Behavioral Learning Equilibria in the New Keynesian Model *

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January 21, 2020

Abstract

We introduce the concept of behavioral learning equilibrium (BLE) into a high dimensional linear framework and apply it to the standard New Keynesian (NK) model. For each endogenous variable, boundedly rational agents use a simple, but optimal AR(1) forecasting rule with parameters consistent with the observed sample mean and autocorrelation of past data. The main contributions of our paper are fivefold: (1) we derive existence and stability conditions of BLE in a general linear framework, (2) we provide a method for Bayesian likelihood estimation of BLE, (3) we estimate the baseline NK model based on U.S. data and show that the relative model fit is better under BLE than REE, (4) we show that multiple E-stable BLE exist in plausible parameter regions characterized by a unique REE, (5) optimal monetary policy under BLE is different from REE and typically more aggressive, suggesting that an optimal policy under REE may perform poorly under BLE.

JEL classification: C11; E62; E03; D83; D84

Keywords: Bounded rationality; Behavioral learning equilibrium; Adaptive learning; behavioral New Keynesian macro-model; Monetary Policy.

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[‡]The views expressed in this paper do not represent the position of the Bank of Canada, De Nederlandsche Bank or the Eurosystem.

Acknowledgements

Earlier versions of this paper have been presented at the Computation in Economics and Finance (CEF) conference, June 20-22, 2015, Taipei, Taiwan; the Workshop Expectations in Dynamic Macroeconomic Models, August 13-15 2015, University of Oregon, USA; the Workshop on Agent-Based and DSGE Macroeconomic Modeling: Bridging the Gap, November 20, 2015, Surrey, UK; the CEF2017 conference, June 28-30, 2017, New York; Workshop on Adaptive Learning, May 7-8, 2018, Bilbao, Spain; Behavioral Macroeconomics Workshop, June 15-16, 2018, Bamberg, Germany; CEF2018 conference, June 19-21, 2018, Milano, Italy; the 14th Dynare Conference, July 5-6, 2018, ECB, Frankurt, Germany; and the ESEM conference, August 27-31, 2018, Köln, Germany. Stimulating discussions and comments from Klaus Adam, Bill Branch, Jim Bullard, George Evans, Stephanie Schmitt-Grohé, Paul Levine, Domenico Massaro, Bruce McGough, Bruce Preston, Sergey Slobodyan, Gianluca Violante, Mike Woodford and Raf Wouters are gratefully acknowledged. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement "Integrated Macro-Financial Modeling for Robust Policy Design (MACFINRO-BODS)", grant no. 612796. Mei Zhu also acknowledges financial support from NSFC funding Studies on equilibria of heterogeneous agents models under adaptive learning (grant no. 11401365), NSFC (71850002), China Scholarship Council (file no. 201506485009) and the Fundamental Research Funds for the Central Universities.

Disclosure Statement

The authors declare that they have no relevant material or financial interests that relate to the research described in this paper. All authors have contributed equally and approved the final article.

1 Introduction

Rational Expectations Equilibrium (REE) requires that economic agents' subjective probability distributions coincide with the objective distribution that is determined, in part, by their subjective beliefs. There is a vast literature that studies the drawbacks of REE. Some of these drawbacks include the fact that REE requires an unrealistic degree of computational power and perfect information on the part of agents. As an alternative to REE, the adaptive learning literature (see, e.g., Evans and Honkapohja (2001, 2013) and Bullard (2006) for extensive surveys and references) replaces Rational Expectations with beliefs that come from an econometric forecasting model with parameters updated using observed time series. A large part of this literature involves studying under which conditions learning will converge to the REE. Convergence of adaptive learning to an REE occurs when the perceived law of motion (PLM) of agents is correctly specified. However, in general the PLM may be misspecified. As shown in White (1994), an economic model or a probability model is only a more or less crude approximation to whatever might be the true relationships among the observed data. Consequently it is necessary to view economic and/or probability models as misspecified to some greater or lesser degree. Whenever agents have *misspecified* PLMs, a reasonable learning process may settle down on a misspecification equilibrium. In the literature, different types of misspecification equilibria have been proposed, e.g. Restricted Perceptions Equilibrium (RPE) where the forecasting model is underparameterized (Sargent, 1991; Evans and Honkapohja, 2001; Adam, 2003; Branch and Evans, 2010) and Stochastic Consistent Expectations Equilibrium (SCEE) (Hommes and Sorger, 1998; Hommes et al., 2013), where agents learn the optimal parameters of a simple, parsimonious AR(1) rule.¹

A SCEE is a very natural misspecification equilibrium, where agents in the economy do not know the actual law of motion or even recognize all relevant explanatory variables, but rather prefer a parsimonious forecasting model. The economy is too complex to fully understand and therefore, as a first-order approximation, agents forecast the state of the economy by simple autoregressive models (e.g. Fuster et al., 2010). In the simplest model applying this idea, agents run a univariate AR(1) regression to generate out-of-sample forecasts of the state of the economy. Hommes and Zhu (2014) provide the first-order SCEE with an *intuitive behavioral* interpretation and refer to them as *Behavioral Learning Equilibria* (BLE). Although it is possible for some agents to use more sophisticated models, one may argue that these practices are neither straightforward nor widespread. A simple, parsimonious BLE seems a more plausible outcome of the coordination process of individual expectations in large complex socio-economic systems (Grandmont, 1998).

 $^{^{1}}$ Branch (2006) provides a stimulating survey discussing the connection between these types of misspecification equilibria.

Hommes and Zhu (2014) formalize the concept of BLE in the simplest class of models one can think of: a one-dimensional linear stochastic model driven by an exogenous linear stochastic AR(1) process. Agents do not recognize, however, that the economy is driven by an exogenous process, but simply forecast the state of the economy using a univariate AR(1) rule by using past observations. The parameters of the AR(1) forecasting rule are not free, but fixed (and learned over time) according to the observed sample average and first-order sample autocorrelation. Within this setup, Hommes and Zhu (2014) fully characterize the existence and multiplicity of BLE and provide stability conditions under a simple adaptive learning scheme –Sample Autocorrelation Learning (SAC-learning). Although this class of models is simple, it contains two important standard applications: an asset pricing model driven by autocorrelated dividends and the New Keynesian Phillips curve with inflation driven by autocorrelated output gap (or marginal costs). As shown in Fuhrer (2009), however, the skeleton model of the New Keynesian Phillips curve with AR(1) driving variable leaves implicit the determination of real output and the role of monetary policy in influencing output and inflation.

In this paper we extend the BLE concept to a general n-dimensional linear stochastic framework and provide a method to estimate these models under BLE. As an application we study the standard 3-equation dynamic stochastic general equilibrium (DSGE) model-the New Keynesian (NK) model-, its empirical fit and the role of monetary policy under BLE. Agents' perceived law of motion (PLM) is a simple univariate AR(1) process for each variable to be forecasted. Two consistency requirements are imposed upon BLE to pin down the parameters of the forecasting model: for each endogenous variable, observed sample averages and first-order sample autocorrelations match the corresponding parameters of the forecasting rule. Agents thus learn the optimal AR(1) forecasting rule for each endogenous variable in the economy.

The main contributions of our paper are fourfold: (1) we derive existence and stability conditions of BLE in a general linear framework, (2) we provide a simple and general method for Bayesian likelihood estimation of BLE, (3) we estimate the baseline NK model based on U.S. data and show that the relative model fit is better under BLE than REE, (4) we show that multiple E-stable BLE exist in plausible parameter regions associated by a unique REE, (5) optimal monetary policy under BLE is different from REE and typically more aggressive, which suggests that an optimal policy under REE may perform poorly under BLE. This result is in line with previous studies in the adaptive learning literature, see e.g. Orphanides & Williams (2003). The main novelty in our framework is to show this as a *misspecification equilibrium* outcome, whereas previous studies typically focus on learning dynamics around a REE.

Many models of learning lead to excess volatility, where the volatility under learning is typically higher than under REE. Our BLE model exhibits another novel feature, *persis*- tence amplification: the persistence of inflation and output gap under BLE is significantly higher than under REE. In fact, even when autocorrelations of the exogenous shocks to fundamentals are small, inflation and output gap along BLE are typically near unit root processes. As a consequence, when we estimate the NK model under BLE², we find important differences in parameter estimates compared with the REE. Further, optimal monetary policy under BLE is finite for a wide range of calibrations, and the transmission channel of monetary policy is stronger under BLE than REE at the estimated parameters.

Related literature

The issue of persistence has been of great interest to macroeconomists and policymakers. A number of models with frictions have been proposed to replicate persistence, such as habit formation in consumption, indexation to lagged inflation in price-setting, rule-of-thumb behavior, or various adjustment costs (Phelps, 1968; Taylor, 1980; Fuhrer and Moore, 1992, 1995; Christiano et al., 2005; Smets and Wouters, 2003, 2005; Boivin and Giannoni, 2006; Giannoni and Woodford, 2003). These models essentially improve the empirical fit by adding lags to the model equations. Estimating these rich models with frictions under the assumption of RE, one typically finds that substantial degrees of persistence are supported by the data. Therefore these additional sources of persistence appear necessary to match the inertia of macroeconomic variables. Estimation of these models typically also involve highly persistent structural shocks. Our BLE model is applied to a New Keynesian framework without habit formation or indexation, but nevertheless exhibits strong persistence. Learning causes persistence amplification: small autocorrelations of exogenous shocks are strongly amplified as agents learn to coordinate on a simple AR(1) forecasting rule with near unit root parameters consistent with observed sample average and sample autocorrelations. The high persistence of inflation and output thus arises from a self-fulfilling mistake (Grandmont, 1998).

Our BLE concept fits with the literature employing adaptive learning to analyze the evolution of U.S. inflation and monetary policy. Adaptive learning can help in understanding some particular historical episodes, such as high inflation in the 1980s, which are often harder to explain under RE. For example, Orphanides and Williams (2003) consider a form of imperfect knowledge in which economic agents rely on adaptive learning to form expectations. This form of learning represents a relatively modest deviation from RE that nests it as a limiting case. They find that policies that would be efficient under RE can perform poorly when knowledge is imperfect. Milani (2005, 2007) also assumes

²The empirical results presented in this paper also hold in more realistic setups. In particular, an estimated hybrid version of the New Keynesian model with lagged inflation and output can be found in our Online Appendix. We also estimate Smets-Wouters (2007) model under BLE in our follow-up paper Hommes et. al. (2019).

that agents form expectations through adaptive learning using correctly specified economic models and updating the parameters through constant-gain learning (CGL) based on historical data. He shows empirically that when learning replaces RE, the estimated degrees of habit formation and indexation drop closer to zero, suggesting that persistence arises in the model economy mainly from expectations and learning. Eusepi and Preston (2011) study expectations-driven business cycles based on learning, and find that learning dynamics generate forecast errors similar to the Survey of Professional Forecasters. Estrella and Fuhrer (2002) study the shortcomings of REE models with a focus on inertia and shock propagation structure. Fuhrer (2009) provides a good survey on inflation persistence. He examines a number of empirical measures of reduced form persistence including the first-order autocorrelation and the autocorrelation function of the inflation series. He also investigates the sources of persistence, including learning of agents in a RE setting.

Numerous empirical studies show that overly parsimonious models with little parameter uncertainty can provide better forecasts than models consistent with the actual datagenerating complex process (e.g. Nelson, 1972; Stock and Watson, 2007; Clark and West, 2007; Enders, 2010). In a similar vein (but without analytical results) Slobodyan and Wouters (2012) study a New Keynesian DSGE model with agents using a constant gain AR(2) forecasting rule. Chung and Xiao (2014) and Xiao and Xu (2014) study learning and predictions with an AR(1) or VAR(1) model in a two dimensional New Keynesian model with limited information and show, based on simulations, that the simple AR(1) model is more likely to prevail in reality when they make predictions. Laboratory experiments in the NK framework also show that simple forecasting rules such as AR(1) describe individual forecasting behavior surprisingly well (Assenza et al., 2014; Pfajfar and Zakelj, 2016).

Our behavioral learning equilibrium concept is closely related to the Exuberance Equilibria (EE) in Bullard et al. (2008), where agents' perceived law of motion is misspecified. However, because of difficulty of computation, in Bullard et al. (2008) there are only numerical results on the exuberance equilibria, while here we analytically show the existence and stability of BLE in a general linear framework with an application to the NK model, as well as empirically validate BLE based on U.S. data. Another related misspecification equilibrium is Limited Information Learning Equilibrium (LILE) defined in Chung and Xiao (2014), which is defined by the least-squares projection of variables on the past information of the actual law of motion equal to that in the perceived law of motion. Different from the LILE, our general Behavioral Learning Equilibrium is defined by the conditions that sample means and first-order autocorrelations of each variable of the actual law of motion are consistent with those corresponding to the perceived law of motion. We further study the effects of monetary policy under the more plausible BLE. The concept of natural expectations in Fuster et al. (2010) and Fuster et al. (2011, 2012) is another related misspecification concept, where agents use simple, misspecified models, e.g., linear autoregressive models. Natural expectations, however, do not pin down the parameters of the forecasting model through consistency requirements as for a restricted perceptions equilibrium nor do they allow the agents to learn an optimal misspecified model through empirical observations. Cho and Kasa (2015) study model validation in an environment where agents are aware of misspecification and try to detect it through adaptive learning. Similarly, Cho and Kasa (2017) study learning in a framework where agents form expectations using a Bayesian averaging based on multiple models. In our BLE misspecification is self-fulfilling and it is the outcome of a learning process. Another related work is Adam and Marcet (2011), who introduce a more sophisticated notion of bounded rationality called internal rationality, and show that even for a small deviation from REE beliefs, with a small prior around the correct REE belief, the outcome of the learning model can be quite different.

The paper is organized as follows. Section 2 introduces the main concepts of BLE in a general n-dimensional setup, the theoretical results on existence and stability of BLE in a linear framework and the empirical estimation methodology. Section 3 applies BLE to the 3-equation New Keynesian model and presents the existence, stability and estimation results. Section 4 studies optimal monetary policy and how policy can mitigate persistence and volatility amplification under BLE. Section 5 concludes.

2 BLE in a Multivariate Framework

Hommes and Zhu (2014) introduced BLE in the simplest setting, a one-dimensional linear stochastic model driven by an exogenous linear stochastic AR(1) process. In this paper we generalize BLE to *n*-dimensional (linear) stochastic models driven by exogenous linear stochastic AR(1) processes of multiple shocks. To ease the exposition we initially follow the presentation in Hommes and Zhu (2014), but generalize their 1-dimensional model to an *n*-dimensional framework. In addition, most macroeconomic models include lagged state variables through features such as interest rate smoothing, habit formation in consumption or indexation in prices and wages. Therefore, we further extend the model with lagged state variables.

Let the law of motion of an economic system be given by the stochastic difference equation

$$\boldsymbol{x}_{t} = \boldsymbol{F}(\boldsymbol{x}_{t+1}^{e}, \, \boldsymbol{x}_{t-1}, \, \boldsymbol{u}_{t}, \, \boldsymbol{v}_{t}),$$
 (2.1)

where \boldsymbol{x}_t is an $n \times 1$ vector of endogenous variables denoted by $[x_{1t}, x_{2t}, \cdots, x_{nt}]'$ and \boldsymbol{x}_{t+1}^e

is the expected value of \boldsymbol{x} at date t + 1. This notation highlights that expectations may not be rational. Here \boldsymbol{F} is a continuous *n*-dimensional vector function, \boldsymbol{u}_t is a vector of exogenous stationary variables and \boldsymbol{v}_t is a vector of white noise disturbances.

Agents are boundedly rational and do not know the exact form of the actual law of motion (2.1). They only use a simple, parsimonious forecasting model where agents' perceived law of motion (PLM) is a simple univariate AR(1) process for each variable to be forecasted. As shown in Enders (2010, p.84-85), coefficient uncertainty increases as the model becomes more complex, and hence it could be that an estimated AR(1) model forecasts a real ARMA(2,1) process better than an estimated ARMA(2,1) model. Numerous empirical studies also show that overly parsimonious models with little parameter uncertainty can provide better forecasts than models consistent with the more complex actual data-generating process (e.g. Nelson, 1972; Stock and Watson, 2007; Clark and West, 2007). Thus agents' perceived law of motion (PLM) is assumed to be the simplest VAR model with minimum parameters, i.e. a restricted VAR(1) process

$$\boldsymbol{x}_t = \boldsymbol{\alpha} + \boldsymbol{\beta}(\boldsymbol{x}_{t-1} - \boldsymbol{\alpha}) + \boldsymbol{\delta}_t, \qquad (2.2)$$

where $\boldsymbol{\alpha}$ is a vector denoted by $[\alpha_1, \alpha_2, \cdots, \alpha_n]'$, $\boldsymbol{\beta}$ is a diagonal matrix³ denoted by $\begin{bmatrix} \beta_1 & 0 & \cdots & 0 \\ 0 & \beta_2 & \cdots & 0 \\ \cdots & & \\ 0 & 0 & \cdots & \beta_n \end{bmatrix}$ with $\beta_i \in (-1, 1)$ and $\{\boldsymbol{\delta}_t\}$ is a white noise process; $\boldsymbol{\alpha}$ is the un-

conditional mean of \mathbf{x}_t and β_i is the first-order autocorrelation coefficient of variable x_i . Given the perceived law of motion (2.2), the 2-period ahead forecasting rule for \mathbf{x}_{t+1} that minimizes the mean-squared forecasting error is

$$\boldsymbol{x}_{t+1}^e = \boldsymbol{\alpha} + \boldsymbol{\beta}^2 (\boldsymbol{x_{t-1}} - \boldsymbol{\alpha}). \tag{2.3}$$

Combining the expectations (2.3) and the law of motion of the economy (2.1), we obtain the implied actual law of motion (ALM)

$$\boldsymbol{x}_t = \boldsymbol{F}(\boldsymbol{\alpha} + \boldsymbol{\beta}^2(\boldsymbol{x}_{t-1} - \boldsymbol{\alpha}), \ \boldsymbol{x}_{t-1}, \ \boldsymbol{u}_t, \ \boldsymbol{v}_t). \tag{2.4}$$

In the case that the ALM (2.4) is stationary, let the variance-covariance matrix $\mathbf{\Gamma}(0) := E[(\mathbf{x}_t - \overline{\mathbf{x}})(\mathbf{x}_t - \overline{\mathbf{x}})']$ and the first order autocovariance matrix $\mathbf{\Gamma}(1) := E[(\mathbf{x}_t - \overline{\mathbf{x}})(\mathbf{x}_{t+1} - \overline{\mathbf{x}})']$,

³Chung and Xiao (2014) also argue using simulations that the simple AR(1) model is more likely to prevail in reality because of limited information restrictions when they model predictions in a two dimensional New Keynesian model. In addition, as far as prediction is concerned, based on our numerous empirical analyses, the short-term forecasts based on an AR(1) model are better than more general VAR models in most cases, because in more general VAR models too many parameters need to be estimated and hence coefficient uncertainty increases.

where $\overline{\boldsymbol{x}}$ is the mean of \boldsymbol{x}_t . Let $\boldsymbol{\Omega}$ be the diagonal matrix in which the *i*th diagonal element is the variance of the *i*th process, that is $\boldsymbol{\Omega} = \text{diag}[\gamma_{11}(0), \gamma_{22}(0), \cdots, \gamma_{nn}(0)]$, where $\gamma_{ii}(0)$ is the *i*th diagonal entry of $\boldsymbol{\Gamma}(0)$. Let \boldsymbol{L} be the diagonal matrix in which the *i*th diagonal element is the first-order autocovariance of the *i*th process, that is $\boldsymbol{L} =$ $\text{diag}[\gamma_{11}(1), \gamma_{22}(1), \cdots, \gamma_{nn}(1)]$, where $\gamma_{ii}(1)$ is the *i*th diagonal entry of $\boldsymbol{\Gamma}(1)$. Let \boldsymbol{G} denote the diagonal matrix in which the *i*th diagonal element is the first-order autocorrelation coefficient of the *i*th process $x_{i,t}$. Hence

$$\boldsymbol{G} = \boldsymbol{L} \boldsymbol{\Omega}^{-1}. \tag{2.5}$$

Behavioral Learning Equilibrium (BLE)

Extending Hommes and Zhu (2014), the concept of BLE is generalized as follows.

Definition 2.1 A vector (μ, α, β) , where μ is a probability measure, α is a vector and β is a diagonal matrix with $\beta_i \in (-1, 1)$ $(i = 1, 2, \dots, n)$, is called a Behavioral Learning Equilibrium (BLE) if the following three conditions are satisfied:

- S1 The probability measure μ is a nondegenerate invariant measure for the stochastic difference equation (2.4);
- S2 The stationary stochastic process defined by (2.4) with the invariant measure μ has unconditional mean $\boldsymbol{\alpha}$, that is, the unconditional mean of x_i is α_i , $(i = 1, 2, \dots, n)$;
- S3 Each element x_i for the stationary stochastic process of \boldsymbol{x} defined by (2.4) with the invariant measure μ has unconditional first-order autocorrelation coefficient β_i , ($i = 1, 2, \dots, n$), that is, $\boldsymbol{G} = \boldsymbol{\beta}$.

In other words, a BLE is characterized by two natural observable consistency requirements: the unconditional means and the unconditional first-order autocorrelation coefficients generated by the actual (unknown) stochastic process (2.4) coincide with the corresponding statistics for the perceived linear VAR(1) process (2.2), as given by the parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$. This means that in a BLE agents correctly perceive the two simplest and most important statistics: the mean and first-order autocorrelation (i.e., persistence) of each relevant variable of the economy, without fully understanding its structure and recognizing all explanatory variables and cross-correlations. A BLE is *parameter free*, as along a BLE the two parameters of each linear forecasting rule are pinned down by simple and observable statistics. Hence, agents do not fully understand the linear structure of the stochastic economy, i.e. they do not observe the shocks and do not take the cross-correlations of state variables into account, but rather use a parsimonious univariate AR(1) forecasting rule for each state variable. A simple BLE may be a plausible outcome of the coordination process of expectations of a large population. Laboratory experiments within the New Keynesian framework also provide empirical evidence of the use of simple univariate AR(1) forecasting rules to forecast inflation and output gap (Adam, 2007; Pfajfar and Zakelj, 2016; Assenza et al., 2014).

Furthermore, we note that along a BLE the orthogonality condition

$$E[x_{i,t} - \alpha_i - \beta_i(x_{i,t-1} - \alpha_i)] = 0,$$

$$E\{[x_{i,t} - \alpha_i - \beta_i(x_{i,t-1} - \alpha_i)]x_{i,t-1}\} = E\{[x_{i,t} - \alpha_i - \beta_i(x_{i,t-1} - \alpha_i)](x_{i,t-1} - \alpha_i)\} = 0$$

is satisfied. That is, the forecast $\alpha_i + \beta_i(x_{i,t-1} - \alpha_i)$ is the linear projection of $x_{i,t}$ on the vector $(1, x_{i,t-1})'$. For each variable, agents cannot detect the correlation between the forecasting error $x_{i,t} - \alpha_i - \beta_i(x_{i,t-1} - \alpha_i)$ and the vector $(1, x_{i,t-1})'$ in the forecast model. The linear projection produces the smallest mean squared error among the class of linear forecasting rules (e.g., Hamilton (1994)). Therefore, for each variable agents use the optimal forecast within their class of univariate AR(1) forecasting rules (Branch, 2006).

Sample autocorrelation learning

In the above definition of BLE, agents' beliefs are described by the linear forecasting rule (2.3) with fixed parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$. However, the parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are usually unknown to agents. In the adaptive learning literature, it is common to assume that agents behave like econometricians using time series observations to estimate the parameters as new observations become available. Following Hommes and Sorger (1998), we assume that agents use sample autocorrelation learning (SAC-learning) to learn the parameters α_i and β_i , $i = 1, 2, \dots, n$. That is, for any finite set of observations $\{x_{i,0}, x_{i,1}, \dots, x_{i,t}\}$, the sample average is given by

$$\alpha_{i,t} = \frac{1}{t+1} \sum_{k=0}^{t} x_{i,k}, \qquad (2.6)$$

and the first-order sample autocorrelation coefficient is given by

$$\beta_{i,t} = \frac{\sum_{k=0}^{t-1} (x_{i,k} - \alpha_{i,t}) (x_{i,k+1} - \alpha_{i,t})}{\sum_{k=0}^{t} (x_{i,k} - \alpha_{i,t})^2}.$$
(2.7)

Hence $\alpha_{i,t}$ and $\beta_{i,t}$ are updated over time as new information arrives. It is easy to check that, independently of the choice of the initial values $(x_{i,0}, \alpha_{i,0}, \beta_{i,0})$, it always holds that $\beta_{i,1} = -\frac{1}{2}$, and that the first-order sample autocorrelation $\beta_{i,t} \in [-1, 1]$ for all $t \ge 1$.

As shown in Hommes and Zhu (2014), define

$$R_{i,t} = \frac{1}{t+1} \sum_{k=0}^{t} (x_{i,k} - \alpha_{i,t})^2$$

Then SAC-learning is equivalent to the following recursive dynamical system⁴:

$$\begin{cases} \alpha_{i,t} = \alpha_{i,t-1} + \frac{1}{t+1} (x_{i,t} - \alpha_{i,t-1}), \\ \beta_{i,t} = \beta_{i,t-1} + \frac{1}{t+1} R_{i,t}^{-1} \Big[(x_{i,t} - \alpha_{i,t-1}) (x_{i,t-1} + \frac{x_{i,0}}{t+1} - \frac{t^2 + 3t + 1}{(t+1)^2} \alpha_{i,t-1} - \frac{1}{(t+1)^2} x_{i,t}) \\ - \frac{t}{t+1} \beta_{i,t-1} (x_{i,t} - \alpha_{i,t-1})^2 \Big], \\ R_{i,t} = R_{i,t-1} + \frac{1}{t+1} \Big[\frac{t}{t+1} (x_{i,t} - \alpha_{i,t-1})^2 - R_{i,t-1} \Big]. \end{cases}$$

$$(2.8)$$

The actual law of motion under SAC-learning is therefore given by

$$\boldsymbol{x}_{t} = \boldsymbol{F}(\boldsymbol{\alpha}_{t-1} + \boldsymbol{\beta}_{t-1}^{2}(\boldsymbol{x}_{t-1} - \boldsymbol{\alpha}_{t-1}), \ \boldsymbol{x}_{t-1}, \ \boldsymbol{u}_{t}, \ \boldsymbol{v}_{t}),$$
(2.9)

with $\alpha_{i,t}$, $\beta_{i,t}$ as in (2.8).

In Hommes and Zhu (2014), F is a one-dimensional linear function. In this paper F may be an *n*-dimensional linear vector function and includes the lagged term \mathbf{x}_{t-1} .

