**CARDIFF BUSINESS SCHOOL**
**WORKING PAPER SERIES**

**Cardiff Economics**
**Working Papers**

Michael G Arghyrou, Andros Gregoriou and Panayiotis M. Pourpourides

# *A new solution to the purchasing power parity puzzles? Risk-aversion, exchange rate uncertainty and the law of one price: Insights from the market of online air-travel tickets*

E2009/2

Cardiff Business School
Cardiff University
Colum Drive
Cardiff CF10 3EU
United Kingdom
t: +44 (0)29 2087 4000
f: +44 (0)29 2087 4419
www.cardiff.ac.uk/carbs

ISSN 1749-6101
January 2009, Updated July 2009

# A new solution to the purchasing power parity puzzles?

# Risk-aversion, exchange rate uncertainty and the law of one price:

# Insights from the market of online air-travel tickets

Michael G. Arghyrou [a,*], Andros Gregoriou [b], Panayiotis M. Pourpourides [a]

Updated July 2009

[a] Cardiff Business School, Cardiff University, Colum Drive, Cardiff, CF10 3EU, United Kingdom

[b] Norwich Business School, University of East Anglia, Norwich, NR4 7TJ, United Kingdom

* Corresponding author. Tel.: +442920875515; fax +442920874419

E-mail addresses: ArghyrouM@cardiff.ac.uk (M.G. Arghyrou); A.Gregoriou@uea.ac.uk (A. Gregoriou); PourpouridesP@cardiff.ac.uk (P.M. Pourpourides).

**Abstract**

We argue that even in perfectly frictionless markets risk aversion driven by exchange rate uncertainty may cause a wedge between the domestic and foreign price of a totally homogeneous good. We test our hypothesis using a natural experiment based on a unique micro-data set from a market with minimum imperfections. The empirical findings validate our hypothesis, as accounting for exchange rate uncertainty we are able to explain a substantial proportion of deviations from the law of one price. Overall, our analysis suggests the possibility of a new solution to the purchasing power parity puzzles.

**Keywords:** law of one price; purchasing power parity; risk aversion; exchange rate uncertainty.

**JEL classification:** F31, F41.

**Acknowledgments:** We would like to thank Gregor Smith, Charles Engel, Lawrence Copeland, Patrick Minford and John Tsoukalas for useful suggestions and comments on earlier versions of the paper. The usual disclaimer applies.

## 1. Introduction

Despite their widespread adoption by theoretical models of international macroeconomics and finance, a large empirical literature in the 1970s and 1980s rejected the law of one price (LOOP) and its generalisation, purchasing power parity (PPP) as equilibrium conditions among industrialised countries for the period of floating exchange rates (Obstfeld and Rogoff, 2000, Taylor, 1995). Failure of long-run PPP is described in the literature as the first PPP puzzle (Taylor et al, 2001). Furthermore, even when long-run PPP is validated, the half-life of shocks to the real exchange rate is estimated between three to five years, too high to be explained by conventional arguments such as nominal rigidities. This gives rise to a second PPP puzzle, summarised by Rogoff (1996, p. 647) as follows: "How can one reconcile the enormous short-run volatility of real exchange rates with the extremely slow rate at which shocks [away from PPP] appear to damp out ?"

Existing explanations of the PPP puzzles in the context of industrialised countries focus on market imperfections. We offer a new explanation based on exchange rate uncertainty and risk aversion. We argue that even under perfectly frictionless markets, risk-averse consumers facing exchange rate uncertainty and having no access to hedging instruments are willing to pay the domestic importer of a foreign good a risk premium over the good's foreign price. They do so in order to fix the cash outflow from the good's purchase when measured in units of domestic currency. This drives a permanent wedge between domestic and foreign prices explaining violations of the LOOP even under frictionless markets. Moreover, a persistent increase in uncertainty about future exchange rates results in persistent deviations of the good's domestic price from its foreign one.

We test our hypothesis on a unique micro-data set from a market with minimum imperfections, namely the market for online air-travel tickets. This provides a natural experiment from which the factors previously identified as the main causes of deviations from the LOOP are excluded. The empirical findings validate our hypothesis as accounting for exchange rate uncertainty we are able to explain a substantial proportion of deviations from the LOOP. Our analysis is too simple to be considered as an integrated theory of price setting under alternative exchange rate regimes. Nevertheless, our natural experiment provides a powerful test of our hypothesis and suggests that co-existence of enormous exchange rate volatility and persistent deviations from the LOOP and PPP may not, after all, be as puzzling as suggested by Rogoff. Indeed, persistent deviations from PPP may be exactly due to enormous exchange rate volatility!

## 2. Previous literature and motivation

### *2.1. Existing solutions to the PPP puzzles*

Existing solutions to the first PPP puzzle (empirical failure of long-run PPP) mainly fall into two categories, giving rise to two literature strands. The first consists of econometric explanations, mainly focusing on the low power of the linear time-series techniques used to test PPP.[1] This strand essentially treats the empirical rejection of long-run PPP as a statistical illusion and aims to develop PPP tests of higher power. In this context a number of studies use long-span samples and panel-data techniques reaching findings more favourable towards PPP (see Sarno, 2005). These, however, have not escaped econometric critiques themselves[2] and have mainly validated PPP in its relative rather than absolute version. Therefore, they largely leave unexplained differences among national price levels when measured in terms of a common currency.[3]

[1] The failure of standard linear unit root test to capture mean-reverting behaviour in the movements of real exchange rates is also related to the possibility of nonlinear adjustment towards PPP (see below).

[2] Long-span studies mix periods from fixed and flexible exchange rates, which may affect the statistical properties of the tests employed. On the other hand, most panel-data studies impose the null hypothesis that all exchange rates included in the panel are not consistent with PPP. This results in a high probability of rejecting the null even when only one of the panel's series is consistent with PPP. For further discussion see Sarno and Taylor (2002), chapter 3.

[3] Another econometric explanation for the empirical failure of long-run PPP has been offered by Taylor (2001) and is based on temporal data aggregation. Taylor shows that a real exchange rate following an AR(1) process at

The second strand treats PPP's long-run failure as a real phenomenon and develops theoretical arguments to explain it. One group of explanations includes shifts in relative demand (e.g. changes in consumers' preferences[4] or fiscal shocks[5]) and relative productivity, as originally suggested by Balassa (1964) and Samuelson (1964).[6] Empirical evidence, however, suggests that demand shocks explain PPP violations to a modest degree only. On the other hand, the Balassa-Samuelson model has been reasonably successful in explaining PPP violations between developed and developing countries.[7] By contrast, with the exception of the Japanese Yen, it has been much less so in the context of industrialised countries (see Rogoff, 1996). Another group of explanations attributes PPP's failure to deviations from the latter's founding cornerstone, the LOOP. Indeed, numerous empirical studies[8] have documented what Engel and Rogers (1996) define as a "border effect" where domestic price differentials, even for highly differentiated goods are smaller, less volatile and less persistent than cross-border price differentials among homogeneous goods.[9] As the LOOP assumes totally frictionless markets, its failure is typically attributed to market imperfections among which transport costs, tariffs and other trade barriers are the predominant (though not exclusive) examples.[10]

---

a higher frequency than the one at which the data is sampled results in an upward bias in the estimated speed of adjustment towards PPP.

