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February 2019

Working Paper No: 19/03

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Estimation of FX Option Implied Density Functions: Nonparametric-Malz Approach

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Abstract

This paper estimates risk-neutral density (RND) for USD-TRY exchange rate through the nonparametric-Malz approach using European FX options for various tenors and a wide range of tails. FX option implied risk-neutral density is a valuable tool in terms of extraction of market assessment about future exchange rates, valuation of financial derivatives, portfolio risk management and monitoring financial stability. However, RND estimation for FX options requires non-trivial data adjustment due to the fact that these options are traded/quoted as structured products in over-the-counter (OTC) markets and the conventions are in terms of deltas rather than strike prices. In this regard, one of the main contributions of the study is that premium-adjusted delta convention used in the quotation of options on USD-TRY exchange rate is taken into account in the construction of implied volatility-delta space, which has been overlooked in the previous studies. Absence of this adjustment leads to a biased estimation of the implied volatility curve and RND, especially at longer-maturity horizons. Empirical findings provide evidence for the existence of volatility smile for the options on USD-TRY exchange rate. Furthermore, the examination of RND surface in recent periods displays the variation in the dispersion of option implied distributions of USD-TRY exchange rate due to volatility in financial markets.

Özet

Bu çalışma; ABD doları-Türk lirası döviz kuru için riske duyarsız dağılımı parametrik olmayan Malz yöntemi ile farklı vade ve geniş bir gözlem setinden oluşan Avrupa tipi kur opsiyonlarını kullanarak tahmin etmektedir. Kur opsiyonlarının ima ettiği dağılımlar döviz kurlarının gelecek dönemdeki seyrine yönelik piyasa beklentilerini yansıtmaları, finansal türev araçların değerlenmesi, portföy risk yönetimi ve finansal istikrarın takibi açılarından önemli bir araçtır. Ancak riske duyarsız dağılım tahmininde kullanılan veriler, tezgahüstü piyasalarda ABD doları-Türk lirası üzerine yazılan opsiyonların yapılandırılmış ürünler şeklinde işlem görmesi ve kotasyonlarının kullanım fiyatı yerine delta cinsinden gerçekleştirilmesi sebepleriyle önemli ölçüde düzeltme gerektirmektedir. Bu kapsamda çalışmanın temel katkılarından biri, ima edilen oynaklık-delta düzleminin oluşturulmasında önceki çalışmalarda göz ardı edilmiş olan, ABD doları-Türk lirası cinsi opsiyonların kotasyonunda kullanılan opsiyon primi ile düzeltilmiş delta yaklaşımının hesaba katılmasıdır. Düzeltmenin göz ardı edilmesi, ima edilen oynaklık eğrisi ve riske duyarsız dağılımın yanlı tahmin edilmesine neden olmakta ve söz konusu yanlılık vade uzadıkça artmaktadır. Ampirik bulgular, ABD doları-Türk lirası döviz kuru üzerine yazılmış opsiyonlar için oynaklık gülümsemesinin (volatility smile) varlığına dair kanıt sağlamaktadır. Ayrıca, riske duyarsız dağılım yüzeyindeki son dönem gelişmeler, dağılımın piyasa oynaklığına bağlı olarak değişiklik gösterdiğine işaret etmektedir.

JEL Classification: G13, G17.

Keyword: Risk-neutral density, options pricing, premium-adjusted delta.

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The views expressed in this paper are those of the author and do not reflect the official views of the Central Bank of the Republic of Turkey. All errors are the author's own. I thank the anonymous referee for useful comments.

Non-Technical Summary

FX option implied risk-neutral density provides an important source of information for investors, risk managers and policymakers in terms of extraction of market assessment, portfolio risk management, formation of trade strategies, valuation of financial derivatives and monitoring financial stability. Additionally, the estimated risk-neutral densities enable one to interpret the market's assessment of the degree of uncertainty or the probability of extreme changes in the exchange rate. In this regard, many methods have been proposed to estimate RNDs in the literature. The models suggested in previous studies have different advantages and drawbacks compared to each other. However, the use of nonparametric models is quite popular due to its flexibility and good fit to data. Thus, this study estimates RND for USD-TRY exchange rate through nonparametric-Malz methodology (2014) using a wide range of tails and tenors.

One of the difficulties in the estimation of RND for exchange rates is the non-trivial data adjustment since FX options are traded/quoted in the forms of structured products rather than plain-vanilla options and the delta conventions differ across maturities and markets. This study takes into account the delta conventions in the process of constructing implied volatility-delta pairs, where most of the previous studies have overlooked. Absence of this adjustment leads to a biased estimation of the implied volatility curve and thus RND, especially at longer-time horizons or when the market volatility is high.

This study provides evidence for the existence of volatility smile for the options on USD-TRY exchange rate, where the implied volatilities of out-of-the-money and in-the-money options tend to be higher than those of at-the-money options. Additionally, RND surface clearly shows the rise in the uncertainty of market assessments for USD-TRY exchange rate in the recent periods. The tail risks indicated by the probabilities of sharp movements for USD-TRY exchange rate tend to rise after 2017 and reach their highest level in August 2018. Besides these findings, the moments up to fourth-degree of RNDs have been presented in the study to interpret the results in a systematic way using both cross-sectional and time-varying properties of RNDs.

I. Introduction

Market expectations regarding future price movements of assets are important tools for investors, academicians and policymakers. One of the most commonly used methods to extract the expectations is through risk-neutral distribution (RND) estimation. Through RND estimation, it is possible to deduce state prices of underlying assets using market prices of derivatives, especially options. One key point that needs to be addressed is the concept of risk-neutrality. Although the risk-neutral and real-world probability distributions differ due to the existence of time-varying risk premia, market participants can compare risk-neutral market expectations with their subjective expectations by using option implied risk-neutral probability densities.

Risk-neutral densities provide information about the distribution of future values of asset prices, which allows us to extract state prices. Through the use of state prices, it is possible to price/value any derivative with the same underlying asset or to deduce the degree of risk premium that market participants attain for the underlying asset. In this regard, information obtained from RNDs is invaluable for many parties. For instance, central banks closely monitor changes in market expectations through RNDs regarding certain variables such as interest rates and exchange rates in order to assess the effectiveness of the monetary and macroprudential policies. RNDs also have the capability of foreseeing the likelihood of sharp movements in underlying asset prices through estimating the tail event probabilities. In this respect, it has predictive power for signaling crises, which is quite crucial for portfolio managers and policymakers. Last but not least another application area of option implied risk-neutral densities is that time series movements of RNDs and its moments at several degrees are used for setting up effective trading strategies.