2.1 Main results in a multivariate linear framework

Assume that a reduced form model is an *n*-dimensional linear stochastic process \boldsymbol{x}_t , driven by an exogenous VAR(1) process \boldsymbol{u}_t . More precisely, the actual law of motion of the economy is given by

$$\boldsymbol{x}_{t} = \boldsymbol{F}(\boldsymbol{x}_{t+1}^{e}, \boldsymbol{u}_{t}, \boldsymbol{v}_{t}) = \boldsymbol{b}_{0} + \boldsymbol{b}_{1}\boldsymbol{x}_{t+1}^{e} + \boldsymbol{b}_{2}\boldsymbol{x}_{t-1} + \boldsymbol{b}_{3}\boldsymbol{u}_{t} + \boldsymbol{b}_{4}\boldsymbol{v}_{t},$$
 (2.10)

$$\boldsymbol{u}_t = \boldsymbol{a} + \boldsymbol{\rho} \boldsymbol{u}_{t-1} + \boldsymbol{\varepsilon}_t, \qquad (2.11)$$

where \boldsymbol{x}_t is an $n \times 1$ vector of endogenous variables, \boldsymbol{b}_0 and \boldsymbol{a} are vectors of constants, $\boldsymbol{b}_1, \boldsymbol{b}_2$ and \boldsymbol{b}_4 are $n \times n$ matrices of coefficients, \boldsymbol{b}_3 is an $n \times m$ matrix, $\boldsymbol{\rho}$ is an $m \times m$ matrix, \boldsymbol{u}_t is an $m \times 1$ vector of exogenous variables which is assumed to follow a stationary VAR(1)

⁴The system in (2.8) is a decreasing gain algorithm, where all observations receive equal weight and therefore the weight on the latest observation decreases as the sample size grows. There is also a constant gain correspondence of SAC-learning, where past observations are discounted at a geometric rate. This can be obtained by replacing the weights $\frac{1}{t+1}$ by some positive constant κ , see the online appendix to Hommes & Zhu (2014) for further details.

as in (2.11), and \boldsymbol{v}_t is an $n \times 1$ vector of i.i.d. stochastic disturbance terms with mean zero and finite absolute moments, with variance-covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{v}}$. Hence all of the eigenvalues of $\boldsymbol{\rho}$ are assumed to be inside the unit circle. In addition, $\boldsymbol{\varepsilon}_t$ is assumed to be an $m \times 1$ vector of i.i.d. stochastic disturbance terms with mean zero and finite absolute moments, with variance-covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}$ and is independent of \boldsymbol{v}_t .

Rational expectations equilibrium

Assume that agents are rational. The perceived law of motion (PLM) corresponding to the minimum state variable REE of the model is:

$$\boldsymbol{x}_{t}^{*} = \boldsymbol{c}_{0} + \boldsymbol{c}_{1} \boldsymbol{x}_{t-1}^{*} + \boldsymbol{c}_{2} \boldsymbol{u}_{t} + \boldsymbol{c}_{3} \boldsymbol{v}_{t}.$$
(2.12)

Assuming that shocks u_t are observable when forecasting x_{t+1} , the one-step ahead forecast is:

$$E_t \boldsymbol{x}_{t+1}^* = \boldsymbol{c}_0 + \boldsymbol{c}_2 \boldsymbol{a} + \boldsymbol{c}_1 \boldsymbol{x}_t^* + \boldsymbol{c}_2 \boldsymbol{\rho} \boldsymbol{u}_t, \qquad (2.13)$$

and the corresponding actual law of motion is:

$$\boldsymbol{x}_{t}^{*} = \boldsymbol{b}_{0} + \boldsymbol{b}_{1}(\boldsymbol{c}_{0} + \boldsymbol{c}_{2}\boldsymbol{a} + \boldsymbol{c}_{1}\boldsymbol{x}_{t}^{*} + \boldsymbol{c}_{2}\boldsymbol{\rho}\boldsymbol{u}_{t}) + \boldsymbol{b}_{2}\boldsymbol{x}_{t-1} + \boldsymbol{b}_{3}\boldsymbol{u}_{t} + \boldsymbol{b}_{4}\boldsymbol{v}_{t}.$$
(2.14)

The rational expectations equilibrium (REE) is the fixed point of

$$c_0 - b_1 c_1 c_0 - b_1 c_0 = b_0 + b_1 c_2 a,$$
 (2.15)

$$c_1 - b_1 c_1^2 = b_2,$$
 (2.16)

$$c_2 - b_1 c_1 c_2 - b_1 c_2 \rho = b_3,$$
 (2.17)

$$c_3 - b_1 c_1 c_3 = b_4.$$
 (2.18)

A straightforward computation (see Appendix A) shows that the mean of the REE $\overline{x^*}$ satisfies

$$\overline{x^*} = (I - b_1 - b_2)^{-1} [b_0 + b_3 (I - \rho)^{-1} a], \qquad (2.19)$$

where I denotes a comfortable identity matrix throughout the paper. In the special case with $\rho = \rho I^{5}$ and $b_{2} = 0$, the rational expectations equilibrium x_{t}^{*} satisfies

$$\boldsymbol{x}_{t}^{*} = (\boldsymbol{I} - \boldsymbol{b}_{1})^{-1}\boldsymbol{b}_{0} + (\boldsymbol{I} - \boldsymbol{b}_{1})^{-1}\boldsymbol{b}_{1}(\boldsymbol{I} - \rho\boldsymbol{b}_{1})^{-1}\boldsymbol{b}_{3}\boldsymbol{a} + (\boldsymbol{I} - \rho\boldsymbol{b}_{1})^{-1}\boldsymbol{b}_{3}\boldsymbol{u}_{t} + \boldsymbol{b}_{4}\boldsymbol{v}_{t}.$$
 (2.20)

⁵Note that ρ is a matrix while ρ is a scalar number throughout the paper.

Thus its unconditional mean is:

$$\overline{\boldsymbol{x}^{*}} = E(\boldsymbol{x}_{t}^{*}) = (1-\rho)^{-1} (\boldsymbol{I} - \boldsymbol{b}_{1})^{-1} [\boldsymbol{b}_{0}(1-\rho) + \boldsymbol{b}_{3}\boldsymbol{a}].$$
(2.21)

Its variance-covariance matrix is:

$$\boldsymbol{\Sigma}_{\boldsymbol{x}^*} = E[(\boldsymbol{x}_t^* - \overline{\boldsymbol{x}^*})(\boldsymbol{x}_t^* - \overline{\boldsymbol{x}^*})'] = (1 - \rho^2)^{-1}(\boldsymbol{I} - \rho \boldsymbol{b}_1)^{-1}\boldsymbol{b}_3\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}[(\boldsymbol{I} - \rho \boldsymbol{b}_1)^{-1}\boldsymbol{b}_3]' + \boldsymbol{b}_4\boldsymbol{\Sigma}_{\boldsymbol{v}}\boldsymbol{b}_4'(2.22)$$

Furthermore, the first-order autocovariance is

$$\boldsymbol{\Sigma}_{\boldsymbol{x}^*\boldsymbol{x}_{-1}^*} = E[(\boldsymbol{x}_t^* - \overline{\boldsymbol{x}^*})(\boldsymbol{x}_{t-1}^* - \overline{\boldsymbol{x}^*})'] = \rho(1 - \rho^2)^{-1}(\boldsymbol{I} - \rho\boldsymbol{b}_1)^{-1}\boldsymbol{b}_3\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}[(\boldsymbol{I} - \rho\boldsymbol{b}_1)^{-1}\boldsymbol{b}_3]'. \quad (2.23)$$

The first-order autocorrelation of the *i*-th-element x_i^* of \boldsymbol{x}^* is the *i*-th diagonal element of matrix $\boldsymbol{\Sigma}_{\boldsymbol{x}^*\boldsymbol{x}_{-1}^*}$ divided by the corresponding *i*-th diagonal element of matrix $\boldsymbol{\Sigma}_{\boldsymbol{x}^*}$. Furthermore, if $\boldsymbol{\Sigma}_{\boldsymbol{v}} = \boldsymbol{0}$, then the first-order autocorrelation of the *i*-th element u_i of \boldsymbol{u} is equal to ρ . In this case the persistence of the *i*-th variable x_i^* in the REE coincides exactly with the persistence of the exogenous driving force $u_{i,t}$. That is, in this case the persistence in the REE only inherits the persistence of the exogenous driving force.

Existence of BLE

Now assume that agents are boundedly rational and do not believe or recognize that the economy is driven by an exogenous VAR(1) process \boldsymbol{u}_t , but use a simple univariate linear rule to forecast the state \boldsymbol{x}_t of the economy. Given that agents' perceived law of motion is a restricted VAR(1) process as in (2.2), the actual law of motion becomes

$$\boldsymbol{x}_{t} = \boldsymbol{b}_{0} + \boldsymbol{b}_{1}[\boldsymbol{\alpha} + \boldsymbol{\beta}^{2}(\boldsymbol{x}_{t-1} - \boldsymbol{\alpha})] + \boldsymbol{b}_{2}\boldsymbol{x}_{t-1} + \boldsymbol{b}_{3}\boldsymbol{u}_{t} + \boldsymbol{b}_{4}\boldsymbol{v}_{t}, \qquad (2.24)$$

with \boldsymbol{u}_t given in (2.11). If all eigenvalues of $\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2$, for each $\beta_i \in [-1, 1], 1 \leq i \leq n$, lie inside the unit circle, then the system (2.24) of \boldsymbol{x}_t is stationary and hence its mean $\overline{\boldsymbol{x}}$ and first-order autocorrelation \boldsymbol{G} exist.

The mean of \boldsymbol{x}_t in (2.24) is computed as

$$\overline{\boldsymbol{x}} = (\boldsymbol{I} - \boldsymbol{b}_1 \boldsymbol{\beta}^2 - \boldsymbol{b}_2)^{-1} [\boldsymbol{b}_0 + \boldsymbol{b}_1 \boldsymbol{\alpha} - \boldsymbol{b}_1 \boldsymbol{\beta}^2 \boldsymbol{\alpha} + \boldsymbol{b}_3 (\boldsymbol{I} - \boldsymbol{\rho})^{-1} \boldsymbol{a}].$$
(2.25)

Imposing the first consistency requirement of a BLE on the mean, i.e. $\bar{\boldsymbol{x}} = \boldsymbol{\alpha}$, and solving for $\boldsymbol{\alpha}$ yields

$$\boldsymbol{\alpha}^* = (\boldsymbol{I} - \boldsymbol{b}_1 - \boldsymbol{b}_2)^{-1} [\boldsymbol{b}_0 + \boldsymbol{b}_3 (\boldsymbol{I} - \boldsymbol{\rho})^{-1} \boldsymbol{a}].$$
(2.26)

Comparing with (2.19), we conclude that in a BLE the unconditional mean $\boldsymbol{\alpha}^*$ coincides with the REE mean. That is to say, in a BLE the state of the economy \boldsymbol{x}_t fluctuates on average around its RE fundamental value x^* .

Consider the second consistency requirement of a BLE on the first-order autocorrelation coefficient matrix $\boldsymbol{\beta}$ of the PLM. The second consistency requirement yields

$$\boldsymbol{G}(\boldsymbol{\beta}) = \boldsymbol{\beta},\tag{2.27}$$

where \boldsymbol{G} as in (2.5) and $\boldsymbol{\beta}$ are diagonal matrices. For convenience let G_i denote the *i*-th diagonal element of the matrix \boldsymbol{G} in (2.5). Under the assumption that all of the eigenvalues of $\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2$ for each $\beta_i \in [-1, 1](i = 1, 2, \dots, n)$ lie inside the unit circle, from the theory of stationary linear time series, $G_i(\beta_1, \beta_2, \dots, \beta_n) \in [-1, 1]$ and is a continuous function with respect to $(\beta_1, \beta_2, \dots, \beta_n)$ and other model parameters, see Appendix B⁶. Based on Brouwer's fixed-point theorem for (G_1, G_2, \dots, G_n) , there exists $\boldsymbol{\beta}^* = (\beta_1^*, \beta_2^*, \dots, \beta_n^*)$ with each $\beta_i^* \in [-1, 1]$, such that $\boldsymbol{G}(\boldsymbol{\beta}^*) = \boldsymbol{\beta}^*$. We conclude:

Proposition 1 If all eigenvalues of $\boldsymbol{\rho}$ and $\boldsymbol{b}_1\boldsymbol{\beta}^2 + \boldsymbol{b}_2$, for each $\beta_i \in [-1,1]$, are inside the unit circle⁷, there exists at least one behavioral learning equilibrium $(\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ for the economic system (2.24) with $\boldsymbol{\alpha}^* = (\boldsymbol{I} - \boldsymbol{b}_1 - \boldsymbol{b}_2)^{-1}[\boldsymbol{b}_0 + \boldsymbol{b}_3(\boldsymbol{I} - \boldsymbol{\rho})^{-1}\boldsymbol{a}] = \overline{\boldsymbol{x}^*}$.

Stability under SAC-learning

In this subsection we study the stability of BLE under SAC-learning. The ALM of the economy under SAC-learning is given by

$$\begin{cases} \boldsymbol{x}_{t} = \boldsymbol{b}_{0} + \boldsymbol{b}_{1} [\boldsymbol{\alpha}_{t-1} + \boldsymbol{\beta}_{t-1}^{2} (\boldsymbol{x}_{t-1} - \boldsymbol{\alpha}_{t-1})] + \boldsymbol{b}_{2} \boldsymbol{x}_{t-1} + \boldsymbol{b}_{3} \boldsymbol{u}_{t} + \boldsymbol{b}_{4} \boldsymbol{v}_{t}, \\ \boldsymbol{u}_{t} = \boldsymbol{a} + \boldsymbol{\rho} \boldsymbol{u}_{t-1} + \boldsymbol{\varepsilon}_{t}. \end{cases}$$
(2.28)

with $\boldsymbol{\alpha}_t$, $\boldsymbol{\beta}_t$ updated based on realized sample average and sample autocorrelation as in (2.8). Appendix C shows that the E-stability principle applies and that stability under SAC-learning is determined by the associated ordinary differential equation (ODE)⁸

$$\begin{cases} \frac{d\boldsymbol{\alpha}}{d\tau} = \overline{\boldsymbol{x}}(\boldsymbol{\alpha},\boldsymbol{\beta}) - \boldsymbol{\alpha} = (\boldsymbol{I} - \boldsymbol{b}_1 \boldsymbol{\beta}^2 - \boldsymbol{b}_2)^{-1} [\boldsymbol{b}_0 + \boldsymbol{b}_1 \boldsymbol{\alpha} - \boldsymbol{b}_1 \boldsymbol{\beta}^2 \boldsymbol{\alpha} + \boldsymbol{b}_3 (\boldsymbol{I} - \boldsymbol{\rho})^{-1} \boldsymbol{a}] - \boldsymbol{\alpha}, \\ \frac{d\boldsymbol{\beta}}{d\tau} = \boldsymbol{G}(\boldsymbol{\beta}) - \boldsymbol{\beta}, \end{cases}$$
(2.29)

⁶For example, refer to the expression (3.9) in Hommes and Zhu (2014) for the special 1-dimensional case n = 1 and $b_2 = 0$. In Section 3 we consider the New Keynesian model with two forward-looking variables and compute the (complicated) expressions of $G_1(\beta_1, \beta_2)$ and $G_2(\beta_1, \beta_2)$ explicitly.

⁷The Schur-Cohn criterion theorem provides necessary and sufficient conditions for all eigenvalues to lie inside the unit circle, see Elaydi (1999). For specific models, one may find sufficient conditions that are independent of $\boldsymbol{\beta}$ to guarantee that all eigenvalues of $\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2$, for each $\beta_i \in [-1, 1]$, are inside the unit circle. For example, in the case of the NK model, the Taylor principle is a sufficient condition to ensure that all eigenvalues of $\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2$ lie inside the unit circle for all $\beta_i \in [-1, 1]$; see Section 3.2, Corollary 2 and Appendix E.

⁸See Evans and Honkapohja (2001) for a discussion and mathematical treatment of E-stability.

where $\overline{\boldsymbol{x}}(\boldsymbol{\alpha},\boldsymbol{\beta})$ is the mean given by (2.25) and $\boldsymbol{G}(\boldsymbol{\beta})$ is the diagonal first-order autocorrelation matrix. A BLE $(\boldsymbol{\alpha}^*,\boldsymbol{\beta}^*)$ corresponds to a fixed point of the ODE (2.29). Moreover, a BLE $(\boldsymbol{\alpha}^*,\boldsymbol{\beta}^*)$ is locally stable under SAC-learning if it is a stable fixed point of the ODE (2.29). Therefore, we have the following property of SAC-learning stability:

Proposition 2 A BLE $(\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ is locally stable (E-stable) under SAC-learning if

- (i) all eigenvalues of $(\boldsymbol{I} \boldsymbol{b}_1 \boldsymbol{\beta}^{*2} \boldsymbol{b}_2)^{-1} (\boldsymbol{b}_1 + \boldsymbol{b}_2 \boldsymbol{I})$ have negative real parts⁹, and
- (ii) all eigenvalues of $DG_{\beta}(\beta^*)$ have real parts less than 1, where DG_{β} is the Jacobian matrix with the (i, j)-th entry $\frac{\partial G_i}{\partial \beta_i}$.

Proof. See Appendix C.

Recall from Subsection 2.1 that $G_i(\beta_1, \beta_2, \dots, \beta_n) \in (-1, 1)$ so that at least one BLE exists. The proposition above implies that the BLE may be E-stable under SAC-learning.

2.2 Estimation of BLE

As our application to the NK model will illustrate in the next section, finding an analytical expression for a BLE is usually not possible. Therefore we provide a general numerical iteration method to estimate a BLE of the linear system (2.10) and (2.11). The main challenge here is the joint estimation of the structural parameters and the BLE belief parameters β^* that satisfy a highly non-linear consistency (fixed point) constraint $\beta^* = G(\beta^*)$. The estimation method proceeds in two steps: we first use the notion of iterative E-stability to find an approximate BLE for a given set of structural parameters, as described in Algorithm I below. An advantage of this method is that when it converges, the BLE must be stable under adaptive learning. We next propose an iterative estimation procedure for the structural and the belief parameters as summarized in Algorithm II below, which is closely linked to the notion of iterative E-stability and which is a recursion of Bayesian estimations of linear models. We first re-write the system by augmenting \boldsymbol{x}_t with \boldsymbol{u}_t to obtain

$$\begin{bmatrix} I & -b_3 \\ 0 & I \end{bmatrix} \begin{bmatrix} x_t \\ u_t \end{bmatrix} = \begin{bmatrix} b_0 \\ a \end{bmatrix} + \begin{bmatrix} b_2 & 0 \\ 0 & \rho \end{bmatrix} \begin{bmatrix} x_{t-1} \\ u_{t-1} \end{bmatrix} + \begin{bmatrix} b_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{t+1} \\ u_{t+1} \end{bmatrix} + \begin{bmatrix} b_4 & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} v_t \\ \epsilon_t \end{bmatrix}.$$
(2.30)

Define¹⁰

$$\begin{bmatrix} \boldsymbol{x}_t \\ \boldsymbol{u}_t \end{bmatrix} = S_t, \begin{bmatrix} \boldsymbol{v}_t \\ \boldsymbol{\epsilon}_t \end{bmatrix} = \eta_t, \begin{bmatrix} \boldsymbol{I} & -\boldsymbol{b}_3 \\ \boldsymbol{0} & \boldsymbol{I} \end{bmatrix} = \tilde{\gamma}, \tilde{\gamma}^{-1} \begin{bmatrix} \boldsymbol{b}_0 \\ \boldsymbol{a} \end{bmatrix} = \bar{\gamma}, \quad \tilde{\gamma}^{-1} \begin{bmatrix} \boldsymbol{b}_2 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\rho} \end{bmatrix} = \gamma_1,$$

 9 The Routh-Hurwitz criterion theorem provides sufficient and necessary conditions for all the *n* eigenvalues having negative real parts, see Brock and Malliaris (1989).

¹⁰We assume the invertibility conditions of the corresponding matrices are satisfied throughout the paper.

$$\tilde{\gamma}^{-1} \begin{bmatrix} \boldsymbol{b}_1 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} = \gamma_2, \ \tilde{\gamma}^{-1} \begin{bmatrix} \boldsymbol{b}_4 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I} \end{bmatrix} = \gamma_3.$$

We can then re-write the law of motion as

$$S_t = \bar{\gamma} + \gamma_1 S_{t-1} + \gamma_2 S_{t+1}^e + \gamma_3 \eta_t.$$
(2.31)

The agent's PLM, the corresponding one-step ahead expectations and the implied ALM are given as¹¹

$$\begin{cases} S_t = \boldsymbol{\alpha} + \boldsymbol{\beta}(S_{t-1} - \boldsymbol{\alpha}) + \boldsymbol{\delta}_t, \\ S_{t+1}^e = \boldsymbol{\alpha} + \boldsymbol{\beta}^2(S_{t-1} - \boldsymbol{\alpha}), \\ S_t = (\bar{\gamma} + \gamma_2(\boldsymbol{\alpha} - \boldsymbol{\beta}^2 \boldsymbol{\alpha})) + \gamma_1 S_{t-1} + \gamma_2 \boldsymbol{\beta}^2 S_{t-1} + \gamma_3 \eta_t. \end{cases}$$
(2.32)

Our main goal in this section is to estimate log-linearized DSGE models, where the mean α^* is available based on (2.26). Without loss of generality, we focus on the case where $\alpha^* = 0$. Denoting by $\Gamma(0)$ and $\Gamma(1)$ the variance-covariance and first-order covariance matrices as before, one can show that¹²

$$\begin{cases} Vec(\boldsymbol{\Gamma}(0)) = [I - M(\boldsymbol{\beta}^*) \otimes M(\boldsymbol{\beta}^*)]^{-1}(\gamma_3 \otimes \gamma_3) Vec(\boldsymbol{\Sigma}_{\boldsymbol{\eta}}), \\ Vec(\boldsymbol{\Gamma}(1)) = [I \otimes M(\boldsymbol{\beta}^*)] Vec(\boldsymbol{\Gamma}(0)), \end{cases}$$
(2.33)

where $M(\boldsymbol{\beta}^*) = \gamma_1 + \gamma_2 \boldsymbol{\beta}^{*2}$, and $\boldsymbol{\Sigma}_{\boldsymbol{\eta}}$ is the variance-covariance matrix of i.i.d disturbances η_t . This implies that $\beta_j^* = \frac{Vec(\boldsymbol{\Gamma}(1))_{N(j-1)+j}}{Vec(\boldsymbol{\Gamma}(0))_{N(j-1)+j}} = G_j(\boldsymbol{\beta}^*, \theta), \ 1 \leq j \leq N$, where θ represents the set of structural parameters in γ_1, γ_2 and γ_3 . Then every BLE satisfies

$$\begin{cases} S_t = \gamma_1 S_{t-1} + \gamma_2 \boldsymbol{\beta}^{*2} S_{t-1} + \gamma_3 \eta_t, \\ \beta_j^* = \frac{Vec(Vec(\boldsymbol{\Gamma}(1))_{N(j-1)+j})}{Vec(\boldsymbol{\Gamma}(0))_{N(j-1)+j}} = G_j(\boldsymbol{\beta}^*, \theta), 1 \le j \le N. \end{cases}$$
(2.34)

The E-stability conditions of Proposition 2 are easily simplified to the case with zero mean. Accordingly, a BLE $(\mathbf{0}, \boldsymbol{\beta}^*)$ is locally stable if all eigenvalues of $(I - \gamma_1 - \gamma_2 \boldsymbol{\beta}^{*2})(\gamma_1 + \gamma_2 - I)$ have negative real parts and all eigenvalues of $DG_{\boldsymbol{\beta}}(\boldsymbol{\beta}^*)$ have real parts less than one. Note that the first condition governs the stability of mean coefficients, while the second condition relates to stability of first-order autocorrelation coefficients *independent* of $\boldsymbol{\alpha}^*$.

¹¹Without loss of generality, we assume the first N variables in S_t are the forward-looking variables and we introduce zeros for the remaining state variables and exogenous shocks.

¹²See Appendix B.

Iterative E-stability and Estimation of BLE

The first-order autocorrelation coefficients $\boldsymbol{\beta}^*$ in (2.34) are functions in terms of the structural parameters θ , which satisfy the nonlinear equilibrium conditions $G(\boldsymbol{\beta}^*, \theta) = \boldsymbol{\beta}^*$ and cannot be computed analytically. In order to find a BLE for a given θ , we use a simple fixed-point iteration, which is formalized below in Algorithm I.

Algorithm I: Approximation of a BLE using Iterative E-stability

Denote by θ the set of structural parameters, and by $G(\boldsymbol{\beta}^{(\boldsymbol{k})}, \theta)$ the first-order autocorrelation function for a given θ .

- Step (0): Initialize the vector of learning parameters at $\beta^{(0)}$.
- Step (I): At each iteration k, using the first-order autocorrelation functions, update the vector of learning parameters as

$$\boldsymbol{\beta}^{(\boldsymbol{k})} = G(\boldsymbol{\beta}^{(\boldsymbol{k-1})}, \theta), \qquad (2.35)$$

where $G(\beta^{(k-1)}, \theta)$ is known from iteration k-1.

• Step (II): Terminate if $||\boldsymbol{\beta}^{(k)} - \boldsymbol{\beta}^{(k-1)}||_p < \epsilon$, for a small scalar $\epsilon > 0^{13}$ and a suitable norm distance $||.||_p$, otherwise repeat Step (I).

A BLE $(\mathbf{0}, \boldsymbol{\beta}^*)$ is locally stable under (2.35) if all eigenvalues of $DG_{\boldsymbol{\beta}}(\boldsymbol{\beta}^*)$ lie inside the unit circle. Then the equilibrium is said to be *iteratively E-stable*. When Algorithm I terminates for some K at a small pre-specified ϵ , we say that it has converged to $\boldsymbol{\beta}^{(K)}$. First note that, if Algorithm I converges, it converges to an approximate BLE since

$$||\boldsymbol{\beta^{(K+1)}} - \boldsymbol{\beta^{(K)}}|| < \epsilon \Rightarrow ||\boldsymbol{G}(\boldsymbol{\beta^{(K)}}) - \boldsymbol{\beta^{(K)}}|| < \epsilon \Rightarrow \boldsymbol{G}(\boldsymbol{\beta^{(K)}}) \approx \boldsymbol{\beta^{(K)}}.$$

Further note that, there is a simple connection between iterative E-stability and E-stability of β^* : for E-stability, the real parts of all eigenvalues of $DG_{\beta}(\beta^*)$ must be less than one, while iterative E-stability requires the eigenvalues to lie inside the unit circle. This immediately implies that iterative E-stability is a stronger condition than E-stability, which gives us the following corollary:

Corollary 1 Iterative E-stability of β^* implies E-stability of β^* . Therefore if Algorithm I converges, it converges to an E-stable approximate BLE.