[4] A related explanation is the existence of a consumers' bias in favour of domestic goods. Typically this is assumed but not derived (see e.g. Benigno and Thoenissen, 2003). Our analysis below provides an explanation for the existence of such a home bias.

[5] See, for example, Alesina and Perotti (1995).

[6] Portfolio balance models (see e.g. Branson, 1983) explain permanent deviations from PPP as the result of accumulated current account imbalances. However, as Rogoff (1996) argues, the empirical validity of this effect is debatable; and even if it exists the causation pattern is unclear, as virtually any kind of correlation between the current account and the real exchange rate can be easily rationalised.

[7] A similar explanation has been offered by Bhagwati (1984) who argued that prices in developed countries are higher than in developing ones due to higher wages caused by higher capital to labour ratios.

[8] See Isard (1977), Richardson (1978), Giovannini (1988), Knetter (1989, 1993), Engel (1993), Engel and Rogers (1995) and Parsley and Wei (1996).

[9] In a recent paper, however, Gorodnichenko and Tesar (2009) argue that the border effect identified by Engel and Rogers (1996) may be overestimated. This is so because in the presence of cross-country heterogeneity in the distribution of within-country price differentials there is no clear benchmark allowing the identification of the border effect. As a result, empirical estimates of the border effect cannot separate the latter from the effect of trading with a country with different internal distribution of prices.

[10] See Knetter (1994), Feenstra (1995), Rogoff (1996) and Feenstra and Kendall (1997). Alternative explanations for LOOP failure due to market frictions include non-traded inputs and non-uniform taxes in the

Market imperfections also underlie the existing explanations for the second PPP puzzle, i.e. excessive persistence of deviations from PPP. A number of authors[11] have developed theoretical models in which transactions' and other sunk costs result in nonlinear adjustment towards the LOOP and, by extension, PPP: Deviations from the LOOP are non-mean reverting (or adjusting very slowly) if smaller than arbitrage-trading costs, but fast mean-reverting once they exceed the latter. Empirical studies have provided significant evidence of such nonlinearities, justifying the previously mentioned failure of linear testing techniques to validate long-run PPP.[12] On the other hand, Imbs et al (2005) show that heterogeneous adjustment dynamics to the LOOP across the individual components of a basket of goods (caused by varying impediments to arbitrage and nominal rigidities across different goods) result in a positive bias in standard panel and time-series estimates of persistence of shocks to the aggregate real exchange rate. Correcting for this bias they obtain estimates of half-lives of shocks to the latter as low as eleven months. They also show that persistent adjustment heterogeneity at the disaggregated level is fully compatible with the nonlinear dynamics observed in the movements of aggregate real exchange rates.

### *2.2. Two unanswered questions and a new hypothesis*

Summarising our discussion above, given the limited evidence in favour of Balassa-Samuelson effects, market imperfections are the main explanation offered by the existing literature for both PPP puzzles in the context of industrialised countries. However, despite its sound theoretical foundations and empirical support, this explanation leaves two important questions unanswered:

---

retail prices of heavily-traded goods (see e.g. Parsley and Wei, 2007); less than perfect homogeneity between domestic and foreign goods; incomplete exchange rate pass-through due to pricing-to-market strategies (see e.g. Krugman 1987, Dixit 1989, Feenstra 1995, Betts and Devereux 2000); and menu/fixed costs faced by importers/consumers when changing prices/switching between suppliers (see e.g. Froot and Klemperer 1989, Kasa 1992).

[11] See e.g. Dumas (1992), Sercu et al. (1995), Obstfeld and Rogoff (2000) and O'Connell and Wei (2001).

[12] Among others see Michael et al. (1997), Taylor, Peel and Sarno (2001) and O'Connell and Wei (2001).

First, if market imperfections are the main reason for PPP's failure among industrialised countries, why do empirical studies consistently validate PPP as a long-run equilibrium condition for these countries over periods of fixed exchange rates?[13] Surely, imperfections such as transportation costs and trade barriers also existed prior to the mid-1970s; if anything they were even more pronounced than they have been in recent years.

Second, given that PPP is generally rejected among industrialised countries for the period of flexible exchange rates, why is it over the same period validated among countries implementing bilateral fixed exchange rate regimes such as those within the European Monetary System (EMS)?[14] True, geographical proximity among EMS countries reduces transactions costs, thereby increasing the probability of validating the LOOP and PPP. Geographical proximity, however, also exists between the USA and Canada, for which Engel and Rogers (1996) found overwhelming evidence of the border effect discussed above.

These questions raise an intriguing possibility: Is it likely that deviations from the PPP and its founding cornerstone, the LOOP, are linked to nominal exchange rate variability and, if yes, why? Section 3 below uses a simple example to formulate and rationalise this hypothesis.[15]

## 3. A simple demand-side example

In this section we provide a simple example where exchange rate uncertainty coupled with risk-aversion induces a violation of the LOOP even under zero transportation and transaction costs. Consider a representative risk-averse agent who plans to purchase good *X*, produced in a foreign country. The agent can buy good *X* either from a domestic supplier

[13] Among others see Friedman and Schwartz (1963), Gaillot (1970) and Taylor and McMahon (1988). See also Sarno (2005) and the references therein.

[14] See Kugler and Lenz (1993), Chowdhury and Sdogati (1993) and Cheung et al. (2005).

[15] Obstfeld and Rogoff (1998) show that equilibrium exchange rates may be affected by a time-varying risk premium term. This insight, however, has not been used to explain deviations from the LOOP and PPP (indeed Obstfeld and Rogoff's model assumes that the LOOP and PPP hold). Our analysis below uses a simple demand-side example to explain deviations from PPP on exchange uncertainty.

(importer) or directly from its foreign producer. Both markets, domestic and foreign, are totally frictionless (zero transportation and other transactions costs). We assume zero trade barriers and, in line with the redux model by Obstfeld and Rogoff (1995), producer-currency-pricing whereby firms set exports' prices in terms of their local currency. In that case, the domestic price of foreign products is a one-to-one function of the nominal exchange rate.[16]

If the agent purchases *X* from the domestic importer her net wealth, after the purchase, will be known with certainty. If, on the other hand, she purchases *X* directly from the foreign supplier her net wealth following the purchase will be subject to some degree of uncertainty. The latter is due to the fact that although the purchase order is given at current time *t*, the transaction will be cleared at a future date where the exchange rate is not known with certainty.[17] In this framework we assume that there are no hedging instruments available for the purchase. Let the time interval between the time the agent makes the purchase and the time the transaction is cleared be denoted by *d*. In addition, let the time-*t* nominal wealth of the agent and nominal exchange rate (defined as domestic currency units per unit of foreign currency) be denoted by $W_t$ and $S_t$ respectively. Note that contrary to $W_t$, which is assumed to remain unchanged over the time interval *d*, $S_t$ exhibits a high frequency variation. Let the price of *X* in the domestic and foreign markets be denoted by $P_t$ and $P_t^f$ respectively. Consequently, if the agent buys *X* from the domestic market, in the absence of other purchases, her net wealth at time *t*+*d*, per unit of the local price, will be $W_{t+d}^l = (W_t - P_t)/P_t$.