The RND estimation methodology is based on the result of Breeden and Litzenberger (1978), which shows that RND can be written as a function of the second derivative of the call option price with respect to strike price as depicted below:

$$f_Q(K) = e^{r\tau} \frac{\partial^2 C_t^{BS}(K)}{\partial K^2} \tag{1}$$

where K, r and τ denote strike price, domestic interest rate and time to maturity, respectively. $C_t^{BS}(K)$ stands for the European call option price at time t and $f_Q(K)$ is the risk-neutral density at strike price K. As can be seen from the equation, RNDs can be obtained from the market prices directly if there exists a continuum of option prices with different strike price levels. However, since the options data is not available for a continuum of strike prices, several approaches have been developed to estimate RNDs where details are presented in the following sections.

Following Breeden and Litzenberger result, RND can be estimated for any underlying asset if there exists a deep and liquid derivatives market, especially options. RND estimation is quite popular and common for exchange rate since expectations about the future values of exchange rate are of interest to market participants. Especially for emerging markets, information about the exchange rates or tools to price FX derivatives are crucial in terms of exchange rate risk management and financial stability for policymakers.

Given the importance of exchange rate dynamics in Turkey, this study estimates RND for USD-TRY exchange rate through the nonparametric-Malz (2014) methodology using a wide range of European type FX options. This approach is one of the most widely used methods to estimate RNDs for exchange rates given its flexibility and good fit to data. Its merits have been acknowledged by academic studies and major central banks such as The Federal Reserve and The Bank of England. One contribution of the study is to correct the non-negligible estimation bias in the implied volatility curve and RNDs stemming from different delta conventions for FX options written on emerging market currencies.[2] This issue has been overlooked in previous studies and RND estimations without the correction lead to systematically wrong inferences mainly about the state prices and tail probabilities, especially in the case of longer time-to-maturities. Additionally, the use of a wide range of observations covering out-of-money options provides higher precision in terms of RND estimation and measuring market assessment. To the best of our knowledge, this is the first study that estimates the RND by taking into account the OTC convention of FX options in Turkey with a nonparametric Malz methodology.

[2] The details about the estimation bias are provided in Data and Methodology section. Empirical evidence section also illustrates the extent of the bias.

Rest of the paper proceeds as follows; the next section provides a comprehensive summary on the literature for extraction of RNDs where different approaches are discussed with their merits and drawbacks. Then the data and methodology used in the study is explained in detail, which presents the difficulties of working with FX options data and necessary data adjustments in the estimation process. Empirical evidence section presents the results of RND estimation in detail and the last section concludes.

II. Literature

Black-Scholes (1973) option pricing model assumes that the underlying asset of an option follows a lognormal distribution. Under this assumption, implied volatility is constant over all strike prices given that other parameters are the same. However; empirical studies, Rubinstein (1994), Toft and Prucyk (1997), Campa, Chang and Reider (1998) demonstrate that options with different strike prices tend to have different implied volatilities, which is called volatility smile. The volatility smile is attributed to two facts: First one is that the distributions of asset returns tend to have a leptokurtic feature in the sense that they have a higher peak and two asymmetric heavier tails than those of the normal distribution and secondly asset returns may exhibit jumps (Kou 2002). Different approaches are adopted in the previous studies in order to derive risk-neutral densities and to price options consistently with the empirical properties of asset returns.

Methodologies adopted in the literature for obtaining risk-neutral densities or valuation of options can be summarized under two groups; structural and non-structural models. Structural models describe the stochastic process of the underlying asset fully whereas non-structural models directly estimate the RND rather than the price dynamics of the underlying asset.

In structural models, the main idea is to improve the Black-Scholes asset pricing model by modeling the stochastic process of the underlying asset consistent with the empirical properties of asset returns. Two main acknowledged models within this framework are jump diffusion and stochastic volatility models. One of the first jump-diffusion models was used by Merton (1976), known as the Merton Jump model. It allows the underlying asset price to exhibit sudden big movements so that the likelihood of extreme events is not negligible. Kou (2002), Zhang, Zhao and Chang (2012) are also among the studies using jump-diffusion processes. The main advantage of the jump models is that corresponding risk-neutral densities to underlying assets better fit the data compared to results of the lognormal distribution. One problem with the jump models is the simplifying assumptions for the distribution of the jump process to find out a closed form solution. For instance, Merton assumes that price jumps are lognormally distributed due to its tractability property. Furthermore; Kou (2002), Kou and Wang (2004) assume an exponential distribution for the jump process.

In order to account for the time variation in implied option volatility, stochastic volatility models are developed where the main application of these models is the Heston (1993) stochastic volatility model. Under the Heston model, volatility is assumed to follow a mean-reverting process. With this specification, Heston shows that spot returns over long periods have asymptotically normal distributions and a positive correlation between volatility and spot return which produces a fat right tail and thin left tail. Although structural models provide a significant improvement over the Black-Scholes model, there exist other problems with structural approaches which are over-parametrization and calibration issues preventing market participants using these models extensively.

As an alternative to structural models, non-structural models tend to put some structure on the terminal distribution of RND rather than defining the price dynamics of the underlying asset. These models can be broadly classified as parametric, semi-parametric and nonparametric depending on their degree of defining the probability distribution. In that sense, parametric models define the RND process completely whereas semi-parametric and nonparametric models propose some approximation for the RND.

Melick and Thomas (1997) develop a parametric “mixture of distributions” method to estimate RNDs. In order to provide a solution to the underestimation of tail risks in the Black-Scholes model, they propose to use a linear combination of lognormal distributions to estimate the distribution of future values of the underlying asset. This approach enables implied RNDs to capture the market’s assessment of extreme risks better given the weights on tails. However, one problem with the mixture of distribution approach is that there exists the problem of inadequate number of observed strike prices against a high number of parameters to be estimated when several distributions are included. Thus data limitations play an important role in the power of mixture distributions. Another issue is that there is not a definite number of distributions to include in the mixture distribution. Additionally, since there is no information regarding the evolution of underlying asset price, it provides little to no use for constructing dynamic hedge.

Another non-structural model employed to estimate RNDs is semi-parametric models, where the main idea is to approximate the distribution of the option values at the maturity. In this regard, Jarrow and Rudd (1982) suggest the Edgeworth expansion around the lognormal distribution as an approximate option valuation technique. An alternative approach to Edgeworth expansion is Hermite polynomial approximation whose theoretical foundation is detailed in Madan and Milne (1994) and applied in Abken, Madan, and Ramamurtie (1996) and Coutant, Jondeau, and Rockinger (2001). This method involves approximation of risk-neutral density by an expansion around a lognormal distribution using Hermite polynomials.

Instead of requiring a parametric form for the distribution itself, nonparametric methods allow greater flexibility in fitting risk-neutral distribution and avoid imposing parametric restrictions. These methods can be grouped broadly into three categories which are kernel regression, tree based models and curve fitting models. Ait-Sahalia and Lo (1998) use kernel regression by assuming that the option-pricing formula is an arbitrary nonlinear function of option characteristics. Unlike parametric methods which estimate risk-neutral density for each cross-section of options, kernel regression takes into account both cross-sectional and time series option prices providing consistency over time for the estimates. On the other hand, the use of kernel regressions is limited in practice as it requires intensive use of data.

