Detecting Political Event Risk In The Option Market

Abstract

This study shows that the option market can ex ante detect and quantify the effects of political event risk. Focussing on the 2016 UK referendum on EU membership, we find that the Risk-Neutral Distribution extracted from GBPUSD futures options whose expiry spans the referendum date becomes bimodal and the Implied Volatility curve exhibits an unusual W-shape. To the contrary, the corresponding effects for FTSE100 are found to be very limited. The large swings in expectations regarding the event outcome during the referendum night allow us to observe the counterfactual and validate the ex ante information revealed in the option market.

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1 Introduction

Political events can exert a significant impact on financial markets (see Bernhard and Leblang, 2006; Fowler, 2006; Snowberg et al., 2007; Kelly et al., 2016). Hence, there is a growing interest in identifying the effects of electoral outcomes on asset prices and volatility. To the extent that an election or referendum outcome can lead to a dramatic shift in the macroeconomic environment, the institutional framework, or government policy, such a political process can give rise to *event risk*.[1] This type of risk naturally affects asset pricing, portfolio choice, and risk management practices.[2]

Equally importantly, *ex ante* identification and quantification of political event risk could affect voters' decision making. This is particularly true for a polarised event where, in the absence of an objective measure of the economic impact of its outcomes in real time, the opposite sides of the campaign typically make sharply contradictory predictions. Wolfers and Zitzewitz (2016, p. 3) argue that a "shortcoming of traditional [political] event studies is that they are retrospective: we usually learn about the expected effects of an event afterwards, but not in time to affect any policy or political decision involved". Our study addresses this shortcoming, showing how the option market can *ex ante* identify the existence and measure the effects of political event risk on asset prices and volatility.

We examine the referendum that took place in the United Kingdom (UK) on 23rd June 2016, asking the electorate whether the UK should remain a member of or leave the European Union (EU). Table 1 contains a chronology of the key political events leading to this referendum.

-Table 1 here-

This referendum provides an ideal laboratory to assess the ability of options to detect and quantify political event risk. It is a single upcoming event with two possible outcomes that may or may not have distinct effects across different assets. Moreover, the event

[1] Following Liu et al. (2003, p. 231), we define event risk as "the risk of a major event precipitating a sudden large shock to security prices and volatilities".

[2] There is a voluminous literature on the implications of event or "jump" risk. See, inter alia, the seminal contributions of Merton (1976), Jorion (1988), Bates (1996, 2000), Duffie et al. (2000), and Liu et al. (2003). The implications of political event risk have recently attracted significant interest among practitioners (see, for example, Clark and Amen, 2017; Putnam et al., 2018; Baker et al., 2018).

date is fixed and publicly known well in advance, so its timing is strictly exogenous to the short-term fluctuations in asset prices just before the referendum. Hence, there is no uncertainty over whether and when this event will occur, but only with respect to the outcome and its impact. In fact, there was substantial disagreement between the opposite sides of the campaign with respect to the economic impact of a Leave outcome (henceforth also termed as "Brexit")[3], leading to contradictory predictions.[4]

Uncertainty regarding the outcome of the referendum and the large swings in the outcome probabilities observed after voting ended render this event an ideal setup for identification purposes. Opinion polls indicated a marginal result in the run up to the referendum. However, following the assassination of the Member of Parliament (MP) Jo Cox on 16th June 2016, a Remain victory was anticipated by the media and the betting market. This anticipation was reinforced as soon as voting ended. Nevertheless, the first official results revealed that the Leave vote performed more strongly than expected. A similar trend was observed throughout the night, albeit with geographical variations, leading to a "surprise" Leave victory with 51.9% of the vote. These large swings in expectations reveal the counterfactual and provide a unique opportunity to validate the ability of the option market to ex ante detect and quantify political event risk.

This "surprising" result was followed by sharp movements in asset prices. GBPUSD dropped from the peak of \$1.50 on the night of 23rd June to the trough of \$1.32 in the early morning of 24th June, i.e., a sharp fall of -12%. The FTSE100 Index opened with a drop of -8.7% relative to the previous day's close, but this drop was contained to -3.2% by the end of the trading day. Interestingly, FTSE100 actually rose by 2.6% and 6.1% by the end of June and July 2016, respectively. To the contrary, GBPUSD continued to

[3]Technically, this referendum outcome did not constitute an immediate change in the EU membership status of the UK. Legally, it was a non-binding mandate from the electorate to the Government and Parliament to trigger the rather prolonged process of the UK leaving the EU, which involved a number of subsequent negotiation rounds, agreements, and ratifications. Nevertheless, at that time, a Leave vote outcome was perceived as a strong democratic mandate that would initiate this process, which is commonly referred to as "Brexit".

[4]Proponents of Brexit were reassuring that such an outcome would not have a significant adverse long-term effect on the UK economy, other than a short-term increase in market volatility. To the contrary, the government's official position was that Brexit would have dramatic economic consequences, including a sharp fall in the sterling pound as well as a large drop in share and house prices, triggering an immediate recession (see HM Treasury, 2016).

trade consistently below \$1.35 until the end of July. Hence, whereas the Brexit outcome has been a major source of event risk for GBPUSD, this is not true for FTSE100, at least from the viewpoint of a domestic investor. Motivated by this observation, we examine not only whether the option market can detect and quantifiy political event risk when there is, but also whether it can signal the absence of significant event risk when there is not. In other words, we ask whether the option market can distinguish the potentially differential effects of the same political event across different assets.

Options are well suited to detect political event risk. First, option prices inherently embed forward-looking information (see Jackwerth, 2004, for an overview). Second, options come with different expiries, allowing us to isolate the effects of a political event on the underlying asset. Comparing the information embedded in options whose expiry spans the event with the corresponding information in similar options that expire before the event, we can identify the effects of the latter on the underlying asset. Third, options come with different strikes, enabling us to measure the counterfactual, even if this is not subsequently realized. The availability of option prices across a range of strikes can yield the entire Risk-Neutral Distribution (RND) of the underlying asset price (see Breeden and Litzenberger, 1978), providing information about the range of possible outcomes and their probabilities. In this study, we utilise options on GBPUSD futures traded at Chicago Mercantile Exchange (CME) and options on the FTSE100 Index traded at the Intercontinental Exchange (ICE) to extract the corresponding RNDs.[5] To this end, we follow the non-parametric methodology of Figlewski (2010), which allows us to flexibly recover the underlying RND without imposing strict parametric assumptions.

Our analysis yields a number of interesting results. First, we compare the RNDs extracted from GBPUSD options on the same trading day but with different expiries, revealing a dramatic shift in the RNDs for options with expiry spanning the referendum date. These RNDs are strongly negatively skewed and exhibit much larger dispersion, as compared to the relatively symmetric RNDs extracted from options that expire before the

[5] We focus on GBPUSD rather than GBPEUR because Brexit could also have a direct effect on the Eurozone economy, blurring the direction of impact of such an outcome on the latter exchange rate. Moreover, we focus on the FTSE100 Index, as there were no actively traded options on any other UK equity index.

referendum. Hence, political event risk with respect to GBPUSD can be clearly detected well in advance of the event. To the contrary, this effect is much less pronounced when we compare the corresponding RNDs extracted from FTSE100 options.

Second, in the run up to the referendum, we uncover consistently bimodal GBPUSD RNDs. Their distinct modes correspond to the range of values that the option market assigns to GBPUSD in each of the two referendum outcomes. In particular, the left mode of these RNDs lies between \$1.31-\$1.35, but with substantial dispersion around it, revealing that the option market anticipates a large drop in GBPUSD in the event of a Leave outcome. In contrast, the right mode lies in the region of \$1.50-\$1.53, with much lower dispersion. As a result, GBPUSD RNDs signal that the full effect of Brexit (relative to a Remain outcome) lies in the approximate range of 15¢-19¢. On the other hand, the RNDs extracted from FTSE100 options remain clearly unimodal, featuring only a moderate increase in its negative skewenss.

Third, we find that the effect of political event risk is only temporary. In particular, the GBPUSD RND reverts to its usual, relatively symmetric, and unimodal shape immediately after the uncertainty regarding the outcome of the referendum is resolved. This finding confirms that the shift in the shape of the RND in the pre-event period can be entirely attributed to event risk.

We obtain similarly interesting results when we examine the corresponding Implied Volatility (IV) curves. In addition to an overall increase in volatility, we find that the IV curve becomes negatively sloped and concave for GBPUSD options with expiry spanning the referendum. In contrast, it features the typical (for currency options) convex and relatively symmetric smile when the expiry does not span this event. This unusual concave shape is another ex ante manifestation of event risk for the underlying asset. To the contrary, we find only a limited impact on the shape of the IV curve for FTSE100 options.

We also exploit the large swings in outcome probabilities during the referendum night. Using over-the-counter (OTC) options, we extract GBPUSD RNDs and their corresponding moments at the 10-minute frequency. This analysis reveals that the option market immediately incorporates information from actual voting results, as these high frequency

RNDs reflect the continuously updated beliefs of market participants regarding the event outcome as well as the price and volatility of GBPUSD. In fact, comparing real-time option-implied information with the corresponding event probabilities implied by betting odds, we show that the Remain outcome is associated with a GBPUSD futures price around $1.52 and a low volatility level (circa 15% p.a.), whereas the Leave outcome is associated with a futures price around $1.34 and a high volatility level (circa 25% p.a.). These findings provide strong validation of the two modes appearing in the GBPUSD RNDs in the run up to the referendum and confirm the ability of the option market to quantify the effect of political event risk.

A number of prior studies have attempted to identify the impact of political event outcomes on asset prices. Most commonly, these studies estimate this impact by regressing changes in asset prices on changes in prediction market- or betting odds-implied probabilities during the pre-event period (see, inter alia, Herron, 2000; Knight, 2006; Coulomb and Sangnier, 2014). However, such estimates may be affected by reverse causality or other omitted factors (see Snowberg et al., 2007, for a critique).

To sidestep these issues, other studies have utilised short windows during which a sharp exogenous shock to the probability of the event outcome is observed (see, for example, Slemrod and Greimel, 1999; Snowberg et al., 2007; Wolfers and Zitzewitz, 2016). These studies typically extrapolate the relationship estimated during this short window to assess the full impact of the political event outcome. Naturally, the validity of this approach depends on the possibility to identify a large political shock and the accuracy of this extrapolation. Wolfers and Zitzewitz (2018) discuss the limitations regarding the external validity of these event studies. In contrast, utilizing option-implied information allows us to ex ante identify political event risk without relying on the occurrence of large political shocks. This is because options come with different strikes, which allow us to measure the full impact of the counterfactual, even if this is not subsequently realized.

Only a few prior studies have examined the informational content of option prices for political events. Most notably, Leahey and Thomas (1996) report a multi-modal RND extracted from options on Canadian dollar futures prior to the 1995 Quebec sovereignty referendum. Gemmill and Saflekos (2000) examine the RNDs extracted from FTSE100 options around three UK parliamentary elections, providing mixed evidence and concluding that RNDs do not have much forecasting power with respect to post-election outcomes. However, both of these studies impose the ad hoc assumption that the RND is a mixture of three or two lognormal distributions, respectively, which may undermine parameter identification and stability. To the contrary, the non-parametric approach of Figlewski (2010) allows us to more accurately capture the true shape of the RND. In addition, Coutant et al. (2001), using a variety of methods, show that the RND extracted from interest rate futures options anticipated the 1997 French snap election a few days before its official announcement.

Our study is closely related to Hanke et al. (2018), who also utilise information from GBPUSD options prior to the Brexit referendum, but their focus is on exchange rate forecasting. Hanke et al. (2018) combine betting odds-implied event probabilities with a mixture of two lognormal densities estimated from option prices to extract a blended density. However, they utilise OTC option data with only 5 strikes, which naturally hinders them from fully recovering the true shape of the RND and the IV curve. In contrast, we use a much wider range of strikes from options traded at CME, which allow us to extract a bimodal RND for GBPUSD and to reveal a concave IV curve in the presence of event risk, relying *solely* on information embedded in option prices. Hence, we demonstrate the ability of the option market to ex ante detect and quantify the impact of political event risk without resorting to betting odds that may not be always available.[6]

The rest of the study is organised as follows. Section 2 describes the data and methodologies employed to extract RNDs and option-implied event probabilities, respectively. Section 3 contains the main results of the study using daily options, whereas Section 4 illustrates the price discovery process during the referendum night. Section 5 extracts option-implied event probabilities, latent state prices and volatilities, Section 6 presents

[6] Using a snapshot of CME data, Baker et al. (2018) also provide evidence of concave IV curves for GBPUSD options prior to the referendum. More recently, Ferreira et al. (2022) examine this event using information from opinion polls as well as from option and betting markets. Different from our study, their focus is on risk-adjusting implied probabilities. They find that markets could have signalled more accurately the actual referendum result under the assumption of a risk-seeking representative agent and speculative trading triggered by this binary political event.

some further results, and Section 7 concludes.

2 Data and Methodology

2.1 Data

We use daily option data on the GBPUSD futures contract traded at CME. These are European-style options with traded quarterly expiries in March, June, September, and December plus two serial months. Their last trading day is on the second Friday prior to the third Wednesday of the expiry month and they are physically settled into futures. Each futures contract amounts to £62,500. Their trading hours are Sunday 5pm to Friday 4pm (Central Time, CT) with a 60-minute break each day beginning at 4pm (CT). Options are quoted in US$ per British pound increment, with a tick size of 0.0001 (i.e., $6.25). We use option data with expiries on 3rd June, 8th July, and 5th August 2016. Daily settlement option and futures prices are sourced from CME Datamine.

We also use daily option data on the FTSE100 Index traded at the ICE. These are European-style options and serial month expiries are traded for up to two years. Their last trading day is on the third Friday of the expiry month and they are cash settled. Their trading hours are from 8am to 4.50pm (London time). Since quarterly FTSE100 futures (March, June, September, December) expire on the same date as the options, the European-style FTSE100 option contract can be actually regarded as an option on the futures. For serial months, when the futures contract is not traded, we utilise the futures price implied by put-call parity. Options are quoted in index points, with a tick size of 0.5, and each contract is valued at £10 per index point. We use options with expiries on 17th June, 15th July, and 19th August 2016. FTSE100 option data are taken from Refinitiv DataScope.

We further utilise intraday GBPUSD option data around the referendum day. In particular, we use the implied volatility surfaces computed from over-the-counter (OTC) options by Bloomberg. More specifically, Bloomberg provides the following information: *i*) at-the-money implied volatility (σ_{ATM}), *ii*) risk reversals for 10-delta ($\sigma_{RR10\Delta}$) and

25-delta ($\sigma_{RR25\Delta}$) options, and *iii*) butterfly spreads for 10-delta ($\sigma_{BF10\Delta}$) and 25-delta ($\sigma_{BF25\Delta}$) options. Following Beber et al. (2010), this information can be used to compute the following 5 implied volatilies in the delta space:

$$\sigma_{50\Delta Call} = \sigma_{ATM} \tag{1}$$

$$\sigma_{10\Delta Call} = \sigma_{ATM} + \sigma_{BF10\Delta} + (1/2)\sigma_{RR10\Delta} \tag{2}$$

$$\sigma_{10\Delta Put} = \sigma_{ATM} + \sigma_{BF10\Delta} - (1/2)\sigma_{RR10\Delta} \tag{3}$$

$$\sigma_{25\Delta Call} = \sigma_{ATM} + \sigma_{BF25\Delta} + (1/2)\sigma_{RR25\Delta} \tag{4}$$

$$\sigma_{25\Delta Put} = \sigma_{ATM} + \sigma_{BF25\Delta} - (1/2)\sigma_{RR25\Delta} \tag{5}$$

We focus on 1-month maturity options and we extract these implied volatilies at the 10-minute frequency on the 23rd and 24th June 2016, using the following conventions: *i*) the underlying asset is the spot exchange rate (with USD as domestic and GBP as foreign currency), *ii*) ATM strike is defined so as to ensure a delta-neutral straddle, *iii*) forward deltas are used, without adjustment for the option premium. Forward rates are also taken from Bloomberg.

In addition, we use the US$ risk-free rate provided by OptionMetrics and we interpolate using a cubic spline to match the horizon of option expiry. Moreover, we use LIBOR as proxy for the risk-free rate for FTSE100 options. This is taken from Refinitiv DataScope, and we interpolate again using a cubic spline to match the horizon of option expiry. We also use the probability of a Leave outcome implied by betting odds. The entire time series of this probability has been provided by Betfair, which is the largest Internet betting exchange.

2.2 Methodology

2.2.1 Extracting Risk-Neutral Distributions

We follow an approach similar to the non-parametric methodology proposed by Figlewski (2010) to extract RNDs from option prices. This approach involves a number of steps. First, we use daily settlement prices of OTM and ATM put and call options and convert them to IVs using Black's (1976) formula. In-the-money options are typically thinly traded and their prices reflect their intrinsic value, so they are discarded. Moreover, we discard extremely deep OTM options. In particular, we discard GBPUSD options with price less than 0.001$ per British pound increment and FTSE100 options with price less than 1 index point. Table 2 reports the average number of strikes per day for the options we use in our analysis after applying the above filters. We obtain a large number of OTM and ATM options that enable us to extract the corresponding RNDs.

-Table 2 here-

Second, we blend the IVs of puts and calls whose strike price X lies within 2% of the underlying futures price into a single point as follows: $IV_{blend}(X) = aIV_{put}(X) + (1-a)IV_{call}(X)$, where $a = (X_{high} - X)/(X_{high} - X_{low})$. This practice avoids creating an artificial jump in the IV curve at the ATM region, which may arise from ATM puts potentially trading at higher IV relative to ATM calls.

In the third step, we interpolate across the computed implied volatilities, fitting a quintic spline using *spaps* in MATLAB. A quintic spline ensures that the third derivative of the IV curve (and option price function) is continuous, leading to a well-behaved RND. This step yields the smoothest IV curve in the strike space subject to an upper bound (tolerance level) for the sum of weighted squared errors between the computed and fitted IVs. In the spirit of Bliss and Panigirtzoglou (2002, 2004), the quintic spline minimizes the following objective function:

$$\rho \sum_{i=1}^{N} w_i \left[IV\left(X_i\right) - \widehat{IV}\left(X_i, \Theta\right) \right]^2 + \int_{-\infty}^{\infty} S^{(3)}(x;\Theta)^2 dx, \tag{6}$$

where w_i is the weight applied to the squared fitted implied volatility error of option i, $IV(X_i)$ is the computed implied volatility for strike X_i, $\widehat{IV}(X_i, \Theta)$ is the corresponding fitted implied volatility, which is a function of the parameters Θ that define the quintic spline $S(x; \Theta)$, and ρ is a smoothing parameter that is optimally selected to ensure that the sum of squared implied volatility errors does not exceed a given tolerance level.[7] We extract daily RNDs using equal weights and setting the tolerance level equal to $\sum_{i=1}^{N}\left(\widetilde{V}_i \text{ x } Tick\right)^2$, where $\widetilde{V}_i$ is the vega of option i and $Tick$ is the option tick size.[8]

The fourth step involves converting the smoothed IV curve back to call prices using again the Black formula. This yields a set of densely and equally spaced option prices. Fifth, using this set of prices, we can recover the RND function, $f(X)$, based on the standard result of Breeden and Litzenberger (1978). In particular, given call option prices for a continuum of strikes, the density function can be computed as:

$$f(X) = e^{rT}\frac{\partial^2 C}{\partial X^2}. \tag{7}$$

In the absence of a continuum of strikes, we approximate $f(X)$ using finite differences:

$$f(X_i) \approx e^{rT}\frac{C_{i+1} - 2C_i + C_{i-1}}{(\Delta X)^2}, \tag{8}$$

whereas the cumulative density function, $F(X)$, is given by:

$$F(X_i) \approx e^{rT}\left[\frac{C_{i+1} - C_{i-1}}{X_{i+1} - X_{i-1}}\right] + 1. \tag{9}$$

The previous steps yield the central part of the RND, from the second lowest to the second highest strikes. To complete the density, we need to append its tails. To this end,

[7] In particular, parameter ρ controls the tradeoff between the goodness-of-fit and the smoothness of the spline function, with the latter captured by its integrated squared third derivative. Setting a low tolerance level ensures that the spline fits well the actual implied volatility points at the expense of smoothness. To the contrary, setting a high tolerance level yields a rather smooth spline that may not fit well all implied volatility points.