[16] There exists a rich literature on the determinants and effects of the currency of invoicing of international trade (see, among others, Corsetti and Pesenti 2005 and Goldberg and Tille, 2008). A number of authors substitute the producer-currency-pricing assumption adopted by Obstfeld and Rogoff (1995, 1998) with pricing-to-market or dollar-pricing assumptions to explain, among others, deviations from the LOOP and PPP as well as international transmission of macroeconomic shocks. Our analysis below explains deviations from the LOOP and PPP maintaining the producer-currency-pricing assumption of Obstfeld and Rogoff's (1995) baseline redux model.

[17] For example, consider the market for electronic air-travel tickets sold online. The agent who purchases an air-ticket from a foreign website does not know with absolute certainty the exchange rate applying to her transaction at the time the foreign company charges her credit card. This market will be analyzed further in the following section.

If she buys $X$ from the foreign market her net wealth, per unit of the local price, will be $W^f_{t+d} = \left(W_t - S_{t+d} P^f_t\right) / P_t$.

Given the assumptions above, when the domestic agent chooses to buy the good from the foreign supplier she does not know her net wealth in time $t+d$ because she does not know with certainty what $S_{t+d}$ will be. Nevertheless, she has expectations for $S_{t+d}$ conditional on her time-$t$ information set. We assume that the growth rate of the exchange rate is random, that is $S_{t+d} / S_t = K_{t+d}$ with $E_t K_{t+d} = 1$ and $E_t K^2_{t+d} = \sigma^2_t + 1$, where $E_t$ denotes the time-$t$ expectation operator. Moreover, we assume that the risk-averse agent has a utility function $u^*\left(W^i, X\right)$ for $i=l,f$, where $u^*\left(W^i, X\right) = u\left(W^i\right) + \beta u(X)$ with $\beta > 0$. Nevertheless, since the agent will buy the good in either case, the second term of the utility function is a constant and thus it is excluded from our subsequent analysis. Function $u\left(W^i\right)$ is continuously differentiable, increasing with wealth and strictly concave (i.e. $u'\left(W^i\right) > 0$ and $u''\left(W^i\right) < 0$). As we explain below, the risk-averse domestic agent may be willing to pay an exchange-rate-induced risk premium, $\pi$, to buy good $X$ from the domestic market. On the other hand, a foreign agent will never be willing to pay a foreign exchange risk premium to buy a good produced in her own country, as the good is already priced in terms of her own (i.e. foreign) currency. In other words, [18]

$$\pi_t = \frac{P_t - S_t P^f_t}{P_t} \geq 0 \tag{1}$$

The good is imported to the domestic market only if $E_t u\left(W^f_{t+d}\right) \leq u\left(W^l_{t+d}\right)$, otherwise domestic consumers will buy the good directly from foreign producers. If this condition holds with strict inequality however, the domestic importer will keep increasing the domestic price,

[18] Equivalently, $\pi^f_t = \dfrac{P^f_t - (1/S_t) P_t}{P^f_t} \leq 0$.

since domestic consumers will be willing to pay more for the good, in order to exploit the profit margin available. Thus, in equilibrium, the domestic agent will be indifferent between buying *X* from the domestic importer or the foreign supplier:

$$E_t u\left(W_{t+d}^f\right) = u\left(W_{t+d}^l\right) \tag{2}$$

Given equation (2), it is straightforward to show, by Jensen's inequality, that the risk-averse domestic agent is willing to pay a strictly positive risk-premium per unit of the local price, i.e. $\pi_t > 0$.[19] Consequently, even under zero transaction and transportation costs if the agent is risk-averse and next period's exchange rate is uncertain the LOOP will not hold.[20]

Figure 1 provides a simple diagrammatical illustration. Suppose the exchange rate in period *t+d* can take only two values, a "low" exchange rate $S^1$ with probability $\alpha$ and a "high" exchange rate $S^2 > S^1$ with probability $(1-\alpha)$. Then, $E_t\left(W_{t+d}^f\right) = \alpha W_{t+d}^{f1} + (1-\alpha)W_{t+d}^{f2}$ and $E_t u\left(W_{t+d}^f\right) = \alpha u\left(W_{t+d}^{f1}\right) + (1-\alpha)u\left(W_{t+d}^{f2}\right)$. As shown in Figure 1 the concavity of *u* signifies that under condition (2) the domestic price $P_t$ incorporates a strictly positive risk premium $\pi$. Notice that if the agent is risk-averse, the higher the uncertainty about the exchange rate at time *t+d*, the higher the risk-premium the agent will be willing to pay.[21] For example, if the value of the "low" exchange rate decreases to $S^{2'} < S^2$, for a given invariant probability distribution for the exchange-rate, the risk premium increases to $\pi' > \pi$.

We may express the risk premium as a function of utility and exchange rate volatility by taking a Taylor expansion of condition (2). Approximating the latter around

---

[19] Since $u$ is concave, $E_t u\left(W_{t+d}^f\right) < u\left(E_t W_{t+d}^f\right)$, by Jensen's inequality. Condition (2) implies that $u\left(W_{t+d}^l\right) < u\left(E_t W_{t+d}^f\right)$. Since $u$ is increasing with $W^i$ it follows that $(W_t - P_t)/P_t < E_t W_{t+d}^f = \left(W_t - S_t P_t^f\right)/P_t$. The latter can be rewritten as $\left(P_t - S_t P_t^f\right)/P_t = \pi_t > 0$

[20] If the agent is risk neutral the LOOP holds. This is so because risk neutrality implies that $u(\bullet)$ is linear. Then, condition (2) reduces to $\left(W_t - S_t P_t^f\right)/P_t = (W_t - P_t)/P_t$ or $S_t P_t^f / P_t = 1$

[21] In addition, the higher the curvature of *u* (i.e. the higher the degree of risk aversion), the higher the value of $\pi$.

$W_t^f = \left(W_t - S_t P_t^f\right)/ P_t$ and assuming that third and higher order terms are negligible and $\pi_t^2 \approx 0$ we obtain:

$$\pi_t \approx \frac{1}{2} r\left(W_t^f\right)\left(\frac{S_t P_t^f}{P_t}\right)^2 \sigma_t^2 \tag{3}$$

where $r\left(W_t^f\right) = -u''\left(W_t^f\right)/ u'\left(W_t^f\right) > 0$ is the Arrow-Pratt coefficient of absolute risk aversion. Rearranging (3) we obtain

$$\frac{S_t P_t^f}{P_t} \approx 1 - \frac{1}{2} r\left(W_t^f\right)\left(\frac{S_t P_t^f}{P_t}\right)^2 \sigma_t^2 \tag{4}$$

Equations (3) and (4) confirm that as long as the agent is risk-averse, (i.e. $r(W^f_t)>0$) non-zero exchange rate uncertainty ($\sigma^2_t >0$) causes a strictly positive risk premium ($\pi_t>0$) resulting in permanent deviations from the LOOP, even in the absence of market imperfections. This is an argument explaining the first PPP puzzle (long-run failure of PPP). The risk premium $\pi_t$ is a positive function of the degree of absolute risk aversion $r(W^f_t)$ and nominal exchange rate uncertainty $\sigma^2_t$. This implies that the persistence of shocks to $\pi_t$ will be closely related to the persistence of the process driving $\sigma^2_t$. Therefore, persistent shocks to exchange rate uncertainty could potentially explain the second PPP puzzle, i.e. excessively persistent deviations from PPP. Moreover, condition (3) suggests that the risk premium may be a non-linear process, which is consistent with the nonlinearities empirically observed in deviations from the LOOP (see e.g. Sarno et al, 2004). Finally, equations (3) and (4) imply that $\pi_t = 0$ if $\sigma_t^2 = 0$, i.e. under fixed exchange rates the LOOP holds. All in all, conditions (3) and (4) provide explanations for both PPP puzzles; capture nonlinear real exchange rate dynamics; and are consistent with the full body of empirical evidence, which upholds and rejects PPP for periods of fixed and floating exchange rates respectively.

