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ESTIMATING NAIRU FOR THE TURKISH ECONOMY USING EXTENDED KALMAN FILTER APPROACH

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ABSTRACT This paper estimates NAIRU (Non-Accelerating Inflation Rate of Unemployment) for the Turkish economy by systems approach. Based on a Phillips curve equation combined with an Okun law for output gap and unemployment gap, the systems approach imposes stochastic laws of motion for NAIRU and potential output and also assumes the parameters to be time-varying. However, the requirement to simultaneously estimate parameters and to solve the state space problem introduces nonlinearity, which requires the use of Extended Kalman Filter (EKF). Estimation results suggest that NAIRU series moves in tandem with the actual unemployment, yet following a more volatile path than the latter. Accordingly, the NAIRU series reacts more sharply to the crises than the actual unemployment. Furthermore, all of the derived series are plausible and capture the significant turning points of the economy. Meanwhile, the time-varying parameters indicate a stable, yet quite a weak link between unemployment and inflation, and a declining, but significant pass-through to inflation. Moreover, the parameters also signal considerable inflation inertia.
JEL C32, C63, E24, E31.
Keywords NAIRU, Systems approach, Phillips curve, Okun law, Extended Kalman filter, Time-varying parameter, Inertia.

ÖZ Bu çalışmada, Türkiye ekonomisi için sistem yaklaşımı yoluyla NAIRU (enflasyonu hızlandırmayan işsizlik oranı) tahmini yapılmaktadır. Sistem yaklaşımında Phillips eğrisi denklemi esas alınarak, çıktı açığı ile işsizlik açığı arasında Okun kanunu çerçevesinde bir ilişki olduğu, NAIRU ve potansiyel üretimin stokastik hareket yasasıyla belirlendiği ve parametrelerin zamanla değiştiği varsayılmaktadır. Ancak, parametrelerin ve durum probleminin eşanlı olarak çözülmesi gerekliliği doğrusal olmama durumu yaratarak, ilerletilmiş Kalman filtresi kullanımını zorunlu kılmaktadır. Tahmin sonuçları, NAIRU serisinin, daha dalgalı bir seyir izlemekle beraber, gerçekleşen işsizlik düzeyiyle uyumlu hareket ettiğini göstermektedir. Bu çerçevede, tahmin edilen NAIRU serisi, kriz dönemlerinde, gerçekleşen işsizlik serisine göre daha sert tepki vermektedir. Buna ek olarak, türetilmiş tüm serilerin makul olduğu ve ekonomideki önemli dönüm noktalarını yakaladığı görülmektedir. Öte yandan, zamanla değişen katsayılar, işsizlik ve enflasyon arasında istikrarlı olmakla beraber zayıf bir ilişki olduğunu, döviz kuru-enflasyon geçişkenliğinin ise azalıyor olmakla beraber anlamlı bulunduğunu göstermektedir. Ayrıca, parametreler enflasyonun kayda değer oranda katılık içerdiğine işaret etmektedir.
TÜRKİYE EKONOMİSİ İÇİN İLERLETİLMİŞ KALMAN FİLTRESİ YAKLAŞIMIYLA NAIRU TAHMİNİ
JEL C32, C63, E24, E31.
Anahtar Kelimeler NAIRU, Sistem yaklaşımı, Phillips eğrisi, Okun kanunu, İlerletilmiş Kalman filtresi, Zamanla değişen parametre, Katılık.

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"I have become convinced that the NAIRU is a useful analytic concept. It is useful as a theory to understand the causes of inflation. It is useful as an empirical basis for predicting changes in the inflation rate. And, it is useful as a general guideline for thinking about macroeconomic policy."

(Stiglitz, 1997)

1. Introduction

Policymakers are confronting the increasing challenge to predict the future course of price dynamics in meeting their overriding goal of maintaining price stability. Another important challenge that the policymakers face in envisaging the general price outlook is to utilize all the available information. In doing so, NAIRU – the Non-Accelerating Inflation Rate of Unemployment – stands out as a key variable in foreseeing the future course of price dynamics.

NAIRU is the rate of unemployment at which there is no upward or downward pressure on inflation rate.[1] The concept arose in the wake of the popularity of the Phillips curve that summarized the observed negative correlation between unemployment and inflation (Phillips, 1958).[2] This

[1] An early form of NAIRU is found in the work of Lerner (1951) that referred to it as "low full employment" attained via the expansion of aggregate demand, in contrast with the "high full employment", which adds incomes policies (wage and price controls) to demand stimulation. NAIRU was later on introduced as the "non-inflationary rate of unemployment" in Modigliani and Papademos (1975) as an improvement over the natural rate of unemployment concept, which was initially put forward by Phelps (1967) and Friedman (1968) as the level of unemployment that is consistent with equilibrium in the structure of real wages. The analysis supporting the natural rate hypothesis was controversial and empirical evidence suggested that the natural rate varied over time in ways that could not be explained by changes in the labor market structure. As a result, the natural rate terminology was largely replaced by that of the NAIRU. This corresponded to the rate of unemployment below which inflation would accelerate, but without making a commitment to any particular theoretical explanation or a prediction that the rate would be stable over time.

[2] The inverse relationship between inflation (money wage changes) and unemployment was documented by Phillips (1958) and later extended by significant contributions from Samuelson and Solow (1960), which addressed the negative relation between unemployment and inflation using price inflation instead of nominal wage inflation. The inverse relationship between inflation and unemployment, which was described via the Phillips curve, implied that it was possible for governments to tolerate higher rate of inflation in return for lower unemployment and this trade-off became an essential part of the policymaking process. However, during the 1970s, Phillips curve faced some serious attacks as many countries experienced simultaneously high levels of inflation and unemployment, also known as stagflation. On the theoretical side, Phelps (1967) and Friedman (1968) rejected the idea of a long-run trade-off and suggested that a trade-off between unemployment and inflation would only be possible in the short run by including expected inflation and the natural rate of unemployment to the Phillips curve equation. Accordingly, the trade-off arises due to the inability of agents to adjust their expectations to anticipated inflation in the short run, whereas in the long run, agents adjust their expectations and actual unemployment returns to the natural rate of unemployment. However, Lucas (1972) showed that, assuming rational expectations, agents may adjust their expectations quickly, so Phillips curve is vertical even in the short run. This neoclassical view was later criticized by the new Keynesian approach, which argued that due to the presence of nominal rigidities in prices and wages, there might be a trade-off between inflation and unemployment in the short run, even assuming rational expectations. This implies that prices and wages cannot instantaneously adjust to changes in economic conditions (Fuhrer and Moore, 1995; Galí and Gertler, 1999; Clarida et al., 1999; Blanchard and Galí, 2007).

correlation, which was previously seen for the U.S. by Fisher (1926), persuaded some analysts that it was impossible for governments to simultaneously target low unemployment and price stability. Therefore, it was government's duty to settle on an unemployment and inflation combination, which is optimal in terms of social welfare.

In view of the fact that NAIRU is derived by exploiting the short-run trade-off between unemployment and inflation, the gap between actual unemployment and NAIRU indicates whether there is a risk of inflationary build-up in the economy. In other words, there must be some level of unemployment, i.e. NAIRU, which is consistent with a stable inflation (Ball and Mankiw, 2002). Therefore, if a contractionary monetary policy shock increases unemployment above NAIRU, inflation rate will decelerate; while inflation rate will accelerate if an expansionary monetary shock decreases the unemployment rate below NAIRU.

NAIRU is often associated with the concept of natural or structural unemployment, which is the unemployment rate that is identified with the structural, institutional or behavioral characteristics of the economy (Fabiani and Mestre, 2000). However, the non-accelerating inflation rate of unemployment may not always coincide with the natural rate of unemployment in the short run. In other words, the unemployment rate consistent with stable inflation may deviate from its long-run equilibrium value when shocks have hysteresis effects on the labor market dynamics.[3]

In addition, NAIRU may well vary over time or inflation may accelerate even if unemployment declines to rates that are compatible with stable inflation (Estrella and Mishkin, 2000). Besides, at times when there are large swings in oil or raw material prices, it is clear that unemployment would have to fluctuate sharply in order to stabilize inflation (Boone et al., 2001). Thus, measuring NAIRU is challenging both at the conceptual and the empirical level.

There are numerous techniques developed for measuring NAIRU. In this regard, NAIRU can be modeled from an economic theory perspective based on a Cobb-Douglas production function setting (Layard et al., 1991; Nickell, 1997). Alternatively, NAIRU can be modeled as a deterministic function of time (Staiger et al., 1997a, 1997b; Cross et al., 1998) or as a function of demographics and labor market dynamics (Weiner, 1993; Staiger et al., 1997b). NAIRU can also be modeled as an unobserved stochastic process (King et al., 1995; Staiger et al., 1997a; Gordon, 1997).

[3] The hysteresis effect was initially introduced by Blanchard and Summers (1987a). Other seminal works on the hysteresis effect are Blanchard and Summers (1987b, 1987c) and Ball (2009).

