EYD

Ekonomik Yaklaşım Derneği / Association

***Ekonomik Yaklaşım* 2016, 27(99): 237-266**

www.ekonomikyaklasim.org
doi: 10.5455/ey.35932

Is there a Purchasing Power Parity (PPP) Puzzle? New Evidence from a Nonlinear Asymmetric Panel Unit Root Test

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19 Şubat 2015'de alındı; 21 Aralık 2015'de kabul edildi.
28 Mart 2016'dan beri erişime açıktır.

Received 19 February 2015; accepted 21 December 2015.
Available online since 28 March 2016.

Araştırma Makalesi/Original Article

Abstract

In this study the validity of the purchasing power parity (PPP) hypothesis is re-investigated for a panel of 24 OECD countries. The econometric methodology implemented not only allows for asymmetric nonlinear mean reversion within a panel context, but also corrects for the cross-sectional dependence bias frequently encountered in panel data. This feature is important because a test that ignores the presence of asymmetry and cross-sectional dependence when they are in fact present in the data would lead to misleading results. We obtain relatively stronger evidence in favor of the PPP hypothesis when compared to the other alternative panel unit root tests. However, on the whole, this support is still weak even after allowing for asymmetric nonlinear mean reversion in the real exchange rate series. Therefore, to reconcile the data with the theory further methods should be developed.

Keywords: *PPP hypothesis, Asymmetric nonlinear mean reversion, Panel unit root test*
JEL Codes: *F31, F41, C33*

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Özet

Satın Alma Gücü Paritesi (PPP) Yapbozu Var mı? Doğrusal-Olmayan Bir Asimetrik Panel Birim Kök Testinden Yeni Kanıt

Bu çalışmada satın alma gücü paritesi hipotezinin geçerliliği 24 OECD ülkesinden oluşan bir panel için yeniden incelenmiştir. Kullanılan ekonometrik yöntem hem panel verilerde asimetrik doğrusal olmayan intibaka izin vermektedir hem de bu verilerde sık rastlanan kesit bağımlılığı problemini de dikkate almaktadır. Eğer veriler bu iki özelliğe de sahip oldukları halde kullanılan ekonometrik yöntem bunları gözardı ederse o zaman yanıltıcı sonuçların alınmasına sebep olur. Satın alma gücü paritesi hipotezinin ampirik çalışmalarda genel olarak reddedilmesinin arkasında yatan temel sebep de kullanılan test yöntemin bu iki özelliği içermemesi olabilir. Çalışmada uygulanan doğrusal olmayan panel birim kök testi diğer testlere oranla daha fazla ülkede satın alma gücü paritesi hipotezinin varlığını doğrulamıştır. Fakat buna rağmen, reel döviz kurlarında doğrusal olmayan asimetrik uyuma izin verilmesi bile bu hipotezin geçerliliğini tüm ülkeler için doğrulayamamıştır. Bu yüzden veriler ve teorinin uzlaştırılması için daha gelişmiş ekonometrik yöntemlerin geliştirilmesine ihtiyaç duyulmaktadır.

Anahtar Kelimeler: *Satın alma gücü paritesi hipotezi, doğrusal olmayan asimetirk intibak, panel birim kök testi.*
JEL Kodları: *F31, F41, C33*

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1. Introduction

Purchasing power parity (PPP) theory, which is the most prominent theory of how exchange rates are determined, asserts that exchange rates between any two countries will adapt in the long-run to indicate changes in the price levels of the two countries. In its simplest form, PPP states that the real exchange rate should equal one. PPP is also one of the crucial pillars of support in the open economy macroeconomic models and thus, its violation brings the validity of these models under question (Taylor, 1995; Sarno, 2005). Furthermore, as stated in Sarno and Taylor (2001), PPP is employed to establish the extent of misalignment of nominal exchange rates and thereby to analyze the income differences across countries, and thus, actions adopted by governments based on these calculations only makes sense when PPP holds. For

all these reasons, analyzing the validity of PPP has become one of the central issues in open economy macroeconomics and international finance [2]. In the real world, however, we would not in general expect PPP to hold exactly and continuously due to the existence of transportation costs and legal barriers to trade, or non-traded goods. Thus, economists consider PPP as a long-run equilibrium condition. However, as in the "overshooting" model, real economic shocks (such as productivity shocks) can give rise to continuing deviations from PPP (Dornbush, 1976). Also Sarno and Taylor (2002) and Rogoff (1996) have argued that, the real exchange rate (RER) becomes close to a random walk principally for supply shocks that show high persistence. A major part of this literature tests the validity of the PPP hypothesis by conducting stationary tests on the RER series. While a real exchange rate with a unit root would violate the PPP, the one that is stationary would verify its existence.

In spite of the burgeoning number of studies in this field, the results of the studies on the PPP hypothesis still remains largely indecisive due to the econometric challenges concerned with identifying stationary RER series. The idea that the deviations from PPP are temporary have met with failure when trying to recoincile the theory with the data. The conventional Dickey-Fuller unit root tests have particularly refuted the PPP theory. This evident inconsistency has brought this issue to economists attention and was named as the "PPP puzzle" (Rogoff, 1996; Taylor, 2001; Sarno and Taylor, 2002). Along these lines, Taylor (2003, 2006) have argued that the conventional tests of unit root do not have enough power and thus, lead to deceiving results. The focus of this research agenda has therefore moved to investigating alternative frameworks within which to verify the purchasing power parity theory and thereby pawed the way for utilizing panel unit root tests and/or permitting nonlinearities in the PPP adjustment. After a comprehensive overview, two main conclusions can be drawn from this more recent econometric analysis. First, studies that utilize a much longer span of data and/or allow for the use cross-sectional information in the panel data tend

[2] See Froot and Rogoff (1995), Rogoff (1996), Sarno and Taylor (2002), and Taylor (2003, 2006) for surveys on the PPP literature.

to find relatively stronger evidence supporting the stationary behaviour in the RER series (e.g. Wei and Parsley, 1995; Oh, 1996; Frankel and Rose, 1996; MacDonald, 1996; Wu, 1996; Papell, 1997, Koedijk et al., 1998; Fleissig and Strauss, 2000; and Kuo and Mikkola, 2001)[3]. Second, there is strong evidence that the RER is mean reverting, but that the adjustment to this mean follows a nonlinear process (Goldberg et al., 1997; Michael et al., 1997; Sarantis, 1999; Taylor and Peel, 2000; Baum et al., 2001; Taylor et al., 2001; Sollis et al., 2002; Liew et al., 2003; Liew, 2004). In this study we take stock of these two findings and in light of them test the PPP hypothesis for the 24 major OECD countries over the period 1990:1–2013:12 using panel data and allowing for nonlinear mean reversion.

