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THE LIBOR RATE TRANSITION

On the implementation of transition approaches
from Interbank Offered Rates to Risk-Free Rates
and the corresponding value impact

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Abstract

This research is conducted with the aim to assess whether currently proposed transition approaches from IBORs towards risk-free rates are viable from a supervisor perspective. We propose a model to improve the currently preferred transition approach and we investigate the transition impact in terms of value transfer on linear and non-linear derivatives. Firstly, we identify the difference in characteristics of IBORs and the proposed risk-free rates which serve as alternative reference rates. Secondly, we evaluate the currently proposed transition methodologies by the International Swaps and Derivatives Association and apply the preferred methodologies to the risk-free rate for spread adjustment and transformation to a term rate. Subsequently, we develop a regression model to predict the corresponding Libor based on the adjusted risk-free rate and additional risk premium. We analyze furthermore if the regression model can be used to backfill historical data to overcome the practical implementation problem of the historical spread approach. Finally, we show that value transfer happens to linear and non-linear derivative contracts as a result of change in respectively level and volatility of the alternative reference rate.

Keywords Interbank Offered Rate · Risk-Free Rate · Compounded Setting in Arrears · Spread adjustment · Linear derivatives · Non-Linear derivatives

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Karlijn Bos, 28 June 2019

Contents

List of acronyms

ARR	Alternative Reference Rate
BBA	British Bankers' Association
CDS	Credit Default Swaps
ECB	European Central Bank
FCA	Financial Conduct Authority
FRA	Forward Rate Agreement
IBOR	Interbank Offered Rate
IRS	Interest Rate Swap
ISDA	International Swaps and Derivatives Association
LIBOR	London Interbank Offered Rate
NPV	Net Present Value
OIS	Overnight Index Swap
RFR	Risk-Free Rate
SOFR	Secured Overnight Financing Rate
SONIA	Sterling Overnight Index Average

Chapter 1

Introduction

Interbank Offered Rates (IBORs) play a key role in the global financial services industry for more than forty years. IBORs, the collective term for Libor, Euribor, Tibor and similar others, represent the cost of funds at which large global banks borrow from each other on the short-term unsecured interbank market [1]. IBORs serve as a reference rate for financial variable-rate instruments [2]. They are important benchmarks with a total market exposure worldwide of over $370 trillion [3]. However, the UK's Financial Conduct Authority (FCA), announced in July 2017 that they intend to no longer support banks currently participating in setting Libor to contribute rates after the end of 2021 [4]. As a result, in several jurisdictions working groups are established to put effort in finding a replacement rate for Libor. For example, in the United States the Federal Reserve appointed a committee and a working group is established in the Euro-area under observation of the European Central Bank (ECB).

The decision to replace Libor is justified by the argument that Libor is based on an insufficient number of actual underlying transactions and the approach is therefore vulnerable to manipulation. As a solution Libor and other IBORs are being replaced by alternative reference rates (ARRs) [2]. Transitioning from IBOR to an ARR could impact the value of financial contracts due to the different underlying characteristics of the ARR resulting in a different behaviour e.g. in terms of volatility. Working groups per jurisdiction are currently working on developing fallback rates in case IBOR is permanently discontinued. Despite the development of specific transition methodologies is still in progress, it is certain that it will impact a broad range of financial products used by a wide range of market participants.

In this research we assess if the current proposed transition methodologies are a viable solution from a supervisor perspective. To address this question we evaluate the transition approaches in terms of; i) adjustment for differences between the rates, ii) practical implementation and iii) value transfer. We quantify the transition impact by means of value transfer on linear and non-linear derivative contracts. This chapter starts with the problem context and research motivation. Subsequently, a research design is developed.

1.1 Problem Context

Libor was first launched by the British Bankers Association (BBA) in 1984 as the BBA Interest Rate Settlement Rates (BBAIRS), which eventually became BBA Libor. Member banks required the BBA to devise a benchmark that could serve as uniform underlying rate for a relatively new class of financial instruments. Among these instruments were interest rate swaps (IRS), forward rate agreements (FRAs) and foreign currency options [5]. Over the years, Libor became the primary benchmark for global short-term interest rates. Although Libor is referred to as "the world's most important number" [6], it is actually a list of figures quoted for different maturities ranging from overnight to one year. By the first publication in 1986, Libor was published in three currencies: US Dollar, Japanese Yen and British Sterling. Since then, the market footprint of Libor has widely expanded.

The Libor era is facing an end since the number appeared to be manipulated by banks. Each day a panel of up to 18 banks are queried on how much they could borrow funds from other banks for loans in various currencies and maturities [7]. The central party that collects these quotes disregards the upper and lower 25% and calculates a simple average of the middle 50%. In periods of economic upswing, the number provided by banks to the central party was artificially distorted in order to make profits on derivative bets. In periods of economic downswing banks manipulated the rate by showing they could borrow for less money than actually the case, in order to look stronger. As a result, settlements have been reached between banks and governments and global regulators have taken several steps to strengthen IBOR, including appointment of a new benchmark administrator, ICE Benchmark Administration [2]. However, IBORs are no longer the desirable benchmark due to systemic risk concerns[1]. The systemic risk concerns are caused by i) the manipulative character of the rate in combination with ii) low liquidity in underlying markets. The lack of robustness and durability of IBORs potentially results in quotes that are not representative of the current market.

i) Manipulative character

IBORs are not based on actual market transactions but based on estimations by banks. This rather subjective approach makes the rate vulnerable to manipulation since banks have incentives to quote rates in their advantage. The proposed alternatives by working groups involve rates with a risk-free nature since they are transaction-based.

ii) Low market liquidity

At the end of each day banks can borrow or lend money on the interbank market to manage their own risks. The supply and demand of money in this market affects the interest rate charged. The decline in market activity on which IBORs are based [8], the unsecured interbank term borrowing market, makes is hard to propose a good reference number for the rate global banks charge each other.

In order to face these problems, working groups per currency region (USD, GBP, CHF, EUR, JPY) are developing fallback methodologies to ensure a risk-free rate (RFR) derivatives market. Whether this process is still in progress, the proposed methodologies involve rates with

[1]Systemic risk refers to an event that triggers a collapse in a wider environment.

a (nearly) risk-free nature since they are transaction-based instead of the current subjective approach. Furthermore, these rates are fully based on liquid markets to overcome the low liquidity problem. However, transitioning to a fallback approach that involves RFRs offers two technical challenges that need to be tackled; i) IBORs are term rates whereas RFRs are overnight rates and ii) IBORs contain a risk premium whereas RFRs are (nearly) risk-free.

i) Overnight rate versus term rate
IBORs are forward-looking term rates, quoted for multiple tenors up to one year. As an example, GBP Libor 3M is the rate for which you can borrow money today with a payment date due 3 months in the future. This rate is forward looking since it is based on future expectations of the market. RFRs are not quoted for multiple tenors but only as overnight rates; quoted every day as a measure of interest rates paid on deposit transactions. To transform this overnight rate to a term rate, a possible approach is using observed data during the period and calculate the backward-looking rate. Proposed methodologies for converting overnight rates to term rates are elaborated on in Chapter 2.

ii) Risk-free rates versus Risk premium
Since IBORs are based on interbank lending, they incorporate a risk premium that consists of several components such as credit risk[2] premium and term premium. The latter is a compensation for uncertainty during the lending period. Since RFRs are overnight rates, they are (nearly) risk-free without the presence of a risk premium. Developing a fallback method based on RFRs requires adding a risk premium by means of a spread to the RFRs. This is required to acquire a comparable rate to the IBOR and prevent value transfers. Proposed methodologies for adding a spread to RFRs are elaborated on in Chapter 2.

These key structural differences will drive ARR - IBOR basis risks that will need to be measured and managed [9] to overcome valuation and risk management challenges.

1.2 Motivation

The combination of complexity and large exposure requires deep understanding of the transition impact to ensure operational readiness, mitigate risks and overcome technical challenges. Major risks that coincide with the transition away from IBORs to ARRs are: i) Risk management challenges, ii) Value transfer and iii) All other risks.

i) Risk management challenges
If we transition away from IBOR to an ARR, several risk management challenges occur. One of the main risk management challenges is compliance with the 'Fundamental Review of the Trading Book (FRTB)'. This standard sets the minimum capital requirements for market risk. Historical data is required in order to calculate the minimum capital requirement. Since historical data is not available for all RFRs, a significant risk management challenge occurs. Furthermore, the changed characteristics of the underlying rate when replacing IBORs by ARRs imposes risk management challenges.

[2]Credit risk refers to the risk that the borrower cannot meet its obligations to the lender

ii) Value transfer
IBOR includes a risk premium whereas RFRs are (nearly) risk free. A spread should be applied as proxy for the risk premium. The spread methodology will influence the level of the new RFR. If a transaction is repriced with an increased or decreased rate value transfer could happen, e.g. when a borrower pays the increased (decreased) rate, there is a value transfer to the lender (borrower). Furthermore, the RFR is an overnight rate which should be adjusted to a term rate. This adjusted RFR has different characteristics compared to current IBORs, resulting in possible value transfers as well.

iii) All other risks
The transition methodology in terms of timing is not specified at this point. The possible options are: i) Two rates are published parallel in the market, ii) Permanent IBOR discontinuation simultaneous with announcement of discontinuation, iii) Permanent IBOR discontinuation announced in advance. Furthermore, even more uncertainty is added since it is currently unknown whether only new contracts will refer to the ARR or legacy contracts as well. As two rates published parallel in the market will result in potential arbitrage opportunities, it is likely that a sudden or announced permanent discontinuation of IBOR takes place. Although specific transition details are unclear, several risks will occur. For example, operational risks, legal risks, risk modelling challenges and the update of valuation tools and hedging strategies.

This research focusses on i) Riks management challenges and ii) Value transfer. We aim to give an overview of potential transition methodologies and corresponding value transfer impact based on current available information. Note that this is subject to change since work is still in progress at this stage, resulting in a likelihood that more information will become available that is not included in this research at the time of publication. This research will contribute by identifying if current transition methodologies are a viable solution and understanding the transition impact in terms of value transfer. Both are crucial for an orderly transition as well as creating a liquid and risk-free rate derivatives market.

1.3 Research Design

The main question of this research is formulated as:

"Are currently proposed methodologies for the transition from Interbank Offered Rates to Risk-Free Rates a viable solution and what is the corresponding value impact?"

We identify a 'viable solution' as a solution that, from a supervisor perspective, addresses the differences between IBORs and RFRs, a solution that is suitable for practical implementation and reduces the potential for value transfer. To identify the value transfer impact, we distinguish between linear and non-linear derivative contracts.

We identified the following research objectives in order to answer the main question.

Identify currently proposed transition approaches to adjust RFRs for differences with IBORs
Develop a model to predict Libor based on a dynamic spread approach and mitigate implementation problems and risk management issues
Investigate the transition impact in terms of value transfer
Conclude on transition approaches as viable solutions and the inherent value impact

1.3.1 Assumptions and Scope

Working groups in each jurisdiction are currently working on finding robust and efficient transition solutions that are simple and easy to understand for market participants. Five working groups are putting effort in identifying alternatives for the i) GBP Libor, ii) USD Libor, iii) EURIBOR and EUR Libor, iv) CHF Libor and v) JPY Libor, JPY Tibor and Euroyen Tibor. Both the pace of work and the availability of historical data of the RFR differs per currency area. The scope of this research is limited to the Sterling Overnight Index Average (SONIA) as for this rate historical data is available. SONIA is the proposed RFR in the GBP currency area. We extend our scope since we aim to backfill data for rates without history. We do this for the proposed RFR in the United States, the Secured Overnight Financing Rate (SOFR). SOFR has a short data history back to April 2018. This would be a first step to make implementation of the transition approaches possible to RFRs without data history.

The following assumptions are applicable to this research, based on assumptions defined by ISDA [10]:

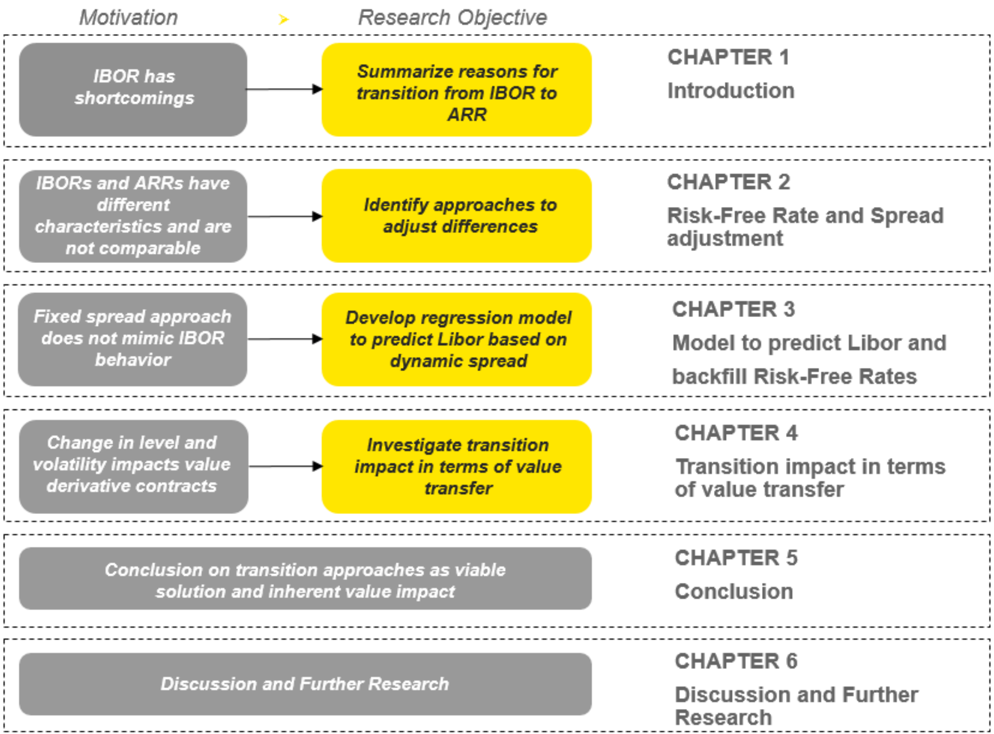
- The RFR fallback methodologies will apply if the corresponding IBOR is permanently discontinued, based on defined triggers. We do not take into account methodologies for a case in which both the IBOR and fallback rate are parallel presented in the market.
- The fallbacks are based on the RFRs that have been identified by the corresponding working groups as part of the recent global benchmark reformations. We focus on SONIA in this research since historical data of this rate is available.
- This research seeks input on the transformation approach in which adjustments are applied to RFRs. Since there are differences between the IBORs and RFRs in each currency area, these adjustments are potentially not suitable to all proposed RFRs.
- As work is still in progress, it is likely that more information will become available which is not included in this research at the time of publication.