Another method for measuring NAIRU is through detrending techniques that can be applied by adopting simple statistical approaches. The detrending method may be univariate, bivariate or multivariate. Accordingly, a simple way for univariately estimating NAIRU is by regressing unemployment on a linear time trend or a quadratic time trend. Another way for univariately estimating NAIRU is to implement conventional filtering techniques, which are the Hodrick-Prescott (HP), Baxter-King (BK) and Christiano-Fitzgerald (CF) filters.[4] These filters decompose unemployment series to its cyclical and trend components.

NAIRU can be estimated bivariately on the basis of a Phillips curve equation assuming that shifts of the Phillips curve share a common trend with the unemployment rate (Laubach, 2001). Alternatively, NAIRU can be estimated via a multivariate filter by using a model that specifies the relationship between inflation, output and unemployment through the Phillips curve equation and the Okun law (Laxton and Tetlow, 1992; Richardson et al., 2000; Benes and N'Diaye, 2004). In this setting, exogenous variables are also taken into consideration in order to account for supply-side factors that explain inflation.

Finally, another methodology for estimating the non-accelerating inflation rate of unemployment is to treat NAIRU as an unobserved variable. In doing so, an unobserved components model is developed where Kalman filter features out as the appropriate estimation algorithm.[5] Kalman filter has been used extensively in the recent economics literature as a recursive estimation technique. It is a powerful algorithm that can easily be employed in linear state space models, as noted in Harvey (1990). Kuttner (1994) is a seminal paper that utilizes this approach for analyzing the U.S. economy, while Gerlach and Smets (1999) adopt this approach for the European economies.

Even though the use of Kalman filter in linear state space models works for industrialized economies with rare incidences of excessive boom-bust cycles, it may fail in emerging market economies where extreme volatility is typical.[6] In order to handle the volatility and the structural change that seem to be likely in these economies, one might allow the parameters of an

[4] For further details, see Hodrick and Prescott (1997), Baxter and King (1999) as well as Christiano and Fitzgerald (2003).
[5] Kalman filter is discussed extensively in Kalman and Bucy (1961), Kalman (1960) and Hamilton (1994a, 1994b).
[6] As discussed in Aguiar and Gopinath (2007) as well as Neumeyer and Perri (2005), business cycles tend to be more volatile in emerging market economies than advanced economies.

unobserved components model to vary over time.[7] However, this requires the adoption of a nonlinear state space form.

In a nonlinear state space setting where state variables and the time-varying parameters need to be estimated simultaneously, Kalman filter should be extended in order to handle the nonlinearity. Hence, the EKF can be proposed as the only possible algorithm. EKF is a powerful algorithm for solving nonlinear state space models; yet it has been employed in a rather limited number of studies (Grillenzoni, 1993; McKiernan, 1996; Bacchetta and Gerlach, 1997).

As for the Turkish economy, there are only a few studies that implement EKF (Özbek et al., 2003; Özbek and Özlale, 2005; Kara et al., 2007; Kara et al., 2007). However, these previous attempts utilizing EKF do not estimate NAIRU. Meanwhile, there are several studies that estimate NAIRU in Turkey (Şıklar et al., 1999; Yavan, 1997; Kaya and Yavan, 2007; Bildirici, 1999; Yiğit and Gökçe, 2012; Temurlenk and Başar, 2012; Gianella et al., 2008). Yet, none of these studies adopt a nonlinear framework.

The absence of previous works on NAIRU that consider the highly volatile nature of the Turkish economy[8] leaves us with a gap for estimating the non-accelerating inflation rate of unemployment using time-varying parameters in a state space form. This gap establishes the main motivation of this study. To our knowledge, this is the first formal attempt to estimate NAIRU for the Turkish economy in a nonlinear setting.

We believe that this paper serves useful in several ways. First of all, findings of this study provide guidance for future research on NAIRU, which is an important tool for monetary policy. In addition, this paper contributes to the existing literature by jointly estimating NAIRU and its time-varying relationship with inflation in a Phillips curve setting. The estimation of NAIRU in this multivariate framework also produces other significant variables like unemployment gap, potential output, output gap and inflation. Moreover, the results shed light on the course of time-varying parameters that indicate inflation persistence and the contribution of demand and supply-side factors to inflation. Furthermore, the findings also lay the

[7] There is a vast amount of evidence for parameter change in most macroeconomic variables suggesting that the assumption of constant coefficients may be a poor one (Stock and Watson, 1999). In the meantime, a huge number of econometric models are present that allow for time variation in parameters (e.g. Markov switching, structural break models, threshold models, etc.). Accordingly, time-varying parameter models are becoming an increasingly popular choice (Cogley and Sargent, 2002, 2005; Primiceri, 2005).

[8] Ertuğrul and Selçuk (2001), Kibritçioğlu et al. (2002) and Metin (1998) give a detailed account of the Turkish economy, while Alp and Elekdağ (2011), Başçı and Kara (2011), Başçı et al. (2007) and Kara (2008, 2013) provide a closer analysis of the recent monetary policy practices.

basis for prospective work that may adopt EKF. But most importantly, this study confirms the view that the conduct of monetary policy should be based on a flexible and comprehensive framework.[9]

It should be underlined that this paper does not intend to explain the evolution of unemployment dynamics in the Turkish economy, nor does it seek to determine the underlying structural forces driving the natural rate of unemployment. Also, the paper does not attempt to explain output or price developments, but it solely tries to exploit the information contained in the dataset in order to extract the unobservable NAIRU.

It should also be kept in mind that the models tested in this paper are chosen according to their in-sample properties and the degree to which they are able to match the behavior of the original series. Thus, the model selection is based on the informal optimization of the plausibility of the resulting estimates, but without any regard to their forecasting properties.

The organization of the paper is as follows: The next section presents the baseline empirical model on NAIRU and its state space representation as well as the alternative model specification with the corresponding state space representation. The third section discusses the estimation results. The following section presents results of the sensitivity analysis for robustness test. The fifth section presents the time-varying parameters. Finally, the last section concludes this paper. The state space representation of the EKF is provided in the appendix.

2. System Specification

Models that have been used to estimate NAIRU are essentially based on a system of equations. The system of equations, which constructs the empirical framework, is in the spirit of Fabiani and Mestre (2004). Accordingly, the system is composed of a Phillips curve, which determines the relation between unobserved cyclical factors and inflation; an Okun-type

[9] Obviously, a more flexible and comprehensive framework in the conduct of monetary policy can be provided by means of a wide-ranging set of policy instruments, the use of which can be supported by legal amendments and relevant changes to the operational structure. As for Turkey, the Central Bank of the Republic of Turkey (CBRT) has already increased the flexibility and the scope of its monetary policy by conducting a new framework starting from late 2010. In this regard, the conventional inflation targeting regime was modified by adopting financial stability as a supplementary objective and a new monetary policy mix was designed that included additional policy tools for pursuing multiple objectives (Başçı and Kara, 2011; Kara, 2013, Alper et al., 2013; Küçüksaraç and Özel, 2012). The new monetary policy framework, which addressed both price stability and financial stability, was already backed by the required legal basis. In other words, as stipulated in Central Bank Law No. 1211, in addition to maintaining price stability, the CBRT is liable to take precautions for enhancing the stability of the financial system. In doing so, the CBRT is empowered to use, determine and implement monetary policy instruments at its own discretion (Central Bank Law No. 1211 is available at http://www.tcmb.gov.tr/yeni/banka/law.pdf).

relationship between output gap and unemployment gap; and a set of equations defining the law of motion for potential output and NAIRU as well as equations defining their trend components. The analysis is conducted using a baseline and an alternative model specification.

2.1. Baseline Model Specification

The baseline model specification follows Fabiani and Mestre (2004). However, given the highly volatile nature of the Turkish economy as discussed in the previous section, the baseline model departs from the original paper by assuming parameters to be time-varying. The variables used in the baseline model are as follows: π_t is the inflation rate (first difference of the log of consumer price index); z_t is the vector of supply-side variables (normally taken to be changes in import prices, real exchange rate or the nominal exchange rate) that pose pressure on inflation; u_t is the unemployment rate; y_t is the (log of) output level; u_t^* and y_t^* represent NAIRU and (the log of) potential output, respectively. Correspondingly, $ugap_t$ and $ygap_t$ are the unemployment gap and the output gap.

Accordingly, dynamics of inflation can be described by an accelerationist-type Phillips curve equation such that:

$$\pi_t = \alpha_{1,t}\pi_{t-1} + \alpha_{2,t}\pi_{t-2} + \alpha_{3,t}ugap_{t-1} + \alpha_{4,t}z_t + \varepsilon_t^{\pi} \qquad (1)$$

where inflation is assumed to be a function of built-in inflation, demand-pull inflation and cost-push inflation, which can be captured by the inclusion of lagged inflation terms, the unemployment gap and the change in nominal exchange rate.[10] The coefficients $\alpha_{1,t}$ and $\alpha_{2,t}$, which show the degree of inflation persistence, are expected to be greater than zero. The coefficient $\alpha_{3,t}$ denotes the degree of demand-pull inflation and it is expected to be less than zero. Finally, $\alpha_{4,t}$ represents the degree of pass-through from exchange rate to inflation and it is expected to be greater than zero. Obviously, ε_t^{π} is the disturbance term.