[8] We use this rather low tolerance level to ensure that the fitted implied volatilities do not considerably deviate from the actual ones. This choice of tolerance level implicitly acknowledges that the "true" option price may lie within one tick size from the observed one. Translated into volatility terms, this choice acknowledges that the "true" implied volatility may lie within the range of $\widetilde{V}_i$ x $Tick$ relative to the observed one.

following Birru and Figlewski (2012), we utilise the Generalized Extreme Value (GEV) distribution and connect each of the right and left tails with the central part of the RND at two points (strikes). This distributional choice follows from the Fisher-Tippett Theorem stating that the GEV distribution is a natural candidate for modelling the tails of an unknown density.

The functional form of the GEV distribution is given by:

$$G(x) = \exp\left[-\left(1+\xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-1/\xi}\right], \tag{10}$$

where ξ controls the tail shape, μ the location, and σ the scale of the distribution. The values of these three distributional parameters are selected for each tail separately to satisfy the following three constraints: *i*) the total probability mass in the fitted tail must equal the missing tail probability, *ii*) the density of the GEV tail must be equal to the central RND at the first connection point; and *iii*) the density of the GEV tail must be equal to the central RND at the second connection point, which is further out in the tail. In particular, to append the right tail, the connection points we use are the highest strike of the central RND, which corresponds to the distribution percentile α_R, and the strike that is closest to the percentile $\alpha_R - 3\%$. For the left tail, we use the lowest strike of the central RND, which corresponds to the distribution percentile α_L, and the strike that is closest to the percentile $\alpha_L + 3\%$.

To extract RNDs from high frequency option data provided by Bloomberg, we adjust the above procedure as follows. Following Reiswich and Wystup (2010), we use the relationship below to convert the provided 5-point IV curve from the delta space to the strike space:

$$X_i = f e^{-\Phi N^{-1}\left(\Phi \Delta_i^f\right)\sigma\sqrt{\tau}+(1/2)\sigma^2\tau}, \tag{11}$$

where f is the forward rate, $\Phi = 1$ (-1) for a call (put) option, N^{-1} is the inverse of the normal cdf, and Δ_i^f is the forward delta of option i. Since we are equipped with the implied volatility-strike surface, we directly fit the smoothing spline as in the third step of the above procedure. However, here we set the tolerance level equal to zero, since there are only 5 IV points available. Moreover, in the fourth step, we convert implied volatilities to option prices using the Garman and Kohlhagen (1983) formula (see Reiswich and Wystup, 2010). The rest of the procedure remains the same.

2.2.2 Option-Implied Event Probabilities

We further utilise option prices to extract information regarding the ex ante probability for each of the two potential referendum outcomes as well as the corresponding latent GBPUSD futures price and volatility. To this end, we follow the methodology proposed by Borochin and Golec (2016).[9]

In particular, the current GBPUSD futures price, F_0, can be regarded as a probability-weighted average of the price F_n, which would prevail in the event of a Remain outcome, and the corresponding price $F_n - V_e$, which would prevail in the event of a Leave outcome:

$$F_0 = p_e\,(F_n - V_e) + (1 - p_e)\,F_n = F_n - p_e V_e, \tag{12}$$

where p_e is the ex ante probability of a Leave outcome, and V_e denotes the full price effect due to a Leave outcome.[10] It should be noted that p_e is a risk-neutral probability. However, since we use a very short event window prior to the referendum, its evolution could be interpreted similarly to the evolution of the corresponding physical probability.

Similarly, the current price $O(X_i)$ of option i with strike X_i, whose expiry spans the referendum date, can be regarded as a probability-weighted average of the theoretical Black price $O^B(F_n, \sigma_n, X_i)$ that would prevail in the event of a Remain outcome and the corresponding price $O^B(F_n - V_e, \sigma_e, X_i)$ that would prevail in the event of a Leave outcome:

$$O(X_i) = p_e O^B(F_n - V_e, \sigma_e, X_i) + (1 - p_e)\,O^B(F_n, \sigma_n, X_i), \text{ for } i = 1, 2, ..., N, \tag{13}$$

where σ_e (σ_n) denotes the volatility in the event of a Leave (Remain) outcome. This

[9] This approach is more restrictive than the one by Figlewski (2010) to extract RNDs, since it implicitly imposes the assumption of mixed lognormality. This is because option prices in each event outcome are assumed to be determined by the relevant Black-Scholes formula or the binomial model.

[10] We can ignore potential discounting effects because the time horizon of the event is quite short.

relationship holds for both call and put options.

We can re-write equation (12) as:

$$p_e = \frac{F_n - F_0}{V_e}, \tag{14}$$

and substitute this expression into the system of equations in (13). The latter is an overidentified system of $N > 4$ equations that can be used to estimate the vector of 4 unknown parameters, $\theta = \{F_n, V_e, \sigma_e, \sigma_n\}$, and compute p_e. In particular, we estimate θ by minimising the following sum of squared errors:

$$SSE = \sum_{i=1}^{N} \left(O(X_i, \theta) - O^M(X_i)\right)^2, \tag{15}$$

where $O(X_i, \theta)$ is the option price for stike X_i determined by the parameter values in θ, as in equation (13), and $O^M(X_i)$ denotes the corresponding observable market price. We minimize this multivariate non-linear objective function using *lsqnonlin* in MATLAB.

We estimate the set of unknown parameters in θ and compute p_e on a daily basis in the run up to the referendum using daily settlement prices of CME options on GBPUSD futures that expire on 8th July 2016. Different from Borochin and Golec (2016), we utilise all available OTM and ATM calls and puts. Since this political event may cause a substantial movement in the underlying asset's price, it is helpful to utilise information from option prices across moneyness levels. We have also found that this approach yields more stable estimates than using only near-the-money options.[11]

3 Main Results

3.1 Early Detection of Political Event Risk

Early detection that a political event may be the source of risk for the underlying asset can be provided by comparing the RND extracted from options whose expiry spans the

[11] We have alternatively extracted event probabilities using only OTM options. The extracted probabilities are very similar to the ones presented in Section 5, confirming their robustness.

event date with the corresponding RND from options whose expiry does not span this date. In particular, major shifts in the RNDs extracted on the same trading day for adjacent expiries can be attributed to a horizon effect and the event occurring between these two expiries. Figure 1 presents this comparison for options on GBPUSD futures (Panel A) and FTSE100 (Panel B). Figure 1 illustrates these RNDs computed on 17th May 2016 as a means of example to show that political event risk can be detected quite early, but very similar patterns are found on other trading days and they are available upon request.

-Figure 1 here-

Panel A shows that the RNDs extracted from options on GBPUSD futures expiring on 8th July and 5th August, i.e., after the referendum, are dramatically different from the corresponding RND computed from options with expiry on 3rd June, i.e., before the referendum.[12] In particular, the RNDs with a post-referendum expiry exhibit a mode shift to the right, much larger dispersion, and fatter tails. Equally importantly, the latter RNDs become strongly negatively skewed, whereas the RND from options with expiry not spanning the referendum is relatively symmetric. Most characteristically, the RNDs from options expiring after the referendum assign a non-negligible probability to GBPUSD futures values below \$1.34, even though these are essentially zero-probability values under the RND extracted from options expiring before the referendum. Interestingly, the shape of the RNDs from options with post-referendum expiries is very similar, and hence there seems to be no substantial horizon effect between them. In sum, this remarkable shift in the shape of RNDs from options whose expiry spans the referendum provides a clear indication that this political event is a major source of risk for GBPUSD futures.

Panel B illustrates the corresponding effect on the RNDs extracted from options on FTSE100. Here, the effect of political event risk is much less pronounced. The RND from options expiring before the referendum is already negatively skewed, as it is typically

[12] The Kolmogorov-Smirnov test rejects the null hypothesis that the RND extracted from options expiring on 8th July is equal to the RND extracted from options expiring on 3rd June with a p-value<0.001. Similarly, it rejects the corresponding null hypothesis of equality between the RNDs extracted from options expiring on 5th August and 3rd June with a p-value<0.001.

the case for equity index options, and it becomes more disperse and more negatively skewed for options expiring after the referendum. Hence, this political event increases the probability of large drops in FTSE100, but its effect is substantially less pronounced in comparison to the corresponding effect on the GBPUSD RND.

Motivated by the previous evidence, it is interesting to see how political event risk is manifested in the IV curve. Figure 2 illustrates the corresponding IV curves for options on GBPUSD futures (Panels A&B) as well as for options on FTSE100 (Panels C&D). As with the above presented RNDs, these IV curves are computed on 17th May 2016 as a means of example, but very similar patterns are found on other trading days, which are available upon request. Panel A shows the IV curve for options expiring on 3rd June, i.e., before the referendum. This curve resembles an "IV smile", which is typically encountered for exchange rate options (see Hull, 2009; p. 391). This shape reveals that both OTM puts and OTM calls exhibit substantially higher implied volatility relative to ATM options. In fact, this pattern is reflected in the relatively symmetric RND extracted for this expiry, as illustrated in Panel A of Figure 1.

-Figure 2 here-

To the contrary, the IV curve becomes slightly concave when options expiring after the referendum are considered. In particular, Panel B of Figure 2 shows this concave IV curve for options on GBPUSD futures with expiry on 8th July.[13] Apart from the overall increase in the level of implied volatility relative to Panel A, this shape reflects two additional features. First, the implied volatility of OTM puts is substantially higher than the implied volatility of both ATM options and OTM calls, giving rise to a negatively sloped curve; this feature is reflected into a highly negatively skewed RND for this expiry, as illustrated in Panel A of Figure 1. Second, the rate by which the implied volatility of OTM puts drops as we approach the ATM region is rather slow, creating this concave shape. In other words, both deep OTM puts and nearer-the-money puts are relatively very expensive, reflecting the willingness of investors to pay a high price to be protected

[13] Interestingly, Hull (2009; p. 400) shows that a concave IV curve can be a reflection of a bimodal RND for the underlying asset.

against a sharp drop in GBPUSD futures. This is another clear indication of event risk arising due to the forthcoming referendum.

Panel C illustrates the IV curve for options on FTSE100 expiring prior to the referendum (17th June). The shape of this curve resembles a "smirk" and it is typical for equity index options, with deep OTM puts being substantially more expensive than both ATM options and OTM calls (see Hull, 2009; p. 394). This typical IV curve is reflected into a moderately negatively skewed RND, as illustrated in Panel B of Figure 1. Panel D of Figure 2 illustrates the corresponding IV curve computed from options with expiry spanning the referendum (15th July). We report again a slightly convex "smirk", which is similar to the one presented in Panel C. Even though the level of implied volatility is overall higher for options expiring after the referendum, it seems that this event does not dramatically affect the shape of the IV curve.

3.2 Effects of Political Event Risk

The above analysis shows that political event risk can be detected quite early by examining the RND and IV curve of options with expiries spanning the event date. To identify more accurately the effects of political event risk, we now focus on RNDs and IV curves around the referendum date from options with the same expiry. Specifically, Figure 3 illustrates the RNDs extracted from options on GBPUSD futures (Panel A) and FTSE100 (Panel B) on 23rd June at settlement, i.e., prior to the polls closing, as well as on 24th June, i.e., after the referendum result is known.

-Figure 3 here-

Panel A reveals the most striking effect of political event risk. The GBPUSD RND extracted on 23rd June clearly exhibits bimodality.[14] The shape of the RND essentially shows that the option market assigns a distinct range of GBPUSD futures values associated with each of the two referendum outcomes. The two distinct modes of the RND correspond to GBPUSD futures values of \$1.34 and \$1.53, respectively. Given that the

[14] The Hartigan and Hartigan (1985) test formally rejects the null of unimodality with a p-value<0.001.

underlying was trading around \$1.48 at CME option settlement on 23rd June, this is a clear indication that the option market was pricing a potential sharp drop in the exchange rate due to the referendum.

A related question is whether the effect of political event risk is permanent or temporary. If the effect of the political event is temporary, the RND and IV curve would revert to their standard shapes once the uncertainty surrounding this event is resolved; otherwise, if this political event causes a structural shift in the RND, this bimodal shape would persist. Panel A shows that the GBPUSD RND extracted on 24th June becomes unimodal and relatively symmetric, a shape similar to the one reported in Panel A of Figure 1 for options whose expiry does not span the referendum date. Since the RND reverts back to its standard shape immediately after the resolution of uncertainty surrounding the political event, we can conclude that the effect of the latter is only temporary.

Another interesting observation is that the GBPUSD RND extracted on 24th June exhibits its unique mode at \$1.38, providing ex post identification of the two modes observed in the bimodal RND extracted on 23rd June. The left mode (\$1.34) can be associated with a Leave outcome, whereas the right mode (\$1.53) can be associated with a Remain outcome. Moreover, the shift of the biggest RND mode from \$1.53 on 23rd June to \$1.38 on 24th June, which corresponds to a percentage decrease of -9.8%, provides an ex post justification for characterizing the referendum as a source of political event risk for GBPUSD.

Panel B presents the corresponding RNDs from options on FTSE100. We clearly observe unimodality in the RND extracted at settlement on 23rd June, so the option market does not assign a distinct mode to each of the two referendum outcomes. The effect of this political event on FTSE100 is manifested via a strongly negatively skewed RND. This effect is again found to be temporary, since the RND extracted on 24th June reverts back to its standard shape of a moderately negatively skewed distribution (see, e.g., Panel B of Figure 1). Moreover, the mode of the RND shifts from 6,621 on 23rd June to 6,382 on the following day, which corresponds to a drop of only -3.6%. This relatively smaller effect reveals that, in fact, the referendum did not pose a substantial event risk for FTSE100.

A plausible explanation for the absence of substantial event risk for FTSE100 lies with the geographic revenue exposure of its constituent stocks. In addition to the largest UK companies, this Index comprises a number of multinational companies which hold assets overseas and whose income is predominantly earned in foreign currency.[15] As a result, for “global” firms, the depreciation of sterling pound would actually increase in GBP terms the value of their overseas assets and income, and hence the value of their equity. This effect could offset the potentially sharp drop in equity values for “domestic” firms triggered by the adverse UK macroeconomic outlook due to a Leave victory.

Validating this conjecture, on the first trading day after the referendum, we indeed observe markedly heterogeneous share price reactions according to firms’ geographic revenue exposure. To illustrate this heterogeneous response, CBOE’s BATS constructed two UK indices based on the proportion of firms’ domestic-to-total revenues.[16] On the one hand, Brexit High 50 Index, which comprises the 50 firms in the BATS UK 100 Index that derive the largest portion of their revenues from the UK market, experienced a sharp drop of -11.8% on 24th June. On the other hand, Brexit Low 50 Index, which comprises the 50 firms in the BATS UK 100 Index that derive the lowest portion of their revenues from the UK market, actually rose by 1.1% on the same day. Providing a characteristic example, the biggest FTSE100 winner was the Africa-based gold-mining company Randgold Resources, whose share price rose by 14.2% on 24th June, whereas the biggest loser was the UK residential developer, Taylor Wimpey, whose share price dropped by -29.3%.

To examine futher this heterogeneous effect, we extract RNDs for the five most "domestic" and the five most "global" FTSE100 firms, as classified on the basis of the percentage of their foreign sales. Specifically, we source from Factset the percentage of foreign sales for all FTSE100 firms for the financial year ending prior to the referendum.

[15] FTSE Russell characterises a company as “global” (“domestic”) if its Global Sales Ratio is greater (lower) than 80% (20%). Using this criterion, they report that 60% of FTSE100 firms are predominantly global, whereas only 10% of FTSE100 firms are considered purely domestic. For more details, see https://hub.ipe.com/download?ac=76863.

[16] For more details, see http://www.cboe.com/resources/general/BatsBrexit5050-Product-Overview-1.pdf

Among those firms that have sufficient option data to construct RNDs, the five most "domestic" firms with the lowest share of foreign sales are: i) Barratt Developments (BDEV), ii) Land Securities Group (LAND), iii) WM Morrison Supermarkets (MRW), iv) Sainsbury's (SBRY), and iv) Travis Perkins (TPK). Figure SA.1 in the Supplementary Appendix presents their RNDs around the referendum date. The five most "global" firms with the highest share of foreign sales are: i) Shire (SHP), ii) Randgold Resources (RRS), iii) Experian (EXPN), iv) Antofagasta (ANTO), and v) Rio Tinto (RIO). Figure SA.2 presents the corresponding RNDs.[17]

Figure SA.1 illustrates that the RNDs of the "domestic" firms were mainly characterised by a substantial degree of negative skewness prior to the referendum. Hence, the option market priced a possible large drop in their share prices due to this political event. In fact, these RNDs reverted to a more symmetric shape after the referendum and their modes exhibited a large shift to the left, following the corresponding drop in the underlying share prices.

To the contrary, the RNDs illustrated in Figure SA.2 confirm the absence of substantial event risk for the "global" firms. These RNDs are mostly symmetric and their shape remains very similar right after the referendum. Interestingly, the modes for some of these firms shifted to the right on the 24th June, as the corresponding share prices actually rose.

Figure 4 illustrates the corresponding effects on the IV curves of GBPUSD and FTSE100. Panel A presents the IV curve for options on GBPUSD futures at settlement on 23rd June, revealing a rather unusual shape. The IV curve exhibits an overall negative slope, with OTM puts trading at substantially higher volatility relative to both ATM options and OTM calls. Implied volatility decreases as the strike increases but the rate of decrease varies at different strike regions. In fact, the IV curve switches from convex to concave and back to convex, with the first inflection point appearing around

[17] Option price data for these companies are taken from Refinitiv DataScope. These are American-style options with expiry on 15th July, 2016. We extract RNDs following the non-parametric methodology of Figlewski (2010). Since these are American-style options, we convert option prices to implied volatilities using the Cox-Ross-Rubinstein binomial tree model via the MATLAB function *opstockbycrr*. Moreover, when fitting the IV curve via *spaps*, we assign a higher (lower) weight to observations with relatively high (low) open interest.

the \$1.34 strike. This unusual W-shape reveals that the option market assigns relatively high prices for OTM puts with strikes between \$1.34-\$1.38. Actually, this feature is the underlying source of bimodality in the RND illustrated in Panel A of Figure 3.

-Figure 4 here-

Panel B of Figure 4 shows that the IV curve for options on GBPUSD futures reverts back to a standard "smile" on 24th June (see also Panel A of Figure 2). In other words, once the uncertainty surrounding this political event is resolved, the IV curve becomes again convex. This shape is consistent with the unimodal and relatively symmetric RND presented in Panel B of Figure 4. In addition, the overall level of implied volatility is now substantially lower.

Panels C and D of Figure 4 repeat this analysis for the FTSE100 IV curve. Panel C shows that, prior to the referendum, the IV curve exhibits a negative slope, with OTM puts trading at substantially higher implied volatility relative to both ATM options and OTM calls. This feature is consistent with the strongly negatively skewed RND presented in Panel B of Figure 3. There is also some evidence of local concavity in the IV curve, but this is much less clear relative to the corresponding patterns in the GBPUSD IV curve.

Panel D of Figure 4 shows that the shape of the FTSE100 IV curve is not dramatically different on 24th June. In particular, there is no substantial reduction in the level of volatility and the curve is still characterised by a negative slope. However, this slope now seems to be less steep, explaining why the corresponding RND on 24th June is less negatively skewed than the RND on the previous day (see Panel B of Figure 3). In sum, the IV curve seems to revert back to its standard shape (see Panel C of Figure 2), and hence we conclude that the effect due to the referendum is only temporary and much less pronounced.

3.3 Bimodality vs. Unimodality and Risk-Neutral Moments

One of the most striking effects of political event risk is the emergence of bimodality in the GBPUSD RND (see Panel A of Figure 3). We examine here how consistent this feature is in the run up to the referendum. Panels A and B of Figure 5 plot GBPUSD RNDs on various trading days prior to the referendum. We find that these RNDs exhibit clear bimodality already on 10th June, revealing that the option market is consistently pricing a possible large drop in GBPUSD.[18] The left mode of these bimodal distributions lies between \$1.31-\$1.35, revealing the option market's anticipation of the exchange rate in the event of a Leave outcome. To the contrary, the right mode of the RND, which is associated with a Remain outcome, lies in the region of \$1.50-\$1.53. The distance between the two modes provides a rough approximation of the full impact of a Leave outcome (relative to Remain), which is 15¢-19¢.