## 4. Modelling deviations from the LOOP in a near-frictionless market

### *4.1. Market and data description*

The perfect ground to test whether deviations from the LOOP are explained by nominal exchange rate uncertainty would be a perfectly frictionless market where, by virtue of their absence, LOOP violations cannot be attributed to the traditional argument of market imperfections. Furthermore, the market should be small enough so as its prices not to affect aggregate exchange rate developments. A near-frictionless market that meets those characteristics is the market for electronic air-travel tickets bought online. We have collected daily price quotations provided by the UK and German sites of Expedia and Travelocity for an identical London Heathrow (LHR) – New York JFK return e-ticket (economy class) on a British Airways (BA) flight departing from LHR four weeks ahead from the date of quotation; and returning from JFK five weeks ahead.[22] Our sample covers the period 1 April 2006 to 6 March 2009, a total of 1071 daily observations. Prices in the UK and German sites are quoted in UK pounds and euros respectively. These include all taxes and booking commissions and are net of insurance fees, as the latter is sold separately. As tickets are electronic, postage costs are zero; price quotations are freely provided by the websites; and the market is constantly open and highly liquid, as the LHR-JFK is the world's busiest intercontinental air route and BA its main operator. Crucially, there are no market-entry barriers, as Germany- and UK-based consumers can purchase e-tickets from any website using German- or UK-registered debit/credit cards. The only departure from the perfect-markets' assumption of section 3 is a foreign exchange conversion fee in the area of 2.5% charged by the cards' issuing banks on foreign purchases. Therefore, the market matches almost perfectly the pricing assumptions of our analysis in section 3, as from a domestic (German) agent's point of view the price of the good (ticket) is set by a foreign supplier

[22] At the time of writing British Airways operates eleven daily flights from LHR to JFK. We always collect data for the cheapest available trip on the day of quotation. This typically consists of flights BA117 (departing flight) and BA178 (returning flight).

(British Airways) in terms of foreign currency (sterling pounds), with the agent being able to buy the good without restrictions (apart from the conversion fee) either from a domestic importer (German website) or from the foreign market (UK website) directly. Overall, the market is very close to the full set of assumptions in section 3, thus providing a natural experiment from which all factors previously identified as the main potential causes of deviations from the LOOP are excluded. As such, it offers a powerful test of our hypothesis that exchange rate uncertainty causes deviations from the LOOP.

Table 1 presents the market's summary statistics. Starting from intra-domain comparisons, on average the LOOP holds between the two UK websites and is reasonably close to holding between the German ones. By contrast, inter-domain comparisons reveal significant violations of the LOOP, with both German websites being significantly more expensive than their UK counterparts by a margin well above the 2.5% difference justified by the foreign exchange conversion fee.[23] Furthermore, inter-domain relative prices are significantly more volatile than intra-domain ones, with the coefficient of variation of the former being more than double the coefficient of variation of the latter. Overall, despite the market's near-perfect nature, Table 1 provides evidence of the border effect discussed in section 2. This, however, cannot be explained by the traditional argument of market imperfections.

Figure 2 presents the inter-domain deviations from the LOOP in logarithmic format. This describes the premium (expressed in percentage terms) German consumers pay over the

[23] For inter-domain comparisons we have converted UK prices into euros using the euro/GBP spot exchange rate quoted by Thomson Reuters, provided by the Financial Times online currency converter tool at the time of the price quotations' collection. These quotations are freely available and are regularly updated throughout business hours, with quotations being delayed by at least ten minutes. As this is a quotation for the mid-point exchange rate prevailing at the wholesale currency market, it is certainly lower than the ask exchange rate consumers will be charged by the institutions issuing their debit/credit cards. As a result, effective deviations from the LOOP are bound to be even more pronounced than those suggested by Table 1. Online facilities quoting ask exchange rates charged by financial institutions on credit/debit card transactions with intra-day updates are not freely available. This implies that the exchange rate uncertainty faced by consumers buying tickets from foreign websites consists of two components. First, uncertainty due to the time difference between the ticket's purchase and the transaction's electronic clearance. Second, uncertainty due to the difference between the publicly quoted mid-exchange rate and the non-publicly available charged ask exchange rate.

UK ticket price when the latter is expressed in euros. The premium is defined as $\omega_t = p_t - s_t - p_t^f$ where $p_t$, $s_t$ and $p_t^f$ respectively denote the logarithm of the price quoted by the German web-site in euros, the nominal exchange rate of the euro against the UK pound, and the price quoted by the UK web-site in sterling pounds. Deviations from the LOOP are highly volatile and include some extreme outliers, for which we account in subsequent analysis using intercept dummy variables. Based on our analysis in section 3 we expect $\omega_t$ to be positive, and indeed this is so both on average terms (see Table 1) as well as for the overwhelming majority of individual observations (85% of the total sample). The fairly small minority of observations for which $\omega_t$ takes negative values are possibly due to unobserved factors specific to the market for electronic air-tickets for which we have no information.

### *4.2. Econometric models and empirical results*

To examine the relationship between inter-domain deviations from the LOOP and nominal exchange rate uncertainty we estimate the following econometric model

$$\omega_t = \alpha_1 + \alpha_2 E_t (s_{t+1} - s_t)^2 + \varepsilon_t \tag{5}$$

$$s_{t+1} = s_t + \kappa_{t+1}, \text{ with } E_t \kappa_{t+1} = 0 \text{ and } E_t \kappa_{t+1}^2 = \theta_t^2 \tag{6}$$

$$\kappa_{t+1}^2 = \beta + \sum_{i=0}^{k} \gamma_i \kappa_{t-i}^2 + \sum_{i=0}^{n} \delta_i u_{t-i} + u_{t+1}, \text{ with } E_t u_{t+1} = 0 \text{ and } E_t u_{t+1}^2 = \phi_t^2 \tag{7}$$

The underlying process driving $s_t$ is taken to be a random walk[24] described by (6). $E_t (s_{t+1} - s_t)^2$ captures the time-$t$ expectation for the volatility of the exchange rate at time $t$+1, reflecting uncertainty about next period's nominal exchange rate. This is modelled by (7) as a GARCH process where the $u_{t-i}$ terms denote moving average components. According to

[24] This hypothesis is well-supported by the data: Estimating a simple AR(1) model for the log of the nominal euro/GBP exchange rate over our sample period yields a first-order autoregressive coefficient exactly equal to unity.

our analysis in section 3 the higher the uncertainty about next-period's exchange rate the higher the value of $\omega_t$. Consequently, we anticipate a positive sign for $\alpha_2$.