Okun law runs from output gap to unemployment gap such that:

$$ygap_t = \beta_{1,t}ugap_{t-1} + \varepsilon_t^{ygap} \qquad (2)$$

[10] Based on the triangle model of Gordon (1991), inflation is viewed to have three root causes: built-in inflation (inflation results from past events and persists into the present), demand-pull inflation (falling unemployment rates or rising output feeds into inflation), and cost-push inflation (increases in the cost of goods and services raise inflation).

where $\beta_{1,t}$ is expected to be negative and ε_t^{ygap} is the error term.

The unemployment gap is modeled as an autoregressive process:

$$ugap_t = \delta_{1,t} ugap_{t-1} + \varepsilon_t^{ugap} \tag{3}$$

where $\delta_{1,t}$ is expected to be positive and ε_t^{ugap} is the error term.

The Beveridge-Nelson (1981) decomposition of output and unemployment is as follows:

$$y_t = y_t^* + ygap_t \tag{4}$$

$$u_t = u_t^* + ugap_t \tag{5}$$

Potential output and NAIRU are assumed to follow a local linear trend model such that:

$$y_t^* = y_{t-1}^* + \gamma_{t-1} + \varepsilon_t^{y^*} \tag{6}$$

$$u_t^* = u_{t-1}^* + \eta_{t-1} + \varepsilon_t^{u^*} \tag{7}$$

where the two stochastic trends γ and η are defined as:

$$\gamma_t = \gamma_{t-1} + \varepsilon_t^{\gamma} \tag{8}$$

$$\eta_t = \eta_{t-1} + \varepsilon_t^{\eta} \tag{9}$$

Obviously, $\varepsilon_t^{y^*}$,$\varepsilon_t^{u^*}$, ε_t^{γ} and ε_t^{η} are the disturbance terms.

The model can be represented in state space as follows:

$$x(t) = Fx(t-1) + Gu(t) + e_1(t) \tag{10}$$

$$y(t) = Hx(t) + e_2(t) \tag{11}$$

where $x(t)$ is the state vector, $y(t)$ is the observation vector, F is the transition matrix, H is the observation matrix and G is a known matrix. $e_1(t)$ and $e_2(t)$ denote vectors of normally distributed i.i.d. shocks, which are assumed to be uncorrelated with each other and have covariance matrices R_1 and R_2, respectively. Furthermore, u(t) is the vector of exogenous variables.

The measurement equation, which shows the evolution of the observed variables, can be described in terms of the state variables as follows:

$$\begin{bmatrix} \pi_t \\ y_t \\ u_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \pi_t \\ \pi_{t-1} \\ ygap_t \\ ugap_t \\ y_t^* \\ u_t^* \\ \gamma_t \\ \eta_t \end{bmatrix} \tag{12}$$

The transition equation can be expressed as:

$$\begin{bmatrix} \pi_t \\ \pi_{t-1} \\ ygap_t \\ ugap_t \\ y_t^* \\ u_t^* \\ \gamma_t \\ \eta_t \end{bmatrix} = \begin{bmatrix} \alpha_{1,t} & \alpha_{2,t} & 0 & \alpha_{3,t} & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \beta_{1,t} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \delta_{1,t} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \pi_{t-1} \\ \pi_{t-2} \\ ygap_{t-1} \\ ugap_{t-1} \\ y_{t-1}^* \\ u_{t-1}^* \\ \gamma_{t-1} \\ \eta_{t-1} \end{bmatrix} + \begin{bmatrix} \alpha_{4,t} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} [z_t] + \begin{bmatrix} \varepsilon_t^{\pi} \\ 0 \\ \varepsilon_t^{ygap} \\ \varepsilon_t^{ugap} \\ \varepsilon_t^{y^*} \\ \varepsilon_t^{u^*} \\ \varepsilon_t^{\gamma} \\ \varepsilon_t^{\eta} \end{bmatrix} \tag{13}$$

2.2. Alternative Model Specification

In order to analyze the robustness of our results to different model specifications, we investigate the possibility that output gap might better capture inflation dynamics than the unemployment gap.[11] In this respect, instead of the unemployment gap, the output gap is used as an indicator for measuring the stance of aggregate demand in the Phillips curve. Correspondingly, Okun law is reversed from unemployment gap to output gap. Therefore, the baseline model is modified and equations (1) and (2) are replaced with the following equations such that:

[11] The output gap is a measure of how far away an economy is from a desirable level of output. Output gap can be important in policy discussions as it presents a gauge of when the economy might be overheating or underperforming. Typically, during a recession, actual output drops below potential, thus creating a negative output gap. In a boom, actual output rises above its potential, resulting in a positive gap. In the latter case, the economy can be described as overheating, which prompts the central bank to cool the economy by raising interest rates. On the other hand, an economy that is performing below its potential can be referred to as underheating, in which case the central bank may need to implement a more stimulating monetary policy (Lubik and Slivinski, 2010).

$$\pi_t = \alpha_{1,t}\pi_{t-1} + \alpha_{2,t}\pi_{t-2} + \alpha_{3,t} ygap_{t-1} + \alpha_{4,t} z_t + \varepsilon_t^{\pi} \qquad (1')$$

$$ugap_t = \beta_{1,t} ygap_{t-1} + \varepsilon_t^{ugap} \qquad (2')$$

where $\alpha_{3,t} > 0$ and $\beta_{1,t} < 0$. Furthermore, the output gap is modeled as an autoregressive process, and hence, equation (3) is modified as:

$$ygap_t = \delta_{1,t} ygap_{t-1} + \varepsilon_t^{ygap} \qquad (3')$$

where $\delta_{1,t}$ is expected to be greater than zero. These modifications imply a re-definition of the transition equation as below:

$$\begin{bmatrix} \pi_t \\ \pi_{t-1} \\ ygap_t \\ ugap_t \\ y_t^* \\ u_t^* \\ \gamma_t \\ \eta_t \end{bmatrix} = \begin{bmatrix} \alpha_{1,t} & \alpha_{2,t} & \alpha_{3,t} & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \delta_{1,t} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta_{1,t} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \pi_{t-1} \\ \pi_{t-2} \\ ygap_{t-1} \\ ugap_{t-1} \\ y_{t-1}^* \\ u_{t-1}^* \\ \gamma_{t-1} \\ \eta_{t-1} \end{bmatrix} + \begin{bmatrix} \alpha_{4,t} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \left[z_t \right] + \begin{bmatrix} \varepsilon_t^{\pi} \\ 0 \\ \varepsilon_t^{ygap} \\ \varepsilon_t^{ugap} \\ \varepsilon_t^{y^*} \\ \varepsilon_t^{u^*} \\ \varepsilon_t^{\gamma^*} \\ \varepsilon_t^{\eta^*} \end{bmatrix} \qquad (13')$$

Meanwhile, the observation equation remains unchanged.

3. Estimation Results

This section reports and discusses the estimation results of the models described above. The models utilize quarterly data on inflation, output, unemployment and nominal exchange rate for the Turkish economy between 2000Q1 and 2013Q3 period.[12,13] Inflation is measured as the logarithmic

[12] Our publicly available data come from the electronic data dissemination system of the CBRT at http://evds.tcmb.gov.tr.

[13] The time period covered in the analysis is crucial for the Turkish economy as it witnessed major crises and regime changes. To be more specific, between 2000Q1 and 2001Q1, the CBRT conducted an IMF-backed exchange-rate-based stabilization (ERBS) program, which eventually collapsed with the outbreak of the financial crisis in February 2001. Starting from May 2001, the CBRT has implemented the transition program for strengthening the Turkish economy (CBRT, 2001). In 2002, the implicit inflation targeting regime was put into effect. This was followed by the implementation of strict inflation targeting regime in 2006. In the last quarter of 2008, the CBRT faced challenges stemming from the global crisis that occurred in September 2008. Consequently, the CBRT adopted anti-crisis measures, which were later withdrawn in April 2010. Finally, as of end-2010, the CBRT has engineered a new monetary policy framework, which departed from strict inflation targeting by the inclusion of financial stability as a supplementary objective to its primary goal of maintaining price stability (Ertuğrul and Selçuk, 2001; Kibritçioğlu et al., 2002; Başçı and Kara, 2011; Başçı et al., 2007; Kara, 2008, 2013).

difference of the seasonally adjusted consumer price index. Output is seasonally adjusted gross domestic product series in logs and unemployment is seasonally adjusted series in percentages. Exchange rate is the logarithmic difference of the USD/TRY spot rate. Seasonal adjustment is handled via TRAMO/SEATS (Gómez and Maravall, 1996). The initial values are set according to Chan and Hsiao (2011).[14]

3.1. Baseline Model Results

Figure 1 presents the estimation results of the baseline model. Accordingly, one can conclude that NAIRU follows a slightly more volatile path than unemployment. This is an expected outcome given the reported evidence on the higher sensitivity of NAIRU to economic fluctuations than the actual unemployment as well as the relatively higher persistence of actual unemployment than NAIRU (Clark and Laxton, 1997). More specifically, during the implementation of the exchange-rate-based stabilization program, the estimated NAIRU series moves in tandem with the actual unemployment rate series. Remaining slightly above the actual unemployment despite the parallel course, the estimated NAIRU series follows a rather volatile pace during the implicit inflation targeting regime.