-Figure 5 here-

On the other hand, Panels C and D of Figure 5 provide no evidence of bimodality in the FTSE100 RND prior to the referendum. The main effect of this event is manifested in terms of a fatter left tail. The consistent unimodality of FTSE100 RNDs in the run up to the referendum provides further evidence that the event risk for FTSE100 is much more limited relative to the corresponding event risk for GBPUSD.

Motivated by the above analysis, we further examine in more detail how this event risk and the subsequent resolution of uncertainty are reflected by the evolution of Risk-Neutral moments computed from the corresponding RND. Figure 6 presents the evolution of Risk-Neutral Volatility (RNV) from 9th May until 5th July.

-Figure 6 here-

Panel A of Figure 6 shows that the GBPUSD RNV computed from options whose expiry spans the referendum date is substantially higher relative to the RNV from options expiring before the referendum. In fact, the RNV computed from options expiring on 8th July is almost twice as high as the RNV from options expiring on 3rd June. We also observe an upward trend in RNV during the last three weeks before the referendum, which reaches a peak of 30.8% p.a. on 22nd June. In contrast, RNV is substantially

[18] In all cases of visually bimodal RNDs, the Hartigan and Hartigan (1985) test formally rejects the null hypothesis of unimodality.

reduced immediately after the referendum; the resolution of uncertainty surrounding this political event halves the RNV to 15.9% p.a. on 29th June. Panel B of Figure 6 illustrates the corresponding effects on FTSE100 RNV. Whereas the RNV computed from options expiring after the referendum is overall higher than the RNV from options expiring before the referendum, the effect is much less pronounced in this case.

Figure 7 presents the corresponding time-variation in Risk-Neutral Skewness (RNS). Panel A shows that the GBPUSD RNS computed from options expiring after the referendum is substantially more negative than the RNS for options expiring before the referendum. This difference arises due to the political event risk that is manifested as a fat left tail or, even more clearly, as a second left mode in the RND (see Panel A of Figures 1 and 3). RNS remains consistently negative in the run up to the referendum but sharply increases towards zero in the aftermath of this event, as the RND reverts to its standard, relatively symmetric shape for currency options (see Panel A of Figure 3).

-Figure 7 here-

To the contrary, Panel B of Figure 7 shows that the FTSE100 RNS is not substantially different when comparing options expiring before and after the referendum. RNS takes substantially negative values throughout the period and across expiries, as it is common for equity index options, reflecting the RND shape in Panel B of Figure 1 and the IV smirk in Panels C and D of Figure 2. Moreover, we observe no notable upward trend in RNS right after the referendum.

We have identified bimodality in the GBPUSD RND as the primary manifestation of political event risk. To examine further this feature, we compute the following Bimodality Coefficient (BC) combining the skewness and kurtosis of a given RND:[19]

$$BC = \frac{Skewness^2 + 1}{Kurtosis}. \tag{16}$$

[19]The value of this coefficient can be compared with the benchmark value of 0.555, which is the BC value of a uniform distribution. Higher values indicate bimodality, whereas lower values indicate unimodality. Nevertheless, it should be noted that high BC values can also result from heavily skewed unimodal distributions.

Panel A of Figure 8 presents the evolution of BC for GBPUSD RNDs. First, we find that the BC for RNDs from options whose expiry spans the referendum date is substantially higher than the one from options expiring before the referendum. Second, we observe an upward trend in the last week before the referendum. Third, BC values exhibit a sharp drop immediately after the referendum.

-Figure 8 here-

Panel B of Figure 8 presents the corresponding BC values for FTSE100 RNDs. The relatively high BC values reported here are due to the negative skewness featured by the unimodal FTSE100 RNDs (see Panel B of Figures 1 and 3). Interestingly, the BC values for RNDs extracted from options expiring on 15th July or 19th August are not substantially higher than the ones for options expiring before the referendum. We also observe an increase in BC in the days just before the referendum, reflecting the decrease in RNS that is observed in the corresponding RND (see Panel B of Figure 7). However, we find no dramatic decrease in BC in the aftermath of the referendum, as FTSE100 RNDs remain negatively skewed (see Panel B of Figure 3).

4 Price Discovery in the Option Market

Having documented the effects of political event risk on GBPUSD options in the previous Section, we examine here their manifestation during the announcement of the referendum results. This referendum provides a unique setup to capture these effects, offering a validation test for the option market expectations. This is because a complete reversal of the anticipated referendum outcome occurred during the vote counting process. In particular, an almost certain Remain victory right after the polls closed at 22:00 British Summer Time (BST) gave way to a Leave victory in the early hours of the following day.[20] Hence, this referendum provides a rare opportunity to observe the counterfactual using information from high frequency option prices. Table 3 outlines the key political events during the night of 23rd and the early morning of 24th June 2016.

[20] All subsequent times are expressed in British Summer Time.

-Table 3 here-

Figure 9 provides an overview of GBPUSD RNDs during the referendum night. First, it presents the RND extracted from CME options at 20:00 (settlement) on 23rd June. As mentioned above, this RND is bimodal, reflecting the effect of each of the two referendum outcomes. Second, Figure 9 illustrates the RND extracted from OTC options at 23:00. By that time, on the basis of opinion polls, it is widely anticipated that the Remain side has won, with leading figures of the Leave campaign conceding their defeat. As a result, the GBPUSD RND is clearly unimodal with a large concentration of probability mass around the mode at \$1.53. The RND is still negatively skewed, but the probability mass below \$1.35 is very low. Third, this Figure also illustrates the RND extracted at 05:30 on 24th June, when the final result is announced with a clear victory for the Leave side. The GBPUSD RND takes a strikingly different shape. The mode of the RND shifts to \$1.38, a reduction of 15¢ relative to the mode of the corresponding RND at 23:00. Moreover, the RND is now much more disperse, leptokurtic, and strongly negatively skewed with a substantial probability mass below \$1.33.

-Figure 9 here-

The availability of high frequency OTC option data allows us to examine more closely how GBPUSD RNDs respond to the announcement of the key results outlined in Table 3. In particular, Figure 10 presents twelve RNDs at different stages of the referendum night. Specifically, Panel A illustrates how the bimodal RND extracted from CME options at 20:00 (settlement) turns into a negatively skewed but unimodal RND by 22:30, when leading figures of the Leave side, including MEP Farage, concede defeat on the basis of private polls as well as the YouGov poll conducted on the same day.

-Figure 10 here-

Panel B shows the dramatic shifts in the RND as a response to unanticipated actual voting results. The surprisingly tight result from Newcastle at 23:59, an area expected to be won by the Remain side with a wide margin, causes a substantial shift of the RND to the left. In particular, the unimodal RND at 23:30, exhibiting a large concentration of probability mass around the mode at \$1.53, shifts to the left at 00:10, with a mode at \$1.47. By 01:00, a number of further results are announced and early indications of results from other areas are communicated by the media. On the one hand, the result from Sunderland confirms a clear pattern that Leave would perform very strongly in North England, whereas on the other hand, there are indications that Remain would gain a very large share of votes in London. As a result, even though the RND exhibits a mode at \$1.50 at 01:00, it becomes very disperse, reflecting the fact that the referendum result is a coin toss.

Panel C presents the corresponding RNDs at 02:00, 03:30, and 04:00, respectively, when actual results from across the country gradually indicate that Leave will most likely win, and that the outperformance of Remain in London is not sufficient to offset the outperformance of Leave in other places. In fact, Panel C illustrates a gradual shift of the RNDs to the left. All RNDs are clearly unimodal and negatively skewed, with the mode shifting from \$1.47 at 02:00 to \$1.44 at 03:30, and \$1.41 at 04:00. This gradual shift reveals how the option market updates its beliefs regarding the referendum outcome.

Panel D illustrates the GBPUSD RND at 04:40, when it becomes certain that the Leave side will be victorious. The RND is clearly unimodal but quite disperse, with the mode shifted to \$1.39. To sum up, the mode of the RND shifts from \$1.53 at 23:30 (see Panel B) to \$1.39 at 04:40, i.e., a reduction of 14¢ in 5 hours, as the anticipation of a Remain victory gives way to the certainty of a Leave victory. The RND becomes less disperse at 05:30, and its mode is at \$1.38. Last but not least, it is interesting to observe that the option market continues reacting to events even after the announcement of the referendum result. Whereas PM Cameron announces at 08:22 that he will reisgn, the Bank of England Governor makes a public statement right after, to reassure the market that the central bank is ready to provide liquidity and take further policy actions to support the economy. Responding to this announcement, the RND extracted at 08:50 shifts to the right and becomes more symmetric, with its mode at \$1.42.

An alternative way to show how the option market responds to the events unfolding during the referendum night is to show the evolution of the GBPUSD futures price and RNV together with the probability of Leave victory implied from betting odds. Panel A of Figure 11 presents the evolution of the futures price (left axis) together with the odds-implied probability of Leave victory (right axis) from 22:00 on 23rd June until 05:50 on 24th June. The overall picture in Panel A is consistent with the sequence of events outlined in Table 3. When voting ends at 22:00, the probability of Leave victory is near 10%, whereas the GBPUSD futures is traded at around \$1.50. This near certainty of a Remain victory is questioned at midnight, leading to a sharp increase in the probability of Leave victory to more than 30% and a sharp drop in the futures price to \$1.45.

-Figure 11 here-

As the results come in favourably for Leave, the probability of its victory exceeds 50% at 02:00 for the first time and the futures contract trades at \$1.42. There is a temporary reversal of the upward trend for the probability of Leave victory around 02:30, when Remain gains a bigger than anticipated vote share in a London borough (Wandsworth). However, as it gradually becomes clear that the outperformance of Remain in London is not sufficient to offset the outperformance of Leave in other places, the probability of Leave victory continues its upward trend, with the latter becoming a certainty at around 04:40, when BBC calls the referendum for Leave. At the same time, the GBPUSD futures price continues its downward trend, trading at a low of \$1.33 at 05:20.

This sequence of events provides us the rare opportunity to observe the counterfactual and identify the impact of each of the referendum outcomes on GBPUSD futures. Specifically, we observe a sharp drop of 17¢, from \$1.50 at 22:40 to \$1.33 at 05:20. Hence, Panel A of Figure 11 provides ex post validation of the two modes appearing in the bimodal GBPUSD RNDs before the referendum (see Panels A & B of Figure 5), confirming the ability of the option market to ex ante identify the effects of political event risk.

Panel B of Figure 11 illustrates the evolution of GBPUSD RNV (left axis) together with the odds-implied probability of Leave victory (right axis). When Remain is almost certain to win at 22:00, RNV fluctuates around 15% p.a.. But as the probability of

Leave victory begins its upward trend, especially after midnight, RNV follows in tandem. Specifically, when the probability of Leave victory stands at 63% at 02:10, RNV is equal to 23.5%. It actually reaches a peak of 32.5% p.a. at 04:10, when the probability of Leave victory exceeds 90% and a sharp drop in the futures price takes place. Interestingly, we also observe a de-escalation of RNV towards 25% p.a., once the uncertainty regarding the referendum outcome is resolved after 05:00 and the futures price is stabilised.

The evolution of RNV during the referendum night is consistent with the corresponding shapes and dispersion of the RNDs illustrated in Figure 10. Moreover, we can clearly identify two distinct states in RNV; a low state around 15% p.a. associated with a Remain victory and a high state around 25% p.a. associated with a Leave victory. In sum, high frequency option prices allow us to identify the effect of this political event not only with respect to the GBPUSD futures price but also with respect to its volatility.

5 Option-Implied Event Probability, State Price and Volatility

The analysis in Section 4 demonstrates that each of the referendum outcomes can be associated with a distinct state of GBPUSD futures price and volatility. Motivated by this evidence, in this Section we follow the approach suggested by Borochin and Golec (2016), as described in Section 2.2.2, to ex ante identify the option-implied GBPUSD futures price and volatility that would prevail in the case of a Remain or a Leave outcome, respectively. This approach also allows us to extract the corresponding option-implied probabilities with respect to the referendum outcome.

Figure 12 presents the option-implied probability, p_e, of Leave victory from 9th May until 23rd June, computed on a daily basis using CME options on GBPUSD futures. We also plot the time series of the corresponding probability implied by betting odds from Betfair. Overall, we observe that the two time series move in a similar direction in the run up to the referendum. In particular, we observe an upward trend in both the option-implied and the betting odds-implied probability of a Leave outcome during the week prior to the murder of the pro-Remain MP Jo Cox on 16th June. In the aftermath of this event, with official campaigning from both sides suspended, there is a sharp drop in both probabilities.

-Figure 12 here-

Furthermore, the option-implied probability series is quite volatile, showing that the outcome of this political event was very uncertain and that the option market continuously updated its beliefs as the events unfolded. Most interestingly, the option-implied probability of Leave victory exceeds 50% on 15th and 16th June. Hence, despite the widespread belief among media and political circles that Remain would win, the option market indicates Leave victory as the most likely outcome one week before the referendum; the peak of the betting-odds probability series is 41.2% on 14th June. Even in the aftermath of the murder of MP Cox, the option-implied probability of a Leave outcome remains high and it is equal to 27.2% on the day of the referendum. To the contrary, the corresponding probability implied by Betfair odds is only 10.6%. In sum, this analysis shows that the option market is not only able to detect political event risk, but it can also quantify the probability of the event's outcome in an informative manner.[21]

Figure 13 illustrates the option-implied GBPUSD futures price (Panel A) and volatility (Panel B) estimates associated with each of the two referendum outcomes. These are again extracted on a daily basis from CME options from 9th May until 23rd June. In Panel A, we observe that the GBPUSD futures price associated with a Remain outcome, F_n, fluctuates around \$1.50 throughout the examined period, with \$1.52 prevailing at settlement on the referendum day.[22] This range of values is consistent with the right mode of the ex ante GBPUSD RNDs illustrated in Figures 3 and 5. The futures price

[21] We have also examined whether there is a lead-lag relationship between the betting and the option market during the sample period analyzed in this Section. To this end, we conduct a Granger-causality analysis. Specifically, we estimate a bivariate VAR model consisted of the betting-odds implied probability of a Leave outcome and the corresponding option-implied probability. The VAR lag length is selected on the basis of the Akaike Information Criterion. We find evidence of bi-directional Granger-causality. In particular, we can reject at the 5% level the null hypothesis that the betting-odds implied probability does not Granger-cause the option-implied probability. We can also reject at the 5% level the null hypothesis that the option-implied probability does not Granger-cause the betting-odds implied probability. We thank an anonymous referee for suggesting this analysis.

[22] The standard deviation of the option-implied futures prices associated with a Remain outcome during the examined period is 1.3¢.

associated with a Leave outcome, $F_n - V_e$, fluctuates in the range \$1.31-\$1.39, which is again consistent with the left mode of the corresponding RNDs before the referendum as well as the prevailing RND once the Leave victory becomes certainty (see Panel D of Figure 10).[23]

-Figure 13 here-

This analysis also allows us to ex ante quantify the full price effect, V_e, of a Leave outcome relative to Remain. This is given by the difference between the two latent futures prices. In particular, we find that this wedge takes values between 12¢-18¢ during the examined period, and it is equal to 13.4¢ at settlement on 23rd June. Again, these estimates are very similar to the difference between the values of the two modes of the GBPUSD RNDs in the run up to the referendum. Interestingly, the high frequency analysis presented in Section 4 confirms these estimates.

Panel A of Figure 13 also illustrates the actual futures price, F_0, during the examined period. In line with equation (12), F_0 fluctuates between the latent prices associated with each of the two referendum outcomes according to the corresponding option-implied probabilities. In particular, as the probability p_e of a Leave outcome increases during the week before the assassination of MP Cox, the futures trades consistently below \$1.45, with F_0 equal to \$1.42 on 15th June. To the contrary, the sharp reduction in p_e right after the assassination is associated with a large increase in F_0, which reaches \$1.48 on the referendum day.

Panel B of Figure 13 shows the evolution of the option-implied volatility estimates for each of the two referendum outcomes. For comparison, it also plots the annualized realized volatility of GBPUSD futures, estimated on a daily basis from intraday 1-min log returns.[24] A Remain outcome is characterised by a low level of volatility, fluctuating

[23] The standard deviation of the option-implied futures prices associated with a Leave outcome during this period is 2.4¢.

[24] We use the futures contract expiring in September because according to the CME rulebook, this is the nearest quarterly futures contract that serves as the underlying for GBPUSD options that expire on 8th July. We compute these intraday returns using mid-quotes from the corresponding CME GBPUSD futures BBO data.

between 10-15% p.a. during the last two weeks before the referendum.[25] To the contrary, the volatility estimate associated with a Leave outcome is much higher and volatile itself. In fact, it fluctuates in the region of 25-35% p.a., reaching a peak of 36% p.a. on 22nd & 23rd June.[26] Interestingly, these ex ante estimates of volatility for each of the two outcomes are validated by the high frequency analysis presented in Section 4. Hence, we conclude that the option market can identify remarkably well not only the value but also the volatility of the underlying asset associated with each of the two potential outcomes of this political event.

6 Further Results

6.1 Risk-adjusted Distributions

Throughout the study, we extract risk-neutral distributions and probabilities from option prices without performing any risk-adjustment. Arguably, the existence of a risk premium could potentially affect the interpretation of our results. Whereas it is obvious that a risk-adjustment would be necessary to compute the physical density for FTSE100, which is an equity index and is expected to carry a risk premium, it is not clear to what extent this adjustment is appropriate for GBPUSD. Hanke et al. (2018, p. 2678) provide an insightful discussion on whether GBPUSD carries a premium or not. In sum, they argue that as long as the interest rate differential is close to zero, which holds true for GBPUSD during the examined period, then the exchange rate would be almost drift-free under the real-world probability measure and the risk premium would be near zero.

Nevertheless, an important question for our analysis is whether the shape of the RNDs for GBPUSD futures and FTSE100 Index would be substantially modified if we used a risk-adjusted distribution. Most characteristically, it is natural to ask whether the bimodality we uncover in the GBPUSD RND prior to the referendum reflects bimodality in the physical density or this is an artefact of risk-neutrality.

[25] The standard deviation of the option-implied volatility associated with a Remain outcome during the examined period is 1.8% p.a.

[26] The standard deviation of the volatility associated with a Leave outcome during the examined period is 5.2% p.a.

To address these potential concerns, we perform a risk-adjustment to convert the GBPUSD and FTSE100 RNDs into physical ones. To this end, we follow the standard approach of Bliss and Panigirtzoglou (2004), as recently implemented in Jackwerth and Menner (2020). Specifically, we assume a power utility function for the representative agent and we compute physical probabilities, $p(S_T)$, using the relationship:

$$p(S_T) = \frac{\frac{q(S_T)}{U'(S_T)}}{\int \frac{q(x)}{U'(x)} dx}, \tag{17}$$

where $U'(S_T) = S_T^{-\gamma}$ denotes the marginal utility function with degree of relative risk aversion γ, S_T is the underlying asset price at expiry T, and $q(S_T)$ is the risk-neutral probability.

To examine how the shape of the physical density would change for different levels of risk aversion, we perform this risk-adjustment using different values of γ. Figure SA.3 in the Supplementary Appendix illustrates the corresponding physical densities computed on 23rd June 2016, together with the RND for GBPUSD futures (Panel A) and the FTSE100 Index (Panel B), respectively.

Given the discussion in Hanke et al. (2018), we illustrate the physical density for GBPUSD futures using a low ($\gamma = 1$) as well as a moderate ($\gamma = 3$) degree of risk aversion. We find that this risk-adjustment has only a minor effect on the shape of the physical density. Most importantly, we find that the physical density remains bimodal with its modes located very close to the corresponding modes of the RND. To this end, we argue that our main conclusions regarding the detection and quantification of political event risk are not affected by the fact that we rely on RNDs.

For FTSE100, we illustrate the physical density using risk aversion coefficients ($\gamma = 2$ and $\gamma = 4$) that are similar in magnitude to the ones employed for equity indices in prior studies (see Bliss and Panigirtzoglou, 2004; Jackwerth and Menner, 2020). Again, we find that the shape of the physical density is very similar to the risk-neutral one. The physical density is clearly unimodal and strongly negatively skewed, and hence the conclusions derived in our main analysis from the corresponding RND remain intact.

