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Life after LIBOR[☆]

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ABSTRACT

We examine the alternative reference rates that are set to replace the London Interbank Offered Rate (LIBOR) as benchmark rate by the end of 2021. After providing the relevant background, we show that: (i) depending on the marginal lenders, tighter regulatory constraints can either increase or decrease the alternative benchmarks; (ii) increases in the amount of government debt outstanding increase the alternative benchmarks, more so for collateralized rates; and (iii) more central bank reserves lower the alternative benchmarks. In addition, we show that term rates based on the alternative reference rates can be detached from banks' marginal funding costs.

1. Introduction

The London Interbank Offered Rate (LIBOR) is arguably the financial world's most important number; it is a proxy for banks' marginal funding costs and serves as the benchmark rate in trillions of loans, floating-rate debt, and financial contracts. The LIBOR manipulation scandal and a shrinking interbank debt market caused a push toward alternative benchmark rates, culminating in the "LIBOR funeral" — a speech by Bailey (2017) announcing that the publication of LIBOR cannot be guaranteed beyond 2021. The LIBOR funeral caused a transition toward transaction-based overnight rates, which will serve as alternative benchmark rates. In theory, overnight rates are virtually risk-free and simply reflect the current level of policy rates. In practice however, the alternative benchmark rates are prone to upward or downward spikes (depending on the region) at regulatory reporting dates, can differ substantially from other overnight rates in the same region, and occasionally exhibit large volatility.[1]

Why are some benchmark rates prone to upward spikes while others are prone to downward spikes? What drives movements in the alternative benchmark rates? What are the implications of the high volatility for term rates? To address these questions, we first describe the alternative benchmarks and the institutional setting. Afterwards, we derive and test three hypotheses about the alternative

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[1] The most dramatic example of such volatility was the "repo squeeze" in mid-September 2019, when the alternative benchmark rate for the US unexpectedly spiked more than 150 bps.

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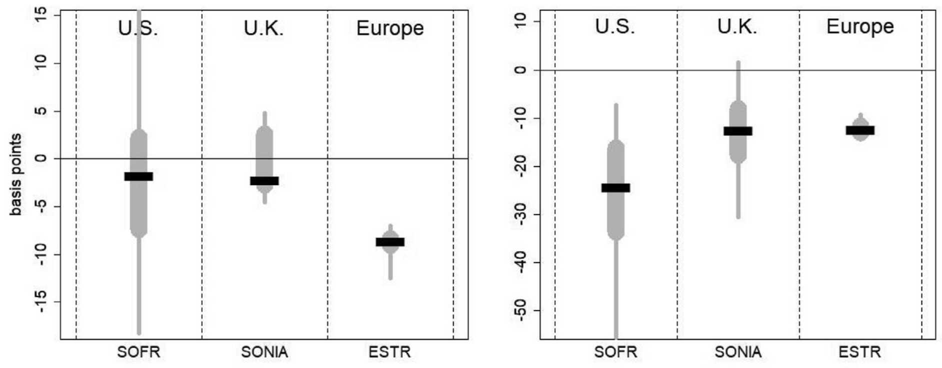


Fig. 1. Spread between the alternative benchmark rates and LIBOR.
This figure shows medians (black bars), ranges between the 25 and 75% quantile (thick grey line), and ranges between the 1 and 99% quantiles (thin grey line) for the spread between the alternative benchmark rate in the US, the UK, and Europe relative to LIBOR (for the US and the UK) or EURIBOR (for Europe). Panel A shows the spread between the alternative benchmark rates and the overnight LIBOR rate (for the US and the UK) or the spread relative to EONIA (the overnight EURIBOR rate for Europe). Panel B shows the spread between 3-month forward-looking averages of the alternative benchmark rates, computed in arrears, and 3-month LIBOR (for the US and the UK) or EURIBOR (for Europe). The sample periods starts in August 2014 for the US, February 2016 for the UK, and December 2016 for Europe and include data until December 2019.

benchmark rates. Finally, we examine the consequences of the LIBOR funeral for term rates and discuss its broader implications.

Focusing on the alternative benchmark rates in the United States, the United Kingdom, and the Eurozone (henceforth, Europe), we start by illustrating the difference between the alternative benchmark rates and LIBOR or, in Europe, its European counterpart EURIBOR. Panel A of Fig. 1 shows whisker plots of the spread between the alternative benchmark rate and overnight LIBOR in the three regions, illustrating large cross-country differences. While the spreads are stable around zero in the UK, they are on average −8.5 bps in Europe with occasional downward spikes and fluctuate between −15 bps and 15 bps in the US. In interpreting these spreads, it is important to note that all rates are overnight lending rates for low-risk borrowers and should therefore be close to the “risk-free” rate. More importantly, given that the alternative rates are intended to replace LIBOR as benchmark rate, spread changes of a few bps can translate to valuation changes of millions of dollars, making a deeper understanding of the drivers behind these alternative benchmarks crucial.

To develop this understanding, we first note that all three alternative benchmark rates are transaction-based and that the transactions underlying these rates can either be collateralized or uncollateralized. Moreover, the underlying transactions can comprise up to three different types: non-bank to bank lending (T1), bank-to-bank lending (T2), and bank-to-non-bank lending (T3). In the US, the alternative benchmark rate is the secured overnight financing rate (SOFR), which comprises *collateralized* transactions of all three types (using US Treasuries as collateral). In the UK and Europe, the alternative benchmarks are the sterling overnight index average (SONIA) and the euro short term rate (ESTR), respectively. Both rates are *uncollateralized* and only comprise transactions where banks borrow from either non-banks or other banks, that is, transaction of type T1 and T2.

As a next step, we link the behavior of the alternative benchmarks to financial regulation and monetary policy, deriving three testable hypotheses. First, whether a rate is prone to upward or downward spikes depends on the types of transactions underlying the rate, the lenders’ financial constraints, and the availability of alternative cash placements. If banks have ample amounts of reserves, tighter regulatory constraints lower their demand for borrowing money and therefore lower interest rates. This is the case in the UK and Europe, where banks have large amounts of reserves and the alternative benchmarks only comprise bank borrowing transactions. By contrast, rates increase with tighter regulatory constraints if banks need cash and are reluctant to lend money. This is the case in the US, where reserves are concentrated within a few large banks and the alternative benchmark also reflects bank-to-non-bank transactions. Second, an increase in government debt increases the alternative benchmarks. This increase is due to a “crowding out” effect, where investors prefer Treasury debt instead of lending money to banks. In addition, the impact of more government debt is amplified for SOFR because an increase in government debt leads to more demand for collateralized borrowing, which directly affects collateralized rates. Third, if banks do not have ample reserves, a drop in central bank reserves increases banks’ demand for borrowing and therefore increases interest rates.

To test our first hypothesis, we use regression analysis to examine spikes in the alternative benchmarks at regulatory reporting dates. On average, SOFR is 20.25 bps higher at quarter-ends compared to other dates. By contrast, both SONIA and ESTR are significantly lower at quarter-ends compared to other dates. However, in comparison to SOFR, the magnitude of these spikes – on average −2.12 bps for

SONIA and −0.51 bps for ESTR – is several orders of magnitude smaller.

Turning to our second and third hypothesis, we examine the link between daily or weekly changes in the alternative benchmarks and the quantities of government debt and bank reserves. In addition, we investigate how changes in transaction volumes affect the alternative benchmarks. For the US, we find a strong positive link between the amount of Treasuries outstanding and SOFR. In addition, more SOFR transactions increase the rate and a higher amount of bank reserves tends to coincide with drops in SOFR (although the relationship is insignificant in this test). In the UK, a higher amount of gilts outstanding significantly increases SONIA and more excess reserves in Europe correspond to a (borderline insignificant) drop in ESTR. In both the UK and Europe, more transactions increase the alternative benchmarks. Contrasting the results for the UK and Europe with the US shows that SOFR is more affected by these micro structure effects; especially fluctuations in the quantity of government debt have a stronger impact on SOFR compared to SONIA and ESTR.

Motivated by these findings and by our hypotheses, we examine changes in SOFR more closely. We construct a proxy of the fraction of non-bank-to-bank lending in SOFR and find that this proxy together with the amount of government debt outstanding explains 13% of the daily variation in SOFR on non-reporting dates. In addition, the impact of changes in reserves on SOFR strengthens between mid-2018 and late 2019, when reserves in the US became less abundant and more primary dealer repos increase SOFR.

To provide a closer link between the reporting date spikes in SOFR, or, more broadly, US repo rates, and regulatory constraints we perform two simple difference-in-difference analyses. First, investigating the 2010–2019 period, we show that quarter-end spikes in US repo rates appear only after January 2013, the date at which financial institutions started reporting their leverage ratios (LRs) to regulators. Second, we examine the difference between banks' repo borrowing on quarter-ends and their quarterly average repo borrowing. We split the sample between US banks, who report quarterly averages of their leverage ratios and hence have no incentive to reduce their positions at quarter-ends, and foreign banking offices (FBOs), who report quarter-end snapshots of their leverage ratios. We find that FBOs significantly decrease their repo borrowing at quarter-ends after 2013 compared to US banks.

Turning to the implications of the LIBOR funeral for term rates, Panel B of Fig. 1 shows the spreads between 3-month averages of the alternative reference rates computed "in arrears" (averaging over the following 90 business days) and 3-month LIBOR rates. The figure shows that term rates based on the alternative benchmarks are substantially lower than term LIBOR rates. Our analysis suggests that a large part of this difference is due to the term and credit premiums embedded in LIBOR.

We next examine how the LIBOR funeral affected the open interest in euro-dollar futures (contracts referencing LIBOR). While the open interest for GBP LIBOR contracts decreased, neither USD LIBOR nor EURIBOR futures were affected. This steady volume in euro-dollar futures suggests a slow transition away from LIBOR and pose practical challenges because LIBOR futures expiring after December 2021 will potentially lack an underlying reference rate.

Finally, we construct SOFR term rates based on futures contracts and highlight two properties of term SOFR. First, SOFR decreased during the March 2020 market turmoil when LIBOR rates were soaring. This observation resonates with Schrimpf and Sushko (2019), who survey the alternative benchmarks and emphasize that, during crisis periods, SOFR can be substantially below financial intermediaries' marginal funding costs, and with Jermann (2019), who argues that replacing LIBOR with SOFR has the potential drawback that banks can be more exposed to funding shocks. Second, the 1-month term rates based on SOFR futures also exhibit predictable upward spikes on regulatory reporting dates with term rates being on average 0.77 bps higher in the last month of a quarter.

Our findings provide insight on the drivers of overnight rates and contribute to a large literature examining the working of the Fed funds market (Furfine, 1999; Ashcraft and Duffie, 2007; Afonso and Lagos, 2015), the different segments of the US repo market (Bartolini et al., 2010; Gorton and Metrick, 2012; Krishnamurthy et al., 2014; Copeland et al., 2014; Munyan, 2017 among many others), European money markets (Mancini et al., 2015; Nyborg, 2019), money markets in the UK (Kotidis and Van Horen, 2018; Bicu et al., 2017) and the impact of post-crisis regulation on these markets (Banegas and Tase, 2017; Duffie, 2017; Munyan, 2017; Ranaldo et al., 2020 among others). Specifically, we show that the composition of the marginal lenders, the Treasury debt outstanding, and the amount of excess reserves are key drivers in the alternative benchmark rates and most pronounced for the US.