Although using the panel data approach has its own merits (i.e., increasing the power of the conventional unit root tests), it also creates additional problems otherwise absent in univariate time series techniques. First, it is well documented in the literature that conventional panel unit root tests that do not consider CSD lead to serious size distortions. Allowing for CSD is especially important when testing for PPP, because RERs by construction contain two common components: the foreign price index, and the value of the numeraire currency, which naturally causes them to be cross-sectionally dependent (O' Connell, 1998; Carvalho and Julio, 2012). Second; if the panel unit root test leads to the rejection of the unit root null, then this does not mean that all of the series in the panel contain a unit root (Taylor and Sarno, 1998; Sarno and Taylor, 1998). In other words, the test does not give us information about the countries for which the unit root null is rejected. To correct for this flaw, after the null hypothesis of a unit root is rejected it is fairly crucial to decompose the panel into its I(0) and I(1) components.

The idea that the RER behaves like a nonlinear stationary process was put forward by theoretical models that highlight the role of transaction costs and frictions in international arbitrage, and monopolistic pricing (e.g. Dumas, 1992; Chari et al.,

[3] There are exceptions, however, with O'Connell (1998) and Smith et al. (2004) showing that the PPP does not hold by employing panel unit root tests.

2000, Sercu et al., 1995). In these models, while large discrepancies from PPP will be eliminated quickly through the arbitrage process, small deviations are not expected to revert to equilibrium. Nonlinearity in the RER series can stem from other sources such as, speculative attacks on currencies, heterogeneity of buyers and sellers, official interventions, and the presence of target zones (Emirmahmutoglu and Omay, 2014). To take such nonlinear behavior into account, the RER series are commonly modelled as a globally stationary exponential smooth transition autoregressive (ESTAR) model with a unit root central regime (Michael et al., 1997; Baum et al., 2001; and Taylor et al., 2001). Fortunately, Kapetanious et al. (2003) have developed a time series unit root test where the alternative hypothesis exactly considers the ESTAR behavior described above.

However, an implicit assumption underlying the ESTAR model is symmetric nonlinear mean reversion (Sollis, 2009). This particular assumption may be overly restrictive for real exchange rates, since official interventions may induce real exchange rates to display asymmetric behavior if policymakers act asymmetrically in reaction to changes in the value of the currency (Enders and Dibooglu, 2001). Along these lines, Sollis et al. (2002) have shown that for a vast number of industrialized countries real appreciations of the U.S. dollar tend to last less than real depreciations of the same amount. Sollis (2009) have corroborated the findings of Sollis et al (2002) by demonstrating strong asymmetry in the RERs of Nordic countries. Dutta and Leon (2002) have also confirmed the existence of asymmetry but with a reverse pattern existing for emerging market economies in the sense that, policymakers now allow real appreciations to persist longer than depreciations. As argued in Enders and Dibooglu (2001), another source of asymmetric adjustment in case of RERs is downward sticky national prices. These authors show that prices and exchange rates adjust differently in reaction to positive and negative deviations from the PPP.

To enable asymmetric mean reversion within the context of the ESTAR model, Sollis (2009) have developed a unit root test from an extended version of the ESTAR model

that allows for asymmetric mean reversion under the alternative hypothesis. Later, Emirmahmutoglu and Omay (2014) (henceforth, EO) have extended this test to a panel context. To correct for the aforementioned size distortion that happens because of CSD, EO have implemented Chang's (2004) sieve bootstrap methodology. Moreover, EO have employed a sequential panel selection method (SPSM) developed by Choartareas and Kapetanios (2009) to break down the panel into its I(0) and I(1) components. In light of these innovations, to verify the PPP hypothesis we employed the EO test, since it seems the best procedure at hand that fits the theoretical and empirical studies on the PPP hypothesis. As aforementioned, the empirical literature accumulated so far highlights the presence of asymmetric nonlinear behavior in RERs, which implies that asymmetric nonlinear mean reversion have to be considered when investigating the stochastic properties of the RERs within a panel context. The results of the EO test will be compared to those of two alternative panel unit root tests. The first one is the test proposed by Ucar and Omay (2009) (henceforth, UO) and the second is the conventional IPS panel unit root test developed by Im et al. (2003).

Our empirical results have shown that the EO test rejects unit-root dynamics in the RERs for 8 out of 24 OECD countries. By contrast, the UO test rejected the unit root null in fewer cases, and the IPS test led to the non-rejection of the unit root null for the entire sample. As a whole it seems that taking the potential asymmetric behavior in the RERs into account is more appropriate for obtaining more conclusive evidence giving support to the PPP hypothesis.

The paper is organized as follows. Section 2 gives a literature survey of the studies conducted to examine the PPP hypothesis. Section 3 explains the law of one price (LOOP) on which the PPP hypothesis is based along with the relative and absolute versions of the PPP. Section 4 introduces the EO nonlinear panel unit root test. Section 5 presents the results of the EO test applied to a panel of OECD countries to verify the PPP hypothesis. Section 6 is reserved for the concluding remarks.

2. Literature Survey

A vast number of studies analyzed the validity of the PPP hypothesis, which is catalyzed by the development of many econometric techniques. In this section, we will try to survey this vast literature by mainly focusing on the recent empirical evidence, especially the studies that were conducted after the 2000s. The studies that test the PPP theory can be decomposed into two main groups according to the econometric methodology applied. The first group tests the PPP hypothesis by applying time series or panel unit root tests that preserve the linearity assumption, while the latter implements tests that are also valid under a nonlinear setting.