The iteration function in (2.35) plays an important role for the above corollary, where our choice of the function G(.) reduces Algorithm I to the simplest fixed-point iteration

¹³Throughout the remainder of this paper, we use the common L^1 -Norm as our norm distance, i.e. $||\boldsymbol{\beta}^{(k)} - \boldsymbol{\beta}^{(k-1)}||_p = \sum_{j=1}^N |\beta_j^{(k)} - \beta_j^{(k-1)}|.$

known as *iterative E-stability* in the adaptive learning literature (Evans & Honkapohja, 2001). Iterations of this type have been used as an eductive learning approach in the earlier literature, see e.g. DeCanio (1979), Bray (1982) and Evans (1985). In this paper, we use it as our approximation method, which allows us to eliminate E-unstable BLE without additional steps. As an alternative, one could also consider a Quasi-Newton iteration of the following form:

$$\boldsymbol{\beta}^{(\boldsymbol{k})} = \boldsymbol{\beta}^{(\boldsymbol{k}-1)} - DF_{\boldsymbol{\beta}}(\boldsymbol{\beta}^{(\boldsymbol{k}-1)}, \theta)^{-1}F(\boldsymbol{\beta}^{(\boldsymbol{k}-1)}, \theta), \qquad (2.36)$$

where $F(\boldsymbol{\beta}, \theta) = \boldsymbol{\beta} - G(\boldsymbol{\beta}, \theta)$ and $DF_{\boldsymbol{\beta}}(\boldsymbol{\beta}, \theta)$ denotes the Jacobian of $F(\boldsymbol{\beta}, \theta)^{14}$. This latter algorithm has been used in e.g. Farmer et. al. (2009) to compute MSV-solutions in Markov-switching models. However, a downside of the Quasi-Newton iteration in our context is that both E-stable and E-unstable BLE are locally stable under (2.36), which means that this iteration method is not informative about E-stability of BLE¹⁵. Therefore we use the notion of *iterative E-stability* in our estimations.

The discussion up to this point is based on finding E-stable BLE for a given set of structural parameters θ . In the following, we provide a straightforward extension of Algorithm I to accommodate the joint estimation of the structural parameters and the BLE parameters. In order to estimate the model, we add a set of measurement equations to the law of motion in (2.34) as follows:

$$Y_t = \psi_0(\theta) + \psi_1(\theta)S_t + h_t,$$
(2.37)

where Y_t denotes a vector of observable variables, h_t is a vector of measurement errors, $\psi_0(\theta)$ and $\psi_1(\theta)$ are matrices of the structural parameters that relate the state variables S_t to the observable variables Y_t . Together with (2.34), (2.37) yields the state-space representation of the DSGE model under BLE. The model is *linear* in the state variables S_t , but the BLE learning parameters $\boldsymbol{\beta}^*$ satisfy a nonlinear constraint in terms of the structural parameters θ to be estimated. On the one hand, whenever $\boldsymbol{\beta}$ is temporarily fixed at some $\boldsymbol{\beta}^{(k)}$ at any iteration k, the model reduces to a linear state-space model that can be estimated using standard Bayesian likelihood methods. On the other hand, given the structural parameters θ one can update the fixed value of $\boldsymbol{\beta}$ as $\boldsymbol{\beta}^{(k+1)} = G(\boldsymbol{\beta}^{(k)}, \theta)$. Based on this, we consider an iterative routine where the structural parameters θ and belief parameters $\boldsymbol{\beta}$ are updated sequentially until convergence. The estimation is summarized below in Algorithm II.

¹⁴At each iteration k, we approximate the Jacobian using $\frac{\partial F_i(\boldsymbol{\beta}^{(k)})}{\partial \beta_j^{(k)}} \approx \frac{F_i(\boldsymbol{\beta}^{(k)} + h\vec{e_j}) - F_i(\boldsymbol{\beta}^{(k)})}{h}, 1 \leq i, j \leq N,$ where $\vec{e_j}$ denotes a suitable unit vector.

¹⁵See Appendix D for a formal treatment of this and our online appendix for an example.

¹⁶For a detailed textbook derivation of the likelihood function and the posterior distribution, see e.g.

Algorithm II: Bayesian Estimation of BLE

Denote by $Y_{1:T} = \{Y_1, \dots, Y_T\}$ the matrix of the observable variables up to period T, and by $p(\theta)$ the prior distributions for the structural parameters θ that appear in matrices γ_1 , γ_2 and γ_3 . Consider the system characterized by (2.34) and (2.37):

$$\begin{cases} S_{t} = \gamma_{1}(\theta)S_{t-1} + \gamma_{2}(\theta)\boldsymbol{\beta}^{*2}S_{t-1} + \gamma_{3}(\theta)\eta_{t}, \\ \beta_{j}^{*} = G_{j}(\boldsymbol{\beta}^{*}, \theta), 1 \leq j \leq N, \\ Y_{t} = \psi_{0}(\theta) + \psi_{1}(\theta)S_{t} + h_{t}. \end{cases}$$
(2.38)

- Step (0) Initialize a set of learning parameters $\beta^{(0)}$. At the (temporarily) fixed $\beta^{(0)}$, the system (2.38) reduces to a standard state-space representation for the linearized DSGE model.
- Step (I-a) At each iteration k, one can obtain the likelihood function using the Kalman filter and the corresponding posterior distribution conditional on $\beta^{(k-1)}$ as follows¹⁶:

$$p(Y_{1:T}|\theta, \boldsymbol{\beta}^{(k-1)}) = \sum_{t=1}^{T} p(Y_t|Y_{1:T-1}, \theta, \boldsymbol{\beta}^{(k-1)}); \quad p(\theta|Y_{1:T}, \boldsymbol{\beta}^{(k-1)}) = \frac{p(Y_{1:T}|\theta, \boldsymbol{\beta}^{(k-1)})p(\theta)}{p(Y_{1:T}, \boldsymbol{\beta}^{(k-1)})},$$
(2.39)

where $\beta^{(k-1)}$ is obtained from iteration k-1, and $p(Y_{1:T}, \beta^{(k-1)})$ denotes the marginal likelihood function. Denote by $\hat{\theta}^{(k)}$ the conditional posterior mode obtained from

$$\hat{\theta}^{(k)} = \underset{\theta}{\operatorname{argmax}} p(\theta | Y_{1:T}, \boldsymbol{\beta^{(k-1)}}).$$
(2.40)

• Step (I-b) Using $\hat{\theta}^{(k)}$, update the matrix of learning parameters:

$$\boldsymbol{\beta}_{j}^{(k)} = G_{j}(\boldsymbol{\beta}^{(k-1)}, \hat{\theta}^{(k)}), 1 \le j \le N.$$
(2.41)

- Proceed to Step (II) if $||\boldsymbol{\beta}^{(k)} \boldsymbol{\beta}^{(k-1)}|| < \epsilon$ and $||\hat{\theta}^{(k)} \hat{\theta}^{(k-1)}|| < \epsilon$ for a given scalar $\epsilon > 0$, otherwise repeat Step (I).
- **Step(II)** Use the Metropolis-Hastings algorithm to construct the posterior distribution *conditional on the BLE* at the posterior mode.

A BLE $(\mathbf{0}, \boldsymbol{\beta^*})$ obtained from Algorithm II, satisfying $G(\boldsymbol{\beta^*}, \theta^*) = \boldsymbol{\beta^*}$ and $\theta^* = \underset{\theta}{\operatorname{argmax}} p(\theta|Y_{1:T}, \boldsymbol{\beta^*})$, is stable under learning if all eigenvalues of $DG(\boldsymbol{\beta^*}, \theta^*)$ lie inside the unit circle^{17,18}.

The estimation routine described above corresponds to a straightforward extension of Algorithm I, where we allow the structural parameters θ (and therefore the matrices γ_1, γ_2 and γ_3) to be re-estimated at each step of the fixed-point iteration in (2.35). Our approach is similar to e.g. the computation of initial beliefs in Slobodyan & Wouters (2012), where the belief coefficients in β are treated as additional structural parameters and estimated along with θ . The main difference here is that we compute the equilibrium beliefs consistent with the underlying BLE, such that the first-order autocorrelations in the PLM coincide with the ALM at the estimated posterior mode. In other words, the belief parameters are consistent with the actual realizations. Our estimation approach is fast and easy to implement, because it allows us to approximate and estimate a BLE at the posterior mode through a sequence of linear models. Since the beliefs in $\boldsymbol{\beta}^{(k)}$ are updated at each step k based on the first-order autocorrelations of the state variables, the estimated parameters $\hat{\theta}^{(k)}$ tend to lead $\boldsymbol{\beta}^{(k)}$ towards the empirically relevant region. In turn, this allows the system to rapidly converge to the underlying BLE as we illustrate in the next section. Once we find a BLE along with estimated structural parameters under Algorithm II, we check for iterative E-stability and multiplicity of stable equilibria using Algorithm I with θ^* and randomized initial values. We further provide Monte Carlo simulations under (2.8) to examine the behaviour of the system under SAC-learning.

As an alternative to this algorithm that directly estimates a BLE, we also consider an estimation routine with SAC-learning based on the Kalman filter output. Since iterative E-stability guarantees convergence under SAC-learning, allowing the agents to learn simultaneously with the Kalman filter recursions serves as an indirect approach to estimate a BLE, as well as a robustness check for the empirical fit of a BLE. The model under SAC-learning is conditionally linear for a given set of belief coefficients and therefore one can use the standard Kalman filter to obtain the likelihood function, where the beliefs are updated in each step using the Kalman filter output. Similar approaches have been used in estimating constant gain least squares and Kalman gain adaptive learning models in Milani (2005, 2007) and Slobodyan & Wouters (2012) respectively. In this paper we

Greenberg (2012) or Herbst & Schorfheide (2015). In this paper, we make use of the routines available in Dynare to estimate the model at each step for a given set of fixed learning parameters.

¹⁷In order to formally rule out explosive outcomes, one can augment the algorithm with a projection facility, where the next iteration is projected to a point inside the unit cube if the iteration $G(\boldsymbol{\beta}^{k-1})$ leads to $|\beta_i^{(k)}| > 1$ for some $1 \le i \le N$. We do not observe explosive outcomes in the NK model considered in this paper and therefore do not use a projection facility.

¹⁸The eigenvalue condition for Algorithm II with (2.40) and (2.41) is different from the eigenvalue condition for Algorithm I with (2.35), since the second argument θ^* of $G(\beta^*, \theta^*)$ also depends on β^* ; see Appendix D for more details.

focus on the decreasing-gain SAC-learning algorithm since our primary interest is the estimation of the underlying fixed-point BLE, rather than the time-variation in beliefs. See Appendix D for a more detailed description of this approach with SAC-learning.

3 Application: a New Keynesian model

3.1 A baseline model

In this section we apply our results within the framework of a standard New Keynesian model along the lines of Woodford (2003) and Galí (2008). Consider a simple version, linearized around the zero inflation steady state, given by

$$\begin{cases} y_t = y_{t+1}^e - \varphi(r_t - \pi_{t+1}^e) + u_{y,t}, \\ \pi_t = \lambda \pi_{t+1}^e + \gamma y_t + u_{\pi,t}, \end{cases}$$
(3.1)

where y_t is the output gap, π_t is the inflation rate, y_{t+1}^e and π_{t+1}^e are expected output gap and expected inflation.

Following Bullard and Mitra (2002) and Bullard et al. (2008) we study the NK-model (3.1) with adaptive learning. The terms $u_{y,t}$, $u_{\pi,t}$ are stochastic shocks and are assumed to follow AR(1) processes

$$u_{y,t} = \rho_y u_{y,t-1} + \varepsilon_{y,t}, \qquad (3.2)$$

$$u_{\pi,t} = \rho_{\pi} u_{\pi,t-1} + \varepsilon_{\pi,t}, \qquad (3.3)$$

where $\rho_i \in [0, 1)$ and $\{\varepsilon_{i,t}\}$ $(i = y, \pi)$ are two uncorrelated i.i.d. stochastic processes with zero mean and finite absolute moments with corresponding variances σ_i^2 .

The first equation in (3.1) is an IS curve that describes the demand side of the economy. In an economy of rational or boundedly rational agents, it is a linear approximation to a representative agent's Euler equation. The parameter $\varphi > 0$ is related to the elasticity of intertemporal substitution in consumption of a representative household, and its inverse can be interpreted as a risk aversion coefficient. The second equation in (3.1) is the New Keynesian Phillips curve which describes the aggregate supply relation. This is obtained by averaging all firms' pricing decisions. The parameter γ is related to the degree of price stickiness in the economy and the parameter $\lambda \in [0, 1)$ is the discount factor of a representative household.

We supplement the equations in (3.1) with a standard Taylor-type policy rule, which represents the behavior of the monetary authority in setting the nominal interest rate:

$$r_t = \phi_\pi \pi_t + \phi_y y_t, \tag{3.4}$$

where r_t is the deviation of the nominal interest rate from the value that is consistent with inflation at target and output at potential. The parameters ϕ_{π}, ϕ_{y} , measuring the response of r_t to the deviation of inflation and output from long run steady states, are assumed to be non-negative¹⁹.

Substituting the Taylor-type policy rule (3.4) into (3.1) and writing the model in matrix form gives

$$\begin{cases} \boldsymbol{x}_{t} = \boldsymbol{B}\boldsymbol{x}_{t+1}^{e} + \boldsymbol{C}\boldsymbol{u}_{t}, \\ \boldsymbol{u}_{t} = \boldsymbol{\rho}\boldsymbol{u}_{t-1} + \boldsymbol{\varepsilon}_{t}, \end{cases}$$
(3.5)

where
$$\boldsymbol{x}_t = [y_t, \pi_t]', \boldsymbol{u}_t = [u_{y,t}, u_{\pi,t}]', \boldsymbol{\varepsilon}_t = [\varepsilon_{y,t}, \varepsilon_{\pi,t}]', \boldsymbol{B} = \frac{1}{1 + \gamma \varphi \phi_{\pi} + \varphi \phi_y} \begin{bmatrix} 1 & \varphi(1 - \lambda \phi_{\pi}) \\ \gamma & \gamma \varphi + \lambda(1 + \varphi \phi_y) \end{bmatrix},$$

$$\boldsymbol{C} = \frac{1}{1 + \gamma \varphi \phi_{\pi} + \varphi \phi_y} \begin{bmatrix} 1 & -\varphi \phi_{\pi} \\ \gamma & 1 + \varphi \phi_y \end{bmatrix}, \boldsymbol{\rho} = \begin{bmatrix} \rho_y & 0 \\ 0 & \rho_{\pi} \end{bmatrix}.$$

Before turning to BLE, we first consider the Rational Expectations Equilibrium.

3.2 Theoretical results

Comparing the NK model (3.5) with the general framework (2.10), we note that $\boldsymbol{a} = \boldsymbol{0}$, $\boldsymbol{b}_0 = \boldsymbol{0}$ and $\boldsymbol{b}_2 = \boldsymbol{0}$. The Rational Expectation Equilibrium (REE) fixed point in (2.15-2.18) then simplifies to

$$(\boldsymbol{I} - \boldsymbol{B})\boldsymbol{\xi} = \boldsymbol{0} \tag{3.6}$$

$$\boldsymbol{\eta} = \mathbf{B}\boldsymbol{\eta}\boldsymbol{\rho} + \mathbf{C}. \tag{3.7}$$

Bullard and Mitra (2002) show that the REE is unique (determinate) if and only if $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$. The REE is then the stable stationary process with mean

$$\overline{\mathbf{x}^*} = \mathbf{0}.\tag{3.8}$$

In the symmetric case $\rho_i = \rho$ for $i = \{y, \pi\}$, the REE \mathbf{x}_t^* satisfies

$$\mathbf{x}_t^* = (\mathbf{I} - \rho \mathbf{B})^{-1} \mathbf{C} \mathbf{u}_t.$$
(3.9)

Thus its covariance is

$$\boldsymbol{\Sigma}_{\mathbf{x}^*} = \mathbf{E}(\mathbf{x}_{\mathbf{t}}^* - \overline{\mathbf{x}^*})(\mathbf{x}_{\mathbf{t}}^* - \overline{\mathbf{x}^*})' = (1 - \rho^2)^{-1}(\mathbf{I} - \rho\mathbf{B})^{-1}\mathbf{C}\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}[(\mathbf{I} - \rho\mathbf{B})^{-1}\mathbf{C}]'. \quad (3.10)$$

Furthermore, the first-order autocorrelation of the *i*-element x_i of **x** is equal to ρ . That

¹⁹In our online appendix we also discuss *lagged* and *forward-looking* Taylor rules, responding to lagged and expected future values of y_t and π_t respectively.

is, in this case the persistence of the REE coincides exactly with the persistence of the exogenous driving force \mathbf{u}_t and the first-order autocorrelations of output gap and inflation are the same, i.e. symmetric, equal to the autocorrelation in the driving force. Under RE, inflation and output gap only inherit the persistence of the shocks.

Behavioral learning equilibria

Bullard and Mitra (2002) study adaptive learning in this NK setting. They consider a PLM which coincides with the minimum state variable solution (MSV) of the form

$$\boldsymbol{x}_t = \widetilde{\boldsymbol{D}} + \widetilde{\boldsymbol{E}} \boldsymbol{x}_{t+1}^e + \widetilde{\boldsymbol{F}} \boldsymbol{u}_t, \qquad (3.11)$$

where \tilde{D} , \tilde{E} and \tilde{F} are conformable matrices. We will consider learning with misspecification. As in the general setup in Section 2, we assume that agents are boundedly rational and use simple univariate linear rules to forecast the output gap y_t and inflation π_t of the economy. Therefore we deviate from Bullard and Mitra (2002) in two important ways: (i) our agents cannot observe or do not use the exogenous shocks u_t , and (ii) agents do not fully understand the linear stochastic structure and do not take into account the cross-correlation between inflation and output. Rather our agents learn simple univariate AR(1) forecasting rules for inflation and output gap, as in (2.2). However these AR(1) rules indirectly, in a boundedly rational way, take exogenous shocks and cross-correlations of endogenous variables into account as agents learn the two parameters of each AR(1) rule consistent with the observable sample averages and first-order autocorrelations of the state variables inflation and output gap. The use of simple AR(1) rule is supported by evidence from the learning-to-forecast laboratory experiments in the NK framework in Adam (2007), Assenza et al. (2014) and Pfajfar and Zakelj (2016).

The actual law of motion (3.5) becomes

$$\begin{cases} \boldsymbol{x}_t = \boldsymbol{B}[\boldsymbol{\alpha} + \boldsymbol{\beta}^2(\boldsymbol{x}_{t-1} - \boldsymbol{\alpha})] + \boldsymbol{C}\boldsymbol{u}_t, \\ \boldsymbol{u}_t = \boldsymbol{\rho}\boldsymbol{u}_{t-1} + \boldsymbol{\varepsilon}_t. \end{cases}$$
(3.12)

For the actual law of motion (ALM) (3.12), the REE determinacy condition $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$ implies that the ALM is stationary for all β , see Appendix E. Thus the means and first-order autocorrelations are

$$\overline{\boldsymbol{x}} = (\boldsymbol{I} - \boldsymbol{B}\boldsymbol{\beta}^2)^{-1}(\boldsymbol{B}\boldsymbol{\alpha} - \boldsymbol{B}\boldsymbol{\beta}^2\boldsymbol{\alpha}),$$

$$\boldsymbol{G}(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \begin{bmatrix} G_1(\beta_y, \beta_\pi) & 0\\ 0 & G_2(\beta_y, \beta_\pi) \end{bmatrix} = \begin{bmatrix} \operatorname{corr}(y_t, y_{t-1}) & 0\\ 0 & \operatorname{corr}(\pi_t, \pi_{t-1})) \end{bmatrix}.$$

In order to obtain analytical expressions for $G_1(\beta_y, \beta_\pi)$ and $G_2(\beta_y, \beta_\pi)$ we focus on the symmetric case with $\rho_y = \rho_\pi = \rho$. The first-order autocorrelations of output gap and inflation can be expressed in terms of the structural parameters through complicated calculations (see Appendix F²⁰)

$$G_1(\beta_y, \beta_\pi) = \frac{\widetilde{f}_1}{\widetilde{g}_1} \tag{3.13}$$

$$G_2(\beta_y, \beta_\pi) = \frac{\widetilde{f}_2}{\widetilde{g}_2} \tag{3.14}$$

where

$$\begin{split} \widetilde{f}_{1} &= \sigma_{\pi}^{2} \Big\{ (\rho + \lambda_{1} + \lambda_{2} - \lambda\beta_{\pi}^{2}) [1 - \lambda\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2})] + [\lambda\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \rho\lambda_{1}\lambda_{2}] \Big\} + \sigma_{y}^{2} \Big\{ (\varphi\phi_{\pi}(\rho + \lambda_{1} + \lambda_{2}) - \varphi\beta_{\pi}^{2})) \\ & [\varphi\phi_{\pi} - \varphi\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2})] + [\varphi\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \varphi\phi_{\pi}\rho\lambda_{1}\lambda_{2}] \\ & [\varphi\phi_{\pi}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \varphi\beta_{\pi}^{2}\rho\lambda_{1}\lambda_{2}] \Big\}, \\ \widetilde{g}_{1} &= \sigma_{\pi}^{2} \Big\{ [(1 + \lambda^{2}\beta_{\pi}^{4}) - 2\lambda\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2}) + (1 + \lambda^{2}\beta_{\pi}^{4})(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})] \\ & -\rho\lambda_{1}\lambda_{2}[(1 + \lambda^{2}\beta_{\pi}^{4})(\rho + \lambda_{1} + \lambda_{2}) - 2\lambda\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) + (1 + \lambda^{2}\beta_{\pi}^{4})\rho\lambda_{1}\lambda_{2}] \Big\} \\ & + \sigma_{\pi}^{2} \Big\{ [((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4}) - 2\varphi\phi_{\pi}\varphi\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2}) + ((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4})(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})] \\ & -\rho\lambda_{1}\lambda_{2}[((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4})(\rho + \lambda_{1} + \lambda_{2}) - 2\varphi\phi_{\pi}\varphi\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})] \Big\} \end{split}$$

$$+((\varphi\phi_{\pi})^{2}+\varphi^{2}\beta_{\pi}^{4})\rho\lambda_{1}\lambda_{2}]\Big\},$$
(3.15)

$$\begin{split} \widetilde{f}_{2} &= \sigma_{y}^{2} \Big\{ \gamma^{2} [(\rho + \lambda_{1} + \lambda_{2}) - \rho \lambda_{1} \lambda_{2} (\rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2})] \Big\} + \sigma_{\pi}^{2} \Big\{ [(1 + \varphi \phi_{y})(\rho + \lambda_{1} + \lambda_{2}) - \beta_{y}^{2}] \cdot \\ &[(1 + \varphi \phi_{y}) - \beta_{y}^{2}(\rho + \lambda_{1} + \lambda_{2})] + [\beta_{y}^{2}(\rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2}) - (1 + \varphi \phi_{y})\rho \lambda_{1} \lambda_{2}] \cdot \\ &[(1 + \varphi \phi_{y})(\rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2}) - \beta_{y}^{2}\rho \lambda_{1} \lambda_{2}] \Big\}, \\ \widetilde{g}_{2} &= \sigma_{y}^{2} \Big\{ \gamma^{2} [1 + \rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2} - \rho \lambda_{1} \lambda_{2} (\rho + \lambda_{1} + \lambda_{2}) - (\rho \lambda_{1} \lambda_{2})^{2}] \Big\} \\ &+ \sigma_{\pi}^{2} \Big\{ [((1 + \varphi \phi_{y})^{2} + \beta_{y}^{4}) - 2(1 + \varphi \phi_{y})\beta_{y}^{2}(\rho + \lambda_{1} + \lambda_{2}) + ((1 + \varphi \phi_{y})^{2} + \beta_{y}^{4}) \\ &(\rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2})] - \rho \lambda_{1} \lambda_{2} [((1 + \varphi \phi_{y})^{2} + \beta_{y}^{4})(\rho + \lambda_{1} + \lambda_{2}) - 2(1 + \varphi \phi_{y})\beta_{y}^{2} \cdot \\ &(\rho \lambda_{1} + \rho \lambda_{2} + \lambda_{1} \lambda_{2}) + ((1 + \varphi \phi_{y})^{2} + \beta_{y}^{4})\rho \lambda_{1} \lambda_{2}] \Big\}, \end{split}$$

$$(3.16)$$

²⁰Appendix F employs the VARMA(1, ∞) representation of the model. Although it is possible to obtain the expressions of $G(\alpha, \beta)$ using the direct method in Appendix B, the analytical expressions are much more complicated. Numerical computations based on the two methods are consistent and also coincide with the simple numerical simulation of the first-order autocorrelation coefficients of output gap and inflation obtained from simulated time series generated by the system (3.12), confirming the complicated expressions (3.13-3.18).

$$\lambda_1 + \lambda_2 = \frac{\beta_y^2 + (\gamma \varphi + \lambda + \lambda \varphi \phi_y) \beta_\pi^2}{1 + \gamma \varphi \phi_\pi + \varphi \phi_y}, \qquad (3.17)$$

$$\lambda_1 \lambda_2 = \frac{\lambda \beta_y^2 \beta_\pi^2}{1 + \gamma \varphi \phi_\pi + \varphi \phi_y}.$$
(3.18)

From these expressions, it is easy to see that $G_1(\beta_y, \beta_\pi)$ and $G_2(\beta_y, \beta_\pi)$ are analytic functions with respect to β_y and β_π , *independent* of $\boldsymbol{\alpha}$.

The actual law of motion (3.5) depends on eight parameters φ , λ , γ , ϕ_y , ϕ_{π} , ρ , σ_{π}^2 and σ_y^2 . Only the ratio $\sigma_{\pi}^2/\sigma_y^2$ of noise terms matters for the persistence $G_i(\beta_y, \beta_{\pi})$ in (3.13) and (3.14). Hence, the existence of BLE ($\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*$) depends on seven structural parameters φ , λ , γ , ρ , ϕ_y , ϕ_{π} and $\sigma_{\pi}^2/\sigma_y^2$ of the NK-model.

Using Proposition 1 and Proposition 2 we have the following properties for the New Keynesian model:

Corollary 2 Under the Taylor rule (3.4), if $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$, then there exists at least one BLE $(\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$, where $\boldsymbol{\alpha}^* = \mathbf{0} = \overline{\boldsymbol{x}^*}$.

Corollary 3 Under the Taylor rule (3.4) and the condition $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_{y} > 0$, a BLE $(\boldsymbol{\alpha}^{*}, \boldsymbol{\beta}^{*})$ is locally stable under SAC-learning if all eigenvalues of $DG_{\boldsymbol{\beta}}(\boldsymbol{\beta}^{*}) = \left(\frac{\partial G_{i}}{\partial \beta_{j}}\right)_{\boldsymbol{\beta}=\boldsymbol{\beta}^{*}}$ have real parts less than 1.

Proof. See Appendix G.

