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Abstract

The fixing of the Libor and Euribor benchmark rates has proven vulnerable to manipulation. Individual rate-setters may have incentives to fraudulently distort their submissions. For the contributing banks to collectively agree on the direction in which to rig the rate, however, their interests need to be sufficiently aligned. In this paper we develop cartel theory to show how an interbank rates cartel can be sustained. The exchange of information allows front running, by which the members both reduce conflicts in their trading interests and gain from inside information. In addition, designated banks engage in costly eligible transactions rigging to support their submissions. As the cartel is not able to always find stable cooperative submissions against occasional extreme exposure values, there is episodic recourse to non-cooperative quoting. Periods of heightened volatility in the rates, or in correlations between rate and position changes may be indicative of cartelization. Recent reforms to broaden the class of transactions eligible for submission and to average over fewer middle quotes can lead to more frequent collusive quoting.

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Trader RBS: "It's just amazing how Libor fixing can make you that much money or lose if opposite. It's a cartel now in London."

Trader Deutsche Bank: "Must be damn difficult to trade man, especially if you are not in the loop."[1]

1   Introduction

The London Interbank Offered Rate (Libor) and the Euro Interbank Offered Rate (Euribor) are financial benchmark rates that globally underlie enormous transaction values, are key variables in portfolio and risk management decisions, and barometers of financial sector health. Since the rise of the over-the-counter (OTC) derivatives markets from the late 1980s, today between 370 trillion and 400 trillion dollars worth of interest rate derivatives, consumer and commercial credit are estimated to directly derive their value from these rates—or over four times global GDP.[2]

The rates are calculated daily for numerous currencies and maturities, ranging from overnight to 12 months, as the trimmed average of submissions by a set panel of banks.[3] A member bank's quote is meant to reflect its capacity to borrow unsecured funds in the interbank market.[4] Each trading day morning, quotes are submitted in time to a central administrator, who discards the extremes, averages a set middle range and publishes the new rates at a given time.[5] All individual submissions are also published.[6]

The fixing of these financial benchmarks has proven vulnerable to manipulation. The contributing banks also trade in the financial products that are valued on the benchmarks, which gives them incentives to manipulate their submissions to favor their exposure positions. The trimming mechanism arguably encourages coordination in the manipulation, as it limits the effect an individual bank has on the rate.[7]

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[1] Transcript of conversations on 19 August 2007, submitted as evidence in *Tan Chi Min v The Royal Bank of Scotland*, S939/2011, Singapore High Court, as quoted in "RBS Instant Messages Show Libor Rates Skewed for Traders," *Bloomberg*, 26 September 2012.

[2] Financial Stability Board, "Reforming Major Interest Rate Benchmarks," July 2014, page 6.

[3] The Libor panels are consistently formed by 11 to 16 banks. The Euribor panel used to include 44 banks, but many members have withdrawn since the scandals. Currently, it consists of 20 banks.

[4] ICE Benchmark Administration (IBA), *Roadmap for ICE Libor*, 18th March 2016 and European Money Markets Institute, *Euribor Code of Conduct*, June 2016.

[5] The Libor quotes are submitted before eleven London Time. The middle 50% of quotes constitute the rate, which is published at 11.45 a.m. GMT. For the Euribor, this is a quarter to eleven Brussels Time, 70% and 11.00 a.m. CET. Production of the Libors used to be by the British Banking Association (BBA), but was recently transferred to ICE Benchmark Administration (IBA). The Euribor is published by the European Banking Federation (EBF), which changed its name to the European Money Markets Institute (EMMI).

[6] As part of on-going reforms, since 2013 individual Libor quotes are no longer published simultaneously with the final rate, but with a 3-month delay. HM Treasury, "The Wheatley Review of Libor: Final Report," 2012. Euribor submissions are still published simultaneously with the rates.

[7] In theory, any group that is strictly larger than the fraction trimmed on either side can have

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Suspicion of manipulation of the benchmark rates arose when in the gathering of the global financial crisis the Libors appeared to diverge periodically from other proxies of bank borrowing costs and risk, in particular credit default swaps (CDS) spreads.[8] Several panel banks admitted to misreporting, allegedly in attempts to appear more creditworthy by underreporting their true borrowing costs in their submissions—so-called 'low-balling'. The aim would have been to appear more creditworthy.

Prosecutions have focussed on misreporting in breach of the rates' code of conduct, mostly within a bank or between individual traders of a few banks. The cases were handled in the US by the Department of Justice's Criminal Division's Fraud Section and the Commodity Futures Trading Commission (CFTC), and in the UK by the Financial Service Authority (FSA). The investigations mostly focused on incidental favors done between individual traders to increase personal trading profits, possibly against the interest of their employer bank.

The evidence uncovered in the fraud investigations suggests, however, that there may have been more widespread coordination amongst the panel members. Communication between bank employees aimed at coordinating manipulation strategies of the benchmark rates to increase trading profits.[9] The FSA concluded that Barclays had acted in concert with other banks.[10] The CFTC found that:

"Libor was routinely being gamed by the banks that set it."[11]

Antitrust cases in financial benchmark setting are nevertheless few so far. While the DoJ's Antitrust Division was involved in the fraud investigations, it did not prosecute for collusion. In a private antitrust damages action, the Federal Court of New York initially even ruled that the Sherman Act would not apply to the Libor setting mechanism, which it deemed a cooperative rather than competitive process.[12]

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an unbounded effect on the rate. For example a group of 5 in a 16 bank Libor panel, or a group of 4 in the current 20 bank Euribor panel. In practice, outstanding quoting will raise suspicion of manipulation, whereas wider coordination can influence the rate more smoothly.

[8] C. Mollenkamp and M. Whitehouse, "Study Casts Doubt on Key Rate; WSJ Suggests Banks may have Reported Flawed Interest Rate Data for Libor," *Wall Street Journal*, 29 May 2008.

[9] For example U.S. Department of Justice, "Statement of Facts, Non-prosecution Agreement: Barclays Bank PLC," 26 June 2012, Commodity Futures Trading Commission, "Order Instituting Proceedings: Barclays Bank PLC," 27 June 2012; and Financial Services Authority, "Final Notice: Barclays Bank PLC," 27 June 2012. Similar documents of DoJ, CFTC and FSA cases exist for Deutsche Bank, Lloyds, Rabobank, RBS and UBS. See also European Commission, "Antitrust: Commission fines banks €1.49 billion for participating in cartels in the interest rate derivatives industry," 4 December 2013.

[10] Financial Services Authority, "Final Notice: Barclays Bank PLC," 27 June 2012, 11.

[11] CFTC head of enforcement Greg Mocek quoted in Vaughan and Finch (2017), page 76.

[12] *In re: LIBOR-Based Financial Instruments Antitrust Litigation*, No. 935 F. Supp. 2d 666, 29 March 2013. This ruling was later overturned on appeal by the United States Court of Appeals for the Second Circuit in Manhattan, which determined that Libor manipulation could constitute price-fixing as a per se antitrust violation under Section 1. *In re: LIBOR-Based Financial Instruments Antitrust Litigation*, No. 13-3565, 2nd Circuit, 23 May 2016.

The European Commission did establish Article 101 TFEU cartel violations in interest rate derivatives against nine of the largest panel banks for record fines, but few details of the alleged cartel mechanism have so far been made public.[13]

How a full cartel in the fixing of the benchmark rates could work is not obvious. Contrary to conventional cartels, in which all members typically want to increase product prices, often the interests of panel banks in manipulating the benchmark fixings will not be aligned when their exposures to the rates, which fluctuate partly unpredictably over time, are opposite. The position a trader or bank faces on any given day is uncertain and largely stochastic, as it is the sum total of a vast number of transactions done by the banks' various trading desks worldwide. Around a kernel of longer-term contracted money in- and outflows, exposure positions are largely driven by positions in OTC derivatives that are highly volatile. Therefore, different banks will regularly find themselves on opposing sides of the market, where some gain from an increase in one or more of the rates, while others benefit from a decrease. Such diverse and constantly changing payoff incentives are a challenge to cartel stability. The trimming of the higher and lower submissions adds to the difficulty.

Rate manipulation can be costly too. While there used to be no prescribed method for panel members to determine their Libor and Euribor submissions, reforms proposed in response to the scandals are aimed at making the rates more transaction-based.[14] A submission is to be the volume weighted average rate of a set of actual so-called 'eligible transactions'. Libor quotes are to be supported by transactions in unsecured deposits, commercial paper and certificate of deposit, where the submitting bank received funding from specified counterparties.[15] For Euribor, only transactions of unsecured cash deposits from specified counterparties traded in the wholesale unsecured money markets are eligible.[16] These reforms imply that if a cartel were to attempt to move the rate, suboptimal transactions against other than the going rates could be necessary, making collusion costly. However, the volume of eligible trans-

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[13] European Commission, *Case A.39914—Euro Interest Rate Derivatives* and European Commission, *Case AT.39861—Yen Interest Rate Derivatives*, a hybrid settlement with Barclays, Deutsche Bank, Société Générale, RBS, UBS, JP Morgan, Citigroup and RP Martin (broker) on 4 December 2013 and later infringement decisions for *YIRD* against broker ICAP for facilitating collusion on 4 February 2015 and for *EIRD* against Crédit Agricole, HSBC and JPMorgan Chase on 7 December 2016; European Commission, *Case AT.39924—Swiss Franc Interest Rate Derivatives*, two settlement decisions on 21 October 2014, one with RBS and JP Morgan on derivatives based on the Swiss franc Libor and one with RBS, UBS, JP Morgan and Crédit Suisse for bid-ask spreads charged on Swiss Franc interest rate derivatives.