Tree-based models are first presented by Rubinstein (1994) and are then developed further in Jackwerth and Rubinstein (1996) and Jackwerth (1999). According to the work of Rubinstein (1994), tree-based models basically infer risk-neutral probabilities or equivalently state contingent prices from the observed prices of European options. These probabilities are then used to infer a binomial tree that is consistent with these probabilities and hence consistent with all of the observed option prices. The method is to minimize the gap between the tree implied probabilities and probabilities obtained from the tree of Cox-Ross-Rubinstein (1979). However, the assumption of assigning equal path probability is founded to be restrictive. Another difficulty with the binomial approach arises due to irregularities in the tails of the distribution which results in excessive kurtosis for the implied distribution.

Another method for obtaining risk-neutral densities is fitting volatility smile onto the space of strike prices or deltas so that unobserved components of options, implied volatilities, can be modeled empirically. The first approach using this method was by Shimko (1993), who propose fitting implied volatilities observed in the market onto strike prices through a quadratic polynomial function. Once the volatility smile is interpolated, option prices are calculated from fitted implied volatilities using the Black-Scholes option price formula for a continuum of strike prices. Eventually, the implied risk-neutral densities can be obtained directly by exploiting the results of Breeden and Litzenberger (1978).

Although conventional volatility smile is plotted against strike price, consistency problems regarding the interpolation of implied volatility can arise due to the variable nature of smile smoothness with respect to strike prices from day to day. As an alternative, Malz (1996) suggests smoothing the volatility smile by using option deltas instead of strike prices through a quadratic function since delta smiles have a more stable degree of smoothness. In this respect, Campa et al. (1998) introduce the use of a smoothing spline for fitting implied volatility curves whereas Bliss et al., apply a natural cubic spline in the volatility/delta space and use a smoothness parameter, which weights the degree of curvature of the spline function. Aydin et al. (2011) also apply Malz (1996) methodology for USD-TRY exchange rate using 25-50-75 delta options.

Besides these studies, several papers compare the results of the different approaches. Campa, Chang and Reider (1998) compare three implied RND estimation methods namely cubic splines, an implied binomial tree, and a mixture of lognormal distributions and do not come up with evidence of large differences across the results. Cooper (1999) and Jondeau and Rockinger (2000) compare a number of methods but they are also unable to draw unambiguous conclusions. The literature on the extraction of RNDs is still undecided and no consensus exists as to which methodology is superior. In this paper, the methodology outlined in Malz (2014) is adopted where volatility smile is modeled with respect to deltas using the clamped cubic spline method. The methodology employed by Malz is widely used in practice since it is easy to implement and yields a good fit with respect to actual data.

III. Data and Methodology

This section firstly introduces the data used in the estimation of risk-neutral density estimation. In this regard, the characteristics of FX options data are covered in detail. Methodology section consists of two subsections; data adjustment and RND estimation approach. The data adjustment process provides details about adjusting the data to be used in RND estimation. Then the nonparametric Malz approach with the clamped cubic spline is introduced.

III.I. Data

Option contracts on USD-TRY exchange rate, the price of a US dollar in Turkish lira, are traded in both organized markets and over the counter (OTC) markets. However, the trade volume in the organized market, VIOP Derivatives Market, is quite limited whereas most of the options transactions take place in OTC markets. Therefore, this study uses FX option contracts traded/quoted in OTC markets, where the data is obtained from Bloomberg. One of the difficulties of working with FX options data is the diversity of conventions and products across markets. Firstly, the quotations for option prices are expressed in terms of implied volatilities consistent with the Black-Scholes option pricing formula rather than being directly quoted as prices.

Another characteristic of FX options is that they are traded as combinations of plain-vanilla FX call and put options where most notables are at-the-money, butterfly and risk reversal. Bloomberg quotation for at-the-money options is the implied volatility of the delta-neutral straddle position. Straddle position consists of purchasing at-the-money call and put options with the same maturities and strike prices, which constitutes zero delta for the portfolio.[3] This strategy allows investors to benefit from price changes of the underlying asset regardless of the direction of price movement. In other words, it allows investors to

[3] The delta convention in Bloomberg quotation for USD-TRY is premium-adjusted spot delta. The details about this convention are provided in the following parts.

bet on the volatility of the underlying asset. Accordingly, at-the-money implied volatility quotation is described as follows:

$$Atm_t = \sigma_t(Delta - Neutral\ Straddle) \tag{2}$$

Butterfly strategy consists of a portfolio with long positions in out-of-the-money call and put options and short positions in at-the-money call and put options. Accordingly, butterfly structure is a combination of one strangle and one straddle strategy and it is quoted as the spread between average volatilities of out-of-the-money call and put options and the volatility of at-the-money call/put option.

$$btf_t(\delta) = \left(\frac{\sigma_t^{call}(\delta)+\sigma_t^{put}(\delta)}{2} - atm_t\right) \tag{3}$$

Lastly, risk reversal strategy involves purchasing an out-of-the-money call option and selling an out-of-the-money put option with the same maturity. A long position in this strategy is motivated to benefit from an upward movement in the price of the underlying asset where its cost is cheapened by selling the put option. The quotation for risk reversal can be stated as follows:

$$rr_t(\delta) = \sigma_t^{call}(\delta) - \sigma_t^{put}(\delta) \tag{4}$$

Another important aspect of FX options traded in OTC markets is that they are quoted in terms of deltas, not strike prices. Delta is the ratio of change in the value of an option with respect to a unit change in the price of the underlying asset. For FX options, delta can be stated in two different ways; spot delta and forward delta but the market quotation for options on USD-TRY exchange rate is in terms of spot delta. Spot delta can be expressed as the amount of foreign currency needed to hedge a short option position to buy one unit of foreign currency at the maturity. The spot delta under the Black-Scholes model can be expressed mathematically as follows:

$$C_t^{BS} = S_t e^{-r_f \tau}\, \Phi(d_1) - K e^{-r\tau}\Phi(d_2) \tag{5}$$

$$\delta = \frac{\partial C_t^{BS}}{\partial S_t} = e^{-r_f \tau}\Phi(d_1) \tag{6}$$

where $$d_1 = \frac{log\left(\frac{S_t}{K}\right) + \left(r - r_f + \frac{1}{2}\sigma^2\right)\tau}{\sigma\sqrt{\tau}} \quad d_2 = d_1 - \sigma\sqrt{\tau} \tag{7}$$

$\Phi, S_t, K, \tau, r, r_f$ and σ stand for cumulative normal distribution, spot exchange rate, strike price, time to maturity, domestic currency rate, foreign currency rate and implied volatility, respectively. As can be seen from the formula, delta is a function of all variables listed above and it changes in accordance with them.