6.2 Alternative Measures of Tail Risk

Our main analysis examines the effect of the Brexit referendum on the shape of RNDs and the evolution of the corresponding risk-neutral moments. To a large extent, these characteristics reflect the price of protection in the option market against a possible sharp drop in the underlying asset values due to this political event. Following the suggestion of an anonymous referee, we examine here alternative measures of tail risk.

First, we estimate the *Slope* of the IV curve, in the spirit of Kelly et al. (2016). Specifically, on each trading day, we regress the implied volatilities of OTM puts on their deltas, including an intercept. We only include delta values that lie in the range of (-0.5, -0.1). The corresponding slope coefficient estimate yields the *Slope* measure on a given trading day for the corresponding option expiry date. Figure SA.4 in the Supplementary Appendix illustrates the evolution of the *Slope* measure for GBPUSD (Panel A) and the FTSE100 Index (Panel B), respectively.

Second, in the spirit of Xing et al. (2010), we compute the $SKEW$ of the IV curve as another measure that captures the expensiveness of OTM puts. $SKEW$ is defined as the difference between the annualized implied volatilities of a deep OTM put and an ATM call. For the deep OTM put, we choose the put with delta closest to -0.25. For the ATM call, we select the call with delta closest to 0.5. Figure SA.5 in the Supplementary Appendix presents the evolution of the $SKEW$ measure for GBPUSD (Panel A) and the FTSE100 Index (Panel B), respectively.

Both of these measures reveal patterns that are similar to the evolution of RNS, as illustrated in Figure 7. For GBPUSD, we observe that on a given trading day, *Slope* and $SKEW$ are substantially higher when computed from options expiring after rather than before the referendum. In addition, the values of these measures remain consistently high in the run up to the referendum but sharply decrease towards zero right after this event. On the other hand, the corresponding effects for FTSE100 are less pronounced when comparing options expiring before and after the referendum. Whereas we observe a spike in *Slope* and $SKEW$ just before the referendum date, there is no clear downward trend in the aftermath of this event.

6.3 Risk-Neutral Distribution for EuroStoxx50

Arguably, this political event could also affect the Eurozone economy since Brexit could undermine the integrity of the European Union and its single market. Hence, it is interesting to examine whether this event risk was priced in the options of a major European stock index. To this end, we extract RNDs from options on EuroStoxx50 Index, which is consisted of European stocks with the largest capitalisation. These are European-style options and we source the relevant price data from Refinitiv DataScope. Figure SA.6 in the Supplementary Appendix illustrates the RNDs extracted on 23rd and 24th June, respectively, from options expiring on 15th July 2016.

We observe that the RND of EuroStoxx50 extracted on 23rd June is clearly unimodal. The main manifestation of event risk is a strongly negatively skewed RND, similar to the effect observed for FTSE100 prior to the referendum (see Panel B of Figure 3). This effect disappears in the aftermath of the referendum, as the RND reverts back to its standard shape of a slightly negatively skewed distribution. Interestingly, whereas the EuroStoxx50 Index experienced a substantial drop from 3,037 on 23rd June to 2,776 on 24th June, it fully recovered its losses by the option expiry date, closing at 2,958 on 15th July. Hence, similar to FTSE100, this provides an ex post confirmation that the referendum did not pose a substantial event risk for EuroStoxx50.

7 Conclusions

There is a growing interest in understanding the information signalled by financial markets with respect to polarised political events. Among other consequences, the outcome of such events can lead to sharp movements in asset prices and volatility, with adverse implications for financial stability and social welfare. However, the opposite sides of the campaign usually make contradictory predictions regarding these effects, causing confusion among voters before the event and regret afterwards. Hence, a main challenge is to measure the potential impact of these outcomes *before* the event takes place, so that voters can make an informed political decision.

This study examines the UK referendum on EU membership in June, 2016. We show that the option market can ex ante detect and quantify the event risk arising due to this referendum. Most characteristically, the RNDs extracted from GBPUSD futures options, whose expiry spanned the referendum date, became bimodal. In the run up to the referendum, the left mode of these RNDs lied between \$1.31-\$1.35, revealing that the option market anticipated a large drop in the exchange rate in the event of a Leave outcome. In contrast, the right mode of these RNDs lied in the region of \$1.50-1.53. Hence, one could infer from the option market that the full effect of a Leave victory on GBPUSD was approximately 15¢-19¢.

This referendum also provides a strong validation test for option market expectations, because the large swings in outcome probabilities during the vote counting process offer us the rare opportunity to observe the counterfactual. Using high frequency option and futures prices during the referendum night, we confirm the ability of the option market to ex ante identify the effects of each outcome.

We also extract option-implied event probabilities. Despite the widespread belief that the Remain side would win, we find that the option market indicated Leave victory as the most likely outcome prior to the murder of MP Cox, one week before the referendum. Therefore, we show that option prices allow us to extract meaningful event probabilities, providing a good alternative to betting odds-implied probabilities.

Last but not least, we show that the option market not only can detect political event risk when there is, but it can also indicate the absence of such risk when there is not. In particular, we show that the effects on the corresponding RNDs and IV curves computed from FTSE100 options are very limited. The RNDs remain clearly unimodal, featuring only a moderate increase in negative skewness. Interestingly, whereas the Leave victory led to a sharp and permanent drop in GBPUSD, the effect on FTSE100 was much less pronounced on the first post-event trading day and it was subsequently reversed, with the index trading by the end of June higher than its pre-referendum close. Hence, we conclude that the option market can distinguish the potentially differential effects of the same political event across different assets.

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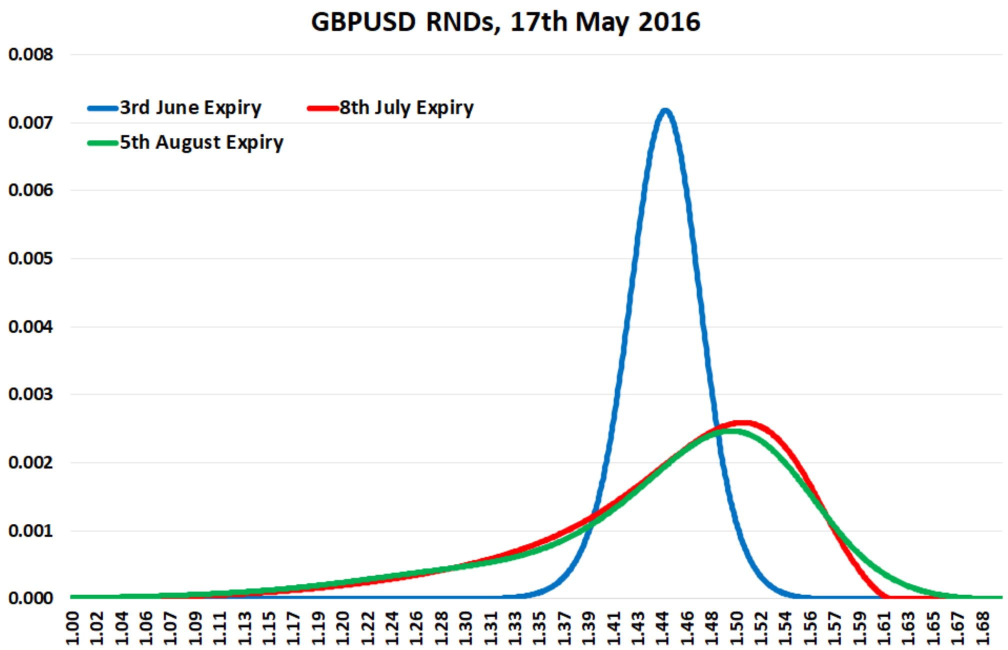
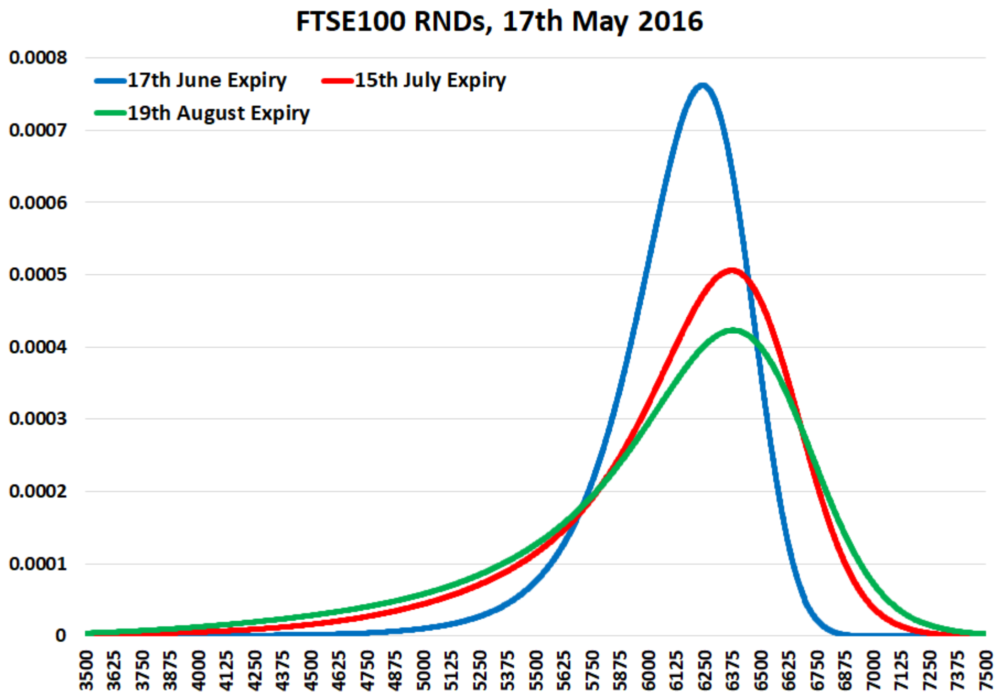
Figure 1

This Figure shows Risk-Neutral Distributions (RNDs) extracted on 17th May 2016 from options with expiry spanning as well as options with expiry not spanning the Brexit Referendum date (23rd June, 2016). In Panel A, RNDs are extracted from options on GBPUSD futures with expiries on 3rd June (blue), 8th July (red), and 5th August 2016 (green). In Panel B, RNDs are extracted from options on FTSE100 Index with expiries on 17th June (blue), 15th July (red), and 19th August 2016 (green).



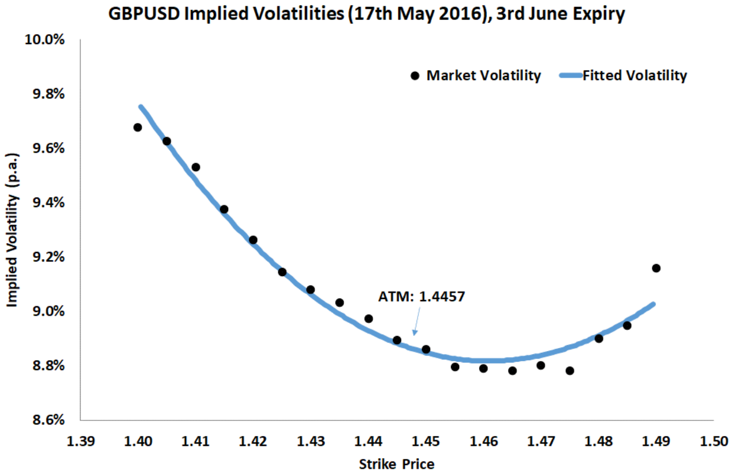
Panel A



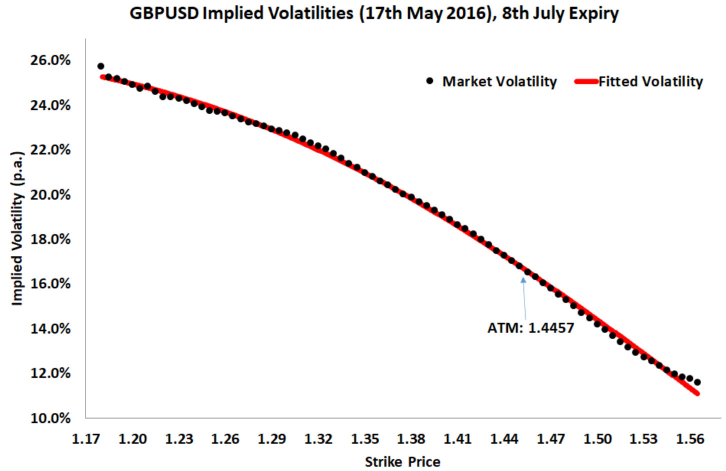
Panel B

Figure 2

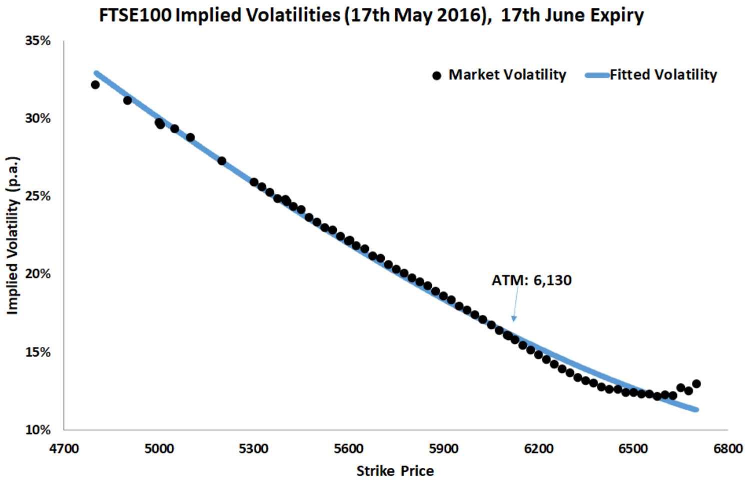
This Figure shows Implied Volatility (IV) curves extracted on 17th May 2016 from options with expiry spanning as well as options with expiry not spanning the Brexit Referendum date (23rd June, 2016). Panels A and B show the IV curves extracted from options on GBPUSD futures with expiry on 3rd June (Panel A) and 8th July 2016 (Panel B). Panels C and D show the IV curves extracted from options on FTSE100 Index with expiry on 17th June (Panel A) and 15th July 2016 (Panel B). In all Panels, black dots represent the IVs (p.a.) computed from observable option prices, whereas the coloured curves depict the fitted implied volatilities according to the spline methodology presented in Section 2.2. The corresponding at-the-money (ATM) point is indicated in all Panels.



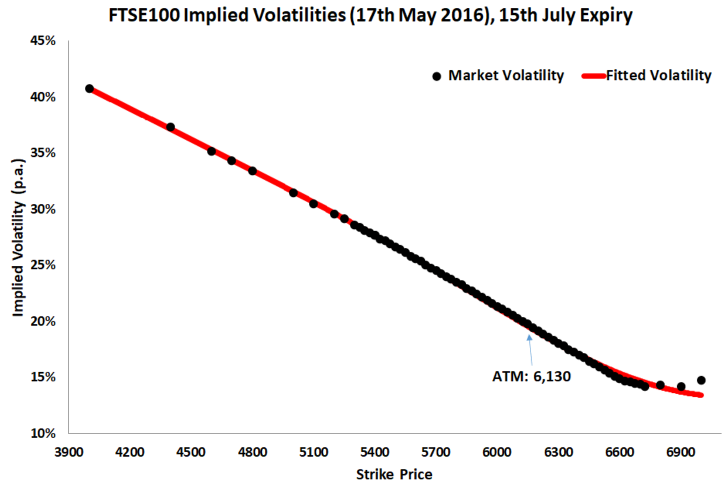
Panel A



Panel B



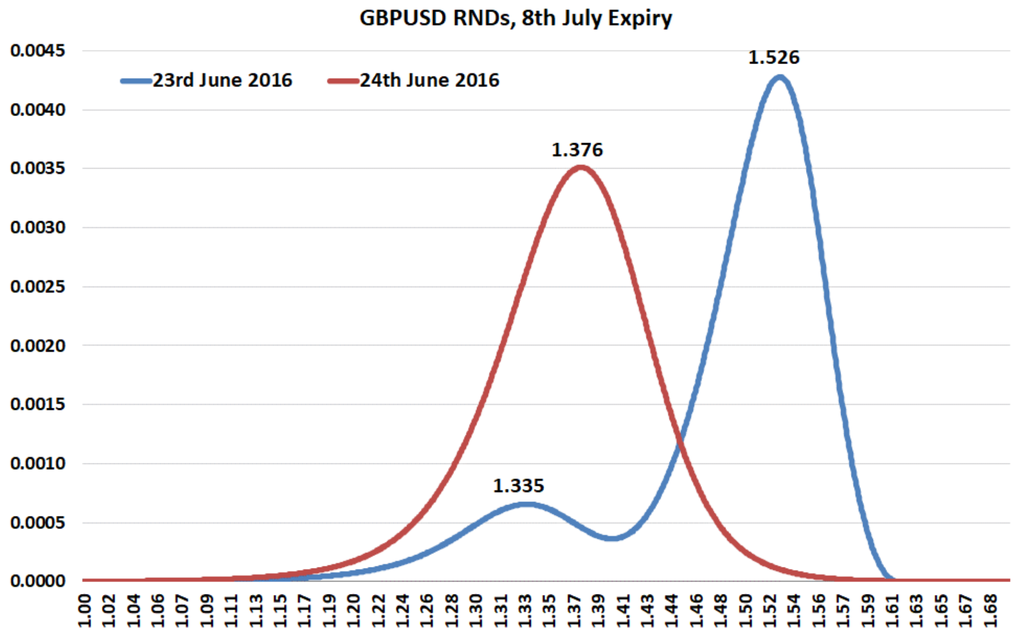
Panel C



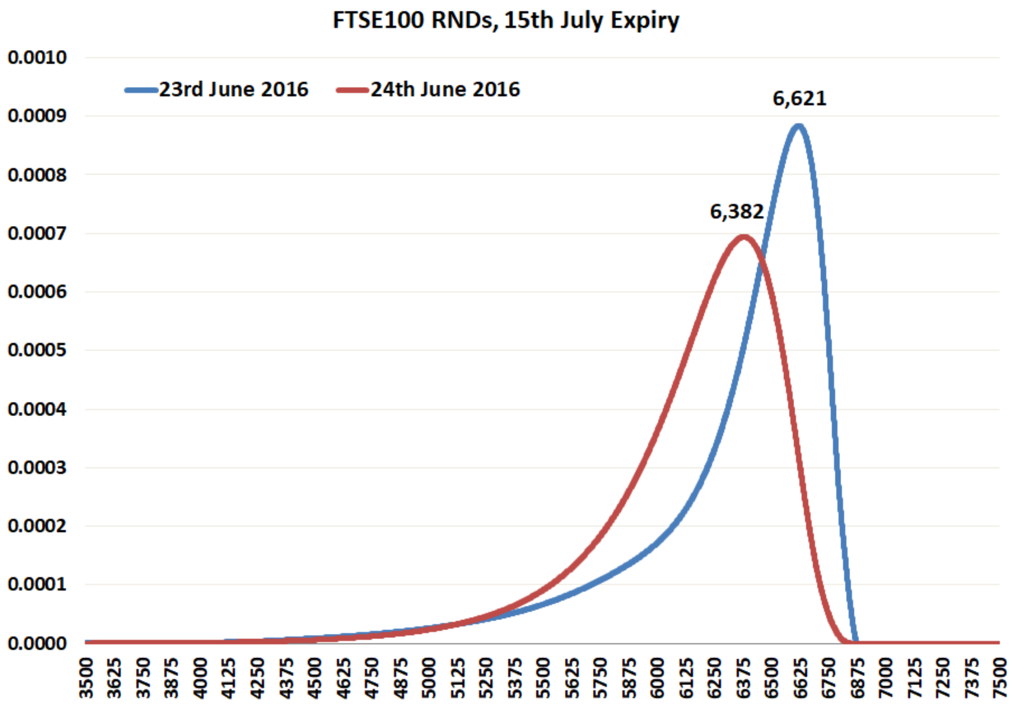
Panel D

Figure 3

This Figure shows Risk-Neutral Distributions (RNDs) extracted around the Brexit Referendum date (23rd June, 2016) from options with same expiry. In Panel A, RNDs are extracted on 23rd June (blue) and 24th June 2016 (red) from options on GBPUSD futures with expiry on 8th July 2016. In Panel B, RNDs are extracted on 23rd June (blue) and 24th June 2016 (red) from options on FTSE100 Index with expiry on 15th July 2016. In both Panels, the mode(s) of the RNDs are indicated.