The estimated NAIRU series moves very close to actual unemployment throughout the implementation of the strict inflation targeting regime. However, during the global crisis period, both series register a sharp increase, while the estimated NAIRU responds more severely to the crisis by displaying a more dramatic rise. As the adverse effects of the global crisis wane, the actual unemployment series starts to decline back to pre-crisis levels. This is accompanied by a sharp fall in the estimated NAIRU series, which remains even below actual unemployment at the end of the global crisis episode.

Finally, with the adoption of the new monetary policy mix, the estimated NAIRU and the actual unemployment series decline considerably below the levels posted during the implementation of both implicit and strict inflation targeting regimes. In fact, this period even witnesses that the estimated NAIRU series is occasionally lower than actual unemployment.

[14] The state space representation for EKF is given in the appendix. Accordingly, it should be noted that the EKF needs pre-defined $P_{0|0}$, Q, R, $\hat{x}_{0|0}$ for initialization. It is acceptable to assign $P_{0|0}$ arbitrarily; however, the values must be large enough to allow good tracking of the parameters. If the states are measured, $\hat{x}_{0|0}$ can be specified by taking the average of the first few data points.

As for the unemployment gap, which is modelled as an autoregressive process, the series is mostly negative throughout the analysis, except for a brief period at the midst of the global crisis. On the potential output front, the baseline model produces a series that is sensitive to the crisis episodes in the economy. In other words, estimation results suggest that the potential output series declines during crisis periods in 2001 and 2008, whereas it continues to trend upwards otherwise. Meanwhile, the estimated output gap series, which is measured as the deviation of actual output from the potential output, follows a volatile path around zero. This can be observed especially during the implementation of the new monetary policy mix, where demand-side pressures on inflation have seemingly been negligible.

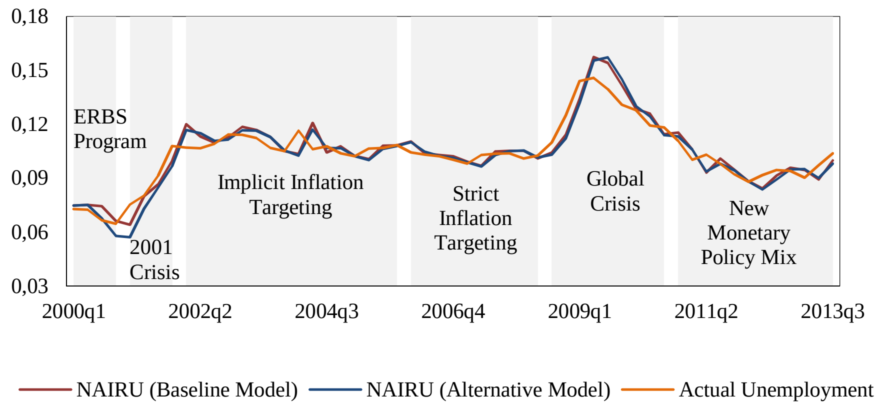
Regarding the estimation of inflation, the model is successful in capturing the inflation dynamics over the period of analysis. Inflation settles on a downward course with the adoption of the ERBS program, which is halted with the outbreak of the financial crisis in 2001 when inflation surges significantly. Inflation re-settles on a declining track during the implicit inflation targeting regime. Afterwards, inflation follows a volatile, yet steady path.

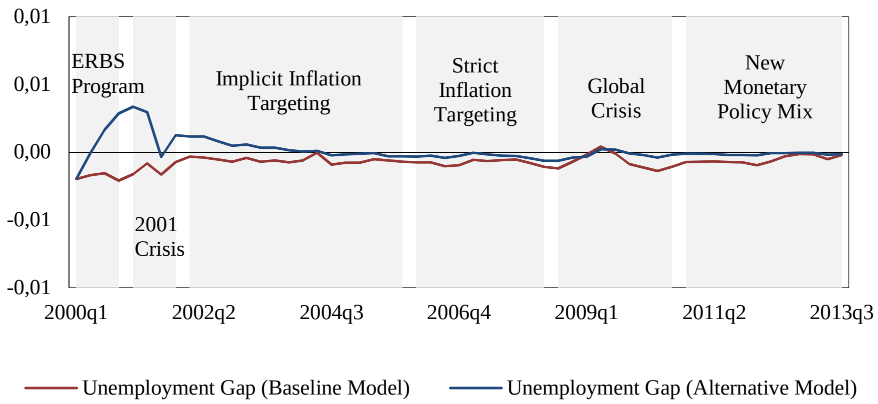
It should be noted that during periods when the NAIRU follows a stable course and moves close to actual unemployment, inflation is also stable, i.e. non-accelerating as expected. This coincides with the implementation of implicit inflation targeting regime from 2002 to 2005 and the launch of strict inflation targeting regime in 2006. However, the NAIRU starts to climb during the global crisis period. After reaching a peak as the adverse effects of the global crisis are felt markedly on the Turkish economy, the NAIRU starts to fall down gradually amid the implementation of anti-crisis measures. Finally, the NAIRU follows a relatively steady path after the adoption of the new monetary policy mix.

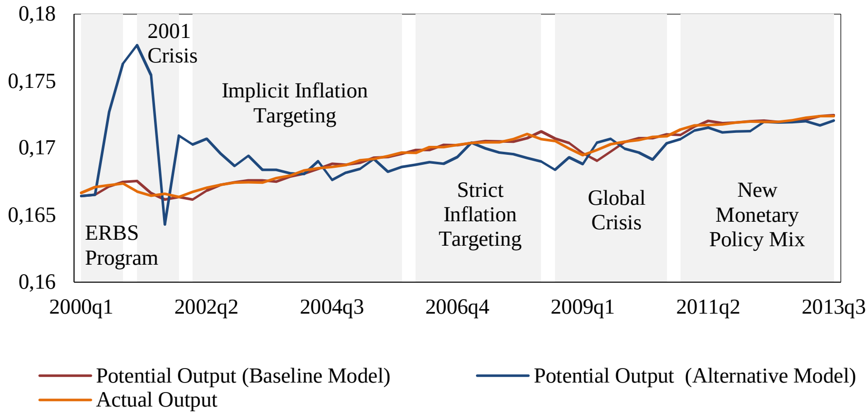
3.2. Alternative Model Results

Figure 1 presents estimation results of the alternative model. Accordingly, the NAIRU and the unemployment gap estimations produced by the alternative model specification are very similar to the baseline model results. However, the alternative model yields a more volatile potential output and output gap series than the original model. This is basically due to the fact that unlike the baseline model where unemployment gap is included in the Phillips curve equation, the output gap enters the Phillips curve equation in the alternative model specification, and so NAIRU and unemployment gap are indirectly derived from potential output and the output gap. This obviously causes the potential output and the output gap to be estimated with a higher precision. On the other hand, inflation estimations are quite similar in both specifications.

Figure 1. Estimation Results






0,18
0,175
0,17
0,165
0,16
2001
Crisis
Implicit Inflation
Targeting
Strict
Inflation
Targeting
Global
Crisis
New
Monetary
Policy Mix
ERBS
Program
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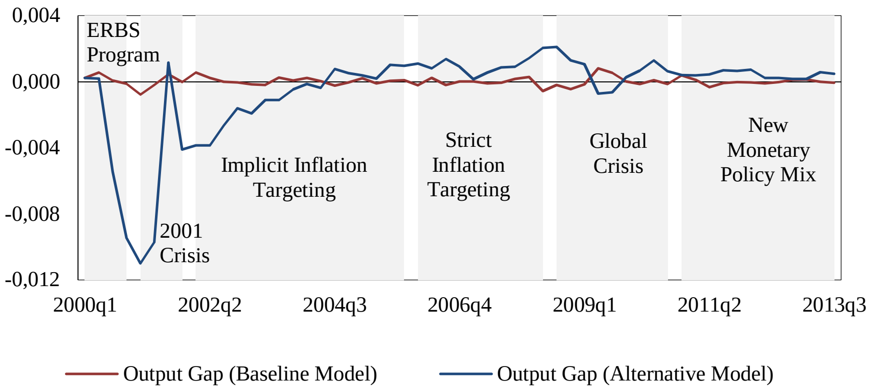
2013q3
Potential Output (Baseline Model)
Potential Output (Alternative Model)
Actual Output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-0,008
-0,012
ERBS
Program
Implicit Inflation
Targeting
Strict
Inflation
Targeting
Global
Crisis
New
Monetary
Policy Mix
2001
Crisis
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2006q4
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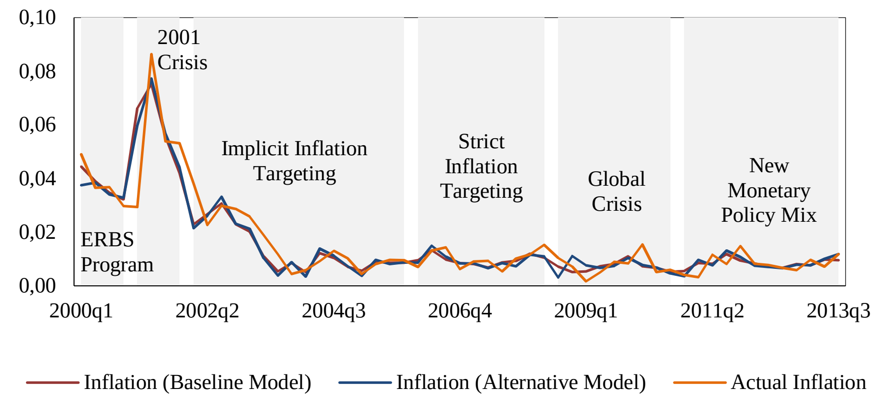
2013q3
Output Gap (Baseline Model)
Output Gap (Alternative Model)