Delta denotes the moneyness of an option, which signals the likelihood of being exercised by the option holder at the end of the maturity. However, Bloomberg delta quotation for USD-TRY currency pair is premium-adjusted spot delta, which is the corrected version of spot delta with the option premium. The reason for the quotation of premium-adjusted delta for emerging markets in practice is that option premium is paid in foreign currency.[4] However, previous studies overlook this issue and do not control for the difference between spot delta and premium-adjusted delta. In case of ignoring the premium adjustment and using spot deltas in the estimation of volatility curve, there would be biases in the estimation of volatility smile curve and risk-neutral density. Mathematically, the premium-adjusted delta for a European call option can be expressed as follows:

$$\delta_{call}^{adj} = \frac{\partial C_t^{BS}}{\partial S_t} - \frac{C_t^{BS}}{S_t} = e^{-r_f \tau}\Phi(d_1) - \frac{C_t^{BS}}{S_t} \tag{8}$$

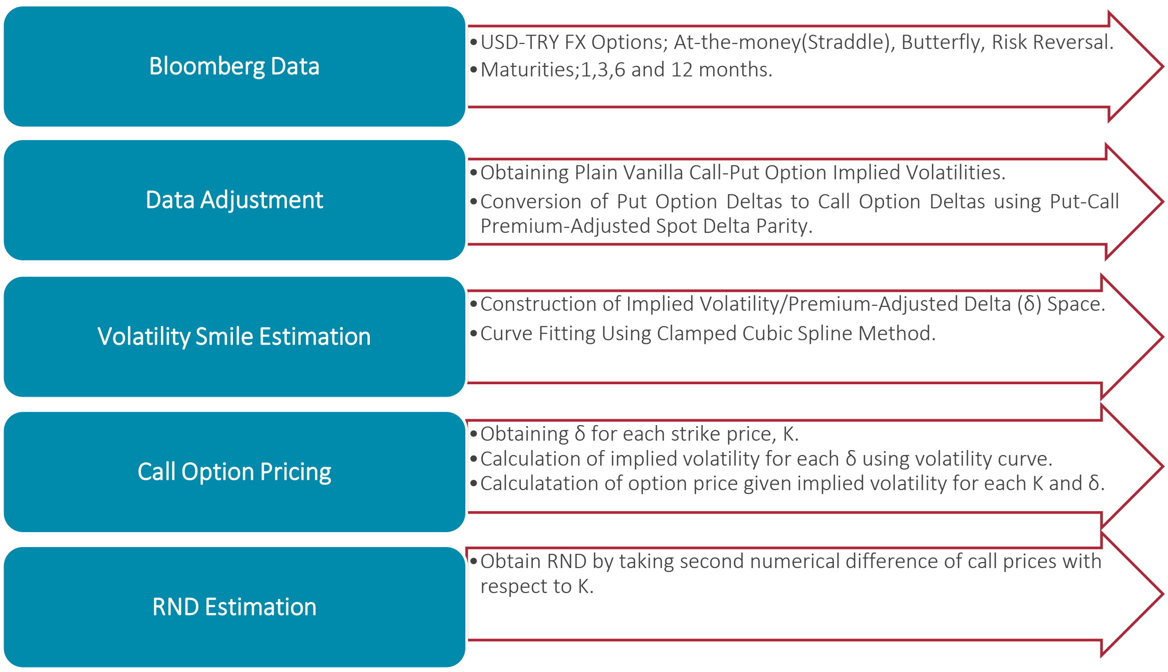
This study performs risk-neutral density estimations for 1, 3, 6, and 12 months using the European FX options written on USD-TRY exchange rate. Bloomberg quotations for the volatilities of risk reversal and butterfly strategies for 10, 15, 25 and 35 deltas together with at-the-money quotation for USD-TRY exchange rate are used for RND estimations. Besides volatility data, USD-TRY forward implied rate and USD LIBOR interest rate are used as domestic and foreign currency rates, respectively. The end-of-day data for USD-TRY spot exchange rate from Bloomberg is another input. The dataset consists of daily observations of all variables listed above from the beginning of January 2010 to December 2018.

[4] For a detailed discussion, Reiswich and Wystup (2010).

III.II. Methodology

RND estimation steps can be summarized as in Diagram 1. Firstly, the main step is the data adjustment, which aims to transform the implied volatilities of structured FX options; at-the-money, butterfly and risk reversal, into implied volatilities of plain-vanilla call/put options with different deltas. Then, premium-adjusted deltas of plain-vanilla put options are translated into deltas of call options using put-call premium-adjusted delta parity. Henceforth the characterization of implied volatility/premium-adjusted delta space is completed, which is crucial in the sense that the volatility-delta pairs obtained in this step are directly used for RND estimation. The next step is to estimate the implied volatility curve using the clamped cubic spline methodology. Then, option prices are calculated based on the estimated implied volatility curve and RND is obtained by taking numerical difference of option prices twice with respect to strike prices.

Diagram 1: RND Estimation Process



Risk-neutral density estimation under nonparametric Malz approach requires the implied volatilities of plain-vanilla options with different deltas. However, as mentioned above, the implied volatilities for plain-vanilla options are not directly observable. Bloomberg provides FX options data in terms of implied volatilities of structured products such as butterfly and risk reversal for premium-adjusted delta levels (0.10, 0.15, 0.25 and 0.35) and at-the-money option which is quoted as the implied volatility of a delta-neutral straddle.

However, using quotations for butterfly, at-the-money and risk reversals, implied volatilities of plain-vanilla call and put options for premium-adjusted deltas can be found out through the following equations.

$$\sigma_t^{call}(\delta) = btf_t(\delta) + atm_t + \frac{rr_t(\delta)}{2} \tag{9}$$

$$\sigma_t^{put}(\delta) = btf_t(\delta) + atm_t - \frac{rr_t(\delta)}{2} \tag{10}$$

Using the equations above, the implied volatilities of plain-vanilla call and put options for premium-adjusted deltas 0.1, 0.15, 0.25 and 0.35 are obtained directly with this step. However, a complete implied volatility curve estimation requires implied volatilities for call (put) options with their relevant deltas. Since the implied volatilities of call and put options with the same strike price are equal, it will be enough to convert put option deltas to call option deltas using put-call premium-adjusted delta parity presented in the following equation:

$$\delta_{call}^{adj} - \delta_{put}^{adj} = \frac{K}{S_t} e^{-r\tau} \tag{11}$$

Put-call premium-adjusted delta parity enables us to calculate premium-adjusted call option deltas for [0.1 0.15 0.25 0.35] put option deltas. Equivalent premium-adjusted call options deltas are different than [0.65 0.75 0.85 0.9]. Further details will be presented in the next section.