The first strand of studies that preserve the linearity assumption can further be divided in two subgroups: the ones that apply conventional time series tests and the ones that utilize panel data techniques. In case of the times series tests, generally the conventional unit root tests such as the Augmented Dickey Fuller (ADF), Dickey Fuller Generalized Least Squares (DF-GLS), Kwiatkowski-Phillips–Schmidt–Shin (KPSS) or the Phillips Perron (PP) unit root tests are applied to the RER series of the selected countries. When these linear univariate tests were applied to the PPP hypothesis, a common finding in the literature is that the PPP fails[4]. Along these lines, Lopez (2003) examined the validity of the PPP theory using the conventional ADF unit root test for 21 industrialized countries for the period 1973 to 2001 and concluded that the univariate unit root tests were inadequate to use when analyzing the PPP under the floating exchange rate regime. Also He et al. (2013) investigated the PPP theory for the transition economies such as Bulgaria, the Czech Republic, Hungary, Latvia, Lithuania, Poland, Romanian, and Russia. By applying the ADF, PP and KPSS unit root tests they have found that the PPP theory failed in the long run for these countries. Similarly, Shiller (2013) has applied the ADF and PP tests to the

[4] There are only a limited number of studies that find evidence in favor of the PPP by applying the conventional univariate unit root tests. For example, Nursai (2003) tested the validity of the PPP theory for 6 Asian countries using the ADF, PP and KPSS tests and showed that PPP holds in four out of the six of these countries. Similarly, Tataloğlu (2009) tested the PPP hypothesis using the ADF test for 25 OECD Countries for the period 1997 to 2004 and found out that the ADF test is significant when structural break is ignored.

RERs of the United Kingdom, United States, France, Germany and Japan for the period 1982 to 1997 and demonstrated that the PPP hypothesis fails. Carvalho and Julio (2012) analyzed the PPP theory for 20 OECD member economies using a large number of unit root tests. The authors failed to provide strong support for the PPP theory by using the standard time series unit root tests. However, the DF-GLS test verified the PPP hypothesis in relatively more number of countries. In another study, Christidou and Panagiotidis (2010) failed to obtain strong evidence supporting the PPP hypothesis by employing the ADF test to 15 European Union Countries for the period between 1973 and 2009. The unit root null could only be rejected for UK and Sweden in the post-Maastricht period. Within this subgroup there are also studies that utilize tests that allow for structural breaks in the RERs. For example, Hoque and Banerjee (2012) have tested the PPP theory for developing countries such as; Bangladesh, Pakistan, India and Sri Lanka by using the ADF and PP tests with structural change. These authors have again failed to find any evidence giving support to the PPP theory for these developing countries. Similarly, the studies including Froot and Rogoff (1995), Rogoff (1996), Sarno and Taylor (2002) have used standard univariate unit root tests and failed to verify the PPP hypothesis.

With the failure of the standard univariate unit root tests to provide significant support for the PPP, many researchers started to use panel data techniques to increase the size and power of the conventional unit root tests. In general, the studies that apply the panel unit root tests tend to find a greater support in favor of the PPP hypothesis when compared to the univariate tests. For instance, Frankel and Rose (1996) gathered a panel data set that spans 152 countries for the period from 1948 to 1992. Their results have rejected the unit root null using post-1973 floating data. Also Coakley and Fuertes (1997) have applied the standard panel tests to the RERs of G10 countries and Switzerland for the period 1973 to 1996, and reported strong support for the PPP hypothesis. Olayungbo (2011) have utilized the standard IPS and LLC (Levin et al., 2002) panel unit root tests to analyze the RERs of the 16 Sub-Saharan African countries from 1980 to 2005. This study finds favorable evidence that supports the

PPP hypothesis, thereby confirming the relatively strong power of the panel unit root tests. In addition, Fleissig and Stratus (2000) have also applied the IPS test to the RERs of 19 OECD countries from 1974 to 1996. This study corroborates the finding that the panel unit root tests are more powerful than their univariate counterparts. Although the panel unit root test results have generally verified the existence of the PPP hypothesis, the findings still very much depend on the span and/or the countries included in the panel. For example, Papell (1997) tested the PPP hypothesis for 20 developed countries employing panel data with monthly and quarterly observations that run from 1973 to 1994 and showed that the PPP fails when quarterly data is used. Along these lines, Carvalho and Julio (2012) applied the LLC, IPS, Fisher-ADF (Maddala and Wu, 1999) and Hadri (Hadri, 2000) panel unit root tests to a selected number of OECD countries. While PPP is verified for the countries included in this study when the IPS and Fisher-ADF tests were used, the LLC and Hadri tests have failed to support it. Likewise, Wu et al. (2011) have tested the PPP hypothesis using the standard IPS test for 76 countries for the period 1976 to 2006. While the study shows that the PPP holds for African and Latin American countries, it fails to hold for Asia and Europe. Similarly, Christidou and Panagiotidis (2010) have showed that the PPP holds when the IPS test is applied to the RERs of the 15 European Union countries for the period between 1973 and 2009, but that it does not hold when the Hadri test is utilized.

It is important to note that the aforementioned panel unit root tests ignore the existence cross sectional dependence (CSD) in the countries under investigation. However, as mentioned above, handling CSD across individual units is crucial in developing a panel unit root test because ignoring cross sectional dependence would produce important power losses and size distortions. To overcome these problems second generation panel unit root tests have proposed that take CSD into account. Along these lines, Christidou and Panagiotidis (2010) have also applied the panel unit root tests proposed by Pesaran (2007) and Hadri and Kurozumi (2008) to the RERs of the 15 European Union countries that allow for CSD. Again contradicting evidence

was found when these second generation panel unit root tests were applied to the data. While the results of the first test supported PPP, the latter refuted it. Similarly, Lau (2009) by applying a modified version of the Breuer, McNown and Wallance (2001) (BNW) test that allows for CSD in a panel of 4 OECD countries have verified the PPP hypothesis in 3 out of 4 countries included in the study. Also, Ramajo and Ferre (2010) have applied Pesaran's (2007) panel unit root test that allows for CSD to analyze the PPP in a panel of 21 OECD countries. Their results indicated support for the PPP hypothesis in the OECD panel used.