0,10
0,08
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0,02
0,00
2001
Crisis
Implicit Inflation
Targeting
Strict
Inflation
Targeting
Global
Crisis
New
Monetary
Policy Mix
ERBS
Program
2000q1
2002q2
2004q3
2006q4
2009q1
2011q2
2013q3
Inflation (Baseline Model)
Inflation (Alternative Model)
Actual Inflation

4. Sensitivity Analysis

In order to check the robustness of our results, a sensitivity analysis is conducted for comparing the performance of EKF to an alternative measurement approach. In this regard, one option is to estimate NAIRU by adopting a simple statistical approach. In doing so, the HP filter is applied, where unemployment series is basically split into its cyclical and trend components.[15]

Another option for checking robustness is to impose dynamic homogeneity constraint[16] to our system of equations by restricting the sum of the coefficients of the explanatory inflation terms in the Phillips curve equation to be equal to unity. Alternatively, the same constraint can be forced by using differenced inflation terms in the Phillips curve equation, and so the unity restriction is automatically satisfied (Fabiani and Mestre, 2004).[17]

4.1. Estimated Series by HP Filter

The results of the sensitivity analysis presented in Figure 2 demonstrate that NAIRU series follows an extremely smoother path when estimated by the HP filter. The fact that NAIRU is "too smooth" when estimated by a conventional statistical method, which was discussed earlier in the paper, is thus confirmed with the data. Accordingly, the unemployment gap series estimated by the HP filter displays higher volatility compared to unemployment gap series produced by other specifications.

As for potential output, the HP-filtered series is smoother than the potential output series estimated by the EKF. However, the corresponding output gap series under the HP filter specification shows a quite similar pattern to the output gap series estimated by the baseline model. Hence, applying the HP filter proves that EKF is undeniably superior in capturing the highly volatile dynamics of the Turkish economy.

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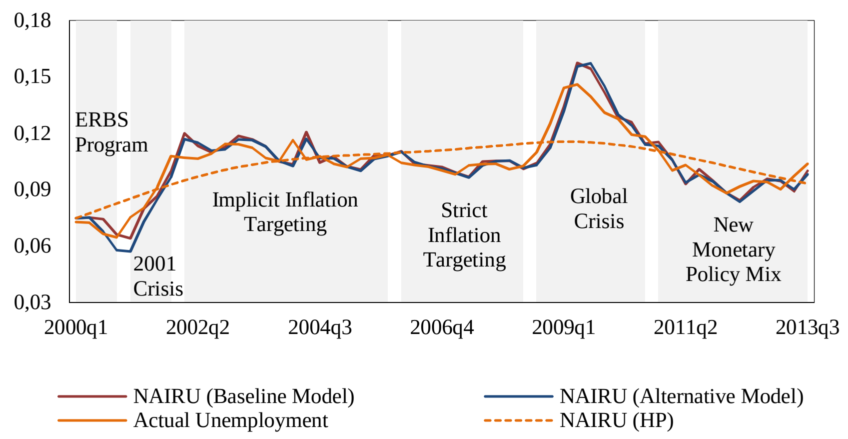
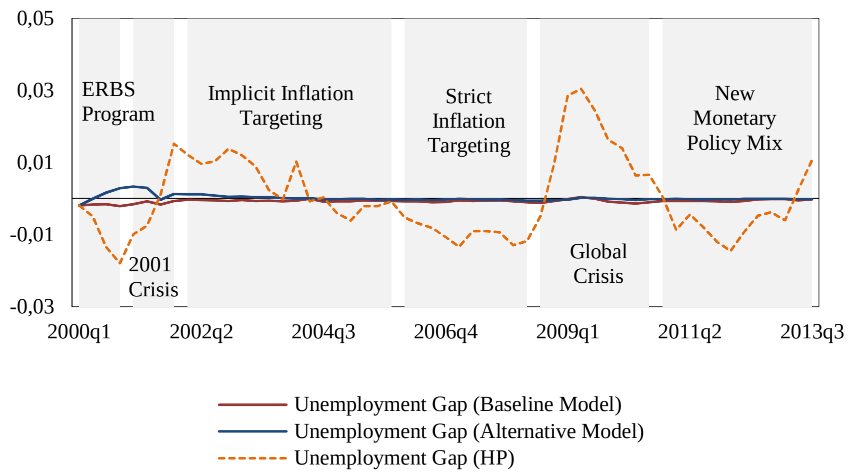
[15] Smoothing parameter lambda is set to its default value, which is 1600 for quarterly data.

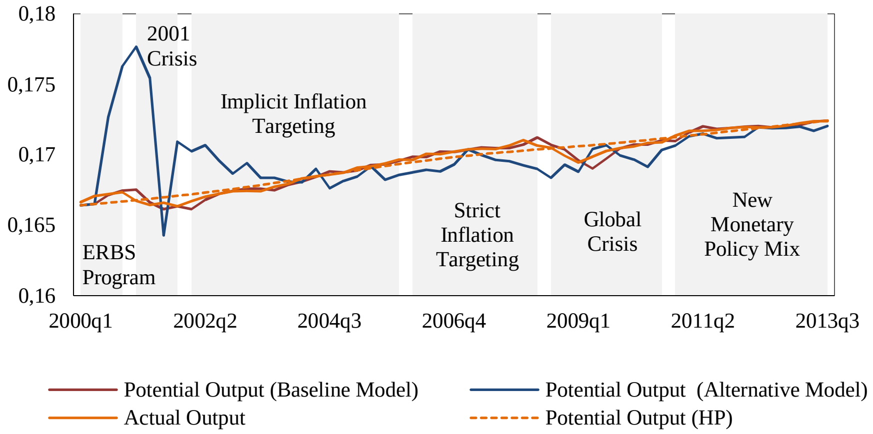
[16] Dynamic homogeneity is the condition that permanent changes in inflation should not affect output in the long run. Imposing dynamic homogeneity to the above system of equations implies that the existence of a trade-off between inflation and output is only limited to short run. Hence, the restriction of dynamic homogeneity enables to derive a more meaningful NAIRU (Greenslade et al., 2003; Batini and Greenslade, 2006). The restriction also implies that prices are determined by nominal factors such as wages and imported costs (Gómez and Julio, 2000).

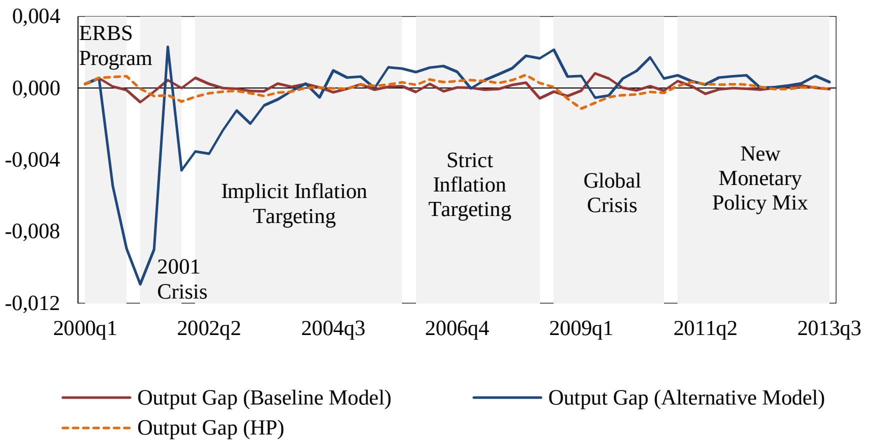
[17] Since our original Phillips curve equation does not contain any differenced inflation terms, this paper sticks to the former approach in imposing dynamic homogeneity. Thus, the sum of lagged inflation terms in the Phillips curve equation is restricted to be equal to unity.