Another data adjustment is also required to obtain the delta level for at-the-money option, which is not directly observable. One of the common assumptions used in the previous studies is to use 0.5 as the delta of at-the-money option. Although this can be a reasonable assumption for spot-delta conventions and shorter-maturity options, it might be misleading for premium-adjusted deltas and longer-maturity options.[5] To account for this issue, the implied delta level from the delta-neutral straddle strategy is obtained for each day by finding out the strike price that produces zero premium-adjusted delta for the portfolio. In other words, we solve equation 12 for the strike price given the implied volatility, time-to-maturity, spot exchange rate and interest rates. Once the strike price that satisfies the

[5] The difference between domestic and foreign currency rates also matter here. As the difference between them gets larger, the deltas tend to deviate from 0.5

premium-adjusted delta neutrality for the portfolio is found, corresponding premium-adjusted delta for at-the-money call option can be calculated directly using equation 8.

$$\delta_{adj}^{call} + \delta_{adj}^{put} = 0 \tag{12}$$

After obtaining all inputs for RND estimation, the next step is to provide the details about RND estimation approach. Firstly, with the obtained premium-adjusted delta space and implied volatility levels, the clamped cubic spline methodology is used to estimate the implied volatility curve. Estimation of volatility curve using call option premium-adjusted spot deltas is based on the following equation:

$$\sigma_t^{malz}(\delta) = \gamma_1 + \gamma_2(\delta - \delta(atm_t)) + \gamma_3(\delta - \delta(atm_t))^2 + \gamma_4(\delta - \delta(atm_t))^3 \tag{13}$$

Using implied volatilities for all nine (9) deltas available for each day, the clamped-cubic spline approach produces a fitted implied volatility that matches the data almost perfectly where the clamped property ensures that extrapolated implied volatilities for deep out-of-the-money or deep-in-the-money options are equalized to the implied volatilities of the options with the closest deltas in the input data.[6] One difference over Malz implied volatility estimation is that in equation (13) this study uses delta of the at-the-money (Atm) implied volatility rather than 0.5 as a scale factor. Although this is not critical for short-term maturities, it provides a better fit for the estimation at longer maturities. Results of the estimation of implied volatility as a function of premium-adjusted call option deltas are presented in the next session.

Next step is the calculation of call option prices given the implied volatility as a function of premium-adjusted delta. Here one issue arises with the calculation of call option price using the Black-Scholes formula given each delta level. Since the risk-neutral density is a function of the second derivative of call option price with respect to strike price, the approach requires numerical difference with respect to strike price and the incremental changes in strike prices should be small. Therefore, we calculate call option prices for each given strike price with small but fixed intervals as in Malz (2014). For this purpose given the estimated functional form for implied volatility and known"S_t, τ, r, r_f", we solve equation 8 for each strike price to find out corresponding premium-adjusted delta. Then using the implied

[6] In this approach, the squared errors of actual and fitted implied volatilities are minimized.

volatility function given premium-adjusted delta, call options prices are obtained for each strike price, which allows us to take numerical differences. We do this step for strike price levels from 1 to 15 with an interval size of 0.01.

Once the call option prices for each strike is obtained, risk-neutral density is estimated through taking numerical differences for each strike price twice as depicted below;

$$f_Q(K) = e^{r\tau} \frac{\partial^2 C_t^{BS}(K)}{\partial K^2} \cong e^{r\tau} \frac{C_t^{BS}(K + \Delta K) - 2C_t^{BS}(K) + C_t^{BS}(K - \Delta K)}{(\Delta K)^2} \tag{14}$$

IV. Empirical Findings

FX implied risk-neutral densities provide significant information about how market participants perceive the likelihood of future changes in the exchange rate. However, RND estimation requires non-trivial data adjustment due to the premium-adjusted delta convention and trading of FX options as a portfolio of plain-vanilla options. The use of miscalculated deltas for the implied volatility curve fitting leads to a biased estimation of implied volatility and thus RNDs. This bias is especially more apparent for longer maturities and for out-of-the-money put options. In this regard, firstly we provide an illustration of the comparison of spot and premium-adjusted deltas for various delta levels of call and put options for one-year maturity. Figure 1 depicts the difference between spot and premium-adjusted deltas for all available delta levels on a random day. For instance, if one neglects premium adjustment for call delta equivalent of 10-delta put for one-year maturity, then 90-delta level would be used mistakenly instead of actual ~70-delta level, which creates an error-in-variables problem for estimation. Additionally, the time series of spot/premium-adjusted deltas are presented in Figure 2 for the period from 2010 to 2018[7]. It is observed that premium-adjusted call delta equivalent of premium-adjusted 10-delta put is below its spot counterpart and premium-adjusted deltas are much volatile than spot-deltas due to the option premium. The figures highlight the magnitude of the correction process. As a reflection of using 25-50-75 delta levels and corresponding volatilities (wrong deltas and a smaller number of observations) in the estimation of volatility curve, differences in risk-

[7] "90-delta" term is used only for convenience in the text. Actual call delta equivalent of 10 delta put is different than 90-delta level due to non-negligible domestic interest rates. One can see the effect of domestic interest rates more clearly after 2017 where the related deltas diverge from 90-delta level as the interest rates increase.

neutral densities and its moments obtained for USDTRY are provided in the appendix for further comparison.

Figure 1 - Spot vs Premium-Adjusted Deltas
(In Terms of Call Delta, 1-Year Maturity)

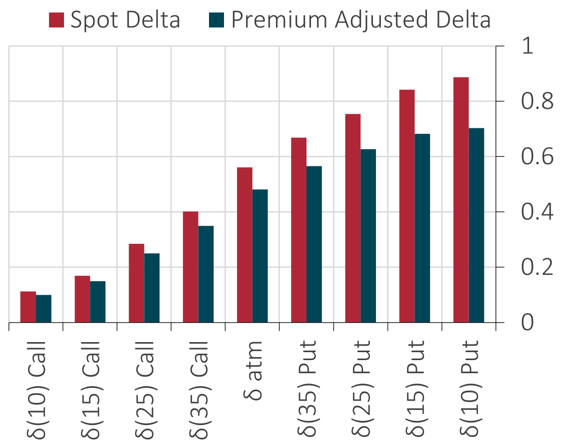
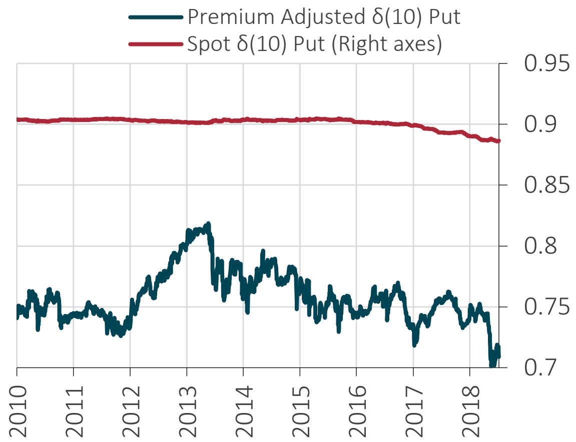


Figure 2 - Spot vs Premium-Adjusted 10 Delta Put
(In Terms of Call Delta, 1-Year Maturity)



As mentioned before, extracting RND is based on the estimation of the implied volatility curve. In this regard, a functional form for the implied volatility is fitted on premium-adjusted delta space using the clamped cubic spline method. The results show that the difference between the fitted implied volatilities and the actual implied volatilities is quite negligible. Figures from 3a to 3d present the implied volatility surface for 1, 3, 6 and 12-month maturities from January 2017 to December 2018. The positive difference between the implied volatilities of out-of-the-money or in-the-money options and at-the-money options indicates the existence of the volatility smile, especially for longer maturity options. Furthermore, the main property of the clamped cubic spline method can be seen from the volatilities corresponding to extreme values of strike prices where the volatility tends to become constant thereafter. Inspection of the volatility surface provides information regarding risk perception of market participants. In this regard, the rise in the level of implied volatilities after August 2018 is striking where the curves shift more than twofold during that period and subside in the following months reflecting the normalization of market sentiment.