1.3.2 Methodology and Thesis Outline

As the IBOR transition to an ARR is a relatively new topic, there is rarely scientific literature available about the transition impact and inherent risks. Therefore, we additionally consult reports from working groups in different jurisdictions. For the transition approaches that are currently proposed, we consult reports published by the International Swaps and Derivatives Association (ISDA), which is the organization that develops best practices for the derivatives market. At the moment of writing, ISDA has proposed transition approaches and a follow-up report with feedback of market participants on these approaches. In this research we assess; if these approaches are viable methods to overcome technical challenges due to different characteristics of IBOR and RFR; if the approaches can be applied based on current available market data; and we identify the impact in terms of value transfer. All these steps are required to enable answering the main research question.

Figure 1.1 shows the motivation for each research objective and the thesis outline. In this chapter we elaborated on the motivation for transition to an ARR and inherent problems regarding to the differences between the two types of rates. In Chapter 2 we discuss the proposed transition methodologies by ISDA and apply the preferred approaches for respectively RFR and spread adjustment to SONIA. In Chapter 3 we develop a model to assess whether we are able to predict Libor based on a dynamic spread approach. Furthermore, we use this model to backfill data for currencies without data history of the proposed RFR. In Chapter 4 we investigate the transition impact in terms of value transfer. We assess whether value transfer is already happening and make a distinction between value impact on linear and non-linear derivative contracts. In Chapter 5 we present our conclusions and the discussion and recommendations for further research are elaborated on in Chapter 6.

Figure 1.1: Methodology and Thesis Outline



Chapter 2

Risk-Free Rate and Spread Adjustment

There are two major differences between the nature of IBORs and RFRs resulting in key challenges concerning the transition. Firstly, the tenor of the quotes is different. The proposed RFRs are referenced by overnight rates, which are set daily and serve as a predictor for short-term interest rate movements. IBORs, on the other hand, are quoted as overnight rates but as well as forward-looking term rates, for tenors up to 1 year. A forward-looking term rate is based on expectations about the future and required for determining a price at the beginning of a period. When the transition occurs from term rates to overnight rates, the proposed RFRs should be adjusted to make them comparable to IBORs.

Secondly, the risk premium included in the rate differs. The RFRs are (nearly) risk-free since they are derived from market transactions, referenced by Overnight Index Swaps (OIS). The proposed alternatives in the US (SOFR) and UK (SONIA) are respectively based on secured and unsecured transactions resulting in (nearly) risk free rates in which a risk premium is excluded. Since IBORs are offered in the interbank market, credit risk is present, which is one of the components of the total risk premium.

The presence of risk premium in IBORs compared to the excluded or limited presence of a risk premium in the (nearly) RFRs offers several challenges when a transition happens. Key challenges that occur, in case the risk premium added to the RFR is not aligned with the risk premium in the IBOR rate, are valuation and risk management challenges. These structural differences will drive ARR-IBOR basis risk that will need to be measured and managed [9]. In this chapter we elaborate on the approaches proposed by ISDA for respectively RFR and spread adjustment.

2.1 Risk-Free Rate adjustment approaches

Since RFRs are referenced by daily overnight rates while IBORs are term rates, a transformation of the RFR from spot rate to term rate is required to make comparison possible with the corresponding IBOR and to make sure that rate characteristics are aligned. ISDA proposed four methodologies to overcome technical issues when transforming RFRs to term rates. These methodologies are developed based on the following criteria:

i) Simplicity and ease of calculating (*Understandable*)
ii) Data requirements (*Data availability*)
iii) Similarity with the structure of overnight index swaps (OIS) that reference RFRs (*Similarity with OIS*)

These criteria are satisfied to different degrees by the individual approaches. An indicative overview of the satisfaction of criteria by each approach is given in Table 2.1. In this section we elaborate on the different approaches and their advantages and disadvantages.

Table 2.1: RFR adjustment approaches and corresponding criteria satisfaction

	Understandable	**Data availability**	**Similarity OIS**
Spot Overnight Rate	+	+	-
Convexity-adjusted Overnight Rate	-	+	-
Compounded Setting in Arrears Rate	+	-	+
Compounded Setting in Advance Rate	+	-	+

Underlying the proposed approaches the following assumptions will hold:

i) The fallbacks will apply if the relevant IBOR is permanently discontinued
ii) The fallbacks will be applied to the alternative RFRs that have been identified for corresponding IBORs as part of global benchmark reformations

The current ISDA consultation covers GBP, CHF, JPY and AUD. However, at this moment, it seems unlikely that different conclusions will be reached for EUR and USD. For these currencies no historical RFR data is available which is the potential reason that they are out of scope of the current consultation.

Spot Overnight Rate
In the spot overnight rate approach, the fallback rate will be the RFR that sets on a date a few business days prior to the start of the corresponding IBOR tenor. The mathematical equations to obtain the spot overnight rate are given in Appendix A.1.1. As shown in Table 2.1, this approach is easy to understand and simple to implement since required data is readily available. Another advantage is that risk-free market conditions are reflected for one day borrowing prior to the start of the IBOR tenor. However, this approach is not selected as the preferred approach since it does not mimic the structure of OIS. Other disadvantages are the ignorance of inherent variation in RFRs over different tenors. Furthermore, there is a chance that this rate is more volatile than it should be when it is considered as a term rate.

Convexity-adjusted Overnight Rate

The convexity-adjusted overnight rate is based on the spot overnight rate approach and differs in the addition of a first-order adjustment for convexity. See Appendix A.1.2 for the mathematical derivation. Since a convexity-adjustment component is added compared to the spot overnight rate, this approach is more complex. Therefore a negative sign is depicted in Table 2.1 for the criterion 'Understandable', but note that this is a subjective qualification. In our opinion, this approach is not desirable since it has the same disadvantages as the spot overnight rate and the added complexity does not outweigh the benefit of the added component.

Compounded Setting in Arrears Rate

This is the preferred approach by market participants resulting from the feedback paper on the ISDA consultation [11]. The main advantages of this approach are the easiness to understand and it mirrors the OIS structure, see Table 2.1. The main disadvantage however, is that the information needed to calculate this rate, is only available at the end of the relevant period. In our opinion, this is critical since it adds another layer of uncertainty during the fixing period. Furthermore, the rate resulting from this approach may not match expectations present in forward looking rates.

Compounded Setting in Advance Rate

The main advantage of the compounded setting in advance rate over the compounded setting in arrears rate, is that this rate is available at the beginning of the fixing period. Besides, it has the same advantages of the compounded setting in arrears rate. The mathematical equations are given in Appendix A.1.3. There is no direct consensus whether both rates are understandable, but from a quantitative perspective we are of the opinion they are and therefore a positive sign is shown in Table 2.1. In contrary with the previous approach, the compounded setting in advance rate does not capture interest rate changes during the relevant period [11]. In our opinion, this is a major drawback since market conditions during the relevant period are not included.

To conclude, none of the proposed approaches satisfies all the criteria. In our opinion it is important that the selected approach is a viable solution and aligned with the current OIS structure. Therefore we prefer the last two options. Now we have to make a trade-off between a rate that captures market conditions but which is only known at the end of the period, and a rate known at the beginning of the period which excludes interest rate changes during the relevant period. Since the fallback approach should be robust and comparable to the current IBOR, we choose for the compounded setting in arrears rate as best RFR adjustment approach so far. This opinion is aligned with the preferences of market participants. In this chapter we will further elaborate on the compounded setting in arrears approach and further investigate the implementation potential and operational readiness based on the shortcomings.

2.2 Compounded Setting in Arrears Rate as RFR adjustment approach

The compounded setting in arrears approach, to transform RFRs to a term rate, relies on a backward-looking method whereas IBORs are forward-looking rates. The former is based on observations while the latter is based on expectations. Figure 2.1 depicts a visualization of the compounded setting in arrears rate approach. The RFR that follows from this method is hereafter referred to as the 'adjusted RFR'.

The term period starts at T and ends at the payment due date, in this example after a period of 3 months ($T+3M$). A few business days, in this example one business day, prior to the payment due date is the *set date*, on this day the rate will be set. The daily values of the overnight rate are compounded daily from T up to the set date. The space between each dot in this figure represents the overnight accrual period. The day or days between the set date and payment date allow for payment calculation and settlement. As mentioned earlier, the main disadvantage of this methodology is that the information needed to determine this rate is available at the set date and not at the start of the term period. Furthermore, actual interest rate movements over the period may not reflect prior expectations, resulting in an additional spread. One of the advantages however, is that it reflects actual daily interest rate movements during the period. Secondly, since the interest rate is derived from daily compounded overnight rates it is less volatile than the spot overnight rate itself.

Figure 2.1: Visualization of compounded setting in arrears rate calculation method

Translating the approach to a mathematical formula, the following will be obtained to calculate the compounded setting in arrears rate at the set date [10].

$$ARR_f(t) = \frac{1}{\delta_f}\left(\prod_{u=T}^{T+f-1bd}(1+\delta_u RFR_u) - 1\right) \tag{2.1}$$

Where δ_f is the cash day count fraction for the accrual period (e.g. $\frac{90}{365}$ for a 3 month period that consists of exactly 90 days, based on 365 days in a year). $T+f$ is the payment date due, in our example $T+3M$. The set date is prior to the payment date due, e.g. 1 business day. Over the compounding period from T to $T+f-1bd$ (set date), the overnight rates are compounded daily. Where δ_u is the cash day count fraction for the overnight accrual period from u to $u+1bd$ (e.g. $\frac{1}{365}$ for a Tuesday when the previous quote was given on Monday, and $\frac{3}{365}$ for a Monday when the previous quote was on the prior Friday). RFR_u is the observed RFR for the overnight accrual period from u to $u+1bd$.

2.2.1 Compounded Setting in Arrears applied to SONIA

In this section we apply the compounded setting in arrears rate to SONIA, the proposed RFR in the UK. SONIA data is obtained from *Reuters* over a period of *01-01-2007* up to

31-12-2018. Figure 2.2 depicts the observed SONIA rate versus 'SONIA adjusted'; a 3-months backward-looking term rate in basis points (bp) that follows from the compounded setting in arrears method. Note that SONIA adjusted can be calculated up to *30-09-2018* as data of future 3 months is required to calculate SONIA adjusted. The first observation from Figure 2.2 is that SONIA adjusted is less volatile due to the averaging character of the compounded setting in arrears approach. Secondly, SONIA adjusted moves ahead of the observed SONIA since it is a backward-looking term rate; based on realized SONIA data of the future 3 months. Therefore, Figure 2.2 shows that the difference between the rates is larger in volatile and uncertain periods compared to stable periods.

Figure 2.3 depicts SONIA adjusted and GBP Libor 3M. Firstly, we observe that SONIA adjusted is less volatile than GBP Libor. Furthermore, we observe a spread between the two in both stable and volatile times. This is the result of the risk premium present in GBP Libor but not present in the RFR. We transformed SONIA to a term rate in a mathematical way, but the risk premium should be added to SONIA adjusted in order to mimic IBOR characteristics. Therefore, we add a spread to the RFR to make comparison possible between the two rates and reduce potential value transfer. The proposed spread methodology by ISDA and execution of this methodology is described in the next section.

Figure 2.2: SONIA versus SONIA Adjusted 3M

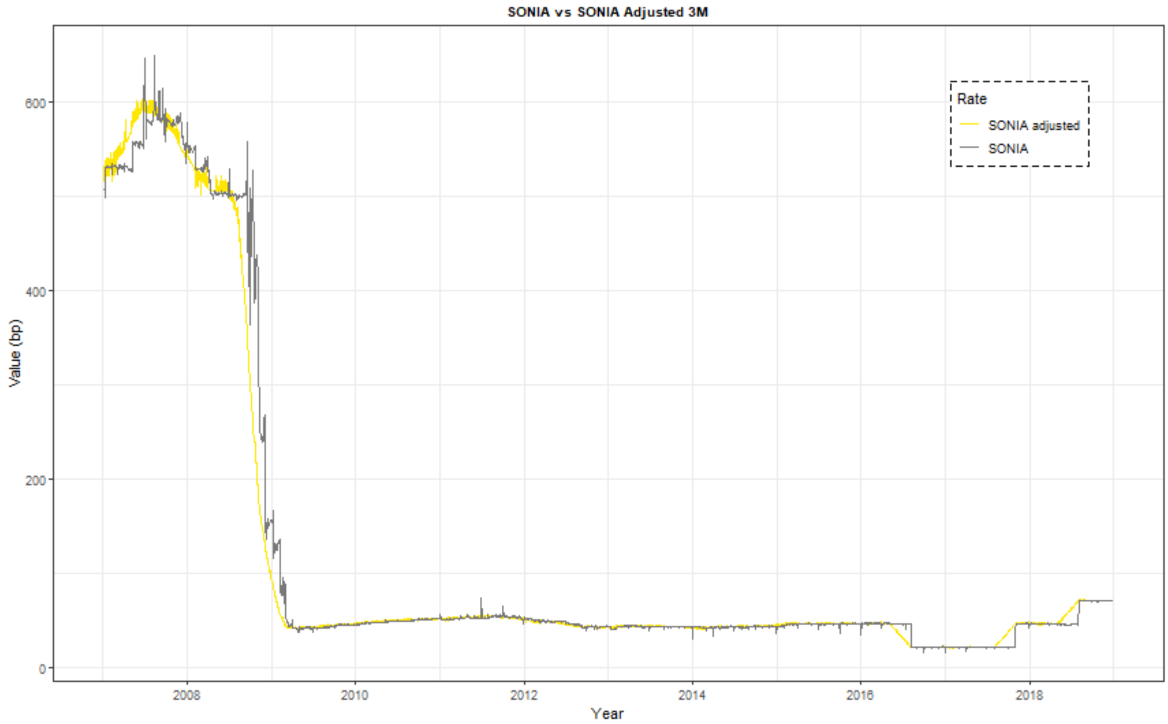
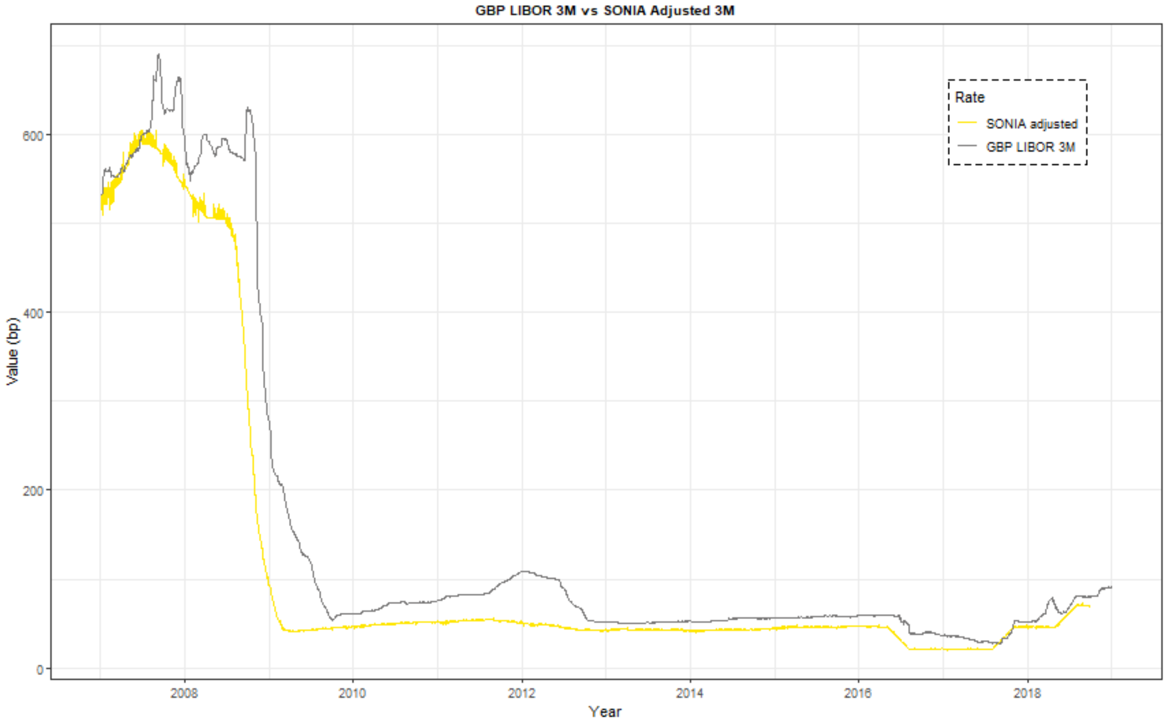