Figure 2. Estimated Series by HP Filter







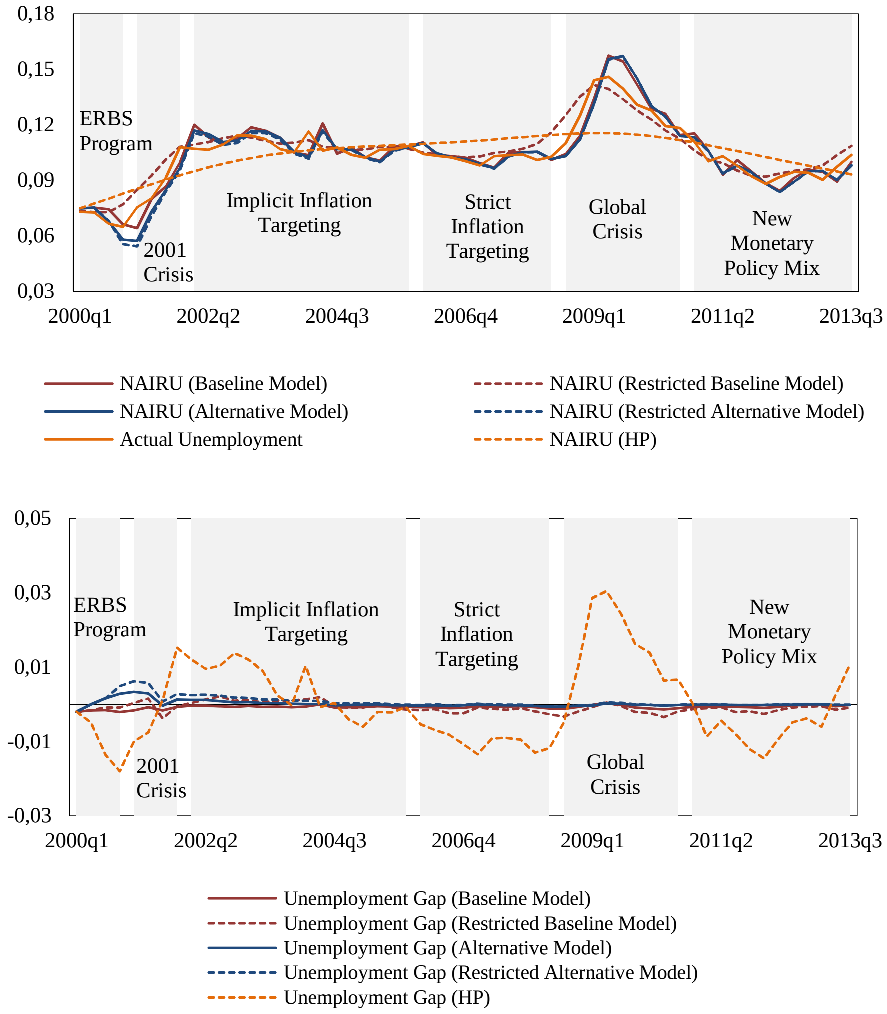


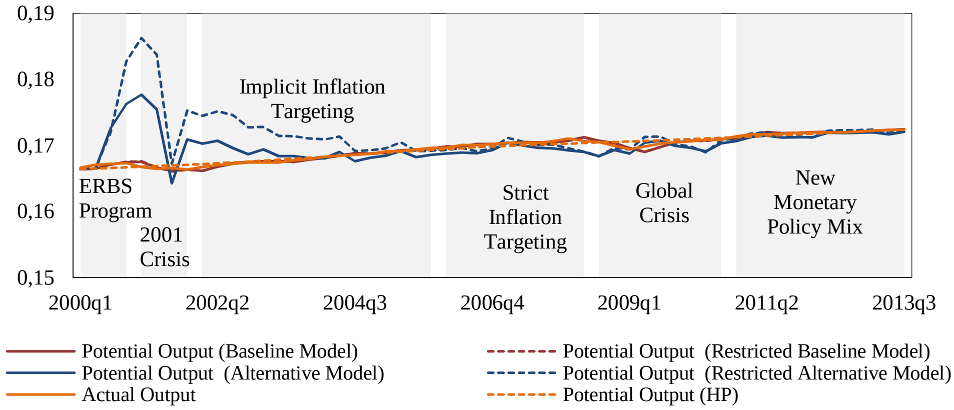
4.2. Estimated Series by Dynamic Homogeneity Constraint

The results of the sensitivity analysis presented in Figure 3 demonstrate that NAIRU follows a smoother path when dynamic homogeneity is imposed in the baseline model. Accordingly, the unemployment gap series estimated by the restricted baseline model displays a marked divergence from unemployment gap series derived under other specifications, especially prior to 2001 and after 2008. In other words, unemployment gap estimated under the dynamic homogeneity restriction in the baseline model points to higher inflation, while unemployment gap series estimated by other specifications implies lower inflation during these episodes (Figure 3).

Dynamic homogeneity constraint does not notably affect potential output and output gap estimations in the baseline model. However, imposing the dynamic homogeneity condition causes potential output and output gap series to react more sharply to the crisis incidents in the alternative model specification. As for the inflation, the constraint for dynamic homogeneity leads to virtually no change under both specifications.

Figure 3. Sensitivity Analysis




0,19
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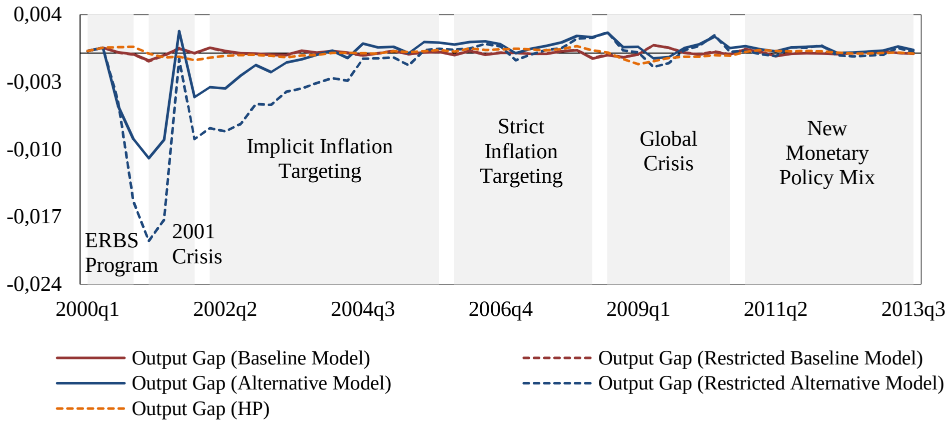
2000q1
2002q2
2004q3
2006q4
2009q1
2011q2
2013q3
ERBS Program
2001 Crisis
Implicit Inflation Targeting
Strict Inflation Targeting
Global Crisis
New Monetary Policy Mix
Potential Output (Baseline Model)
Potential Output (Alternative Model)
Actual Output
Potential Output (Restricted Baseline Model)
Potential Output (Restricted Alternative Model)
Potential Output (HP)


0,004
-0,003
-0,010
-0,017
-0,024
2000q1
2002q2
2004q3
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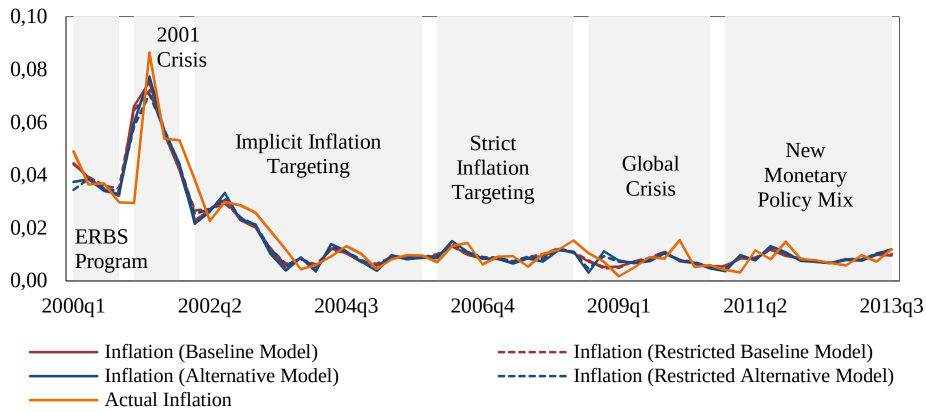
2013q3
ERBS Program
2001 Crisis
Implicit Inflation Targeting
Strict Inflation Targeting
Global Crisis
New Monetary Policy Mix
Output Gap (Baseline Model)
Output Gap (Alternative Model)
Output Gap (HP)
Output Gap (Restricted Baseline Model)
Output Gap (Restricted Alternative Model)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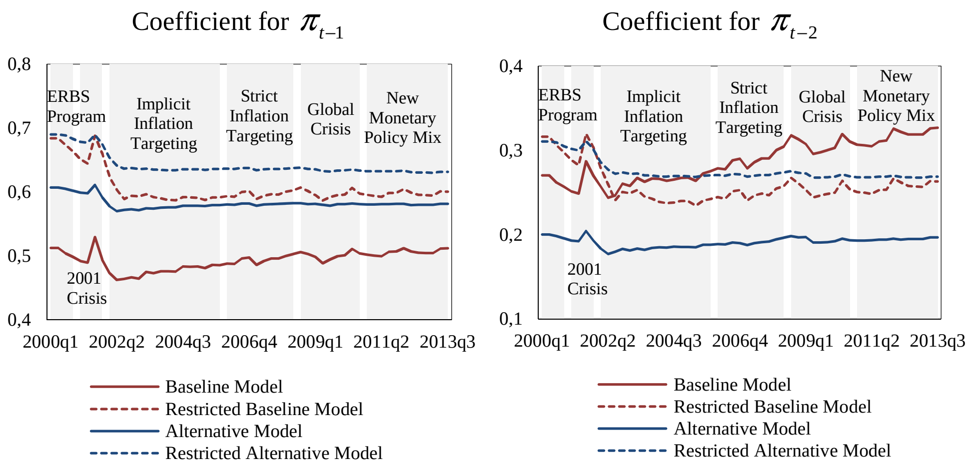
2013q3
2001 Crisis
ERBS Program
Implicit Inflation Targeting
Strict Inflation Targeting
Global Crisis
New Monetary Policy Mix
Inflation (Baseline Model)
Inflation (Alternative Model)
Actual Inflation
Inflation (Restricted Baseline Model)
Inflation (Restricted Alternative Model)