Our finding that the amount of Treasury debt outstanding affects short-term rates resonates with Vandeweyer (2019), who shows that, after the financial crisis of 2007–2008, the supply of US Treasuries affects repo rates and provides a theory linking this observation to tighter regulatory constraints and increasing excess reserves. Moreover, Correa et al. (2020) examine the connection between fluctuations in reserves and the US repo markets. These authors show that global systemically important banks (GSIBs) sustain their dollar supply in the repo market during periods of US dollar shortage by drawing on excess reserves and simultaneously reducing their repo borrowing. We contribute to the literature by studying the impact of these variables on the alternative benchmark rates that are set to replace LIBOR and by expanding the analysis beyond the US.

2. Background and hypothesis development

To understand the main drivers of the alternative benchmark rates and why they are prone to either upward or downward spikes, we give an overview of their main features and provide a detailed background on the different types of transactions that can be part of these alternative rates. Next, we discuss the impact of regulatory constraints on the different transactions and derive three

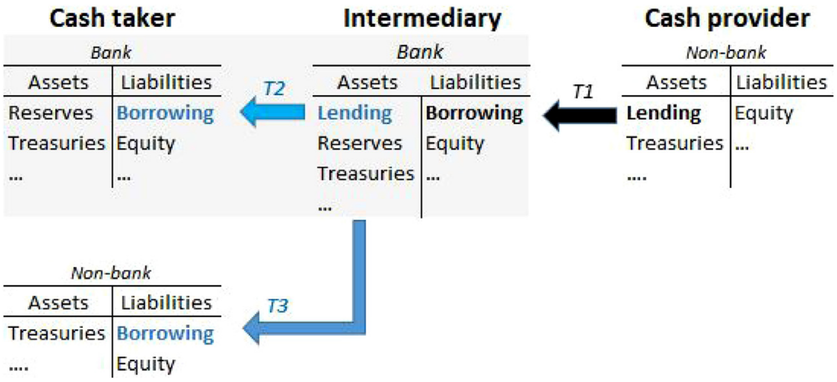


Fig. 2. The different transaction types in the alternative benchmarks.
This figure gives a stylized overview of the different types of transactions that can be part of the alternative benchmarks, abstracting from whether the underlying transaction is collateralized or uncollateralized. The figure shows lending from right to left, starting with a non-bank cash provider who lends to a bank (T1) that acts as intermediary and, in turn, lends to a cash taker. The cash taker can either be another bank (T2) or a non-bank (T3). The grey area highlights the interbank transactions.

testable hypotheses about the behavior of the alternative benchmarks.

2.1. The alternative reference rates

The alternative benchmark rates in the US, the UK, and Europe are all transaction-based overnight rates. In the US, the underlying transactions are collateralized (with US Treasuries) while they are uncollateralized in the UK and Europe. Moreover, the underlying transactions can be grouped into three different types: non-bank to bank lending (T1), bank to bank lending (T2), and bank to non-bank lending (T3) (see Fig. 2). In transactions of type T1, the non-bank lenders are typically cash-rich companies or money market mutual funds (MMFs), who place part of their cash holdings in overnight transactions with banks. Banks use these overnight loans to fund their own positions or act as intermediaries, channeling the funds either to other banks (transactions of type T2) or to non-bank cash takers like hedge funds and investment managers (transactions of type T3).

In contrast to the alternative benchmarks, LIBOR is an interbank rate that should reflect the interbank rate at which one prime bank could borrow money from another prime bank. Traditionally, this rate is based on "expert judgments" by each panel bank, but the LIBOR manipulation scandal led to a reform (see Wheatley, 2012), pushing LIBOR panel banks to replace these "expert judgments" with market-based rates (such as commercial paper rates), where possible. As a result, the Intercontinental Exchange (ICE) took over the publication of LIBOR in 2014 and announced the transition toward the reformed LIBOR methodology in April 2018 (see ICE, 2018). Hence, LIBOR rates can be thought of as hypothetical interbank transactions of type T2 and, more recently, as non-bank-to-bank transactions of type T1 because non-banks are the main commercial paper investors. Similarly, EURIBOR was largely based on "expert judgements" and recently reformed by the European money market institute (EMMI) to reflect actual transactions where possible. In contrast to LIBOR, there is no overnight EURIBOR rate and we therefore compare ESTR to the European overnight index average (EONIA), which, according to the EMMI, can be considered as the one day EURIBOR rate.[2]

To examine fluctuations in the different rates that are not simply driven by changes in policy targets, we focus on the spreads between overnight rates and key policy rates that reflect the level of the target interest rate in each respective area. For the US, we use the interest on excess reserves (IOER) that banks receive for placing their excess reserves with the Federal Reserve Bank (Fed). For the key policy rate for the UK, we use the "bank rate," which is the rate at which banks' central bank reserves are remunerated at the Bank of England (BoE). For Europe, we use the "deposit rate" that banks receive for placing their central bank reserves with the European central bank (ECB). Because all three policy rates are constant unless central banks change their policy targets, the resulting spreads reflect any rate moves that are unrelated to policy rate changes. The thin lines in Fig. 3 show the alternative benchmarks relative to the policy rates and the thick lines show overnight LIBOR rates for the US and the UK or EONIA rates for Europe, all relative to respective policy rates. As we can see from the figure, the alternative benchmarks exhibit large volatility at quarter-end dates (as illustrated by the gray vertical lines) and the UK overnight LIBOR rate shows a visible decline in mid-2018, which, as we explain in more detail below, can be attributed to the LIBOR reform starting in May 2018.

2.1.1. The secured overnight financing rate

The secured overnight financing rate (SOFR) is the proposed US LIBOR replacement, suggested by the Alternative Reference Rates Committee (ARRC). It is based on collateralized overnight transactions (repos) with US Treasuries as collateral and comprises three types of transactions. First, broad repos (similar to T1), also called tri-party repos (because they are cleared through a third party which

[2] EONIA is based on interbank transactions executed by a similar panel of banks as EURIBOR. The key difference between EONIA and overnight LIBOR in the US and the UK is that EONIA is fully transaction-based.

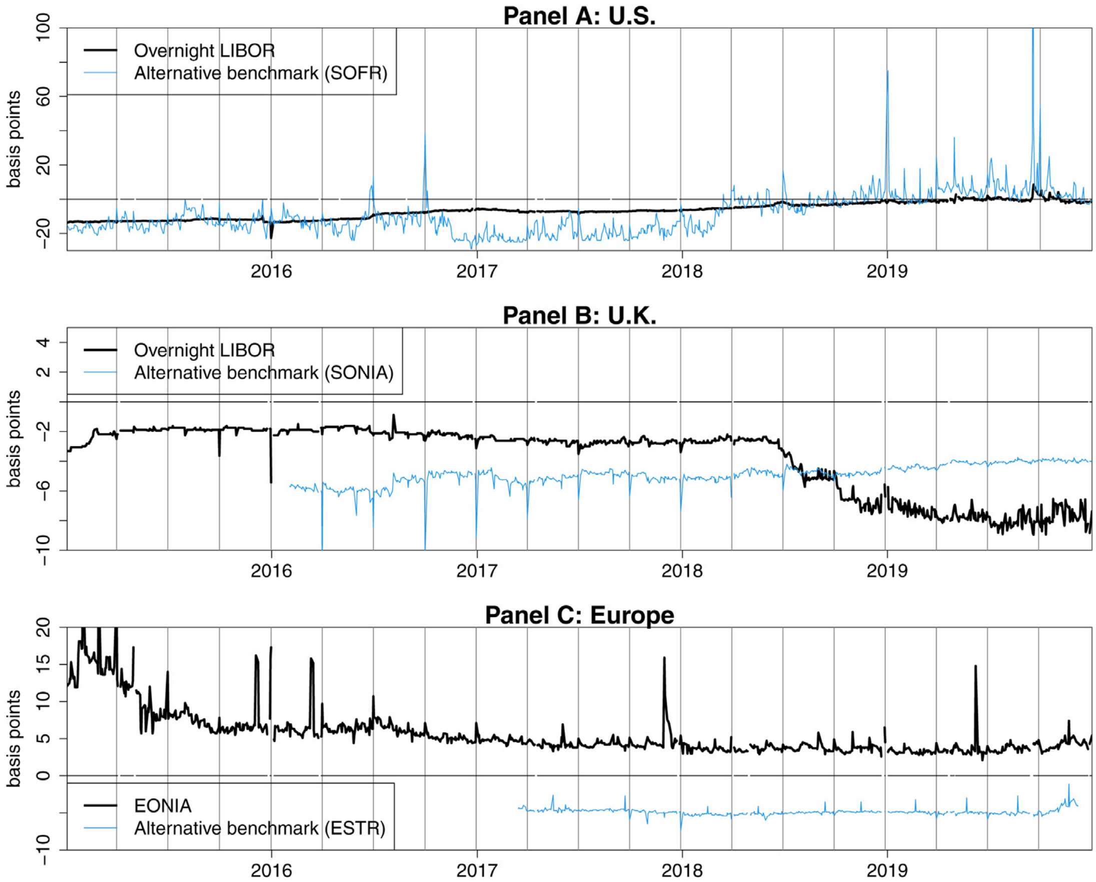


Fig. 3. Alternative benchmarks and overnight LIBOR in different regions.
This figure provides a comparison of the level of the alternative benchmark rates (thin lines) in the US, the UK, and Europe to the overnight LIBOR rates (for the US and the UK) or EONIA (the overnight EURIBOR rate for Europe). To remove the effect of changes in policy target rates, each line represents the spread between an overnight rate and a proxy of the policy target rate in the respective region. These policy targets are the interest on excess reserves (IOER) for the US, the "bank rate" at which banks can deposit money with the Bank of England for the UK, and the rate that banks receive for placing their reserves with the European central bank for Europe. The vertical lines indicate quarter-ends.

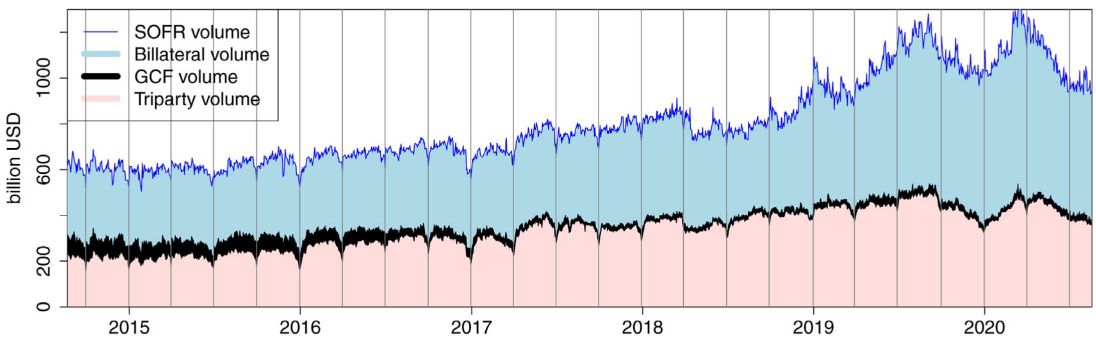


Fig. 4. Underlying repo volumes in SOFR.
This figure shows the volumes of the different types of repo transactions underlying SOFR. The three different types are (from top to bottom): billateral repo volumes, GCF repo volumes, and tri-party repo volumes. The vertical lines indicate quarter-ends.

is either Bank of New York Mellon or JP Morgan Chase), in which the typical lenders are MMFs and other non-banks. Second, inter-dealer repos (similar to T2), which are called general collateral financing (GCF) repos. Third, bilateral repo transactions, which are typically between dealers and non-banks (similar to T3). Fig. 4 shows that bilateral and tri-party repos (types T3 and T1) dominate SOFR while GCF repo comprise a small share of the volume.