[14] Financial Stability Board, "Market Participants Group on Reference Rate Reform, Final report," March 2014. EMMI reform proposals also include that Euribor be calculated as the average of only the middle 4 or 5 of all quotes. European Money Markets Institute, "Consultative Paper on the Evolution of Euribor," 30 October 2015, page 14. Libor remains to subsequently be calculated as the average of 50% of the submitted rates.

[15] See ICE Benchmark Administration, "ICE LIBOR Evolution Report," 25 April 2018, page 16 for details.

[16] See European Money Markets Institute, "The Path Forward to Transaction-based Euribor," 21 June 2016, page 5 for details.

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actions is small compared to the panel banks' total exposure positions to the rates, so that these costs are limited.[17] They can also be reduced by matching eligible transactions at the intended cartel rate between cartel members.

In this paper, we show how a full for-profit cartel in the fixing of interbank rates could work despite conflicting and time-varying interests, with the latest reforms implemented and without the need for side-payments. We develop a model in which panel banks exchange information and use it to agree on their contributions to the fixing and subsequent adaptations to their exposure positions. Two complementary mechanisms, for which the fraud investigations give evidence, make this possible. The first mechanism involves designated banks rigging eligible transactions in order to distort the rates in the joint-profit maximizing direction. The second mechanism entails colluding banks engage in front running, benefitting from the self-created inside information about the new cartel rate that they have within a time window before publication. This form of insider trading allows them to adjust their trading books and adopt more favorable exposure positions, at the expense of uninformed other market participants. It also makes alignment of panel members' interests, and thereby agreement on collusive submissions, possible. We establish stability of an equilibrium in continuous collusion strategies in which all the cartel members revert temporarily to independent quoting to stabilize the cartel against the occasional extreme exposure value that gives one (or more) of the panel banks incentive to deviate. A pure exchange of information cartel that facilitates individual front running is a special case.

The remainder of the paper is organized as follows. In Section 2, the relevant literature is reviewed. Section 3 provides more detail on the benchmark rate setting process and evidence of preemptive cartel portfolio changes—eligible transactions rigging obviously would only be observed after the current reforms. Section 4 lays out the model and results on cartel stability.[18] In Section 5, simulation exercises give insight into collusive rate patterns and the possible effects of proposed reforms. In Section 6, we discuss several possible extensions of our model. Section 7 concludes. The source code of a software that calculates optimal cartel strategies is given in an appendix.

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[17]The Financial Stability Board (FSB) reported in 2014 that over 170 trillion dollars in OTC derivatives are tied to the USD Libor, and over 197 trillion dollars to the Euribor. In comparison, the second highest and most USD Libor-related asset class are syndicated loans with an estimated 3.4 trillion dollars. Financial Stability Board, "Market Participants Group on Reference Rate Reform, Final report," March 2014, pages 243 and 348.

[18]We develop the model in the text for one Libor rate, whereas there are various benchmark rates set for different maturities on a daily basis. Since the exposures to each of these rates are in principle unrelated, also the rates on various rungs of the maturity ladder can have been so manipulated independently.

2   Relevant Literature

The emerging literature on benchmark rates focuses almost exclusively on manipulation by one or a few rates-setters. Abrantes-Metz et al. (2012) point at episodes of low variation in Libor submissions by individual banks before August 2007 as suspicious of collusion, yet do not find that the rate is significantly different from its predicted level in comparison to the federal fund effective rate and 1-month T-Bill rates. Using a revealed preference approach, Youle (2014) identifies unobserved bank exposures and finds evidence suggesting that Libor was downward biased during the recent crisis.

Abrantes-Metz and Sokol (2012) suggest that screens could have detected interbank rate manipulation and collusion earlier. Monticini and Thornton (2013) find more material anomalous patterns for the same period when using the relationship between Libor and large, unsecured certificate of deposit rates. Kuo et al. (2012) compare Libor quotes to bank bids in the Federal Reserve Term Auction Facility and deduced borrowing costs to find that Libor submissions were significantly lower than comparison rates during the crisis, which could indicate such low-balling. And Gandhi et al. (2017) estimate monthly Libor-related positions and find a relation between the positions and banks' submissions, which is initially stronger for banks that were sanctioned by the regulators.

Snider and Youle (2012) study the incentives behind portfolio based manipulation of strategic Libor quote submission as signals of creditworthiness between individual banks that each maximize their own trading profits. Chen (2017) finds in a signaling game that banks' individual manipulations decrease with the panel size and number of quotes used in the calculation. His result of a distribution-free bias does not hold under collusion however. Diehl (2013) models portfolio and reputation incentives and compares the performance of different aggregates, such as the mean and the median, under individual manipulation.

A few papers raise the possibility of agreements between two or several panel members, but none of them models how collusion could work. Eisl et al. (2017) calculate how Libor misreporting by one or several banks together could have moved the average, but do not analyze incentives. Using a time-varying threshold regression model, Fouquau and Spieser (2015) argue that the breaks they find are not consistent with exogenous money market shocks, suggesting manipulation by small groups of panel banks, which they propose to identify using a hierarchical clustering method.

Abrantes-Metz (2012) suggests changes to reduce the risk of collusion in the interbank benchmark rates, but this has not been the objective of the reforms. Duffie and Dworczak (2014) propose a mechanism and Duffie and Stein (2015) reforms against individual manipulation, not collusion, for both types of benchmark rate—including calculation on the basis of a wide set of transactions. Coulter et al. (forthcoming) also use mechanism design to obtain unbiased estimates of the true rates, basing the benchmark on bank transactions. Collusion is briefly discussed, but their focus is on

preventing unilateral manipulation.

We develop novel cartel theory to specific features of benchmark rate-setting. Whereas in a classic cartel, the attraction of defecting is to steal the full cartel profit, deviation from a benchmark cartel only affects the final rate to the extent of the deviator's submission—and not the demand or portfolio exposure position of the other banks. This also results in the benchmark rate cartel being easier to sustain when the number of panel banks is larger. When a bank draws a private extreme value portfolio position it has incentive to deviate, as during booms in Rotemberg and Saloner (1986). However, in our model there is no obvious 'competitive' strategy the cartel could fall back to in order to avoid defection and assure continuous collusion. Instead, if agreeing on a collusive submission is not possible for the period, there is episodic recourse to non-cooperative quoting, as in Fershtman and Pakes (2000). Such 'price wars' are short run unprofitable, as in Green and Porter (1984), but an integral part of the collusive strategy, not punishment. Each cartel member incurs occasional losses as a part of the cartel strategy, but randomly and not by a history-dependent favoring of certain players based on productive efficiency, as in Athey and Bagwell (2001).

3   Benchmark Rate Fixing

The designs of the benchmark-setting processes make them vulnerable to cooperative manipulation. The panels consist for long periods of time of the same known banks. Financial markets are transparent and monitoring of adherence to a collusive agreement is easy from the published rates alone, which facilitates the implementation of punishment strategies to stabilize it against unilateral defection. Evidence from the investigations suggests that the panel banks' individual submissions are closely monitored, as they were found to have been discussed amongst conspiring panel banks in relation to previously agreed targets.[19] The potential trading gains from even a small move in the rates are large.[20]

The rate manipulations documented reveal that banks aimed at enhancing trading results.[21] The BBA knew that:

> "Many institutions set their Libors based on their derivative reset positions."[22]

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[19] European Commission, *Case A.39914—Euro Interest Rate Derivatives*, 4 December 2013, 33.

[20] Internal documents from Deutsche Bank, for example, show that on 30 September 2008 Deutsche Bank tallied that it could gain up to €68 million for each basis point change in Euribor and Libor. "Bank Made Huge Bed, and Profit, on Libor," *Wall Street Journal*, 10 January 2013.

[21] European Commission, *Case A.39914—Euro Interest Rate Derivatives*, 4 December 2013, 32.

[22] Bank of Scotland trader in an email to the BBA's Libor Director quoted in Vaughan and Finch (2017), page 163.

Money market desks are in a position to know their banks' overall net expose to the various rates and how they would gain or lose from their movements. Traders requested submissions aimed at benefiting their trading positions, illustrating how a bank with a net lending position would profit from a higher Libor or Euribor, while a bank with a net borrowing position would prefer a lower one.[23] Tom Hayes, a convicted derivatives trader for UBS and later Citigroup, stated at his trial that his employer had instructed to base submissions on the bank's derivatives position, for which spreadsheets were kept that calculated the exact effects of a change in Libor in each currency and maturity on trading profits.[24]

There is also evidence that traders benefitted from adjusting their exposure in advance to the rate, front running on their information about the future rate—for example found the European Commission that:

> "On occasion, certain traders also explored possibilities to align their EIRD trading positions on the basis of ... communicated preferences for an unchanged, low or high fixing of certain EURIBORS tenors [which] depended on their trading positions/exposures ... [and] ... detailed not publicly known/available information on the trading positions."[25]

Using inside information to front run on partly self-created variation, the cartel banks could shift their exposure position in their own favor, at the expense of these other market participants. Particularly suited for front running are OTC derivatives, which are highly volatile, short and long, and not eligible for calculation of the submissions. The portfolio-related gains from manipulating the rate can therefore be of a much larger magnitude than the cost involved in eligible transactions rigging.

The collusive gains would be at the expense of uninformed counterparties who lent or borrowed at distorted rates tied to Libor or other interbank benchmarks, including non-panel banks and traders such as insurance companies, municipalities, corporations and investors.