Figure 2.3: GBP Libor 3M versus SONIA adjusted 3M



2.3 Spread adjustment approaches

IBORs contain a risk premium while the newly proposed RFRs are (nearly) risk-free. As these risk premium factors are not present in the current RFR, we will add a spread to the RFR. The proposed approaches to calculate the level of the spread rely on a static spread approach. Note that in reality the spread between IBOR and RFR is dynamic. The approaches proposed by ISDA are developed based on their ability to mitigate the following risks:

i) Risk of value transfer
ii) Risk of manipulation
iii) Risk of market disruption

These risks are mitigated to different degrees by the individual approaches. An indicative overview of the risk resistance by each approach is given in Table 2.2, where a positive sign means that the risk corresponding to this approach is mitigated and a negative sign means that this approach is vulnerable to that risk. In this section we will elaborate on the different approaches and their advantages and disadvantages.

Table 2.2: Spread adjustment approaches and their resistance against risks

	Risk		
	Value transfer	**Manipulation**	**Market disruption**
Forward	+	-	-
Historical mean/median	-	+	-
Spot-spread	-	-	-

Forward approach
In the forward approach, the static spread results from the observed forward spread in the market between the IBOR and adjusted RFR for the corresponding tenor. As this approach calculates the spread based on the market expectation, a value transfer would be minimized in theory. However, there exists a possibility that the spread expectation will be temporarily high due to e.g. manipulation or other factors resulting in a market disruption. Another disadvantage is the reliance on data availability and market liquidity which is possibly not satisfying at the moment of transition.

Historical mean/median approach
The historical mean/median approach calculates the fixed spread based on the mean or median spread level of 5 or 10 years prior to the announcement date that the fallback will be triggered on a certain date. The main advantage of this approach is that risk of manipulation is limited since a relatively long time frame is used and it does not rely on expectations. Furthermore, recent market conditions are captured when a 5-year time horizon is used. But to capture the economic cycle a 10-year time horizon should be used. The static spread level depends on the chosen time horizon and mean or median approach. This choice leads potentially to a value transfer and market disruption cannot be mitigated. Another disadvantage is that historical RFR data is required, which is not available for all newly proposed RFRs.

Spot-spread approach
This approach is similar to the historical mean/median approach in that it is calculated based on the spread between the IBOR and adjusted RFR on the day before the fallback is announced. However, it is not based on a long-term lookback period. IBOR and RFR fixings at the moment of triggering will satisfy this approach. This leads to the disadvantage that it is vulnerable to manipulation due to the short-term character. Since historical and expected market conditions are not present in this approach, market disruptions and corresponding value transfers are not mitigated.

To conclude, the main reason for transitioning away from IBORs is the manipulative character of these rates. Therefore, in our opinion the historical mean/median approach will be the best choice as in this approach manipulation risk is limited. Hereby we agree with the majority of market participants. However, the value transfer should be mitigated by selecting an appropriate lookback period and averaging technique. Furthermore, historical data is required which is not available for some RFRs, e.g. SOFR. This is a crucial drawback of this approach.

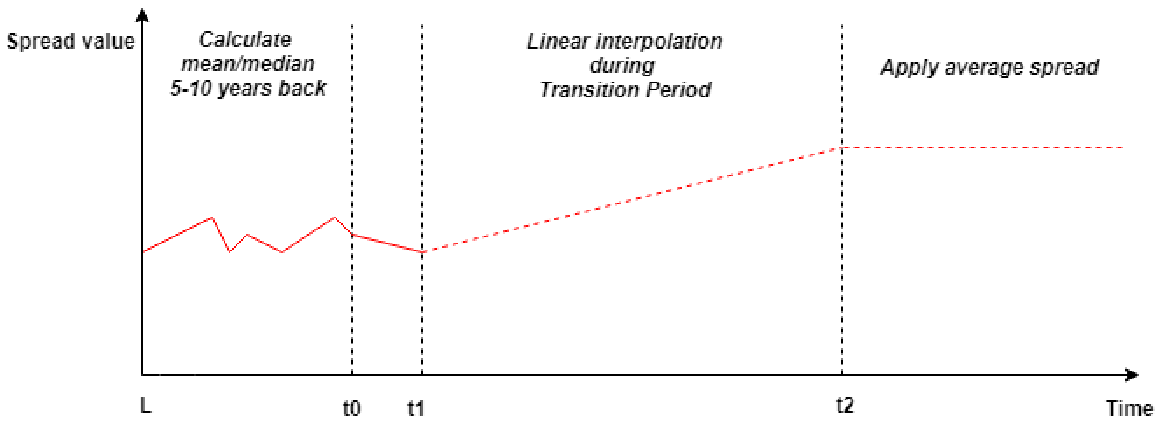
2.4 Historical mean/median as spread adjustment approach

In this section we elaborate further on the historical mean/median approach and inherent choices that should be made. The advantage of using the median spot spread is the removal of outliers and it is less volatile compared to the mean approach. Nonetheless, the mean approach gives a better representation of the market as outliers are incorporated. As mentioned before, a lookback period of 5 years reflects recent market conditions and is long enough to mitigate the risk of manipulation. On the contrary, a lookback period of 10 years captures the full economic cycle. If this approach will be selected as the static spread calculation method, the impact of these inherent choices should be clear.

2.4.1 Explanation of mean/median approach

The methodology for the historical mean/median approach is depicted in Figure 2.4, where the spread value is indicative and the figure is not scaled. In this figure, t_0 refers to the date of announcement that the fallback will be triggered, t_1 is the date the fallback rate takes effect and t_2 is the end of the transition period, one year after the fallback rate entered the market. Note that this approach is based on the assumption that the fallback rate applies when the IBOR is permanently discontinued and therefore the two rates cannot co-exist. Based on the 5 to 10 years prior to t_0 the mean or median spread between IBOR and the RFR will be calculated. Since t_0 is the announcement date, no data after the announcement date will be taken into account since these data potentially affects the historical mean or median. As of t_2, the average spread will be applied as a fixed spread to the adjusted RFR. To overcome a *cliff effect*, the spread value will result from linear interpolation between t_1 and t_2. Where the spread value at t_1 is the observed spot IBOR-adjusted RFR spread on the last day that IBOR is published.

Figure 2.4: Visualization of Setting the Spread



Translating this methodology into mathematics, two formulas are obtained for calculating the (credit) spread (CS) for both the transition period (Equation 2.3) and the period after the transition period (Equation 2.2) [10]. Note that when combining this approach with the compounded setting in arrears approach for RFR adjustment, the end date of the integral in 2.2 needs to be reduced by $f + 1bd$ to make sure the adjusted RFR is known by calibration date t_0.

$$CS_f(t_2) = \frac{1}{L}\int_{t_0-L}^{t_0} (L_f(t) - R_f(t)) \tag{2.2}$$

$$CS_f(t) = \left(\frac{t_2 - t}{t_2 - t_1}\right)(L_f(t_0) - R_f(t_0)) + \left(\frac{t - t_1}{t_2 - t_1}\right)CS_f(t_2) \tag{2.3}$$

In Equation 2.2, L is the lookback period for calculation of the average up to t_0, $L_f(t)$ is the spot IBOR rate for the accrual period beginning in two business days and $R_f(t)$ is the RFR under the selected approach with period f. In equation 2.3, $L_f(t_0)$ is the spot IBOR at calibration date t_0 and $R_f(t_0)$ is the selected adjusted RFR at calibration date.

The fallback rate between the transition period, $LF_f(t)$, is defined as:

$$LF_f(t) = R_f(t) + CS_f(t) \tag{2.4}$$

The fallback rate after the transition period will be:

$$LF_f(t) = R_f(t) + CS_f(t_2) \tag{2.5}$$

One of the advantages of this approach is that it reflects current market conditions since the starting point of the transition period is the current spot spread between IBOR and the adjusted RFR and linearly interpolates to a long-term average over time. The long-term average used in this approach overcomes the problem of market distortion and possible manipulation at the point of triggering. Furthermore, it captures the characteristic of interest rates being mean reverting and it is based on readily available information which makes the approach robust and simple [10]. However, one of the disadvantages is that spot rates are not consistent with forward rates due to a mismatch between observed market conditions and expected market conditions. This results in a situation on the calibration date which is unlikely to be present value neutral. Furthermore, historical data is required for both the IBOR and adjusted RFR fixings, which is a potential problem for the relatively new RFRs.

2.4.2 Application of mean/median approach

We apply the historical mean/median approach to calculate the fixed spread between SONIA adjusted and GBP libor 3M. The obtained spreads are depicted in Figure 2.5. As the fixed spread methodology will be calculated up to the day of announcement that the fallback will be triggered, we can only calculate the fixed spread as a proxy. We use a rolling time frame from 5 and 10 years starting from *01-10-2018* and shifting back on a daily basis further in the past. As expected, the spreads with a 10-year horizon exceed the 5-year horizon spreads as the former takes the financial crisis of 2008 into account. We already noticed that the spread level increases with volatility and uncertainty. The hypothesis that the mean spread exceeds the median spread is true, since the mean spread takes outliers into account (e.g. financial crisis) whether the median approach excludes outliers. Based on Figure 2.5 we conclude that three factors have an impact on the fixed spread; the approach (mean/median), the lookback period (5 or 10 years) and level of economic stability (stable/moderate/stress). Table 2.3 shows that the economic cycle impacts the 5 year horizon spread by 4-5 bp and the 10-year horizon spread by 9 bp.

Figure 2.5: Fixed rolling spread between Sonia adjusted 3M and GBP libor 3M

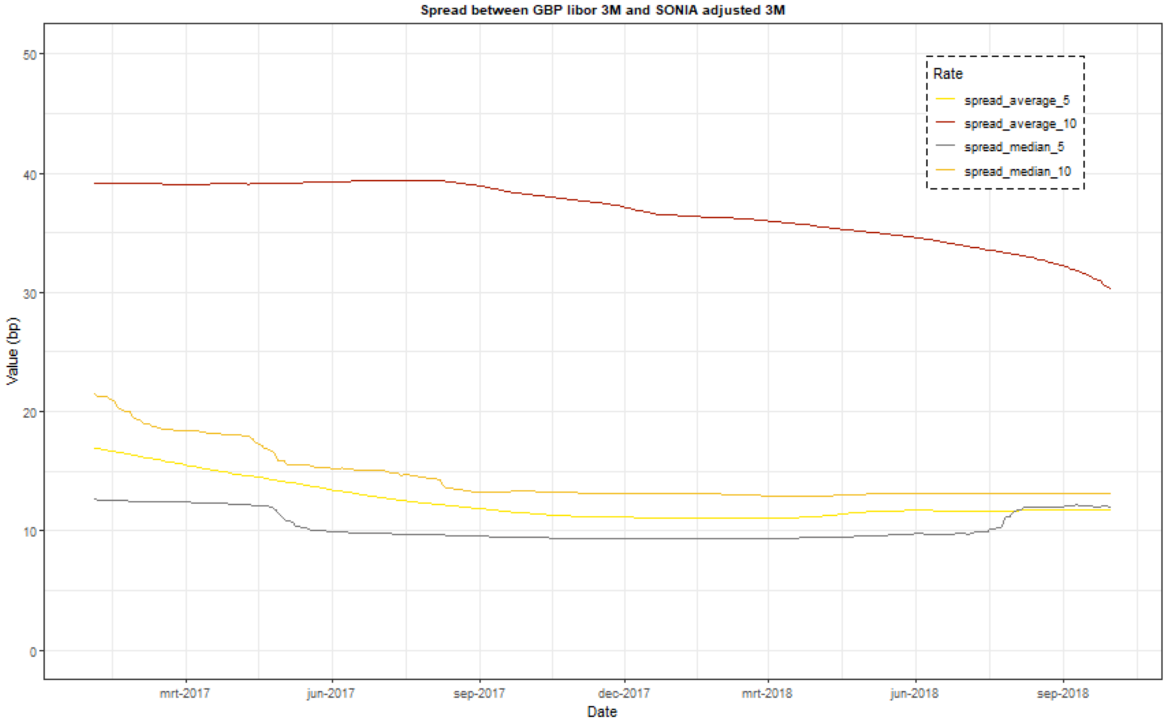


Table 2.3: Fixed spread ranges on rolling basis from *01-01-2017* to *1-10-2018* in basis points

Spread (bp)	5 years	10 years
Mean approach	12-17	30-39
Median approach	9-13	13-22

Chapter 3

Model to predict Libor and backfill Risk-Free Rates

In this chapter we assess if we are able to obtain a good proxy for Libor by a dynamic spread approach. We develop a regression model based on SONIA and risk premium components to obtain a proxy for GBP Libor 3M. The model is fitted over a historical period up to *2016* and the output is used to predict GBP Libor 3M over *2017-2018*. We start with SONIA as RFR since historical data is available. The predicted GBP Libor 3M over *2017-2018* is referred to as 'Model Libor' in this chapter. We assess the following hypothesis:

H 3.1) The RFR with additional risk-premium gives an accurate proxy of the corresponding Libor rate.