We estimate equation (5) using OLS and correct standard errors for autocorrelation and heteroscedasiticity using Andrews's (1991) correction.[25] The results are reported in Table 2, column (a). Consistent with our analysis in section 3 we obtain statistically significant positive coefficients for $\alpha_2$.[26] Compared to the $\omega_t$ series, applying the Granger and Teräsvirta (1993) general nonlinearity test on the estimated residuals of (5) reduces but does not eliminate evidence of nonlinear mean-reversion. This is consistent with condition (3) which allows for a nonlinear link between $\theta_t^2$ (capturing $\sigma_t^2$) and $\omega_t$ through the interaction of $\sigma_t^2$ with the risk-aversion parameter $r(W^f)$. Given the high frequency of our data, the high volatility of our dependent variable and possible nonlinearities, the data fit of the simple linear model given by equation (5) is satisfactory. Overall, the findings reported in Table 2 combined with the near-perfect nature of the market to which they refer are consistent with the hypothesis that exchange rate uncertainty causes violations of the LOOP.

We have tested the robustness of our findings in a number of ways. First, we added to the right-hand side of equation (5) the first lag of the dependent variable (see Table 2, column (b)). Second, we have added an intercept dummy variable (Dneg) taking the value of unity for negative observations of $\omega_t$, zero otherwise (Table 2, column (c)). Third, we have re-estimated equation (5) setting the value of $\omega_t$ and $E_t(s_{t+1}-s_t)^2$ equal to zero for negative observations of $\omega_t$ (Table 2, column (d)).[27] In all cases the term capturing exchange rate uncertainty remained positive and statistically significant. Finally, we repeated all estimations defining $\omega_t$ and $E_t(s_{t+1}-s_t)^2$ respectively as the 30-day moving average of deviations from the

[25] The lag structure of the AR and MA components in equation (7) is determined by the Akaike information criterion. This suggested a GARCH (3,1) specification. The results are available upon request.
[26] The statistical significance of $\alpha_2$ is robust to the correction of standard errors for non-normality using the wild bootstrap methodology (see e.g. Arghyrou and Gregoriou, 2007). The results are available upon request.
[27] This is equivalent to eliminating all negative $\omega_t$ observations from our estimation sample.

LOOP and the 30-day moving variance of the nominal exchange rate. The results (available upon request) remain unchanged.

We conclude our empirical investigation by estimating a model allowing for non-linear effects of exchange rate uncertainty on deviations from the LOOP, as suggested by the nonlinearity tests reported in Table 2. More specifically, we estimate the logistic smooth threshold autoregressive (LSTAR) model given by equations (6) to (9) below, where $\varepsilon_t$, $u_{1t}$ and $u_{2t}$ are white noise error terms:

$$\omega_t = \alpha_0 + q_t\ \omega_{1t} + (1-q_t)\ \omega_{2t} + \varepsilon_t \tag{8}$$

$$\omega_{1t} = \alpha_{11}\ \omega_{t-1}\ + \alpha_{12}\, E_t(s_{t+1}\text{-}s_t)^2 + u_{1t} \tag{9}$$

$$\omega_{2t} = \alpha_{21}\ \omega_{t-1} + \alpha_{22}\ E_t(s_{t+1}\text{-}s_t)^2\ + u_{2t} \tag{10}$$

$$q_t = pr\ \left\{\tau \geq \hat{\theta}^2{}_{t-\delta}\right\} = 1\ \text{-}\ \frac{1}{1+e^{-\sigma[\hat{\theta}^2_{t-\delta}-\tau]}} \tag{11}$$

Equation (8) models deviations from the LOOP on a constant and a weighted average of two regimes, a lower ($\omega_{1t}$) and an upper ($\omega_{2t}$) corresponding to periods of low and high exchange rate uncertainty respectively. The regime applying each period is determined according to whether the model's transition variable $\hat{\theta}^2_{t-\delta}$, a lagged value of the estimated exchange rate uncertainty obtain from equation (7), takes values below or above an endogenously determined threshold $\tau$, where $\delta$ denotes the model's delay parameter. The weight attached in equation (8) to the lower regime, $q_t$, is modeled by the logistic function in equation (11) as the probability that $\hat{\theta}^2_{t-\delta}$ takes values below $\tau$, where the parameter $\sigma$ is the speed of transition between the two regimes.[28] The estimates of the LSTAR model are presented in Table 2, column (e). In view of the nonlinearity tests reported in column (a), we

[28] In practice $\sigma$ is usually estimated very imprecisely as the likelihood function in (7) is very insensitive to this parameter (see the detailed discussion on this point in van Dijk et al., 2002).

set $\delta$=1 for Travelocity and $\delta$=2 for Expedia.[29] The reported equations confirm the presence of nonlinearities in the link between exchange rate uncertainty and deviations from the LOOP: In the lower regime, i.e. for values of $\hat{\theta}^2_{t-\delta}$ below a small but well-defined critical threshold $\tau$, exchange rate uncertainty is not significant in explaining deviations from the LOOP. On the other hand, in the upper regime, to which approximately three quarters of all observations belong,[30] the coefficient of exchange rate uncertainty is statistically significant and positive. This suggests that exchange rate uncertainty matters in explaining deviations from the law of one price as long as it is sufficiently high.

## 5. Concluding remarks

Market imperfections are the main explanation offered by the existing literature for permanent or highly persistent deviations from the law of one price (LOOP) and purchasing power parity (PPP) in the context of industrialised countries. We contribute to this literature in three distinct ways. First, we propose a new explanation for violations of the LOOP arguing that even in perfectly frictionless markets risk aversion driven by exchange rate uncertainty may cause a wedge between the domestic and foreign price of a totally homogeneous good. Second, we test our hypothesis on a unique micro-data set from a market with minimum imperfection. This provides a natural experiment from which the factors previously identified as the main potential causes of deviations from the LOOP are excluded. Finally, we validate our hypothesis empirically, as in the context of our near-perfect market accounting for exchange rate uncertainty we are able to explain a substantial proportion of deviations from the LOOP.

[29] The results reported in column (e) for Expedia remain unaffected when $d$ is set equal to 1.
[30] The estimated series of the conditional variance of the euro/GBP nominal exchange rate, determining to which regime each observation belongs, is available upon request.

Our analysis is too simple to be considered as an integrated theory of price setting under alternative exchange rate regimes. Nevertheless, our natural experiment provides a powerful test of our hypothesis and suggests that co-existence of enormous exchange rate volatility and persistent deviations from the LOOP and PPP may not, after all, be as puzzling as suggested by Rogoff (1996). To the latter's question (p. 647) as to how can one reconcile the enormous short-run volatility of real exchange rates with the extremely slow rate at which shocks [away from PPP] appear to damp out, our analysis suggests that deviations from PPP may be exactly due to enormous exchange rate volatility. This is consistent with the full range of previous empirical evidence on PPP which reject PPP for industrialised countries for floating but validates it for fixed exchange rates regimes. It also motivates further research on the role of exchange rate uncertainty in explaining deviations from PPP at the aggregate level.

**References**

Alesina, A. and R. Perotti (1995), "Taxation and redistribution in an open economy", *European Economic Review*, 39, 1471-1487.