Coordination of the rates appears to have been pervasive, yet not continuous. Attempts to coordinate submissions were not always successful, for example when a coconspirator was unable to accommodate another trader's request due to opposing interests. Incidents of independent quoting happened episodically. For example, did a Lloyds submitter explain to two new colleagues making the Yen Libor submissions:

> "We usually try and help each other out. .. but only if it suits .. .!"[26]

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[23] Financial Services Authority, "Final Notice: Barclays Bank PLC," 27 June 2012, pages 2-3; European Commission, *Case A.39914—Euro Interest Rate Derivatives*, 4 December 2013, 32.

[24] An internal document titled 'Publishing Libor Rates' was recovered from the communal drive at UBS which contained such instructions. Vaughan and Finch (2017), page 23 and 154.

[25] European Commission, *Case A.39914—Euro Interest Rate Derivatives*, 4 December 2013, 32. In line with this, Hayes explained to another submitter by email: "If we know ahead of time we can position and scalp the market." Vaughan and Finch (2017), page 114.

[26] Commodity Futures Trading Commission, "Order Instituting Proceedings: Lloyds Banking Group PLC," 28 July 2014, page 12.

There was consensus that even though coordination would not be possible every period, the longer term collusive arrangement was valid and valuable. A submitter preemptively contacted a trader at another bank with "Submitter-4: 'morning skip - [Trader-5] has asked me to set high libors today - gave me levels of lm 82, 3m 94....6m 1.02', in effect to excuse that the trader could not follow in manipulation of the rate that day:

> Trader-B: 'sry mate cant oblige today...i need em lower!!!'
>
> Submitter-4: 'yes was told by [a third party]...just thought i'd let you know why mine will be higher...and you don't get cross with me.'"[27]

On another occasion, a submitter who was asked to submit 3-month Euribor "at the ceiling" explained that he couldn't because:

> "long swaps need it low."[28]

Agreeing episodically to break-up coordination of submissions when the circumstances were not quite right appears to have been part of ongoing collusive fixing.

4   A Model of Benchmark Rate Collusion

Consider a panel of N banks $i = 1, ..., N$ that play an infinitely repeated simultaneous move game. On trading day t, let v_{0it} be bank i's baseline portfolio position by which it is exposed to changes in the interbank rate for a certain maturity. The true borrowing costs, against which bank i can do eligible transactions on the day are c_{0it}. A bank's eligible transactions are not part of its exposure to the benchmark rate. Both v_{0it} and c_{0it} are private value daily draws. Variations in v_{0it} reflect changes in the bank's net trading book exposure to all its Libor-related activities. Changes in c_{0it} reflect variations over time of the bank's ability to borrow on the money market, which is affected by bank-specifics such as capital structure and liquidity position.

At the start of each day t, the valid interbank rate is L_{t-1}, as published the day before. The new rate, L_t, is to be fixed on the basis of all panel banks' rate submissions $(c_{11t}, ..., c_{1Nt})$. If a bank intends to submit a rate c_{1it} that is different from c_{0it}, it will have to engage in eligible transactions against the intended rate, rather than the true rate. In addition, banks can adjust their portfolio position with an eye on the new rate. Bank i's eligible transactions rate submission is $c_{1it} = c_{0it} + \Delta c_{it}$, and at the time the new benchmark rate is published, its realized exposure position is $v_{1it} = v_{0it} + \Delta v_{it}$. We refer to choice variables Δc_{it} and Δv_{it} as 'eligible transactions rigging' and 'front running' respectively, which can be either positive or negative.

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[27]Transcript of conversations on 28 March 2008 in U.S. Department of Justice, "Statement of Facts, Deferred Prosecution Agreement: Rabobank," 29 October 2013, page 33.

[28]*Op. cit.*, page 37.

It is assumed that panel banks can always find counterparties for their intended trades in the derivatives markets. Front running takes place at the going prices in these vast and liquid markets. Eligible transactions rigging happens in a thinner market, yet on terms that can be profitable for outsiders. The intended rigged future benchmark rate for which a panel bank seeks eligible transactions is different from the going one. Either it borrows at a higher rate, with counterparties gaining directly, or it offers conditions to a loan it requires at a lower rate in order to make it an attractive proposition. Even if some market participants may have suspected collusion, the sheer size of the markets would have meant that the offers of the panel banks could go through. Alternatively, the cartel members could do offsetting internal transactions, either to bring portfolio exposure positions more in line or to generate eligible transactions at the desired rate.

The new interbank rate L_t is determined as the trimmed average of all N quotes. We call the set of submissions from which the upper and lower share of ranked quotes are discarded the 'trimmed range' $\mathcal{T}$ consisting of n banks. Hence,

$$L_t = \frac{1}{n} \sum_{j \in \mathcal{T}} c_{1jt}. \tag{1}$$

Since the majority of financial contracts, such as swaps, futures and corporate loans, have linear payouts to the rate, bank i's gains from changes in the rate from the current to the next trading day are

$$\pi_{it} = v_{1it} \left(L_t - L_{t-1} \right) - C_i \left(\Delta c_{it}, \Delta v_{it} \right), \tag{2}$$

where $C_i \left(\Delta c_{it}, \Delta v_{it} \right)$ are any costs associated with bank-specific changes in exposure and rate.

Manipulation in either direction is costly since eligible transactions rigging requires banks to borrow on otherwise suboptimal terms and front running involves direct transaction costs, trade risks and liquidity constraints. Extreme adjustments are further constrained by the risk of raising suspicion of manipulation with other market participants or regulators increasing in the degree of front running and eligible transactions rigging. In the following, we simplify to the symmetric case $C_i \left(\Delta c_{it}, \Delta v_{it} \right) = C \left(\Delta c_{it}, \Delta v_{it} \right)$ for all $i = 1, ..., N$. It is natural to assume that $C \left(\Delta c_{it}, \Delta v_{it} \right)$ is strictly convex in both Δc_{it} and Δv_{it}. This assures that a global maximum for each bank i's objective function π_{it} exists and is unique if also $C''_{\Delta v_{it} \Delta c_{it}}(\cdot)$ is small enough, which is a mild assumption since the two manipulation mechanisms relate to very different classes of transactions.[29]

Through L_t, the payoff function of each bank depends not only on its own exposure and eligible transactions, but also on the eligible transactions of the other banks in

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[29] Since the first part of π_i is linear in both Δv_{it} and Δc_{it}, together with positive and increasing marginal costs, a necessary and sufficient condition for global maximum is that $C''_{\Delta v_{it} \Delta v_{it}}(\cdot) \times C''_{\Delta c_{it} \Delta c_{it}}(\cdot) - C''_{\Delta v_{it} \Delta c_{it}}(\cdot)^2 > 0$.

$\mathcal{T}$. As a result, there is an incentive to coordinate behavior. If the panel colludes, the baseline values (c_{0it}, v_{0it}) for all $i = 1, ..., N$ are shared and the cartel determines the joint-profit-maximizing front running and eligible transactions rigging strategies collectively.

Figure 1 illustrates the timing of cartel events in the Libor rate-setting process relative to the opening and closing bells of the trading day at the London Stock Exchange—OB and CB. At opening, L_{t-1} is the current Libor rate. Suppose that at time 0_t, shortly into day t, all banks learn their private values c_{i0t} and v_{i0t}.[30] Without collusion, strategies are determined independently. If they collude, the panel banks share their private information at cartel meeting C_t in which the designated joint-profit-maximizing front running and eligible transactions rigging is determined for each member. Latest at 11.00 a.m. GMT (S_t), all banks submit their Libor quote based on c_{1it}, which closes the window for eligible transactions rigging.[31] The window for front running remains open until publication of the rate at 11.55 a.m. (L_t), which then no longer is inside information to the cartel members.[32]

FIGURE 1 HERE

Both v_{0it} and c_{0it} are assumed to be independent and identically distributed, each according to a symmetric and commonly known continuous distribution. The overall exposure position of the panel banks to the rate is assumed to fluctuate around zero, i.e. $E[v_{0it}] = 0$. This setup captures that exposure in large part stems from transactions in OTC derivative markets, which have a buyer and seller for every contract and are volatile and liquid enough for all banks to regularly find themselves flipped from one side of the market to the other.

The baseline eligible transaction rates c_{0it} are drawn from a common distribution with mean $E[c_{0it}] = L_{t-1}$, reflecting that Libor is a main signal to creditors, who

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[30]Note that although illustrated in Figure 1 at a specific point in time (0_t shortly after OB), in practice the banks see their baseline values change continuously, as OTC trading in particular takes place around the clock worldwide and unforeseen events or market-moving news could constantly affect the baseline values. The cartel can accommodate such multiple changes by sharing the relevant information and updating the cartel strategy throughout, as long as the windows for manipulation are open.

[31]Note that eligible transactions for Libor submissions on day t are those executed between the previous submission and the new submission at S_t. Collusive eligible transactions rigging can only be done after information has been exchanged at time C_t. For Euribor submissions on day t, all transactions executed on trading day $t - 1$ are eligible. Therefore, the eligible transactions rigging window for Euribor is somewhat different from the one in Figure 1. The Euribor cartel would use earlier baseline information and need to meet earlier, so as to manipulate eligible transactions the day before.

[32]For Libor, the difference between the eligible transactions and front-running windows is less than an hour. For Euribor it is longer, as the time between the end of trading day $t - 1$, which varies, and when the rate is published shortly after 11.00 a.m. CET on day t.

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would not have known about any manipulation. The mean is assumed to be equal across panel banks, which are all global systemically important banks (G-SIBs) facing similar regulatory requirements. Shocks to the panel banks' respective borrowing capacities are assumed to be non-persistent.[33]

We study collusion without side-payments, neither as explicit transactions nor in more sophisticated forms, such as partially swapping positions internally, in which a cartel member with a major profitable position to the cartel strategy would trade with other members to mitigate their positions opposite to the general cartel interest. Such internal alignment of interests would further facilitate collusive manipulation— but not increase cartel profits, since the panel's overall net portfolio position generally revolves around zero. Wash trades or doing offsetting eligible transactions between cartel members, which could reduce manipulation costs, are also ignored. The following subsections describe banks' strategies in case of independent behavior, collusion and defection.