Another issue is the lack of historical data since some proposed RFRs are relatively new with no or a few years of historical data. The requirements for historical data are bifurcated in:

i) The preferred spread adjustment method requires 5 or 10 years of historical data.
ii) Historical data is required for compliance with 'Fundamental Review of the Trading Book' (FRTB) standards. In absence of historical data, companies face risk management and compliance problems.

In the second section of this chapter we use our regression model the other way around; we aim to backfill the RFR by subtracting the risk premium from the corresponding Libor. Firstly, we start with the backfill of SONIA ('Model SONIA'). Since historical SONIA data is available, we are able to backtest the model by analyzing the difference between Model SONIA and the observed SONIA. Secondly, we expand our analysis to SOFR, the proposed RFR in the UK, for which historical data is available as of April *2018*. We do this to assess the following hypothesis:

H 3.2) If the regression model is able to make future short-term predictions that are close to reality, it can also serve as a tool to backfill historical data on a long-term when limited historical data is available.

3.1 Multiple Linear Regression Model to predict Libor

The difference between RFR and corresponding Libor is identified as variable spread. This variable spread is a result of the risk premium that is present in IBORs but not included in the RFR. As it is not possible to identify all components affecting the variable spread, we identify the following components of the risk premium reflecting bank credit risk as well as characteristics of the borrowing bank and market wide conditions [12]; credit risk premium, term premium, and premiums related to the level of funding liquidity, the level of market liquidity and the microstructure of the market.

Credit risk
Credit risk can be referred to as the potential that a bank borrower or counterparty will fail to meet its obligations in accordance with agreed terms [13]. So, it is the compensation for the risk of default. Defaults of borrowers are usually not independent [14]. The probability of default is relatively high in periods of stress compared to a low probability of default in stable periods.

Term premium
The development of overnight rates in the future is unsure, this is reflected in the term premium. In general, a longer term coincides with higher risk and therefore a higher term premium. But uncertainty about the future can also result in a lower term premium for longer terms; some investors require a lower yield on long-term debts as the corresponding rate is fixed, compared to a higher rate required for several short-term loans with fluctuating interest rates [15].

Funding liquidity
The funding liquidity of the borrowing bank is based on the demand for funds. For example, if customers want to withdraw their funds, the bank should be able to meet this demand. The risk that the bank has insufficient liquidity to meet customers demand of withdrawing their funds is called funding liquidity risk.

Market liquidity
Market liquidity can be decomposed in: liquidity risk in trading and liquidity risk in funding [16]. Liquidity risk in trading reflects the ease of trading; how quickly can one sell or buy an asset or security without affecting the price.

Microstructure market
The market microstructure refers to the translation of potential demands by investors to executed trades in terms of prices and volumes. The microstructure impacts market liquidity due to changes in market participant's behavior, which we can identify in two stages; the time between the market participant's demand and actual order is placed, and the period in which orders are accumulated and trades executed [17].

We develop a multiple linear regression model to predict Libor based on the corresponding RFR and additional fluctuating risk premium. Equation 3.1 shows the multiple linear regression equation with GBP Libor 3M as dependent variable (*GBP Libor 3M*). The independent variables are; SONIA ($SONIA$), credit risk premium ($Credit_{prem}$) and term premium ($Term_{prem}$). Note that we use SONIA instead of SONIA adjusted. Since the historical spread calculation by ISDA is based on SONIA fixings, we use SONIA in order to be consistent with ISDA spread calculations. This enables us to compare our dynamic spread approach with the static spread approach as proposed by ISDA. Our regression is limited to credit risk premium and term premium as risk-premium components. Coefficient β_0 is the intercept and β_i with *i=1,2,3* represent the impact of a change in the independent variable to the change in the dependent variable. We execute an ordinary least squares (OLS) regression to estimate the beta coefficients (β_0 and β_i). The OLS fits the best line in order to minimize the error, i.e. minimizes the squared deviations from the line; the difference between the observed value (Y) and predicted value (Ŷ). The OLS equations are given in Appendix A.2.

$$GBP\ Libor\ 3M = \beta_0 + \beta_1 * SONIA + \beta_2 * Credit_{prem} + \beta_3 * Term_{prem} \tag{3.1}$$

Credit risk premium measure

To quantify credit risk premium, we use the 5 year point of the Credit Default Swap (CDS)[3] curve for a sample of panel banks setting the GBP Libor; BNP Paribas (*bnp*), Citibank (*citi*), Crédit Agricole (*agri*), HSBC Bank (*hsbc*), JPMorgan Chase Bank (*jpm*) and Santander (*sant*). We obtain this data from *Reuters* over the period *17-12-2007*[4] up to *31-12-2018*. Based on CDS data of the panel banks, we obtain an average CDS measure (*average*) that will serve as input for credit premium ($Credit_{prem}$) in Equation 3.1.

Figure 3.1 depicts that the post-crisis CDS value of Citibank is very high compared to the other banks. This can be explained by the fact that Citibank was at the brink of bankruptcy in the financial crisis of 2008. There attitude towards risk-taking in combination with the crisis exacerbated their CDS rating.

Term premium measure

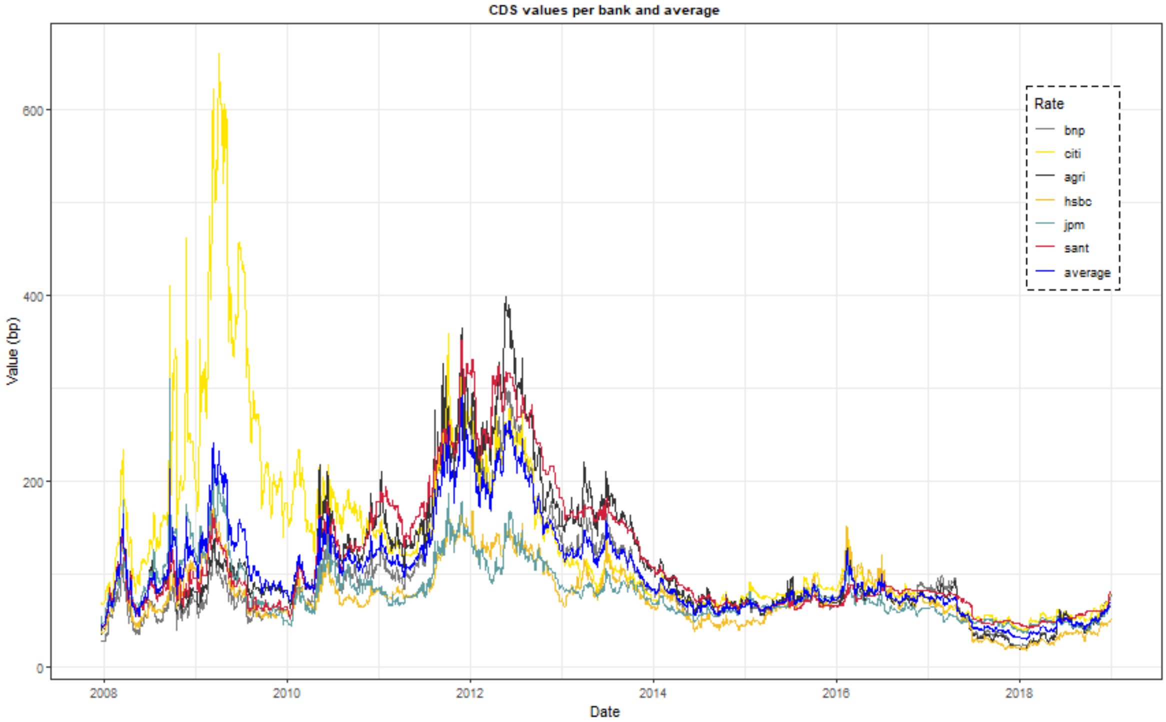
To quantify the 3-month term premium, we calculate the difference between GBP Libor 6M and GBP Libor 3M. Note that this is a proxy for term premium since more factors affect the term premium. However it is not possible to extract the exact amount of term premium from the spread.

Figure 3.2 depicts the GBP Libor 3M, GBP Libor 6M and the difference between the two, denoted as 'Term proxy 3M'. From this graph we derive two observations. Firstly, it seems that the term premium does not fluctuate with the volatility in Libor. For example, the Libor rate at the end of *2008* differs significantly from the level in *2010*, whereas the level of the term proxy is relatively stable. Secondly, we observe a negative term premium at the end of *2007*. This indicates that the GBP Libor 3M exceeds the GBP Libor 6M. In this unstable period with fluctuating Libor rates, a potential explanation is the hypothesis stated earlier; that investors require a higher yield for short-term loans since series of short-term loans are

[3]A CDS is a financial agreement that enables the investor to transfer credit risk with another investor.

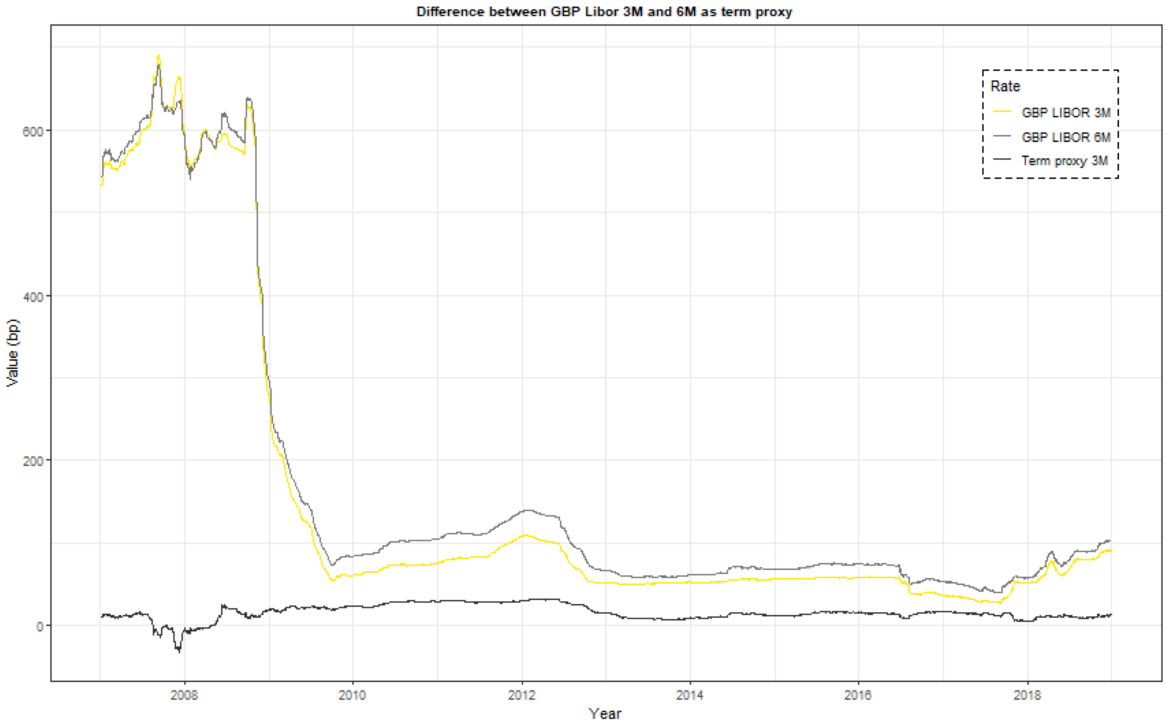
[4]Due to limited CDS data availability, we have data as of 17-12-2007 instead of 1-1-2007

Figure 3.1: CDS data per panel bank and corresponding equal-weighted average



more insecure due to fluctuating interest rates than a long-term loan against a fixed yield. To conclude, based on Figure 3.2, the term premium does not depend significantly on the level of the Libor rate, but it is affected by short-term fluctuations.

Figure 3.2: Difference between GBP Libor 3M-6M as term proxy



3.2 Predict Libor based on regression model

We fit our regression model over the period *2010-2016*. We do not include data prior to 2010 for two reasons:
i) The data for CDS and term premium prior to 2010 is not representative for the current economic situation. The CDS data of Citibank drives the average CDS up and furthermore the term premium is negative during the financial crisis of 2008. This period of turmoil will affect the goodness-of-fit of our regression.
ii) Another reason to exclude data prior to 2010 is that this period will be excluded as well by ISDA when transitioning to the fallback rate takes place. At the moment of transition after the year end of *2021*, the financial crisis is not present in the lookback period of 10 years.

The outcomes of the regression model are shown in Table 3.1. Both term premium (Term) and credit risk premium (CDS) have a positive Beta, as these risk premium components should be added to SONIA to obtain GBP Libor 3M. We observe that for a confidence level of 95%, all independent variables are significant. The R Square (R^2) shows the percentage of variance in the dependent variable explained by the independent variables. We show the Adjusted R^2 since we have a multiple linear regression model[5]. In general, the higher the (Adjusted) R^2, the better the model fits the data. Since the Adjusted R^2 is high (99.16%) we are able to obtain close proxies of GBP Libor 3M based on SONIA and the risk premium components.