Figure 3.a Volatility Surface
1-Month Maturity

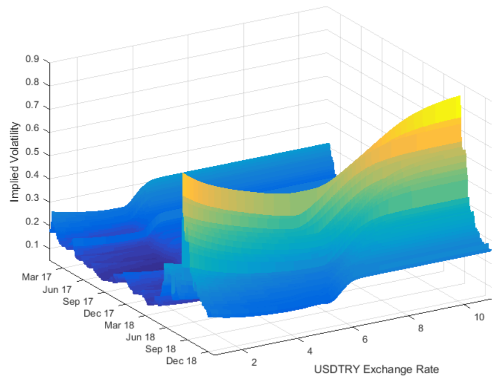


Figure 3.b Volatility Surface
3-Months Maturity

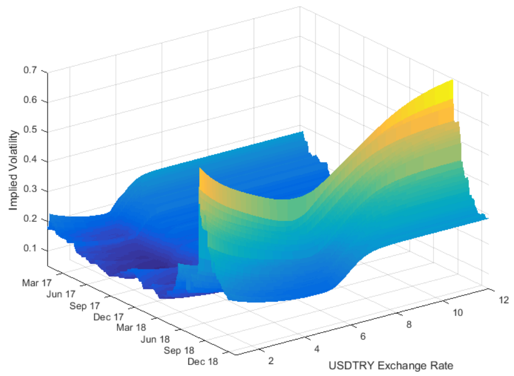


Figure 3.c Volatility Surface
6-Months Maturity

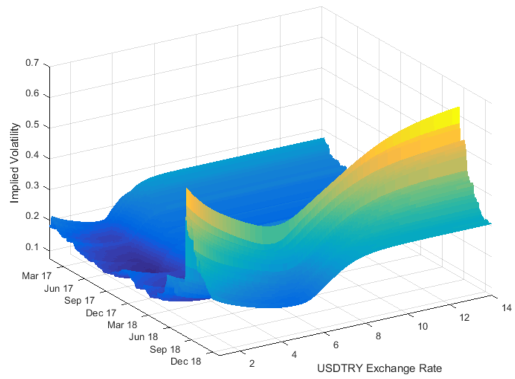
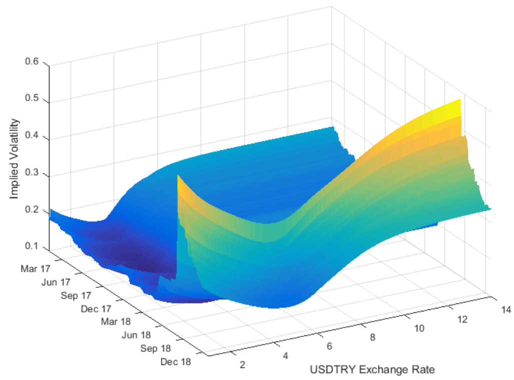


Figure 3.d Volatility Surface
12-Months Maturity



As explained in the previous chapter RND is obtained by taking the second difference of call option price numerically based on the results of Breeden-Litzenberger. To this end, call options on USD-TRY exchange rate are valued using the estimated implied volatilities. Figures from 4a to 4d present the estimated RNDs regarding USD-TRY exchange rate for different maturities. The first observation is that the distributions tend to shift leftwards to the end of 2017, which indicates that the market participants expect an improvement in the value of Turkish lira against US dollar. However, from thereafter the distributions tend to shift rightwards, reflecting deterioration in the expectations for the value of Turkish lira. Besides, the dispersion of the distributions widens sharply after 2018, which reflects the dramatic rise in the uncertainty regarding the risk-neutral market expectations in this period. Accordingly, the likelihood of extreme values for USD-TRY exchange rate tends to increase during the sell-off period in TRY, which is visible through the extended tails of RND.

Figure 4.a Risk-Neutral Density
1-Month Maturity

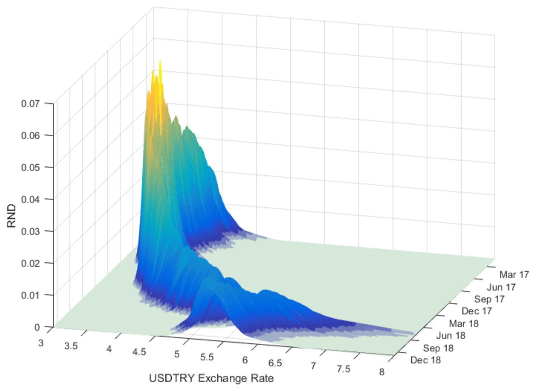


Figure 4.b Risk-Neutral Density
3-Months Maturity

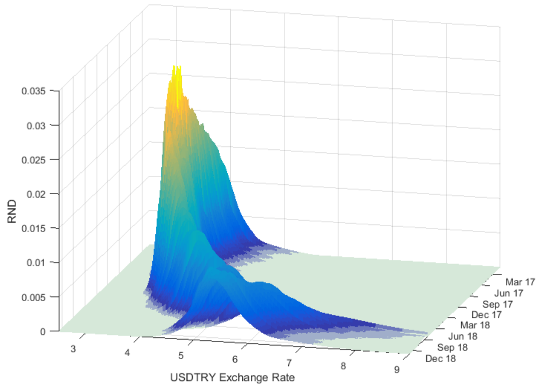


Figure 4.c Risk-Neutral Density
6-Months Maturity

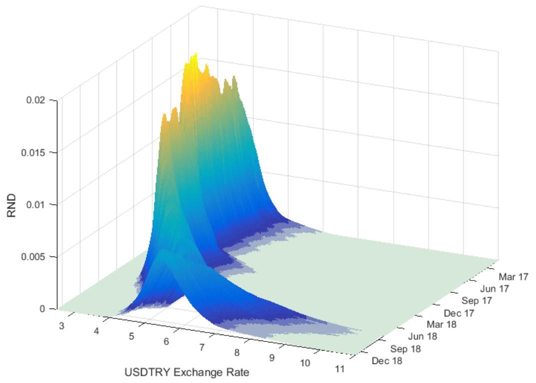
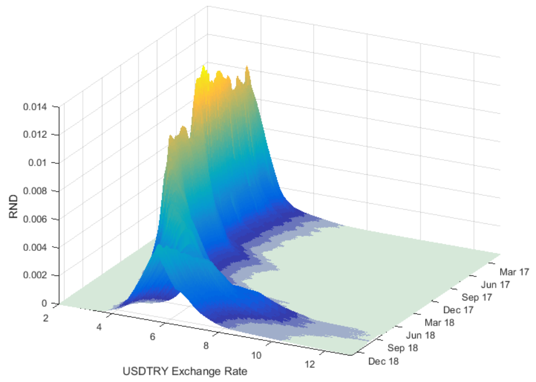