To understand the potential impact of the different types of transactions on SOFR, we first note that interest rates in the bilateral segment can be driven by the lender's demand for borrowing a specific security instead of the borrower's demand for cash (see, e.g., Duffie, 1996). However, the calculation methodology in SOFR accounts for this by removing the bottom 25th percentile of the rate distribution within this segment. In addition, transactions of types T2 and T3 in SOFR are largely driven by demand for cash because central bank reserves in the US are concentrated within the largest banks and small banks or non-banks are unable to borrow directly in transactions of type T1. Moreover, a key difference between the US and other jurisdictions is that the Fed's reverse repo facility (introduced in September 2014) allows MMFs and other investors to engage in overnight repo transactions with the Fed at a pre-specified rate. This reverse repo facility effectively puts a lower bound on repo rates because lenders with access to the facility have no incentive to lend at a rate below the Fed's reverse repo rate.

As illustrated in Panel A of Fig. 3, SOFR is significantly more volatile than the overnight LIBOR rate and exhibits large upward spikes that frequently occur at quarter-end dates. Note that the y-axis in Panel A is truncated at 100 bps, which SOFR exceeded in September 2019. By comparison, the overnight LIBOR rate is stable with no visible upward or downward spikes.

2.1.2. The sterling overnight index average

The sterling overnight index average (SONIA) captures overnight funding costs in sterling and is a wholesale funding rate which comprises both non-bank-to-bank and bank-to-bank lending (transactions of type T1 and T2). SONIA already serves as benchmark rate in overnight index swaps (OIS) and was reformed in April 2018, including an even broader set of wholesale transactions (more transactions of type T1) and adjusting the averaging methodology.[3] This reformed SONIA rate is the proposed LIBOR replacement in the UK.

Panel B of Fig. 3 provides a comparison of SONIA and the UK LIBOR rate. The thin line shows the reformed SONIA rate, which the BoE calculates from 2016 on. As we can see from the graph, SONIA tends to spike downward on reporting dates and these spikes have somewhat diminished since mid-2018. By contrast, the overnight LIBOR rate does not exhibit any regular upward or downward spikes. However, the implementation of the new waterfall methodology in 2018 led to a drop in overnight LIBOR from approximately −3 bps in 2018:Q2 to −7 bps in 2018:Q4. When comparing SONIA to the rates in the US, it is important to note the different scaling of the y-axis in Panel B, which ranges from −10 bps to 5 bps, suggesting that SONIA is significantly less volatile than SOFR.

2.1.3. The euro short-term rate

The euro short-term rate (ESTR) is an uncollateralized overnight rate that comprises non-bank-to-bank and bank-to-bank lending (transactions of types T1 and T2) and the proposed LIBOR replacement for the euro area. This rate is officially published from October 2019 on and a pre-ESTR version is available from 2016 on.

Instead of LIBOR, the benchmark rate for the euro-area is the European interbank offered rate (EURIBOR) and because overnight EURIBOR does not exist, we compare ESTR to the European Overnight Index Average (EONIA), which is an average of overnight interbank transactions (of type T2), executed by 28 panel banks. According to the benchmark provider, EONIA can be considered as the one day EURIBOR rate and also serves as the current benchmark in euro-denominated overnight index swaps. While the transactions underlying ESTR are reported by a similar panel of banks as in EONIA, the ESTR transaction volume is on average ten times larger than the EONIA volume, suggesting that the majority of ESTR transactions are of type T1.

Panel C of Fig. 3 provides a comparison of ESTR and EONIA. As we can see from the figure, ESTR is significantly lower than EONIA and exhibits small downward spikes at quarter-ends and irregular upward spikes. The large difference between EONIA and ESTR can be explained by the fact that a large part of the lending in ESTR comes from non-banks (transaction type T1), which do not have access to the ECB deposit facility and therefore accept rates below the deposit rate.[4]

2.2. The impact of regulatory constraints

We distinguish two types of regulatory constraints that affect the interest rates in the three transactions shown in Fig. 2.[5] The first constraint is risk-weighted capital requirements (based on value-at-risk type constraints), which lower banks' incentives to lend money uncollateralized because uncollateralized lending increases the risk-weighted assets. The second constraint is the leverage ratio (LR), which is defined as:

$$\mathrm{LR} = \frac{\textsc{Tier 1 Capital}}{\textsc{Total Exposure}}, \tag{1}$$

where Total Exposure comprises on-balance-sheet assets, securities-financing transactions (SFTs), such as repos and security lending, and off-balance sheet items (e.g., derivatives).

Because the computation of Total Exposure only limited netting with the same counterparty when specific criteria are met, borrowing money typically increases the Total Exposure, irrespective of whether the borrowed money is invested in safe or risky assets. Hence, the LR lowers banks' incentives to borrow money and gives banks an in-

[3] As explained by the BoE, "the coverage of SONIA [is] being broadened to include overnight unsecured transactions negotiated bilaterally as well as those arranged via brokers [...]" [see https://www.bankofengland.co.uk/-/media/boe/files/markets/benchmarks/sonia-as-the-risk-free-reference-rate-and-approaches-to-adoption.pdf?la=en%26hash=35A8953638C9101CAB7204688918D501DA04D7C0]

[4] The ECB explains on its website that ESTR reflects banks borrowing from other banks as well as other counterparties, such as money market funds, insurance companies and other financial corporations (see https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/euro_short-term_rate/html/eurostr_qa.en.html). Hence, most transactions in ESTR can be thought of as T1.

[5] We simplify our examination of the regulatory background by not discussing the Liquidity Coverage Ratio (LCR) because this regulation mainly affects term rates with longer maturities.

centive to reduce their repo intermediation (i.e., borrowing from one party to lend to another; see Duffie, 2017).

The LR was introduced after the financial crisis of 2007–2008, banks started reporting their LRs to regulators in January 2013, and public disclosure of the LR was introduced in January 2015. The way Total Exposure is reported varies across countries. In the US, banks report quarterly averages based on daily data for on-balance-sheet items, but quarterly averages based on month-end snapshots for SFTs and off-balance-sheet items. In the UK, banks reported Total Exposure based on quarterly averages of month-end snapshots until December 2017 and now report quarterly averages based on daily observations.[6] Banks in Europe report their LR using quarter-end snapshots. The use of month-end or quarter-end snapshots for LR reporting implies tighter regulatory constraints at month-ends or quarter-ends and allows us to test the impact of regulatory constraints on the alternative benchmarks.

We now discuss the impact of regulatory constraints on borrowing and lending in transactions T1–T3. First, lending from non-banks to banks (T1) increases banks' liabilities, independent of whether the transaction is uncollateralized or collateralized. Hence, all else equal, a more binding leverage ratio makes banks reluctant to borrow and lowers the interest rate banks are willing to pay non-banks.

Second, in interbank transactions (T2), tighter regulatory constraints can lower both the borrowers' supply and the lenders' demand for cash. Because uncollateralized transactions increase the lenders' risk-weighted assets, tighter constraints reduce the supply in T2 transactions. Moreover, because the borrower in T2 is another bank and all borrowing affects the LR, tighter regulatory constraints can lower demand in T2 transactions. However, this is only the case if liquidity in the interbank market is abundant and banks have little incentive to borrow cash. If liquidity is unevenly distributed (e.g., because some banks do not have access to non-bank funding), tighter regulatory constraints leave the borrowing demand in T2 transactions largely unaffected. In this situation, banks in need of liquidity push collateralized interbank rates up because tighter regulatory constraints give lenders fewer incentives to perform repo intermediation. This effect is particularly strong if the interest rates on lending from non-banks to banks (T1) are floored by central bank facilities that open up for non-banks to place money directly in the central bank.

Finally, for lending from banks to non-banks (T3), the borrowers' demand for cash is unaffected by regulatory constraints while the lenders' supply of cash decreases. For uncollateralized transactions, supply decreases because uncollateralized lending increases banks' risk-weighted assets. Collateralized transactions are impacted indirectly because a tighter LR constraint lowers banks' incentives for repo intermediation. Hence, tighter regulatory constraints tend to increase rates in transactions of type T3.

[6] The concern that month-end snapshots could led to window-dressing lead the BoE to change the reporting requirement (see Jones, 2016).

2.3. The impact of government debt and excess reserves

We next discuss the impact of government debt and excess reserves on overnight rates. Fig. 2 suggests that Treasuries offer an alternative way of placing cash for non-bank lenders. Because government debt issued by developed countries is arguably the safest and most liquid investment, lenders tend to prefer investing in Treasuries and a higher Treasury supply lowers the lending supply.[7] Hence, more Treasury supply has a "crowding out" effect that increases interest rates in transactions of type T1. In addition, more Treasury supply directly impacts collateralized rates because levered Treasury investors need to finance a larger quantity of positions. This increased financing need increases the demand for repo borrowing and collateralized rates in T1–T3.

Another asset on banks' balance sheets illustrated in Fig. 2 is central bank reserves. If a bank has more central bank reserves, it has more cash available for investments and a lower demand for borrowing. Hence, more central bank reserves lower banks' demand for borrowing, which can lower interest rates in transactions of type T1. However, if reserves are ample, a small change in reserves is less likely affect banks' demand for cash (see Afonso et al., 2020). While the amount of central bank reserves increased sharply after the financial crisis of 2007–2008, it is worth noting that reserves in the US are concentrated within a few large banks (see Cœuré, 2019). This reserve concentration leads to more demand for cash by banks and hence, tighter regulatory constraints increase interbank rates in the US.

2.4. Testable hypotheses

In Panel A of Table 1, we summarize the background behind the three alternative benchmarks. While the marginal lenders in SOFR can be banks or non-banks, most lending in SONIA and ESTR is done by non-banks. In addition, SOFR is different from the other two rates because non-bank lenders in SOFR can alternatively place their money at the Fed's reverse repo facility (which serves as a floor for the rates), because SOFR also includes transactions of type T3, and because SOFR is collateralized. By contrast, non-banks in the UK and Europe do not have access to a deposit facility, thus both SONIA and ESTR are uncollateralized and only include transactions of type T1 and T2.

To derive our hypotheses, we build on theories of segmented markets in which an unconstrained non-bank interacts with a constrained bank intermediary (see, e.g., He and Krishnamurthy, 2012 or Garleanu and Pedersen, 2011). In these theories, a more binding capital constraint reduces the bank's ability to borrow money from the non-bank. Hence, in equilibrium, non-bank-to-bank lending rates decrease to induce the non-bank to lend less.

[7] This argument rests on the Treasury department placing the proceeds on its account in the central bank, thereby temporarily reducing the money supply. After the financial crisis of 2007–2008, it has been common practice for Treasury departments in the US, the UK, and several European countries to place their proceeds in the central bank.

Table 1
Properties of the alternative benchmark rates.
Panel A gives an overview of the background behind the alternative benchmark rates in the US (SOFR), the UK (SONIA), and Europe (ESTR). Panel B gives a summary of how regulatory constraints, a larger quantity of Treasury debt, and more central bank reserves affect the different rates.

	Panel A: Background			**Panel B:** Impact on rates		
Name	Transactions included	Alternatives for non-bank lenders	Collateralized	Regulatory constraints	More Treasuries	More reserves
SOFR	T1, T2, T3	Fed's RRP	✓	↑	↑	↘
SONIA	T1, T2	✗	✗	↘	↗	↘
ESTR	T1, T2	✗	✗	↘	↗	↘

At the same time, a more binding capital constraint lowers the bank's ability to lend money to other banks, thereby increasing interbank rates. In the Appendix, we illustrate this mechanism in a simple model where the bank faces a LR constraint.