Table 3.1: Regression Model Results to predict GBP Libor 3M

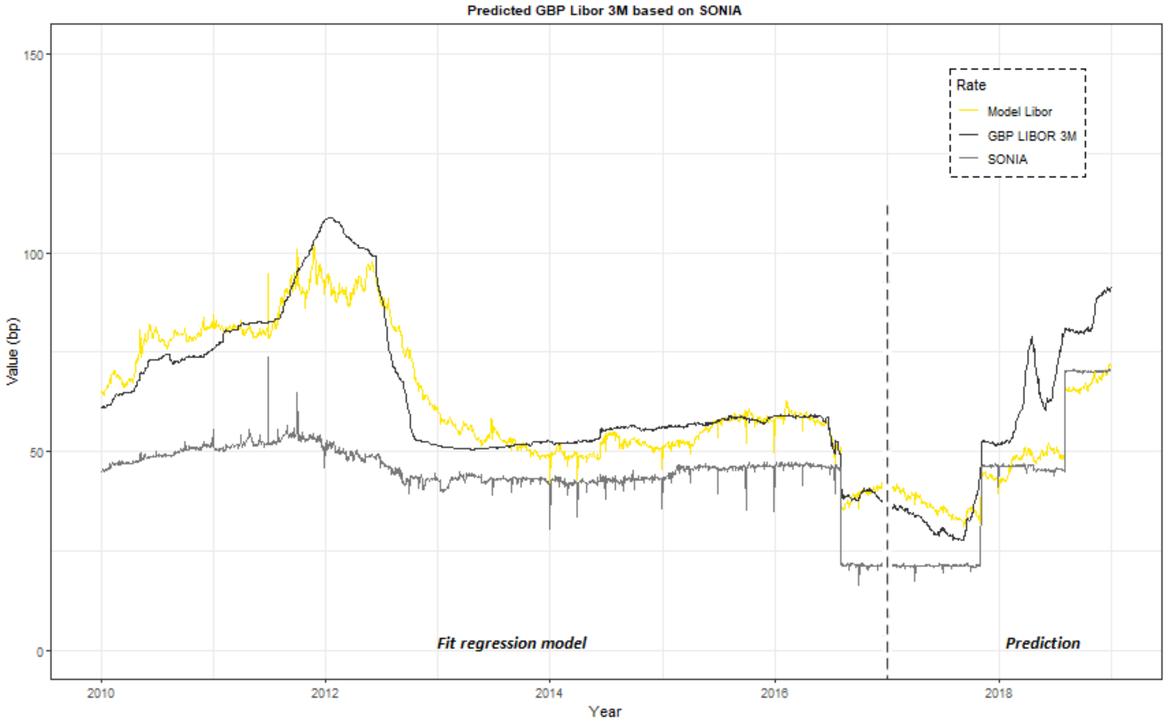
Regression model results (y=GBP Libor 3M)			
Fit period: 2010-2016 (n=1768)			
Adjusted R Square: 0.9916			
Independent variable	**Beta**	**S.E.**	**P-value**
SONIA	0.722716	0.009814	0.000000
Term	1.026727	0.023567	3.851E-282
CDS	0.111243	0.003572	4.172E-170

Figure 3.3 shows the predicted GBP Libor 3M over *2017-2018*, denoted as 'Model Libor', based on outcomes (Beta's) of the regression model depicted in Table 3.1. 'Model Libor' is a close approximation for the observed Libor in periods of economic stability. In the prediction period, 'Model Libor' deviates from the observed Libor due to the decrease in CDS (See 3.1).

Figure 3.4 depicts the spread and the residuals. The spread is calculated by subtracting SONIA from 'Model Libor' and the residuals show the accuracy of the prediction, calculated by subtracting the observed Libor from 'Model Libor'.

[5] R^2 will always increase by adding more independent variables, even in cases where the additional independent variable is irrelevant. Therefore, we look at the Adjusted R^2 which gives a better representation of the goodness-of-fit of our multiple linear regression model.

Figure 3.3: Prediction of GBP Libor 3M based on dynamic spread

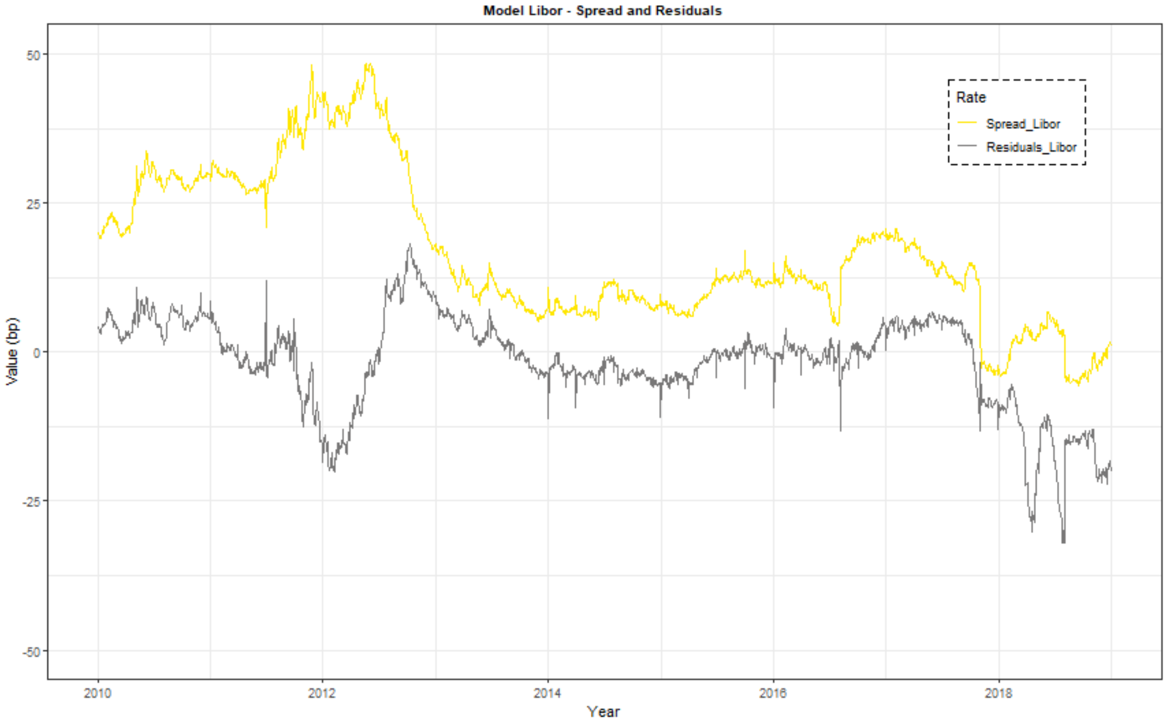


We conclude the following based on Figure 3.4:
i) In general, the spread increases with economic instability; in stable periods the spread is relatively low and increases with the level of instability.
ii) The accuracy of our model, depicted by the residuals, is around zero in stable periods. The accuracy of our model is lower in the more volatile period prior to *2014*.

The information in this section enables us to answer the hypothesis formulated as:
H 3.1) The adjusted RFR with additional risk-premium is an accurate proxy of the corresponding Libor rate.

We showed that we are able to identify a relationship between SONIA and GBP Libor 3M based on riks premium components, since the Adjusted R^2 of our model is high and both risk premium components are significant. In the prediction period of *Q1-Q3* of *2017*, the residuals are relatively low indicating a good prediction of GBP Libor 3M. As GBP Libor 3M becomes more volatile in *2018*, the accuracy of our model decreases. Furthermore, we observe from Figure 3.4 that in periods of stability, the observed spread is approximately 10-15 bp.

Figure 3.4: Model Libor Spread and Residuals



3.3 Multiple Linear Regression Model to predict SONIA

We apply the same technique to obtain a prediction for SONIA. If the predicted SONIA is a good approximation of the observed SONIA, we use the resulting regression coefficients for backfilling purposes. The regression equation to predict SONIA is given by Equation 3.2.

$$SONIA = \beta_0 + \beta_1 * GBP\ Libor\ 3M + \beta_2 * Credit_{prem} + \beta_3 * Term_{prem} \tag{3.2}$$

The outcomes of the regression model are shown in Table 3.2. Both Term and CDS have a negative Beta, as these risk premium components should be subtracted from GBP Libor 3M to obtain SONIA. We observe that for a confidence level of 95%, all independent variables are significant. The goodness-of-fit of our model is high since the Adjusted R^2 equals 97.48%.

Figure 3.5 shows both the fit of our regression model over the period *2010-2016* and the prediction of SONIA during *2017* and *2018*. From this figure we observe that 'Model SONIA' follows the path of GBP Libor 3M but is shifted downwards. The fit is very good in stable periods but moves closer to GBP Libor 3M during the prediction period. This is again the result of decrease in CDS. In theory, this behavior can be explained since the spread becomes smaller in stable periods since the CDS value decreases.

Table 3.2: Regression Model Results to predict SONIA

Regression model results (y=SONIA)			
Fit period: 2010-2016 (n=1768)			
Adjusted R Square: 0.9748			
Independent variable	**Beta**	**S.E.**	**P-value**
GBP Libor 3M	1.043937	0.014175	0.000000
Term	-0.763066	0.036539	9.925E-87
CDS	-0.081182	0.004982	1.006E-55

Figure 3.5: Historical SONIA versus Modelled SONIA

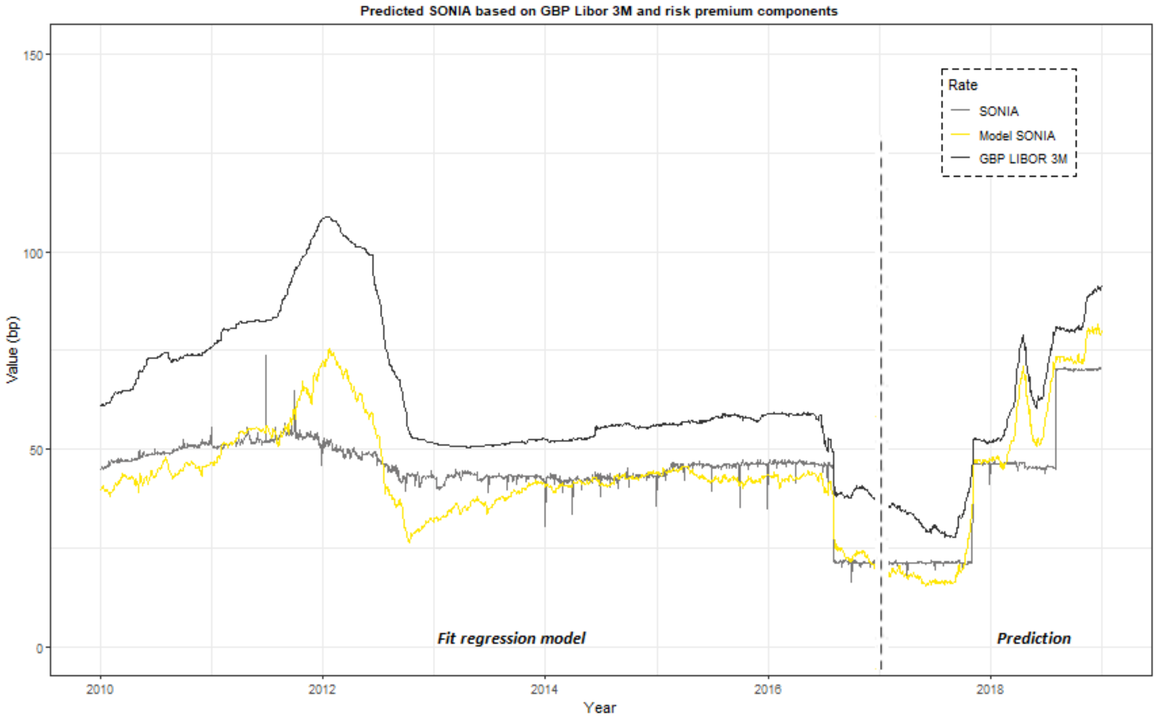


Figure 3.6 shows both the spread and residuals for'Model SONIA'. Based on this figure, we conclude that;
i) Again, the spread increases with economic instability
ii) The residuals are high, both positive and negative, in volatile periods. Which makes the prediction of corresponding spread level less accurate.
iii) The residuals are relatively low *Q1-Q3* of *2017* of the prediction period, however they show spikes in *2018*. This will affect the goodness-of-fit of our model when we apply the regression model over the period *2017-2018* and use the outcomes to backfill historical data prior to *2017*.

Figure 3.6: Model Sonia Spread and Residuals

3.4 Backfill RFR based on regression model

In the previous section we have shown that the regression model is a good measure to forecast short-term Libor. In this section we use the regression model with the purpose of backfilling RFR data when only recent historical data is available. The aim of backfilling by regression is to show a relatively simple tool to overcome the practical implementation problem of the historical mean/median approach for RFRs without sufficient data history. Furthermore, historical data is required to comply with FRTB standards.

The historical data of SONIA serves as a benchmark for the backfilled SONIA. By depicting both the observed historical data and the historical data resulting from our model, we are able to assess the accuracy of our backfill model.

Figure 3.7 depicts the fit of the regression over the period *2017-2018*. The regression results are shown in Appendix A.3. The Figure shows that the regression fit over the observation period mimics the fluctuations in the corresponding Libor. The backfilled SONIA prior to *2017*, based on the regression outcomes, is close to the observed SONIA over the period *2013-2016*. When GBP Libor 3M becomes more volatile, the deviation from the observed SONIA is high. However, we conclude that our regression is a relatively simple tool to backfill historical data in periods of economic stability.

Figure 3.8 shows the regression applied to the period *01-04-2018* until *31-12-2018* since historical SOFR data is only available as of *01-04-2018*. The regression results are shown in Appendix A.4. We conclude that 9 months of historical data is not sufficient to backfill the RFR over a long-term period.