Figure 4.d Risk-Neutral Density
12-Months Maturity



While it is informative to analyze the changes in risk-neutral densities at different time periods, it would be more insightful to see the systematic movements in the moments of the distribution through time which are mean, variance, skewness and kurtosis. These indicators collectively describe the form of the distribution function under risk-neutral measure at hand. In particular, among the moments of estimated RND in this paper, mean gives the expectation of participants in the FX options market for the value of the USD-TRY exchange rate at the maturity. Standard deviation reflects the uncertainty that participants attribute to their expectations. Skewness presents the asymmetry of the risk-neutral distribution measuring the market participants' view regarding the direction towards which exchange rates are expected to move. For example, positive skewness for USD-TRY exchange rate indicates that traders consider depreciation of TRY against USD with respect to expected spot exchange rate more probable than the case of appreciation. On the other hand, kurtosis is often used as a measure of the likelihood of extreme events and increases with outliers in either tail.

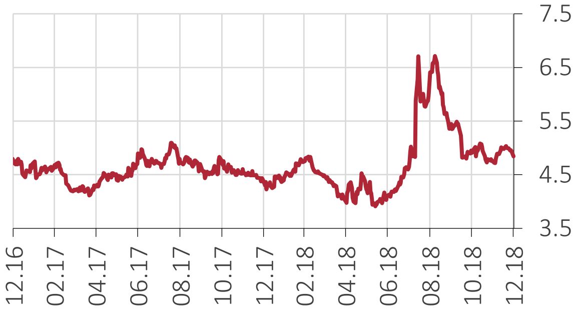
The evolution of the moments since 2017 for the implied risk-neutral distributions obtained from options on USD-TRY with 1-month maturity are depicted below. In line with the evolution of USD-TRY exchange rate since the last quarter of 2017, investors' expectations for future exchange rate levels have increased consistently and peaked in August 2018 sell-off period after then subsiding around a stable level. As an indicator of uncertainty for future exchange rates, standard deviation of the risk-neutral distribution hovers around within a band most of the time until May 2018. However, a dramatic rise in the standard deviation is observed in the aforementioned sharp depreciation period, which points out the degree of uncertainty in the expectations of market participants regarding future exchange rates. The skewness of RND through time takes only positive values even when the whole period is considered since 2010. In the meantime, the degree to which the market attains a relatively higher probability to the future TRY depreciation as compared to the TRY appreciation against US dollar oscillates in an interval except for the August 2018 sell-off period. Finally, kurtosis, as an indicator for the probabilities of dramatic up and down movements in the future exchange rate, demonstrates similar movements as skewness.

Figure 5.a 1st Moment (Mean) of RND
1-Month Maturity

Figure 5.b 2nd Moment (Standard Deviation) of RND
1-Month Maturity

Figure 5.c 3rd Moment (Skewness) of RND
1-Month Maturity

Figure 5.d 4th Moment (Kurtosis) of RND
1-Month Maturity



To illustrate how perceptions of market participants are reflected in RNDs, Figure 6 compares the distributions for specific days. Estimated RNDs for three different days show the changes in tail probabilities distinctly. Table 1 gives the descriptive statistics for selected RNDs in Figure 6. RND for the 13th of August presents a higher median expectation as well as higher uncertainty and tail risks compared to other dates. Effect of a higher uncertainty shows itself as the dispersion whereas the skewness depicts the shape of RND where more positive numbers mean more probability is assigned to USD-TRY levels above mean. Kurtosis, on the other hand, gives the respective tail risk probabilities where the magnitude of this presents an important market assessment regarding extreme changes in the USD-TRY exchange rate. For a detailed inspection of tails, cumulative probabilities corresponding to future exchange rates reaching levels higher than 10 % and 20 % of each day's spot exchange rate are shown in Figure 7. With this analysis, it is possible to gauge the probability of tail events for USD-TRY exchange rate in one-month horizon. It can be seen that extreme market risks to currency are captured well over time where the stress periods exhibit noticeable hikes.

Figure 6 - RND for USD-TRY Exchange Rate
1-Month Maturity

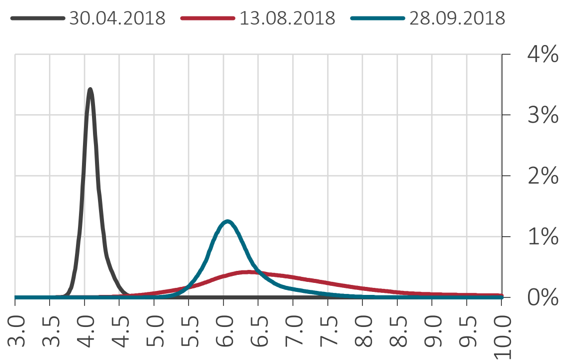


Figure 7 - Tail Risk Probabilities
1-Month Maturity

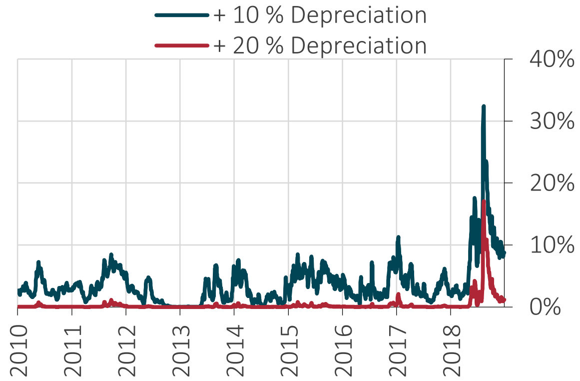


Table 1: Implied Moments

Dates	Mean (μ)	Standard Deviation (σ)	Skewness (α_3)	Kurtosis (α_4)
30.04.2018	4.11	0.14	0.64	4.00
13.08.2018	7.02	1.41	1.47	6.28
28.09.2018	6.18	0.45	1.18	5.36

V. Conclusion

FX option implied risk-neutral densities are important tools used by investors, risk managers and policymakers in order to deduce market views about the future path of the exchange rate and to price derivative products with the same underlying asset. These densities also provide insight about the uncertainty, direction of market view and the possibility of extreme risk scenarios for future exchange rates. Given the wide range of its uses, it is critical to estimate and interpret the changes in RNDs. In this regard, this study estimates RND for USD-TRY exchange rate for various maturities through nonparametric Malz approach, which is one of the most widely used RND estimation methods.

