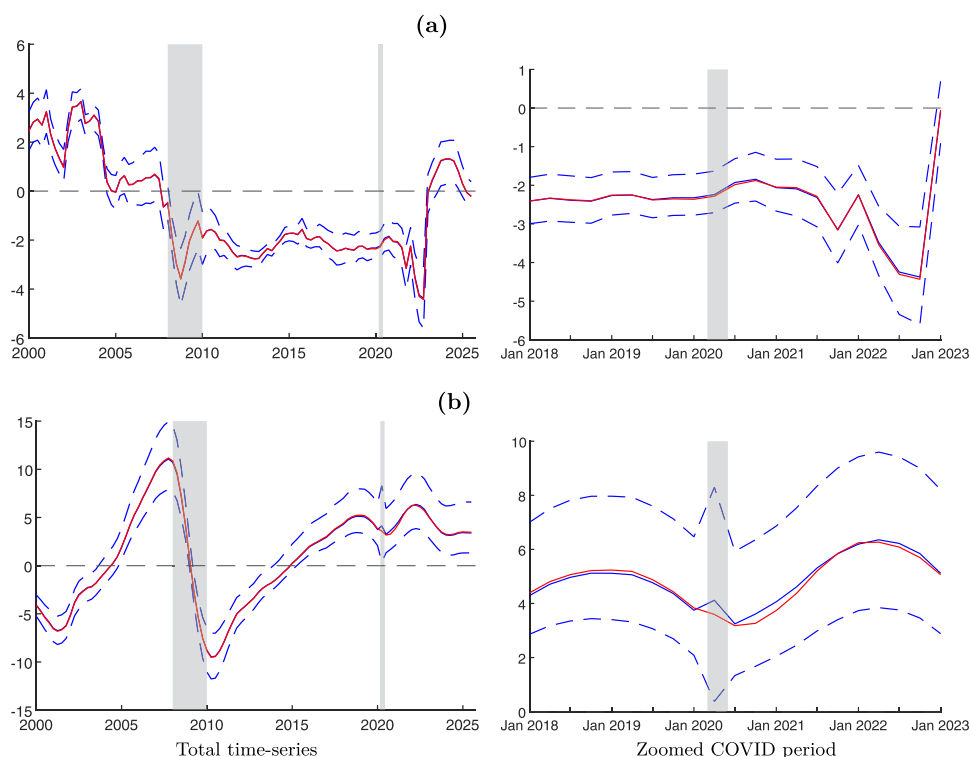


Figure A8. Restricting COVID-19 correction to 2020q2. (a) Natural Real Interest Rate and (b) Output Gap estimates.

Note: Both panels report the baseline estimates and compare them with alternative specifications. The blue solid line denotes the posterior median of the baseline estimate, while the blue dashed lines denote the corresponding 90% credible interval. The red line shows estimates that restrict the COVID correction sample only to 2020q2. Panel (a) presents estimates of the natural real interest rate, and Panel (b) reports output gap estimates. Figures on the left show the full sample, while figures on the right focus on the COVID-19 period. Shaded grey areas indicate periods of economic downturn.