Figure 3.7: Backfill SONIA

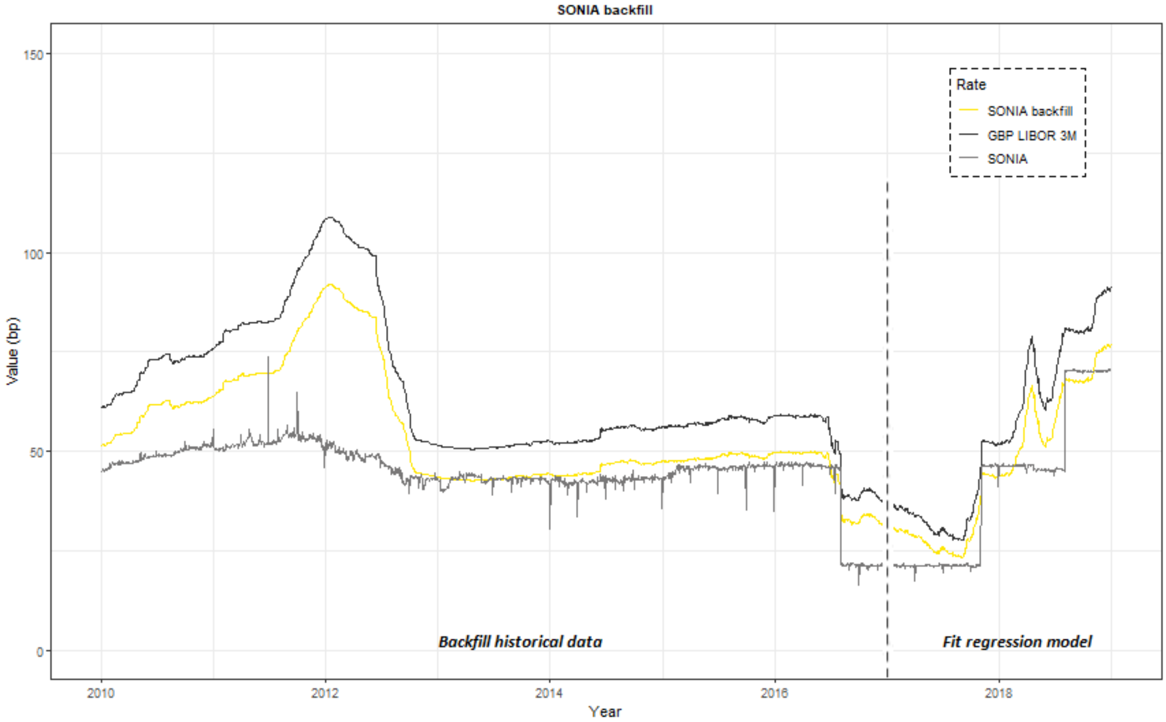
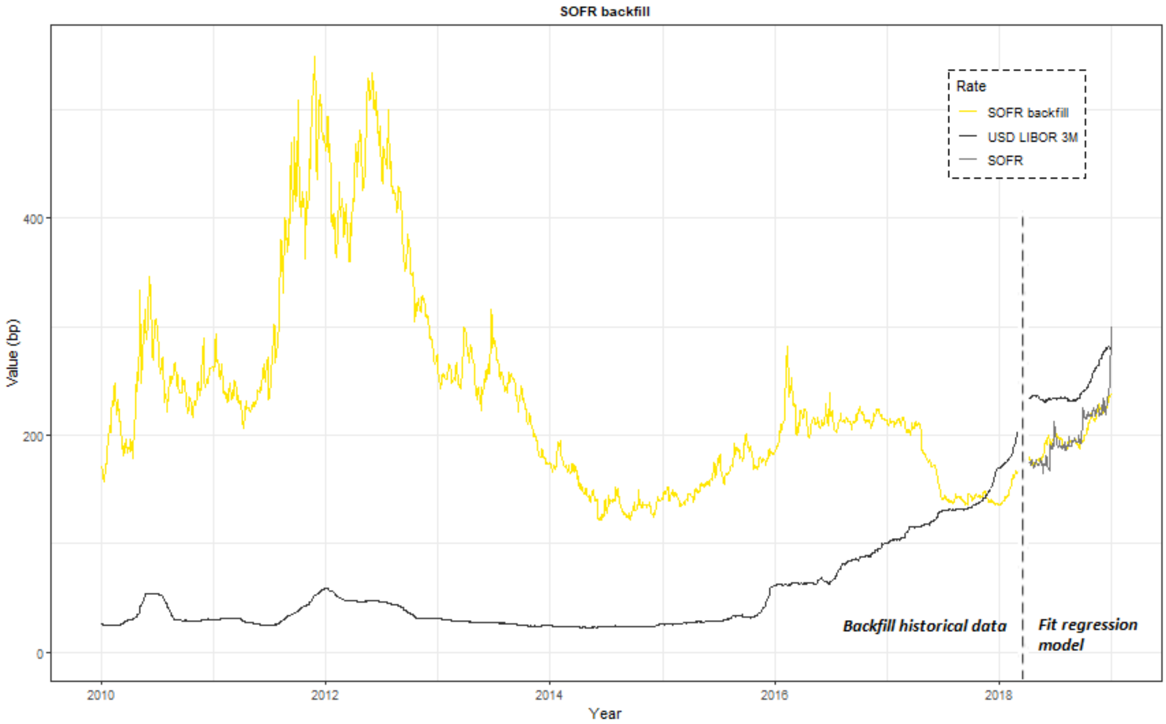


Figure 3.8: Backfill SOFR



Chapter 4

Transition impact in terms of value transfer

In this chapter we elaborate on value transfer as transition impact measure. Value transfer occurs when financial contracts with IBOR as underlying rate are repriced with an RFR plus fixed spread as underlying rate that deviates from the theoretical IBOR. If the borrower pays an increased (decreased) interest rate value transfer occurs to the lender (borrower). This type of value transfer potentially happens at the date of permanent IBOR discontinuation, as well as prior to this date. In the ISDA consultation is referred to the permanent discontinuation date of IBOR when talking about value transfer. We assess if value transfer is already happening by assessing the hypothesis:

H.4.1) Value transfer is already happening as a consequence of fallback methodology announcements

When value transfer occurs as a result of the transition, the impact on financial contracts will be different. We make a distinction between two types of interest rate derivative contracts. Firstly we assess the impact on linear derivatives and subsequently the impact on non-linear derivatives. The corresponding hypotheses we assess are formulated as:

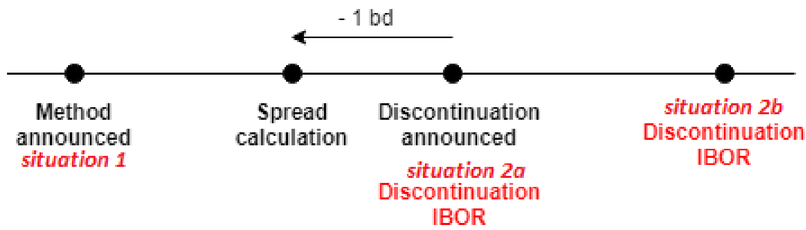
H.4.2) The transition away from IBORs causes value transfer in linear derivative contracts
H.4.3) The transition away from IBORs causes value transfer in non-linear derivative contracts

4.1 Value transfer as a consequence of methodology announcements

Figure 4.1 depicts an indicative timeline with potential value impact dates. The most obvious value transfer date is the date of permanent IBOR discontinuation. The permanent discontinuation is either simultaneous with the discontinuation announcement (*situation 2a*) or announced in advance (*situation 2b*). In case of announcement in advance, the spread that will be applied at the IBOR discontinuation date (*situation 2b*) will be calculated one business day before the discontinuation announcement date. This approach aims to avoid market distortion. Figure 4.1 shows that there exists a period between the spread calculation date and IBOR discontinuation date on which the spread will be applied. Note that spread calculation in advance will not happen in case of the historical mean/median spread application, since in this situation linear interpolation (Figure 2.4) takes place during the transition period.

However, if value transfer is already happening as a result of methodology announcements (*situation 1*), the observable impact at discontinuation date will be reduced. For example, if the current spread moves in the direction of the historical spread, the observed spread at discontinuation date will equal the announced spread in case the exact methodology is known. This indicates that minimal observable value transfer takes place at the discontinuation date. In this section, we assess the hypothesis that value transfer is already happening as a result of transition methodology announcements.

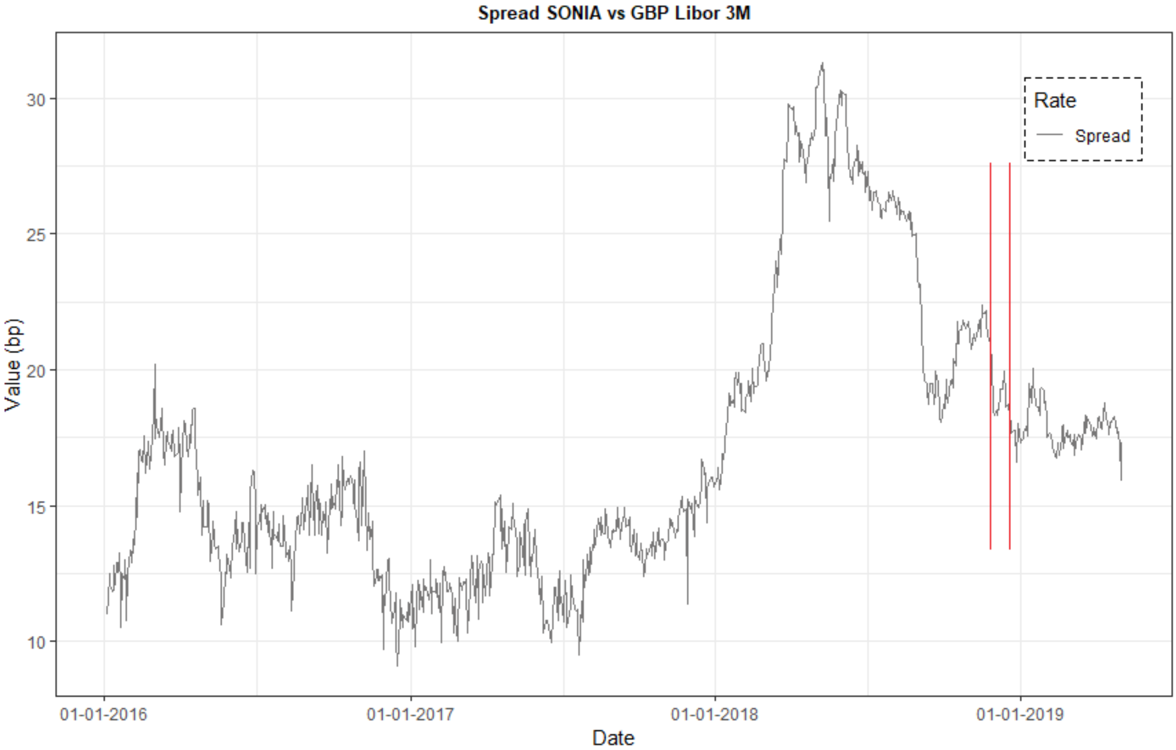
Figure 4.1: Potential value impact dates



The idea of analyzing (historical) spreads to assess whether value transfer is already happening is proposed by Henrard (2019) [18]. Figure 4.2 depicts the spread level between SONIA and GBP Libor 3M forward rates with a tenor of 30 years. This is the most liquid GBP spread [18]. The vertical red lines indicate the announcement date of the preliminary results on *27-11-2018* and the announcement date of final consultation results on *20-12-2018*. The graph shows a decline in the spread level after the preliminary results announcement. It even further declines after the final consultation results announcement. If we consider the spread before the announcements and after the announcements, we observe that the spread dropped from 22 bp on *23-11-2018* to 17 bp on *31-12-2018*. If this is a result of the announcements, the historical average spread should be lower than the observed spread level. The historical mean spread over a lookback period of 5 years equals 13 bp. This is the potential explanation of the decrease in the spread since information about the preferred spread methodology became available.

Table 4.1 shows spread information for the following forward rates with a 30 year tenor: i) SONIA vs. GBP Libor 3M, ii) GBP Libor 3M vs. GBP Libor 6M and iii) GBP Libor 1M

Figure 4.2: Historical spread SONIA vs. GBP Libor 3M forward rates with 30 year tenor



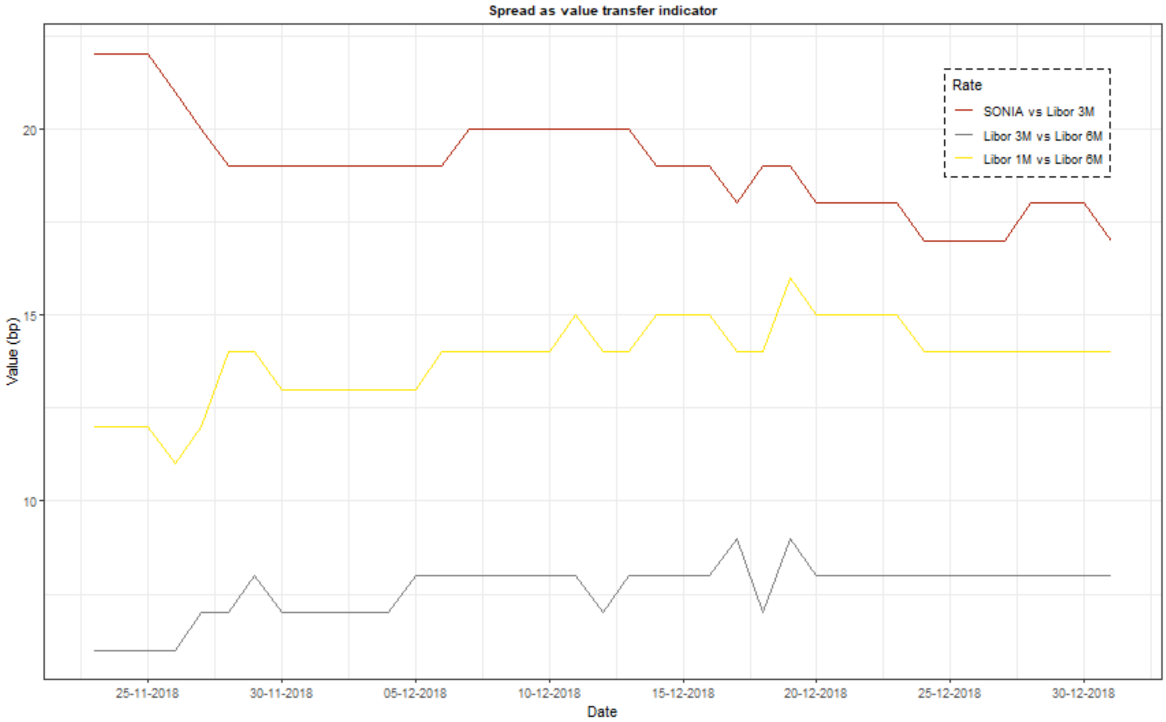
vs GBP Libor 6M. It contains expectations and observations of the spread levels after the announcements. Figure 4.3 depicts the development of the three spreads over the period *23-11-2018* up to *31-12-2018*. We already noted that the hypothesis for SONIA vs. GBP Libor 3M is true. If we consider ii) GBP Libor 3M vs. GBP Libor 6M, the spread level on *23-11-2018* was 6 bp. This spread level is lower than the historical average of 13 bp, indicating an increase in spread over the relevant period. If we look again at Figure 4.1, this is the case as the spread has been increased up to 8 bp on *31-12-2018*.