Andrews, D. W. K. (1991). "Heteroskedasticity and autocorrelation consistent covariance matrix estimation", *Econometrica* 59, 817-858.

Arghyrou, M.G. and A. Gregoriou (2007), "Testing for purchasing power parity correcting for non-normality using the wild bootstrap", *Economics Letters*, 95, 285-290.

Balassa, B. (1964). "The purchasing power parity doctrine: A reappraisal", *Journal of Political Economy*, 72, 584-596.

Benigno, G. and C. Thoenissen (2003), "Equilibrium exchange rates and supply-side performance", *Economic Journal*, 113, C103-C124.

Betts, C. and M.B. Deveraux (2000), “Exchange rate dynamics in a model of pricing-to-market”, *Journal of International Economics*, 50, 215-244.

Bhagwati, J.N. (1984), “Why are services cheaper in poor countries?”, *Economic Journal*, 94, 279-286.

Branson, W.H. (1983), “Macroeconomic determinants of real exchange risk”, in R.J. Herring (ed.) *Managing Foreign Exchange Risk*, Cambridge: Cambridge University Press.

Cheung, Y.W., Fung, H.G.. Lai, K.S. and Lo, W.C. (1995), “Purchasing power parity under the European Monetary System”, *Journal of International, Money and Finance*, 179-189.

Chowdhury, A.R. and F. Sdogati (1993), “Purchasing power parity in the major EMS countries: The role of exchange rate adjustment”, *Journal of Macroeconomics*, 15, 25-45.

Corsetti, G. and P. Pesenti (2005), “The simple geometry of transmission and stabilisation in closed and open economies”, Discussion Paper No. 5080, Centre for Economic Policy and Research.

Dickey, D.A. and W.A Fuller (1979), “Distribution of the estimators for autoregressive time series with a unit root”, *Journal of American Statistical Association*, 74, 427-431.

Dixit, A.K. (1989), “Hysteresis, import penetration and exchange rate pass-through”, *Quarterly Journal of Economics*, 104, 205-228.

Dumas, B. (1992), “Dynamic equilibrium and the real exchange rate in spatially separated world”, *Review of Financial Studies*, 5, 153-80.

Engel, C. (1993), “Real exchange rates and relative prices: an empirical investigation”, *Journal of Monetary Economics*, 32, 35-50.

Engel, C. and J.H. Rogers (1996), “How wide is the border?”, *American Economic Review* 86, 1112-25.

Feenstra, R.C. (1995), “Exact hedonic price indexes”, *Review of Economics and Statistics*, 77, 634-653.

Feenstra, R.C. and J.D. Kendall (1997), “Pass-through of exchange rates and purchasing power parity”, *Journal of International Economics*, 43, 237-261.

Friedman, M. and A.J. Schwartz (1963), *A Monetary History of the United States: 1867-1960*, Princeton, N.J.: Princeton University Press for the National Bureau of Economic Research.

Froot , K.A. and P.D. Klemperer (1989), “Exchange rate pass-through when market share matters”, *American Economic Review*, 79, 637-654.

Gaillot, H.J. (1970), “Purchasing power parity as an explanation of long-term changes in exchange rates”, *Journal of Money, Credit and Banking*, 2, 348-357.

Goldberg, L.S. and C. Tille (2008), “Vehicle currency use in international trade”, *Journal of International Economics*, 76, 177-192.

Gorodnichenko, Y. and L.L. Tesar (2009), “Border effect or country effect? Seattle may not be so far from Vancouver after all”, *American Economic Journal: Macroeconomics*, 1, 219-241.

Giovannini, A. (1988), “Exchange rates and traded goods prices”, *Journal of International Economics*, 24, 45-68.

Granger, C.W.J. and T. Teräsvirta (1993), *Modelling Nonlinear Economic Relationships,* Oxford University Press, Oxford.

Imbs, J., Mumtaz, H., Ravn, M.O. and H. Rey (2005), “PPP strikes back: Aggregation and the real exchange rate”, *Quarterly Journal of* Economics, 120, 1-43.

Isard, P. (1977), “How far can we push the “Law of One Price”?”, *American Economic Review*, 67, 942-948.

Kasa, K. (1992), "Adjustment costs and pricing-to-market: Theory and evidence", *Journal of International Economics*, 32, 1-30.

Knetter, M.M. (1989), "Price discrimination by U.S. and German exporters", *American Economic Review*, 79, 198-210.

Knetter, M.M. (1993), "International comparisons of price-to-market behaviour", *American Economic Review*, 83, 473-486.

Knetter, M.M. (1994), "Did the strong dollar increase competition in the U.S. product markets?", *Review of Economics and Statistics*, 76, 192-195.

Krugman, P.R. (1987), "Purchasing power parity and exchange rates: Another look at the evidence", in S.W. Arndt and J.D. Richardson (eds.), *Real-Financial Linkages Among Open Economies,* Cambridge, Massachusetts: MIT Press.

Kugler, P. and C. Lenz (1993), "Multivariate cointegration analysis and the long-run validity of PPP", *Review of Economics and Statistics*, 75, 180-184.

MacDonald, R (1993), "Long-run purchasing power parity: is it for real?", *Review of Economics and Statistics* 75, 690-695.

MacKinnon J. (1991), "Critical values for co-integration tests", in R.F. Engle and C.W.J. Granger (eds.) *Long-Run Economic Relationships*, Oxford University Press, 267-276.

Michael, P., Nobay, A.R. and D.A. Peel (1997), "Transactions costs and nonlinear adjustment in real exchange rates: An empirical investigation", *Journal of Political Economy*, 105, 862-879.

Obstfeld, M. and K. Rogoff (1995), "Exchange rate dynamics redux", *Journal of Political Economy*, 103, 624-660.

Obstfeld, M. and K. Rogoff (1998), "Risk and exchange rates", Working Paper No 6694, National Bureau of Economic Research.

Obstfeld, M. and K. Rogoff (2000), "The six major puzzles in international macroeconomics: is there a common cause?", *NBER Macroeconomics Annual*, 15, 403-411.

O'Connell, P.J. and S.J. Wei (2001), "The bigger they are, the harder they fall: retail price differences across U.S. cities", *Journal of International Economics*, 56, 21-53.

Parsley, D.C. and S.J. Wei (1996), "Convergence to the law of one price without trade barriers or currency fluctuations", *Quarterly Journal of Economics*, 111, 1211-1236.

Parsley, D.C. and S.J. Wei (2007), "A prism into the PPP-puzzles: The micro-foundations of Big Mac real exchange rates", *Economic Journal*, 117, 1336-1356l.

Richardson, J.D. (1978), "Some empirical evidence on commodity arbitrage and the Law of One Price", *Journal of International Economics*, 8, 341-351.

Rogoff, K. (1996), "The purchasing power parity puzzle", *Journal of Economic Literature* 34, 647- 668.

Sarno, L. (2005), "Towards a solution to the puzzles in exchange rate economics: Where do we stand?", *Canadian Journal of Economics*, 38, 673-708.

Sarno, L. and Taylor, M.P. (2002). *The economics of exchange rates*. Cambridge University Press: Cambridge.