4.1 Independent Quoting

If panel banks formulate their contributions independently, they determine their portfolio changes and submissions with incomplete information. If all banks follow the banking code of conduct and accordingly honestly submit their true borrowing cost and do not front run, the strategy of bank i at period t is $\Delta v_{it}^* = \Delta c_{it}^* = 0$ with payoff π_{it}^*. It then follows directly from the distributional assumptions that $E_{it}[\pi_{it}^*] = E[\pi^*] = 0$ for all $i = 1, ...N$ and $t = 1, ..., \infty$.

To follow the banking code of conduct is not individually optimal, however. Instead, maximizing own expected gains in the benchmark-setting gives:

$$\pi_{it}^{BN} : \max_{\Delta v_{it}, \Delta c_{it}} E_{it}[\pi_{it}] \quad \forall i = 1, ..., N, \tag{3}$$

potentially induces each bank independently to engage in some amount of front running and eligible transactions rigging. Manipulation is unilateral, under the assumption that the other panel members report honestly, since banks have no information on the baseline positions of the other banks. Equilibria are in pure strategies. Let π_{it}^{BN} be the payoff of bank i in period t in the static Bayesian-Nash equilibrium, with expected payoff $E_{it}[\pi_{it}^{BN}]$. Under the symmetry and distributional assumptions, $E_{it}[\pi_{it}^{BN}] = E[\pi^{BN}] \geq 0$ for all banks i and each period t.

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[33]The daily rate drawings can alternatively be assumed from an unmanipulated mean, in particular a daily rate that follows from honest reporting only. If manipulation was indeed widespread and commonly known, a 'shadow Libor rate' may have accounted for the actual borrowing standard. The effects of alternative means on rate patterns and screening are discussed in Section 5.

4.2 Collusive Quoting

If the panel banks form a cartel instead, they share the baseline information v_{0it} and c_{0it} on all banks $i = 1, ..., N$ at the beginning of each trading day. With this inside information, the joint-profit-maximizing new rates are established, as well as by how much each member is to engage in eligible transactions against their target submission in order to support the target rate. Additionally, the front running is determined that reduces misalignment of exposures between the panel banks and gives the cartel optimal exposure to the future rate.

The complete information cartel strategy in period t follows as

$$\pi_t^C : \max_{\Delta v_t, \Delta c_t} \sum_{i=1}^{N} \pi_{it}, \tag{4}$$

where Δv_t and Δc_t are vectors of the front running and eligible transactions rigging targets.[34] We denote the vector of N realized payoffs by π_t^C and offer the following result.

Proposition 1 *There exists a per-period unique globally optimal cartel strategy.*

Proof. As part of the equilibrium conditions, the marginal bank-specific costs of changes in the eligible transaction rate are assumed to increase in Δc_{it}, i.e. $C''_{\Delta c_{it}} > 0$. Therefore, if the cartel would change the ranking of the eligible transaction rates, the same set of final rates $(c_{11t}, ..., c_{1Nt})$ could have been achieved at lower total eligible transaction rate rigging costs by retaining the ranking. This implies that the following inequality constraints hold

$$c_{0(i+1)t} + \Delta c_{(i+1)t} \leq c_{0it} + \Delta c_{it} \quad \forall i = 1, ..., N-1, \tag{5}$$

where bank indicator i is now equal to its rank based on the baseline eligible transaction rates $(c_{01t}, ..., c_{0Nt})$. Since the baseline eligible transaction rates are drawn from a continuous distribution, there exist various possible strategies where the ranking does not change and all constraints hold with inequality—an obvious candidate is the strategy of no manipulation, $(\Delta c_t, \Delta v_t) = (0, 0)$. These are Slater points, the existence of which is both necessary and sufficient for the existence of a global optimum in a non-linear optimization problem with inequality constraints. See, for example, Brinkhuis and Tikhomirov (2005), pages 210-211. ∎

Let π_{it}^C be the realized payoff of bank i in the cartel optimum in period t, following the optimization. Ex ante, the per-period expected payoffs from participating in the

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[34] An alternative cartel strategy is to only use the information exchanged to front run and not manipulate the rate—i.e. to determine $\max_{\Delta v_t} \sum_{i=1}^{N} \pi_{it}$ given $\Delta c_{it} = 0$ for all $i = 1, ..., N$. This behavior may not strictly break the rates' code of conduct, but it would be punishable under the competition laws—and possibly also as insider trading—while the cartel can do better.

cartel are $E_{it}\left[\pi_{it}^C\right] = E[\pi^C]$. While π_{it}^C may be negative, and even lower than under independent behavior as cartel members occasionally have to 'take one for the team' by submitting quotes that are not optimal given their baseline exposure position, over time all banks can expect to profit from colluding equally. This ensures that no explicit side-payments are necessary. These occasional losses are entirely due to eligible transactions rigging: front running is always profitable. Further note that $E\left[\pi^C\right] > E\left[\pi^{BN}\right] \geq E\left[\pi^*\right] = 0$, since it is always possible for a bank participating in the cartel at least to front run. The cartel's ability to create inside information of the rate's future movement makes it even more attractive to participate. As counterparties trading in financial products tied to the rate are less well-informed of where the future rate will go, cartel members can profit at their expense.

The cartel is efficient in the sense that the order of the baseline transaction rates is preserved in the submissions that are asked of the members, which minimizes the cartel's total eligible transactions rigging costs. Apart from the n banks in the trimmed range $\mathcal{T}$, up to either all the banks that will end up in the lower, or the upper ranked share of discarded submissions are asked to engage in eligible transactions rigging. This is between half and three-quarter of the panel in the case of Libor. Which banks are included in $\mathcal{T}$ and which are not varies with the daily drawings. Banks outside $\mathcal{T}$, even though their submissions are discarded in the determination of the interbank rate, may also be called upon to engage in eligible transactions rigging in order to move over and accommodate the rigging by banks within $\mathcal{T}$.

FIGURE 2 HERE

Figure 2 illustrates such a situation in the case of four panel banks, the middle two of which are in the trimmed range. Bank 1 moves over to the right, so that banks 2 and 3 together can drive up L_1 as their average submission. Never, however, does a bank in the periphery (banks 1 or 4) cross over into $\mathcal{T}$ and move the rate instead of the bank(s) with an interior position, as this is always more costly. Banks both inside and outside $\mathcal{T}$ will always find it in their private interest to front run, independent of the cartel strategy.

Note that the assumption that the panel members report their true borrowing costs and baseline exposure positions to the cartel truthfully is not that stringent, in the sense that it is not obvious how a bank would be better off lying—when the cartel requires all banks to report their position and rate simultaneously. In principle, banks reporting different than actual values would not be easily discovered, as long as they subsequently behave according to cartel instructions. A motive could be to try to avoid cost of collusion, by pretending to have relatively low or high borrowing costs, or increase chances of the optimal cartel quote being more favorable by overstating its exposure position. However, reporting other than true costs may just as well land a bank at the wrong side of true borrowing cost—ending up being assigned

higher eligible transactions rigging costs than it would with the truth. Similarly, by overstating its exposure position a bank risks too extreme optimal cartel quotes, for which its manipulation costs would exceed the gains from trying to manipulate the cartel agreement, or even from collusion as a whole.

4.3   Defection

After banks have shared their private information and determined the optimal cartel strategy for the day, each bank may have the incentive to unilaterally defect. For example, one or more banks within the trimmed range $\mathcal{T}$ may have a negative exposure to changes in the interbank rate, but still be designated to facilitate upwards rigging of L_t for the benefit of the cartel. By unilaterally defecting, a bank in such a position would benefit from reducing the upward manipulation of L_t and forego the costs of its eligible transactions rigging—at the expense of the other cartel member banks.

The optimal deviation of bank i in period t follows from

$$\pi_{it}^D : \max_{\Delta v_{it}, \Delta c_{it}} \pi_{it}\big|_{\left(\Delta v_{-it}^C, \Delta c_{-it}^C\right)}, \tag{6}$$

in which Δv_{-it}^C and Δc_{-it}^C refer to the front running and eligible transactions rigging of all panel members but bank i under the collusive optimum. We denote the optimal defection payoff of bank i following this optimization by π_{it}^D.

The trimming limits the scope for deviating. For a bank in the trimmed range $\mathcal{T}$, defection always increases profits. A bank not in the cartel $\mathcal{T}$ can decide to position itself at any point within it to make its quote count, yet this need not be optimal, depending on its position. For example in Figure 2, if bank 4 had a negative exposure it would want to see the new rate as low as possible, whereas positioning itself within $\mathcal{T}$ would only result in a (weakly) higher rate and positive eligible transactions rigging costs. Therefore, a deviating bank will either position itself in $\mathcal{T}$ in order to attempt to influence the rate, or not engage in eligible transactions rigging at all, whichever gives higher payoff.

Internal monitoring of quotes is perfect. Once the interbank rate is published, all the cartel members can immediately infer from the rate whether there has been defection from the collusive eligible transactions rigging strategies. While it is not obviously possible to observe whether a bank has deviated from the agreed collusive exposure position changes, these are individually optimal for each cartel member to carry out, given the rate agreed. Also deviations in Δv_{it} have no effect on the profits of other cartel members.