It is useful to discuss the special case in which shocks are not persistent, that is, $\rho = 0$ (no autocorrelation in the shocks). It is easy to see that

$$G_1(0,0)\big|_{\rho=0} = 0, \qquad G_2(0,0)\big|_{\rho=0} = 0.$$

That is to say (0,0) is a BLE for $\rho = 0$. Hence, when there is no persistence in the exogenous shocks, the BLE coincides with the rational expectation equilibrium.

It is also useful to briefly discuss the non-stationary case, that is, when the coefficient matrix **B** for expectations \boldsymbol{x}_{t+1}^e in (3.5) has at least one eigenvalue outside the unit circle²¹. In that case, SAC-learning of an AR(1) rule typically leads to explosive dynamics with $\alpha_t \to \pm \infty$ and $\beta_t \to 1$. In the non-stationary case, learning of BLE thus typically leads to explosive time paths of inflation and output.

Persistence amplification

To illustrate the typical output-inflation dynamics under BLE, we present a calibration exercise for empirically plausible parameter values.

²¹This case may only occur if the condition $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$ is violated.

As in the Clarida et al. (1999) calibration we fix $\varphi = 1, \lambda = 0.99$. We fix $\gamma = 0.04$, which lies between the calibrations $\gamma = 0.3$ in Clarida et al. (1999) and $\gamma = 0.024$ in Woodford (2003). For the exogenous shocks, we set the ratio of shocks $\frac{\sigma_{\pi}}{\sigma_y} = 0.5$, which is within the possible range suggested in Fuhrer (2006). We consider the symmetric case $\rho_y = \rho_{\pi} = \rho = 0.5$, with weak persistence in the shocks. The baseline parameters on the policy response to inflation deviation and output gap follow a broad literature, $\phi_{\pi} = 1.5, \phi_y = 0.5$, see for example Fuhrer (2006, 2009). At these parameter values, the two eigenvalues of the Jacobian matrix $DG_{\beta}(\beta^*)$ are $0.5012 \pm 0.7348i$ (with real parts less than 1), which implies that the BLE is E-stable under SAC-learning based on our theoretical results. The numerical results shown below are robust across a range of plausible parameter values.

Figure 1 illustrates the existence of a unique E-stable BLE $(\beta_y^*, \beta_\pi^*) = (0.9, 0.9592)^{22}$. In order to obtain (β_y^*, β_π^*) , we numerically compute the corresponding fixed point $\beta_\pi^*(\beta_y)$ satisfying $G_2(\beta_y, \beta_\pi^*) = \beta_\pi^*$ for each β_y and the corresponding fixed point $\beta_y^*(\beta_\pi)$ satisfying $G_1(\beta_y^*, \beta_\pi) = \beta_y^*$ for each β_π as illustrated in Figure 1. Hence their intersection point (β_y^*, β_π^*) satisfies $G_1(\beta_y^*, \beta_\pi^*) = \beta_y^*$ and $G_2(\beta_y^*, \beta_\pi^*) = \beta_\pi^*$.

A striking and typical feature of the BLE is that the first-order autocorrelation coefficients of output gap and inflation $(\beta_y^*, \beta_\pi^*) = (0.9, 0.9592)$ are substantially higher than those at the REE, that is, the persistence is much higher than the persistence $\rho(=0.5)$ of the exogenous shocks. We refer to this phenomenon as *persistence amplification*. Agents fail to recognize the exact linear structure and cross-correlations of the economy, but rather learn to coordinate on simple univariate AR(1) rules consistent with simple observable statistics, the mean and the first-order autocorrelations of inflation and output gap. As a result of this *self-fulfilling mistake*, shocks to the economy are strongly amplified.

Figure 2 illustrates how these results depend on the persistence ρ of the exogenous shocks. The figure shows the BLE, i.e. the first-order autocorrelations β_y^* of output gap and β_{π}^* of inflation, as a function of the parameter ρ . This figure clearly shows the *persistence amplification* along BLE, with much higher persistence than under RE, for all values of $0 < \rho < 1$. Especially for $\rho \ge 0.5$ we have $\beta_y^*, \beta_{\pi}^* \ge 0.9$, implying that output gap and inflation have significantly higher persistence than the exogenous driving forces. Figure 2 (right plot) also illustrates the *volatility amplification* under BLE compared to REE. For output gap the ratio of variances $\sigma_y^2/\sigma_{y^*}^2$ reaches a peak of about 2.5 for $\rho \approx 0.75$, while for inflation the ratio of variances $\sigma_{\pi}^2/\sigma_{\pi^*}^2$ reaches its peak of about 3.5 for $\rho \approx 0.65$. These results suggest that, given the same parameter values, the moments of inflation and output gap implied by BLE and REE are substantially different due to persistence and volatility amplification under BLE. Therefore if the model is estimated on the same dataset under BLE and REE, one might expect important differences in the resulting

²²Note that $(\alpha_y^*, \alpha_\pi^*) = (0, 0).$



Figure 1: A unique BLE $(\beta_y^*, \beta_\pi^*) = (0.9, 0.9592)$ obtained as the intersection point of the fixed point curves $\beta_\pi^*(\beta_y)$ and $\beta_y^*(\beta_\pi)$. The BLE exhibits strong persistence amplification compared to REE (red dot, with $\rho = 0.5$). Parameters are: $\lambda = 0.99, \varphi = 1, \gamma = 0.04, \rho = 0.5, \phi_\pi = 1.5, \phi_y = 0.5, \frac{\sigma_\pi}{\sigma_y} = 0.5$.



Figure 2: BLE (β_y^*, β_π^*) as a function of the persistence ρ of the exogenous shocks. (a) $\beta_i^*(i = 1, 2)$ with respect to ρ ; (b) the ratio of variances $(\sigma_y^2/\sigma_{y^*}^2, \sigma_\pi^2/\sigma_{\pi^*}^2)$ of the BLE (β_y^*, β_π^*) w.r.t. the REE. Parameters are: $\lambda = 0.99, \varphi = 1, \gamma = 0.04, \phi_\pi = 1.5, \phi_y = 0.5, \frac{\sigma_\pi}{\sigma_y} = 0.5.$

parameter estimates and the resulting shock propagation mechanism of the model. We explore this implication in the next section by estimating the NK-model under BLE and REE based on U.S. data.

3.3 Estimation of the New Keynesian Model

Sample Period and Prior Distributions

In this section, we compare the empirical fit of the 3-equation New Keynesian model under REE, BLE and SAC-learning²³. We augment the Taylor rule with an i.i.d monetary policy shock and an interest rate smoothing parameter to allow the model to match the inertia of the historical interest rate:

$$r_t = \rho_r r_{t-1} + (1 - \rho_r)(\phi_\pi \pi_t + \phi_x y_t) + \epsilon_{r,t}.$$
(3.19)

We estimate the small-scale system of (3.1) and (3.19) for the U.S economy over the period 1966:I-2016:IV using quarterly macroeconomic data. We also investigate whether our results are sensitive to structural breaks such as the large volatility reduction for most macroeconomic time series during the mid-80s, often referred to as the Great Moderation, or the near-zero level of nominal interest rates that followed the 2007-08 crisis period.

We use the following measurement equations for output gap, inflation and interest rate²⁴ without measurement errors:

$$\begin{cases} log(y_t^{obs}) = \bar{\gamma} + y_t \\ log(\pi_t^{obs}) = \bar{\pi} + \pi_t \\ log(r_t^{obs}) = \bar{r} + r_t, \end{cases}$$
(3.20)

where y_t^{obs} , π_t^{obs} and r_t^{obs} denote the quarterly historical output gap, inflation and interest rate, while $\bar{\gamma}, \bar{\pi}$ and \bar{r} correspond to the historical mean of each time series respectively. We use the cycle component of HP-filtered output as our primary measure of output gap, and we also present our results with an output gap based on CBO's measure of the potential output level. A third alternative measure based on de-trended output can be found in Appendix H. The results are qualitatively similar across all measures, although some parameters such as the slope of the Phillips curve γ are sensitive to which measure is used.

 $^{^{23}}$ We only present the estimation results for the baseline model here, but similar results hold in more realistic setups. In particular, our Online Appendix considers a hybrid version of the New Keynesian model with lagged inflation and output gap, and our follow-up paper Hommes et. al. (2019) considers the medium-scale Smets-Wouters (2007) model under BLE.

²⁴See Appendix I for more details on the observable variables.

The model is estimated using the same prior distributions under all specifications, which guarantees that any differences that arise between the estimations is due to the difference in the expectation formation rule. The prior distributions are kept close to those commonly assumed in the literature. Following An & Schorfheide (2007), the risk aversion coefficient $\tau = \frac{1}{\varphi}$ is assigned a gamma distribution centered at 2 with a standard deviation of 0.5. The slope of the Phillips curve γ is assigned a Beta distribution with mean 0.3 and standard deviation 0.15 which falls between the prior in An & Schorfheide (2007) and Smets & Wouters (2007), covering both flat and steep cases for the Phillips curve²⁵. The policy response parameters for output gap ϕ_y and inflation ϕ_{π} are assigned beta distributions centered around 0.5 and 1.5, which are standard values associated with the Taylor rule in the literature. The autocorrelation coefficients have a Beta distribution centered at 0.5, and the standard deviations for the shock processes are assumed to follow an Inverted Gamma distribution with a mean of 0.1 and standard deviation of 2, same as in Smets & Wouters (2007). The priors for the historical mean of inflation rate, output growth and interest rate are normal distributions centered at their pre-sample means of 0.47, -0.2 and 0.72 respectively, where the pre-sample period covers data from 1954: I to 1965: IV. Finally, we fix the HH discount rate λ at 0.99, which is a standard assumption in most empirical studies.

Convergence Diagnostics

Before moving onto the posterior estimation results, it is useful to briefly discuss the convergence diagnostics of BLE and SAC-learning models. Our discussion here is based on the results with the HP-filtered measure of output gap, but similar results follow under the two alternative measures. Under BLE, initializing both β_y and β_{π} at fairly low values of 0.5 and using a convergence criterion $\epsilon = 10^{-5}$, our estimation algorithm takes only 5 steps to converge²⁶. The resulting BLE is $(\beta_u^*, \beta_\pi^*) = (0.88, 0.89)$ at the final step. This is fairly close to the first-order autocorrelations of the data over this period, given as (0.87, 0.89). The left panel of Figure 3 shows the norm distances between two consecutive sets of $\boldsymbol{\beta}^{(k)}$ and $\theta^{(k)}$ at each step k, both of which rapidly converge towards 0. The largest eigenvalue of the Jacobian matrix $DG(\boldsymbol{\beta}^{(k)}, \theta^{(k)})$ remains strictly inside the unit circle during the estimation, and stabilizes after the second step. The right panel of the same figure shows the convergence of Algorithm I towards β^* at the estimated posterior mode with randomized initial values, suggesting that the estimated equilibrium is the unique iteratively E-stable BLE. Similar results emerge when we examine the Monte

²⁵In particular if we denote the nominal price stickiness as ω , its relation with γ is given as $\gamma =$ $\frac{(1-\lambda\omega)(1-\omega)}{\omega}$ (Gali, 2008). Smets & Wouters (2007) assume a prior for ω with mean 0.5. ¹ The results are robust to initial values of β_y and β_{π} .

Carlo simulations of the model under SAC-learning in Figure 4: the left panel shows the histograms of β_y and β_{π} over 1000 simulations, each of length 5000, under decreasing gain learning, while the right panel shows the constant gain equivalent with a small gain value of 0.001. It is readily seen that none of the distributions show signs of multiple equilibria²⁷. To formally check this, we provide the approximate distributions of β_y and β_{π} by smoothing the histograms and applying Hartigan's Dip Test of Unimodality²⁸. The dip test does not reject the null hypothesis of unimodality, suggesting that there is no evidence of multiple BLE at the estimated structural parameter values based on the simulations. We also observe a small bias in the simulations for both cases, where the peak of the distributions slightly deviates from the underlying BLE denoted by the dotted line. These Monte Carlo simulations illustrate the advantage of SAC-learning over the standard recursive least squares learning approach: although the autocorrelation coefficients are fairly close to unity for both y_t and π_t , the time series never become explosive in our simulations. This is due to the natural projection facility of SAC-learning with autocorrelations always satisfying $-1 \leq \beta \leq 1$, which makes explosive time paths less likely as discussed in Section 2.

Figure 5 shows the mean and persistence coefficients along with the filtered variables of inflation and output gap under the SAC-learning estimation. For this specification, following the recommendation in Galimberti & Jacqueson (2017), we use a training-sample based initialization as follows: we use the unconditional moment of 0 for the intercept coefficients, and the diffuse moment 0 for the estimated variance of each variable R_t^{29} . We use five years over 1961:I-1965:IV as the transient period for the belief coefficients, and compute the likelihood from 1966:I onwards. It is readily seen that the mean coefficients do not substantially deviate from the unconditional mean of 0 and the persistence coefficients indeed converge over the estimation sample, with final values of $\beta^* = (0.86, 0.89)$: this is fairly close to the equilibrium resulting under the BLE estimation.

We observe similar convergence patterns and a unique equilibrium at the posterior mode in our estimations with the CBO-based output gap measure. However, under this alternative measure, we can find regions with multiple stable equilibria in a close neighbourhood of estimated monetary policy and some of the structural parameters. A more detailed discussion of this phenomenon is left to Section 4.

 $^{^{27}\}alpha_{y}$ and α_{π} have similar distributions centered around 0; they are omitted here for brevity.

 $^{^{28}}$ Hartigan's Dip Test is based on checking for multimodality by using the maximum difference between the empirical distribution, and the theoretical unimodal distribution function that minimizes the maximum difference. The null hypothesis of the test is unimodality, see Hartigan & Hartigan (1985) for more details.

²⁹The initial choice of first-order autocorrelations does not matter since $\beta_{1,t} = -\frac{1}{2}$ regardless of $\beta_{0,t}$.



Figure 3: The estimated BLE is $(\beta_y^*, \beta_\pi^*) = (0.88, 0.89)$. The left panel shows the largest eigenvalue, and the norm distances between consecutive values of $\boldsymbol{\beta}^{(k)}$, as well as $\theta^{(k)}$ across iterations. The second panel shows convergence towards the unique (iteratively) E-stable BLE (β_y^*, β_π^*) with randomized initial values.



Figure 4: Monte Carlo Simulations: frequency distributions and unimodality test for β_y and β_{π} resulting from 1000 simulations. Each simulation is of length 5000, initialized at random values over the interval (0, 1). Hartigan's unimodality test p-values are 0.98 and 0.94 for β_y and β_{π} under constant gain simulations, and 0.99 and 0.99 for the decreasing gain simulations. Hence the null hypothesis of unimodality is not rejected for any of the distributions.



Figure 5: Filtered variables and learning parameters over the estimation sample under SAC-learning, where Kalman filter output is used to update the belief coefficients. Converged values of first-order autocorrelations are 0.86 and 0.89 for output gap and inflation respectively.

Posterior Results: HP-filtered Output Gap

Table 2 presents the posterior estimation results for the REE, BLE and SAC-learning models.³⁰, where we use the cycle component of the HP-filtered historical output as our measure of output gap. Starting with a comparison of the BLE and REE results, we observe several important differences in the estimates of structural parameters: both persistence parameters for the inflation and output shocks, ρ_{π} and ρ_{y} , are substantially lower under BLE, namely with 0.31 and 0.42 respectively, while they are 0.88 and 0.87 under REE. This is a direct consequence of the difference in the expectation formation rule. As such, the estimation results confirm the *persistence amplification* property of BLE: the backward-looking expectation formation rule endogenously generates additional inertia for inflation and output gap, which in turn leads to much smaller persistence in the exogenous shocks. The low autocorrelations in u_{π} and u_{y} under BLE immediately imply higher estimated standard deviations for the i.i.d shocks of these AR(1) processes at 0.29 and 0.73, while these are 0.04 and 0.16 under REE³¹. Since interest-rate is not

 $^{^{30}}$ BLE and REE models are estimated using the Dynare toolbox (Adjemian et. al, 2011), while our own toolbox is used for the SAC-learning estimations since it requires an additional learning step in the filter recursions. The posterior distributions are constructed using the Metropolis-Hastings algorithm with 250000 draws, using the first 50000 as the burn-in sample. The step size for the scale parameter of the jumping distribution's covariance matrix is adjusted in both models to obtain a rejection rate of 70% in both models, which is in the commonly assumed appropriate range for the MH algorithm.

³¹Note that for an AR(1) process $x_t = \rho_x x_{t-1} + u_t, u_t \sim iid(0, \sigma_u)$, the unconditional variance is given by $var(x) = \frac{\sigma_u}{1-\rho_z^2}$. This implies, as ρ_x increases, var(x) also increases.

forward-looking, this result does not extend to the interest-rate smoothing ρ_r , which is estimated at 0.85 and 0.80 under BLE and REE respectively, while the volatility of monetary policy shocks is the same at 0.29 under both specifications. The historical mean parameters turn out fairly similar under both estimations, since they relate to sample means of the observable variables and are not affected by the expectation rule. The estimates of monetary policy parameters, ϕ_{π} and ϕ_{y} , also turn out similar under both estimations, with 1.36 and 0.48 under BLE, and 1.39 and 0.46 under REE. Finally turning to the two structural parameters that determine the contemporaneous relation between the state variables, both the risk aversion coefficient $\frac{1}{\alpha}$ and the slope of the NKPC γ are fairly different: these are estimated at 3.02 and 0.035 under BLE, while they are 4.27 and 0.007 under REE respectively. These differences arise due to altered cross-restrictions under learning: the additional inertia that we introduce under BLE comes at the cost of a weaker contemporaneous relation between the state variables and shocks. While the state variables are only related to the shocks through $\frac{1}{\varphi}$ and γ under BLE, they are also indirectly related through expectations under REE. As a result, the risk aversion coefficient turns out lower under learning, implying a larger direct impact from the ex-ante risk premium on output gap under BLE. Similarly, γ turns out higher under BLE, implying a stronger direct effect from output gap on inflation. It is also interesting to note that confidence intervals for γ are almost mutually exclusive under these two specifications, with a lower bound of 0.015 under BLE and an upper bound of 0.017 under REE^{32} .

An important consequence of a higher Phillips curve slope and a lower risk aversion coefficient under BLE is on the shock propagation: Figure 6 shows the impulse responses of output gap and inflation to a monetary policy shock under BLE and REE at the posterior mode³³. The cumulative impact of the shock is larger under BLE, particularly for inflation, but the initial impact is larger under REE since the shock affects current output gap and inflation contemporaneously through expectations. Under BLE, the shock takes several quarters to reach its full impact, leading to hump-shaped responses for both inflation and output gap. The hump-shaped pattern is consistent with previous experimental evidence on small forecasting rules (Adam, 2007), as well as with empirical studies in the literature, where a contractionary monetary policy shock typically leads to hump-shaped decreases in output and inflation with peaks after one to two years; see e.g. Leeper et al. (1996) and Christiano et al. (1999). This effect is absent at REE since there no lagged state variables in the model, and it shows that the persistence amplification at BLE is also

 $^{^{32}}$ As noted in the previous section, the first-order coefficients are computed based on the posterior mode values. Therefore for completeness, the discussion and comparison of these results (both in this section and in the upcoming ones) are based on the posterior mode. It is worth noting that, given the small differences across the posterior means and modes, a similar discussion can be easily extended to the posterior mean.

³³Note that the shock size is the same under both specifications in this case, since the estimated standard deviation of the monetary policy shock is 0.29 both under BLE and REE

indirectly reflected in the system's response to an exogenous monetary policy shock.



Figure 6: Impulse response functions of output gap and inflation to a one standard deviation monetary policy shock.

Overall, our results suggest important differences in the estimated parameters and the propagation of shocks under BLE. These changes lead to a substantial improvement in the empirical fit, evident from the (log marginal) likelihood of -337 under BLE compared with -348 under REE, which yields a Bayes' Factor 4.78 in favor of BLE³⁴. Comparing the results to SAC-learning, it is readily seen that there are no substantial differences with the BLE specification. Relative to the REE estimations, the exogenous shocks have lower persistence and larger standard deviations, the risk aversion coefficient is lower, Phillips curve slope is higher and monetary policy coefficients are similar. A noticeable difference with the BLE model arises in the historical mean values of inflation and interest rate, which turn out lower under the SAC-learning estimation. This is due to the fact that the learning coefficients are time-varying under SAC-learning and Figure 5 suggests that they are above zero on average, which drives down the estimates of the historical mean parameters³⁵. Another difference with the BLE model arises in the Phillips curve slope, which is somewhat higher under SAC-learning. However, the HPD-interval under SAC-learning is also wider, suggesting that time-variation in beliefs introduces more uncertainty for this parameter. Further, the point estimates under both BLE and SAC-learning specifications fall within the HPD-interval of each other. Other than these small differences, all parameter estimates are fairly close under BLE and SAC-learning, with implied HPDintervals well within the range of each other. The likelihood turns out to be -341 under SAC-learning, which is still better than the fit of REE, with a Bayes' Factor of 3.08 in

³⁴Based on Jeffrey's Guidelines (Greenberg, 2012), if the Bayes' Factor in favor of a model is larger than 2, then this provides *decisive support* for the model under consideration.

³⁵Shutting off the learning dynamics about mean coefficients and letting the agents learn only about the first-order autocorrelations indeed yields historical mean values similar to BLE.

					95~%	0.83	0.33	0.32	0.22	0.75	1.06	0.08	3.94	1.69	0.76	0.68	0.38	0.81			F 000T
					5~%	0.68	0.28	0.27	-0.6	0.18	0.33	0.019	2.04	1.03	0.29	0.46	0.14	0.81			
SAC	-341	-341	3.04		Mean	0.76	0.3	0.29	-0.19	0.45	0.7	0.048	2.98	1.35	0.51	0.57	0.26	0.86			
				Post.	Mode	0.75	0.3	0.29	-0.21	0.41	0.65	0.048	2.86	1.32	0.48	0.57	0.25	0.85	0.86	0.89	
					95~%	0.8	0.32	0.32	-0.17	0.91	1.32	0.065	3.98	1.67	0.73	0.53	0.43	0.91			•
					5~%	0.68	0.27	0.27	0.17	0.67	0.85	0.015	2.33	1.1	0.31	0.32	0.22	0.82			7
BLE	-337	-337	4.78		Mean	0.74	0.3	0.29	-0.4	0.79	1.09	0.037	3.15	1.38	0.52	0.43	0.32	0.86			F
				Post.	Mode	0.73	0.29	0.29	-0.12	0.79	1.1	0.035	3.02	1.36	0.49	0.43	0.32	0.85	0.88	0.89	
					95~%	0.22	0.05	0.33	-0.12	0.9	1.26	0.017	5.37	1.65	0.67	0.92	0.91	0.84			· •
					5~%	0.12	0.03	0.28	0.18	0.53	0.71	0.002	3.35	1.16	0.34	0.83	0.82	0.76			-
REE	-348	-348	1		Mean	0.17	0.04	0.3	-0.49	0.71	0.98	0.01	4.35	1.4	0.51	0.86	0.87	0.8			و
				$\operatorname{Post.}$	Mode	0.16	0.04	0.29	-0.15	0.7	0.98	0.007	4.27	1.38	0.48	0.87	0.88	0.8			-
	Laplace	MHM	Bayes Factor		St. Dev	2	2	2	0.25	0.25	0.25	0.15	0.5	0.25	0.25	0.2	0.2	0.2			
					Mean	0.1	0.1	0.1	-0.2	0.47	0.72	0.3	2	1.5	0.5	0.5	0.5	0.5			
				Prior	Dist.	Inv. Gamma	Inv. Gamma	Inv. Gamma	Normal	Normal	Normal	Beta	Gamma	Gamma	Gamma	Beta	Beta	Beta			
					Para.	σ_y	σ_{π}	σ_r	\bar{y}	$\bar{\pi}$	\bar{r}	3	-19	ϕ_{π}	ϕ_y	ρ_y	$ ho_{\pi}$	$ ho_r$	β^*_u	β^{*}_{π}	- - -

sterior results with the HP-filtered measulate refers to the Laplace approximation te of likelihood based on the posterior d
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favor of SAC-learning, but slightly worse than BLE, with a Bayes' Factor of 1.7 in favor of BLE³⁶. This result suggests that transitory dynamics and the resulting time-variation in the learning parameters do not improve the model fit in our decreasing-gain learning setup. Overall, these results also allow us to illustrate the advantage of using Algorithm II to estimate a BLE: the estimation under SAC-learning requires a relatively large burn-in sample for the convergence of first-order autocorrelation coefficients. This might become an issue if the researcher does not have a sufficiently long dataset, as is typical in most quarterly macroeconomic time series. Furthermore, as we have already seen in Figure 4, the simulations under learning have a relatively large Monte-Carlo variance. In other words, while the simulations converge to the underlying BLE on average, there might be relatively large deviations from the underlying fixed-point for any given simulation. Hence what comes out of the estimation in a real-time learning setup is similar to a single simulation of the model under learning, which in general may not accurately reflect the underlying fixed-point.

Posterior Results: CBO's Measure of Output Gap

We repeat the estimation exercise for all three specifications under our measure of output gap derived from CBO's estimate of potential output³⁷. This measure results in a time series of output gap that is generally more volatile and has a smaller sample average³⁸. As a consequence, the estimated historical mean of output gap is lower across all three specifications compared to the previous section. Under BLE and SAC-learning specifications, the higher volatility of output gap is reflected in a smaller risk aversion parameter $\frac{1}{\varphi}$ (i.e. a larger feedback from the ex-ante real interest rate to output gap), a smaller Phillips curve coefficient γ and a weaker policy reaction coefficient ϕ_y . Under REE, γ is only marginally smaller and $\frac{1}{\varphi}$ is actually slightly larger compared to the HPfiltered measure. Instead, the higher volatility of output gap is reflected in a higher persistence parameter ρ_y and a smaller reaction coefficient ϕ_y . The remaining parameter estimates are similar to the previous section under all three specifications, which we do not discuss in further detail. We also have similar results in terms of the model fit: the (log marginal) likelihood of BLE and SAC-learning models are -341 and -342 respectively, compared with -366 under REE. These yield Bayes' Factors of 10.41 and 10.52 in favor of BLE and SAC-learning models respectively. In this case, unlike the previous section, the SAC-learning model yields a slightly better fit than the BLE model, but the difference is negligible.

³⁶Based on Jeffrey's Guidelines, this provides *very strong* evidence in favor of BLE.

 $^{^{37}\}mathrm{See}$ Appendix I for the exact definition of output gap measure used here.