RND estimation for FX options requires a non-trivial data adjustment since structured products are traded/quoted instead of plain-vanilla options in OTC markets and the conventions are in terms of deltas rather than strike prices. Therefore, several adjustments are needed to obtain implied volatility/premium-adjusted delta pairs, which are essential to RND estimation. Accordingly, one of the main contributions of the study is the use of premium-adjusted spot delta, where implied volatilities of FX options for USD-TRY until 1-year maturity are quoted. Although many previous studies neglect this issue, it leads to biased estimation for implied volatility curve and RND, especially for longer-term options.

Results of the study deliver several important points for the USD-TRY FX options and expectations about future exchange rates. One of the findings is that changes in the level of implied volatility surface reflect deterioration in the expectations for USD-TRY exchange rate. Additionally, shape of the curves presents the volatility smile for USD-TRY options where out-of-the-money and in-the-money option implied volatilities are higher than the at-the-money option implied volatilities. Moreover, empirical evidence for RND estimation shows that USD-TRY option implied distributions tend to be more dispersed around expected exchange rate reflecting the uncertainty that market participants assigned to USD-TRY exchange rate. Moreover, distributions tend to be more right-skewed and fat tails become more apparent reflecting the non-negligible probabilities for extreme depreciation risks in Turkish lira.

Besides the visual inspection of the distributions, moments up to fourth-degree are calculated in order to describe the shape of the distributions. These parameters provide a shortcut to infer about the current state of the expectations as well as the changes in market trends through time. Especially in the third quarter of 2018, expectations for the level and dispersion of future exchange rates increased dramatically. The last evidence presented in this study is the calculation of the likelihood of worst-case scenarios for Turkish lira against US dollar. Tail probabilities reflecting the probabilities of Turkish lira depreciating more than 10 % and 20 % are drawn. Results imply that the likelihood of tail events for Turkish lira has subsided recently after a dramatic rise in the sell-off period. To sum up, this study offers valuable tools for various parties in terms of extraction of USD-TRY exchange rate expectations, asset pricing, portfolio risk management, and financial stability.

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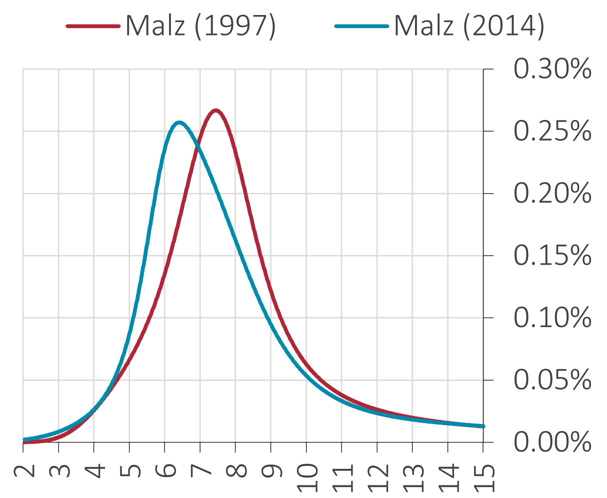
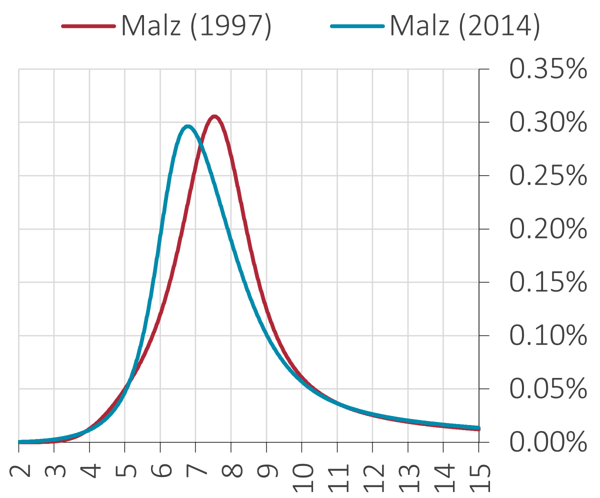
Appendix

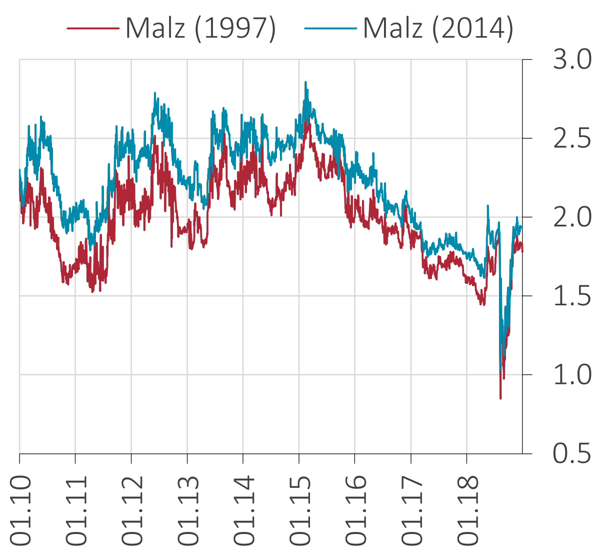
Comparison of RNDs-13.08.2018
12-Months Maturity



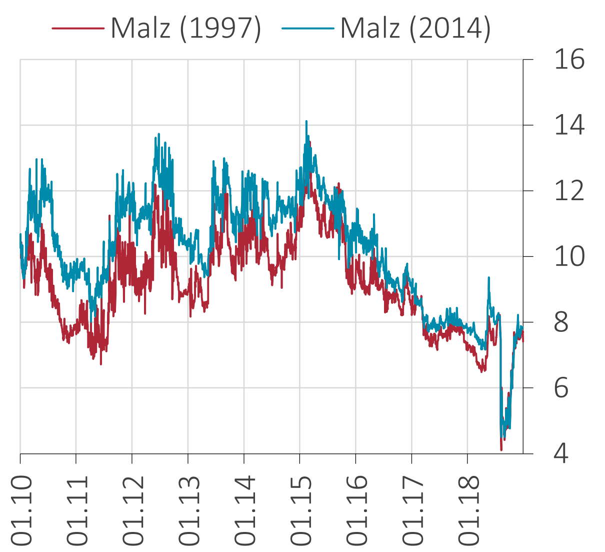
Comparison of RNDs-05.09.2018
12-Months Maturity



Comparison of Skewness
12-Months Maturity



Comparison of Kurtosis
12-Months Maturity



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