After applying the standard time series unit root tests and linear panel unit root tests to study the PPP hypothesis, still researchers were unable to reach to a conclusive result about the merits of the PPP hypothesis. Therefore, studies in this second strand of literature started to employ nonlinear models to obtain more supportive evidence on behalf of the PPP hypothesis when compared to their linear counterparts. For example, Su et al. (2014) analyzed the PPP hypothesis for 61 countries between the period 1994 and 2012 by using the univariate nonlinear unit root test proposed by Kapetanious et al. (2003) (KSS test) and showed that PPP held strongly for all of the 61 countries. Similarly, Cuestas and Regis (2013) have found strong empirical evidence supporting the PPP utilizing the KSS test and applying it to the RERs of the OECD countries for the period from 1972 to 2010. In addition, by utilizing the KSS test Christidou and Panagiotidis (2010) have found strong evidence supporting the PPP hypothesis in Sweden and UK for the period from 1973 to 2009. Similarly, Bahmani-Oskooee et al. (2007) have corroborated the findings of Christidou and Panagiotidis (2010) for 7 non-EU industrialiazed countries (Australia, Canada, Japan, New Zealand, Norway, Switzerland, and the U.S.). Chortareas et al. (2002) have applied the KSS test with the optimal lag length selection and showed that PPP holds for the majority of the G7 countries as opposed to the ADF test that accepts the PPP for only one country. Chang et al. (2006) have applied a variety of standard univariate tests and the unit root test proposed by Leybourne et al. (1998) to verify the validity of PPP for 22 African countries and obtained favourable evidence for PPP in 6 out of

22 cases. The number of rejections has considerably decreased to one when the other conventional tests were applied. Christopoulas and Leon-Ledesma (2010) have applied a nonlinear unit root test that accounts for structural breaks and thereby verified the PPP hypothesis in 14 out of 15 OECD countries. Kapetanious and Shin (2006) have developed a new nonlinear three regime SETAR unit root test and verified the validity of the PPP for in 3 out of 5 G7 countries. Jiménez-Martin and Robles-Fernandez (2010) have applied two different nonlinear unit root tests that enable asymmetric adjustment within the context of the ADF test to analyze the PPP for 18 bilateral US exchange rate series. Their results show that nonlinearity exists and PPP holds in 9 out of 18 countries.

Despite the fact that last decade has witnessed important advances in unit root testing procedures based on a univariate nonlinear framework, studies that extend these testing methodologies to a panel framework have been rather limited. Examples concerning the presence of unit roots within a univariate nonlinear context include, among others, Enders and Granger (1998), Leybourne et. al. (1998), Sollis et. al (2002), Kapetanios et al. (2003), and Sollis (2004, 2009). The most extensively applied nonlinear panel unit root test within the context of the PPP hypothesis is the one developed by Uçar and Omay (2009). He et al. (2013) have investigated the PPP hypothesis for transition economies (including Bulgaria, Czech Republic, Hungary, Latvia, Lithuania, Poland, Romanian, and Russia) by using monthly data that runs from 1995 to 2011. In addition to the nonlinear univariate KSS unit root test, they have also utilized the nonlinear Ucar and Omay (2009) (UO) panel unit root test. These authors indicate that the PPP theory is successful for Bulgaria, Lithuanian, Poland, Latvian and Romanian. Another study investigating the PPP hypothesis by utilizing nonlinear panel unit root test pertain to He and Chang (2013). They have analyzed the PPP for 14 transition countries for the period between 1994 and 2012. They have used the UO test together with the sequential panel selection method proposed by Choartareas and Kapetanios (2009) and showed that the PPP is accepted for 2 out of 14 countries included in their study. Along these lines, Oskooee et al.

(2013) have investigated the PPP for BRICS and MIST countries between 1994 and 2012 years using the UO test. Their results have indicated that the PPP theory is valid for South Korea, India and Indonesia. In addition to the UO test, there are studies that apply the panel SURKSS test developed by Wu and Lee (2009) to test the validity of the PPP hypothesis. For example Chang et al. (2010) by applying the panel SURKSS test to the RERs of the G7 countries have showed that the PPP fails for only the RERs of Canada and Japan. Similarly, Chang et al. (2011) and Chang and Su (2010) have corroborated Chang et al. (2010)'s findings for 5 out of 7 Central and East European countries and 4 out of 7 major OPEC countries, respectively.

3. The Law of One Price, Absolute PPP and Relative PPP

The law of one price (LOOP) suggests that homogeneous goods are sold at the same price in two separate countries and can be stated as follows

$$P_{i,t}^{j} = E_{j/\$,t} \times P_{i,t}^{US} \tag{3.1}$$

where, $P_{i,t}^{US}$ is the US dollar (i.e. numeraire currency) price of good *i* at time *t*, $P_{i,t}^{j}$ denotes the price of good *i* in country *j* at time *t* and $E_{j/\$,t}$ gives the nominal exchange rate between US dollar and country *j*'s currency at time *t* and is expressed as units of national currency (i.e. in country *j*) per foreign currency (i.e. in US).

If $P_{i,t}^{j} < P_{i,t}^{US}$ in equation (3.1), there is an arbitrage opportunity and one can buy goods from the domestic market at P_{j}^{i} and sell it in the foreign market at P_{US}^{i}. This arbitrage process will continue until equality holds between the two price levels. The same is true for the reverse case in which $P_{i,t}^{j} > P_{i,t}^{US}$. Therefore, if the LOOP doesn't hold, the arbitrage opportunity will occur and the price levels will eventually converge to each other.

The theory supposes that are no transaction costs, taxes, trade barriers to international trade, and also assume that perfect competition exists in the markets. If these

assumptions do not hold, then arbitrage opportunities can emerge for importers and exporters in the international market.