Sarno, L., Taylor, M.P. and I. Chowdhury (2004), "Nonlinear dynamics in deviations from the law of one price: a broad-based empirical study", *Journal of International Money and Finance*, 23, 1-25.

Samuelson, P.A. (1964), "Theoretical notes on trade problems", *Review of Economics and Statistics*, 46, 145-154.

Sercu, P., Uppal, R. and C. van Hulle (1995), "The exchange rate in the presence of transaction costs: Implications for tests of Purchasing Power Parity", *Journal of Finance*, 50, 1309-1319.

Taylor, A.M. (2001), "Potential pitfall for purchasing power parity puzzle? Sampling and specification biases in mean reversion tests of the Law of One Price", *Econometrica*, 69, 473-498.

Taylor, M.P. and P.C. McMahon (1988), "Long-run purchasing power parity in the 1920s", *European Economic Review*, 32, 179-197.

Taylor, M.P, Peel, D.A. and L. Sarno (2001), "Nonlinear mean-reversion in real exchange rates: Towards a solution to the purchasing power parity puzzles", *International Economic Review*, 42, 1015-1042.

Van Dijk, D., Teräsvirta, T. and P.H. Franses (2002). "Smooth transition autoregressive models: A survey of recent developments", *Econometric Reviews*, 21, 1-47.

Figure 1: A two-state exchange rate example

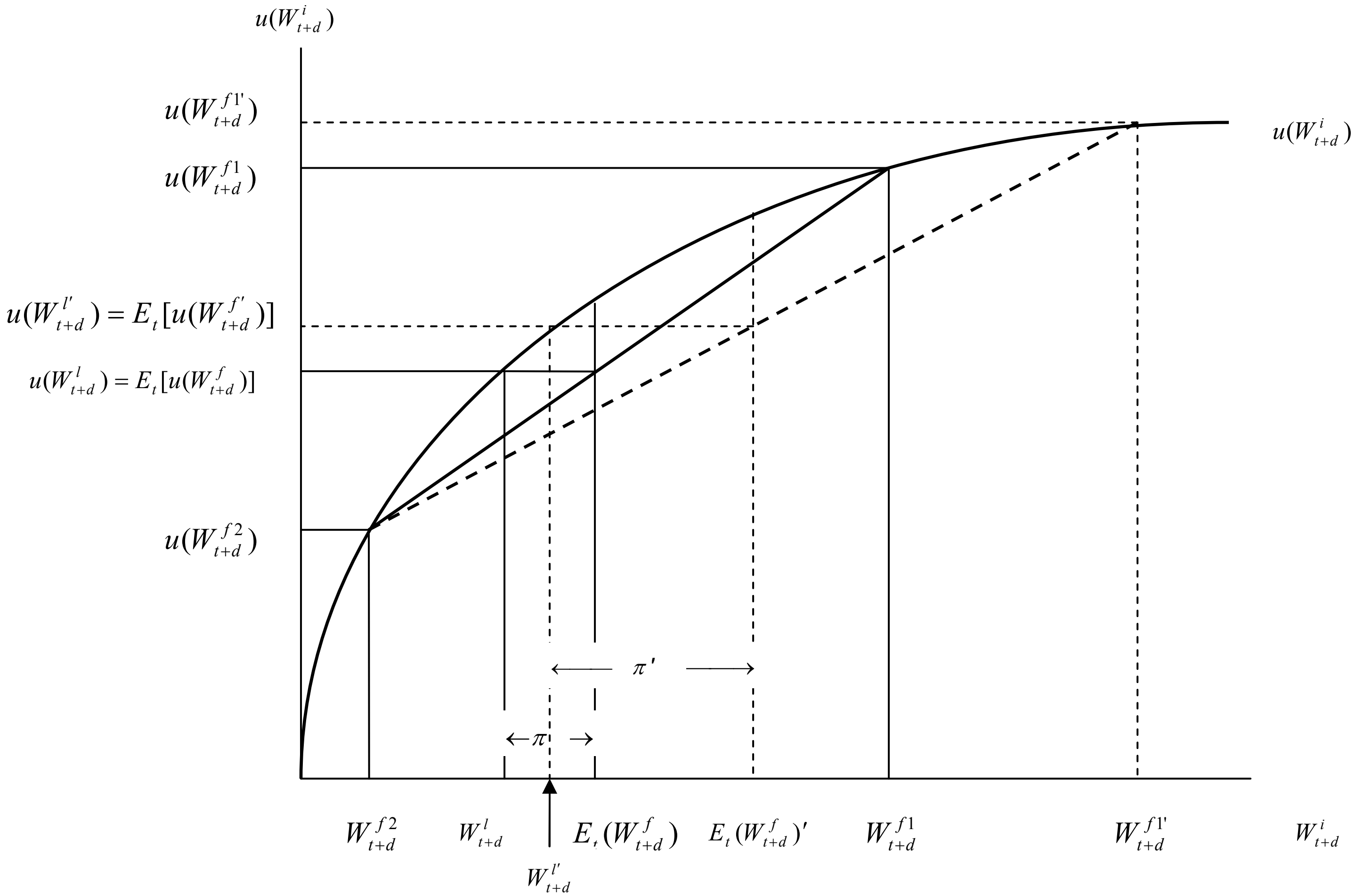
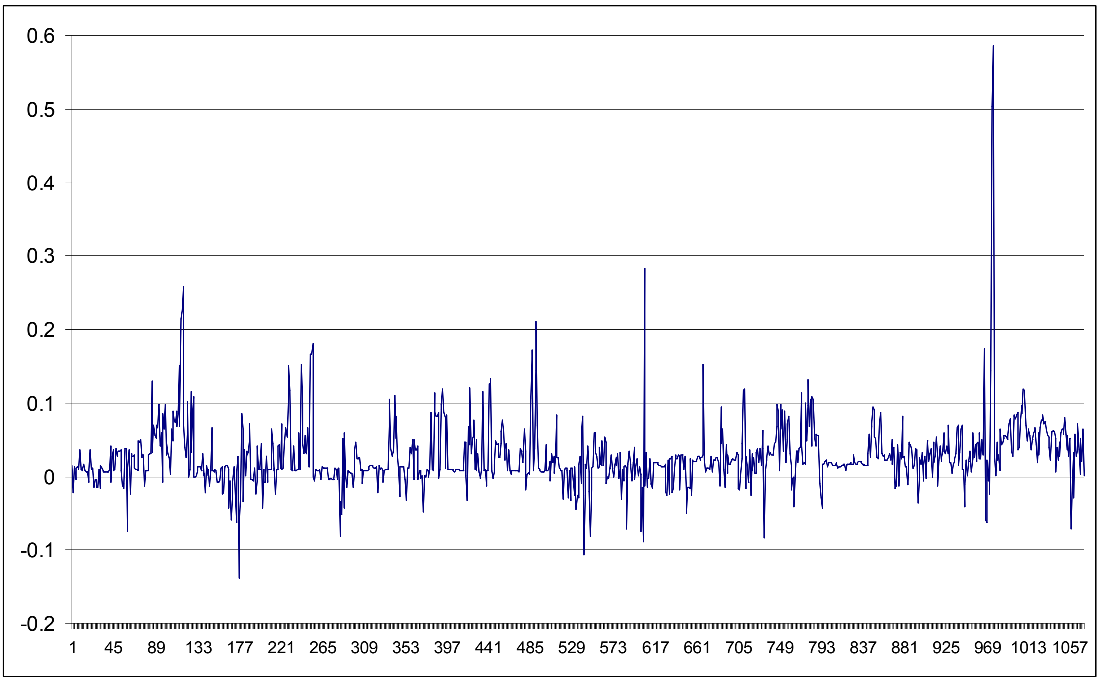
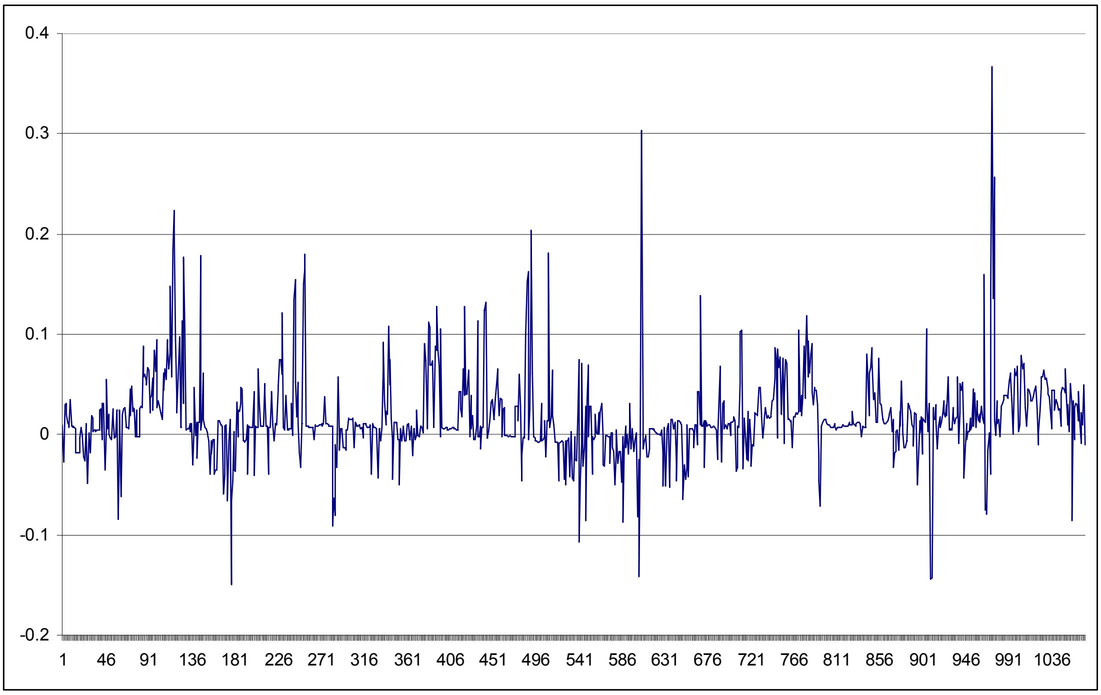