Table 4.1: Spread levels (bp) and corresponding observation and expectation

	23-11-2018	**Historical mean**	**Expectation**	**31-12-2018**	**Observation**
SONIA - Libor 3M	22	13	down	17	down
Libor 3M - 6M	6	13	up	8	up
Libor 1M - 6M	12	21	up	14	up

Subsequently, we observe the spread of iii) GBP Libor 1M vs. GBP Libor 6M. The spread level before the announcements was 12 bp, this is lower than the historical average of 21 bp, indicating an increasing spread. If we look at the development of the spread over the relevant period, we observe again that the spread has moved in the direction of the historical average. To conclude, three out of three spreads move in the direction of the historical average during the announcement period. This indicates that value transfer is already happening. For example, if the historical average spread is lower and forces the current spread level to decrease, Libor moves towards the RFR and causes value transfer from lender to borrower.

Figure 4.3: Spread SONIA vs GBP Libor rates with tenor 30Y



In this section we assessed the hypothesis:
H.4.1) Value transfer is already happening as a consequence of fallback methodology announcements

The observation that the market spread moves in the direction of the historical spread gives an indication that value transfer is already happening as a consequence of fallback methodology announcements.

4.2 Price impact on linear derivatives

In this section we assess the transition impact on linear derivatives in terms of price. Linear derivatives are financial products with a value that is linearly related to the value of the underlying rate. In this section we consider the impact on an interest rate swap (IRS), as an example of a linear derivative contract. The most commonly traded IRS exchange a fixed rate against a floating rate based on IBORs [19]. Since the IRS market is highly dependent on IBORs, it is a relevant derivative group to assess for value transfer.

4.2.1 Pricing an Interest Rate Swap

In a payer swap you are the payer of the fixed rate in exchange for the floating rate on the same notional principal and vice versa for the receiver swap. There are two approaches for the valuation of an IRS contract [20], [21]:
i) Regarding the swap as the difference between two bonds
ii) Regarding the swap as a portfolio of Forward Rate Agreements (FRAs)

Swap valuation based on Bond Prices

We assume that principal payments are paid and received at maturity of the IRS without changing the value of the swap. Based on this assumption, from the view of a payer IRS, we consider the IRS as a short position in a fixed rate bond and a long position in a floating rate bond. The value of the IRS at time t with strike K is then given by

$$V_{swap} = B_{float}(t) - B_{fixed}(t, K) \tag{4.1}$$

The value of the fixed rate bond (B_{fixed}), in case of continuous compounding, is given by

$$B_{fixed} = \sum_{t=1}^{n} \frac{C}{e^{rt}} + \frac{M}{e^{rn}} \tag{4.2}$$

where C are the coupon payments, r the fixed interest rate, M the maturity value and n the number of payments.

To value the floating rate of the bond (B_{float}), we note that immediately after each interest payment, the bond is worth the notional principal ($B_{float} = N$) [20]. This exchange of interest can be considered as a fair deal where the borrower pays the floating leg (Libor) for each subsequent accrual period. If the subsequent payment is $k*$ at $t*$, it follows that immediately before the payment we have $B_{float} = N + k^*$. By discounting we obtain the value of the floating-rate bond today. In case of continuous compounding, this is given by

$$B_{float} = \frac{N + k^*}{e^{r^* t^*}} \tag{4.3}$$

where r^* is the LIBOR rate for maturity t^*.

Swap valuation based on FRAs

A swap can be interpreted as a portfolio of FRAs. An FRA is an agreement that ensures that a certain interest rate will be applied to the borrowing or lending party of a principal amount during a specified period of time in the future. These FRAs are valued by assuming that forward rates are realized; by no-arbitrage arguments. It assumes that borrowing and lending would be done at Libor, using forward Libor interest rates. Let $T_0,...,T_{n-1}$ be the reset dates in the future, which are the dates on which the floating rate is determined. Consider $T_1,...,T_n$ as the payment dates, the days on which payments are exchanged. Let us denote $\delta_j := T_j - T_{j-1}$ as year fractions between two consecutive dates for $j = 1,...,n$. In the remainder we assume constant year fractions by $\delta_j = \delta$. We define the forward Libor rate $F(t, T_{j-1}, T_j)$ by

$$F(t, T_{j-1}, T_j) := \frac{1}{\delta}\left(\frac{P(t, T_j) - P(t, T_{j-1})}{P(t, T_{j-1})}\right) \tag{4.4}$$

Assume that the discounted payoff of the IRS is given by

$$\sum_{j=1}^{n} P(t, T_j) N_\delta (L(T_{j-1}, T_j) - K) \tag{4.5}$$

in which K is the fixed rate (swap rate) and N the notional value.

To obtain the value of the IRS on future time t, we substitute the forward rate in the IRS discounted payoff formula, for a payer IRS given by:

$$\mathbf{IRS}(t,\delta,N,K) = \sum_{j=1}^{n} P(t,T_j) N_\delta (F(t,T_{j-1},T_j) - K) \tag{4.6}$$

$$:= \mathbf{FRA}(t,T_{j-1},T_j,N,K) \tag{4.7}$$

4.2.2 Case study: Price impact on Interest Rate Swap

From Equation 4.6, the price of the IRS is affected by the level of the forward rate $F(t,T_{j-1},T_j)$ and discount rate $P(t,T_j)$ for a given notional (N) and strike (K). In the previous section we have shown that during the relevant period, the spread level of SONIA vs. Libor 3M decreased with 5 bp. We assume that this is caused by a decrease in Libor towards SONIA. If you are the payer of the fixed rate and you receive the floating rate, your discounted payoff will decrease as a result of the decreased floating rate. We can simply subtract 5 bp from the forward curve to obtain the new discounted payoff.

Table 4.2 shows an IRS contract for a 30-year period. The forward rate is the GBP Libor 3M forward curve with a 30-year tenor. The discount rate follows from the GBP OIS curve. On valuation date *02-01-2019* the NPV of the IRS is zero for a par coupon of 1.45%. If we subtract 5 bp from the respective forward curve, the NPV decreases to an amount of GBP -124,182.10. The Net Present Value (NPV) of the payer swap decreases as a result of a downward shift of the forward curve. To conclude, a decrease in the SONIA vs. GBP Libor 3M spread negatively affects the price of a payer IRS.

Table 4.2: IRS Contract

Interest Rate Swap Contract	
Trade date	2-1-2020
Effective date	2-1-2020
Maturity date	2-1-2050
Forward rate	GBP Libor 3M
Par Coupon	1.45%
Discount rate	GBP OIS
Day count	Actual/365
Notional value	10MM
Currency	GBP

Based on our analyses, we conclude that the transition causes value transfer in linear derivative contracts. The analysis that the market spread moves in the direction of the historical spread, gives an indication that value transfer is already happening. We assume that the change in spread is forced by an increasing or decreasing forward rate. The level of the forward rate impacts the value of an IRS in which the fixed rate is exchanged for the (changed) forward rate. The direction of spread movement (similar to forward rate movement) and the impact on the value of a payer swap are positively correlated. The indication for value transfer is based on a short-term analysis of three spreads. We are unable to derive the indication that the spread level changes structurally. Several economic factors affect the spread level which makes it hard to prove that systematic, long-term value transfer will happen.

4.3 Price impact on non-linear derivatives

In this section we assess the transition impact on non-linear derivatives in terms of price change. Non-linear derivatives are financial products in which the value of the product evolves non-linearly with the value of the underlying [22]. To identify the impact on non-linear products, we assess the impact on a cap as an example.

4.3.1 Pricing an Interest Rate Cap

An interest rate cap is an agreement designed to provide insurance for a situation in which the interest on the floating rate note exceeds a certain level, the cap rate. The discounted payoff of a cap is given by

$$\sum_{i=1}^{n} P(t,T_j)N_\delta(L(T_{j-1},T_j)-K)^+ \tag{4.8}$$

It is similar to a payer IRS but only pays out when the floating rate exceeds the cap rate. An interest rate cap can be considered as a collection of caplets. An FRA that only pays out when their value is positive is considered a caplet. It is an option that pays out only if the forward rate exceeds the fixed rate at time t. We use Black's formula [21] under the assumption that the forward rate is log-normally distributed with volatility σ. The resulting cap price is given by

$$Cap^{Black}(t,\delta,N,K,\sigma_{0,n}) := \sum_{j=1}^{n} Caplet^{Black}(t,T_{j-1},T_j,N,K,\sigma_{0,n}\sqrt{T_{j-1}-t}) \tag{4.9}$$

$$= N\sum_{j=1}^{n} P(t,T_j)_\delta \mathbf{BL}(K,F(t,T_{j-1},T_j)\sigma_{0,n}\sqrt{T_{j-1}-t}) \tag{4.10}$$

where $P(t,T_j)$ is the price of a zero-coupon bond at time t, maturing at time T_j. The forward rate is denoted by $F(t,T_{j-1},T_j)$, the cap volatility is denoted by $\sigma_{0,n}$ and $\mathbf{BL}(\cdot)$ represents the Black-76 formula per single caplet, which is given by

$$\mathbf{BL}(K,F,v) = F\Phi(d_1(K,F,v)) - K\Phi(d_2(K,F,v)) \tag{4.11}$$

$$d_{1,2}(K,F,v) = \frac{ln(\frac{F}{K}) \pm \frac{v^2}{2}}{v} \tag{4.12}$$

in which Φ represents a Gaussian distribution.

4.3.2 Case study: Price impact on Cap

In this section we execute a case study to investigate the impact on the cap price as a result of the transition from IBORs to RFRs. Note that a cap is a non-linear derivative contract and therefore affected by the volatility of the underlying instead of the level of the underlying. As Libor representative we have the GBP Libor 3M and as RFR representative we have SONIA. We apply the volatility adjustment as proposed by Lyashenko and Mercurio (2019) [1].

Explanation cap valuation under model proposed by Lyashenko and Mercurio

Lyashenko and Mercurio define and model forward risk-free term rates, based on the benchmarks that will replace IBORs. In their model, $R_j(t)$ represents the backward-looking forward rate. For a detailed description, the reader is referred to their research paper [1]. In their model, $R_j(t)$ is a martingale under the corresponding T_j-forward measure with $j = 1,..,M$. To model the behavior of its volatility in the accrual period, they choose a piece-wise differentiable deterministic function g_j. The dynamics of $R_j(t)$ become:

$$dR_j(t) = \sigma_j R_j(t) g_j(t) dW_j(t) \tag{4.13}$$

For each given j and associated application period $[T_{j-1}, T_j]$, the payoff at time T_j of two distinct caplets with strike K are given below.
The payoff of the forward-looking caplet is given by

$$[R_j(T_{j-1}) - K]^+ \tag{4.14}$$

The payoff of the backward-looking caplet is given by

$$[R_j(T_j) - K]^+ \tag{4.15}$$

Note that the former is known at the beginning of the period T_{j-1} and the latter at the end of the period T_j. The valuation relies on the modeling of the forward rate $R_j(t)$ in the T_j-forward measure. However, by the tower property of conditional expectations and the Jensen inequality, we have that, for $t \leq T_{j-1}$,

$$\begin{aligned} E^{T_j}[(R_j(T_j) - K)^+ \mid \mathcal{F}_t] &= E^{T_j}\left\{E^{T_j}[(R_j(T_j) - K)^+ \mid \mathcal{F}_{T_{j-1}}] \mid \mathcal{F}_t\right\} \\ &\geq E^{T_j}\left\{[E^{T_j}(R_j(T_j) \mid \mathcal{F}_{T_{j-1}}) - K]^+ \mid \mathcal{F}_t\right\} \\ &= E^{T_j}\left\{[R_j(T_{j-1}) - K]^+ \mid \mathcal{F}_t\right\} \end{aligned} \tag{4.16}$$

where the martingale property is applied of $R_j(t)$, that is $E^{T_j}[R_j(T_j) \mid \mathcal{F}_{T_{j-1}}] = R_j(T_{j-1})$. This implies that the backward-looking caplet is always more expensive than the forward-looking caplet.

Lyashenko and Mercurio [1] assume the dynamics to be lognormal with constant volatility denoted by σ_j:

$$dR_j(t) = \sigma_j R_j(t) g_j(t) dW)j(T) \tag{4.17}$$

where decay function g_j is assumed to be the piece-wise linear function. This leads to the Black-like prices of both caplets. The Black forward price of the caplet is denoted by

$$\mathbf{BL}(R, K, v) = R\Phi\left(\frac{ln(R/K) + \frac{1}{2}v^2}{v}\right) - K\Phi\left(\frac{ln(R/K) - \frac{1}{2}v^2}{v}\right) \tag{4.18}$$

where Φ is the standard normal distribution function. The time-t prices of the forward-looking and backward-looking caplets are given by respectively $C_j^F(t)$ and $C_j^B(t)$:

$$
\begin{aligned}
C_j^F(t) &= P_j(t)\mathbf{BL}(R_j(t), K, \sum_j^F \sqrt{T_{j-1}}) \\
C_j^B(t) &= P_j(t)\mathbf{BL}(R_j(t), K, \sum_j^R \sqrt{T_j})
\end{aligned}
\tag{4.19}
$$

where,

$$
\begin{aligned}
\sum_j^F &= \sigma_j \\
\sum_j^R &= \sigma_j \sqrt{\frac{1}{3} + \frac{2}{3}\frac{T_{j-1}}{T_j}}
\end{aligned}
\tag{4.20}
$$

The value of $\sum_j^R$ is obtained by calculating the integrated variance of $R_j(t)$ up to time T_j:

$$
\left(\sum_j^R\right)^2 T_j = \sigma_j^2 T_{j-1} + \int_{T_{j-1}}^{T_j} \sigma_j^2 \left(\frac{T_j - t}{T_j - T_{j-1}}\right)^2 dt \tag{4.21}
$$

Since $\left(\sum_j^R\right)^2 T_j \geq \sigma_j^2 T_{j-1}$, we can confirm that $C_j^B(t) \geq C_j^F(t)$.

Application cap valuation under model proposed by Lyashenko and Mercurio

The forward-looking rate $R_j(T_{j-1})$ and the backward-looking rate $R_j(T_j)$ have the same mean, but the variance of the backward looking rate exceeds the variance of the forward looking rate as proved by [1]. Let us demonstrate this based on the Caplet Contract in Table 4.3.