Applying this logic to our context, recall that non-bank lenders in the US have access to the Fed's reverse repo facility while non-bank lenders in the UK and Europe cannot place cash with their central banks. Hence, tighter regulatory constraints lower the rates in transactions of type T1 for SONIA and ESTR but not for SOFR. In addition, small banks and non-banks in the US are usually unable to borrow directly from MMFs but rely on repo intermediation from large banks. Moreover, according to CGFS (2017), European banks are an important counterparty in US repo markets, suggesting that their regulatory quarter-end constraints impact US repo rates. Taken together, for SOFR, tighter regulatory constraints increase the rates in transactions of type T2 or T3, and we hypothesize that tighter regulatory constraints lead to large increases in SOFR. For SONIA and ESTR, the rates in transactions of type T2 likely increase with tighter regulatory constraints, but because transactions of type T1 make up the majority of the volumes, we expect that tighter regulatory constraints decrease SONIA and ESTR. This leads to our first hypothesis.

Hypothesis 1. Tighter regulatory constraints correspond to large increases in SOFR and moderate decreases in SONIA and ESTR.

Next, because SOFR is a collateralized rate, increases in the Treasury supply increase the demand for repo financing and therefore have a direct impact, increasing the repo rate. In addition, as discussed in Section 3.2, an increase in the supply of safe assets increases rates in T1 transactions because non-bank lenders can invest more in Treasuries. Hence, we posit in Hypothesis 2 that an increase in Treasury debt outstanding increases interest rates for all alternative benchmarks but has a stronger effect on the collateralized rate SOFR.

Hypothesis 2. An increase in Treasury debt outstanding increases all three alternative benchmark rates and has the largest impact on SOFR.

Finally, building on our discussion in Section 3.2, we argue that more central bank reserves lower banks' demand for overnight borrowing, which lowers interest rates. However, the impact of changing reserves diminishes when banks have ample reserves and their demand for liquidity is saturated.

Hypothesis 3. If banks are not saturated with central bank reserves, a decrease in the amount of central bank reserves increases the alternative benchmark rates.

In Panel B of Table 1, we summarize our three hypotheses and shows how tighter regulatory constraints, more Treasury debt outstanding, and more central bank reserves affect SOFR, SONIA, and ESTR.

3. Drivers of the alternative benchmark rates

In this section, we examine how regulatory reporting dates, government debt, and excess reserves affect the alternative benchmark rates. We test our three hypotheses for the alternative benchmarks in the US, the UK, and Europe and conduct additional tests for the alternative benchmark in the US, where we expect the largest effects.

3.1. Reporting date spikes

We test Hypothesis 1 by comparing the average of the alternative benchmarks to their value at quarter-ends, year-ends, and month-ends, using regression analysis. We focus on three dummy variables, $QEnd$, $YEnd$, and $MEnd \setminus QEnd$, which are equal to one if the observation is from the last trading day of the quarter, the last trading day of the year, or the last trading day of the month but not the quarter-end, respectively. As in Fig. 3 before, we use the full period for which the alternative benchmarks are available and focus on their spread over the key policy rate, which captures rate moves unrelated to changes in key policy rates.

Column 1 of Table 2 shows that SOFR is on average 20.25 bps higher at quarter ends and 10.06 bps higher at month-ends, compared to its time series average. Column 2 reports the results of the analysis with year-quarter fixed effects. Adding year-quarter fixed effects reduces the potential impact of a time trend and ensures that QEnd reflects the difference between the quarterly average and the quarter-end value of SOFR. As we can see from column 2, adding year-quarter fixed effects leaves the coefficients virtually unchanged. Focusing next on reformed SONIA, column 3 of Table 2 shows significant average downward spikes of −2.12 bps at quarter-end dates and less-significant average downward spikes of −0.38 bps at other month-end dates. The results in column 4 confirm the robustness of this finding to controlling for year-quarter fixed effects. Turning to ESTR, column 5 shows small downward spikes of −0.51 bps at quarter-ends, which are more pronounced at year-ends, and column 6 confirms that these

Table 2
Reporting-date spikes in the alternative benchmark rates.
This table shows the results of regressing the alternative benchmark rates on three dummy variables capturing regulatory reporting dates. *QEnd* equals one on the last trading day of a quarter and zero otherwise, *YEnd* equals one on the last trading day of a year and zero otherwise, and *MEnd* \ *QEnd* equals one on the last trading day of a month which is not quarter-end and zero otherwise. Columns 2, 4, and 6 include year-quarter fixed effects. The independent variables are SOFR (column 1 and 2), SONIA (columns 3 and 4), and ESTR (columns 5 and 6). To remove fluctuations in these rates due to changes in policy rates, we use the spread of these rates over the policy targets in the three regions. The sample periods start in August 2014 for SOFR, February 2016 for SONIA, and December 2016 for ESTR, including data until December 2019. The numbers in parantheses are Newey-West *t*-statistics. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	SOFR		SONIA		ESTR	
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	−2.39***		−4.89***		−4.81***	
	(−7.87)		(−242.31)		(−158.90)	
QEnd	20.25***	20.00***	−2.12***	−2.04***	−0.51***	−0.57***
	(4.73)	(5.39)	(−2.68)	(−3.29)	(−2.83)	(−3.45)
YEnd	−2.20	−1.27	0.61	0.33	−1.57***	−1.48***
	(−0.22)	(−0.14)	(0.48)	(0.31)	(−3.97)	(−3.97)
MEnd \ QEnd	10.06***	10.10***	−0.38**	−0.39***	−0.16	−0.16
	(9.25)	(10.19)	(−2.35)	(−5.07)	(−1.26)	(−1.52)
FEs	–	YQ	–	YQ	–	YQ
Adj. R^2	0.07	0.29	0.11	0.75	0.02	0.13
Num. obs.	1337	1337	987	987	695	695

spikes are robust to controlling for year-quarter fixed effects. In contrast to SOFR and SONIA, ESTR does not exhibit any significant month-end spikes.

Taken together, Table 2 documents a qualitative difference between SOFR, which is prone to upward spikes, and SONIA or ESTR, which are prone to downward spikes, as well as a quantitative difference — spikes in SOFR are several orders of magnitude larger than the spikes in SONIA or ESTR. In line with Hypothesis 1, the large upward spikes in SOFR reflect borrowers' cash demand in transactions T2 and T3, as well as the floor introduced by the reverse repo facility for T1 transactions. By contrast, the downward spikes in SONIA and ESTR reflect the absence of a floor for transactions of type T1 and the fact that these rates mainly comprise transactions of type T1. In addition, the significant month-end spikes in SOFR and SONIA are in line with regulatory reporting based on month-end snapshots in the US and the UK while the absence of month-end spikes in ESTR reflects the quarter-end reporting in Europe.

3.2. The impact of government debt and excess reserves

We next examine the main drivers of the alternative benchmarks aside from regulatory reporting dates. To that end, we remove all month-end observations from the data and examine daily or weekly changes in the alternative benchmarks relative to the key policy rates in the respective area.[8]

We construct two variables that are available on a daily basis: the amount of government debt outstanding and the transaction volume underlying the alternative benchmarks. First, to obtain the quantity of government debt outstanding, we collect auction data for US Treasuries, UK gilts, and German Treasuries. We then use the issuance volumes, auction dates, and maturity dates to construct daily volumes of US and UK government debt outstanding and to approximate the volume of safe assets in the euro area. Second, because a more detailed breakdown into transaction types is only available for SOFR, we simply use the total transaction volumes underlying the alternative benchmark rates in this section and conduct additional tests for SOFR later. In interpreting the role of transaction volumes, it is important to note that SONIA and ESTR volumes are largely transactions of type T1, while changes in bilateral repo volumes are the main driver of daily fluctuations in SOFR volumes. Hence, higher SONIA or ESTR volumes reflect banks' demand for funds from non-banks, which increases the rate. Similarly, a higher SOFR volume reflects stronger demand for funds from non-banks in the bilateral repo, also increasing the rate.

In addition, we use a weekly measure of bank reserves in the US, the UK and Europe and also reexamine the impact of government debt and transaction sizes on a weekly frequency.

Confirming Hypothesis 2, column 1 of Table 3 shows that an increase in Treasury debt outstanding corresponds to large, statistically significant increases in SOFR. This impact remains statistically significant in column 2, where we examine weekly changes instead of daily changes and control for changes in reserves. In addition, more underlying transactions increase SOFR and, together with changes in government debt outstanding, the two variables explain 12% of the daily variation in SOFR. Focusing next on the UK, column 3 of Table 3 shows that an increase in gilts outstanding increases reformed SONIA, while daily changes in transaction volumes have an insignificant impact. For weekly instead of daily changes, column 4 shows that gilts outstanding become insignificant while increases in transaction volumes correspond to significant increases in reformed SONIA, although only at a 10% significance level. Examining ESTR, columns 5 and 6 show an insignificant impact of changes in the amount of German Treasuries outstanding, while fluctuations in transaction vol-

[8] Because the goal of these tests is to examine the link between SOFR and other variables under "normal" market conditions, we also remove the week from September 16, to September 20, 2019, when SOFR spiked up to 5.23% to avoid our results being driven by large outliers in the data.

Table 3
Drivers of the alternative benchmark rates in the U.K. and Europe.
This table shows the results of regressing changes in the alternative benchmark rates on the indicated variables. Columns 1, 3 and 5 examine daily changes. Columns 2, 4 and 6 examine weekly changes (sampled on Wednesdays). For the US, the UK, and Europe, $\Delta \log(Debt)$ are changes in the total amount of US Treasuries, Gilts, or German Treasuries outstanding, respectively. $\Delta \log(Transact.\ Volume)$ are changes in the total trading volume underlying the alternative benchmark rates, and $\Delta \log(Reserves)$ are changes in the total amount of bank reserves in the respective area. The independent variables are SOFR (columns 1 and 2), SONIA (columns 3 and 4), and ESTR (columns 5 and 6). To remove fluctuations in these rates due to changes in policy rates, we use the spread of these rates over the policy targets in the three regions. The last, second-last, and first trading day of each month as well as five days after September 15, are removed from the sample to avoid large outliers and reporting-date spikes driving the results. The sample periods start in August 2014 for SOFR, February 2016 for SONIA, and December 2016 for ESTR, including data until December 2019. The numbers in parantheses are heteroskedaticity-robust t-statistics. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	SOFR		SONIA		ESTR	
	(1)	(2)	(3)	(4)	(5)	(6)
Intercept	−0.00***	−0.01	0.00	0.00	−0.00	0.00
	(−2.91)	(−1.50)	(0.11)	(0.41)	(−0.19)	(0.33)
$\Delta \log(Debt)$	9.73***	4.00***	0.06**	0.01	−0.21	0.07
	(8.80)	(3.03)	(2.01)	(0.37)	(−1.09)	(1.14)
$\Delta \log(Transact.\ Volume)$	0.09**	0.20***	0.00	0.00*	0.02***	0.02***
	(2.46)	(2.68)	(1.22)	(1.85)	(4.10)	(3.92)
$\Delta \log(Reserves)$		−0.14		0.01		−0.03
		(−1.15)		(0.74)		(−1.47)
Adj. R^2	0.12	0.07	0.01	0.00	0.06	0.22
Num. obs.	1186	241	850	179	597	124

umes have a positive and significant impact in both specifications. Taken together, Table 3 confirms Hypothesis 2, which suggests that the impact of government debt is strongest for the US because SOFR is collateralized with Treasury debt and therefore changes in the volume of debt outstanding have a direct impact on SOFR.