4.4   Cartel Stability

The cartel would need to stabilize adherence to its agreements against incentives to deviate. That is, it plays the per-period strategy that maximizes joint profits, subject

to the constraints that for each bank i in period t the expected value of collusion (V_{it}^C) is at least as high as the expected value of defection (V_{it}^D). Note that the effects of deviating here are different from a conventional cartel, in which defection profits are higher relative to collusive profits, the more cartel members there are to share the pie with. In a benchmark cartel, more cartel members means that every individual bank has a smaller impact on the rate, and therefore defection profits are smaller instead. As a result, benchmark collusion can be more easily sustained for larger numbers of participating banks.

Using π_{it}^C, π_{it}^D and π_{it}^{BN} and discount rate $\delta \in (0, 1)$, we can specify for bank i in period t the expected value of collusion as the sum of current-period payoffs and discounted continuation values, i.e.

$$V_{it}^C = \pi_{it}^C + \delta E\left[V^C\right]. \tag{7}$$

$E\left[V^C\right] = \sum_{t=0}^{\infty} \delta^t E\left[\pi^C\right]$ is the expected discounted continuation value of collusion.

The instantaneous payoff from deviating plus the expected discounted value of its consequences when discovered and punished is

$$V_{it}^D = \pi_{it}^D + \delta E\left[V^P\right]. \tag{8}$$

For every punishment strategy in which defection triggers $T \geq 0$ periods of reversion to non-cooperative contributions, the off-equilibrium occurrence of punishment means that increasing T only increases cartel stability, so that it is optimal to set $T \to \infty$ and specify $E\left[V^P\right] = \sum_{t=0}^{\infty} \delta^t E\left[\pi^{BN}\right]$. The grim trigger strategy is credible, since the Bayesian-Nash punishment is a sub-game perfect equilibrium. However, the cartel would as well be stable for any (possibly stochastic) sufficiently large finite T.

To assure adherence to the cartel by bank i, in each period t the panel maximizes joint profits (4), subject to $V_{it}^D \leq V_{it}^C$. This solves as

$$\pi_{it}^D - \pi_{it}^C \leq \frac{\delta}{1-\delta}\left(E\left[\pi^C\right] - E\left[\pi^{BN}\right]\right) \quad \forall i = 1, ..., N. \tag{9}$$

The left-hand side payoff differentials vary between banks and periods, depending on the current private values. The right-hand side of condition (9) is a fixed critical cut-off value that decreases in discount rate δ. Note that if these incentive compatibility constraints hold for Bayesian-Nash independent quoting, they certainly do for honest quoting, since $E\left[\pi^{BN}\right] \geq E\left[\pi^*\right]$.

Using this supergame structure, we first identify the first-best continuous collusion strategy and explain why this strategy is so computationally demanding to be infeasible. We subsequently identify a practical cartel strategy that involves episodic break-up.

4.4.1 Continuous Collusion

The optimal cartel strategy would be continuous collusion, in which the cartel adjusts the profit maximizing vector of eligible transactions rigging and front running each period, such that the incentive compatibility constraints resulting from individual banks' baseline value draws hold. That is, each day the cartel is to keep each payoff differential $\pi_{it}^D - \pi_{it}^C$ below the critical value by potentially adjusting π_{it}^C, and thereby indirectly also π_{it}^D in the incentive compatibility constraints (9) to

$$\max_{\Delta v_t, \Delta c_t} \sum_{i=1}^{N} \pi_{it} \quad \text{subject to} \quad \max_{i=1,..,N} \left(\pi_{it}^D - \pi_{it}^C \right) \leq \frac{\delta}{1 - \delta} \left(E\left[\pi^C \right] - E\left[\pi^{BN} \right] \right), \quad (10)$$

in which the bank that poses the tightest constraint is endogenously determined.

Continuous collusion on benchmark rates is considerably more complex than in conventional markets. Generically the payoff functions are asymmetric and provide N different inequality constraints, each of which results from the optimization problem by which each bank determines its optimal defection strategy π_{it}^D for its portfolio position and rate, given that all other panel banks behave according to the cartel agreement. Rotemberg and Saloner (1986) rely on the cartel having the option to fall back on marginal cost pricing, from which no cartel member would deviate, during booms, when the incentive to deviate is largest. By lowering the payoff differential from defecting, the cartel remains stable under infinite punishment. Such a fixed fallback option does not exist in our model of benchmark rates collusion, since the incentives to deviate vary with individual positions and rates. For instance, if the cartel would instruct to revert to a case where the rate is not manipulated, each member would still have incentive to unilaterally manipulate and front run, given that the panel exchanged information. Portfolio position-specific stable collusive actions therefore need to be determined every day anew.

However, finding common ground in the daily cartel optimization problem is computationally demanding for several reasons. Solving (10) requires knowing the expected collusion payoff $E\left[\pi^C \right]$, which is not a priori determined. In addition, both the optimization and its constraints are endogenous, since π_{it}^C and π_{it}^D both follow from the solution of (10) *and* are part of the constraints used to obtain it. Defection profits π_{it}^D even follow from a separate optimization by each bank, maximizing its own profits given that the other banks play the previously determined collusive strategy π_{it}^C. Furthermore, the optimal cartel strategy can include that a bank with a lower baseline eligible transaction rate is required to submit higher quotes than a bank with a higher rate that has an incentive to deviate, in order to keep cartel stability. Since the ranking of eligible transaction rates no longer needs to preserve the order of the baseline transaction rates, the proof of Proposition 1, which relies on the absence of cross-overs and thereby significantly reduces the strategy space, no longer holds. Note that one cartel member incurring higher manipulation costs to allow another a

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larger cartel profit can be seen as a form of side-payments and makes the continuous collusion strategy cost-inefficient.

Brute force calculations are hard to do on (10). To derive all outcomes of each possible strategy set and identify the global optimum among the subset of outcomes for which the constraints hold would require a discretization and ex ante restriction of the strategy space, as the choice variables are continuous and unbounded. The number of strategies that would subsequently need to be checked is infeasibly high—it is equal to the necessary high number of small bins to the power $2N$, the dimensionality of the choice variables.[35]

4.4.2 Episodic Break-up

The benchmark cartel is feasible using an episodic break-up strategy, as in Fershtman and Pakes (2000). In this much simpler strategy, all panel banks choose the unconstrained joint profit maximizing strategy as long as it satisfies per period the incentive compatibility constraints of all banks, until at least one panel bank would deviate, in which case all banks revert to non-cooperative contributions for that period.[36] The cartel is continuous in that each period information is shared, but also breaks up episodically in unstable periods to determine strategies individually. Only deviation from this strategy would be punished with reversion to non-collusive contributions forever after.

During a break-up, the panel banks determine their contributions non-cooperatively with complete information as

$$\pi_{it}^N : \max_{\Delta v_{it}, \Delta c_{it}} \pi_{it} \quad \forall i = 1, ..., N, \tag{11}$$

which involves front running and eligible transactions rigging that is independently done by all members, but on the basis of full information exchange.

Let the one-period static Nash equilibrium with full information of the panel banks be π_{it}^N, with $E_{it}\left[\pi_{it}^N\right] = E\left[\pi^N\right]$ for all $i = 1, , ...N$ and $t = 1, ..., \infty$. Since interests are typically conflicting, the Nash equilibrium need not be unique, nor exist in pure strategies. Note however that $E\left[\pi^N\right] > E\left[\pi^{BN}\right]$, since all banks are fully informed in formulating the break-up contributions and any information that helps a bank to better predict the new rate allows it to front run lucratively and increase expected payoff. Without agreement on the rate, banks can only front run in the direction of where they expect the rate to go. Generally, their portfolio changes will be more conservative than under full collusion.

To analyze the pattern of switching between full collusion and episodic break-ups, let $\rho \in [0, 1]$ be the probability that the unconstrained joint-profit-maximum

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[35] For example, with 16 banks choosing the two choice variables bounded and discretized (somewhat arbitrarily) to 300 bins, the cartel algorithm would still need to check $300^{2 \times 16}$, or approximately 10^{80} cases—which is of the same order of magnitude as the number of atoms that are in the universe.

[36] We are indebted to Joe Harrington for suggesting this.

violates one or more of the incentive compatibility constraints and the cartel reverts to one-period static Nash. Per-period expected payoff from colluding then is

$$(1 - \rho) E\left[\pi^C\right] + \rho E\left[\pi^N\right], \tag{12}$$

where $E\left[\pi^N\right]$ is conditional on there being a break-up, and $E\left[\pi^N\right]$ on not. Since break-up occurs at extreme value positions that the panel bank(s) can exploit with their shared information, it may well be that $E\left[\pi^N\right] > E\left[\pi^C\right]$.

Given infinite punishment, the net present value of all forgone future expected payoffs in case of cartel defection becomes

$$\frac{\delta}{1-\delta}\left((1 - \rho) E\left[\pi^C\right] + \rho E\left[\pi^N\right] - E\left[\pi^{BN}\right]\right) \equiv \Psi\left(\delta, \rho\right), \tag{13}$$

since only in a punishment phase is quoting truly non-collusive, resulting in π_{it}^{BN}—or possibly π_{it}^* if the panel banks choose to follow the code of conduct. $\Psi\left(\delta, \rho\right)$ is then defined as the critical cut-off value for the value differential $\pi_{it}^D - \pi_{it}^C$, below which collusion is stable.

The probability ρ of episodic cartel break-up is now defined implicitly by the tightest stability constraint through

$$\rho = 1 - Pr\left[\max_{i=1,..,N}\left(\pi_{it}^D - \pi_{it}^C\right) \leq \Psi\left(\delta, \rho\right)\right]. \tag{14}$$

Given $\Psi(\delta, \rho)$, the value of ρ is under the remaining tail of the probability density function of $\max_i \left(\pi_{it}^D - \pi_{it}^C\right)$, which derives from the distributions over bank i's initial portfolio position v_{0it} and eligible transaction rate c_{0it}. Figure 3 illustrates.