Panel A



Panel B

Figure 4

This Figure shows Implied Volatility (IV) curves extracted around the Brexit Referendum date (23rd June, 2016) from options with same expiry. Panels A and B show the IV curves extracted on 23rd June (Panel A) and 24th June 2016 (Panel B) from options on GBPUSD futures with expiry on 8th July 2016. Panels C and D show the IV curves extracted on 23rd June (Panel C) and 24th June 2016 (Panel D) from options on FTSE100 Index with expiry on 15th July 2016. In all Panels, black dots represent the IVs (p.a.) computed from observable option prices, whereas the coloured curves depict the fitted implied volatilities according to the spline methodology presented in Section 2.2.

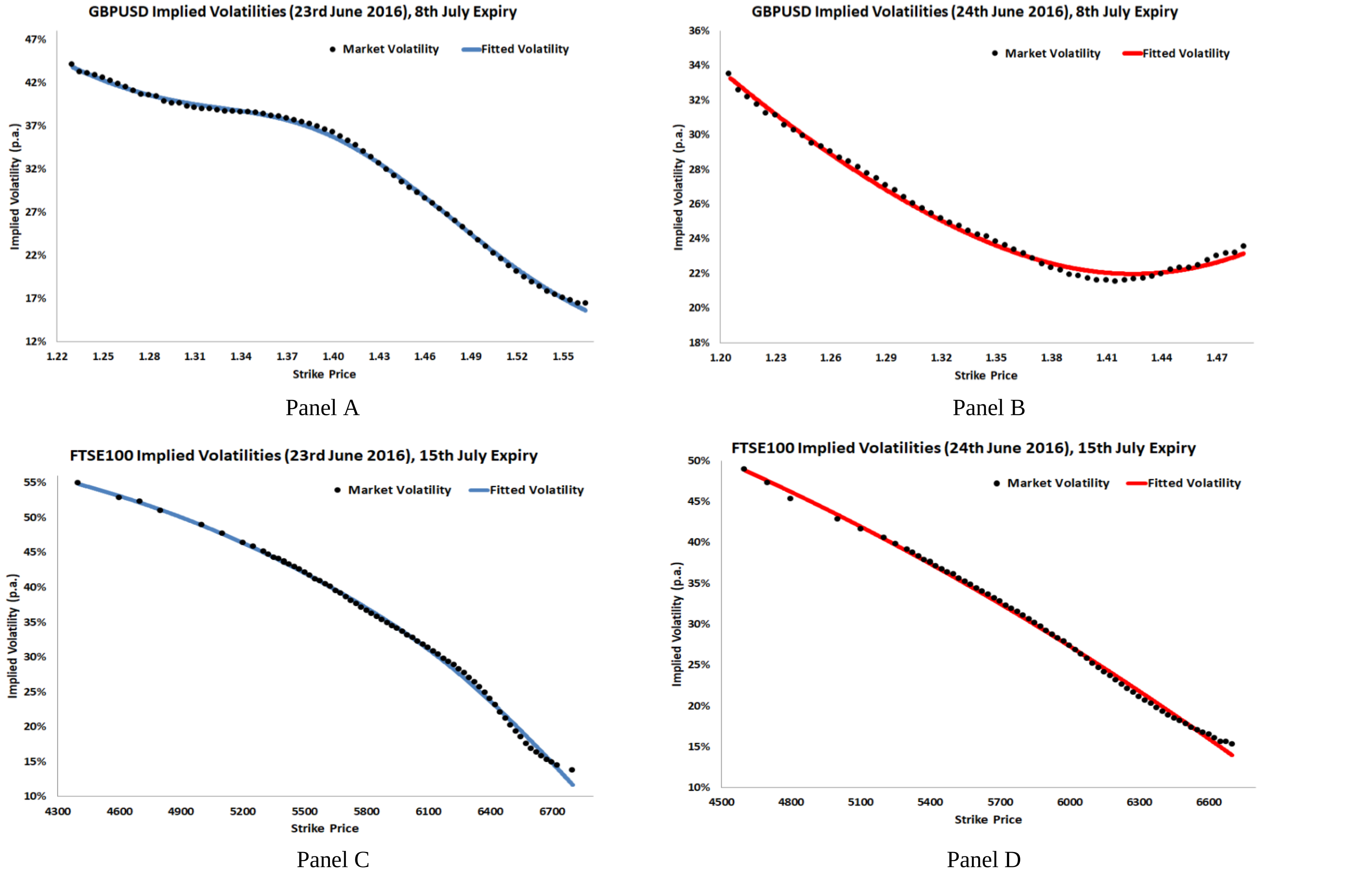
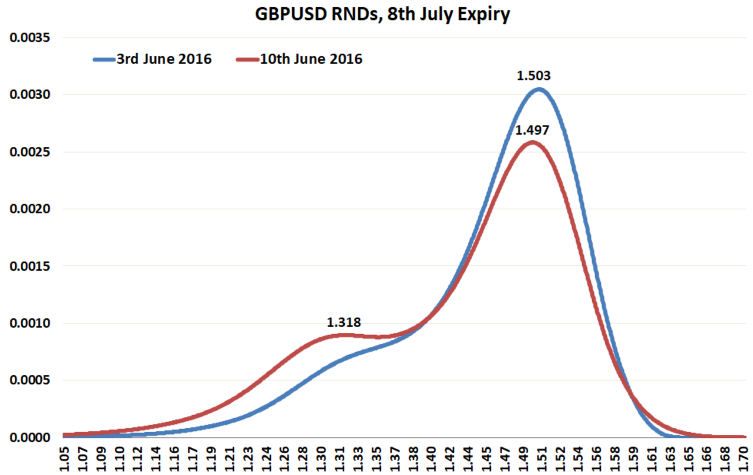
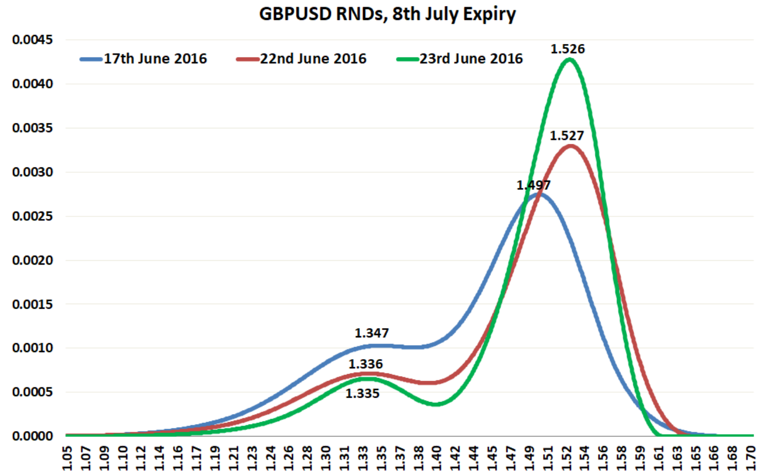


Figure 5

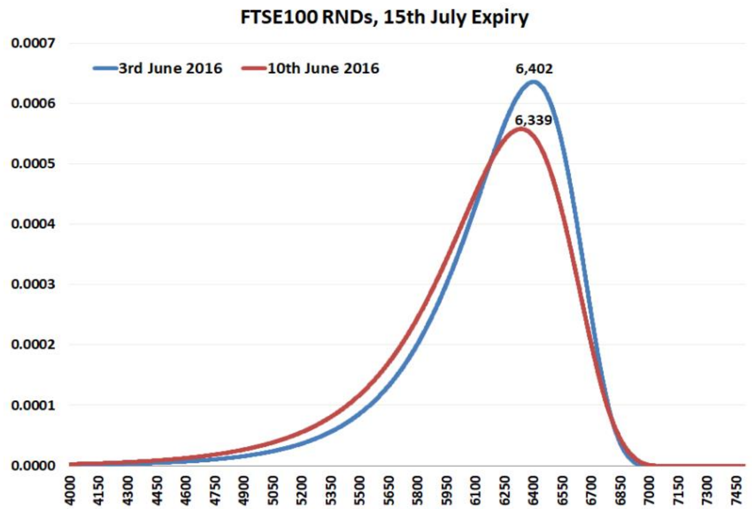
This Figure shows Risk-Neutral Distributions (RNDs) extracted on days in the run up to the Brexit Referendum date (23rd June, 2016). In Panels A and B, RNDs are extracted from options on GBPUSD futures with expiry on 8th July 2016. Specifically, Panel A shows RNDs extracted on 3rd June (blue) and 10th June 2016 (red), Panel B shows RNDs extracted on 17th June (blue), 22nd June (red), and 23rd June 2016 (green). In Panels C and D, RNDs are extracted from options on FTSE100 Index with expiry on 15th July 2016. Specifically, Panel C shows RNDs extracted on 3rd June (blue) and 10th June 2016 (red), whereas Panel D shows RNDs extracted on 17th June (blue), 22nd June (red), and 23rd June 2016 (green). In all Panels, the mode(s) of the RNDs are indicated.



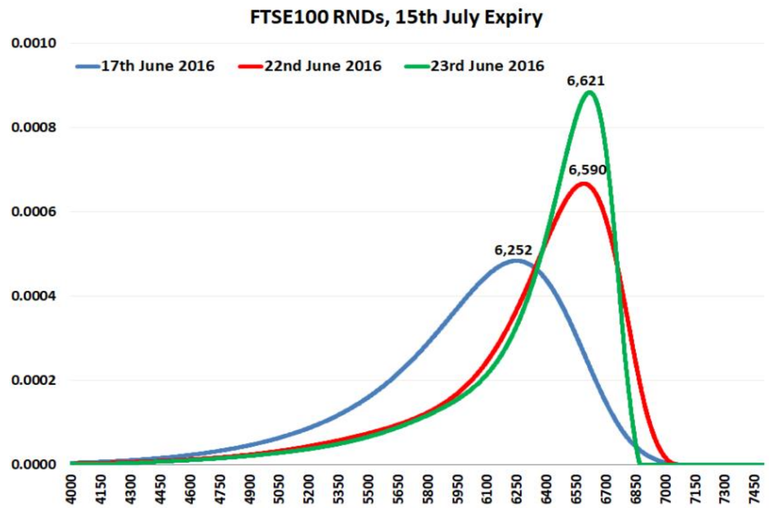
Panel A



Panel B



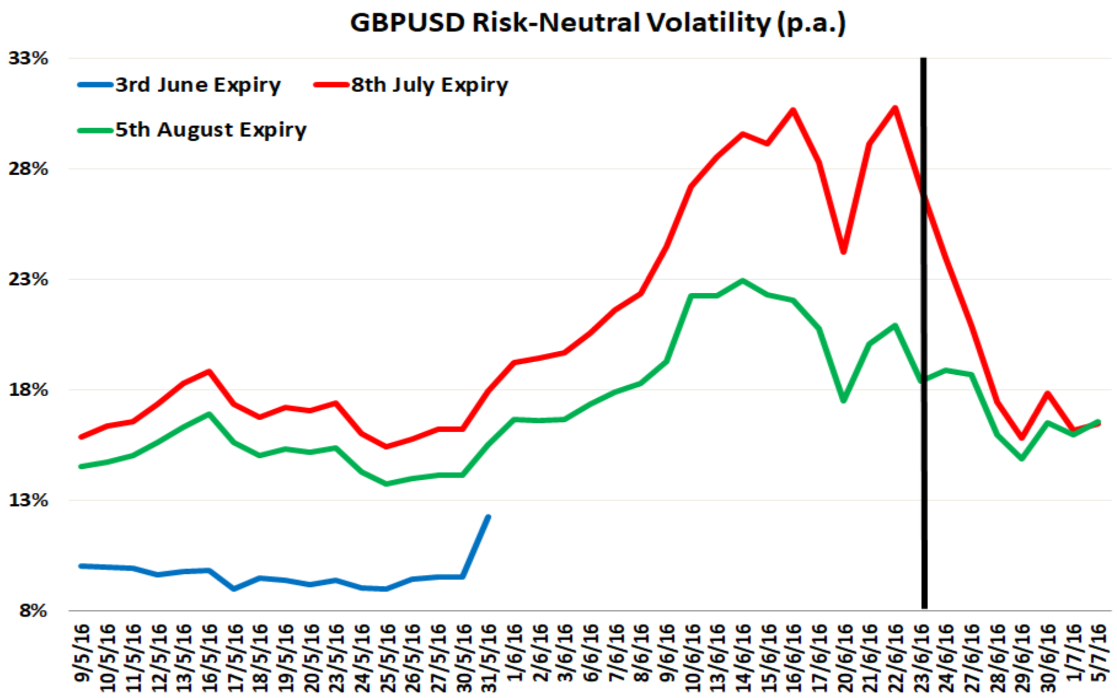
Panel C



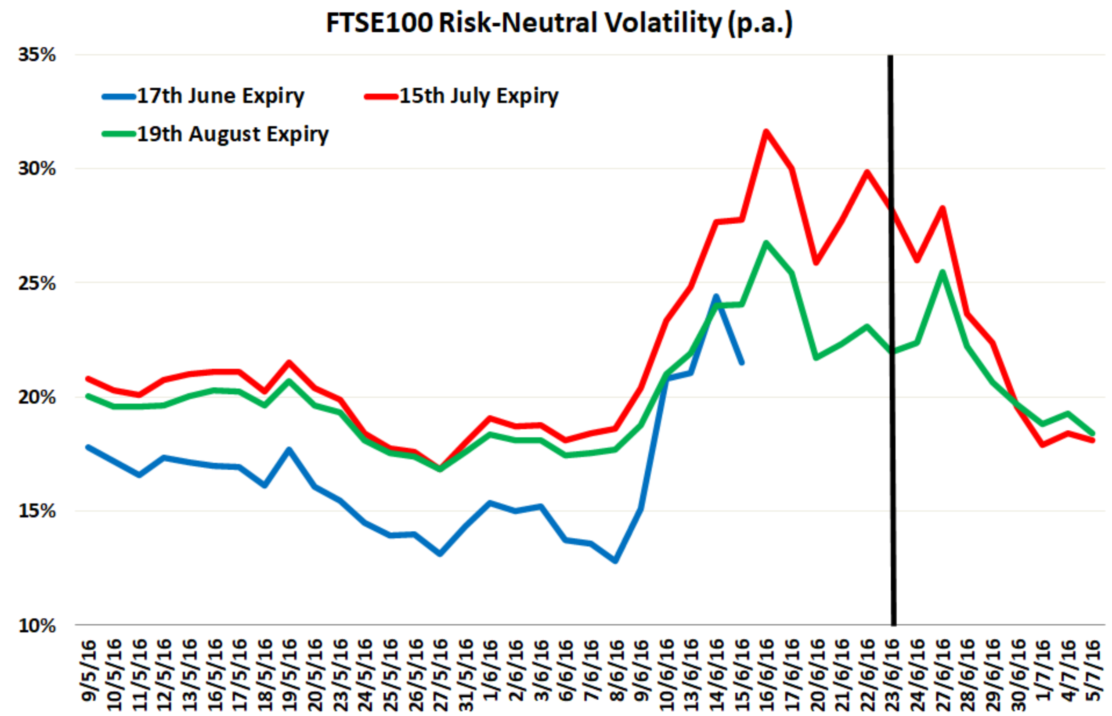
Panel D

Figure 6

This Figure shows the evolution of Risk-Neutral Volatility (RNV) (p.a.), which is computed from the corresponding Risk-Neutral Distribution, extracted from 9th May until 5th July 2016. Panel A shows RNVs extracted from options on GBPUSD futures with expiry on 3rd June (blue), 8th July (red), and 5th August 2016 (green). Panel B shows RNVs extracted from options on FTSE100 Index with expiry on 17th June (blue), 15th July (red), and 19th August 2016 (green). The vertical black line indicates the Brexit Referendum date (23rd June, 2016).



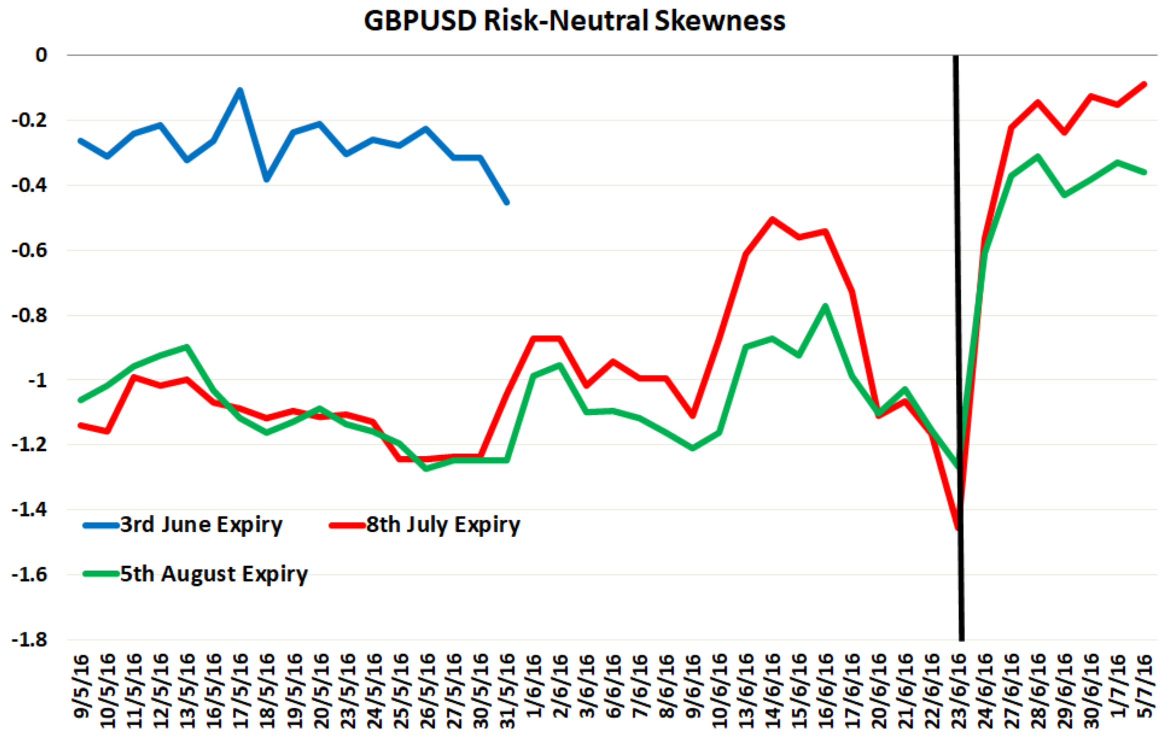
Panel A



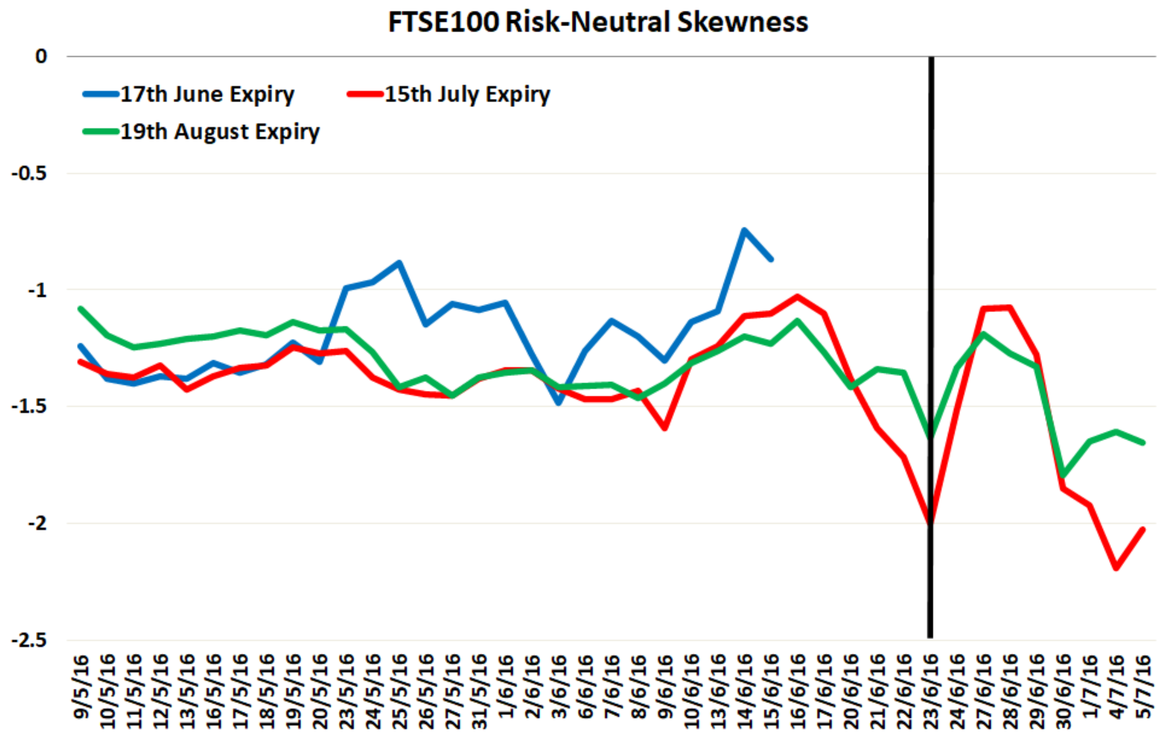
Panel B

Figure 7

This Figure shows the evolution of Risk-Neutral Skewness (RNS) (p.a.), which is computed from the corresponding Risk-Neutral Distribution, extracted from 9th May until 5th July 2016. Panel A shows RNSs extracted from options on GBPUSD futures with expiry on 3rd June (blue), 8th July (red), and 5th August 2016 (green). Panel B shows RNSs extracted from options on FTSE100 Index with expiry on 17th June (blue), 15th July (red), and 19th August 2016 (green). The vertical black line indicates the Brexit Referendum date (23rd June, 2016).