Turning to Hypothesis 3, we find that both SOFR and SONIA are largely unaffected by changes in reserves, while we find a borderline insignificant impact for ESTR.[9] The insignificant impact of reserves on the alternative benchmarks can reflect the fact that banks had ample reserves for most of the sample; only US banks struggled with less ample reserves from mid-2018 and we re-examine the impact of reserves for this period in the following section.

3.3. Additional evidence from the US

Because the results so far suggest that SOFR is most affected by the market idiosyncracies described in Section 2, we next utilize the more granular US data to conduct additional tests of our hypotheses for SOFR.

First, instead of using daily changes in total SOFR volumes, we construct the share of tri-party repos underlying SOFR. An increase in this share corresponds to more transactions of type T1 in SOFR, which lowers the rate because rates in which non-banks act as lenders are usually lower than rates in which banks act as marginal lenders. In line with this assertion, column 1 of Table 4 shows a strong negative link between SOFR and the tri-party share in SOFR, while the impact of changes in Treasury debt outstanding remains virtually unchanged. While the link between tri-party share and SOFR is arguably mechanical (tri-party repo rates are typically below GCF and bilateral rates), it highlights that movements in SOFR can be due to compositional changes in the repo market that are unrelated to banks' funding costs; for example, unusually low bilateral transaction volumes (e.g., because hedge funds scale down their leverage), combined with unchanged tri-party volumes lower SOFR without having an obvious impact on banks' funding costs.

Next, we focus on weekly changes and add the total amount of bank reserves as an explanatory variable. In addition, we obtain data on overnight Treasury repos and reverse repos by primary dealers. Primary dealers are net repo borrowers since 2013, which allows us to use log-changes for our analysis. We expect that more primary dealer net repo borrowing will increase SOFR because it reflects an elevated demand for repo funding from the financial sector. In line with these arguments, column 2 of Table 4 shows that all explanatory variables have the expected signs; a higher amount of reserves lowers SOFR while more primary dealer net repos increase SOFR.

We next test whether the link between SOFR and reserves is stronger when the aggregate level of reserves is relatively low. To that end, we interact changes in reserves with a dummy variable that equals one from mid-2018 on (when reserves reached a low level) and zero otherwise. Column 3 of Table 4 shows that the impact of reserves is over ten times stronger and statistically significant ($t = -2.64$) when interacted with the mid-2018 dummy variable.

Finally, we address a potential shortcoming of our analysis. Due to central bank purchases, the amount of Treasury debt can differ from the publicly-available debt level. In particular, an increase in reserves can decrease the amount of publicly-available debt and therefore affect SOFR through a change in the supply of safe assets. To address this concern, we construct a measure of publicly-available Treasury debt outstanding by subtracting Federal Reserve Treasury holdings from the total amount of Trea-

[9] Despite being borderline insignificant for ESTR, controlling for changes in reserves increases the daily R^2 of 6% to a weekly R^2 of 22%, suggesting that fluctuations in reserves help explain fluctuations in ESTR.

Table 4
What makes SOFR tick?
This table shows the results of regressing changes in SOFR on the indicated variables. To avoid capturing fluctuations in SOFR due to changes in the policy target rate, we analyze the spread between SOFR and the upper bound of the of the Federal fund's target rate. $\Delta \log(Debt)$ are changes in the total amount of Treasuries outstanding, $\Delta \log(TPV/SORFV)$ are changes in the fraction of triparty repo in SOFR, $\Delta \log(PD\ NetRepo)$ are changes in the net amount of overnight repos of primary dealers, $\Delta \log(Reserves)$ are changes in the total amount of bank reserves in the US, $\mathbb{1}_{\geq Jul\ 2018}$ is a dummy variable that equals from July 2018 on and zero otherwise, $\Delta \log(Debt \setminus FED)$ are changes in the amount of Treasuries outstanding minus FED Treasury holdings, and $\Delta \log(Other\ Hold)$ are changes in the amount of non-Treasury securities on the FED balance sheet. Column 1 shows the results for daily changes, columns 2–5 show the results for weekly changes (sampled on Wednesdays). The last, second-last and first trading day of each month as well as five days after September 15, are removed from the sample to avoid reporting-date spikes or the large September 15, 2019 spike driving the results. The sample period is August 2014 to December 2019. The numbers in parantheses are Newey-West t-statistics. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)
Intercept	−0.00***	−0.01	−0.01	−0.01	−0.01*
	(−3.03)	(−1.31)	(−1.34)	(−1.51)	(−1.93)
$\Delta \log(Debt)$	10.17***	3.56**	3.43**		
	(11.25)	(2.39)	(2.45)		
$\Delta \log\left(\frac{TPV}{SOFRV}\right)$	−0.07***	−0.08	−0.09	−0.08	−0.11
	(−2.80)	(−1.08)	(−1.30)	(−1.05)	(−1.52)
$\Delta \log(PD\ NetRepo)$		0.21***	0.20***	0.20***	0.20***
		(3.51)	(3.48)	(3.33)	(3.22)
$\Delta \log(Reserves)$		−0.26*	−0.08	−0.24*	
		(−1.90)	(−0.56)	(−1.80)	
$\Delta \log(Reserves) \times \mathbb{1}_{\geq Jul\ 2018}$			−0.94***		
			(−2.64)		
$\Delta \log(Debt \setminus FED)$				3.39***	3.79***
				(2.94)	(3.51)
$\Delta \log(Other\ Hold)$					−1.53*
					(−1.79)
Adj. R^2	0.13	0.08	0.11	0.08	0.09
Num. obs.	1135	235	235	235	235

suries outstanding. Column 4 of Table 4 shows that using this modified version of debt outstanding leaves our results virtually unchanged. In addition, we replace the amount of reserves with the amount of non-Treasury securities held by the Fed. This measure can capture changes in reserves that leave the publicly-available Treasury debt unaffected and column 5 shows that it has a qualitatively similar impact on SOFR as reserves.

3.3.1. The impact of financial regulation

We next test whether the introduction of the LR in January 2013 (more precisely, the reporting of the LR to regulators from 2013 on) impacted rates. Because SOFR is only backward calculated until August 2014 and because the triparty repo rate is only available from September 2012 on, we focus our analysis of the pre-2013 period on the GCF repo rate. In columns 1 and 2 of Table 5, we contrast the month-end and quarter-end spikes in the 2010–2013 period with the 2013–2019 period and find massive average quarter-end spikes of 18.55 bps in the post-2013 period, which did not exist before. This behavior is opposite to the pre-crisis results (using the 2000–2005 period) reported in Bartolini et al. (2010), who find significant *downward* spikes in the GCF repo rate at quarter-ends. Column 2 of Table 5 shows the results for the tri-party repo rate in the 2013 – 2019 period; the rate exhibits a less significant volatility at quarter-ends than the GCF rate. As explained in Section 2, any potential downward spikes in tri-party repo rates are limited by the Fed reverse repo program, while quarter-end spikes in other repo market segments could spill over to the tri-party market.

Columns 3 and 4 of Table 5 illustrate the mechanisms in the repo market from a different perspective, using the difference between quarter-end and quarterly average repo holdings for individual banks as independent variables. We regress this measure on a dummy variable (FBO) that equals one if the bank is a foreign banking office and zero otherwise, and a post-2013 dummy variable, interacted with FBO. The idea behind this test is that, in contrast to US banks, who report quarterly averages, foreign bank offices report quarter-end snapshots of their leverage ratio to regulators. With the beginning of leverage ratio reporting to regulators in 2013, we therefore expect an impact on foreign banking offices that is not present for US banks.

Columns 3 and 4 of Table 5 show the regression results for repo borrowing and repo lending, respectively. Column 3 shows that, in the post-2013 period, foreign banking offices reduce their quarter-end borrowing significantly compared to US banks, suggesting that foreign bank offices engage in window dressing to increase their LR over reporting dates. Column 4 shows a qualitatively similar, but weaker, pattern for repo lending. The weaker result is in line with repo lending being, in principle, balance sheet neutral and only affecting constraints due to repo intermediation.

4. Implications for term rates

In this section, we first examine how term rates based on the alternative benchmarks deviate from LIBOR term rates. We then study the transition of derivatives markets

Table 5
Changing reporting-date effects in US rates.
Columns 1 and 2 show the results of regressing the spread between GCF or triparty repo rates and the IOER rate on three dummy variables: *QEnd*, which equals one on the last trading day of a quarter and zero otherwise, *YEnd*, which equals one on the last trading day of a year and zero otherwise, and $MEnd \setminus QEnd$, which equals one on the last trading day of a month that is not quarter-end, and zero otherwise. $\mathbb{1}_{\geq 2013}$ is a dummy variable that equals one if the observation is after January 2013 and zero otherwise. Both specifications include year-quarter fixed effects. The sample period is January 2010 to December 2019. Columns 3 and 4 show the results of regressing the difference between banks repo holdings (borrowing and lending) on quarter end and the quarterly average during the quarter on $\mathbb{1}_{\geq 2013}$ and FBO, which equals one if the bank is a foreign banking office operating in the US and zero if it is a US bank. The sample period is first quarter 2000 to fourth quarter 2018. The data is obtained from regulatory filings to Federal Financial Institutions Examination Council's (FFIEC). The numbers in parantheses are Newey-West t-statistics. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	GCF (1)	TPR (2)		Borrowing (3)	Lending (4)
QEnd	0.93		Intercept	−0.91**	−0.57*
	(0.39)			(−2.19)	(−1.72)
YEnd	−4.40		FBO	0.78*	−0.24
	(−1.11)			(1.83)	(−0.60)
MEnd \ QEnd	3.92***		$\mathbb{1}_{t\geq 2013}$	0.55	0.46
	(4.29)			(1.58)	(1.62)
QEnd × $\mathbb{1}_{\{\geq 2013\}}$	18.55***	9.15***	FBO × $\mathbb{1}_{t\geq 2013}$	−0.97**	−0.83
	(3.90)	(3.54)		(−2.08)	(−1.58)
YEnd × $\mathbb{1}_{\{\geq 2013\}}$	29.27	0.29			
	(0.85)	(0.04)			
MEnd \ QEnd × $\mathbb{1}_{\{\geq 2013\}}$	1.98	4.50***			
	(1.41)	(3.68)			
Adj. R^2	0.33	0.27	Adj. R^2	0.00	0.00
Num. obs.	2498	1337	Num. obs.	21,979	21,887

toward the alternative benchmarks and conclude with an overview of the implications for discount rates.

4.1. Comparison to term LIBOR

An important difference between term LIBOR (LIBOR tenors with more than one day to maturity) and term rates based on the alternative benchmarks is that LIBOR contains a term premium. This term premium comprises a liquidity premium to compensate lenders for committing funds over longer time periods and a credit premium accounting for the risk that the borrower defaults during the term of the loan (see Filipović and Trolle, 2013 for a decomposition of the term premium in LIBOR).[10] By contrast, term rates based on the alternative benchmarks will be averages of overnight rates and therefore lacking a term premium.

To illustrate the different ways of averaging the alternative benchmarks, assume that we want to compute a 3-month term rate. The simplest approach is to compute the average of the overnight rate over the past 90 days. This approach is also called averaging "in advance" because the resulting term rate is available in advance of a payment.[11] Averaging in advance has the shortcoming that it results in a backward-looking rate that, unlike LIBOR, does not reflect market expectations about interest rates in the following 3 months. An alternative approach partly addressing this shortcoming is averaging "in arrears." In our example, that means computing the 3-month term rate as the average overnight rate over the following 90 days. Despite the drawback that these in arrears averages are not available in real time and reflect realized instead of expected rates, regulators explicitly advocate the use of this approach (see, e.g., ARRC, 2020a; "A users guide to SOFR"). A third approach is extracting forward-looking averages from derivatives, which would incorporate future rate expectations and be available in advance. However, the drawback of this approach is that derivatives prices are not as robust as transaction-based overnight rates. In theory, dealer banks could collude to manipulate the derivatives prices, which would undermine the fact that the underlying overnight rate fulfills all the requirements to a robust benchmark rate.