FIGURE 3 HERE

We can now establish conditions for the existence of stable continuous collusion with episodic break-up.

Proposition 2 *For a continuous and sufficiently widely supported distribution of* $\max_i \left(\pi_{it}^D - \pi_{it}^C\right)$, *there exists a unique* $0 < \rho < 1$ *that maximizes cartel profits.*

Proof. The implicit definition of ρ in equation (14) is a continuous mapping from a nonempty, compact and convex set $\rho \in [0, 1]$ onto itself, so that at least one fixed point solution exists. Let the support of the continuous distribution of the maximum payoff differential $\max_i \left(\pi_{it}^D - \pi_{it}^C\right)$ be $[a, b]$. For a lower bound $a < \Psi\left(\delta, \rho = 1\right) = \frac{\delta}{1-\delta}\left(E\left[\pi^N\right] - E\left[\pi^{BN}\right]\right)$ and an upper bound $b > \Psi\left(\delta, \rho = 0\right) = \frac{\delta}{1-\delta}\left(E\left[\pi^C\right] - E\left[\pi^{BN}\right]\right)$, the largest payoff differential can occur with positive probability for which the cartel always breaks up and for which the cartel never breaks up. Hence, $\rho = 1$ and $\rho = 0$ can not be a fixed point and ρ must lie strictly between 0 and 1. While there may be

more than one solution to (14), there is a unique fixed-point that maximizes expected cartel profit. ■

For reasonable assumptions on the underlying stochastics, the cartel always exists to share information, regularly quotes collusively ($\rho < 1$), but occasionally reverts back to non-coordinated quoting with inside information ($\rho > 0$) to deal with extreme value exposure and eligible transaction rate drawings. Note that while switches between collusion and break-up are discrete, the cartel agreement itself is continuous in that actual deviation is off-equilibrium.

We say the cartel is more 'steady' if ρ is closer to 0, so that it breaks up less regularly. Equation (14) does not yield a closed-form solution for the effect of the discount factor δ or manipulation cost $C\left(\Delta c_{it}, \Delta v_{it}\right)$ on cartel steadiness ρ in general, which is probability distribution-specific. However, a negative relationship between δ and ρ is to be expected, since the more patient the panel banks are, the less tempted they are to deviate with a more extreme position.

Higher manipulation cost on the one hand make defection less attractive, so that higher extreme value positions can be sustained without the cartel having to break up—alternatively, with very low manipulation costs the cartel breaks up constantly, to the point of being merely an exchange of information to play Nash rather than Bayesian-Nash. On the other hand do higher manipulation costs reduce cartel profits, making collusion less attractive. The combined effect on cartel steadiness (ρ) is ambiguous. Yet even if it breaks up less often, the cartel would be manipulating the rates less extremely when manipulation costs are higher. Therefore, while likely reducing the extent of manipulation, the reforms to broaden the class of eligible transactions—which increase the cost involved in manipulating the benchmarks—can increase the frequency of collusive quoting.

Decreasing the trimmed range $\mathcal{T}$ by discarding more of the highest and lowest quotes also has opposing effects on incentives to collude. While fewer banks can influence the rate by deviating from the collusive agreement, each one has a larger individual effect on the published rate, as a smaller number of quotes are averaged, so that the overall effect on defection incentives is ambiguous. The same is true for a lower number of panel banks N, which in addition increases the likelihood that extreme position drawings are of the same sign as the average portfolio, reducing the expected cost of collusion.

If the cartel for some reason were to apply a finite T punishment period, the effect of it is confined to a reduction of the critical cut-off value $\Psi(\cdot)$, increasing ρ, so that the episodic break-up strategy would become less steady. Note that while the cartel strategy of continuous collusion with episodic break-ups is not first-best—in the sense that total profits in Nash-quoting periods can be lower than under coordinated quoting—it does minimize total costs of collusion and uses no implicit side-payments in manipulation costs sharing. A stable cartel with episodic break-ups would also be sustainable under continuous adjustments, if it were feasible.

5 Collusive Rate Patterns

To illustrate how benchmark rate collusion could play out in practice and the type of empirical trail it may leave, we simulated a data generating process and determined the strategies of continuous collusion with episodic break-up using the cost function

$$C\left(\Delta c_{it}, \Delta v_{it}\right) = \alpha \Delta c_{it}^2 + \beta \Delta v_{it}^2, \tag{15}$$

in which α and β are positive cost parameters. Note that eligible transactions rigging and front running are implied to each be equally costly in either direction. The resulting linear-quadratic payoff function satisfies the conditions for a unique global maximum. Parameter values are: $N = 16$, $n = 8$, $\alpha = \beta = 1$, $v_{0it} \sim N(0, 0.1)$ and $c_{0it} \sim N(L_{t-1}, 0.1)$, with starting value $L_0 = 1$.[37]

First, using Monte Carlo simulations the implicit probability of break-up was calculated for different discount rates. Providing convergence in the sample distribution, we simulated 100.000 daily draws of baseline eligible transaction rates c_{0it} and baseline exposures v_{0it}, derived payoffs in static Bayesian-Nash (π_{it}^{BN}), collusion (π_{it}^C), defection (π_{it}^D) and static Nash (π_{it}^N) in each draw, for each bank $i = 1, ..., N$, and determined the expected (conditional) payoffs $E[\pi^{BN}]$, $E[\pi^C]$ and $E[\pi^N]$. These identified the simulated distribution of the largest payoff differential $\max_i(\pi_{it}^D - \pi_{it}^C)$ and the fixed point ρ as a function of discount rate δ. Second, with the elements obtained a 240-day time series of the interbank rate was generated, looking separately at honest, Bayesian-Nash and optimal collusive behavior. The MATLAB® source code of the cartel routine, including advised positions and submission targets, for $N = 4$ is given as appendix.

5.1 Payoffs and Break-ups

Figure 4 gives the simulated payoff frequency distributions for independent Bayesian-Nash (grey) and collusive (black) quoting. Under independent quoting, payoffs are more closely concentrated around zero—the mean is slightly positive because of the independent manipulation benefits, which are small.[38] The cartel materializes higher profits more often, but also losses: there are more instances in which cartel members take one for the team in the sense that they would have done better under independent quoting. Yet in collusion, both losses and profits are more concentrated on the right side of their spectra: losses are more often closer to zero and profits are more often large. As a result, the average expected payoff is almost forty times higher under collusion than under independent quoting. All panel banks gain in expectation from participating in the collusion.

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[37]Qualitatively similar results obtain for different values of α, β and the variances—in particular for $\alpha \gg \beta$ and the variance of v_{0it} of a higher order than that of c_{0it}.

[38]$E[\pi^{BN}] \approx 0.000024$, $\sigma_{BN} \approx 0.00274$; $E[\pi^C] \approx 0.000898$, $\sigma_C \approx 0.00679$; $E[\pi^N] \approx 0.000218$, $\sigma_N \approx 0.00283$.

FIGURE 4 HERE

The frequency table for the $\max_i \left(\pi_i^D - \pi_i^C \right)$ has a shape close to the probability density function in Figure 3. For $\delta = 0.90$, the critical cut-off value below which collusion is stable is $\Psi \approx 0.0028$. Together with the conditional expected collusion payoff this implies $\rho \approx 0.38$, which is unique.[39]

Figure 5 plots break-up probability ρ as a function of δ for different cost levels of eligible transactions rigging (α) and different trimmed ranges ($\mathcal{T}$). For this specification, cartel steadiness increases in δ and the cost of manipulation: monotonic increases in the cost of eligible transactions rigging decrease the probability of break-up for all discount factors. While the higher manipulation cost reduce both defection and future cartel profits, the decrease is larger for defection profits, which results in more steady continuous collusion. The same is true for averaging over fewer middle quotes by discarding a larger part of extreme submissions. The effect of different panel sizes N on ρ is negligible.

FIGURE 5 HERE

Note that the special case of colluding only to exchange information and front run individually arises when eligible transactions rigging is punitively costly (α very high). Without an incentive to deviate, the cartel never breaks up. The published benchmark rate is unaffected.

5.2 Time series

With the fixed point determined, we simulate time series. Figure 6 displays an interbank rate over time for $\delta = 0.90$, first when banks determine their submissions independently, respectively honest and individually optimal for 60 days each, and after that in continuous collusion with episodic break-up for 120 days. In the collusion period, the vertical shaded areas are episodes of non-cooperative quoting following an extreme value drawing.[40]

While the rate pattern may seem somewhat different between the collusive and non-collusive periods, it is not evident from the simulated benchmark rates alone whether the banks quoted independently or collusively, nor which cartel periods were break-ups. Any drift in the mean is random hysteresis since the rate follows a random walk around 1 and the effects on volatility are not obvious.

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[39] $E[\pi^C|\text{no break-up}] \approx 0.00012$, $E[\pi^N|\text{break-up}] \approx 0.00069$ and $\rho \approx 0.37901$.

[40] This happened 48 out of the 120 days of collusion, which is in the neighborhood of the 38% projected.

The intraday variance patterns are not statistically different between the regimes, either for the full panel or the banks that determine the rate.[41] Colluding banks may be expected to 'bunch' together around one of the boundaries of the trimmed range, which would decrease the intraday variance of bank quotes. However, for the full panel this intraday variance decreasing effect is partially offset by a larger distance between the manipulating banks and the share of trimmed banks on the other extreme. Within the trimmed range, there is more bunching together around one of the pivotal quotes in the same direction than under independent quoting, so that a decreased intraday variance may be more likely found. Abrantes-Metz et al. (2012) conjectured that the reduced intraday variance they found was indicative of collusion, but we do not find evidence for it in our illustration.