The absolute PPP theory is an aggregated version of the LOOP given in equation (3.1) and suggests that

$$P_t = E_t \times P_t^* \tag{3.2}$$

where $P_t = \sum_{i=1}^{K} \beta_i P_{i,t}^j$ denotes the domestic price index at time *t*, $P_t^* = \sum_{i=1}^{K} \beta_i P_{i,t}^{US}$ gives the foreign price index at time *t* and E_t denotes the nominal exchange rate between the domestic and foreign country at time *t*. Equation (3.2) can be expresses in logaritmic terms as follows

$$p = e + p^* \tag{3.3}$$

where lower case letters denote the same variables given in equation (3.2) in natural logarithm.

According to the equation (3.2), absolute PPP prevails if the same basket of goods costs the same when prices are converted to a common currency. Stated differently, absolute PPP necessitates a zero real exchange rate. One of the most important problems about absolute PPP is the selection of the price index. There is no general price index to calculate each weight of the commodities for each country in the international market.

Relative PPP prevails if the ratio of two broadly defined price indices stays constant when corrected for changes in the exchange rate. That is, if

$$e + p^* - p = q \tag{3.4}$$

where $q = \ln(Q)$ in fact denotes the natural logarithm of the real exchange rate given with Q. In equation (3.4) the home and foreign aggregate price indices are obtained by applying the same mechanism discussed above for the absolute PPP. According to equation (3.4), relative PPP postulates that the real exchange rate is a constant. In equation (3.4), q can also be interpreted as a positive constant that is included in the equation to take into account for trade barriers such as transportation costs, tariffs and quotas etc. The absolute version of the PPP is more stronger than its relative version. If absolute PPP is violated, then the relative PPP will also be violated. However, relative PPP violation does not necessitate the violation of the absolute PP condition.

4. Methodology

In this section we first describe the asymmetric ESTAR (AESTAR) model developed by Sollis (2009) and then present the unit root testing procedure proposed by Emirmahmutoglu and Omay (2014), which is an extension of the Sollis (2009) test to heterogenous panels.

The AESTAR model hypothesizes that the real exchange rate adjusts according to the following process:

$$\Delta q_t = \phi q_{t-1} + G_t(\gamma_1, q_{t-1})\{S_t(\gamma_2, q_{t-1})\rho_1 + (1 - S_t(\gamma_2, q_{t-1}))\rho_2\}q_{t-1} + \varepsilon_t, \quad (4.1)$$

$$G_t(\gamma_1, q_{t-1}) = 1 - \exp(-\gamma_1 q_{t-1}^2) \quad \gamma_1 \geq 0 \quad (4.2)$$

$$S_t(\gamma_2, q_{t-1}) = [1 + \exp(-\gamma_2 q_{t-1})]^{-1} \quad \gamma_2 \geq 0 \quad (4.2)$$

where $\varepsilon_t \sim iid(0, \sigma^2)$. The function given in (4.2) is bounded between zero and unity, and γ_1 and γ_2 measure the speed of mean reversion.

The extended ESTAR model given above is called as an asymmetric ESTAR (AESTAR) model, since it utilizes both an exponential function and a logistic function (Sollis, 2009). In the model given above, the central or middle regime

corresponds to $q_{t-1} = 0$ when $G = 0$, while the outer regimes correspond to $q_{t-1} = \mp\infty$ when $G = 1$.

Michael et al. (1997) assert that transaction costs including transportation costs, tariff payments, import licensing fees, and the purchase of foreign exchange, are an important characteristic of international trade[5]. These market frictions establishes a band within which the discrepancies from the PPP are not corrected since they are fairly small to cover the transaction costs. However; if the deviation from the PPP is large (ie., outside this band), then the profitability of arbitrage is also higher (than when this deviation is small) and as a result large discepancies happen to be mean reverting (i.e., they are arbitraged away). As a result, the speed of adjustment to PPP equilibrium varies inversely with the size of the deviation itself. In other words, the larger the discrepancy from the PPP the more quickly is the discrepancy eliminated through the process of commodity arbitrage. In the context of the model given above, if RERs are nonlinearly mean-reverting, then the model given above implies that q_t may be characterized by a unit root component for small discrepancies from the long-run equilibrium (corresponding to the middle regime for which $G = 0$) but should eventually be mean-reverting the larger is the discrepancy from equilibrium (corresponding to the outer regimes for which $G = 1$). This implies that while $\phi \geq 0$ is possible, PPP is valid (and the model is globally stationary) if $\rho_1 < 0$, $\rho_2 < 0$, and $\gamma_1 > 0$.

Within this context, Sollis (2009) considers that the process q_t has a unit root in the center regime by imposing that $\phi = 0$, and then analyzes whether large deviations from the PPP are mean reverting by evaluating the null hypothesis of $\gamma_1 = 0$ against the alternative of $\gamma_1 > 0$.

[5] See also Dumas (1992), Uppal (1993), and Sercu et al. (1995).

An ESTAR model assumes that the adjustment to PPP deviations must be the same for positive and negative deviations from equilibrium. Although the studies including Michael et al. (1997), Taylor et al. (2001) and Baum et al. (2001) assume symmetric adjustment in the real exchange rate, there are others in the literature that allow for asymmetric adjustment. For instance, Liew (2004), Sollis et al. (2002), and Dutta and Leon (2002) have demonstrated that the US dollar based real exchange rates exhibited asymmetrical responds towards appreciation and depreciation. For developed countries depreciations seem to persist more than appreciations of the same amount, which is rationalized on the grounds that depreciations stimulate net exports and therefore are allowed to persist more by policy makers.