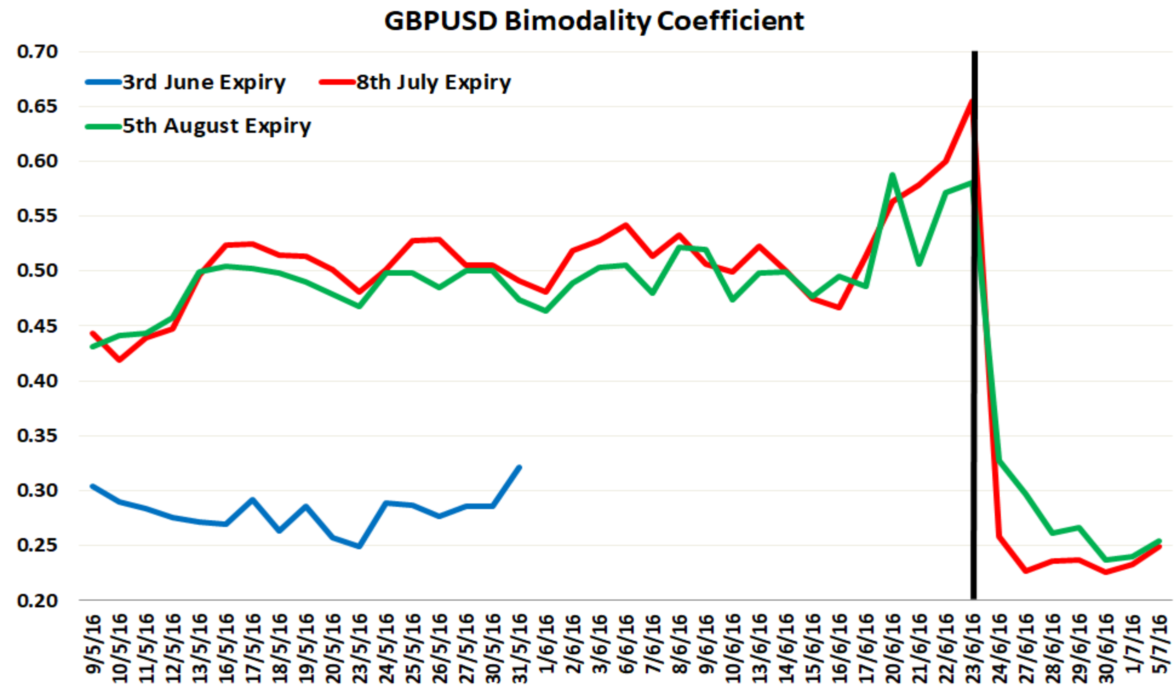
Panel A



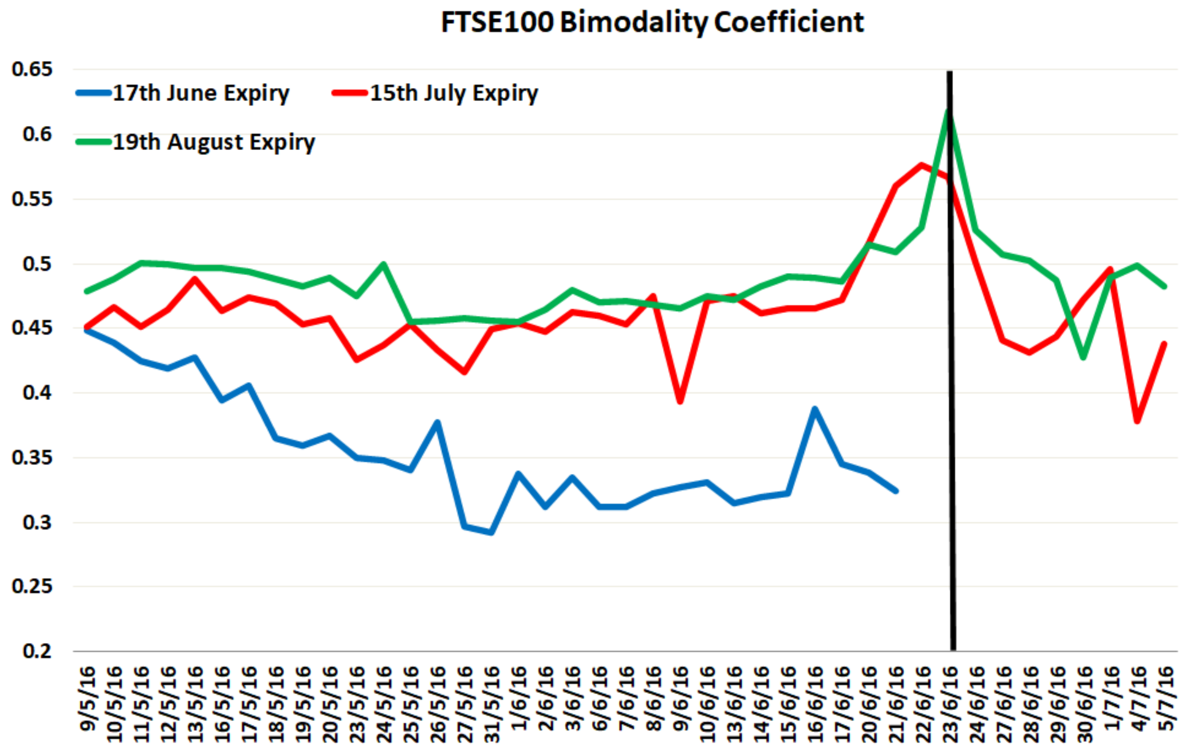
Panel B

Figure 8

This Figure shows the evolution of the Bimodality Coefficient of the corresponding Risk-Neutral Distribution (RND), extracted from 9th May until 5th July 2016. Panel A shows the Bimodality Coefficient of the RND extracted from options on GBPUSD futures with expiry on 3rd June (blue), 8th July (red), and 5th August 2016 (green). Panel B shows the Bimodality Coefficient of the RND extracted from options on FTSE100 Index with expiry on 17th June (blue), 15th July (red), and 19th August 2016 (green). The vertical black line indicates the Brexit Referendum date (23rd June, 2016).



Panel A



Panel B

Figure 9

This Figure shows GBPUSD Risk-Neutral Distributions (RNDs) extracted on the Brexit Referendum night (23rd to 24th June, 2016). The blue curve illustrates the RND extracted at settlement (20:00 BST) on 23rd June from CME options on GBPUSD futures with expiry on 8th July. The red curve illustrates the RND extracted on 23rd June at 23:00 BST from options on GBPUSD with 1-month maturity, sourced from Bloomberg. The green curve illustrates the corresponding RND extracted on 24th June at 05:30 BST from options on GBPUSD with 1-month maturity, sourced from Bloomberg. In all cases, the mode(s) of the RNDs are indicated.

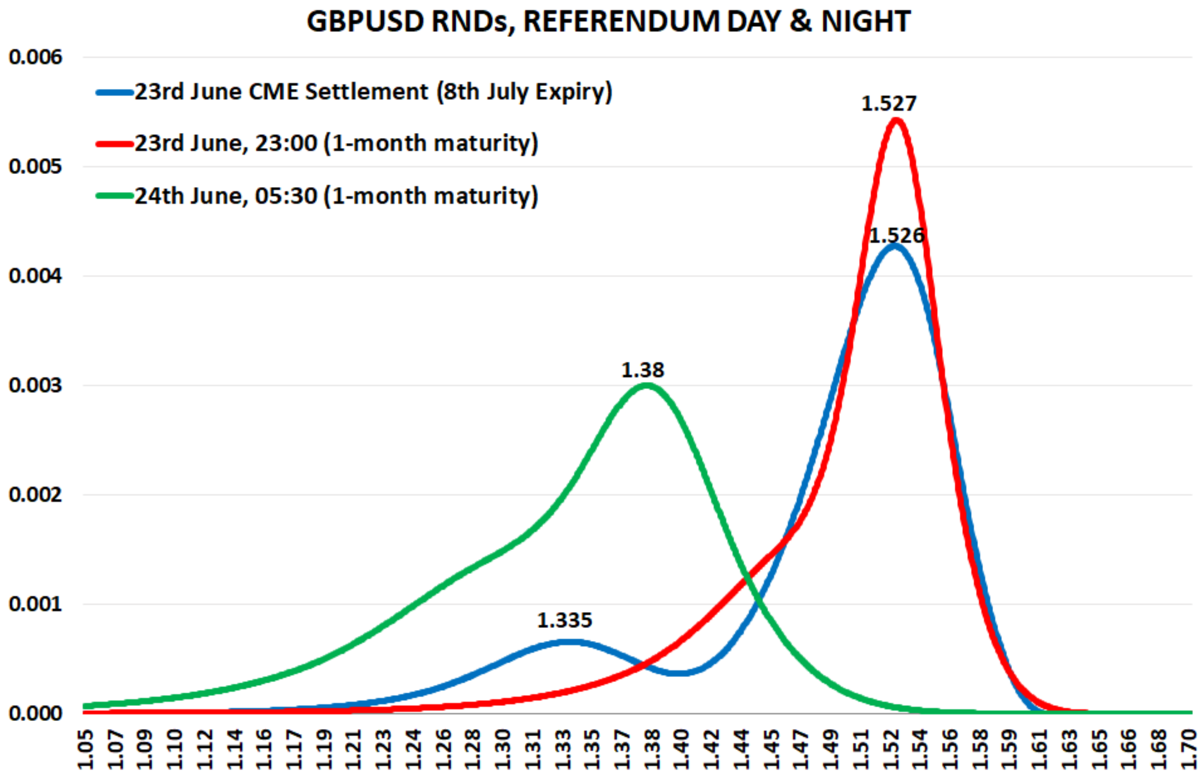
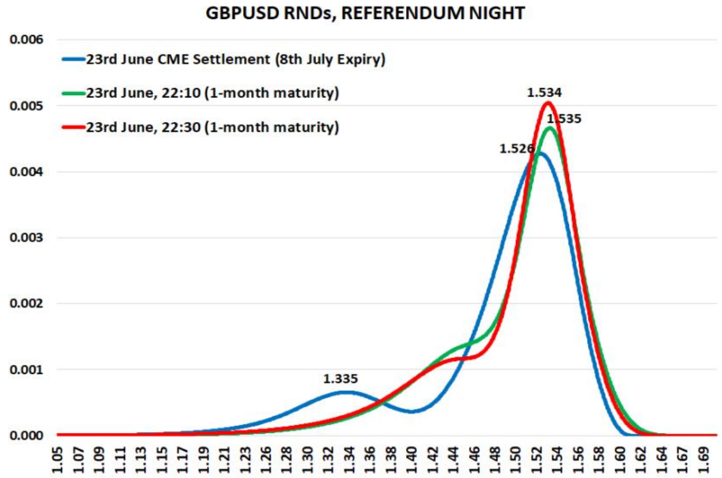
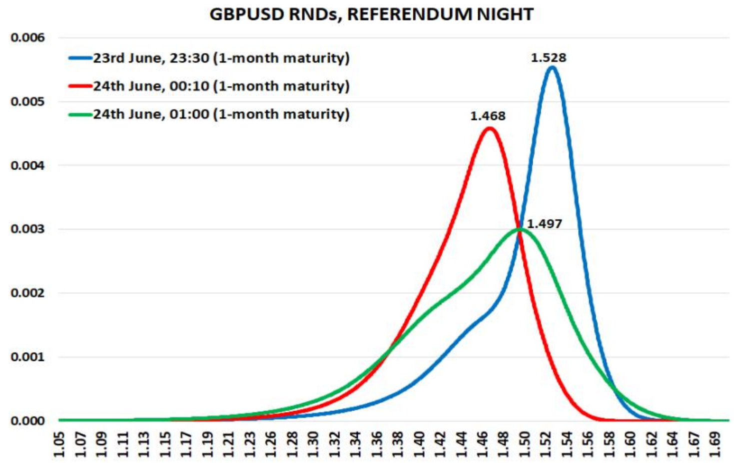


Figure 10

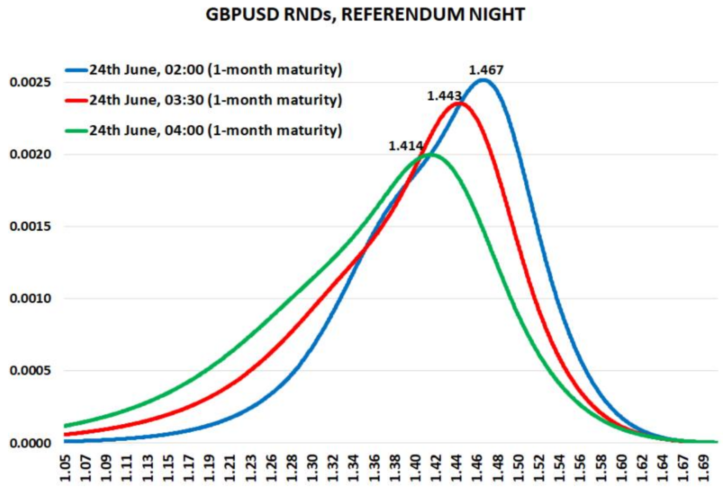
This Figure shows GBPUSD Risk-Neutral Distributions (RNDs) extracted on the Brexit Referendum night (23rd to 24th June, 2016). In Panel A, the blue curve presents the RND extracted at settlement (20:00 BST) on 23rd June from CME options on GBPUSD futures with expiry on 8th July. The green curve presents the RND extracted on 23rd June at 22:10 BST from options on GBPUSD with 1-month maturity, sourced from Bloomberg, whereas the red curve presents the corresponding RND extracted at 22:30 BST. Panel B presents the corresponding RNDs at 23:30 (blue), 00:10 (red), and 01:00 BST (green). Panel C presents the corresponding RNDs at 02:00 (blue), 03:30 (red), and 04:00 BST (green). Panel D presents the corresponding RNDs at 04:40 (blue), 05:30 (red), and 08:50 (green). In all cases, the mode(s) of the RNDs are indicated.



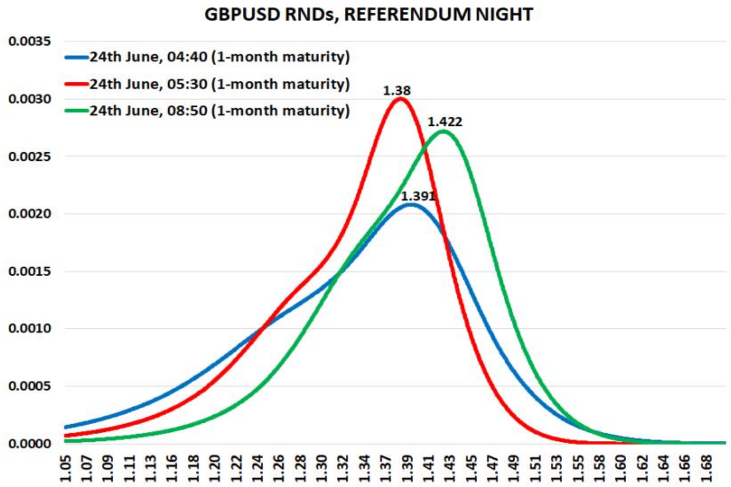
Panel A



Panel B



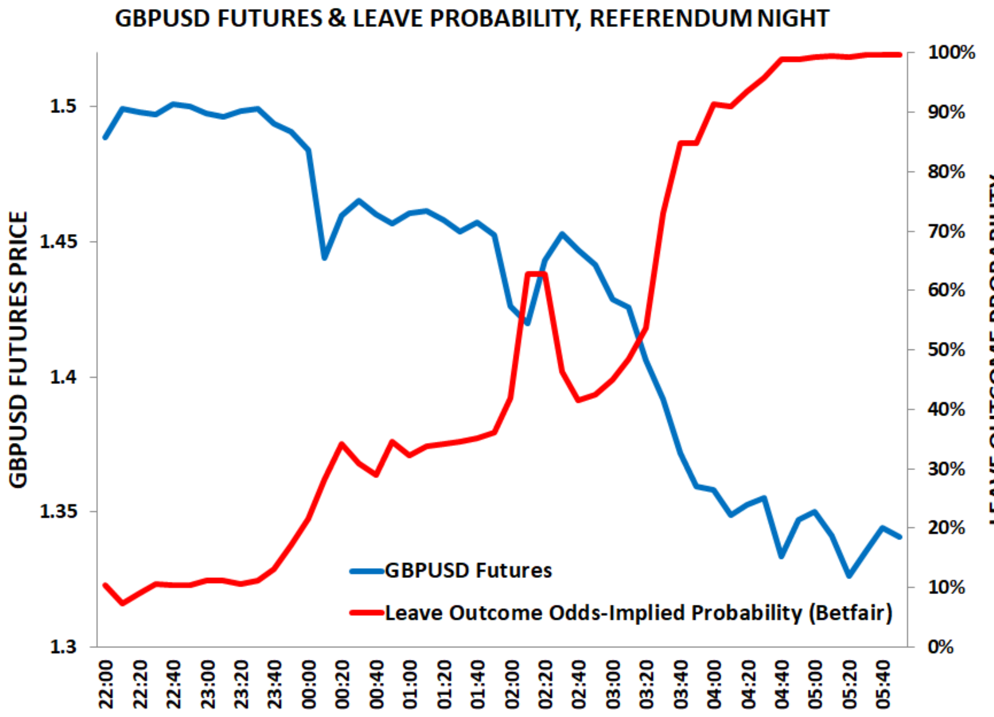
Panel C



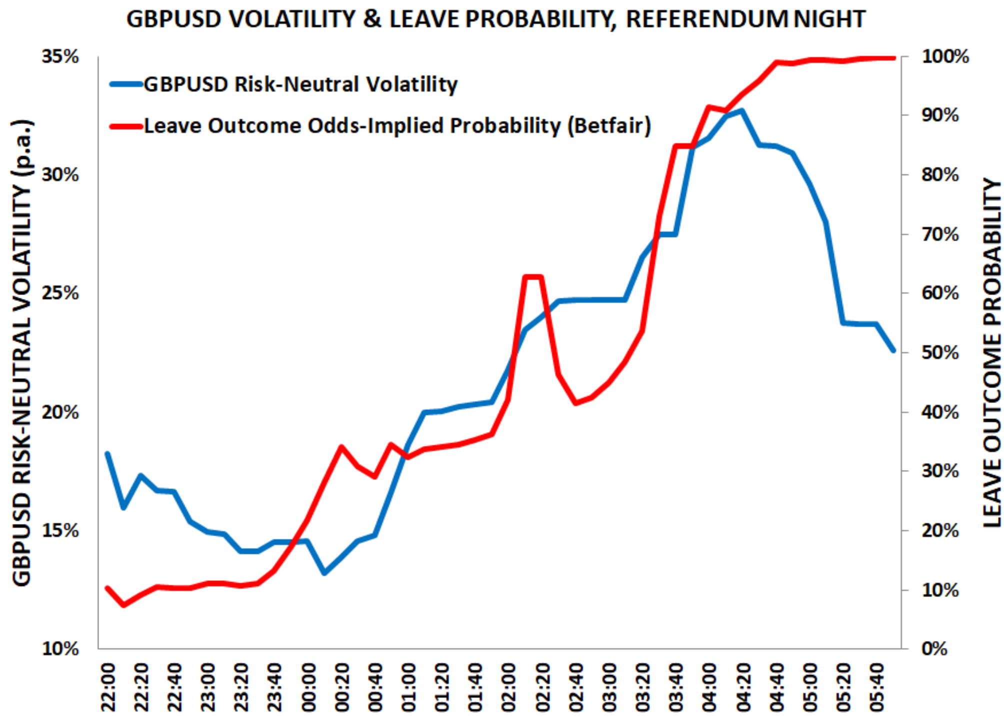
Panel D

Figure 11

This Figure shows the GBPUSD futures price and Risk-Neutral Volatility on the Brexit Referendum night from 22:00 BST on 23rd June to 06:00 BST on 24th June 2016. Panel A presents the evolution of the GBPUSD futures price (blue, left axis) together with the probability of a Leave Vote outcome implied by betting odds (red, right axis), provided by Betfair. Panel B presents the evolution of the Risk-Neutral Volatility (p.a.) (blue, left axis), extracted from options on GBPUSD with 1-month maturity, sourced from Bloomberg, together with the probability of a Leave Vote outcome implied by betting odds (red, right axis), provided by Betfair.