In addition to choosing between in advance and in arrears averaging, we also need to distinguish two different ways of computing averages: compounding the interest as a geometric average $\frac{360}{N}[\prod_{i=1}^{N}\left(1+\frac{1}{360}r_i\right)-1]$ or simple averaging as $\frac{1}{N}\sum_{i=1}^{N} r_i$, where N is the time period over which rates are compounded. We use simple averaging to compute averages in arrears and provide summary statistics of the spread between term rates based on the new benchmarks and 3-month LIBOR rates in Panel B of Fig. 1. As we can see from the figure, the median spread is negative in all three rates and significantly lower than the spreads in Panel A, which provides a comparison of the alternative benchmarks to the overnight LIBOR.

To better understand the spread between term rates based on averaging the alternative benchmarks ($\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON}$) and term LIBOR ($\ell_t^{3m}$), we next decompose the spread into two components — a proxy for the term premium and the benchmark spread:

$$\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON} - \ell_t^{3m}$$

[10] In theory, even overnight rates can contain a credit premium, but for borrowers with high credit quality, the default risk decreases with shorter times to maturity. Hence, the credit premium is negligible for overnight rates.

[11] One example of such term rates are the SOFR term rates published by the New York Fed (https://apps.newyorkfed.org/markets/autorates/sofr-avg-ind).

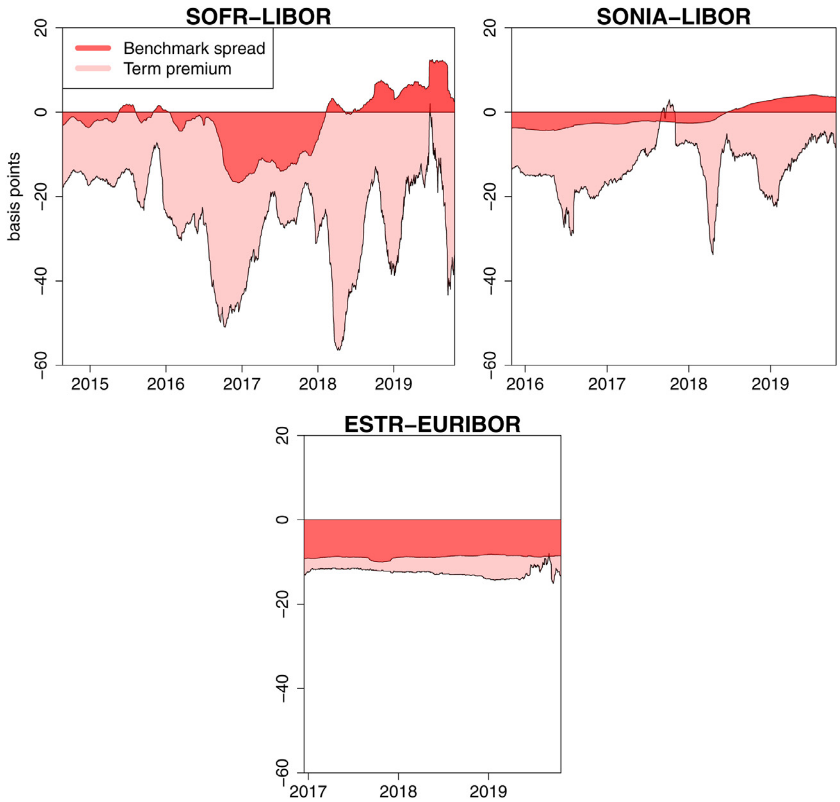


Fig. 5. Spread between 3-month average of alternative benchmarks and LIBOR.
This figure shows a decomposition of the spread between 3-month averages of the alternative benchmarks, computed in arrears, and 3-month LIBOR into a term spread component and a benchmark spread component. The light-shaded areas show the component of the spread due to term premium. This component is estimated as the spread between the 3-month average of overnight LIBOR (or EONIA; both computed in arrears) and 3-month term LIBOR. The dark-shaded areas show the component of the spread due to differences in overnight rates. This component is computed as the 3-month average of the spread between the alternative benchmarks and overnight LIBOR. On days where the spread between overnight rates is positive, the term premium is the sum of the light-shaded and dark-shaded areas in the graph. On days where the term premium component is positive, the term premium is the sum of the light-shaded and dark-shaded areas in the graph.

$$= \underbrace{\left(\frac{1}{90}\sum_{i=1}^{90}\ell_{t+i}^{ON} - \ell_t^{3m}\right)}_{\approx \text{ Term premium}} + \underbrace{\left(\frac{1}{90}\sum_{i=1}^{90} r_{t+i}^{ON} - \frac{1}{90}\sum_{i=1}^{90}\ell_{t+i}^{ON}\right)}_{\approx \text{ Benchmark spread}}. \tag{2}$$

The resulting proxy for the term premium has three components. In addition to the liquidity premium and credit premium discussed above, it also contains an “expectations error” because the in arrears average of overnight LIBOR reflects the realized level of interest rates while the 3-month LIBOR reflects the market expectation for rates over the next three months (this error is not present when using OIS contracts instead).

Fig. 5 shows the results of this decomposition. As we can see from the figure, the term premium occasionally exceeds −50 bps in the US, reaches almost −40 bps in the UK, and is between 0 bps and −5 bps in Europe. In addition, Fig. 5 shows that the US benchmark spread exhibits large variation between −20 bps and 15 bps, with a noticeable spike in mid-2019, while the benchmark spread in the UK is relatively stable with the only noticeable change in 2018, when the LIBOR reform led to a decrease in LIBOR rates. In Europe, the term spread is virtually constant at 8.5 bps and significantly larger than the term premium.[12]

4.2. The impact on derivatives markets

We next examine how the LIBOR funeral affects the open interest of euro-dollar futures for contracts referencing either USD LIBOR, GBP LIBOR, or EURIBOR. Euro-dollar futures are exchange-traded derivatives that pay the 3-month LIBOR or EURIBOR rate at expiry (which is the third Wednesday of a quarter). The price of each futures contract reflects the expected 3-month LIBOR (or EURIBOR) rate at a future valuation date and contracts with valuation dates up to 60 months in the future are liquidly traded in all three currencies.

Focusing on the open interest of euro-dollar futures allows us to test whether market participants reduced their

[12] The missing term premium in the alternative benchmarks makes it difficult to compare term rates based on averaging the alternative benchmarks with other proxies for the risk-free rate. For instance, Van Binsbergen et al. (2019) derive an option-implied risk-free rate. We compare this option-implied rate to Treasury yields and average SOFR rates the Online Appendix, showing that the average SOFR rate is significantly lower.

Table 6
The impact of the LIBOR funeral of futures volumes.
This table shows the results of regressing the logarithm of the open interest in LIBOR futures contracts with maturities between 27 and 60 months on three dummy variables. $\mathbb{1}_{t\geq Jul/2017}$ is a dummy variable that equals one after the LIBOR funeral announcement in July 2017 and zero otherwise. $\mathbb{1}_{T>Dec2021}$ is a dummy variable that equals one if the contract expires after December 2021 and zero if it expires earlier. Columns 1 and 2 show the results for USD LIBOR futures. Columns 3 and 4 show the results for GBP LIBOR futures. Columns 5 and 6 show the results for EURIBOR futures. All panels include time-to-maturity (TTM) type fixed effects and year fixed effects. The numbers in parantheses are Newey-West t-statistics, clustered at the date and type level. ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

	USD Libor	GBP Libor	Euribor
$\mathbb{1}_{\{t>Funeral\}} \times \mathbb{1}_{\{T>Discontinue\}}$	−0.03	−0.60**	0.40***
	(−0.46)	(−2.20)	(4.69)
$\mathbb{1}_{\{t>Funeral\}}$	−0.02	0.06	−0.06
	(−0.36)	(0.38)	(−0.63)
$\mathbb{1}_{\{T>Discontinue\}}$	−0.02	1.80***	−0.04
	(−0.28)	(8.84)	(−0.50)
TTM FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Adj. R^2	0.93	0.87	0.95
Num. obs.	14,592	14,545	14,568

LIBOR exposure in contracts with valuation dates after December 2021 once Bailey (2017) announced the LIBOR funeral on July 27, 2017. Table 6 shows the results of regressing the log-open interest in contracts with valuation dates between 27 and 60 months on the interaction between a dummy variable that equals one after the LIBOR funeral announcement ($\mathbb{1}_{t>Funderal}$) and a dummy variable that equals one if the valuation date of the underlying contract is after December 2021 ($\mathbb{1}_{T>Discontinued}$). We remove contracts with less than 27 months to maturity to keep the focus on contracts that reference LIBOR after December 2021 at least once during our January 2015 to December 2019 period. To control for potential differences in open interest for contracts with different maturities, we add time-to-maturity (TTM) fixed effects. In addition, each specification includes year fixed effects, $\mathbb{1}_{t>Funderal}$, and $\mathbb{1}_{T>Discontinued}$ as controls.

If market participants reduced their LIBOR exposure after the funeral announcement, we would expect a negative coefficient on the interaction term. However, as we can see from column 1 of Table 6, the LIBOR funeral had no significant effect on USD futures contracts that reference LIBOR after December 2021. By contrast, column 2 suggests that the open interest in GBP contracts with valuation dates after December 2021 dropped after the LIBOR funeral, while column 3 suggests the opposite is true for EURIBOR futures, where the open interest increased. The increase for EURIBOR futures reflects the different approach of European regulators, who decided to reform EURIBOR instead of discontinuing it after 2021 (see EMMI, 2018). Moreover, the significant decrease for GBP contracts is in line with SONIA derivatives already being liquidly traded and therefore allowing investors to transition away from LIBOR. By contrast, activity in SOFR-linked derivatives is picking up slowly, which can explain the insignificant drop in USD LIBOR futures. Confirming the different developments in derivatives markets, ISDA (2020) estimates that 31.8% of the risk in OTC interest rate derivatives for GBP are already linked to SONIA, while only 3.8% of USD derivatives are linked to SOFR.

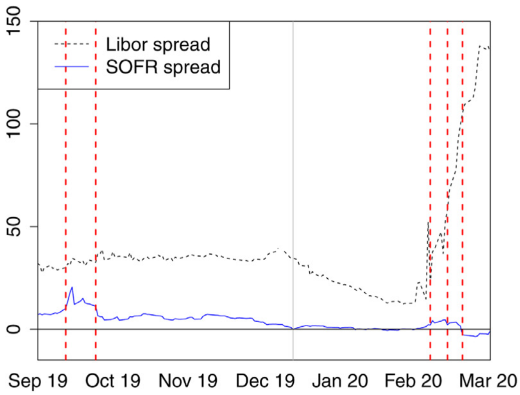
4.3. Implications for discount rates

To discount future cash-flows and value derivatives, it is common to use a rate that is close to risk-free. Since the financial crisis of 2007–2008, market participants such a s clearinghouses and derivatives traders rely on overnight index swap (OIS) rates as discount rates (see, e.g., Hull and White, 2013). The LIBOR funeral will impact this practice by changing these discount rates from the current OIS benchmarks to OIS referencing the alternative benchmarks. For the UK, which uses a reformed version of its OIS benchmark as LIBOR replacement, this switch is already implemented. In Europe, the old OIS benchmark is EONIA and the transition comprises two steps; from EONIA to ESTR plus 8.5 bps and from ESTR plus 8.5 bps to ESTR flat. We discuss the practical implications of this 8.5 bp switch in Section 4.4 and focus this section on implications for US benchmarks.