5. Time-Varying Parameters

This section presents the analysis of time-varying parameters measured by EKF under all specifications, including the dynamic homogeneity constraint. Accordingly, the results reveal that, among all the specification estimates, the pass-through from lagged inflation to current inflation estimated under the baseline model is the lowest; whereas the one estimated by the alternative model specification with the dynamic homogeneity constraint is the highest. The results show that the coefficient of π_{t-1} declines over time and reaches a lower plateau in all specifications, except for the baseline model yielding a stable coefficient throughout the period of analysis (Figure 4).

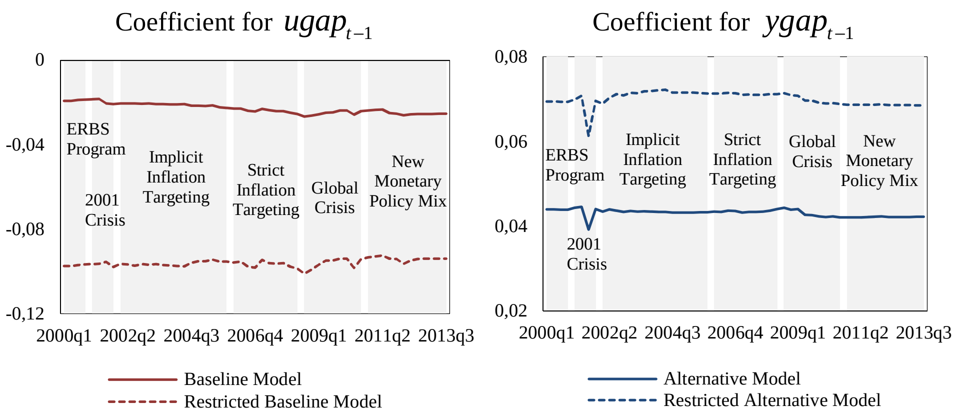
The impact of π_{t-2} on current inflation is initially the strongest in the baseline model specification under the dynamic homogeneity constraint, while the weakest impact is produced under the alternative model specification. When dynamic homogeneity constraint is imposed, the coefficient of π_{t-2} declines in both the baseline model and the alternative model. The coefficient of π_{t-2} is stable in the alternative model, whereas it increases over time in the baseline model (Figure 4).

Figure 4. Inflation Persistence



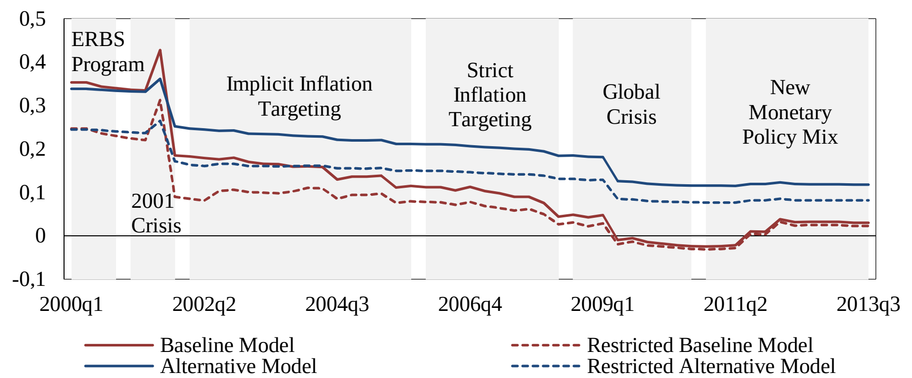
The analysis shows that demand-pull inflation is weak, yet stable. This can be proven by the steady course of the coefficients for unemployment gap and the output gap over the period of analysis. The dynamic homogeneity restriction causes both coefficients to increase, implying that demand-side factors are more effective in inflation dynamics if dynamic homogeneity is imposed (Figure 5).

Figure 5. Degree of Demand-Pull Inflation



Finally, the estimation results indicate that cost-push inflation as measured by the degree of pass-through from exchange rate to inflation declines considerably over the period of analysis. Furthermore, the pass-through coefficient produced by the alternative model is slightly higher than that of the baseline model (Figure 6).

Figure 6. Degree of Cost-Push Inflation



6. Conclusion

NAIRU is a vital concept in explaining the extent to which aggregate demand may expand without accelerating inflation. By definition, NAIRU is the unemployment rate that corresponds to a stable inflation. Yet, attempting to model NAIRU in a period where inflation has not been stable is obviously a challenge. This challenge is even more magnified for the Turkish economy, which is characterized by rapidly changing macroeconomic dynamics. Apparently, conventional methods for estimating NAIRU may fail to capture these dynamics and produce too smooth trends.

This study takes the above discussion as its starting point and attempts to estimate NAIRU for the Turkish economy. The system of equations, which constructs the empirical framework, is in the spirit of Fabiani and Mestre (2004). Accordingly, the system is composed of a Phillips curve, which determines the relation between unobserved cyclical factors and inflation; an Okun-type relationship that links output gap to unemployment gap; and a set of equations defining the law of motion for potential output and NAIRU.

In view of the highly volatile nature of the Turkish economy, this study improves over the methodology in Fabiani and Mestre (2004) by introducing time-varying parameters into the model. Since time-varying parameters and state variables are estimated simultaneously, the model presents nonlinearity, which can be handled via EKF – the use of standard Kalman filter equations to the first-order Taylor approximation of the nonlinear model about the last estimate.

EKF is a useful algorithm that can successfully control the issue of nonlinearity introduced by the requirement to simultaneously estimate time-varying parameters and to solve the state problem. Moreover, the use of EKF avoids the problem of finding a “too smooth” trend without having to resort to the strong restrictions that are imposed on the parameters in previous studies.

The results reveal that the estimated parameters are fairly reasonable. NAIRU moves in tandem with the actual unemployment, but it follows a more volatile path than the latter. Consequently, the estimated NAIRU series is more responsive to the crisis episodes than the actual unemployment, which is characterized by a relatively more persistent nature.

The same observation is true for the potential output, which seems to be more volatile than the actual output. Hence, unlike earlier work on NAIRU, this study succeeds in deriving a NAIRU and a potential output series that do not appear to have an overly smooth trend. Accordingly, the two major crises in 2001 and 2008 are successfully captured by the estimated NAIRU series.

The time-varying parameters indicate a stable, but weak demand-pull inflation as evident by the considerably low and steady parameter for the unemployment gap. This result is in line with the previous studies in the literature citing the poor link between unemployment and inflation in the Turkish economy. This can be attributed to the fact that unemployment and inflation have very different dynamics and determinants.[18] In fact, an earlier work by Karahan et al. (2012) shows that inflation and unemployment trade-off only exists in the short run. Another work by Kuştepeli (2005) investigates the existence of a Phillips curve in Turkey and the results indicate the absence of a meaningful relationship between inflation and unemployment for the Turkish economy. Finally, Uysal and Erdoğan (2003) report evidence for a statistically significant, yet quite a weak link between unemployment and inflation in Turkey.

The same conclusion holds true when output gap is used in the Phillips curve equation. This result is in line with the prior findings by Özbek and Özlale (2005), which contradict with the more general view that demand-side dynamics are the main determinants of inflation in Turkey.

Meanwhile, estimation results suggest a weakening, but significant pass-through from nominal exchange rate to inflation. This result confirms earlier observations, which indicate that pass-through of exchange rate to inflation has gradually declined in the post-2001 period (Kara and Öğünç, 2005, 2008; Kara et al., 2007; Karasoy et al., 2005).