To take these potential asymmetries into account, Sollis (2009) has developed a test whose alternative hypothesis allows for a globally stationary asymmetric or symmetric ESTAR nonlinearity with a unit root central regime. It can be seen from equation (4.1) that for $\phi = 0$ and $\rho_1 \neq \rho_2$ the autoregressive adjustment is asymmetric. This causes an ESTAR transition to occur between the central regime model, $\Delta q_t = \varepsilon_t$, and outer regime model, $\Delta q_t = \rho_2 q_{t-1} + \varepsilon_t$; if $\gamma_1 > 0$ and $\gamma_2 \to \infty$, as q_{t-1} moves from zero towards $-\infty$, since $S_t(\gamma_2, q_{t-1}) \to 0$. Thus, if the deviation is large and in the negative direction γ_2 determines the speed of the transition. On the other hand, as q_{t-1} moves from zero towards ∞, since $S_t(\gamma_2, q_{t-1}) \to 1$; an ESTAR transition occurs between the central regime model, $\Delta q_t = \varepsilon_t$, and this time the outer regime model, $\Delta q_t = \rho_1 q_{t-1} + \varepsilon_t$.

Emirmahmutoglu and Omay (2014) have extended the above AESTAR model to heterogeneous panels. Their nonlinear asymmetric heterogeneous panel data model postulates that the RER follows a process

$$\Delta q_{it} = G_{it}(\gamma_{1i}, q_{i,t-1})\{S_{it}(\gamma_{2i}, q_{i,t-1})\rho_{1i} + (1 - S_{it}(\gamma_{2i}, q_{i,t-1}))\rho_{2i}\}q_{i,t-1} + \varepsilon_{it}, \tag{4.4}$$

$$G_{it}(\gamma_{1i}, q_{i,t-1}) = 1 - \exp(-\gamma_{1i}\, q_{i,t-1}^2) \quad \gamma_{1i} \geq 0 \ \text{ for all } i \tag{4.5}$$

$$S_{it}(\gamma_{2i}, q_{i,t-1}) = [1+\exp(-\gamma_{2i}\, q_{i,t-1})]^{-1} \quad \gamma_{2i} \geq 0 \ \text{ for all } i \tag{4.6}$$

where $\varepsilon_{it} \sim iid(0,\sigma_i^2)$. If $\rho_{1i} = \rho_{2i} = \rho_i$ for all *i*, then the autoregressive adjustment is symmetric and the specification given in (4.4) nests the panel symmetric ESTAR specification of the UO test.

For serially correlated errors, EO have extended equation (4.4) to allow for higher order dynamics as follows:

$$\Delta q_{it} = G_{it}\left(\gamma_{1i}, q_{i,t-1}\right)\left\{S_{it}\left(\gamma_{2i}, q_{i,t-1}\right)\rho_{1i} + \left(1 - S_{it}\left(\gamma_{2i}, q_{i,t-1}\right)\right)\rho_{2i}\right\} q_{i,t-1} + \sum_{j=1}^{p_i}\delta_{ij}\Delta q_{i,t-j} + \varepsilon_{it} \tag{4.7}$$

In the above given equation, the unit root hypothesis can be tested against the alternative hypothesis of globally stationary symmetric or asymmetric ESTAR nonlinearity with a unit root central regime by testing $H_0 : \gamma_{1i} = 0$. However, to overcome the unidentified parameters problem, EO have derived the following augmented auxiliary equation using a Taylor approximation as follows:

$$\Delta q_{it} = \phi_{1i} q_{i,t-1}^3 + \phi_{2i} q_{i,t-1}^4 + \sum_{j=1}^{p_i}\delta_{ij}\Delta q_{i,t-j} + \varepsilon_{it} \tag{4.8}$$

In this framework, the null hypothesis becomes $H_0 : \phi_{1i} = \phi_{2i} = 0$ for all i and the test statistic is computed by taking the average of the individual $F_{i,AE}$ statistics developed by Sollis (2009). Thus,

$$\bar{F}_{AE} = N^{-1}\sum_{i=1}^{N} F_{i,AE}. \tag{4.9}$$

EO have stated that the exact critical values of $\bar{F}_{AE}$ should be computed via stochastic simulation for different values of *N* and *T*. In addition, to circumvent the CSD

problem EO have implemented the Sieve bootstrap methodology proposed by Chang (2004) to obtain the empirical distributions of the bootstrap statistic $\bar{F}_{AE}^{*}$ [6].

5. Data and Results

In this section, the PPP hypothesis is examined for 24 OECD countries over the period 1990:01-2013:12[7]. The data on bilateral exchange rates against the U.S. dollar and consumer price indices (CPI) were taken from International Monetary Fund's *International Financial Statistics* database[8]. The base year for the CPI is 1997. The analysis includes 24 developed countries: Austria, Belgium, Canada, Denmark, Finland, France, Greece, Hungary, Iceland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, Norway, Netherlands, Poland, Portugal, Sweden, Switzerland, Spain, Turkey, and the UK. All variables were put into natural logarithms before the analysis.

We define the log of the RER for each country *j* as $r_{jt} = e_{jt} + p_{jt} - p_t^*$, where e_{jt} is the log of the nominal exchange rate in country *j* defined as the US dollars per unit of domestic currency at time *t*, $p_{jt} = \ln(CPI_{jt})$ and CPI_{jt} is the consumer price index of country *j* at time *t*, and $p_t^* = \ln(CPI_t^*)$ and CPI_t^* is the consumer price index of the US at time *t*.

To test whether the RERs exhibit mean reversion, in addition to the EO test, two alternative panel unit root tests were also applied to the RERs of the OECD countries for comparison. The first of these tests is the conventional panel unit root test of IPS. However, the IPS test is criticized on the grounds that it ignores CSD. This assumption is very restrictive given the cross-section correlation and repurcussion effects that exists in the RERs across countries. Therefore, to solve the size problem

[6] For details of this methodology, see Emirmahmutoglu and Omay (2014).

[7] The same data set was utilized in an earlier study by Özdamarlar (2014). She has tested the PPP hypothesis for the same set of countries and time interval using a battery of unit root tests with the exception of the EO test, which is the main focus of our study.

[8] The CPI data is seasonally adjusted.

that occurs because of CSD, we have implemented Chang's (2004) bootstrap methodology in the context of the IPS test. Another aforementioned weakness of the standard IPS test is that it is based on the assumption that the RERs follow a linear adjustment process, which may not be true according to the existing empirical evidence. Thus, to allow for nonlinear mean reversion in the RERs, the UO panel unit root test was also applied to the RERs that also allows for CSD. The UO test is obtained by extending the Kapetanios, Shin and Snell (2003) time series unit root test to a panel setting. However, the UO test ignores the possibility of asymmetric adjustment. Since the RERs are documented theoretically and empirically to diplay asymmetric behaviour, we further apply the EO test to the RERs that also uses additional information from the cross sectional units to achieve a power gain.