FIGURE 6 HERE

The interday variance (or volatility) of the interbank rate over a certain time window does give distinct differences in some of the runs. Figure 7 shows the interday variance for an 11-day and a 5-day rolling window. Clearly, the benchmark rate under collusion displays more extreme behavior than during independent quoting—while again it is not possible to tell apart optimal Bayesian-Nash from honest independent quoting. The average volatility under collusive quoting is about twice as high as under independent behavior. This difference is statistically significant for both windows.[42] Note that it is not driven by the occasional break-up, as the underlying cause of the volatility is eligible transactions rigging.

FIGURE 7 HERE

Also the average absolute change in the interbank rate is statistically significantly different between the break-up and full collusion regimes.[43] Moreover, within the collusion period it is statistically significantly higher in no break-up than during

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[41]On average, the intraday variance is 0.0098 for the full panel and 0.0019 for the trimmed range during the 60 honest days and 0.0099 for the full panel and 0.0017 for the trimmed range during the 120 manipulation days. These differences are not statistically significant. Also within the 120 manipulation days there is not significant difference between collusion days and temporary break-up days.

[42]Using a one-sided Wilcoxon ranked sum test, p-value below 0.00001. The average interday variance is 0.0011 for the 11-day window and 0.0006 for the 5-day window during the 60 honest days and 0.0021 for the 11-day window and 0.0012 for the 5-day window during the 120 manipulation days.

[43]At the 1% level. On average, the absolute change in the interbank rate is 0.0193 during the 60 honest days and 0.0304 during the 120 manipulation days.

break-up.[44] These markers are robust against changes in the length of the rolling window.

In line with our theory, the benchmark cartel benefits from more volatility in the rates over time, as that allows the panel bank members to better exploit their inside information about the rates movements in advance by adjusting their portfolio exposures, against non-initiated financial institutions and investors. During break-ups, these benefits are much smaller, as cartel members no longer take into account the externality effects of their behavior. It can also cause them to pursue conflicting directional changes, reducing volatility. Nevertheless, in a substantial part of simulations volatility patterns are not identifiably different.

5.3   Screening

The different benchmark rate patterns that our cartel theory predicts suggest empirical screens that can help identify signs of manipulation after the reforms and target deeper investigations, by government agencies or private counterparties that are potentially affected. Fluctuations in the rate are more pronounced during periods of collusion (no break-up or break-up) than independent quoting (Bayesian-Nash or honest), which suggests non-standard variance screens. With the actual periods of collusive quoting unknown, Bai-Perron structural break tests can be used to identify cartel episodes more systematically.[45] On the 5-day volatility of this section, the Bai-Perron test identifies one and only one break occurring at day 129, which is close to the actual break day 120. The fitted values are drawn in Figure 7. Similar distinction is found using the 11-day volatility.

For accurate application in practice, such collusion screens would need to be further calibrated and controlled for other drivers of volatility in benchmark rates, in order to avoid them falsely flagging as suspicious increased volatility between different days that is due to legitimate market events. However, banks' quotes are difficult to rationalize with other measures of bank borrowing costs, as Snider and Youle (2010) show, even when including banks' own quotes in other currency panels. Kuo et al. (2012) list several reasons why comparable measures of bank borrowing cost would follow quite different paths than Libor. These volatility screens would require a considerable level of sophistication to be powerful in different circumstances.

We note that the increased volatility under collusion in Figure 7 results in large part from the true borrowing costs following the published, manipulated Libor, i.e. that $E[c_{0it}] = L_{t-1}$. Upward (downwards) manipulation is followed by a higher

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[44]Using a one-sided Wilcoxon rank sum test, the null that the mean of the volatility is the same during no break-up and break-up within the collusion period is rejected with a p-value of 0.0301. The absolute change in the interbank rate is 0.0332 during collusion and 0.0262 during break-up.

[45]Bai and Perron (1998, 2003) provide a collection of tests that allow for identifying structural changes, break dates and magnitudes of change in time series when both the number and the dates of the breaks are unknown. For an application to identifying the begin and end dates of cartel effects, see Boswijk et al. (2017).

(lower) baseline value draw in the next period, which combines with the collusive variance. If we use a more stable mean for the daily rate drawing instead, volatility alone remains a sufficient statistic to tell apart independent from coordinated quoting only rarely. If manipulation was indeed widespread and commonly known, possibly the initiated financial institutions accounted for an actual borrowing standard that would have followed from honest reporting only—as a 'shadow Libor'. Yet even if there were purer determinants for the true cost of borrowing of the panel banks, it seems reasonable to expect those to have at least been somewhat contaminated by the Libor manipulations.

Alternatively, correlation tests may be used to identify signs of front running. Periods of collusion would in particular leave traces in transactions over time, as the banks involved change their exposure position in the same direction in which the rate is rigged. A high correlation between a bank's transactions in the front-running window and the subsequent change in the rate could be an indication of suspicious exposure alignment. A screen would flag increases in these combined correlations over time or compared to non-panel banks. An advantage of correlations over variances is that they are not largely driven by larger banks with more extensive trading books or lower front-running costs.

Figure 8 shows a simulation of the correlation between changes in the interbank rate ($L_t - L_{t-1}$) and in daily positions (Δv_{it} for all $i = 1, ..., N$) for a 5-day and a 11-day rolling window. Under the assumptions in our model, in collusion banks adapt their portfolio exposure position perfectly in the same direction as the future rate, so that the correlation is 1, compared to 0 for honest quoting. The correlations are positive and fluctuate for Bayesian-Nash quoting, reflecting minor front running based only on private information. The screen can also be applied to individual submissions Δc_{it} instead of the rate, or to panel members individually.

FIGURE 8 HERE

Applied to real data, heterogeneity among banks and other trading during the day will make the correlation-screen distinction non-binary. For example will the exact moment of information exchange (C_t)—that is, the opening of the front-running window—not be known outside the cartel. Also can other transactions that classify as eligible take place simultaneously for non-collusive reasons. Panel banks may not involve all of their trading activities world-wide—facing internal coordination issues or possibly lacking a complete picture themselves. While correlations will be different in magnitude as a result, in general they can be markedly higher even with a somewhat shifted window, transaction set, or general noise in the transaction data. To complement, robustness checks for different length front-running windows up to the submission time (S_t) can be used.

However, while data on the interbank rates and individual submissions of panel banks is readily available, the transaction data to reconstruct overall exposure positions is not. They are only starting to be systematically collected. Eligible transactions, although limited to interbank loan data, could to a certain extent be retrieved from the TARGET2 real-time gross settlements system, using a method such as the Furfine (1999) algorithm, for transactions within Europe. A similar data set, the Fedwire Funds Service, is the large-value bank payments system operated by the U.S. Federal Reserve banks. Kuo et al. (2013) develop a methodology to infer information about individual term dollar interbank loans settled through this system. However, the real challenge lies in identifying banks' overall exposure positions to the rate, as these are largely driven by OTC derivatives transactions, which take place without an exchange. Data on those transactions is not (yet) publicly available.

Recent initiatives to construct Trade Repositories (TRs) aim at maintaining electronic records of all transactions data, including OTC derivatives transactions in which one of the counterparties is of the same nationality as the repository. If sufficiently developed in the future across different countries, these repositories could provide authorities with the necessary transactions data on a sufficiently detailed level to be useful in screening for collusive benchmark rates fixing. Our analysis advises on what data to collect for this purpose.

Screening for increased intraday variance patterns may deter manipulation if panel banks are aware of this. It would be hard to simultaneously circumvent these screens and gain from collusion, as the volatility the cartel generates to have inside information is an important source of cartel profits. Dodging the screens thus undermines cartel stability. As an alternative to government oversight, counterparties to panel banks would have an interest to monitor for rate manipulations, as they structurally loose out on their OTC trades with panel members that front run. Systematic differences in their rates of return on trades with panel and non-panel institutions may be indicative of collusive benchmark rates fixing.

6   Extensions

Several of the assumptions we make warrant some further discussion. We model portfolio positions as independently distributed around zero, so that there is no accumulation and expectations on future positions are unrelated to current positions. Even though trade in OTC derivatives is fast-changing and vast in comparison, banks may have a relatively stable exposure profile of the same sign, such as long-term mortgage contracts with Libor-based rates. However, a steady bank-specific exposure profile, positive or negative, while still generating changing conflicts of interests with sufficiently large variances, introduces a drift in the rate manipulation in the direction of the sign of the panel's overall mean. Our symmetric model can instead be interpreted as an approximation on the larger part of the portfolio, or alternatively as being about a desks or traders cartel maximizing joint profits on their liquid trading

books only, and not their employer banks' overall exposures. In that case the panel bank as a whole may incur losses on its remaining smaller part of the portfolio.

We assume that panel banks' borrowing capacities fluctuate around the same mean and that shocks to baseline borrowing costs or exposure positions are not persistent. In practice, some banks may be able to borrow at lower rates than others, due to reputation, portfolio risk profile or scale for example. The model can be extended to each bank i having an idiosyncratic mean of the common distribution, such that $E_i[c_{0it}] = L_{t-1} + \theta_i$. As long as the distribution of θ_i is symmetric around zero, this will still be consistent with the absence of drift in the (manipulated) published rate. If in addition it varies in time, such persistence in shocks to true borrowing costs introduces complex dynamic optimization, as do trade book building, expectations about future demand, correlation of demand shocks and other features of business cycles as analyzed in, among others, Haltiwanger and Harrington (1991), Kandori (1991) and Bagwell and Staiger (1997). The effect of such extensions on cartel stability or cartel formation incentives in our model is not obvious. They are likely to introduce the necessity of side-payments or rotation on which banks are supposed to pay the eligible transactions rigging costs, for which there is some evidence.[46] Break-up periods may be longer if it takes time to get trading books incentives aligned again and find a stable cartel strategy. While the literature thus has extended Rotemberg and Saloner (1986), dynamic collusive benchmark rates fixing is left for future research.