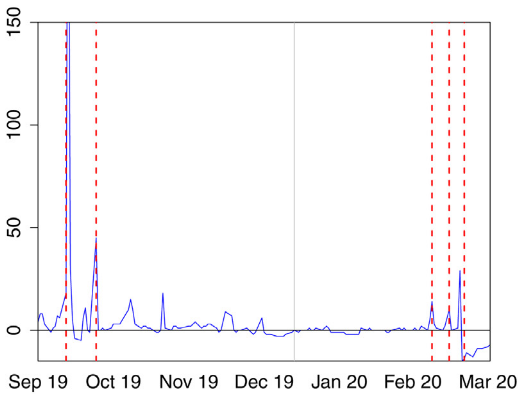
4.3.1. SOFR-OIS spreads

In this section, we use futures contracts to construct a 3-month SOFR-OIS spread, which we compare to the 3-month LIBOR-OIS spread. To construct this spread, we rely on Fed funds futures and SOFR futures. Fed funds futures are widely-used hedging instruments that mature at the end of each calendar month and reference the arithmetic average of the effective Fed funds rate (EFFR) during that month. SOFR futures were introduced in May 2018, reference SOFR instead of the EFFR, and, apart from that, have exactly the same contract details as Fed funds futures.[13] We use the implied futures rates in these contracts to construct discount and forward-discount factors that allow us to compute discount factors from the current date to the end of month $t+2$ and the end of month $t+3$. We then use these discount factors to extract corresponding term

[13] In addition to this type of SOFR futures, there is a second type that closely resembles euro-dollar futures, referencing the 3-month average SOFR and maturing at the same dates as the euro-dollar futures. We provide additional details on this type of futures in Appendix A.



Panel A: 3-month spread



Panel B: Overnight spread

Fig. 6. Spreads relative to the EFFR. Panel A shows the spread between the 3-month SOFR rate and the 3-month Fed funds rate, extracted from SOFR and Fed funds futures as well as the spread between 3-month LIBOR and the 3-month OIS rate based Fed funds. Panel B shows the spread between overnight SOFR and the Fed funds rate. We focus on the September 2019 to March 2020 period and the vertical dashed daa lines highlight the repo squeeze on September 16, 2019, the quarter-end date September 30, 2019, the rate cut by 50 bps on March 4, 2020, the introduction of the Fed term repo program on March 12, 2020, and the announcement of the Fed overnight repo program on March 19, 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rates and obtain 3-month SOFR and EFFR by interpolating between the rates for month $t+2$ and $t+3$.

Panel A of Fig. 6 provides a comparison of the resulting 3-month SOFR-OIS spread and the observed 3-month LIBOR-OIS spread. As we can see, the repo squeeze on September 16, 2019 led to an increase in the SOFR-OIS spread, which only normalized after the quarter-end date on September 30, while having virtually no effect on the LIBOR-OIS spreads. By contrast, in March 2020, when COVID-19 started hitting the US economy – the third red line in Fig. 6 highlights the date when the Fed cut interest rates by 50 bps – we see a sharp increase in LIBOR-OIS spreads while SOFR-EFFR spreads show a moderate initial increase. During March 2020, we then observe a further increase in LIBOR-OIS spreads while SOFR-EFFR spreads reverse into negative. These increases in LIBOR, combined with decreases in SOFR resonate with Schrimpf and Sushko (2019), who argue that the difference between LIBOR and collateralized rates becomes most apparent during crises.

To better understand the term rate during this turbulent period, Panel B shows the spread between overnight SOFR and EFFR. As we can see from the figure, the overnight SOFR-EFFR spread spiked above 150 bps at the September repo squeeze followed by an increase to around 50 bps at quarter-end in late September. In early March 2020, the volatility of the SOFR-EFFR spread starts increasing. On March 12, (fourth red line), the Fed's term repo program schedule was announced and on March 17, the Fed announced the overnight repo program (announcing 500 billion of overnight repo lending every day), which stabilized repo markets and lead to a drop of the SOFR-FFR spread into negative territory. Taken together, Fig. 6 highlights a fundamental difference between LIBOR rates and SOFR – during a crisis period, repo rates do not increase as significantly as uncollateralized bank lending.

4.3.2. Spikes in SOFR term rates

We next use SOFR futures to examine spikes in SOFR term rates. We first focus on SOFR-EFFR futures spreads and contracts with maturities between 2 months and 6 months, removing the 1-month contract (because we are interested in expectations about future term rates) and dropping less liquid contracts with more than 6 months to maturity. We then examine whether the futures-implied SOFR-EFFR spread is higher for contracts that expire in the last month of the quarter or the last month of the year. Column 1 of Table 7 shows that this is indeed the case; the average SOFR-EFFR futures spread is positive at 3.44 bps and 0.79 bps higher in the last month of the quarter and more than 2 bps $(0.79+1.39)$ higher in the last month the calendar year. Column 6 shows that these results remains virtually unchanged after adding year-quarter and maturity-type fixed effects.

Because the EFFR can be prone to downward spikes at regulatory reporting dates (see our discussion in Online Appendix), part of the quarter-end and year-end spikes in columns 1 and 2 could be a result of expected downward spikes in the EFFR instead of expected upward spikes in SOFR. We therefore use an alternative approach to examine expected quarter-end spikes in SOFR. Similar to Fleckenstein and Longstaff (2019), who examine year-end effects in euro-dollar futures, we construct an interpolated SOFR futures rate for month t by linearly interpolating between SOFR futures rate in month $t-1$ and in month $t+1$ and then examine the spread of the SOFR-implied futures rates for month t and the interpolated rate. As we can see from columns 3 and 4 in Table 7, this approach leads to qualitatively similar but less significant results. Given that downward spikes in the EFFR are much smaller than the upward spikes in SOFR and diminish after 2018:Q2 (our futures sample starts in May 2018), we argue that the SOFR-EFFR spreads in columns 1 and 2 more closely reflect the expected quarter-end behavior of SOFR than the simple spline estimates in columns 3 and 4.

Table 7
Reporting-date spikes in SOFR futures.
This table shows the results of regressing the spread between monthly SOFR futures and either Fed funds futures (columns 1 and 2) or the interpolated SOFR futures rate for contracts maturing in month $T-1$ and $T+1$ (columns 3 and 4) for 2, 3, 4, 5, and 6 months to maturity on two dummy variables: *QEnd* equals one if the contracts expire in the last calendar month of a given quarter and zero otherwise, and *YEnd* equals one if the contracts expire in the last calendar month of a given year and zero otherwise. The sample comprises daily observations for the May 4, 2018 (the date when SOFR futures trading started) to December 2019 period. The numbers in parantheses are Newey-West t-statistics, clustered by time-to-maturity type. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

	SOFR-FFF		SOFR-Spline	
	(1)	(2)	(3)	(4)
Intercept	3.44***		−0.27***	
	(188.00)		(−2.66)	
QEnd	0.79***	0.94***	0.61**	0.45
	(3.42)	(4.90)	(2.25)	(1.56)
YEnd	1.39***	1.16***	0.43**	0.91***
	(2.97)	(2.69)	(2.06)	(3.53)
FEs	–	YQ & Type	–	YQ & Type
Adj. R^2	0.07	0.63	0.01	0.03
Num. obs.	2060	2060	2060	2060

4.4. Practical issues going forward

We now discuss six practical issues stemming from the LIBOR funeral. First, even though market participants know the overnight rates set to replace LIBOR, the construction of corresponding term rates can vary across market segments. For example, USD interest rate swaps and floating rate notes (FRNs) reference SOFR compounded averages in arrears, syndicated loans reference SOFR simple averages in arrears, and mortgage-backed securities (MBSs) reference SOFR compounded in advance. Moreover, the ARRC recommends in arrears averaging for business loans (see ARRC, 2020b), while this approach is not possible for mortgages where regulation requires that consumers know their interest rate 45 days in advance. Complicating the transition further, compounded ESTR is problematic for Germany and Italy, where compounded interest is illegal in consumer loans (see Rega-Jones, 2019). The difference between in arrears and in advance compounding can be substantial when key policy rates change unexpectedly, while the difference between simple averaging and compounding is negligible, especially when interest rates are low (see ARRC, 2020c).

Second, the fact that term rates based on alternative benchmarks are detached from banks' marginal funding costs (especially for the US, where term spreads are high), poses a problem for bank loans. LIBOR was originally introduced as a benchmark in syndicated loans, allowing banks to charge a spread relative to their own funding costs (see, Vaughan and Finch, 2017). Replacing the floating rate in a loan with an overnight rate exposes banks to fluctuations in term premiums and can be especially problematic for products like credit lines, where the probability of customers drawing on such lines increases during market turmoil. These issues contribute to a slow growth in SOFR-denominated debt, mainly issued by US agencies so far (see Smith, 2020a) and opposed by smaller banks (see Banker, 2020) and received heightened attention during the market turmoil in March 2020 when LIBOR spreads soared (e.g., Jermann, 2020). To resolve these issues, the US established a credit sensitivity group (CSG) and a likely fix is constructing a measure of bank credit risk that can be added to SOFR (see Berndt et al., 2020 for one proposal and a discussion of this approach).

Third, changing the reference rate in the vast quantity of derivatives referencing LIBOR and maturing after 2021 is a challenge. One possible solution is to determine the compensation for switching the underlying derivatives benchmark from LIBOR to alternative benchmarks in an auction, thereby retiring large parts of LIBOR derivatives before December 2021 (see Duffie, 2018 or Zhu, 2019 for a discussion of different mechanisms). The International Swaps and Derivatives Association (ISDA), suggests amending the derivatives contracts with a fallback protocol: Should LIBOR be discontinued, the benchmark rate will be replaced with the alternative benchmark, compounded in arrears, plus a fallback spread. The fallback spread is the five-year historical median spread between LIBOR and the compounded alternative benchmark (see ISDA, 2019). As discussed in Section 4.2, dervatives markets transitions slowly toward referencing the alternative benchmarks. Hence, to increase trading volumes in derivatives that reference the alternative benchmarks, the US Treasury considers issuing FRNs linked to SOFR (see Zhu, 2020 for a comment on this idea). In addition, clearing houses change the discount rates for derivatives pricing and collateral valuation from OIS discounting (with the EFFR or EONIA as benchmark in the US and Europe, respectively) to using discount rates based on the alternative benchmarks.

Fourth, this discounting switch poses a challenge for derivatives markets in the US and Europe. In Europe, the EONIA reform first replaces EONIA with ESTR plus 8.5 bps, reflecting the almost constant spread between EONIA and ESTR. In a second step, ESTR plus 8.5 bps is replaced by ESTR flat. This 8.5 bp switch in discount rates changes the valuation of interest rate swaps and other derivatives. While regulators can impose a compensation scheme for cleared derivatives, the compensation scheme is voluntary for uncleared derivatives. This is especially problematic for levered swap positions such as options to engage in swaps (commonly known as swaptions), where changes in discount rates can lead to windfall profits or losses (see

Becker, 2020). In addition to these potential windfall profits, the situation in the US is challenging because SOFR-EFFR spreads are more volatile.