Panel A



Panel B

Figure 12

This Figure shows two sets of probabilities of a Leave Vote outcome, computed on a daily basis in the run up to the Brexit Referendum date (23rd June, 2016). The blue line indicates the probability of a Leave Vote outcome implied by the prices of options on GBPUSD futures with expiry on 8th July 2016. The red line indicates the corresponding probability implied by betting odds provided by Betfair. The vertical black line indicates the date of the murder of MP Jo Cox (16th June, 2016).

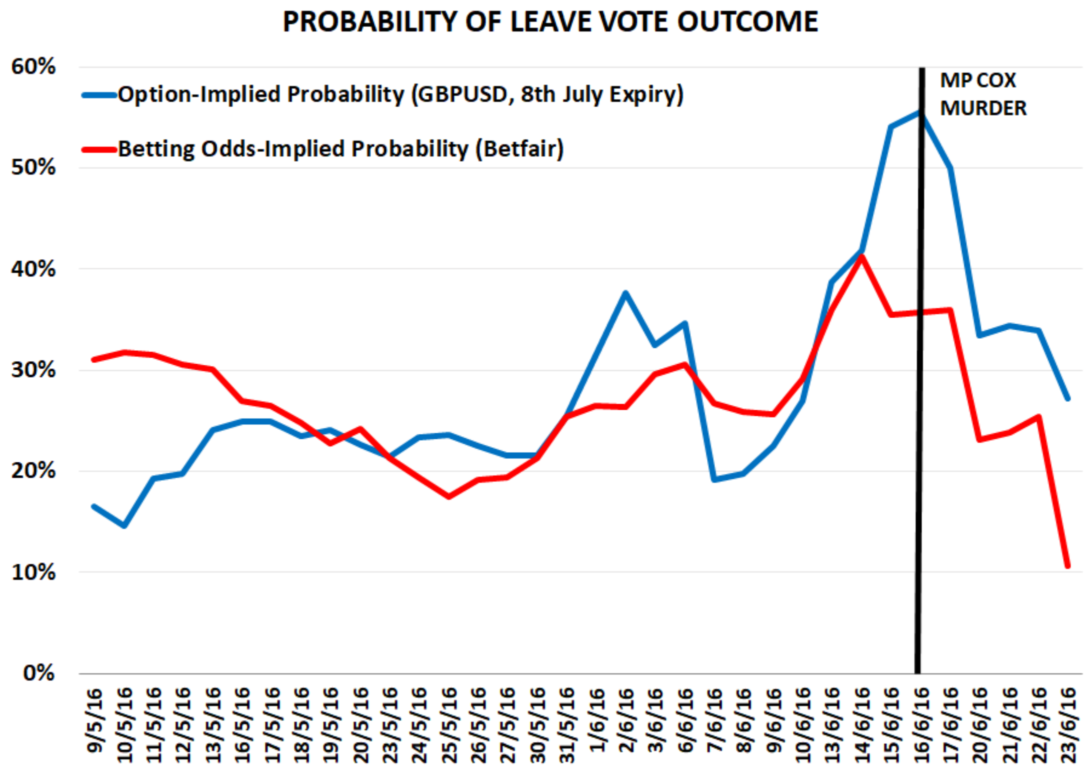
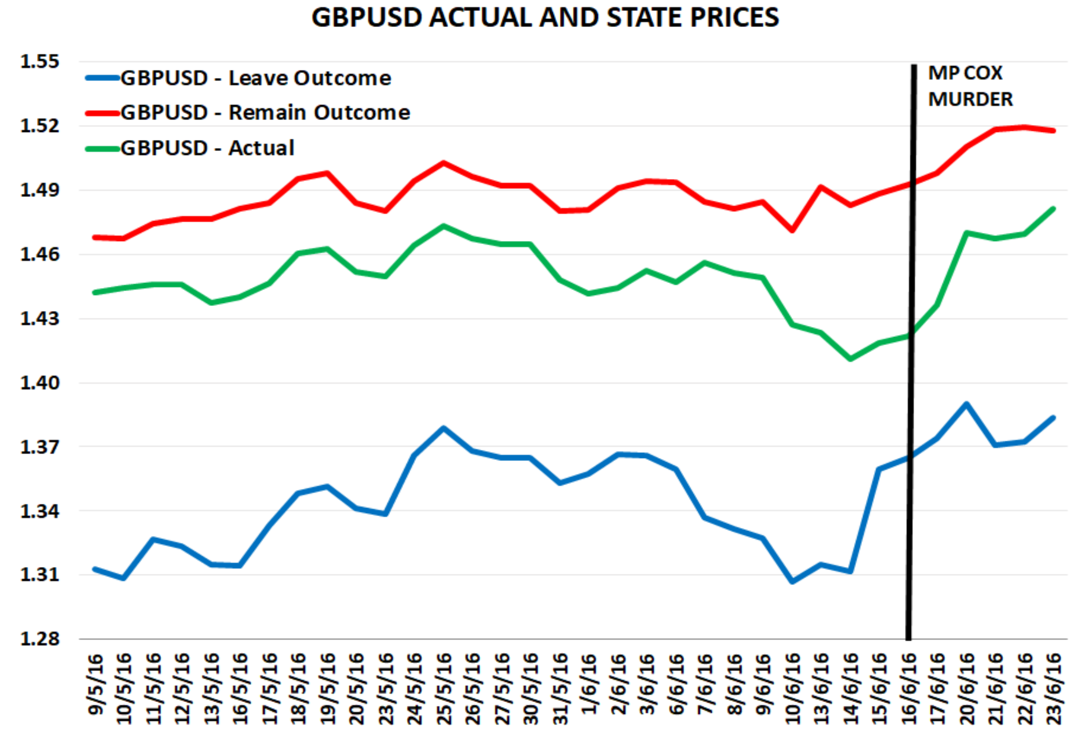
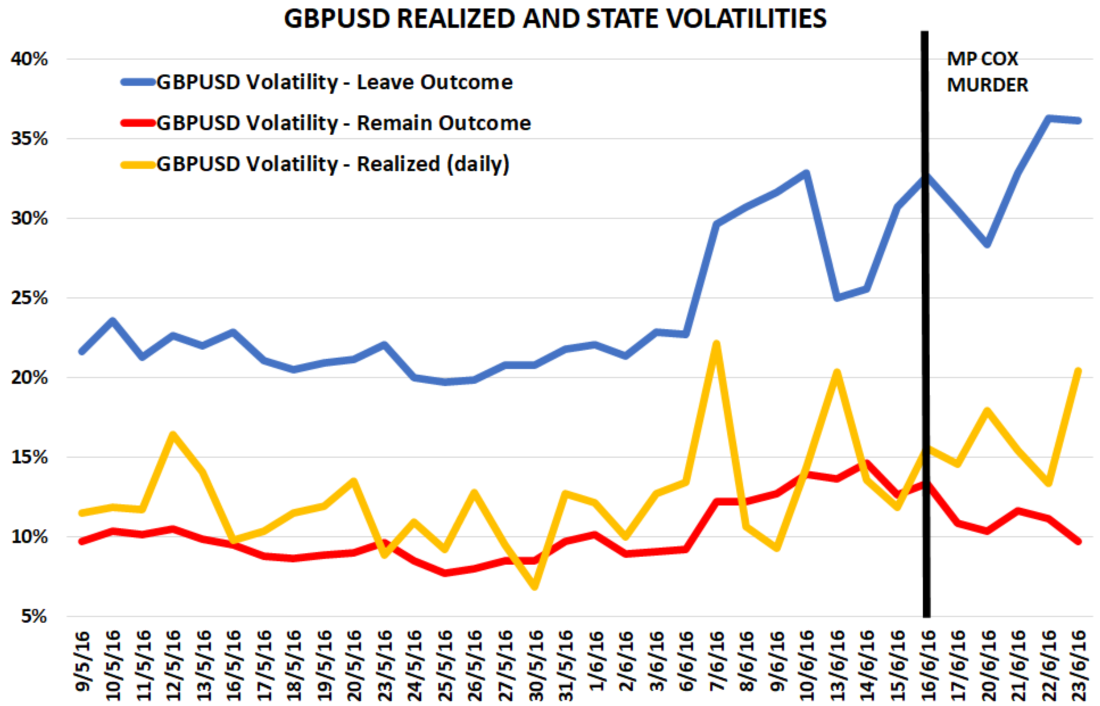


Figure 13

This Figure illustrates the GBPUSD futures price (Panel A) and Implied Volatility (Panel B) in the run up to the Brexit Referendum date (23rd June, 2016), corresponding to the event of a Remain or a Leave Vote outcome, respectively, as computed from options on GBPUSD futures with expiry on 8th July 2016. Panel A shows the GBPUSD futures price in the event of a Remain (red) or a Leave (blue) Vote outcome, together with the actual futures price (green). Panel B shows the GBPUSD futures Implied Volatility (p.a.) in the event of a Remain (red) or a Leave (blue) Vote outcome, together with the realized volatility (p.a.) computed on a daily basis from intraday 1-min GBPUSD futures log returns (yellow). The vertical black line indicates the date of the murder of MP Jo Cox (16th June, 2016).



Panel A



Panel B

Table 1
This Table presents an outline of key political events leading to and associated with the Brexit 2016 Referendum.

Date	Event
23rd January, 2013	Bloomberg Speech: Prime Minister (PM) David Cameron calls for fundamental reform of the EU and promises an in-out referendum on UK membership should the Conservatives win a parliamentary majority at the 2015 General Election
May, 2013	The Conservatives publish a draft EU Referendum Bill, which would be held no later than 31st December, 2017
22nd May, 2014	UK Independence Party (UKIP) tops the polls for the European Parliament elections
7th May, 2015	UK General Election: Conservatives win absolute majority in the House of Commons. Their electoral manifesto included Cameron's commitment to hold an in-out referendum on UK membership of the EU by the end of 2017
27th May, 2015	Planned referendum is included in the Queen's speech
9th June, 2015	The European Union Referendum Act 2015 passes the second reading in the House of Commons, voted by 544 to 53 in favour
17th December, 2015	The European Union Referendum Act receives Royal Assent. Voters will be asked whether the UK should Remain a member of EU or Leave the EU
20th February, 2016	PM Cameron announces that the referendum will be held on 23rd June, 2016
21st February, 2016	Former Mayor of London and Member of Parliament (MP) Boris Johnson announces that he will campaign for Vote Leave
16th June, 2016	Pro-Remain Labour MP, Jo Cox, is murdered by an allegedly far-right supporter. Official campaigning is suspended for three days
21st June, 2016	The final "Great Debate" is broadcasted by BBC from Wembley Arena
23rd June, 2016	Referendum is held
24th June, 2016	Referendum result is announced. Leave wins, receiving 51.89% of valid votes. Cameron announces that he will resign as PM
13th July, 2016	Theresa May succeeds Cameron as PM

Table 2

This Table reports the average number of strikes per day and the number of trading days for the options used to extract Risk-Neutral Densities for GBPUSD futures and the FTSE100 Index, respectively, during the period from 9th May until 5th July 2016.

	GBPUSD			FTSE100		
Expiry	3rd June	8th July	5th August	17th June	15th July	19th August
Average number of strikes used per day	18	69	83	54	67	64
Number of trading days	17	41	41	27	41	41

Table 3

This Table presents the key events and announcements related to the Brexit Referendum during the night of 23rd June and the early morning of 24th June, 2016. All time stamps are in British Summer Time (BST) and correspond to BBC's election night broadcasting.

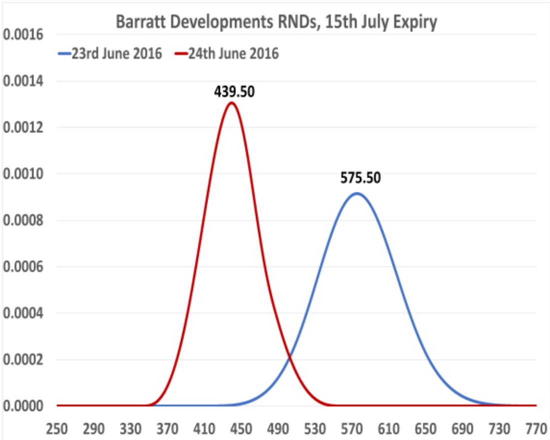
Time (BST)	Event/Announcement
22:00	Polls Close. No "public" Exit Poll was conducted
22:07	BBC quotes the leader of UKIP, MEP Nigel Farage, saying that "Remain has just edged it"
22:23	BBC psephologist says that the YouGov poll conducted on the same day indicates a Remain lead by 52% to 48%
22:54	BBC quotes that Farage has "unconceded" the Remain victory
23:59	Result for Newcastle is announced. Marginal victory for Remain (50.7% to 49.3%). Much lower vote share for Remain than the one anticipated for this area
00:16	Result for Sunderland is announced. Very strong victory for Leave (61% to 39%). A marginal victory for Leave was anticipated.
00:44	BBC quotes sources from Lewisham (London borough) that Remain may have gained 83% of the vote in this area
00:53	Result for Swindon is announced. Victory for Leave (55% to 45%). Anticipated result if national vote was split 50%-50%
01:18	Result for South Tyneside is announced. Bigger than anticipated victory for Leave (62% to 38%)
01:42	Result for Hartlepool is announced. Bigger than anticipated victory for Leave (70% to 30%)
01:54	Result for City of London is announced. Remain victory by 75% to 25%
02:01	Result for Swansea is announced. Victory for Leave by 52% to 48%, whereas a Remain victory was anticipated
02:04	BBC presenter quotes a leading figure in Labour party saying that they believe it will be a Leave win
02:14	Arron Banks, a donor and co-founder of Leave.EU campaign, says that Leave has won. He states that their own poll showed a Leave win by 52% to 48%
02:19	Result for Lambeth. Bigger than anticipated victory for Remain (79% to 21%). First big London borough to declare result
02:28	Result for Wandsworth (London borough). Bigger than anticipated victory for Remain (75% to 25%)
03:14	BBC psephologist states that London outperformance for Remain does not seem sufficient to offset the outperformance of Leave in other places
03:22	Leave vote has surpassed 51% with 159/382 counting authorities declared
03:46	BBC quotes Farage saying that he "now dares to dream of an independent UK at dawn"
04:01	Farage claims that Leave has won
04:39	BBC calls the Referendum for Leave, projecting a 52% share of the vote
07:01	Final result: Leave 17,410,742 votes (51.9%) – Remain 16,141,241 votes (48.1%)
08:22	Cameron announces that he will resign as PM
08:46	Statement by the Bank of England Governor, Mark Carney, that the Bank is ready to provide liquidity and take further policy actions

Detecting Political Event Risk In The Option Market

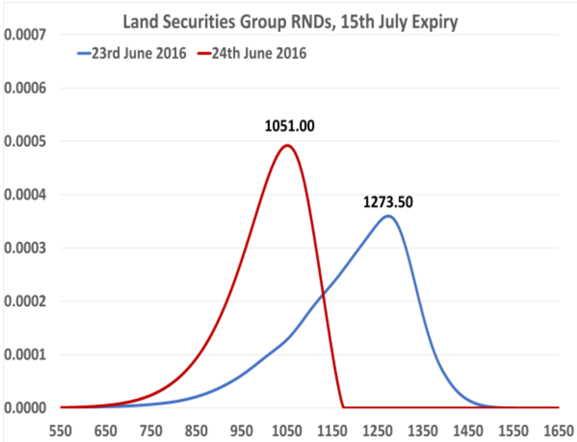
Supplementary Appendix

Figure SA.1

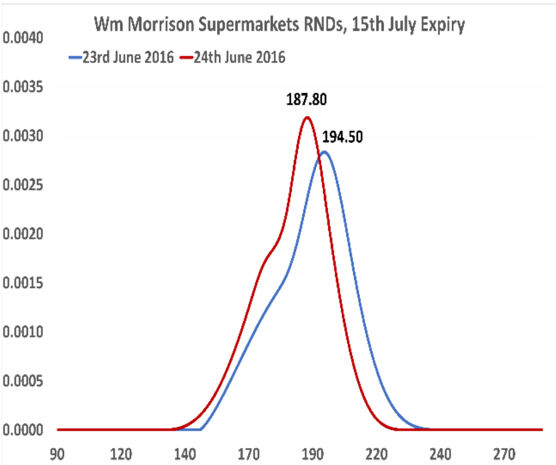
This Figure shows Risk-Neutral Distributions (RNDs) extracted on 23rd June (blue) and 24th June (red) from options with expiry on 15th July 2016 for the five most "domestic" FTSE100 firms according to the percentage of their foreign sales. Panel A illustrates the RNDs for Barratt Developments (BDEV), Panel B for Land Securities Group (LAND), Panel C for WM Morrison (MRW), Panel D for Sainsbury's (SBRY) and Panel E for Travis Perkins (TPK). In all Panels, the modes of the RNDs are indicated.