Figure 2: Deviations from the law of one price for the market of online air-travel tickets

(a) Travelocity.de to Travelocity.co.uk




(b) Expedia.de to Expedia.co.uk




Sample period: 1 April 2006 – 6 March 2009 (1071 daily observations)

Table 1: Summary statistics for the market of online air-travel tickets

| | Mean | Standard Deviation | Coefficient of variation |
|---|---|---|---|
| *Intra-domain comparisons* | | | |
| Travelocity.co.uk/Expedia.co.uk | 0.997 | 0.039 | 0.039 |
| Travelocity.de/Expedia.de | 1.022 | 0.057 | 0.056 |
| *Inter-domain comparisons* | | | |
| Travelocity.de/Travelocity.co.uk | 1.073 | 0.167 | 0.156 |
| Expedia.de/Expedia.co.uk | 1.046 | 0.113 | 0.108 |

*Notes*: Sample: 1 April 2006 – 6 March 2009 (1071 daily observations). The reported figures have been calculated using publicly available price quotations collected by the authors.

Table 2: Modelling deviations from the law of one price ($\omega_t$) for the market of online air-travel tickets

| | (a) | (b) | (c) | (d) | (e) | |
|---|---|---|---|---|---|---|
| Travelocity.de to Travelocity.co.uk | | | | | Lower regime | Upper regime |
| constant | .0.020 (0.001)** | 0.013 (0.001)** | 0.030 (0.002)** | 0.022 (0.001)** | 0.014 (0.002)** | |
| $E_t(s_{t+1}\text{-}s_t)^2$ | 1230 (180)** | 777 (169)** | 899 (152)** | 1498 (151)** | -1.368e-005 (955) | 777 (198)** |
| $\omega_{t\text{-}1}$ | | 0.343 (0.025)** | | | 0.396 (0.030)** | 0.263 (0.042)** |
| Dneg | | | -0.053 (0.003)** | | | |
| $\tau$ | | | | | 3.62990e-006 (3.879e-007)** | |
| $R^2$ | 0.45 | 0.53 | 0.61 | 0.54 | 0.53 | |
| Nonlinearity test $\omega_t$ | 20.198** [1] | | | | | |
| Nonlinearity test $\varepsilon_t$ | 5.063** [1] | | | | | |
| Expedia.de to Expedia.co.uk | | | | | | |
| constant | 0.012 (0.001)** | 0.007 (0.001)** | 0.027 (0.001)** | 0.017 (0.001)** | 0.008 (0.002)** | |
| $E_t(s_{t+1}\text{-}s_t)^2$ | 819 (208)** | 469 (172)** | 305 (156)* | 1075 (147)** | -7.016e-006 (1220) | 469 (199)* |
| $\omega_{t\text{-}1}$ | | 0.398 (0.025)** | | | 0.435 (0.030)** | 0.324 (0.046)** |
| Dneg | | | -0.050 (0.002)** | | | |
| $\tau$ | | | | | 3.159e-006 (2.980e-007)** | |
| $R^2$ | 0.23 | 0.37 | 0.49 | 0.32 | 0.37 | |
| Nonlinearity test $\omega_t$ | 6.848** [2] | | | | | |
| Nonlinearity test $\varepsilon_t$ | 4.035** [1] | | | | | |

*Notes:* Estimation sample: 1 April 2006 – 6 March 2009 (1071 daily observations). *, ** denote statistical significance at the 5 and 1 per cent level respectively. All equations have been estimated using intercept dummies capturing the effects of extreme outliers. For Travelocity, these are observations 116, 117, 118, 606, 974, 975 and 976; for Expedia observations 116, 117, 118, 492, 607, 974 and 976. Standard errors in parentheses have been calculated using Andrews's (1991) correction for autocorrelation and heteroscedasticity. The statistical significance of the reported coefficients is robust to the correction of standard errors for non-normality using the wild bootstrap methodology. Nonlinear adjustment is tested using the general nonlinearity test by Granger and Teräsvirta (1993), testing the null hypothesis of linear mean reversion against the alternative of non-linear mean-reversion. The lag structure of the nonlinearity tests has been chosen using the series' partial autocorrelation function (available upon request). Figures in square brackets denote the value of the delay parameter $\delta$ for which the nonlinearity test yields the strongest rejection of the null hypothesis of linear adjustment