³⁸The HP-filter leads to more smoothing compared to CBO-based measure. Therefore downturns generally have a larger impact under the CBO-based measure, which leads to a lower average and more volatility in the resulting time series.
					95~%	0.84	0.33	0.32	-0.05	0.65	1.08	0.06	3.4	1.83	0.61	0.63	0.36	0.93															
					5~%	0.69	0.27	0.27	-0.94	0.12	0.35	0.019	1.75	1.11	0.19	0.41	0.11	0.83															
SAC	-341	-342	10.52		Mean	0.76	0.3	0.29	-0.49	0.38	0.71	0.039	2.52	1.47	0.39	0.53	0.24	0.88			•												
				Post.	Mode	0.76	0.3	0.29	-0.48	0.34	0.66	0.039	2.38	1.45	0.35	0.52	0.23	0.88	0.94	0.89	-												
					95~%	0.81	0.32	0.32	-0.17	0.94	1.36	0.04	3.52	1.77	0.59	0.53	0.43	0.94			•												
					5~%	0.69	0.27	0.27	-0.88	0.68	0.85	0.01	2.07	1.12	0.2	0.32	0.21	0.85			- (-												
BLE	-342	-342	10.41		Mean	0.75	0.3	0.3	-0.53	0.81	1.12	0.027	2.78	1.44	0.4	0.43	0.32	0.89			- F												
																Post.	Mode	0.74	0.29	0.29	-0.54	0.81	1.15	0.025	2.65	1.41	0.36	0.43	0.31	0.88	0.92	0.79	
					95~%	0.16	0.05	0.33	-0.04	0.81	1.35	0.015	5.65	1.73	0.4	0.95	0.93	0.85			-												
					5~%	0.08	0.03	0.28	-0.8	0.38	0.72	0.002	3.61	1.2	0.19	0.88	0.84	0.77			-												
REE	-366	-366	1		Mean	0.12	0.04	0.3	-0.43	0.59	1.03	0.009	4.62	1.47	0.29	0.91	0.88	0.81			و												
				Post.	Mode	0.11	0.04	0.3	-0.42	0.59	1.05	0.006	4.57	1.42	0.27	0.92	0.89	0.8															
	Laplace	MHM	Bayes Factor		St. Dev	2	2	2	0.25	0.25	0.25	0.15	0.5	0.25	0.25	0.2	0.2	0.2															
					Mean	0.1	0.1	0.1	-0.2	0.47	0.72	0.3	2	1.5	1.5	0.5	0.5	0.5															
				Prior	Dist.	Inv. Gamma	Inv. Gamma	Inv. Gamma	Normal	Normal	Normal	Beta	Gamma	Gamma	Gamma	Beta	Beta	Beta			- - -												
					Para.	σ_y	σ_{π}	σ_r	\bar{y}	π	\bar{r}	Z	-19	ϕ_{π}	ϕ_y	$ ho_y$	$ ho_{\pi}$	$ ho_r$	β^*_u	β^{*}_{π}													

Table 2: Posterior results with the CBO-based measure of output gap under REE, BLE and SAC-learning over the estimation period 1966:I-2016:IV. Laplace refers to the Laplace approximation of likelihood based on the posterior mode, while MHM refers to the Modified Harmonic Mean estimate of likelihood based on the posterior distribution.

The results presented in this section are generally robust across different subsamples, as well as with our third measure of output gap based on de-trended output, see Appendix H for more details. In the following, we analyze monetary policy under BLE.

4 Monetary Policy

Our results show that BLE and SAC-learning generally provide better model fits than REE for the 3-equation New Keynesian model, with important differences in the estimated structural parameters and the shock propagation under BLE and REE. This leaves an important question for the transmission of monetary policy and how it differs under BLE and REE. In this section, we investigate this issue from two different angles: we first analyze over which parameter regions multiple BLE exist, and how monetary policy under BLE and REE based on an expected loss function. In both cases, we find important differences in terms of monetary policy implications under BLE compared to REE. Particularly, we find that plausible parameter regions with a unique REE may be characterized by multiple E-stable BLE, and a monetary policy that is optimal under REE may perform poorly under BLE.

4.1 Multiple Equilibria

Our analysis so far focuses on cases with a unique E-stable BLE. However, in general, multiple E-stable BLE may coexist. In this section, we provide several examples of how this phenomenon might occur, and how monetary policy might mitigate multiplicity of equilibria. For this analysis, we use our parameter estimates at the posterior mode with the CBO-based measure of output gap: even though the equilibrium is unique at the posterior mode, we find that two E-stable BLE may coexist when there are small changes in the monetary policy and some of the structural parameters. We do not observe this multiplicity when considering the parameter estimates under the HP-filtered measure of output gap, which will be discussed further below.

As a first example, Figure 7a shows the equilibrium persistence of inflation, β_{π}^* as a function of the inflation reaction parameter ϕ_{π} . At the estimated reaction parameter 1.41, there is a unique E-stable equilibrium with $\beta_{\pi}^* \approx 0.79$ as discussed earlier. If we decrease the reaction parameter, a second, high-persistence equilibrium becomes E-stable around $\phi_{\pi} = 1.36$. There is a small range of values over [1.26, 1.36] for ϕ_{π} where two Estable equilibria coexist, seperated by a third, E-unstable equilibrium³⁹. The coexistence

³⁹The plots in Figure 7 are obtained by using a grid search, where we specify a grid of length 20 over the unit interval for the initial values of β_{π} and β_{y} , and a grid of length 100 for each parameter under

of two E-stable equilibria occurs with respect to not only ϕ_{π} , but across a wide range of parameters. The remaining panels in Figure 7 show three examples of this, where we project the multiple equilibrium regions for inflation persistence under three different pairs of parameter values⁴⁰. Figure 7b shows the multiplicity region, i.e. the blue region, for both policy reaction parameters ϕ_{π} and ϕ_y over the ranges [1, 2.5] and [0.25, 0.5] respectively: it is readily seen that the system remains in the low persistence region as long as both parameters are sufficiently high. If either parameter becomes lower, the system first enters the multiplicity region, where both low- and high-persistence equilibria coexist. When the parameters are lowered further, the low-persistence equilibrium loses its stability. This figure suggests that, in order to avoid the multiplicity and high-persistence regions, a weaker reaction to one variable requires a more aggressive reaction to the other variable. For example at $\phi_y = 0.4$, an inflation reaction of $\phi_{\pi} = 1.2$ is sufficient to avoid the multiplicity region, whereas at $\phi_y = 0.3$, this value increases to $\phi_{\pi} = 2$.

Figure 7c shows the same analysis with respect to ϕ_{π} and interest rate smoothing ρ_r over the ranges [1, 3.5] and [0.8, 0.95]. We observe that, similar to the previous case, different values of these two parameters give rise to regions with high- and low-persistence BLE, separated by a multiplicity region where both equilibria coexist. This figure reveals that interest rate smoothing is crucial in terms of driving the multiple equilibria results: for values of $\rho_r < 0.86$, the system remains in the low-persistence equilibrium as long as the Taylor principle of $\phi_{\pi} > 1$ is satisfied. For values of $\rho_r > 0.91$, it is not possible to avoid the high-persistence region for any values of ϕ_{π} . In fact, over this region with high ρ_r , increasing ϕ_{π} has the opposite of the desired effect and generates at least one explosive BLE. As such, our analysis suggests that keeping the interest rate smoothing parameter sufficiently small is more effective than the inflation reaction parameter in terms of avoiding multiple equilibria. Finally, 7d illustrates how multiple equilibria may arise with respect to other structural parameters of the system. For this exercise we use the shock persistence parameters ρ_{π} and ρ_{y} over the ranges [0, 0.4] and [0, 0.9] respectively. In this case we also obtain the starting point of the multiple equilibrium region, i.e. the blue region, which is near [0.31, 0.41]. For values of $\rho_{\pi} > 0.31$, the system is characterized by a unique E-stable equilibrium for all values of ρ_y . Values of $\rho_\pi < 0.31$ divide the system into three regions with the low- and high-persistence BLE, separated by the multiple equilibrium region where both E-stable BLE coexist along with one E-unstable BLE. This phenomenon is known as a *cusp bifurcation*: the boundaries of the blue region

consideration. Further, we use the quasi-Newton method to obtain the E-unstable equilibrium in Figure 7a since Algorithm I cannot converge to it by construction. The remaining panels are obtained by using Algorithm I.

⁴⁰For this exercise, the remaining parameters are fixed at their estimated posterior mode under the CBO-based measure. Also note that the same analysis holds for output gap persistence, we only present and discuss inflation persistence here due to space limitations.

represent saddle-node bifurcation curves, where an additional E-stable BLE is created. These saddle-node curves merge at a limiting curve to a *cusp bifurcation* (Kutnetsov, 2013 p.397).

The analysis above can be extended to other structural parameters of the model: for example, the slope of the Phillips curve γ also plays a crucial role, where a higher parameter leads first to multiplicity and high-persistence regions, then to explosive equilibria similar to interest rate smoothing. These cases are left to our Online Appendix. Further note that, if we repeat the analysis in this section under our HP-filtered estimates, we find no evidence of multiple equilibria in a nearby region. Given our results in this section and our Online Appendix, the small differences in the estimates of γ (lower under the CBO-based measure) and ρ_r (higher under the CBO-based measure) emerge as the key drivers of this result.

The important takeaway from this section is that, multiple E-stable BLE coexist in plausible parameter regions even if the Taylor principle of $\phi_{\pi} > 1$ is satisfied. This is different than REE, where the Taylor principle ensures the equilibrium uniqueness. In these multiple equilibrium regions, a sufficiently aggressive monetary policy can de-stabilize the high-persistence BLE and ensure that the system remains in the low-persistence BLE. In particular, an interest rate smoothing parameter $\rho_r < 0.85$ ensures that multiple E-stable equilibria do not arise. When a low smoothing parameter is not feasible, sufficiently aggressive reaction coefficients are able to achieve the same result.

For the remainder of this section, we turn to a comparison of *optimal monetary policy* under BLE and REE, for which we use both our baseline calibration from Section 3.2, as well as our baseline estimation with the HP-filtered output gap from Section 3.3. The key result in both of these cases is that optimal policy under BLE typically looks different than REE, even if we consider a parameter space with a unique E-stable BLE.



(c) Inflation reaction and interest rate (d) Shock persistence parameters. smoothing.

Figure 7: Multiple BLE: the first panel (top left) shows a saddle-node bifurcation with respect to ϕ_{π} , where two stable BLE are separated by an unstable BLE over the region [1.26, 1.36]. The remaining panels shows the projections of multiple equilibria over twodimensional parameter regions. The blue regions correspond to cases where we observe two coexisting E-stable BLE, whereas the red regions correspond to cases with no E-stable BLE. The red dots correspond to the estimated parameter values under CBO-based output gap.

4.2 Optimal Policy

4.2.1 Calibrated Parameters

In this section we analyze optimal Taylor rules under BLE and REE. We start by assuming that the central bank wishes to minimize an expected loss function E[L] in terms of the discounted sum of weighted squared inflation, output gap and interest rate

$$E[L] = (1 - \vartheta) E\left[\sum_{t=0}^{\infty} \vartheta^t [\omega_\pi \pi_t^2 + \omega_y y_t^2 + \omega_r r_t^2]\right] = \omega_\pi \sigma_\pi^2 + \omega_y \sigma_y^2 + \omega_r \sigma_r^2, \qquad (4.1)$$

where ω_i , $i \in \{\pi, y, r\}$ is the relative weight that the central bank places on inflation, output gap and interest rate respectively. The stabilization objective for inflation and output gap is a standard assumption in the literature, see e.g. Boehm and House (2014),



Figure 8: Optimal policies at the BLE and at the REE. Parameters are: $\lambda = 0.99, \varphi = 1, \rho_{\pi} = \rho_{y} = 0.5, \rho_{r} = 0, \gamma = 0.04, \sigma_{y} = 1, \sigma_{\pi} = 0.5$ and $\omega_{y} = 0.1, \omega_{r} = 0.05$.

Evans and Honkapohja (2003) and Woodford (2003). The weight on interest rate variance can be motivated by different interpretations: Woodford (1999) and Giannoni (2014) suggest that it can proxy for welfare costs of transactions and/or an approximation on the zero lower bound on nominal interest rates, while Caplin and Leahy (1996) suggest that it can represent a gradual learning process for the central bank that is uncertain about the consequences of interest rate fluctuations.

Based on our calculations and equations (F.12) and (F.13), the unconditional moments under BLE are given as

$$\sigma_{y}^{2} = \frac{\widetilde{g}_{1}}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \rho\lambda_{2})(1 - \lambda_{1}^{2})(1 - \lambda_{2}^{2})(1 - \lambda_{1}\lambda_{2})}, (4.2)$$

$$\sigma_{\pi}^{2} = \frac{\widetilde{g}_{2}}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \rho\lambda_{2})(1 - \lambda_{1}^{2})(1 - \lambda_{2}^{2})(1 - \lambda_{1}\lambda_{2})}, (4.3)$$

$$\sigma_{r}^{2} = \phi_{y}^{2}\sigma_{y}^{2} + \phi_{\pi}^{2}\sigma_{\pi}^{2} + 2\phi_{y}\phi_{\pi}E(y_{t}\pi_{t}), \qquad (4.4)$$

where \tilde{g}_1 , \tilde{g}_2 , λ_1 , λ_2 are given by the equations (3.15)-(3.18), and $E(y_t \pi_t)$ is a complicated expression in terms of the structural parameters and first-order autocorrelations β_y and β_{π}^{41} .

In the following we study the optimal values (ϕ_y^*, ϕ_π^*) that minimize the central bank's loss function (4.1) under BLE and REE.

We first examine monetary policy under BLE and REE at our baseline calibration, where we use the parameters $\lambda = 0.99, \varphi = 1, \gamma = 0.04, \rho_y = \rho_{\pi} = \rho = 0.5, \rho_r = 0, \sigma_{\pi} = 0.5$ and $\sigma_y = 1$ for both BLE and REE. Using this calibration serves two purposes: first, using the same parameter values under both specifications ensures that the data generating process only differs in terms of the expectation formation rule. Second, in

⁴¹See Appendix F, equation (F.16).



Figure 9: Loss function along the optimal paths (ϕ_y^*, ϕ_π^*) in Figure 8 at the BLE (a) and REE (b). Parameters are: $\lambda = 0.99, \varphi = 1, \rho_\pi = \rho_y = \rho = 0.5, \rho_r = 0, \gamma = 0.04, \sigma_y = 1, \sigma_\pi = 0.5$ and $\omega_y = 0.1, \omega_r = 0.05$.

the absence of interest rate smoothing and given the assumption of $\rho_{\pi} = \rho_y$, we can use the expressions in (3.13)-(3.18) to evaluate BLE, which allows us to provide some insight on how optimal monetary policy under BLE depends on model parameters, such as the persistence of exogenous shocks.

As we saw in previous sections, there are important differences in the moments of endogenous variables due to volatility and persistence amplification at BLE. In particular, the implied variances of inflation, output gap and interest rate are different under BLE and REE at the calibrated parameter values. Following Woodford (1999) and Giannoni (2014), we normalize the weight on inflation to $\omega_{\pi} = 1$. We first focus on a special case with $\omega_y = 0.1$ and $\omega_r = 0.05$, that is, the central bank places a relatively large weight on inflation and a small one on interest rates. The small weight on interest rates allows us to first focus on the trade-off between inflation and output gap stabilization. We leave the discussion of how optimal policy depends on these policy weights to the case of estimated parameter values.

Interestingly, we find that the optimal Taylor rule coefficients (ϕ_y^*, ϕ_π^*) are finite under BLE⁴². As shown in Figure 8, the corresponding optimal policy is $(\phi_y^*, \phi_\pi^*) = (0.91, 4.88)$. This is different from REE, where there is no finite optimal policy except when the weight

⁴²We first select a policy parameter domain (e.g. $[0, 100] \times [1, 100]$) and define a lattice with some small step (e.g. 0.01). Then for each lattice point (ϕ_y, ϕ_π) , we find the BLE $(\beta_1^*(\phi_y, \phi_\pi), \beta_2^*(\phi_y, \phi_\pi))$ and the corresponding central bank's expected loss function E[L] at the BLE. Finally we interpolate the loss function with respect to (ϕ_y, ϕ_π) to find the finite optimal values. It is easy to get analytic expressions of the variances and optimal policy parameters under REE. In contrast, it is impossible to obtain analytic expressions of the optimal policy parameters under BLE and therefore we have to rely on numerical approximations. We find consistent results using different ways to calculate the variances (i.e. based on (4.2) and (4.3) or computing the variances as in Appendix B).



Figure 10: Optimal policies at the BLE with respect to ρ (a) and corresponding optimal manifolds for three different ρ (connection points of solid and dotted curves corresponding to finite optimal policies) (b). Parameters are: $\lambda = 0.99, \varphi = 1, \gamma = 0.04, \sigma_y = 1, \sigma_{\pi} = 0.5$ and $\omega_y = 0.1, \omega_r = 0.05$.

on interest rates is increased, or when measurement errors are considered as shown in Boehm and House $(2014)^{43}$. In fact, from Figure 8 it can be seen that in the case ϕ_y^* is small enough (i.e. < 0.91) the coefficients ϕ_y^* and ϕ_π^* lie on a manifold and the loss function (4.1) decreases gradually along the manifold within this region, which is similar to REE but with higher ϕ_π^* . However, for $\phi_y^* > 0.91$, the loss function (4.1) starts to increase, while in the REE the loss function (4.1) still decreases as shown in Figure 9. In other words, there exist finite optimal Taylor rule coefficients at the BLE, but not at the REE. This is mainly because at the BLE the actual law of motion has higher variance than at the REE for the endogenous variables (especially inflation) and minimizing the loss function, i.e. minimizing the weighted variances of output gap, inflation and interest rate, requires balancing the different responses in terms of policy parameters (ϕ_u, ϕ_π).

Next we investigate how optimal monetary policy changes as the persistence of the underlying shocks is varied. At the REE with measurement error the finite coefficients ϕ_y^* and ϕ_π^* increase as the persistence of shocks grows within some range, see Boehm and House (2014). At the BLE, in addition to this, we find that when the persistence of exogenous shocks becomes sufficiently small with $\rho < 0.4$, the finite coefficients ϕ_y^* and ϕ_π^* increase in a small region as shown in Figure 10a, before they start decreasing again. Furthermore, Figure 10b suggests that the optimal manifold always moves up as the persistence of shocks ρ grows. The finite optimal policy lies at the point in the optimal

⁴³The loss function considered in Boehm and House (2014) does not include interest rate variance. Including interest rates in our loss function here does not affect the result that optimal policy at REE does not exit as long as ω_r remains sufficiently small. Optimal policy becomes finite when ω_r is sufficiently large, these cases are discussed under the estimated parameter values.

manifold connecting the solid and dotted lines in Figure 10b. The location of the optimal point corresponding to finite optimal policies depends on the relative values of variances of inflation, output gap and interest rate. In the case where ρ is large enough, the loss function is mainly dominated by the variance of inflation and hence the optimal policy ϕ_{π}^* grows quickly converging to ∞ , and the slope of $\frac{\phi_{\pi}}{\phi_y^*}$ converging to a large constant. As ρ becomes smaller, the variance of interest rate starts to play a more dominant role, which leads to smaller values for both ϕ_{π}^* and ϕ_y^* . The region with small values of ρ is more relevant for U.S. data since both shock persistence parameters are low at the BLE in our estimation exercises.

These results show that optimal policy exists under BLE for this parameterization, different than REE, and that the optimal rule (ϕ_y^*, ϕ_π^*) under BLE crucially depends on the persistence of exogenous shocks.

4.2.2 Estimated Parameters

Next we examine optimal monetary policy for the empirically more relevant case of estimated parameters. In this case the underlying structural parameters are different at BLE and REE, but the variances of inflation, output gap and interest rate are close under these two specifications. In particular, given the estimated parameter values and our benchmark policy weights of $(\omega_y, \omega_r) = (0.1, 0.05)$, the expected loss function E[L] is 0.57 at BLE and 0.55 at REE⁴⁴. This allows us to compare monetary policy under BLE and REE with a similar starting point for the loss function.

For this exercise, we limit our attention to Taylor parameters ϕ_y and ϕ_{π} over the range [0, 15]. In this case we find that optimal monetary policy exists not only at BLE, but also at REE for a wide range of policy weights⁴⁵. The difference at REE between calibrated and estimated parameters is driven by the exogenous shocks, which are estimated to be highly persistent, and the Phillips curve, which is estimated to be flatter compared to the calibration. This introduces a larger trade-off between inflation and output gap stabilization at REE, which leads to a finite optimal policy for a wide range of policy weights. Given this result, we can compare how the optimal parameters differ at BLE and REE.

Table 3 shows the optimal Taylor rules for several pairs of (ω_y, ω_r) , along with some key statistics at BLE and REE. The first two rows show our benchmark calibration of

⁴⁴Our analysis with calibrated parameter values is based on the expressions (4.2)-(4.4). These expressions are no longer applicable for the estimated version of the model since it also includes an interest rate smoothing parameter, and the assumption of the same persistence for the exogenous shocks is relaxed. Rather, we use the (different) estimated shock persistence parameters. Therefore we proceed by computing the BLE and the associated variances for each value of policy parameters using the Iterative E-stability algorithm.

⁴⁵See our Online Appendix for the optimal parameters at BLE and REE for weights ω_y and ω_r over the range [0, 0.25].

(0.1, 0.05), while the second row considers a calibration (0.048, 0.236) as in Woodford (1999) and Giannoni (2014). The remaining two rows show the effects of increasing the weight on output gap and interest rate relative to the benchmark calibration, where we consider weights of (0.1, 0.15) and (0.2, 0.05) respectively. Several observations stand out from the table: first, it is readily seen that optimal policy at BLE is typically more aggressive in both parameters ϕ_{π}^* and ϕ_y^* , when the relative weight on interest rates is large enough. To make this point more clear, Figure 11 shows the optimal parameters at BLE and REE as a function of the relative weight on interest rates, $\frac{\omega_T}{\omega_y}$. When $\frac{\omega_T}{\omega_y}$ approaches zero, optimal parameters under both BLE and REE quickly start converging to infinity, whereas when $\frac{\omega_T}{\omega_y}$ increases, optimal parameters under both BLE and REE and REE termains higher than REE across all combinations of weights, suggesting a more aggressive response to output gap. ϕ_{π}^* under BLE remains smaller than REE until $\frac{\omega_T}{\omega_y} \approx 1.5$, after which the optimal parameter under BLE always remains larger than REE.

These results suggest that ϕ_{π}^* under BLE is less sensitive to changes in the policy weights, while ϕ_y^* under BLE is more sensitive. In other words, optimal policy at REE responds to changes in policy weights mainly through ϕ_{π}^* , while optimal policy at BLE responds to these changes through ϕ_y^* . This result is mainly driven by the estimates of $\frac{1}{\varphi}$ and γ , both of which are larger under BLE: a larger $\frac{1}{\varphi}$ implies a stronger impact from interest rates to output gap, while a larger γ implies a stronger impact from output gap to inflation. As a consequence of this, stabilizing output gap plays a more dominant role at BLE compared to REE, since the effect of this on inflation is also larger⁴⁶. A side effect of this stronger channel at BLE is on the loss function: the columns $E[L^*]$ and $\Delta E[L^*]$ show the value of the loss function at the optimal parameter values, and the percentage improvement in the loss function compared to the benchmark value of the loss function. It is readily seen that the improvements achieved under BLE are substantially larger compared to REE, suggesting a stronger influence on the economy from interest rates. This is in line with our earlier finding that impulse responses of inflation and output gap to a monetary policy shock are larger under BLE.

As a final exercise, we consider optimal parameters when the interest rate smoothing parameter is shut off, which serves two purposes: since the estimated value of interest rate smoothing is different under BLE and REE, this allows us to compare optimal policies with an equal rate of smoothing. Second, our results from multiple equilibria section suggest that excessive interest rate smoothing is undesirable, since it may lead to multiple stable BLE and even de-stabilize the economy. Here we check whether there are any benefits to

⁴⁶For the cases where the Taylor rule of $\phi_{\pi} > 1$ is violated in Table 3, the REE model is still determinate since the estimated Phillips curve slope is very small. Further, in all cases considered here, we have a unique E-stable BLE since the interest rate smoothing parameter is not excessively large.

interest rate smoothing at BLE in the absence of multiple equilibria.

In this case we find optimal parameters under both BLE and REE that are generally smaller compared to the previous case, which is not surprising since shutting off ρ_r allows for larger movements in interest rates, which in turn leads to smaller optimal parameters. More importantly, this exercise reveals that, while interest rate smoothing is typically welfare improving at REE, this is never the case at BLE: $E[L^*]$ is uniformly smaller and $\Delta E[L^*]$ uniformly larger at BLE when interest rate smoothing is shut off, while the opposite holds at REE. The result for REE is well-known from Woodford (1999), where a commitment to interest rate smoothing has a stabilizing effect with forward-looking agents who anticipate and take into account future changes in interest rate. This is different than a BLE with backward-looking agents, where such a commitment does not have a stabilizing effect since agents are unaware of the commitment or do not take it into account when forming their expectations. In other words, agents confuse a higher degree of interest rate smoothing with weaker reactions coefficients in a BLE. An important implication of this for a central bank is that, not communicating an interest rate smoothing objective in a credible manner to the public may have welfare decreasing effects.

Overall, our results in this section yield important differences on the effects of monetary policy under BLE and REE. In particular, we find that (i) multiple E-stable BLE may coexist in plausible parameter regions typically associated with a unique REE, (ii) optimal policy at BLE exist in parameter regions where there is no optimal policy at REE, (iii) optimal parameters are typically different in regions where optimal policy exists for both BLE and REE. These results imply that a monetary policy that is optimal under REE may perform poorly under BLE.



Figure 11: Changes in optimal parameters as a function of the relative weight on the interest rate.