Fifth, while the construction of LIBOR is similar across countries, the construction of the new benchmark rates differs across countries and the rates exhibit quantitatively different patterns. Hence, in addition to the basis risk between LIBOR and the new benchmark rates, the LIBOR funeral also introduces additional basis risk across countries. This basis risk can be amplified by different conventions for obtaining term rates in different regions (see Smith, 2020b).

Finally, the LIBOR funeral poses difficulties for the risk management of UK insurance companies. On the one hand, the financial conduct authority (FCA) urges insurances to transition away from LIBOR (see the FCA "Dear CEO LIBOR Letter,") while insurance regulation under Solvency II explicitly uses discount rates linked to LIBOR swap rates. Hence, UK insurers using SONIA derivatives instead of LIBOR derivatives can face regulatory capital charges for transitioning to the alternative benchmarks.

5. Concluding remarks

We examine the alternative benchmark rates in the US, the UK, and Europe, provide a detailed overview of the micro-structure behind these rates, and highlight their three main drivers. First, tighter regulatory constraints increase SOFR but decrease SONIA and ESTR. Second, besides the predictable reporting date spikes, a higher volume of government debt outstanding corresponds to a significant increase in SOFR and less-significant increases in SONIA and ESTR. Finally, when reserves are at a low level, an increase in the amount of reserves lowers the alternative benchmarks. Our analysis provides a better understanding of the alternative benchmark rates, which is important given that these rates are intended to replace LIBOR in trillions of loans, floating rate debt, and financial contracts. In addition, we show that term rates based on the alternative benchmark rates can be affected by regulatory reporting spikes but are more stable than LIBOR rates, lacking a term premium.

While the transition away from LIBOR to alternative benchmark rates will enhance the transparency and robustness of benchmark rates, our paper highlights three potential issues for the "life after LIBOR." First, the type of transactions underlying the alternative benchmarks affect the interest rates and introduce volatility unrelated to banks' marginal funding costs. More broadly, while the inclusion of non-bank-to-bank transactions in the alternative benchmarks ensures that transaction volumes are robust, borrowing from non-banks might not be readily available for some banks, putting a wedge between the rates and banks' marginal funding costs. Second, we show that the supply of government debt affects the alternative rates. For collateralized rates, the impact of government debt supply is even more pronounced because the rates are also affected by the availability of government debt collateral. Finally, term rates based on the alternative benchmarks lack a term premium, which detaches these rates from banks' costs of term funding and introduces problems for loan issuance.

Appendix A. Additional details on SOFR

This section contains additional details and descriptive statistics for SOFR. Fig. A.1 illustrates the impact of including different market segments into the computation of SOFR. The upper line shows the spread between SOFR and the broad general collateral rate (BGCR), which removes bilateral repo transactions from SOFR. As we can see from the figure, the SOFR-BGCR is virtually always positive and spikes upward at quarter-ends. Moreover, the lower line in Fig. A.1 shows the spread between BGCR and the tri-party general collateral rate (TGCR), which removes GCF transactions from the BGCR. Removing the GCF transactions has a small effect on the rate, which is in line with the small share of GCF transactions in the overall SOFR volume.

Appendix B. The term structure of SOFR-LIBOR spreads

We now use euro-dollar futures and the second type of SOFR futures (the 3-month SOFR futures) to examine the term structure of the SOFR-LIBOR spreads. The 3-month SOFR contracts have the same contract specifications as euro-dollar futures – they have the same expiry dates, settlement dates, and collateral requirements – but reference the arithmetic 3-month average of the SOFR rate in-

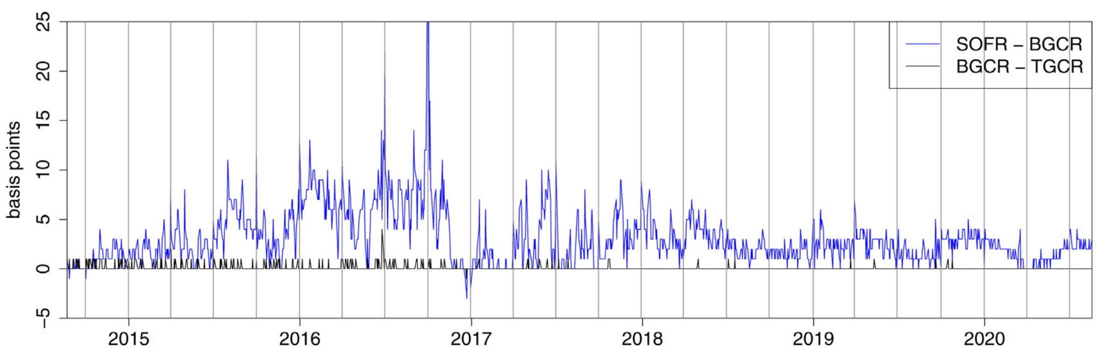
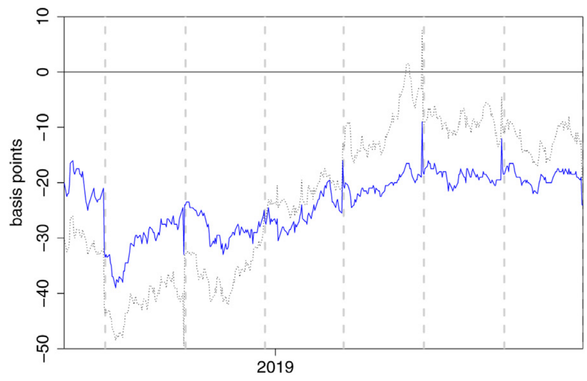
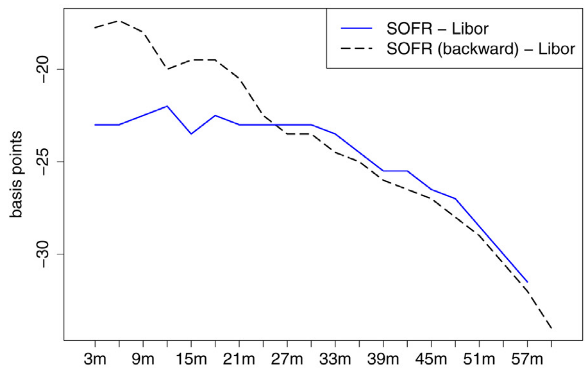


Fig. A.1. Different repo rates in SOFR.
This figure provides additional background for SOFR, illustrating the spread between SOFR and BGCR (removing bilateral transactions) and the spread between BGCR and TGCR, removing GCF transactions. The vertical lines indicate quarter-ends.



Panel A: 12-month spread



Panel B: Term-structure

Fig. A.2. Spread between different SOFR futures rates and Libor futures rates.
This figure illustrates SOFR-LIBOR spreads extracted from 3-month SOFR and euro-dollar futures contracts. Panel A shows the SOFR-LIBOR spread for futures contracts that mature in 12-months. Panel B shows the median SOFR-LIBOR spread for different maturities, ranging from 3 months to 60 months. The solid line is the SOFR-LIBOR spread, where forward-looking averages are used and the solid line is the SOFR-LIBOR spread, where backward-looking averges are used. The dashed vertical lines in Panel A are IMM dates. The sample period is May 2018 to December 2019.

stead of 3-month LIBOR. We use these futures contracts to construct forward-looking spreads, where we match SOFR futures that pay the average SOFR rate over the following three months with euro-dollar futures. In addition, we compute backward-looking spreads by using SOFR futures that pay the average SOFR rate over the past three months instead.

Panel A of Fig. A.2 provides a comparison of the two spreads for futures contracts with 12 months to maturity. The solid line shows the SOFR-LIBOR spread using forward-looking SOFR futures, while the dashed line uses backward-looking SOFR futures. The spread for forward-looking contracts fluctuates between −35 bps and −15 bps while the spread for backward-looking contracts is more volatile and fluctuates between −50 bps and 10 bps. Panel B illustrates the median term structure of SOFR-LIBOR spreads for the May 2018 to December 2019 period. Panel B illustrate the term structure for forward-looking and backward-looking spreads, respectively. As we can see from the figure, both term structures are downward-sloping, suggesting that investors expect SOFR-LIBOR spreads to be more negative in the long run. Comparing the two term structures, Panel B shows that the median forward-looking spread is below the median backward-looking spread for maturities up to 30 months. For the longer end of the term structure, the median spreads are almost identical.

Appendix C. An illustrative model

We now illustrate the impact of tighter financial constraints and fluctuations in available government debt on different overnight rates through a simple model. Two types of agents, A and B, can invest in a risky asset in a perfectly elastic supply with final payoff $D \sim \mathcal{N}(1+\mu, \sigma^2)$ and price normalized to one. In addition, the agents lend money to each other or invest in government debt with limited fixed supply $\mathcal{S}$. Both government debt and lending between A and B earn the same return r, which we determine below. Moreover, agent B can lend money to another agent (e.g., another bank or hedge fund, which we do not model explicitly) at a rate ρ that we also determine below. Both agents have the same risk aversion γ and agent $G \in \{A, B\}$ maximizes the mean-variance utility of end-of-period wealth W^G:

$$\max_{g,\bar{g}} \left[g(\mu - r - \gamma g \frac{\sigma^2}{2}) + \bar{g}(\rho - r) \right],$$

where $\bar{g}$ is the amount of money that agent B lends out.

Agent A can be thought of as a cash-rich investor, such as a MMF, that does not face regulatory constraints. This agent can only lend to agent B ($\bar{a} = 0$), invests in the risky and risk-free asset, and lends its remaining wealth to other agents (or invests in the risk-free asset) at the broad lending rate r. Agent B is a bank that faces regulatory constraints and can borrow money from A at the rate r. Agent B's regulatory constraint limits its risky investments and capacity to lend out money, thus the constraint can be thought of as leverage ratio constraint:

$$\frac{W^B}{b + \bar{b}} \geq x,$$

where W^B can be interpreted as the banks' capital, $b + \bar{b}$ as the total exposure, and x as a fixed number between 3% and 6%. We restrict the model parameters such that we end up in the realistic case where agents' A and B take long positions in the risky asset and assume that there is a fixed demand $\bar{c}$ for cash by another agent, which could be another bank or a non-bank. Proposition 1 illustrates how r and ρ are affected by tighter regulatory constraints.

Proposition 1. Let $\Omega = W^A + W^B$ *and* $\mathcal{B} = \frac{\frac{1}{x} W^B}{\Omega - \mathcal{S} + \bar{b}}$.

(a) *If* $\mathcal{B} \geq \frac{1}{2}$, *the bank is unconstrained and* $r = \rho = \mu - \frac{\gamma \sigma^2}{2}(\Omega - \mathcal{S} - \bar{b})$

(b) *If $\mathcal{B} < \frac{1}{2}$, the bank is constrained and*

$$r = \mu - \gamma\sigma^2[(1-\mathcal{B})(\Omega - \mathcal{S}) - \mathcal{B}\bar{b}]$$
$$\rho = \mu - \gamma\sigma^2[\mathcal{B}(\Omega - \mathcal{S}) + (1+\mathcal{B})\bar{b}].$$

We relegate the proof of Proposition 1 to the Internet Appendix and focus on the economic intuition behind the proposition instead. The variable $\mathcal{B}$ can be interpreted as the tightness of the bank's constraint (i.e., a lower $\mathcal{B}$ implies that the bank is more constrained). Focusing on part (b), the proposition shows that tighter constraints, reflected by a lower $\mathcal{B}$, decreases r but increases ρ. Hence, Proposition 1 illustrates how a binding LR constraint affects interest rates differently, depending on whether the marginal lender is an unconstrained non-bank or a constrained bank.

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