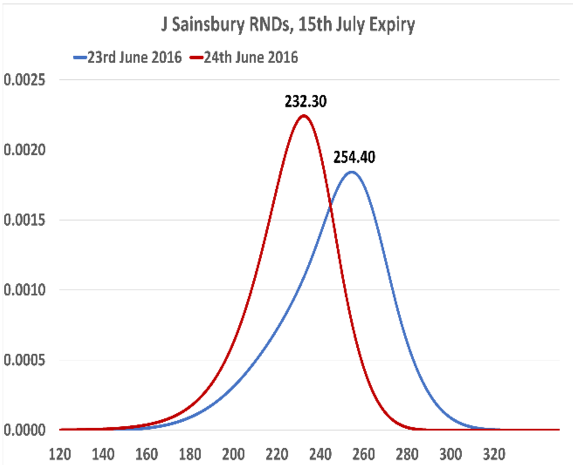
Panel A



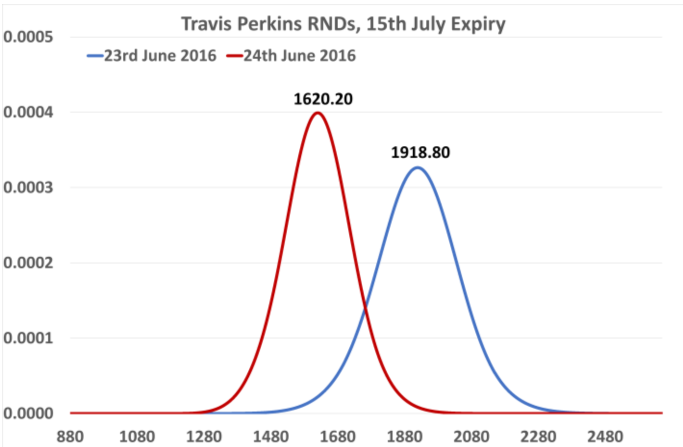
Panel B



Panel C



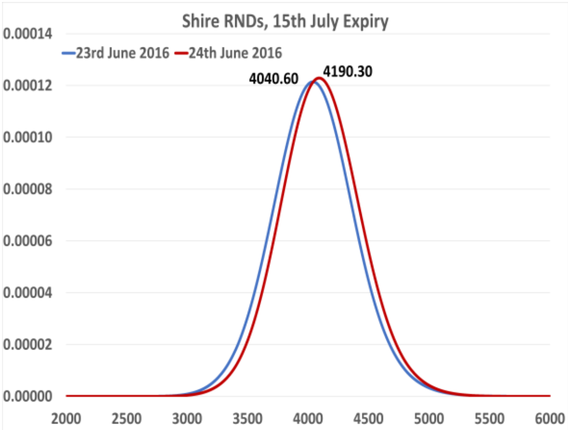
Panel D



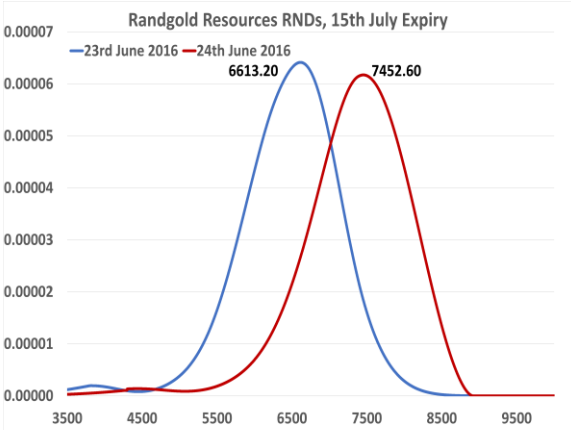
Panel E

Figure SA.2

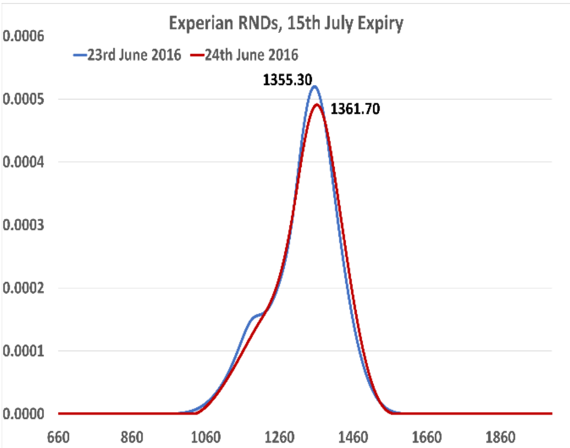
This Figure shows Risk-Neutral Distributions (RNDs) extracted on 23rd June (blue) and 24th June (red) from options with expiry on 15th July 2016 for the most “global” FTSE100 firms according to the percentage of their foreign sales. Panel A illustrates the RNDs for Shire (SHP), Panel B for Randgold Resources (RRS), Panel C for Experian (EXPN), Panel D for Antofagasta (ANTO) and Panel E for Rio Tinto (RIO). In all Panels, the modes of the RNDs are indicated.



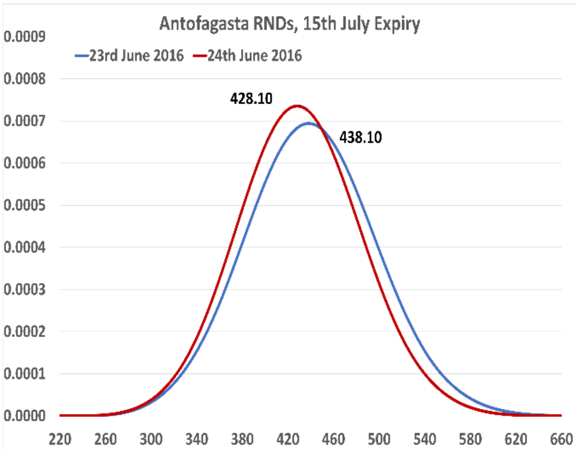
Panel A



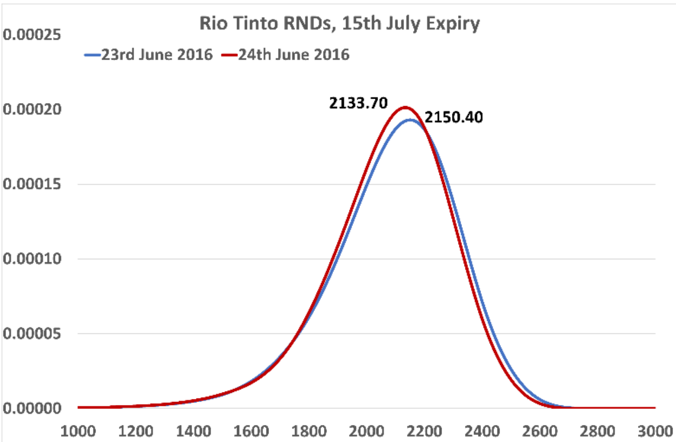
Panel B



Panel C



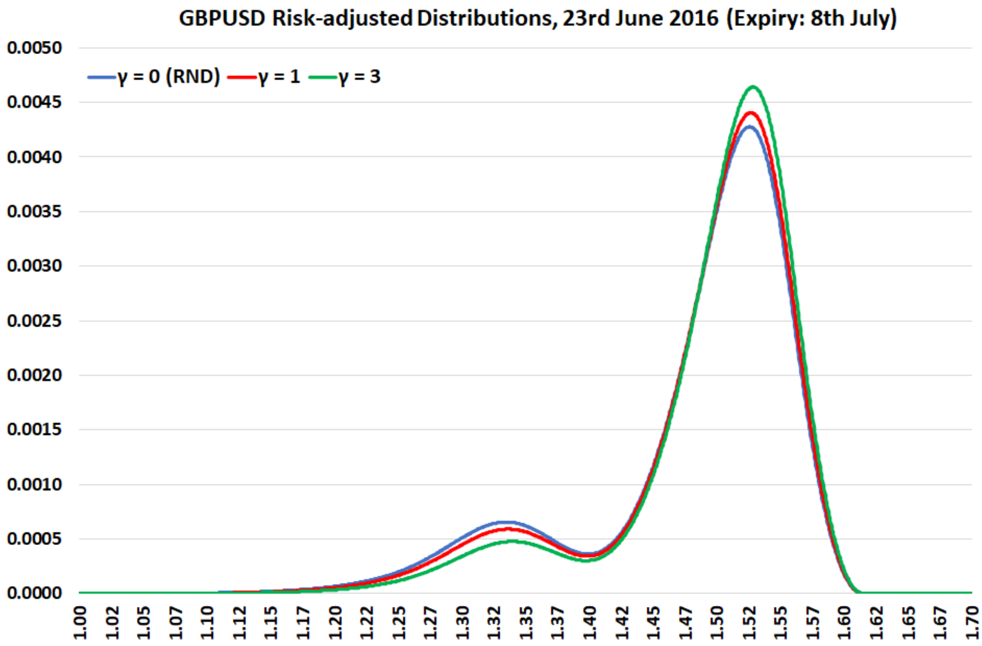
Panel D



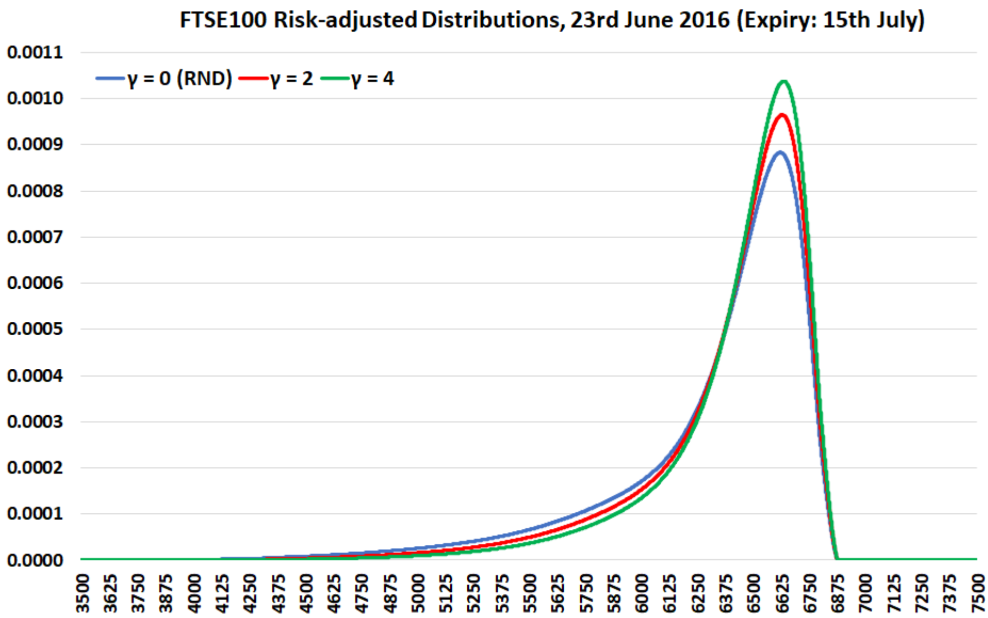
Panel E

Figure SA.3

This Figure shows risk-adjusted distributions extracted on 23rd June 2016, for different degrees of risk aversion (γ) of the representative agent, using the methodology of Bliss and Panigirtzoglou (2004). Panel A illustrates risk-adjusted distributions for GBPUSD futures using γ=1 (red) and γ=3 (green), together with the RND (blue) extracted from options with expiry on 8th July. Panel B illustrates risk-adjusted distributions for FTSE100 Index using γ=2 (red) and γ=4 (green), together with the RND (blue) extracted from options with expiry on 15th July.



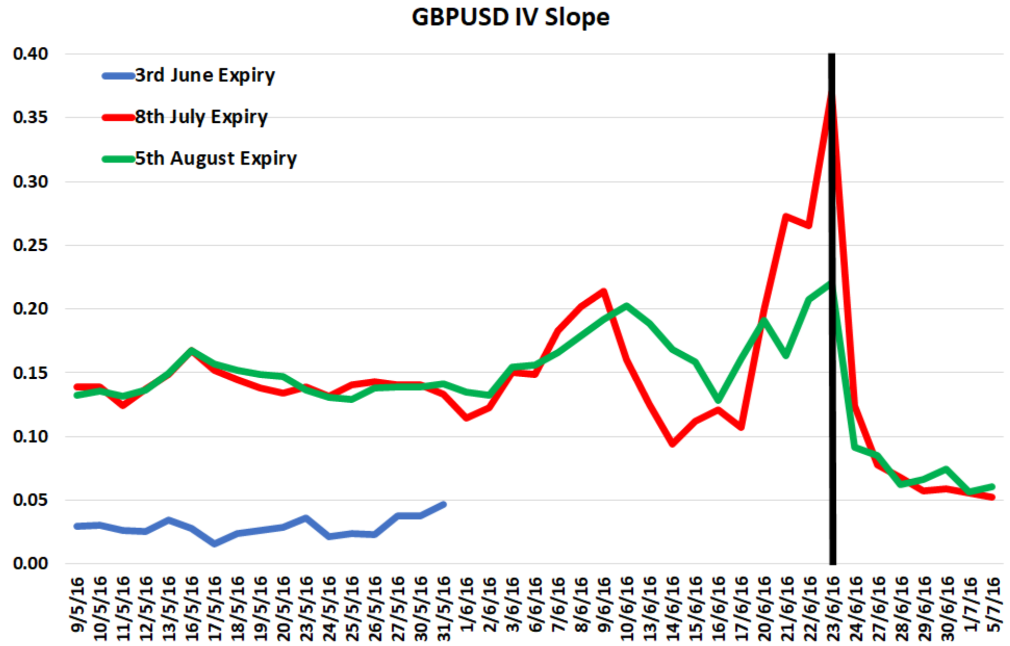
Panel A



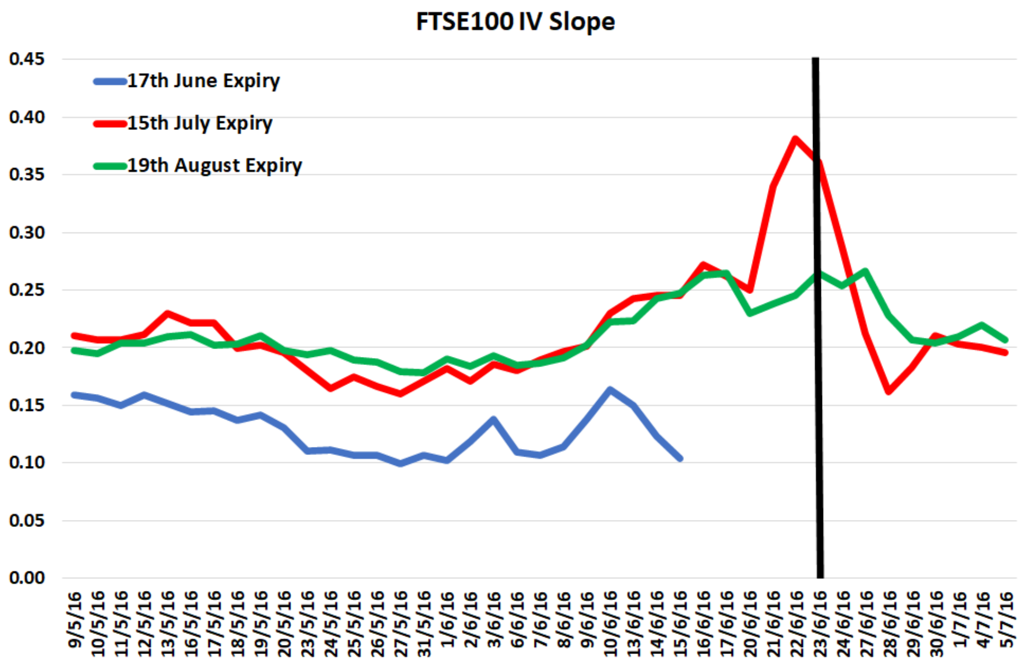
Panel B

Figure SA.4

This Figure shows the evolution of the Slope of the IV curve, which is estimated on a daily basis by regressing the implied volatilities of out-of-the-money puts on their deltas and an intercept, from 9th May until 5th July 2016. Panel A shows the Slope estimated from options on GBPUSD futures with expiry on 3rd June (blue), 8th July (red), and 5th August 2016 (green). Panel B shows the corresponding Slope estimated from options on FTSE100 Index with expiry on 17th June (blue), 15th July (red), and 19th August 2016 (green). The vertical black line indicates the Brexit Referendum date (23rd June, 2016).



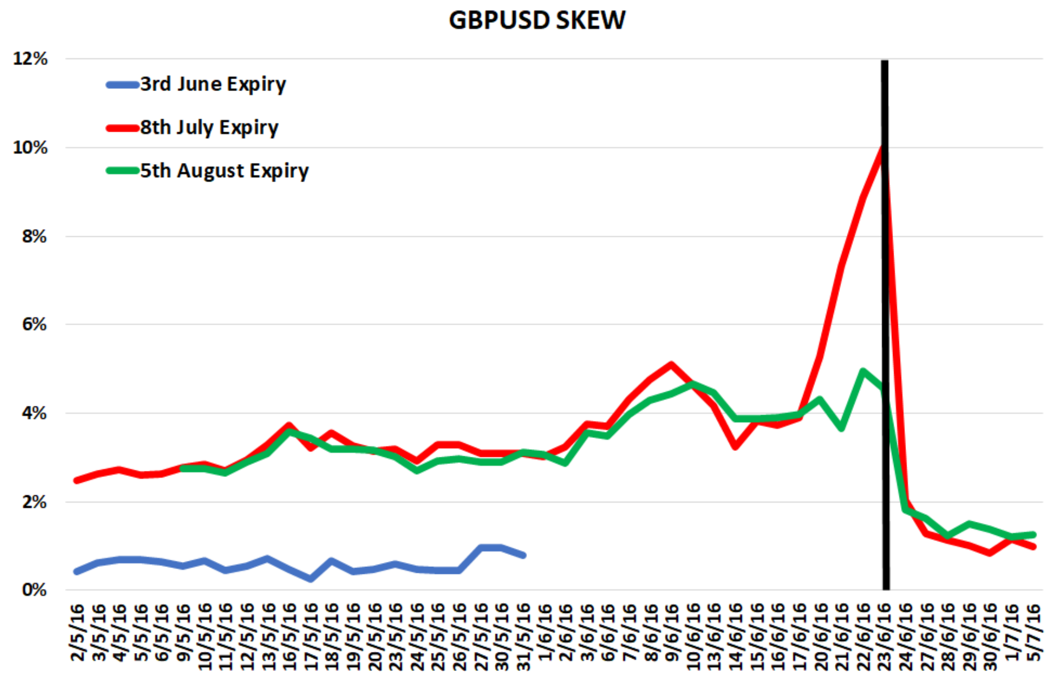
Panel A



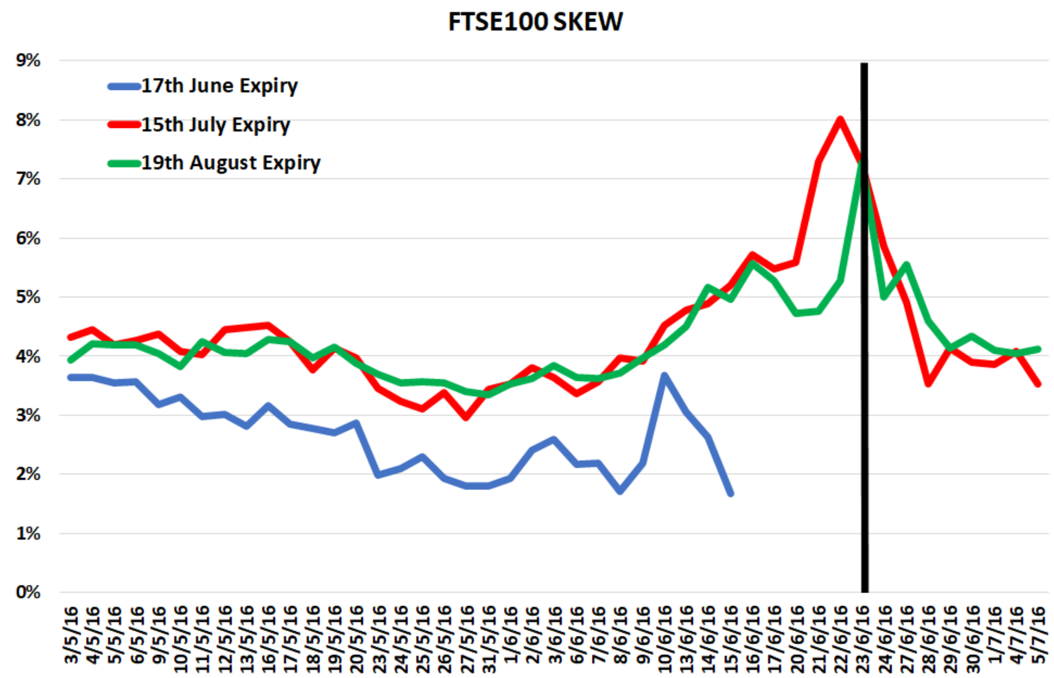
Panel B

Figure SA.5

This Figure shows the evolution of the SKEW of the IV curve from 9th May until 5th July 2016. SKEW is computed on a daily basis as the difference between the annualized implied volatility of a deep out-of-the-money put, with delta closest to -0.25, and the annualized implied volatility of an at-the-money call, with delta closest to 0.5. Panel A shows the SKEW computed from options on GBPUSD futures with expiry on 3rd June (blue), 8th July (red), and 5th August 2016 (green). Panel B shows the corresponding SKEW computed from options on FTSE100 Index with expiry on 17th June (blue), 15th July (red), and 19th August 2016 (green). The vertical black line indicates the Brexit Referendum date (23rd June, 2016).



Panel A



Panel B

Figure SA.6

This Figure shows Risk-Neutral Distributions (RNDs) extracted on 23rd June (blue) and 24th June 2016 (red) from options on EuroStoxx50 Index with expiry on 15th July 2016. The mode of the RNDs is indicated on the Figure.