ω_{π}	ω_y	ω_r	BLE		REE		BLE		REE	
			$\rho_r = 0.85$		$\rho_r = 0.8$		$\rho_r = 0.85$		$\rho_r = 0.8$	
			ϕ_y^*	ϕ_{π}^{*}	ϕ_y^*	ϕ^*_π	$E[L^*]$	$\Delta E[L^*]$	$E[L^*]$	$\Delta E[L^*]$
1	0.1	0.05	3.94	3.49	2.74	4.43	0.24	58 %	0.40	27~%
1	0.048	0.236	1.67	1.56	0.94	0.75	0.34	32~%	0.55	1 %
1	0.1	0.15	2.42	1.82	1.25	1.96	0.32	48~%	0.52	15~%
1	0.2	0.05	6.67	3.94	2.64	8.51	0.28	68~%	0.41	46~%
ω_{π}	ω_y	ω_r	BLE		REE		BLE		REE	
			a = 0						0	
			$p_r = 0$		$\rho_r = 0$		$\rho_r = 0$		$\rho_r = 0$	
			$\frac{\rho_r = 0}{\phi_y^*}$	ϕ_{π}^{*}	$\begin{array}{c} \rho_r = 0\\ \phi_y^* \end{array}$	ϕ_{π}^{*}	$\rho_r = 0$ $E[L^*]$	$\Delta E[L^*]$	$\rho_r = 0$ $E[L^*]$	$\Delta E[L^*]$
1	0.1	0.05	$\frac{\rho_r = 0}{\phi_y^*}$ 1.21	ϕ_{π}^{*} 1.67	$\rho_r = 0$ ϕ_y^* 2.17	ϕ_{π}^{*} 4.91	$\rho_r = 0$ $E[L^*]$ 0.24	$\Delta E[L^*] = 59 \%$	$\rho_r = 0$ $E[L^*]$ 0.43	$\Delta E[L^*]$ 21 %
1 1	0.1 0.048	$0.05 \\ 0.236$		ϕ^*_{π} 1.67 0.91	$\rho_r = 0$ ϕ_y^* 2.17 0.38	ϕ_{π}^{*} 4.91 0.49	$\rho_r = 0$ $E[L^*]$ 0.24 0.30	$\Delta E[L^*]$ 59 % 40 %	$ \rho_r = 0 $ $ E[L^*] $ 0.43 0.64	$\begin{array}{c} \Delta E[L^*] \\ 21 \ \% \\ -16 \ \% \end{array}$
$\begin{array}{c} 1 \\ 1 \\ 1 \\ 1 \end{array}$	0.1 0.048 0.1	$0.05 \\ 0.236 \\ 0.15$	$ \begin{array}{c} \rho_r = 0 \\ \phi_y^* \\ 1.21 \\ 0.46 \\ 0.76 \end{array} $	ϕ^*_{π} 1.67 0.91 1.06	$ \begin{array}{c} \rho_r = 0 \\ \phi_y^* \\ 2.17 \\ 0.38 \\ 0.62 \end{array} $	ϕ^*_{π} 4.91 0.49 1.62	$ \begin{array}{l} \rho_r = 0 \\ \overline{E[L^*]} \\ 0.24 \\ 0.30 \\ 0.31 \end{array} $	$\begin{array}{c} \Delta E[L^*] \\ 59 \% \\ 40 \% \\ 59 \% \end{array}$	$\rho_r = 0$ $E[L^*]$ 0.43 0.64 0.61	$\begin{array}{c} \Delta E[L^*] \\ 21 \% \\ -16 \% \\ 1 \% \end{array}$

Table 3: Optimal Taylor rules and some key statistics at BLE and REE: top panel shows the results under the estimated parameter values in each case, while the bottom panel shows the same results without interest rate smoothing, i.e. $\rho_r = 0$. $E[L^*]$ shows the loss function value at the optimal policy, while $\Delta E[L^*]$ shows the percentage improvement at the optimal policy relative to the loss function at the estimated parameters.

5 Concluding Remarks

We have generalized the Behavioral Learning Equilibria concept to an n-dimensional linear stochastic framework and provided a general iterative method to approximate and estimate BLE. We have applied our framework to the 3-equation New Keynesian model. Boundedly rational agents use univariate AR(1) forecasting rules for output gap and inflation. A BLE is parameter free, as along the BLE the two parameters of each rule are pinned down by two observable statistics: the unconditional mean and the first-order autocorrelation. Hence, along a first-order approximation, the simple linear forecasting rule is optimal within the class of AR(1) heuristics and consistent with observed realizations. Agents gradually update the two coefficients –sample mean and first-order autocorrelation– of their linear rule through sample autocorrelation learning. In the long run, agents thus learn to coordinate on the best univariate linear forecasting rule for each endogenous state variable, without fully recognizing the more complex structure of the economy. In higher-dimensional systems, BLE exist under general conditions and we provide simple stability conditions under learning. In the New Keynesian model without interest rate smoothing, a BLE always exists when the Taylor Principle is satisfied.

A striking feature of BLE is the strong *persistence amplification*: the persistence of output and inflation along a BLE is much higher, often near unit root, than the persistence in the exogenous shocks driving the economy. Estimating the 3-equation model on historical U.S. data under BLE yields a better model fit and a different shock propagation compared with the REE model. This leaves an important role for monetary policy with

the goal of stabilizing output gap, inflation and interest rates. Different from REE, we find that multiple E-stable BLE may coexist in plausible parameter regions where the Taylor principle is satisfied. We find a finite optimal Taylor rule under our benchmark calibration, unlike REE where no finite policy exists. Furthermore, in parameter regions where optimal policy exists under REE, we find that the optimal parameters are different and typically less aggressive compared to BLE. These results suggest that a monetary policy that is optimal under REE may perform poorly under BLE. In our follow-up paper, Hommes et. al. (2019), we extend the estimation of BLE to the more realistic setup of the medium-scale Smets-Wouters (2007) model, and also consider out-of-sample forecasting under BLE.

Appendix

A Mean of the rational expectations equilibrium

Using (2.10-2.11) and (2.15-2.18) the mean of the REE satisfies

$$\overline{\mathbf{x}^*} = (\mathbf{I} - \mathbf{c}_1)^{-1} (\mathbf{c}_0 + \mathbf{c}_2 \overline{\mathbf{u}}) = (\mathbf{I} - \mathbf{c}_1)^{-1} (\mathbf{I} - \mathbf{b}_1 \mathbf{c}_1 - \mathbf{b}_1)^{-1} (\mathbf{b}_0 + \mathbf{b}_1 \mathbf{c}_2 \mathbf{a}) + (\mathbf{I} - \mathbf{c}_1)^{-1} \mathbf{c}_2 (\mathbf{I} - \boldsymbol{\rho})^{-1} \mathbf{a} = (\mathbf{I} - \mathbf{c}_1)^{-1} (\mathbf{I} - \mathbf{b}_1 \mathbf{c}_1 - \mathbf{b}_1)^{-1} [\mathbf{b}_0 + (\mathbf{b}_1 \mathbf{c}_2 (\mathbf{I} - \boldsymbol{\rho}) + (\mathbf{I} - \mathbf{b}_1 \mathbf{c}_1 - \mathbf{b}_1) \mathbf{c}_2) (\mathbf{I} - \boldsymbol{\rho})^{-1} \mathbf{a}] = [(\mathbf{I} - \mathbf{b}_1 \mathbf{c}_1 - \mathbf{b}_1) (\mathbf{I} - \mathbf{c}_1)]^{-1} [\mathbf{b}_0 + \mathbf{b}_3 (\mathbf{I} - \boldsymbol{\rho})^{-1} \mathbf{a}] = (\mathbf{I} - \mathbf{b}_1 - \mathbf{b}_2)^{-1} [\mathbf{b}_0 + \mathbf{b}_3 (\mathbf{I} - \boldsymbol{\rho})^{-1} \mathbf{a}].$$

B Autocorrelation in the *n*-dimensional case

The purpose of this appendix is to show that the first-order autocorrelation coefficients of the stochastic stationary system (2.24) are continuous functions with respect to $(\beta_1, \beta_2, \dots, \beta_n)$ and the other related parameters. Rewrite model (2.24) as

$$\begin{cases} \boldsymbol{x}_t - \overline{\boldsymbol{x}} = (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2)(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}}) + \boldsymbol{b}_3(\boldsymbol{u}_t - \overline{\boldsymbol{u}}) + \boldsymbol{b}_4 \boldsymbol{v}_t, \\ \boldsymbol{u}_t - \overline{\boldsymbol{u}} = \boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}}) + \boldsymbol{\varepsilon}_t. \end{cases}$$
(B.1)

That is,

$$\begin{cases} \boldsymbol{x}_t - \overline{\boldsymbol{x}} = (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2)(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}}) + \boldsymbol{b}_3 \boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}}) + \boldsymbol{b}_3 \boldsymbol{\varepsilon}_t + \boldsymbol{b}_4 \boldsymbol{v}_t, \\ \boldsymbol{u}_t - \overline{\boldsymbol{u}} = \boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}}) + \boldsymbol{\varepsilon}_t. \end{cases}$$
(B.2)

$$\Gamma(-1) = E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})']$$

$$= E\Big[(\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})' + \boldsymbol{b}_{3}\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})' + \boldsymbol{b}_{3}\varepsilon_{t}(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})'$$

$$+ \boldsymbol{b}_{4}\boldsymbol{v}_{t}(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})'\Big]$$

$$= (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})\Gamma(0) + \boldsymbol{b}_{3}\boldsymbol{\rho}E[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})']$$

$$= (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})\Gamma(0) + \boldsymbol{b}_{3}\boldsymbol{\rho}E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})'].$$

$$(B.3)$$

$$\begin{split} \mathbf{\Gamma}(0) &= E[(\mathbf{x}_t - \overline{\mathbf{x}})(\mathbf{x}_t - \overline{\mathbf{x}})'] \\ &= E\Big[(\mathbf{b}_1 \mathbf{\beta}^2 + \mathbf{b}_2)(\mathbf{x}_{t-1} - \overline{\mathbf{x}})(\mathbf{x}_t - \overline{\mathbf{x}})' + \mathbf{b}_3 \mathbf{\rho}(\mathbf{u}_{t-1} - \overline{\mathbf{u}})(\mathbf{x}_t - \overline{\mathbf{x}})' + \mathbf{b}_3 \mathbf{\varepsilon}_t (\mathbf{x}_t - \overline{\mathbf{x}})' + \mathbf{b}_4 \mathbf{v}_t (\mathbf{x}_t - \overline{\mathbf{x}})'\Big] \\ &= (\mathbf{b}_1 \mathbf{\beta}^2 + \mathbf{b}_2) \mathbf{\Gamma}(1) + \mathbf{b}_3 \mathbf{\rho} E[(\mathbf{u}_{t-1} - \overline{\mathbf{u}})(\mathbf{x}_t - \overline{\mathbf{x}})'] + \mathbf{b}_3 E[\mathbf{\varepsilon}_t (\mathbf{x}_t - \overline{\mathbf{x}})'] + \mathbf{b}_4 E[\mathbf{v}_t (\mathbf{x}_t - \overline{\mathbf{x}})'] \\ &= (\mathbf{b}_1 \mathbf{\beta}^2 + \mathbf{b}_2) \mathbf{\Gamma}(1) + \mathbf{b}_3 \mathbf{\rho} E[(\mathbf{u}_{t-1} - \overline{\mathbf{u}})(\mathbf{x}_t - \overline{\mathbf{x}})'] + \mathbf{b}_3 \mathbf{\Sigma}_{\mathbf{\varepsilon}} \mathbf{b}_3' + \mathbf{b}_4 \mathbf{\Sigma}_{\mathbf{v}} \mathbf{b}_4'. \end{split}$$
(B.4)

Note that $E[\boldsymbol{\varepsilon}_t(\boldsymbol{x}_t - \overline{\boldsymbol{x}})'] = E\left[\boldsymbol{\varepsilon}_t((\boldsymbol{b}_1\boldsymbol{\beta}^2 + \boldsymbol{b}_2)(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}}))' + \boldsymbol{\varepsilon}_t(\boldsymbol{b}_3\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}}))' + \boldsymbol{\varepsilon}_t(\boldsymbol{b}_3\boldsymbol{\varepsilon}_t)' + \boldsymbol{\varepsilon}_t(\boldsymbol{b}_4\boldsymbol{v}_t)'\right] = \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}\boldsymbol{b}_3' \text{ and } E[\boldsymbol{v}_t(\boldsymbol{x}_t - \overline{\boldsymbol{x}})'] = E\left[\boldsymbol{v}_t((\boldsymbol{b}_1\boldsymbol{\beta}^2 + \boldsymbol{b}_2)(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}}))' + \boldsymbol{v}_t(\boldsymbol{b}_3\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}}))' + \boldsymbol{v}_t(\boldsymbol{b}_3\boldsymbol{\varepsilon}_t)' + \boldsymbol{v}_t(\boldsymbol{b}_4\boldsymbol{v}_t)'\right] = \boldsymbol{\Sigma}_{\boldsymbol{v}}\boldsymbol{b}_4'.$ Based on (B.3), (B.4) and $\boldsymbol{\Gamma}(-1) = \boldsymbol{\Gamma}(1)',$

$$\Gamma(0) = (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2) \Gamma(0) (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2)' + (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2) E[(\boldsymbol{x}_t - \overline{\boldsymbol{x}})(\boldsymbol{u}_t - \overline{\boldsymbol{u}})'] (\boldsymbol{b}_3 \boldsymbol{\rho})' + \boldsymbol{b}_3 \boldsymbol{\rho} E[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_t - \overline{\boldsymbol{x}})'] + \boldsymbol{b}_3 \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} \boldsymbol{b}_3' + \boldsymbol{b}_4 \boldsymbol{\Sigma}_{\boldsymbol{v}} \boldsymbol{b}_4'.$$

In order to obtain the expression of $\Gamma(0)$, we use column stacks of matrices. Suppose $vec(\mathbf{K})$ is the vectorization of a matrix \mathbf{K} and \otimes is the Kronecker product⁴⁷. Under the assumption that all the eigenvalues of $\mathbf{b}_1 \boldsymbol{\beta}^2$ are inside the unit circle, based on the property of Kronecker product⁴⁸, it is easy to see all the eigenvalues of $(\mathbf{b}_1 \boldsymbol{\beta}^2 + \mathbf{b}_2) \otimes (\mathbf{b}_1 \boldsymbol{\beta}^2 + \mathbf{b}_2)$ lie inside the unit circle and hence $[\mathbf{I} - (\mathbf{b}_1 \boldsymbol{\beta}^2 + \mathbf{b}_2) \otimes (\mathbf{b}_1 \boldsymbol{\beta}^2 + \mathbf{b}_2)]^{-1}$ exist. Therefore,

$$vec(\boldsymbol{\Gamma}(0)) = [\boldsymbol{I} - (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2) \otimes (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2)]^{-1}[((\boldsymbol{b}_3 \boldsymbol{\rho}) \otimes (\boldsymbol{b}_1 \boldsymbol{\beta}^2 + \boldsymbol{b}_2))vec(E[(\boldsymbol{x}_t - \overline{\boldsymbol{x}})(\boldsymbol{u}_t - \overline{\boldsymbol{u}})']) + (\boldsymbol{I} \otimes (\boldsymbol{b}_3 \boldsymbol{\rho}))vec(E[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_t - \overline{\boldsymbol{x}})']) + vec(\boldsymbol{b}_3 \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} \boldsymbol{b}_3' + \boldsymbol{b}_4 \boldsymbol{\Sigma}_{\boldsymbol{v}} \boldsymbol{b}_4')].$$
(B.5)

Thus in order to obtain $\Gamma(1)$ and $\Gamma(0)$, we need calculate $E[(\boldsymbol{x}_t - \overline{\boldsymbol{x}})(\boldsymbol{u}_t - \overline{\boldsymbol{u}})']$ and $E[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_t - \overline{\boldsymbol{x}})']$.

$$E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})']$$

$$= E\left[(\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{3}\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{3}\boldsymbol{\varepsilon}_{t}(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{4}\boldsymbol{v}_{t}(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})'\right]$$

$$= E\left[(\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'\boldsymbol{\rho}' + \boldsymbol{\varepsilon}_{t}'] + \boldsymbol{b}_{3}\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'\boldsymbol{\rho}' + \boldsymbol{\varepsilon}_{t}'] + \boldsymbol{b}_{3}\boldsymbol{\varepsilon}_{t}[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'\boldsymbol{\rho}' + \boldsymbol{\varepsilon}_{t}']\right]$$

$$= (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})E[(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})']\boldsymbol{\rho}' + \boldsymbol{b}_{3}\boldsymbol{\rho}E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})']\boldsymbol{\rho}' + \boldsymbol{b}_{3}\boldsymbol{\Sigma}_{\varepsilon}.$$

⁴⁷One property of column stacks is that the column stack of a product of three matrices is $vec(ABC) = (C' \otimes A)vec(B)$. For more details on this and related properties, see Magnus and Neudecker(1988, Chapter 2) and Evans and Honkapohja (2001, Section 5.7).

⁴⁸The eigenvalues of $\widehat{A} \otimes \widehat{B}$ are the mn numbers $\lambda_r \mu_s, r = 1, 2, \cdots, m, s = 1, 2, \cdots, n$ where $\lambda_1, \cdots, \lambda_m$ are the eigenvalues of $m \times m$ matrix \widehat{A} and μ_1, \cdots, μ_n are the eigenvalues of $n \times n$ matrix \widehat{B} ; see Lancaster and Tismenetsky (1985).

Correspondingly,

$$vec(E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})'])$$

$$= [\boldsymbol{I} - \boldsymbol{\rho} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})]^{-1}[vec(\boldsymbol{b}_{3}\boldsymbol{\rho}E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})']\boldsymbol{\rho}') + vec(\boldsymbol{b}_{3}\boldsymbol{\Sigma}_{\varepsilon})]$$

$$= [\boldsymbol{I} - \boldsymbol{\rho} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})]^{-1}[(\boldsymbol{\rho} \otimes (\boldsymbol{b}_{3}\boldsymbol{\rho}))vec(E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})']) + (\boldsymbol{I} \otimes \boldsymbol{b}_{3})vec\boldsymbol{\Sigma}_{\varepsilon})]$$

$$= [\boldsymbol{I} - \boldsymbol{\rho} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})]^{-1}[(\boldsymbol{\rho} \otimes (\boldsymbol{b}_{3}\boldsymbol{\rho}))[\boldsymbol{I} - \boldsymbol{\rho} \otimes \boldsymbol{\rho}]^{-1} + (\boldsymbol{I} \otimes \boldsymbol{b}_{3})]vec(\boldsymbol{\Sigma}_{\varepsilon}). \quad (B.6)$$

Furthermore,

$$E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})']$$

$$= E\left[(\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})(\boldsymbol{x}_{t-1} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{3}\boldsymbol{\rho}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{3}\boldsymbol{\varepsilon}_{t}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})' + \boldsymbol{b}_{4}\boldsymbol{v}_{t}(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'\right]$$

$$= (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})'] + \boldsymbol{b}_{3}\boldsymbol{\rho}E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})'].$$

Thus based on (B.6),

$$vec(E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'])$$

$$= (\boldsymbol{I} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2}))vec(E[(\boldsymbol{x}_{t} - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})']) + (\boldsymbol{I} \otimes (\boldsymbol{b}_{3}\boldsymbol{\rho}))vec(E[(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})(\boldsymbol{u}_{t} - \overline{\boldsymbol{u}})'])$$

$$= (\boldsymbol{I} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2}))[\boldsymbol{I} - \boldsymbol{\rho} \otimes (\boldsymbol{b}_{1}\boldsymbol{\beta}^{2} + \boldsymbol{b}_{2})]^{-1}[(\boldsymbol{\rho} \otimes (\boldsymbol{b}_{3}\boldsymbol{\rho}))[\boldsymbol{I} - \boldsymbol{\rho} \otimes \boldsymbol{\rho}]^{-1} + (\boldsymbol{I} \otimes \boldsymbol{b}_{3})]vec(\boldsymbol{\Sigma}_{\varepsilon})$$

$$+ (\boldsymbol{I} \otimes (\boldsymbol{b}_{3}\boldsymbol{\rho}))[\boldsymbol{I} - \boldsymbol{\rho} \otimes \boldsymbol{\rho}]^{-1}vec(\boldsymbol{\Sigma}_{\varepsilon}). \tag{B.7}$$

Therefore based on (B.7), the expression of matrix $E[(\boldsymbol{x}_t - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})'$ can be obtained. Then by transposing the matrix $E[(\boldsymbol{x}_t - \overline{\boldsymbol{x}})(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})',$ we obtain $vec(E[(\boldsymbol{u}_{t-1} - \overline{\boldsymbol{u}})(\boldsymbol{x}_t - \overline{\boldsymbol{x}})'])$. Furthermore, combining this with (B.6), we obtain the variance-covariance matrix $\Gamma(0)$ from (B.5) and $\Gamma(1)$ from (B.3). Based on the properties of matrix operations, it is easy to see that the entries of matrices $\Gamma(0)$ and $\Gamma(1)$ are continuous functions with respect to $(\beta_1, \beta_3, \dots, \beta_n)$ and the other related parameters. Thus the first-order autocorrelation coefficients of the nontrivial stochastic stationary system (2.24) are continuous functions with respect to $(\beta_1, \beta_3, \dots, \beta_n)$ and the other related parameters.

Zero-mean Special Case

Taking (2.32) as the starting point and assuming $\bar{\gamma} = \mathbf{0}$, we have

$$S_t = \gamma_1 S_{t-1} + \gamma_2 \boldsymbol{\beta}^2 S_{t-1} + \gamma_3 \eta_t \tag{B.8}$$

The first-order covariance matrix is given by:

$$\boldsymbol{\Gamma}(1) = E[S_t S'_{t-1}] = (\gamma_1 + \gamma_2 \boldsymbol{\beta}^2) E[S_{t-1} S'_{t-1}] + \gamma_3 E[\eta_t S'_{t-1}].$$
(B.9)

We have $E[\eta_t S'_{t-1}] = 0$, while $E[\eta_{t-1}S'_{t-1}] = E[\eta_{t-1}((\gamma_1 + \gamma_2 \boldsymbol{\beta}^2)S_{t-2} + \gamma_3 \eta_{t-1})'] = (\gamma_3 \boldsymbol{\Sigma}_{\boldsymbol{\eta}})'$. Further denoting $(\gamma_1 + \gamma_2 \boldsymbol{\beta}^2) = M(\boldsymbol{\beta})$, the expression in (B.9) reduces to:

$$\boldsymbol{\Gamma}(1) = M(\boldsymbol{\beta})\boldsymbol{\Gamma}(0), \tag{B.10}$$

with $\Gamma(0)$ the variance-covariance matrix. Taking the variance on both sides of (B.8) yields:

$$\boldsymbol{\Gamma}(0) = M(\boldsymbol{\beta})\boldsymbol{\Gamma}(0)M(\boldsymbol{\beta})' + \gamma_3 \boldsymbol{\Sigma}_{\boldsymbol{\eta}} \gamma_3'.$$
(B.11)

Vectorizing both sides and using $Vec(ABC) = (C' \otimes A)Vec(B)$, the expression above reduces to:

$$Vec(\boldsymbol{\Gamma}(0)) = (M(\boldsymbol{\beta}) \otimes M(\boldsymbol{\beta}))Vec(\boldsymbol{\Gamma}(0)) + (\gamma_3 \otimes \gamma_3)Vec(\boldsymbol{\Sigma}_{\boldsymbol{\eta}}).$$
(B.12)

Hence

$$Vec(\mathbf{\Gamma}(0)) = [I - M(\boldsymbol{\beta}) \otimes M(\boldsymbol{\beta})]^{-1} (\gamma_3 \otimes \gamma_3) Vec(\boldsymbol{\Sigma}_{\boldsymbol{\eta}}),$$
(B.13)

which yields (2.33).

C Proof of Proposition 2 (stability of SAC-learning under SAC-learning)

This appendix derives the E-stability conditions for a BLE $(\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$. Set $\gamma_t = (1+t)^{-1}$. For the learning dynamics in (2.28) and (2.8)⁴⁹, since all functions are smooth, the SAClearning rule satisfies the conditions (A.1-A.3) of Section 6.2.1 in Evans and Honkapohja (2001, p.124).

In order to check the conditions (B.1-B.2) of Section 6.2.1 in Evans and Honkapohja (2001, p.125), we rewrite the system in matrix form by

$$\boldsymbol{X}_t = \widetilde{\boldsymbol{A}}(\boldsymbol{\theta}_{t-1}) \boldsymbol{X}_{t-1} + \widetilde{\boldsymbol{B}}(\boldsymbol{\theta}_{t-1}) \boldsymbol{W}_t,$$

where $\boldsymbol{\theta}_t' = (\boldsymbol{\alpha}_t, \boldsymbol{\beta}_t, \boldsymbol{R}_t), \boldsymbol{X}_t' = (1, \boldsymbol{x}_t', \boldsymbol{x}_{t-1}', \boldsymbol{u}_t')$ and $\boldsymbol{W}_t' = (1, \boldsymbol{v}_t', \boldsymbol{\varepsilon}_t'),$

$$\widetilde{A}(\theta) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ b_0 + b_1(I - \beta^2)\alpha + b_2a & b_1\beta^2 & 0 & b_2\rho \\ 0 & I & 0 & 0 \\ a & 0 & 0 & \rho \end{pmatrix},$$

⁴⁹For convenience of theoretical analysis, one can set $\mathbf{S}_{t-1} = \mathbf{R}_t$.

$$\widetilde{B}(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathbf{I} & \mathbf{b_2} \\ 0 & 0 & 0 \\ 0 & 0 & \mathbf{I} \end{pmatrix}.$$

Based on the properties of eigenvalues, see e.g. Evans and Honkapohja (2001, p.117), all the eigenvalues of $\widetilde{A}(\theta)$ include 0 (multiple n + 1), the eigenvalues of ρ and $b_1\beta^2$. Thus based on the assumptions, all the eigenvalues of $\widetilde{A}(\theta)$ lie inside the unit circle. Moreover, it is easy to see all the other conditions for Section 6.2.1 of Chapter 6 in Evans and Honkapohja (2001) are also satisfied.

Since \boldsymbol{x}_t is stationary, then the limits

$$\sigma_i^2 := \lim_{t \to \infty} E(x_{i,t} - \alpha_i)^2, \qquad \sigma_{x_i x_{i,-1}}^2 := \lim_{t \to \infty} E(x_{i,t} - \alpha_i)(x_{i,t-1} - \alpha_i)$$

exist and are finite. Hence according to Section 6.2.1 of Chapter 6 in Evans and Honkapohja (2001, p.126), the associated ODE is

$$\begin{cases} \frac{d\boldsymbol{\alpha}}{d\tau} = \bar{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{\beta}) - \boldsymbol{\alpha}, \\ \frac{d\boldsymbol{\beta}}{d\tau} = \boldsymbol{R}^{-1}[\boldsymbol{E} - \boldsymbol{\beta}\boldsymbol{\Omega}] = \boldsymbol{R}^{-1}\boldsymbol{\Omega}[\boldsymbol{E}\boldsymbol{\Omega}^{-1} - \boldsymbol{\beta}], \\ \frac{d\boldsymbol{R}}{d\tau} = \boldsymbol{\Omega} - \boldsymbol{R}, \end{cases}$$
(C.1)

where \mathbf{R} is a diagonal matrix with the *i*-th diagonal entry R_i and $\mathbf{\Omega}$, \mathbf{E} are also diagonal matrices as defined in Section 2. As shown in Evans and Honkapohja (2001), a BLE corresponds to a fixed point of the following ODE (C.2).

$$\begin{cases} \frac{d\boldsymbol{\alpha}}{d\tau} = \overline{\boldsymbol{x}}(\boldsymbol{\alpha}, \boldsymbol{\beta}) - \boldsymbol{\alpha}, \\ \frac{d\boldsymbol{\beta}}{d\tau} = \boldsymbol{G} - \boldsymbol{\beta}. \end{cases}$$
(C.2)

Note that β and G are both diagonal matrices. The Jacobian matrix of C.2 is, in fact, equivalent to

$$\left(egin{array}{ccc} (I-b_1eta^{*2})^{-1}(b_1-I) & oldsymbol{arrho} \ 0 & DG_eta(eta^*)-I \end{array}
ight),$$

where DG_{β} is a Jacobian matrix with the (i, j)-th entry $\frac{\partial G_i}{\partial \beta_j}$ and the form of matrix $\boldsymbol{\varrho}$ is omitted since it is not needed in the proof. Therefore, if all the eigenvalues of $(\boldsymbol{I} - \boldsymbol{b}_1 \boldsymbol{\beta}^{*2})^{-1}(\boldsymbol{b}_1 - \boldsymbol{I})$ have negative real parts, and all the eigenvalues of $DG_{\beta}(\boldsymbol{\beta}^*)$ have real parts less than 1, the SAC-learning $(\boldsymbol{\alpha}_t, \boldsymbol{\beta}_t)$ converges to the BLE $(\boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ as time t tends to ∞ .