Table 4.3: Caplet contract

Caplet Contract		
Trade date	2-1-2020	
Effective date	2-1-2020	
Maturity date	2-4-2020	
Forward rate	1.06%	GBP Libor 3M
Cap strike	1.20%	(Out of the money)
Discount rate	99.02%	GBP OIS
Implied volatility	49.94%	
Day count	Actual/365	
Notional value	10MM	
Currency	GBP	

The volatility of the forward-looking rate and backward-looking rate, which serve as input in the Black formula (Equation 4.18), are given by v_f and v_b respectively. As we consider a period of 3 months, we have $T_{j-1} = 1$ and $T_j = 1.25$, expressed in a year fraction. By substitution of Equation 4.20 in 4.19, we obtain the volatilities of the backward-looking and forward-looking rates.

$$
\begin{aligned}
v_f &= \sum_j^F \sqrt{T_{j-1}} = \sigma_j \sqrt{T_{j-1}} = 0.4994\sqrt{1} = 0.4994 \\
v_b &= \sum_j^R \sqrt{T_j} = \sigma_j \sqrt{\frac{1}{3} + \frac{2}{3}\frac{T_{j-1}}{T_j}} \sqrt{T_j} = 0.4994 \sqrt{\frac{1}{3} + \frac{2}{3}\frac{1}{1.25}} \sqrt{1.25} = 0.5198
\end{aligned}
\tag{4.22}
$$

Based on the Caplet Contract given in Table 4.3, we obtain the price on valuation date *02-01-2019* of the forward-looking and backward-looking caplets given by $C_j^F(t)$ and $C_j^B(t)$ respectively. The yearly caplet rates resulting from Equation 4.19 are given in Equation 4.23. The result is that $C_j^B(t) \geq C_j^F(t)$ with a difference of 0.8 bp.

$$
\begin{aligned}
C_j^F(t) &= 0.9902 * \mathbf{BL}(0.0106, 0.0120, 0.4994) = 0.00158 = 0.158\% \\
C_j^B(t) &= 0.9902 * \mathbf{BL}(0.0106, 0.0120, 0.5198) = 0.00166 = 0.166\%
\end{aligned}
\tag{4.23}
$$

It follows that for a period of 3 months, the corresponding rates are:

$$
\begin{aligned}
C_j^F(t) &= \frac{0.158}{4} = 0.0395\% \\
C_j^B(t) &= \frac{0.166}{4} = 0.0415\%
\end{aligned}
\tag{4.24}
$$

Given a notional amount of 10 million, the corresponding caplet prices are given in Table 4.4. The difference of GBP 200 is caused by the larger variance of $R_j(T_j)$.

Table 4.4: Net Present Value of forward-looking and backward-looking caplet

	Caplet price
Forward	GBP 3950
Backward	GBP 4150

In this section we assessed the hypothesis:
H.4.3) The transition away from Libor causes value transfer in non-linear derivative contracts

We conclude that a structural value transfer takes place as a result of the larger variance of the forward-rate $R_j(T_j)$ compared to $R_j(T_{j-1})$ under the dynamics of the model proposed by Mercurio and Lyashenko [1]. The variance of the forward rate $R_j(t)$ is positively correlated with the caplet price. Based on the caplet price that follows from our caplet contract, we observe that the 2% increase in volatility causes an increase of 5% in the caplet price of a backward-looking caplet compared to the price of a forward-looking caplet.

Chapter 5

Conclusion

This research is conducted with the aim to answer the following question:
"Are currently proposed methodologies for the transition from Interbank Offered Rates to Risk-Free Rates a viable solution and what is the corresponding value impact?"

We agree with market participants that the compounded setting in arrears approach in combination with the historical spread application approach is preferred among the currently proposed approaches by ISDA. The main drawback of the historical spread approach is that the dynamics of the ARR will be different since macroeconomic factors are not captured in the fixed spread. Therefore, we have developed a model to identify the relationship between SONIA and GBP Libor 3M based on risk premium factors. We showed that the model is able to give a close proxy of GBP Libor 3M in stable periods. Furthermore, we analyzed the value impact as a result of the transition. Firstly, we conclude that value transfer is already happening as a result of spread methodology announcements by ISDA. Secondly, we conclude that the affected spread level impacts the value of linear derivatives on the short-term. However, we are unsure if the value of linear derivatives on the long-term will be affected. Thirdly, we conclude that the value of non-linear derivatives will be affected due to increased volatility in backward-looking rates.

- **Since compounded setting in arrears approach is backward-looking several challenges occur** The compounded setting in arrears approach is preferred among others since it is transparent, easy to understand and shows similarity with OIS that reference RFRs. However, the approach is backward-looking whereas IBORs are forward-looking. The first implication is that ARRs are not known at the beginning of the period. Secondly, since observations will mismatch expectations a theoretical spread will exist between the ARR and IBOR.

- **We showed that the dynamic spread is an alternative to the static spread in periods of economic stability.** The historical average spread approach is preferred among other approaches proposed by ISDA. However, we observe two drawbacks; i) application of a static spread to the RFR would not capture the influence of macroeconomic factors and lead to an ARR with different characteristics and ii) the approach is not applicable to RFRs without several years of data history. To overcome these problems, we developed a model to capture the dynamic spread based on risk premium components. We used this model to identify the relationship between SONIA and GBP Libor 3M. We showed that the relationship can be explained by the risk components CDS and term premium. Our model enables us to obtain short-term proxies of both GBP Libor 3M and SONIA. The spread level increases with economic instability. Based on our GBP Libor 3M prediction model, we observe a spread range of 10-15 bp. Furthermore, it serves as backfill tool when more than two years of historical data is available. The backfill of SONIA is close to observations in stable periods. As we only have 9 months of historical data of SOFR, we were unable to backfill historical SOFR data.

- **Value transfer is happening caused by methodology announcements. Historical spread affects forward rate and thus IRS value on short-term** From a financial perspective, we analyzed that value transfer is already happening as a result of methodology announcements. The market spread is moving in the direction of the historical spread. For example, if the historical spread is lower than the current spread, we observed that the GBP Libor 3M forward rate moves in the direction of SONIA resulting in a smaller spread. The level of the forward rate impacts the value of IRS contracts. Despite the indication that value transfer is currently happening, we are unable to draw conclusions for the long-term. However, we proposed a method that, in case the long-term spread is moving towards the historical average, gives you the opportunity to advocate for yourself being disadvantaged by the transition.

- **Value of backward-looking cap will exceed value of forward-looking cap due to increase in variance under model proposed by Lyashenko and Mercurio (2019)** Lastly, we identified the transition impact on non-linear derivatives by showing the value impact on a cap. We demonstrated that under the model proposed by Lyashenko and Mercurio (2019) [1], the variance of the backward-looking rate exceeds the variance of the forward-looking rate. If volatility increases, the chance that the floating rate exceeds the cap rate increases. This leads to an increased value of the cap. We demonstrated that the increased volatility, in a ceteris paribus situation, will lead to an increased value of the caplet. Since a cap is considered as a sum of caplets, and forces work in the same direction, the value of the cap will increase as well.

Chapter 6

Discussion and Further Research

In this research we focused on the application of RFR and spread adjustment approaches to SONIA. We are of the opinion that conclusions for other RFRs based on corresponding IBORs are aligned. Despite this opinion, it should be proved that the characteristics of IBORs and RFRs in other jurisdictions are comparable in order to draw the same conclusions. Furthermore, as we focused on GBP Libor 3M as Libor representative, we solely focused on a tenor of 3 months. Conclusions about spread levels and volatility potentially deviate for rates with other tenors. Another drawback is that this research is conducted based on a situation in which IBORs are permanently discontinued. We do not consider the situation in which both IBORs and ARRs are published parallel. Other limitations are that this thesis is built upon the proposed approaches by ISDA and as a result forward-looking RFR adjustment approaches are not included. Regarding to the spread application, we proposed an alternative to the historical spread approach proposed by ISDA, but this is still a deterministic approach. Stochastic approaches are not considered.

We already concluded that there exists no perfect fallback approach that mimics IBOR characteristics, is resistant to manipulation and eliminates value transfer. Therefore, the trade-off exists between i) propose an alternative reference rate (ARR) that closely mimics IBOR but is complex and manipulative or ii) propose an ARR with different characteristics that causes the potential for value transfer. Irrespective of the final approach, there should be a solid plan of how to cope with the ARR in new and existing contracts and a coordinated transition in terms of timing and geography should be facilitated. A deliberate choice should be made about launching the ARR parallel in the market or after permanent IBOR discontinuation and a consistent transition between benchmarks is required. Below, we propose key topics for further research.

- **Extend current regression model** In our regression model, term premium and credit risk premium are included as risk premium components. The model could be extended with measures for funding liquidity, market liquidity and the microstructure of the market. If these factors are quantified correctly, the model should be more accurate in predicting the corresponding Libor, especially in periods of economic instability.

- **Stochastic spread modelling** Our regression model is based on deterministic variables. It can only be applied if historical data of the risk premium components is available. To obtain a prediction of the spread level, a stochastic model should be used. A stochastic models requires input parameters that are calibrated on market data. This in an issue since currently no market prices are available based upon the ARR. For example, since there are no optionalities on both the Libor and corresponding RFR, one can not simply observe the difference to obtain a term structure for the RFR. However, since the transition is already announced, the RFR is the implicit underlying. Suppose, you enter into an agreement today for a future period of 30 years, you know that the IBOR will be replaced by the RFR and thus the RFR is the implicit underlying of the contract. By this assumption, market data of the RFR is available. This makes calibration of parameters possible, required to obtain a stochastic model to predict the future spread path.

- **Application to different product types** In this research we focused on derivative contracts. It should be assessed whether the proposed transition methodology is applicable to cash products and exotic derivatives. For example, exotic derivatives could pay out prior to the end date of the period. There will be a mismatch between these products and backward-looking rates available at the end of the period.

- **Applicable to all relevant benchmarks** In this research we applied the transition approach to SONIA. We already showed that the approach is not applicable to rates without historical data. To ensure consistency, it should be assessed if the final transition approach is applicable to all the benchmarks in the relevant jurisdictions.

- **Simultaneous geographical transition** To facilitate an orderly transition, the transition in each jurisdiction is required to be simultaneous. This is especially important for consistency in the foreign exchange market. It should be assessed if a simultaneous transition is possible on a global level. A potential issue that arises is the low-liquidity volumes in relevant regions.

- **Tenor adjusted spread** In this research we focused on a 3-month tenor. The spread as result of the mismatch between forward-looking and backward-looking rates is different for different tenors. It should be assessed whether the spread should be adjusted for each tenor.

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Appendix

A.1 RFR adjustment approaches

For the equations in this section [10], regarding to the RFR adjustment approaches, the following notations hold: T denotes the start date of the IBOR accrual period, f is the IBOR term (e.g. 3 months), $T+f$ denotes both the accrual end date and payment date, t denotes the IBOR setting date, which is assumed to be two business days before the start date, given by $T-2bd$. Regarding to forward rates, s denotes the forward observation date.

A.1.1 Spot Overnight Rate

The spot overnight rate is given by:

$$SOR_f(t) = RFR_t \tag{A.1}$$

in which, RFR_t is the overnight rate set on date t, this overnight rate is used as adjusted RFR from the period T to $T+f$, where $T = t + 2bd$.

A.1.2 Convexity-adjusted Overnight Rate

First-order correction for convexity is given by:

$$COR_f(t) = RFR_t(1+\delta_1 RFR_t)^{\frac{\delta_f}{\delta_1}} \tag{A.2}$$

in which, RFR_t is the overnight rate for [t, t + 1bd], δ_f is the cash day count fraction for the period from t + 1bd to $T+f$ and δ_1 is the cash day count fraction for one calender day.

The forward for this rate, observed at time $s \leq t$, is by approximation given by:

$$FwdCOR_f(s,t) = \mathbb{E}_{T+f}(COR_f(t)|\mathcal{F}_s) = r(s,t)(1+\delta_f r(s,t)) \tag{A.3}$$

in which, $r(s,t)$ is the forward adjusted RFR.

A.1.3 Compounded Setting in Advance Rate

The compound setting in advance rate, which is a first-order correction for the convexity introduced by $RA_f(t)$, is given by:

$$ADR_f(t) = RA_f(t)(1 + \delta_f RA_f(t)) \tag{A.4}$$

in which,

$$RA_f(t) := \frac{1}{\delta_A}\left(\prod_{u=T-f}^{T-1bd}(1 + \delta_u RFR_u) - 1\right) \tag{A.5}$$

in which, δ_f is the cash day count fraction for the period from t to $T + f$, δ_A is the cash day count fraction for the period from $t - f$ to t, and δ_u is the cash day count fraction for the overnight accrual period from u + 1bd.

A.2 Ordinary Least Squares method

The population regression function (PRF) for a simple linear regression is given by:

$$Y_i = \beta_0 + \beta_1 * X_i + U_i \tag{A.6}$$

in which U_i is the error term.

The sample regression function (SRF) is given by:

$$\hat{Y_i} = \hat{\beta_0} + \hat{\beta_1} * X_i \tag{A.7}$$

Since we use the actual values in the SRF, we have X without a hat and no error term.

We want to find the values of β_0 and β_1 that satisfy the Ordinary Least Squares (OLS) Normal Equations. From the equations in A.8-A.10,

$$-2\sum(Y_i - \hat{\beta_0} - \hat{\beta_1}X_i) = 0 \tag{A.8}$$

$$-2\sum X_i(Y_i - \beta_0 - \hat{\beta_1}X_i) = 0 \tag{A.9}$$

in which,

$$Y_i - \beta_0 - \hat{\beta_1}X_i = \sum e_i \tag{A.10}$$

we obtain the normal equations, given in A.11 and A.12.

$$\sum Y_i = n\hat{\beta_0} + \hat{\beta_1}\sum X_i \tag{A.11}$$

$$\sum X_i Y_i = \beta_0 \sum X_i + \hat{\beta_1}\sum X_i^2 \tag{A.12}$$

A.3 Regression Model Coefficients for Backfill SONIA

Regression model results (y=SONIA)			
Fit period: 2017-2018 (n=506)			
Adjusted R Square: 0.9830			
Independent variable	**Beta**	**S.E.**	**P-value**
GBP Libor 3M	0.843294	0.009258	0.000000
Term	-0.718501	0.099978	2.417E-12
CDS	0.065877	0.027387	0.016515

A.4 Regression Model Coefficients for Backfill SOFR

Regression model results (y=SOFR)			
Fit period: Apr-Dec 2018 (n=190)			
Adjusted R Square: 0.9920			
Independent variable	**Beta**	**S.E.**	**P-value**
USD Libor 3M	0.355168	0.040592	1.240E-15
Term	1.334261	0.177668	2.357E-12
CDS	1.819771	0.169200	2.612E-21