We started by conducting the IPS test to the full sample of OECD countries, and concluded that the null hypothesis of a unit root in the RERs could not be rejected (producing the value -2.109)[9]. Thus, the conventional linear panel unit root test has rejected the PPP hypothesis for the whole set of countries included in our sample. Afterwards, to investigate for the possibility of nonlinear mean reversion in the RERs we performed the UO ($\bar{t}_{nl}$) and EO ($\bar{F}^{*}_{AE}$) unit root tests that allow this possibility. The results of the $\bar{t}_{nl}$ and $\bar{F}^{*}_{AE}$ tests are given in Panels A and B of Table 1. Panel A presents the results of the UO unit root test applied using the Chang's (2004) Sieve bootstrap test and is taken from Özdamarlar (2014). We also give a sequence of UO tests applied on a reducing dataset using the SPSM procedure (third column), the individual minimum KSS (the univariate counterpart of the UO test) statistics used to decide on the individual series to be dropped from the panel (second column), and the stationary series identified using this procedure each time (first column). Panel B reports the results of the EO test applied using again Chang's (2004) Sieve bootstrap methodology.

[9] For further details one can refer to Özdamarlar (2014).

Table 1. Nonlinear Panel Unit Root Test Results for the PPP hypothesis

Panel A: UO test			**Panel B: EO test**		
Countries	**Min. KSS**	$\overline{t}_{nl}$	**Countries**	**Max.** $F_{AE,\mu}$	$\overline{F}^{*}_{AE}$
Mexico	-5.160	-2.507**	Mexico	14.539	4.596***
		(0.027)			(0.009)
Iceland	-4.113	-2.391*	Turkey	10.581	4.164**
		(0.058)			(0.033)
Poland	-4.048	-2.313*	Poland	9.543	3.963**
		(0.063)			(0.041)
Turkey	-3.858	-2.231*	Iceland	9.506	3.745*
		(0.078)			(0.052)
UK	-3.636	-2.149*	UK	7.619	3.507*
		(0.089)			(0.061)
Greece	-3.442	-2.071*	Greece	6.003	3.343*
		(0.097)			(0.073)
Korea	-3.426	-1.995	Korea	5.860	3.196*
		(0.112)			(0.084)
Hungary	-2.794	-1.910	Switzerland	5.453	3.039*
					(0.090)
Switzerland	-2.280	-1.855	Hungary	4.891	2.951
					(0.101)
Israel	-2.277	-1.827	Norway	4.860	2.888
Sweden	-2.206	-1.795	Finland	4.636	2.818
Portugal	-2.178	-1.763	Belgium	4.538	2.755
Japan	-2.151	-1.729	Israel	3.449	2.690
Spain	-1.970	-1.690	Austria	3.440	2.621
Finland	-1.856	-1.662	France	3.253	2.539
Norway	-1.725	-1.641	Netherlands	2.890	2.460
Italy	-1.695	-1.630	Denmark	2.650	2.406
Austria	-1.679	-1.621	Portugal	2.650	2.372
Netherlands	-1.677	-1.611	Luxembourg	2.638	2.325
Denmark	-1.649	-1.598	Sweden	2.632	2.263
France	-1.646	-1.585	Japan	2.601	2.171
Belgium	-1.623	-1.565	Spain	2.341	2.027
Canada	-1.548	-1.537	Italy	2.109	1.871
Luxemboug	-1.525	-1.525	Canada	1.632	4.596

Notes: In all cases ***,**, and * denote rejection of the unit root null hypothesis at %1, %5 and %10 significance levels, respectively. We include only a constant term in the test regressions. Test results are obtained employing 1000 bootstrap replications. The optimal lags are selected using the Schwartz Information Criteria (SIC).

The sequence of EO tests applied using the SPSM procedure (sixth column), the individual maximum Sollis's (2009) *F*-statistics (the univariate counterpart of the EO test) that are used to carry out the reduction of the individual series (fifth column), and the countries with the stationary series identified using this procedure each time

(fourth column) are also given in this panel. In each panel, the countries given in the first and fourth columns are sorted in a descending order according to the univariate counterparts of each panel unit root test applied on the RERs of the OECD countries included in the study.

Evidence from Table 1 makes it clear that the PPP hypothesis is rejected when the UO and EO tests are first applied to the full sample, producing the values -2.507 and 4.596, respectively. To be able to identify the countries for which the PPP holds from the countries in which it does not hold the SPSM procedure is implemented. After implementing the SPSM procedure, the RER series of Mexico was found to be stationary with the minimum KSS and maximum *F*-statistic values of -5.160 and 14.539, respectively. Therefore, Mexico was removed from the panel in both tests and the tests were applied again on the remaining set of series. In doing so, we have found that the UO and the EO tests still reject the unit root null for the remaining 23 countries producing values of -2.391 and 4.164, respectively. Meanwhile, the RER series of Iceland and Turkey were found to be stationary according to the minimum KSS and maximum Sollis's *F*-statistics with values of -4.113 and 10.581, respectively. Hence, Iceland (Turkey) was taken out from the sample and the UO (EO) test was conducted on the countries still present in the panel. By doing so we discovered that the UO and EO tests still reject the PPP hypothesis for the remaining 23 countries with values of -2.313 and 3.963, respectively. The SPSM procedure was continued in this fashion until the UO and EO tests could not reject the PPP hypothesis at the 10% significance level. This occurs for the UO and EO tests when the RER series of 6 countries (i.e., Mexico, Iceland, Poland, Turkey, UK and Greece) and 8 countries (i.e., Mexico, Turkey, Poland, Iceland, UK, Greece, Korea and Switzerland) were removed from the panel, respectively. Therefore, the UO test suggests mean reverting dynamics for the panel and by further applying the SPSM methodology we show that only 6 out of the 24 RER series are stationary. On the other hand, when potential asymmetry in the RER series are considered and the EO

test is applied to the panel, the results again point to the stationarity of the panel, but this time with 8 out of 24 countries being stationary. Thus, accounting for asymmetry within a panel context has increased the number of unit root rejections by two countries. In this case the RER series of Korea and Switzerland are found to support asymmetric nonlinear mean reversion.