D Local Stability Conditions and Kalman Filter with SAC-learning

Local Stability of Quasi-Newton Iteration

This section studies the convergence of the Quasi-Newton iteration in (2.36). In particular, we show that the condition $\rho(DG_{\beta}(\beta^*)) < 1$ is not necessary for local stability. Note that the iteration is given as

$$\boldsymbol{\beta}^{(\boldsymbol{k+1})} = \boldsymbol{\beta}^{(\boldsymbol{k})} - DF_{\boldsymbol{\beta}}(\boldsymbol{\beta}^{(\boldsymbol{k})}, \theta)^{-1}F(\boldsymbol{\beta}^{(\boldsymbol{k})}, \theta), \qquad (D.1)$$

with $F(\boldsymbol{\beta^{(k)}}, \theta) = G(\boldsymbol{\beta^{(k)}}, \theta) - \boldsymbol{\beta^{(k)}}$. Defining⁵⁰ $H(\boldsymbol{\beta}) = \boldsymbol{\beta} - DF_{\boldsymbol{\beta}}(\boldsymbol{\beta})^{-1}F(\boldsymbol{\beta})$, we need to show that $H(\boldsymbol{\beta})$ is locally stable. Note that:

$$DH_{\boldsymbol{\beta}}(\boldsymbol{\beta}) = DF_{\boldsymbol{\beta}}(\boldsymbol{\beta})^{-2}D_{\boldsymbol{\beta}}^{2}F(\boldsymbol{\beta})F(\boldsymbol{\beta}),$$

with $DF_{\beta}(\beta) = DG_{\beta}(\beta) - I$ and $D^2_{\beta}F(\beta) = D^2_{\beta}G(\beta)$, which implies

$$DH_{\boldsymbol{\beta}}(\boldsymbol{\beta}) = (D_{\boldsymbol{\beta}}G(\boldsymbol{\beta}) - I)^{-2}D_{\boldsymbol{\beta}}^{2}G(\boldsymbol{\beta})(G(\boldsymbol{\beta}) - \boldsymbol{\beta}).$$

Since $\boldsymbol{\beta}^* = G(\boldsymbol{\beta}^*)$ at a BLE by definition, it follows that $\rho(DH_{\boldsymbol{\beta}}(\boldsymbol{\beta}^*)) < 1$. Hence (D.1) is locally stable at any BLE $\boldsymbol{\beta}^*$ and one can find a neighbourhood \hat{D} around $\boldsymbol{\beta}^*$ such that:

$$lim_{k\to\infty}H^k(\boldsymbol{\beta^{(0)}}) = \boldsymbol{\beta^*}, \forall \boldsymbol{\beta^{(0)}} \in \hat{D}.$$
 (D.2)

Importantly, this result holds for all E-stable and E-unstable BLE. Therefore the Quasi-Newton iteration may converge to E-unstable fixed-points.

Local Stability of Algorithm II

This section derives the local stability condition for Algorithm II. We first re-write the maximization problem to derive the local stability condition. Let $(\mathbf{0}, \boldsymbol{\beta^*})$ be an iteratively E-stable fixed-point at the estimated parameter values $\hat{\theta}^*$. Then the belief parameters $\boldsymbol{\beta^*}$ and the structural parameters $\hat{\theta}^*$ satisfy the following conditions:

$$\begin{cases} \boldsymbol{\beta^*} = G(\boldsymbol{\beta^*}, \theta^*) \\ \theta^* = \operatorname*{argmax}_{\theta} p(\theta | Y_{1:T}, \boldsymbol{\beta^*}). \end{cases}$$
(D.3)

⁵⁰For the remainder, we omit the dependence of $G(\beta, \theta)$ on the structural parameters θ for ease of notation.

Since the dataset $Y_{1:T}$ remains fixed at each step of the iteration, the second condition can be written as:

$$\theta^* = \underset{\theta}{\operatorname{argmax}} p(\theta | Y_{1:T}, \boldsymbol{\beta^*}) = p_m(\boldsymbol{\beta^*}), \qquad (D.4)$$

for some $p_m(.)$. This implies that the estimated structural parameters θ^* are given as a function of the equilibrium belief parameters β^* for a given dataset and likelihood function. Plugging this back into the first condition yields:

$$\boldsymbol{\beta}^* = G(\boldsymbol{\beta}^*, p_m(\boldsymbol{\beta}^*)). \tag{D.5}$$

(D.5) has the same functional form as the fixed-point iteration in (2.35). In this case the Jacobian matrix at the equilibrium β^* and θ^* is given by

$$DG_{\boldsymbol{\beta}}(\boldsymbol{\beta^*}) = \frac{\partial G}{\partial \boldsymbol{\beta}}_{|\boldsymbol{\beta^*},\theta^*} + \frac{\partial G}{\partial \theta^*} \frac{\partial \theta^*}{\partial \boldsymbol{\beta}}_{|\boldsymbol{\beta^*},\theta^*}.$$
 (D.6)

Note that the first component in (D.6) corresponds to the Jacobian matrix of $G(\boldsymbol{\beta})$ in the case with fixed parameters, while the second component appears due to the fact that the structural parameters also depend on $\boldsymbol{\beta}^*$. Further note that, all three partial derivatives that appear in (D.6) can be numerically evaluated. If the eigenvalue condition $\rho(DG(\boldsymbol{\beta}^*)) < 1$ is satisfied, it follows that $\boldsymbol{\beta}^* = G(\boldsymbol{\beta}^*, \theta^*)$ is locally stable under (2.40) and (2.41).

Kalman Filter with SAC learning

This section describes the Kalman filter algorithm used in the SAC-learning estimations in Section 3.3. The main filter block follows standard steps, and we use the filter output at the end of each iteration to update the belief parameters. Consider the law of motion (2.32), which can be rewritten as

$$S_t = \tilde{\gamma}_t + (\gamma_1 + \gamma_2 \beta_t^2) S_{t-1} + \gamma_3 \eta_t, \qquad (D.7)$$

where $\tilde{\gamma}_t = \bar{\gamma} + \gamma_2(\alpha_t + \beta_t^2 \alpha_t)$. Denote by $S_{0|0}, P_{0|0}, \boldsymbol{\alpha}_0, \boldsymbol{\beta}_0, \boldsymbol{R}_0$ the initial state vector, state covariance matrix, initial belief parameters and their initial covariance matrix respectively. Denoting by L, N and T the number of shocks, forward-looking variables and length of the dataset respectively, the recursion is given as follows:

For
$$\mathbf{t} = \mathbf{1} : \mathbf{T}$$

$$S_{t|t-1} = \tilde{\gamma}_{t-1} + (\gamma_1 + \gamma_2 \beta_{t-1}^2) S_{t-1|t-1},$$

$$P_{t|t-1} = (\gamma_1 + \gamma_2 \beta_{t-1}^2) P_{t-1|t-1} (\gamma_1 + \gamma_2 \beta_{t-1}^2)' + \gamma_3 \Sigma_{\eta} \gamma'_3,$$

$$v_t = Y_t - \phi_0 - \phi_1 S_{t|t-1},$$

$$\Sigma_t = \phi_1 P_{t|t-1} \phi'_1,$$

$$S_{t|t} = S_{t|t-1} + P_{t|t-1} \phi'_1 \Sigma_t^{-1} v_t,$$

$$P_{t|t} = P_{t|t-1} \phi'_1 \Sigma_t^{-1} \phi_1 P_{t|t-1},$$

$$p(y_t | \alpha_{t-1}, \beta_{t-1}) = -\frac{L}{2} ln(2\pi) - \frac{1}{2} ln | \Sigma_t| - \frac{1}{2} (v'_t \Sigma_t^{-1} v_t)$$
For $\mathbf{i} = \mathbf{1} : \mathbf{N}$

$$\alpha_{i,t} = \alpha_{i,t-1} + \frac{1}{t+1} (x_{i,t} - \alpha_{i,t-1}),$$

$$\beta_{i,t} = \beta_{i,t-1} + \frac{1}{t+1} R_{i,t}^{-1} [(x_{i,t} - \alpha_{i,t-1}) (x_{i,t-1} + \frac{x_{i,0}}{t+1} - \frac{t^2 + 3t + 1}{(t+1)^2} \alpha_{i,t-1} - \frac{1}{(t+1)^2} x_{i,t})$$

$$- \frac{t}{t+1} \beta_{i,t-1} (x_{i,t} - \alpha_{i,t-1})^2],$$

$$R_{i,t} = R_{i,t-1} + \frac{1}{t+1} [\frac{t}{t+1} (x_{i,t} - \alpha_{i,t-1})^2 - R_{i,t-1}].$$
End
(D.8)

The resulting likelihood function is combined with the prior distributions to obtain the posterior distribution that is estimated.

E Eigenvalues of matrix $B\beta^2$

This appendix shows the sufficiency condition for the existence of BLE in Corollary 2. The characteristic polynomial of $\mathbf{B}\beta^2$ is given by $h(\nu) = \nu^2 + c_1\nu + c_2$, where

$$c_1 = -\frac{\beta_y^2 + [\gamma \varphi + \lambda (1 + \varphi \phi_y)] \beta_\pi^2}{1 + \gamma \varphi \phi_\pi + \varphi \phi_y}, \quad c_2 = \frac{\lambda \beta_y^2 \beta_\pi^2}{1 + \gamma \varphi \phi_\pi + \varphi \phi_y}.$$

Both of the eigenvalues of $\mathbf{B}\beta^2$ are inside the unit circle if and only if both of the following conditions hold (see Elaydi, 1999):

$$h(1) > 0$$
, $h(-1) > 0$, $|h(0)| < 1$.

It is easy to see h(-1) > 0, |h(0)| < 1 for any $\beta_i \in [-1, 1]$. Note that

$$h(1) = \frac{(1 - \beta_y^2)(1 - \lambda\beta_\pi^2) + \gamma\varphi\phi_\pi + \varphi\phi_y - (\gamma\varphi + \lambda\varphi\phi_y)\beta_\pi^2}{1 + \gamma\varphi\phi_\pi + \varphi\phi_y}$$

$$\geq \frac{\varphi[\gamma(\phi_\pi - 1) + (1 - \lambda)\phi_y]}{1 + \gamma\varphi\phi_\pi + \varphi\phi_y}.$$

Thus if $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$, then h(1) > 0. Therefore, both eigenvalues of **B** β^2 lie inside the unit circle for all $\beta_i \in [-1, 1]$.

F First-order autocorrelation coefficients of output gap and inflation

This appendix derives the first-order autocorrelation coefficients for output gap and inflation in the New-Keynesian model. Define $\mathbf{z}_t = \mathbf{x}_t - \bar{\mathbf{x}}$. Then in order to obtain $\mathbf{G}(\boldsymbol{\alpha}, \boldsymbol{\beta})$, we first calculate $\mathbf{E}(z_t z'_{t-1})$ and $\mathbf{E}(z_t z'_t)$. Rewrite model (3.12) into its VARMA $(1, \infty)$ representation

$$\boldsymbol{z}_{t} = \boldsymbol{B}\boldsymbol{\beta}^{2}\boldsymbol{z}_{t-1} + \boldsymbol{C}\sum_{n=0}^{\infty}\rho^{n}\boldsymbol{\varepsilon}_{t-n}.$$
 (F.1)

Since both eigenvalues of $B\beta^2$ lie inside the unit circle under the assumption $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$ (see Appendix E), then

$$oldsymbol{z}_t = \mathbf{C}[
ho \mathbf{I} - \mathbf{C}^{-1} oldsymbol{B} oldsymbol{eta}^2 \mathbf{C}]^{-1} \sum_{n=0}^{\infty} [
ho^{n+1} \mathbf{I} - \mathbf{C}^{-1} (oldsymbol{B} oldsymbol{eta}^2)^{n+1} \mathbf{C}] oldsymbol{arepsilon}_{t-n}.$$

Note ρ is a scalar number and I is a 2 × 2 identity matrix. Based on i.i.d. assumption of ε_t ,

$$Ez_{t}z'_{t} = \mathbf{C}[\rho\mathbf{I} - \mathbf{C}^{-1}B\beta^{2}\mathbf{C}]^{-1}\sum_{n=0}^{\infty} [\rho^{n+1}\mathbf{I} - \mathbf{C}^{-1}(B\beta^{2})^{n+1}\mathbf{C}]\boldsymbol{\Sigma}[\rho^{n+1}\mathbf{I} - (\mathbf{C}^{-1}(B\beta^{2})^{n+1}\mathbf{C})'] \cdot [\rho\mathbf{I} - (\mathbf{C}^{-1}B\beta^{2}\mathbf{C})']^{-1}\mathbf{C}',$$
(F.2)

where $\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{bmatrix}$.

In the following we try to obtain the expression of the matrix $\boldsymbol{E} z_t \boldsymbol{z}'_t$ and hence we first calculate the matrix $\sum_{n=0}^{\infty} [\rho^{n+1}\mathbf{I} - \mathbf{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^2)^{n+1}\mathbf{C}]\boldsymbol{\Sigma}[\rho^{n+1}\mathbf{I} - (\mathbf{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^2)^{n+1}\mathbf{C})']$ and $\mathbf{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^2)^{n+1}\mathbf{C}$.

Note that

$$\boldsymbol{B}\boldsymbol{\beta}^{2} = \frac{1}{1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y}} \begin{bmatrix} \beta_{y}^{2} & \varphi(1 - \lambda\phi_{\pi})\beta_{\pi}^{2} \\ \gamma\beta_{y}^{2} & (\gamma\varphi + \lambda(1 + \varphi\phi_{y}))\beta_{\pi}^{2} \end{bmatrix}.$$

 $\pmb{B}\pmb{\beta}^2$ has two eigenvalues 51

$$\lambda_{1} = \frac{\left[\beta_{y}^{2} + (\gamma\varphi + \lambda + \lambda\varphi\phi_{y})\beta_{\pi}^{2}\right] + \sqrt{\left[\beta_{y}^{2} + (\gamma\varphi + \lambda + \lambda\varphi\phi_{y})\beta_{\pi}^{2}\right]^{2} - 4\lambda\beta_{y}^{2}\beta_{\pi}^{2}(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})}{2(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})},$$

$$\lambda_{2} = \frac{\left[\beta_{y}^{2} + (\gamma\varphi + \lambda + \lambda\varphi\phi_{y})\beta_{\pi}^{2}\right] - \sqrt{\left[\beta_{y}^{2} + (\gamma\varphi + \lambda + \lambda\varphi\phi_{y})\beta_{\pi}^{2}\right]^{2} - 4\lambda\beta_{y}^{2}\beta_{\pi}^{2}(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})}{2(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})}.$$

Their corresponding eigenvectors are

$$P_{1} = \left[\frac{\varphi(1-\lambda\phi_{\pi})\beta_{\pi}^{2}}{1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}}, \lambda_{1}-\frac{\beta_{y}^{2}}{1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}}\right]',$$
$$P_{2} = \left[\frac{\varphi(1-\lambda\phi_{\pi})\beta_{\pi}^{2}}{1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}}, \lambda_{2}-\frac{\beta_{y}^{2}}{1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}}\right]'.$$

Let $P = [P_1, P_2]$. Then

$$C^{-1}B\beta^2 C = C^{-1}P\begin{bmatrix}\lambda_1 & 0\\ 0 & \lambda_2\end{bmatrix}(C^{-1}P)^{-1},$$

where

$$\begin{array}{l} & \boldsymbol{C^{-1}P} \\ = & \left[\begin{array}{c} \frac{(1+\varphi\phi_y)\varphi(1-\lambda\phi_\pi)\beta_\pi^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y} + \varphi\phi_\pi \left(\lambda_1 - \frac{\beta_y^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y}\right) & \frac{(1+\varphi\phi_y)\varphi(1-\lambda\phi_\pi)\beta_\pi^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y} + \varphi\phi_\pi \left(\lambda_2 - \frac{\beta_y^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y}\right) \\ & \frac{-\gamma\varphi(1-\lambda\phi_\pi)\beta_\pi^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y} + \left(\lambda_1 - \frac{\beta_y^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y}\right) & \frac{-\gamma\varphi(1-\lambda\phi_\pi)\beta_\pi^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y} + \left(\lambda_2 - \frac{\beta_y^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y}\right) \end{array} \right] \\ =: & \left[\begin{array}{c} d_1 & d_2 \\ d_3 & d_4 \end{array} \right]. \end{array}$$

Correspondingly

$$(C^{-1}P)^{-1} = rac{1}{d_1d_4 - d_2d_3} \begin{bmatrix} d_4 & -d_2 \\ -d_3 & d_1 \end{bmatrix},$$

⁵¹In the special case $\lambda_1 = \lambda_2$, although $B\beta^2$ is not diagonalizable, the expressions of first-order autocorrelations (3.13) and (3.14) still hold based on the Jordan normal form of matrix $B\beta^2$. Without loss of generality, in the following we assume $\lambda_1 \neq \lambda_2$.

where

$$d_1d_4 - d_2d_3 = \det(\boldsymbol{C}^{-1}P) = \varphi(1 - \lambda\phi_\pi)\beta_\pi^2(\lambda_2 - \lambda_1).$$

Hence

$$\begin{aligned} \boldsymbol{C^{-1}}(\boldsymbol{B\beta^2})^{n+1}\boldsymbol{C} &= \boldsymbol{C^{-1}}\boldsymbol{P} \begin{bmatrix} \lambda_1^{n+1} & 0\\ 0 & \lambda_2^{n+1} \end{bmatrix} (\boldsymbol{C^{-1}}\boldsymbol{P})^{-1} \\ &= \frac{1}{d_1d_4 - d_2d_3} \begin{bmatrix} d_1d_4\lambda_1^{n+1} - d_2d_3\lambda_2^{n+1} & d_1d_2(\lambda_2^{n+1} - \lambda_1^{n+1})\\ d_3d_4(\lambda_1^{n+1} - \lambda_2^{n+1}) & d_1d_4\lambda_2^{n+1} - d_2d_3\lambda_1^{n+1} \end{bmatrix}. \end{aligned}$$

Thus

$$\begin{split} \rho^{n+1}I - C^{-1}(B\beta^2)^{n+1}C &= \\ \frac{1}{d_1d_4 - d_2d_3} \begin{bmatrix} d_1d_4(\rho^{n+1} - \lambda_1^{n+1}) - d_2d_3(\rho^{n+1} - \lambda_2^{n+1}) & -d_1d_2(\lambda_2^{n+1} - \lambda_1^{n+1}) \\ -d_3d_4(\lambda_1^{n+1} - \lambda_2^{n+1}) & d_1d_4(\rho^{n+1} - \lambda_2^{n+1}) - d_2d_3(\rho^{n+1} - \lambda_1^{n+1}) \end{bmatrix} \end{split}$$

.

Therefore

$$[\rho^{n+1}I - C^{-1}(B\beta^2)^{n+1}C]\Sigma[\rho^{n+1}I - (C^{-1}(B\beta^2)^{n+1}C)'] = \frac{1}{(d_1d_4 - d_2d_3)^2} \begin{bmatrix} s_1(n+1) & s_2(n+1) \\ s_2(n+1) & s_3(n+1) \end{bmatrix},$$

where

$$\begin{split} s_1(n+1) &= \sigma_1^2 [d_1 d_4(\rho^{n+1} - \lambda_1^{n+1}) - d_2 d_3(\rho^{n+1} - \lambda_2^{n+1})]^2 + \sigma_2^2 [d_1 d_2(\lambda_2^{n+1} - \lambda_1^{n+1})]^2, \\ s_2(n+1) &= \sigma_1^2 d_3 d_4(\lambda_2^{n+1} - \lambda_1^{n+1}) [d_1 d_4(\rho^{n+1} - \lambda_1^{n+1}) - d_2 d_3(\rho^{n+1} - \lambda_2^{n+1})] + \\ &\quad \sigma_2^2 d_1 d_2(\lambda_1^{n+1} - \lambda_2^{n+1}) [d_1 d_4(\rho^{n+1} - \lambda_2^{n+1}) - d_2 d_3(\rho^{n+1} - \lambda_1^{n+1})], \\ s_3(n+1) &= \sigma_1^2 [d_3 d_4(\lambda_2^{n+1} - \lambda_1^{n+1})]^2 + \sigma_2^2 [d_1 d_4(\rho^{n+1} - \lambda_2^{n+1}) - d_2 d_3(\rho^{n+1} - \lambda_1^{n+1})]^2. \end{split}$$

Correspondingly it is natural to have

$$\sum_{n=0}^{\infty} \left[\rho^{n+1} I - C^{-1} (B\beta^2)^{n+1} C \right] \Sigma \left[\rho^{n+1} I - (C^{-1} (B\beta^2)^{n+1} C)' \right]$$

$$= \frac{1}{(d_1 d_4 - d_2 d_3)^2} \begin{bmatrix} \sum_{n=0}^{\infty} s_1(n+1) & \sum_{n=0}^{\infty} s_2(n+1) \\ \sum_{n=0}^{\infty} s_2(n+1) & \sum_{n=0}^{\infty} s_3(n+1) \end{bmatrix}$$

$$= \frac{1}{(d_1 d_4 - d_2 d_3)^2} \begin{bmatrix} s_1^* & s_2^* \\ s_2^* & s_3^* \end{bmatrix}, \quad (F.3)$$

where

$$s_{1}^{*} = \sigma_{1}^{2} \Big[(d_{1}d_{4} - d_{2}d_{3})^{2} \frac{1}{1 - \rho^{2}} - 2d_{1}d_{4}(d_{1}d_{4} - d_{2}d_{3}) \frac{1}{1 - \rho\lambda_{1}} + (d_{1}d_{4})^{2} \frac{1}{1 - \lambda_{1}^{2}} \\ + 2d_{2}d_{3}(d_{1}d_{4} - d_{2}d_{3}) \frac{1}{1 - \rho\lambda_{2}} - 2d_{1}d_{2}d_{3}d_{4} \frac{1}{1 - \lambda_{1}\lambda_{2}} + (d_{2}d_{3})^{2} \frac{1}{1 - \lambda_{2}^{2}} \Big] \\ + \sigma_{2}^{2} \Big[(d_{1}d_{2})^{2} \Big(\frac{1}{1 - \lambda_{2}^{2}} - \frac{2}{1 - \lambda_{1}\lambda_{2}} + \frac{1}{1 - \lambda_{1}^{2}} \Big) \Big],$$
(F.4)

$$s_{2}^{*} = \sigma_{1}^{2} \left[d_{3}d_{4} \left\{ (d_{1}d_{4} - d_{2}d_{3}) \left(\frac{1}{1 - \rho\lambda_{2}} - \frac{1}{1 - \rho\lambda_{1}} \right) + \frac{d_{1}d_{4}}{1 - \lambda_{1}^{2}} - \frac{d_{1}d_{4} + d_{2}d_{3}}{1 - \lambda_{1}\lambda_{2}} + \frac{d_{2}d_{3}}{1 - \lambda_{2}^{2}} \right\} \right] + \sigma_{2}^{2} \cdot \left[d_{1}d_{2} \left\{ (d_{1}d_{4} - d_{2}d_{3}) \left(\frac{1}{1 - \rho\lambda_{1}} - \frac{1}{1 - \rho\lambda_{2}} \right) + \frac{d_{1}d_{4}}{1 - \lambda_{2}^{2}} - \frac{d_{1}d_{4} + d_{2}d_{3}}{1 - \lambda_{1}\lambda_{2}} + \frac{d_{2}d_{3}}{1 - \lambda_{1}^{2}} \right\} \right], \quad (F.5)$$

$$s_{3}^{*} = \sigma_{1}^{2} \left[(d_{3}d_{4})^{2} \left(\frac{1}{1 - \lambda_{2}^{2}} - \frac{2}{1 - \lambda_{1}\lambda_{2}} + \frac{1}{1 - \lambda_{1}^{2}} \right) \right]$$

$$+\sigma_{2}^{2} \Big[(d_{1}d_{4} - d_{2}d_{3})^{2} \frac{1}{1 - \rho^{2}} - 2d_{1}d_{4}(d_{1}d_{4} - d_{2}d_{3}) \frac{1}{1 - \rho\lambda_{2}} + (d_{1}d_{4})^{2} \frac{1}{1 - \lambda_{2}^{2}} \\ + 2d_{2}d_{3}(d_{1}d_{4} - d_{2}d_{3}) \frac{1}{1 - \rho\lambda_{1}} - 2d_{1}d_{2}d_{3}d_{4} \frac{1}{1 - \lambda_{1}\lambda_{2}} + (d_{2}d_{3})^{2} \frac{1}{1 - \lambda_{1}^{2}} \Big].$$
(F.6)

Therefore based on (F.2) and (F.3), we can further obtain the expression of $Ez_t z'_t$. Note that

$$[\boldsymbol{\rho}\boldsymbol{I} - \boldsymbol{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^{2})\boldsymbol{C}]^{-1} = \frac{1}{\widetilde{m}} \begin{bmatrix} d_{1}d_{4}(\boldsymbol{\rho} - \lambda_{2}) - d_{2}d_{3}(\boldsymbol{\rho} - \lambda_{1}) & d_{1}d_{2}(\lambda_{2} - \lambda_{1}) \\ d_{3}d_{4}(\lambda_{1} - \lambda_{2}) & d_{1}d_{4}(\boldsymbol{\rho} - \lambda_{1}) - d_{2}d_{3}(\boldsymbol{\rho} - \lambda_{2}) \end{bmatrix},$$

where $\widetilde{m} = (d_1d_4 - d_2d_3)(\rho - \lambda_1)(\rho - \lambda_2)$, and

$$\boldsymbol{C}[\boldsymbol{\rho}\boldsymbol{I} - \boldsymbol{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^{2})\boldsymbol{C}]^{-1} = \frac{1}{\widetilde{m}(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})} \begin{bmatrix} k_{1} & k_{2} \\ k_{3} & k_{4} \end{bmatrix},$$

where

$$k_1 = d_1 d_4 (\rho - \lambda_2) - d_2 d_3 (\rho - \lambda_1) - \varphi \phi_\pi d_3 d_4 (\lambda_1 - \lambda_2),$$
 (F.7)

$$k_{2} = d_{1}d_{2}(\lambda_{2} - \lambda_{1}) - \varphi \phi_{\pi}[d_{1}d_{4}(\rho - \lambda_{1}) - d_{2}d_{3}(\rho - \lambda_{2})],$$
 (F.8)

$$k_3 = \gamma [d_1 d_4 (\rho - \lambda_2) - d_2 d_3 (\rho - \lambda_1)] + (1 + \varphi \phi_y) d_3 d_4 (\lambda_1 - \lambda_2),$$
(F.9)

$$k_4 = \gamma d_1 d_2 (\lambda_2 - \lambda_1) + (1 + \varphi \phi_y) [d_1 d_4 (\rho - \lambda_1) - d_2 d_3 (\rho - \lambda_2)].$$
(F.10)

Thus we have

$$\boldsymbol{E} z_t \boldsymbol{z}_t' = \widetilde{k} \cdot \begin{bmatrix} k_1^2 s_1^* + 2k_1 k_2 s_2^* + k_2^2 s_3^* & k_1 k_3 s_1^* + (k_1 k_4 + k_2 k_3) s_2^* + k_2 k_4 s_3^* \\ k_1 k_3 s_1^* + (k_1 k_4 + k_2 k_3) s_2^* + k_2 k_4 s_3^* & k_3^2 s_1^* + 2k_3 k_4 s_2^* + k_4^2 s_3^* \end{bmatrix}$$
(F.11)

where $\tilde{k} = \frac{1}{(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})^{2}(d_{1}d_{4}-d_{2}d_{3})^{4}(\rho-\lambda_{1})^{2}(\rho-\lambda_{2})^{2}}$, s_{i}^{*} is given in (F.4)-(F.6) and k_{i} is given in (F.7)-(F.10).