The estimation findings also point to the presence of a considerable inertia in inflation. This can be proven by the size as well as the relative stability of coefficients for past inflation. These results confirm previous findings by Özçiçek (2011) and Tunay (2009) hinting at significant inflation persistence even after the disinflation period in Turkey.

[18] Economic theory and previous empirical studies have identified the determinants of unemployment, which include unemployment benefits, taxes, trade union bargaining power and the structure of collective bargaining, employment protection legislation, anti-competitive product market regulation, active labor market policies, minimum wages and housing policies (Bassanini and Duval, 2006). Bildirici et al. (2012) report that rapid population growth, internal and external migration, technological advances, interregional differences in development, productivity and wages, educational policy, political and economic instability, lack of sufficient investment, labor quality, low capacity utilization ratios, the inadequacy of training, credit and organization facilities for entrepreneurs are the main determinants of unemployment in Turkey. On the other hand, major determinants of inflation in Turkey are viewed to be credit growth and exchange rates as the former plays an important role on the demand channel, while the latter is the main determinant of the cost channel (Kara, 2013).

It should be noted that the estimations are based on aggregate data on unemployment, output and inflation. Obviously, the structure of unemployment may vary by sectors. Similarly, aggregate demand and inflation may have different dynamics by subcategories. This may affect Phillips curve assumptions. More specifically, the degree of persistence and pass-through as well as the sensitivity of inflation to unemployment gap and output gap in the Phillips curve equation may differ depending on whether aggregate data is used for inflation, output and unemployment. This obviously influences the derivation of the NAIRU series.[19]

In conclusion, this paper serves useful for future research on the Turkish economy and it provides guidance for further work on NAIRU. In addition, this study contributes to the existing literature by jointly estimating NAIRU and its time-varying relationship with inflation in a Phillips curve setting. The estimation of NAIRU in this multivariate framework also produces other significant variables like unemployment gap, potential output, output gap and inflation. Moreover, the results shed light on the course of time-varying parameters that indicate inflation persistence and the contribution of demand and supply-side factors to inflation. Furthermore, the findings lay the basis for prospective work that may adopt EKF. But most importantly, this study confirms the view that the conduct of monetary policy should be based on a flexible and comprehensive framework.

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[19] For further details on the sensitivity of estimation results to using aggregate data, see Altissimo et al. (2009), Tillmann (2012), Ceritoğlu et al. (2012), Öğünç and Sarıkaya (2011), Alp et al. (2012), Başer et al. (2012), Atuk et al. (2013), Erdoğan-Coşar et al. (2012) and Özçiçek (2011).

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Appendix

Nonlinear State Space Models and the EKF

A nonlinear state space model can be represented as:

$$x_{k+1} = f_k(x_k) + H_k(x_k)\xi_k \qquad \text{(A1)}$$

$$y_k = g_k(x_k) + \eta_k \qquad \text{(A2)}$$

The f_k and g_k are vector-valued functions, while ξ_k and η_k represent white noise processes with the covariance matrices, Q_k and R_k, respectively. The starting values for the EKF algorithm are:

$$P_0 = \text{cov}(x_0) \qquad \text{(A3)}$$

$$\hat{x}_0 = E(x_0) \qquad \text{(A4)}$$

As mentioned in Chui and Chen (1991), the updating equations can be written as:

$$P_{k|k-1} = \left[\frac{\partial f_{k-1}}{\partial x_{k-1}}(\hat{x}_{k-1})\right] P_{k-1} \left[\frac{\partial f_{k-1}}{\partial x_{k-1}}(\hat{x}_{k-1})\right]' + H_{k-1}(\hat{x}_{k-1}) Q_{k-1} H'_{k-1}(\hat{x}_{k-1}) \qquad \text{(A5)}$$

$$\hat{x}_{k|k-1} = f_{k-1}(\hat{x}_{k-1}) \qquad \text{(A6)}$$

$$K_k = P_{k|k-1}\left[\frac{\partial g_k}{\partial x_k}(\hat{x}_{k|k-1})\right] P_{k|k-1}\left[\left[\frac{\partial g_k}{\partial x_k}(\hat{x}_{k|k-1})\right] P_{k|k-1}\left[\frac{\partial g_k}{\partial x_k}(\hat{x}_{k|k-1})\right]' + R_k\right]^{-1} \qquad \text{(A7)}$$

$$P_k = \left[I - K_k\left[\frac{\partial g_k}{\partial x_k}(\hat{x}_{k|k-1})\right]\right] P_{k|k-1} \qquad \text{(A8)}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k\left[y_k - g_k(\hat{x}_{k|k-1})\right] \qquad \text{(A9)}$$

where equations A5-A9 denote the optimal Kalman gain, the updated estimate covariance, the updated state estimate, the predicted estimate covariance and the predicted state, respectively.

In order to apply EKF, the matrices in the state space representation above should be written in terms of functions, which depend on the unknown parameter vector θ_k. In other words, let the matrices be represented by

$\Phi_k(\theta_k)$, $G_k(\theta_k)$ and $H_k(\theta_k)$. Furthermore, let θ_k be a random walk process. In this case, the above equations can be rewritten as:

$$x_{k+1} = \Phi_k(\theta_k)x_k + G_k(\theta_k)w_k \tag{A10}$$

$$y_k = H_k(\theta_k)x_k + v_k \tag{A11}$$

and the parameter vector is:

$$\theta_{k+1} = \theta_k + \zeta_k \tag{A12}$$

The state space representation using functional form is:

$$\begin{bmatrix} x_{k+1} \\ \theta_{k+1} \end{bmatrix} = \begin{bmatrix} \Phi_k(\theta_k)x_k \\ \theta_k \end{bmatrix} + \begin{bmatrix} G_k(\theta_k)w_k \\ \zeta_k \end{bmatrix} \tag{A13}$$

$$y_k = \begin{bmatrix} H_k(\theta_k)x_k & 0 \end{bmatrix} \begin{bmatrix} x_k \\ \theta_k \end{bmatrix} + v_k \tag{A14}$$

where equations A13 and A14 denote the state space representation for the state vector and the observation vector, respectively. The above model is nonlinear where EKF can be readily applied. ζ_k shows the white noise process for which the covariance matrix is assumed to be $cov(\zeta_k) = S_k = S > 0$. In the particular case where $S = 0$, the parameter vector is assumed to be time-invariant and EKF cannot be operative. If EKF algorithm is applied to equations A13 and A14, depending on the starting values, which are as follows:

$$\begin{bmatrix} \hat{x}_0 \\ \hat{\theta}_0 \end{bmatrix} = \begin{bmatrix} E(x_0) \\ E(\theta_0) \end{bmatrix} \tag{A15}$$

$$\text{and } P_0 = \begin{bmatrix} \text{cov}(x_0) & 0 \\ 0 & S_0 \end{bmatrix} \tag{A16}$$

We obtain the following equations:

$$\begin{bmatrix} \hat{x}_{k|k-1} \\ \hat{\theta}_{k|k-1} \end{bmatrix} = \begin{bmatrix} \Phi_{k|k-1}(\hat{\theta}_{k-1})\hat{x}_{k-1} \\ \hat{\theta}_{k-1} \end{bmatrix} \tag{A17}$$

$$P_{k|k-1} = \begin{bmatrix} \Phi_{k-1}(\theta_{k-1}) & \frac{\partial}{\partial\theta}(\Phi_{k-1}(\theta_{k-1}))\hat{x}_{k-1} \\ 0 & I \end{bmatrix} P_{k-1} \begin{bmatrix} \Phi_{k-1}(\theta_{k-1}) & \frac{\partial}{\partial\theta}(\Phi_{k-1}(\theta_{k-1}))\hat{x}_{k-1} \\ 0 & I \end{bmatrix}' + \begin{bmatrix} G_{k-1}(\hat{\theta}_{k-1})\hat{\theta}_{k-1}G'_{k-1}(\hat{\theta}_{k-1}) & 0 \\ 0 & S_{k-1} \end{bmatrix} \quad \text{(A18)}$$

$$K_k = P_{k|k-1}\begin{bmatrix} H_k(\hat{\theta}_{k-1}) & 0 \end{bmatrix} P_{k|k-1}\left[\begin{bmatrix} H_k(\hat{\theta}_{k-1}) & 0 \end{bmatrix} P_{k|k-1} \begin{bmatrix} H_k(\hat{\theta}_{k-1}) & 0 \end{bmatrix}' + R_k\right]^{-1} \quad \text{(A19)}$$

$$P_k = \left[I - K_k \begin{bmatrix} H_k(\hat{\theta}_{k-1}) & 0 \end{bmatrix}\right] P_{k|k-1} \quad \text{(A20)}$$

$$\begin{bmatrix} \hat{x}_k \\ \hat{\theta}_k \end{bmatrix} = \begin{bmatrix} \hat{x}_{k|k-1} \\ \hat{\theta}_{k|k-1} \end{bmatrix} + K_k\left[y_k - \left[H_k(\hat{\theta}_{k-1})\hat{x}_{k|k-1}\right]\right] \quad \text{(A21)}$$