Overall, three main conclusions can be made with regards to our findings in Table 1. First, the conventional linear IPS test rejects the PPP hypothesis for the entire panel. Second, the unit root null in the RER series can only be refuted for 25% of our sample when the UO test is applied, which assumes symmetric adjustment for the RERs. Second, by considering the presence of asymmetry in the RER series and further applying the EO test we can uncover additional mean reverting dynamics in 2 more cases, which corresponds to a total of 33% of rejections of the random walk hypothesis for the full sample. This result underlines the necessity of taking the potential asymmetry into account to increase the number of rejections when testing the PPP hypothesis. However, even if a possibility of asymmetric adjustment in the RERs was taken into account, the test did not yield very strong evidence that the RER series behave like a stationary process. The EO test still fails to produce broad evidence in favor of stationary RERs (still in 67% of the countries mean reversion in the RERs cannot be uncovered), though it provides additional 2 and 8 rejections of unit root compared to the results of the UO and IPS tests. On the whole, neither the symmetric nor the asymmetric panel model can overwhelmingly support the long-run mean reversion of the RER series for our sample.

When the results obtained here are compared to that of EO, we observe that EO founds mean reversion in the RERs of the 8 out of 15 EU countries against the US dollar (corresponding to about 53% of rejections). Thus, EO has in fact uncovered more broad evidence in favor of PPP than our study has. In addition; while EO founds that the RERs of France, Belgium, Austria and Finland are stationary, we report the opposite. This difference between the results can be attributed to the different time dimension and country groups considered in these two studies. The different patterns

of cross sectional correlation inherent in the EU and the OECD panel have led to different results regarding the validity of PPP. Papell (1997) and Liu and Maddala (1996) also demonstrate that the rejection of the PPP hypothesis in panels depends very much on the groups of countries included. When constructing panel data sets to perform macroeconomic analysis, the degree of integration and thereby the degree of cross country links between the countries is very important in terms of the results obtained. The utilization of a relatively well defined homogenous panel of countries, like the EU panel employed by EO, has led more evidence in favor of the PPP. This study shows that using a relatively heterogeneous panel of countries has led in fact to a higher number of rejections of the PPP hypothesis. Thus, the more favorable results obtained by EO depends on its choice of countries. Therefore, this study corroborates the finding that the verification of the PPP hypothesis in panels is very sensitive to the choice of countries within the context of the newly developed asymmetric panel unit root test.

6. Conclusion

This article centers on the PPP theory, which has been one of the most important and controversial relations in macroeconomics. While the PPP theory suggests that RERs should be stationary so that shocks to this variable die out quickly, in numerous empirical studies the RERs have shown to display high persistence. This apparent inconsistency between the data and the theory has an enormous and ever-growing empirical literature on PPP to develop. While numerous articles testing the PPP theory have been published, still there is no clear consensus on its validity.

To provide some further insights into this literature, in this study we reinvestigate the PPP hypothesis and provide new evidence on its validity by testing for the presence of unit root in the RER series for a group of OECD countries using a recently developed panel unit root test. We examine the behaviour of cross-country RERs for 24 major industrial economies from 1990:1 to 2013:12. The voluminous literature on PPP points to the presence of asymmetric nonlinear behavior in RERs, which implies that

asymmetric nonlinear mean reversion should be considered when investigating the stochastic features of these series in a panel context. In addition, handling cross-sectional dependence is especially important in analyzing macroeconomic variables with close cross country links like the RERs. Thus, in our study we use panel unit root test statistics that take the presence of symmetric or asymmetric nonlinearity and cross-sectional dependence into consideration. The power of these tests increases relative to that of the standard univariate unit root and stationarity tests when the cross-sectional information is utilized and the data span is increased. Accounting for these characteristics is crucial to succeed in dealing with the potential biases of statistical inference.

When the RERs were tested for the existence of unit roots against the alternative of linear and symmetric mean reversion using the IPS test, the PPP hypothesis was strongly rejected for the entire set of OECD countries included in the study. However, by allowing the possibility of nonlinear but symmetric mean reversion, PPP is found to hold for Mexico, Iceland, Poland, Turkey, UK and Greece. The UO test was able to provide favourable evidence for PPP in 25% of the sample. When the possibility of asymmetric mean reversion was further allowed and the EO test was applied, the RERs of additionally Korea and Switzerland were shown to display asymmetric mean reversion.

On the whole, allowing for asymmetry has improved the results of the unit root tests when testing the PPP hypothesis. However, the asymmetric panel model still cannot overwhelmingly support the long-run mean reversion of the RER series for our sample. Our result in this sense confirms the results of the other studies surveyed in the literature: the empirical results do not support the PPP hypothesis. So what comes next? The results obtained in this study may mean that the RERs do not revert to an equilibrium value even in the long-run and thus, new theoretical models should be developed incorporating changing equilibrium levels over time. Another possibility is that the PPP holds only over the very long-run and we have insufficient data to verify its validity. This second possibility would be in line with the findings in the literature

that the deviations from the PPP are corrected a very slow rate[10]. A final possibility is that the PPP hypothesis holds but to reconcile the data with the theory more powerful econometric methods should be developed. In the present study we utilized a test that marries the two strands in the literature: panel unit root tests and asymmetric nonlinearity. However, as argued above when conducting the panel unit root tests the presence of cross sectional dependence and thereby the degree of heterogeneity in the panel alters the results in a great way. This study shows that the researchers should be careful in this respect. Moreover, in this study the presence for structural breaks are overlooked. A further extension in this perspective can be the development of panel unit root tests that allow for both structural change and nonlinearity simultaneously.

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[10] See, among others, Rogoff (1996).

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