Through complicated calculations⁵², the variances of output gap and inflations can be further simplified as

$$\begin{split} E(y_{t}^{2}) &= \frac{1}{\tilde{k}} (k_{1}^{2}s_{1}^{*} + 2k_{1}k_{2}s_{2}^{*} + k_{2}^{2}s_{3}^{*}) \\ &= \frac{1}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \lambda_{1}^{2})(1 - \rho\lambda_{2})(1 - \lambda_{1}\lambda_{2})} \\ \left\{ \sigma_{1}^{2} \Big[[(1 + \lambda^{2}\beta_{\pi}^{4}) - 2\lambda\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2}) + (1 + \lambda^{2}\beta_{\pi}^{4})(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})] \\ -\rho\lambda_{1}\lambda_{2} [(1 + \lambda^{2}\beta_{\pi}^{4})(\rho + \lambda_{1} + \lambda_{2}) - 2\lambda\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) + (1 + \lambda^{2}\beta_{\pi}^{4})\rho\lambda_{1}\lambda_{2}] \Big] \\ +\sigma_{2}^{2} \Big[[((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4}) - 2\varphi\phi_{\pi}\varphi\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2}) + ((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4})(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})] \\ -\rho\lambda_{1}\lambda_{2} [((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4})(\rho + \lambda_{1} + \lambda_{2}) - 2\varphi\phi_{\pi}\varphi\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) \\ + ((\varphi\phi_{\pi})^{2} + \varphi^{2}\beta_{\pi}^{4})\rho\lambda_{1}\lambda_{2}] \Big] \Big\}, \qquad (F.12) \\ E(\pi_{t}^{2}) &= \frac{1}{\tilde{k}} (k_{3}^{2}s_{1}^{*} + 2k_{3}k_{4}s_{2}^{*} + k_{4}^{2}s_{3}^{*}) \\ = \frac{1}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \lambda_{1}^{2})(1 - \rho\lambda_{2})(1 - \lambda_{2}^{2})(1 - \lambda_{1}\lambda_{2})} \\ \left\{ \sigma_{1}^{2} \Big[\gamma^{2} [1 + \rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2} - \rho\lambda_{1}\lambda_{2}(\rho + \lambda_{1} + \lambda_{2}) - (\rho\lambda_{1}\lambda_{2})^{2}] \Big] \\ +\sigma_{2}^{2} \Big[[((1 + \varphi\phi_{y})^{2} + \beta_{y}^{4}) - 2(1 + \varphi\phi_{y})\beta_{y}^{2}(\rho + \lambda_{1} + \lambda_{2}) + ((1 + \varphi\phi_{y})^{2} + \beta_{y}^{4}) \\ (\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - (\rho\lambda_{1}\lambda_{2}] \Big] \Big\}. \qquad (F.13)$$

Note that here $E(y_t^2)$ and $E(\pi_t^2)$ in fact depend on the trace $\lambda_1 + \lambda_2$ and determinant $\lambda_1 \lambda_2$.

With the expression of covariance matrix $Ez_t z'_t$, in order to obtain the expressions of first-order autocorrelation coefficient of output gap and inflation, we need to further calculate the first-order autocovariance $Ez_t z'_{t-1}$.

Following the similar calculations to $\boldsymbol{E} z_t \boldsymbol{z}_t'$, we can obtain

$$\begin{split} \boldsymbol{E}\boldsymbol{z}_{t}\boldsymbol{z}_{t-1}' &= \mathbf{C}[\rho\mathbf{I} - \mathbf{C}^{-1}\boldsymbol{B}\boldsymbol{\beta}^{2}\mathbf{C}]^{-1}\sum_{n=1}^{\infty}[\rho^{n+1}\mathbf{I} - \mathbf{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^{2})^{n+1}\mathbf{C}]\boldsymbol{\Sigma}[\rho^{n}\mathbf{I} - (\mathbf{C}^{-1}(\boldsymbol{B}\boldsymbol{\beta}^{2})^{n}\mathbf{C})'] \cdot \\ & \left[\rho\mathbf{I} - (\mathbf{C}^{-1}\boldsymbol{B}\boldsymbol{\beta}^{2}\mathbf{C})'\right]^{-1}\mathbf{C}' \\ &= \widetilde{k} \begin{bmatrix} k_{1}^{2}w_{1}^{*} + k_{1}k_{2}(w_{2}^{*} + w_{3}^{*}) + k_{2}^{2}w_{4}^{*} & k_{1}k_{3}w_{1}^{*} + k_{1}k_{4}w_{2}^{*} + k_{2}k_{3}w_{3}^{*} + k_{2}k_{4}w_{4}^{*} \\ k_{1}k_{3}w_{1}^{*} + k_{2}k_{3}w_{2}^{*} + k_{1}k_{4}w_{3}^{*} + k_{2}k_{4}w_{4}^{*} & k_{3}^{2}w_{1}^{*} + k_{3}k_{4}(w_{2}^{*} + w_{3}^{*}) + k_{4}^{2}w_{4}^{*} \end{bmatrix} \end{split}$$

,

 $^{^{52}\}mathrm{Because}$ of limit of pages, we drop the calculations here.

where \tilde{k} , k_i are given in (F.11) and (F.7)-(F.10), and

$$\begin{split} w_1^* &= \sigma_1^2 \Big\{ (d_1 d_4 - d_2 d_3)^2 \frac{\rho}{1 - \rho^2} - d_1 d_4 (d_1 d_4 - d_2 d_3) \frac{\rho + \lambda_1}{1 - \rho\lambda_1} + (d_1 d_4)^2 \frac{\lambda_1}{1 - \lambda_1^2} \\ &+ d_2 d_3 (d_1 d_4 - d_2 d_3) \frac{\rho + \lambda_2}{1 - \rho\lambda_2} - d_1 d_2 d_3 d_4 \frac{\lambda_1 + \lambda_2}{1 - \lambda_1 \lambda_2} + (d_2 d_3)^2 \frac{\lambda_2}{1 - \lambda_2^2} \Big\} \\ &+ \sigma_2^2 (d_1 d_2)^2 \Big[\frac{\lambda_2}{1 - \lambda_2^2} - \frac{\lambda_1 + \lambda_2}{1 - \lambda_1 \lambda_2} + \frac{\lambda_1}{1 - \lambda_1^2} \Big], \\ w_2^* &= \sigma_1^2 d_3 d_4 \Big\{ (d_1 d_4 - d_2 d_3) \Big[\frac{\rho}{1 - \rho\lambda_2} - \frac{\rho}{1 - \rho\lambda_1} \Big] + \frac{d_1 d_4 \lambda_1}{1 - \lambda_1^2} - \frac{d_1 d_4 \lambda_1 + d_2 d_3 \lambda_2}{1 - \lambda_1 \lambda_2} + \frac{d_2 d_3 \lambda_2}{1 - \lambda_1^2} \Big\} \\ &+ \sigma_2^2 d_1 d_2 \Big\{ (d_1 d_4 - d_2 d_3) \Big[\frac{\lambda_1}{1 - \rho\lambda_1} - \frac{\lambda_2}{1 - \rho\lambda_2} \Big] + \frac{d_2 d_3 \lambda_1}{1 - \lambda_1^2} - \frac{d_1 d_4 \lambda_1 + d_2 d_3 \lambda_2}{1 - \lambda_1 \lambda_2} + \frac{d_1 d_4 \lambda_2}{1 - \lambda_2^2} \Big\} \\ w_3^* &= \sigma_1^2 d_3 d_4 \Big\{ (d_1 d_4 - d_2 d_3) \Big[\frac{\lambda_2}{1 - \rho\lambda_2} - \frac{\lambda_1}{1 - \rho\lambda_1} \Big] + \frac{d_1 d_4 \lambda_1}{1 - \lambda_1^2} - \frac{d_1 d_4 \lambda_2 + d_2 d_3 \lambda_1}{1 - \lambda_1 \lambda_2} + \frac{d_2 d_3 \lambda_2}{1 - \lambda_2^2} \Big\} \\ &+ \sigma_2^2 d_1 d_2 \Big\{ (d_1 d_4 - d_2 d_3) \Big[\frac{\rho}{1 - \rho\lambda_1} - \frac{\rho}{1 - \rho\lambda_2} \Big] + \frac{d_1 d_4 \lambda_2}{1 - \lambda_2^2} - \frac{d_1 d_4 \lambda_2 + d_2 d_3 \lambda_1}{1 - \lambda_1 \lambda_2} + \frac{d_2 d_3 \lambda_1}{1 - \lambda_1^2} \Big\} , \\ w_4^* &= \sigma_1^2 (d_3 d_4)^2 \Big[\frac{\lambda_2}{1 - \lambda_2^2} - \frac{\lambda_1 + \lambda_2}{1 - \lambda_1 \lambda_2} + \frac{\lambda_1}{1 - \lambda_1^2} \Big] + \sigma_2^2 \Big\{ (d_1 d_4 - d_2 d_3)^2 \frac{\rho}{1 - \rho^2} \\ &- d_1 d_4 (d_1 d_4 - d_2 d_3) \frac{\rho + \lambda_2}{1 - \rho\lambda_2} + (d_1 d_4)^2 \frac{\lambda_2}{1 - \lambda_2^2} + d_2 d_3 (d_1 d_4 - d_2 d_3)^2 \frac{\rho + \lambda_1}{1 - \rho\lambda_1} \\ &- d_1 d_2 d_3 d_4 \frac{\lambda_1 + \lambda_2}{1 - \lambda_1 \lambda_2} + (d_2 d_3)^2 \frac{\lambda_1}{1 - \lambda_1^2} \Big\} . \end{split}$$

Again through technical calculations, the first-order auto-covariances of output gap and inflations are further simplified as

$$E(y_{t}y_{t-1}) = \frac{1}{\tilde{k}}(k_{1}^{2}w_{1}^{*} + k_{1}k_{2}(w_{2}^{*} + w_{3}^{*}) + k_{2}^{2}w_{4}^{*})$$

$$= \frac{1}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \lambda_{1}^{2})(1 - \rho\lambda_{2})(1 - \lambda_{2}^{2})(1 - \lambda_{1}\lambda_{2})} \left\{\sigma_{1}^{2}\left[(\rho + \lambda_{1} + \lambda_{2} - \lambda\beta_{\pi}^{2})[1 - \lambda\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2})] + [\lambda\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \rho\lambda_{1}\lambda_{2}][(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \lambda\beta_{\pi}^{2}\rho\lambda_{1}\lambda_{2}]\right] + \sigma_{2}^{2}\left[(\varphi\phi_{\pi}(\rho + \lambda_{1} + \lambda_{2}) - \varphi\beta_{\pi}^{2}))\right] \left[\varphi\phi_{\pi} - \varphi\beta_{\pi}^{2}(\rho + \lambda_{1} + \lambda_{2})] + [\varphi\beta_{\pi}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \varphi\phi_{\pi}\rho\lambda_{1}\lambda_{2}] \left[\varphi\phi_{\pi}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \varphi\beta_{\pi}^{2}\rho\lambda_{1}\lambda_{2}]\right]\right\},$$
(F.14)

$$E(\pi_{t}\pi_{t-1}) = \frac{1}{\tilde{k}}(k_{3}^{2}w_{1}^{*} + k_{3}k_{4}(w_{2}^{*} + w_{3}^{*}) + k_{4}^{2}w_{4}^{*})$$

$$= \frac{1}{(1 + \gamma\varphi\phi_{\pi} + \varphi\phi_{y})^{2}(1 - \rho^{2})(1 - \rho\lambda_{1})(1 - \lambda_{1}^{2})(1 - \rho\lambda_{2})(1 - \lambda_{2}^{2})(1 - \lambda_{1}\lambda_{2})} \left\{\sigma_{1}^{2}\left[\gamma^{2}[(\rho + \lambda_{1} + \lambda_{2}) - \rho\lambda_{1}\lambda_{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2})]\right] + \sigma_{2}^{2}\left[[(1 + \varphi\phi_{y})(\rho + \lambda_{1} + \lambda_{2}) - \beta_{y}^{2}] \cdot \left[(1 + \varphi\phi_{y}) - \beta_{y}^{2}(\rho + \lambda_{1} + \lambda_{2})\right] + \left[\beta_{y}^{2}(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - (1 + \varphi\phi_{y})\rho\lambda_{1}\lambda_{2}\right] \cdot \left[(1 + \varphi\phi_{y})(\rho\lambda_{1} + \rho\lambda_{2} + \lambda_{1}\lambda_{2}) - \beta_{y}^{2}\rho\lambda_{1}\lambda_{2}\right]\right\}.$$
(F.15)

Therefore, the first-order autocorrelation coefficients of output gap and inflation

$$G_1(\beta_y, \beta_\pi) = \frac{E(y_t y_{t-1})}{E(y_t^2)}, \quad G_2(\beta_y, \beta_\pi) = \frac{E(\pi_t \pi_{t-1})}{E(\pi_t^2)},$$

i.e. the equations (3.13-3.18). Finally, the covariance between output gap and inflation is given as

$$E(y_{t}\pi_{t}) = \left(-\sigma_{y}^{2}\gamma\left(-(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}+\beta_{y}^{2}\rho)+\beta_{\pi}^{4}\lambda(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y}+\beta_{y}^{2}\rho)(\lambda+\gamma\varphi+\lambda\varphi\phi_{y})+\beta_{\pi}^{2}\rho[\beta_{y}^{4}\lambda+\beta_{y}^{2}\lambda\rho(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})+\gamma\varphi\right.\\\left.\left.\left(-1+\lambda\phi_{\pi})(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})\right]-\beta_{y}^{2}\beta_{\pi}^{6}\lambda^{2}\rho(\beta_{y}^{2}\lambda+\rho(\lambda+\gamma\varphi+\lambda\varphi\phi_{y}))\right)+\sigma_{\pi}^{2}\varphi\right.\\\left.\left(-\phi_{\pi}(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})[-\beta_{y}^{4}-\beta_{y}^{2}\gamma\rho\varphi\phi_{\pi}+(1+\varphi\phi_{y})(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})]+\beta_{y}^{2}\beta_{\pi}^{6}\lambda\rho\right.\\\left.\left.\left(-\gamma\varphi(-\beta_{y}^{2}+\rho+\rho\varphi\phi_{y})+\lambda\rho(\beta_{y}^{4}-(1+\varphi\phi_{y})^{2})\right)+\beta_{\pi}^{4}(\gamma\varphi(1-\beta_{y}^{2}\rho+\varphi\phi_{y})(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{\pi}+\varphi\phi_{y})+\lambda(-1+\beta_{y}^{2}\rho-\varphi(\gamma\phi_{\pi}+\phi_{y}))(\beta_{y}^{4}-(1+\varphi\phi_{y})^{2})+\beta_{y}^{2}\lambda^{2}\rho\phi_{\pi}(-\beta_{y}^{4}+(1+\varphi\phi_{y})^{2})\right)+\beta_{\pi}^{2}\rho[-\beta_{y}^{6}\lambda\rho\phi_{\pi}+\beta_{y}^{2}\lambda\rho\phi_{\pi}(1+\varphi\phi_{y})(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})-(-1+\lambda\phi_{\pi})(1+\varphi\phi_{y})^{2}(1+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})+\beta_{y}^{4}(-1-\varphi(\gamma\phi_{\pi}+\varphi_{y})+\lambda(\phi_{\pi}+\varphi\phi_{\pi}\phi_{y}))]\right)\right)\right/\\\left.\left(\left(-1+\rho^{2})(-1+\beta_{y}^{2}\beta_{\pi}^{2}\lambda-\varphi(\gamma\phi_{\pi}+\phi_{y}))(1+\beta_{y}^{2}\rho(-1+\beta_{\pi}^{2}\lambda\rho)+\gamma\varphi\phi_{\pi}+\varphi\phi_{y})-\beta_{\pi}^{2}\rho(\lambda+\gamma\varphi+\lambda\varphi\phi_{y})^{2}\right)\right).\right)$$
(F.16)

G Stability for the Taylor rule

This appendix shows the E-stability condition in Corollary 3. Based on Proposition 2, we only need to show that both of the eigenvalues of $(\boldsymbol{I} - \boldsymbol{B}\boldsymbol{\beta}^2)^{-1}(\boldsymbol{B} - \boldsymbol{I})$ have negative real parts if $\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y > 0$.

The characteristic polynomial of $(\boldsymbol{I} - \boldsymbol{B}\boldsymbol{\beta}^2)^{-1}(\boldsymbol{B} - \boldsymbol{I})$ is given by $h(\nu) = \nu^2 - c_1\nu + c_2$, where c_1 is the trace and c_2 is the determinant of matrix $(\boldsymbol{I} - \boldsymbol{B}\boldsymbol{\beta}^2)^{-1}(\boldsymbol{B} - \boldsymbol{I})$. Direct calculation shows that

$$c_1 = \frac{-(1-\lambda)(1-\beta_y^2) - 2\varphi(\gamma\phi_\pi + \phi_y) + \varphi(\gamma + \lambda\phi_y)(1+\beta_\pi^2)}{\Delta (1+\gamma\varphi\phi_\pi + \varphi\phi_y)}, \quad (G.1)$$

$$c_2 = \frac{\varphi[\gamma(\phi_{\pi} - 1) + (1 - \lambda)\phi_y]}{\Delta (1 + \gamma\varphi\phi_{\pi} + \varphi\phi_y)}, \qquad (G.2)$$

where $\Delta = \frac{(1-\beta_y^2)(1-\lambda\beta_\pi^2)+\gamma\varphi\phi_\pi+\varphi\phi_y-(\gamma\varphi+\lambda\varphi\phi_y)\beta_\pi^2}{1+\gamma\varphi\phi_\pi+\varphi\phi_y}$. Both of the eigenvalues of $(\boldsymbol{I}-\boldsymbol{B}\boldsymbol{\beta}^2)^{-1}(\boldsymbol{B}-\boldsymbol{I})$ have negative real parts if and only if $c_1 < 0$ and $c_2 > 0$ (these conditions are obtained by applying the *Routh-Hurwitz criterion* theorem; see Brock and Malliaris, 1989). If $\gamma(\phi_{\pi}-1) + (1-\lambda)\phi_y > 0$, from Appendix E it is easy to see $\Delta > 0$. Furthermore,

$$c_1 \le \frac{-2\varphi[(\gamma(\phi_{\pi}-1) + (1-\lambda)\phi_y]}{\Delta (1 + \gamma\varphi\phi_{\pi} + \varphi\phi_y)} < 0, \quad c_2 > 0.$$

Η Robustness Checks

This appendix provides some robustness checks on our estimations by considering subsamples of our main dataset and using a third alternative definition of output gap based on de-trended output.

Subsample Estimations

We first chek whether our main results hold across different sample periods. To this end, we use our HP-filtered measure of output gap and consider three periods: 1966:I-1979:II, the period before Great Moderation; 1966:I-2008:IV, the period before Great Recession (i.e. before the zero lower bound episode); and 1984:I-2008:IV, the Great Moderation period.

Table 4 reports the posterior mode and the corresponding Laplace approximation for all periods under BLE and REE. It is readily seen that the difference between parameter estimates are preserved across all three periods: BLE is characterized by lower persistence but larger standard deviation estimates in shocks, a steeper Phillips curve characterized by larger γ , and a smaller risk aversion coefficient. The estimation under BLE provides a better model fit under all three subsamples, with Bayes' Factors of 1.67, 3.93 and 2.44 in favor of the BLE model.

Period	66:I-79:II		66:I-08:IV		84:I-08:IV	
	BLE	REE	BLE	REE	BLE	REE
Laplace	-118.63	-122.47	-313.16	-322.10	-34.32	-39.93
Bayes Factor	1.67		3.93		2.44	
Parameter	Mode		Mode		Mode	
η_y	0.94	0.24	0.76	0.17	0.53	0.09
η_{π}	0.38	0.06	0.3	0.04	0.18	0.08
η_r	0.20	0.20	0.31	0.32	0.15	0.15
$ar{y}$	-0.22	-0.14	-0.09	-0.14	0.05	-0.14
$\bar{\pi}$	0.93	0.75	0.84	0.71	0.61	0.58
$ar{r}$	1.03	0.86	1.25	1.08	1.14	0.97
γ	0.054	0.01	0.033	0.006	0.046	0.007
$\frac{1}{\varphi}$	2.44	2.77	4.03	3.78	2.82	3.15
$\dot{\phi}_{\pi}$	1.03	1.07	1.29	1.31	1.55	1.57
ϕ_y	0.39	0.36	0.45	0.42	0.48	0.54
$ ho_y$	0.5	0.87	0.42	0.88	0.44	0.94
$ ho_{\pi}$	0.31	0.85	0.32	0.87	0.24	0.55
$ ho_r$	0.72	0.68	0.83	0.77	0.9	0.85

Table 4: Comparison of the sub-sample estimations under BLE and REE: 66:I-79:II, the period before Great Moderation; 66:I-08:IV, the period before Great Recession and the zero lower bound episode; and 84:I-08:IV, the Great Moderation period.

Alternative Definition of Output Gap: Based on De-trended Output

Next we repeat our estimations using a third alternative measure of output gap based on de-trended output. The estimations over the main sample are reported in Table 5, which also includes the CBO-based estimates for reference. It is readily seen that the conclusions from this exercise are similar: BLE is characterized by lower persistence but larger standard deviation estimates in shocks, a steeper Phillips curve characterized by larger γ , and a smaller risk aversion coefficient. The likelihood is also better under BLE, with a Bayes' Factors of 11.49. Comparing the BLE estimates under de-trended and CBO-based measures, we observe mainly similar measures with a few exeptions: with the de-trended measure, we have a slightly lower γ and ϕ_y , while $\frac{1}{\varphi}$ and η_y are slightly higher. This suggests that the de-trended measure of output gap is even more volatile than CBO-based measure, which in turn is more volatile than the HP-filtered measure based on our results in Section 3.

As a final check, we compare the likelihoods across the three sub-samples with these two measures of output gap, which is reported in Table 6: it is readily seen that the likelihood under BLE is better for both measures under all sub-samples, although the difference for the Great Moderation period 1985-I:2008:IV is much smaller. These results are consistent with our previous findings.

	BLE det.	REE det.	BLE CBO.	REE CBO.
Laplace	-360.96	-387.42	-342.9	-366.88
Bayes Factor	11.49		10.41	
	Post.		Post.	
Parameter	Mode	Mode	Mode	Mode
η_y	0.78	0.08	0.74	0.11
η_{π}	0.3	0.04	0.29	0.04
η_r	0.3	0.31	0.29	0.3
\bar{y}	-0.13	-0.19	-0.54	-0.42
$\bar{\pi}$	0.79	0.66	0.81	0.59
\overline{r}	1.09	0.92	1.15	1.05
γ	0.017	0.004	0.024	0.006
$\frac{1}{\varphi}$	2.92	4.86	2.65	4.57
ϕ_{π}	1.44	1.45	1.41	1.43
ϕ_y	0.22	0.16	0.36	0.27
$ ho_y$	0.42	0.88	0.42	0.89
ρ_{π}	0.31	0.94	0.31	0.92
ρ_r	0.88	0.79	0.88	0.8

Table 5: Alternative estimations of the 3-equation NKPC model: we compare the results under BLE and REE with two alternative specifications of output gap. In the first case output gap is defined as the deviation of output from a quadratic trend, while in the latter we take the output gap based on CBO's measure of potential output.

	66:I-79:II		66:I-08:IV		84:I-08:IV	
	BLE	REE	BLE	REE	BLE	REE
CBO's estimate	-126.07	-127.6	-321.9	-344.4	-36.7	-46.9
Bayes Factor	0.66		9.77		4.43	
Detrended output	-129.9	-133.1	-333.1	-353.2	-48.4	-66.9
Bayes Factor	1.39		8.73		8.03	

Table 6: Sub-sample estimations with alternative definitions of output gap.

I Data Appendix

This appendix describes the dataset used in our estimations. The observable variables used in our estimations follow the definitions in Smets & Wouters (2007). Accordingly:

$$\begin{cases} y_t^{obs} = 100 \log(GDPC09_t/LNS_{index_t}) \\ \pi_t^{obs} = 100 \log(\frac{GDPDEF09_t}{GDPDEF09_{t-1}}) \\ r_t^{obs} = 100 \log(\frac{Funds_t}{4}) \end{cases}$$
(I.1)

where the time series are given as:

GDPC09: Real GDP, Billions of Chained 2009 Dollars, Seasonally Adjusted Annual Rate. Source: Federal Reserve Economic Data (FRED).

GDPDEF09: GDP-Implicit Price Deflator, 2009=100, Seasonally Adjusted. Source: FRED.

LNU0000000:Unadjusted civilian noninstitutional population, Thousands, 16 years& over. Source: U.S. Bureau of Labor Statistics (BLS)

LNS10000000: Civilian noninstitutional populations, Thousands, 16 years & over, Seasonally Adjusted.

Source: BLS.

 $LNS_{index} = \frac{LNS_{10000000}}{LNS_{10000000(1992:03)}}$ Source: FRED.

Funds: Federal Funds Rate, Daily Figure Averages in Percentages. Source: FRED.

The observable variable x_t^{obs} for the output gap in our main estimations is based on the HP-filtered series of y_t^{obs} , while the CBO-based output gap is defined as: $x_t = 100 \frac{GDPC09-GDPPOT}{GDPPOT}$

with **GDPPOT**⁵³: CBO's Estimate of the Potential Output, Billions of Chained 2009 Dollars, Not Seasonally Adjusted Quarterly Rate. Source: FRED.

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 $^{^{53}}$ In order to calculate the potential output, CBO uses the theoretical framework in a standard Solow growth model setup, see CBO (2001) for more details.

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