We model manipulation costs equal across all panel banks, which is reasonable to assume for the main cost components, in particular raising suspicion and suboptimal transactions in eligible transactions rigging. In front running, however, certain panel banks may face lower costs than others, depending on their core activities and size. Our proof of existence of a one-shot collusively optimal set of submissions relies on the fact that with equal manipulation costs, banks with the highest baseline true cost parameter submit the highest quote and that the cost parameters are equal across banks. With heterogeneous costs, this order may be broken and a certain set of collusive submissions in theory may be achieved in different ways: either by choosing the minimum amount of eligible transactions rigging or by letting banks with lower manipulation costs engage in more eligible transactions rigging than others. Given banks' heterogeneous cost functions, the probability of a collusive outcome not being unique—which would require the exact occurrence of certain draws—is zero, so that a unique global cartel optimum remains, provided all individual cost functions satisfy the existence conditions.

As noted, the trimmed average can be manipulated already by a small subset of the panel coordinating. Rather than a full panel cartel, one or various smaller

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[46]In Commodity Futures Trading Commission, "Order Instituting Proceedings: Deutsche Bank AG," 23 April 2015, on page 27 it is reported that: "The UBS Senior Yen Trader also offered to enter into trades at rates detrimental to him but beneficial to the Senior Yen Trader-Submitter to ensure the Senior Yen Trader-Submitter's involvement in his plans and to entice him to make Deutsche Bank' s Yen LIBOR submissions in the manner he desired."

combinations of banks may have colluded unbeknownst to the others. However, establishing the common interests needed to form sub-coalitions requires panel wide communication, and no panel bank knowing that some collusion was going-on would tolerate manipulation in directions adverse to its own interest—possibly also inciting offsetting manipulations. Partial arrangements involving all panel banks could be scenario's in which a sub-set of the panel carries on colluding for the break-up period, not including those for whom the incentive constraints do not hold. Such a partial cartel as part of the continuous collusion strategy can allow all panel banks to benefit from front running and can increase expected cartel profits. An individual bank may also want to skip a period of cartel participation, for example when it drew a position close to neutral.

Allowing for sub-coalitions can make full collusion less stable, however, as banks could temporarily freeride on a partial cartel. The benefits of not participating a period, such as saving manipulation costs, may be larger than the effect of not having the bank's interests internalized by the collusive coalition. At the same time the trimming mechanism dictates a minimum size cartel coalition, as marginal contributions to, and benefits of the manipulated rate are high for the first couple of banks that get inside the trimmed range. Although partial benchmark rate cartel theory remains to formally be developed, cartel clusters in partial collusion could be identified by a high correlation between their members' exposure position trades and rates.

Information sharing in the cartel is modeled to be perfect, which reveals to all members everyone's options to deviate. Alternatively, the colluding banks could employ an independent administrator who collects the information, runs the cartel software and then only provides personal instructions to each bank. If all panel banks manage to commit to such a central ringleader, it would significantly increase cartel stability by largely taking away the incentives to deviate.

7   Concluding Remarks

Despite evidence of wider coordination in the benchmark rate fixings, most investigations and academic work has focussed on individual manipulation by a few rogue traders. In this paper we develop novel cartel theory to show how a full stable for-profit benchmark rates cartel could work, despite the design of the rates and the panel banks' interests typically not being aligned—and without a need for side-payments. Two mechanisms reinforce each other in facilitating collusion: front running and eligible transactions rigging. By creating inside information, panel banks are in a position to front run and create a more beneficial exposure position to the upcoming rate, thereby reducing conflicting interests in their trading books. Some cartel banks would also have to engage in eligible transactions rigging, placing transactions at rates required to allow the cartel to justify the collusively optimal quotes.

Collusion is costly, nevertheless worthwhile. Occasionally, participating banks may be required to incur manipulation costs exceeding the period cartel gains. Even

though these can be substantial, a panel bank's average expected collusion payoff is substantially higher than under independent quoting. Panel banks would often bear costs on the smaller book of eligible transactions for the occasional large gain on the exposure when the rate is manipulated favorably for them. This picture is broadly consistent with evidence on the money markets involved, in which panel members are in multi-market contact over a variety of financial products linked to different maturities and currencies, typically meeting short-term inside liquidity demands also sometimes at a small loss, in order to maintain longer-term banking relationships and benefit from large outside business gains. A cartel can reduce total manipulation costs by doing internal eligible transactions between the members, as well as align portfolios partly by swapping positions—although the latter does not increase overall cartel profits.

Consistent with the evidence found, our cartel model is characterized by episodic recourse to independent quoting. We explain these temporary break-ups as part of an ongoing collusive strategy, to which the cartel reverts in response to occasional extreme exposure values that give incentive to deviate. These reflect that payoffs in financial markets can be volatile and cartel deviation is nonstandard. We describe in detail how a cartel could be administered. Collusion leaves no obvious traces in the benchmark patterns over time, nor in intraday variance in the quotes. It does markedly increase the volatility in quotes between trading days. On this basis, we propose volatility screens, ideally supplemented with transactions data, to monitor submissions for periods of collusive manipulation. Once systematically collected, trade repositories can be used to screen for suspiciously strong correlations between changes in the exposure positions of banks and in the rates.

To the extent that movements in the pricing of futures, options and derivatives are zero-sum games, where there is a winning contract for every correlative losing one, the overall effect of collusion on welfare may have been limited to primarily rent shifting from other financial market participants to panel members. However, Libor and Euribor are the fundament of financial and real markets around the world. The manipulation scandals have affected the benchmarks' trustworthiness as foundations of value and signals of underlying risks. This will likely have had consequences for financial market stability.[47] It may also have induced different borrowing behavior and could thereby have affected countless underlying markets, likely also impacting the efficient allocation of resources. The plain costs of manipulation are a dead-weight loss. However, some cartel agreements found were also aimed at reducing transaction risks, maintaining narrower spreads for trades in order to lower the members' own transaction costs and maintaining liquidity between them.[48] The assessment of damages due to the benchmark rates cartels therefore will be highly case-specific and

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[47]Duffie and Stein (2015) and Bank of International Settlements, "Timothy Lane: Financial benchmarks— a question of trust," 24 March 2014.

[48]European Commission, "Antitrust: Commission settles cartel on bid-ask spreads charged on Swiss Franc interest rate derivatives; fines four major banks € 32.3 million," 21 October 2014.

complex.

The main mechanisms we model also apply to the collusive rigging of foreign exchange (forex) rates, which similarly relies on exchanging inside information, aligning exposure positions and planning eligible transactions. Even though the number of traders is larger and can vary, and their individual impact on the forex rates is asymmetric, banging the close is essentially eligible transactions rigging, as those trades in the window are eligible for calculation of the rate and a cartel is able to exercise more influence on the rate jointly than any individual bank. Exchanging information on large client orders to be executed in the future and on manipulation strategies towards them, banks in the forex cartel were able to front run as they had inside information on the direction in which the rate would move in the future. Other possible applications include insider trading in benchmarks and price reference points in gold, energy and commodities markets–some of which have been subject to allegations of misconduct.

The benchmarks remain vulnerable to collusion, despite recent and proposed reforms. Extending the class of eligible transactions increases manipulation costs and may thereby limit the room to manipulate, while also reducing defection gains. It therefore has no obvious effect on cartel stability. Calculating the rate on the basis of fewer quotes by reducing the trimmed range, as proposed for Euribor, has similar ambiguous effects. Both reforms may potentially lead to more steady collusion. The announced transition to the Secured Overnight Funding Rate (SOFR), which is based on a larger volume of transactions, may reduce incentives to manipulate but certainly does not take them away.[49] A mechanism design approach, as taken in Coulter and Shapiro (forthcoming) and Duffie and Dworczak (2014) for individual manipulation incentives, could help make benchmark rates fixing collusion-proof.

References

[1] Abrantes-Metz, R.M., M. Kraten, A.D. Metz and G.S. Seow (2012), "LIBOR Manipulation?," *Journal of Banking & Finance*, **36**, 136-150.

[2] Abrantes-Metz, R.M. (2012), "Why and How Should the Libor Be Reformed?," *working paper*, SSRN 2094542.

[3] Abrantes-Metz, R.M. and D.D. Sokol (2012), "The Lessons from Libor for Detection and Deterrence of Cartel Wrongdoing," *Harvard Business Law Review Online*, **3**, 10-16.

[4] Bagwell, K. and R.W. Staiger (1997), "Collusion over the Business Cycle," *The RAND Journal of Economics*, **28**, 82-106.

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[49]On this U.S. Alternative Reference Rates Committee (ARRC) recommendation, see Jerome H. Powell "Introductory Remarks at the Roundtable of the Alternative Reference Rates Committee," *The Federal Reserve Bank of New York*, 2 November 2017.

[5] Bai, J. and P. Perron (1998), "Estimating and Testing Linear Models with Multiple Structural Changes," *Econometrica*, **66**, 47-78.

[6] Bai, J. and P. Perron (2003), "Computation and Analysis of Multiple Structural Change Models," *Journal of Applied Econometrics*, **18**, 1-22.

[7] Boswijk, H.P., M.J.G. Bun and M.P. Schinkel (2017), "Cartel Dating," *Tinbergen Institute Discussion Paper* 16-092/VII.

[8] Brinkhuis, J. and V. Tikhomirov (2005), *Optimization: Insights and Applications*, Princeton University Press.

[9] Chen, J. (2017), "LIBOR's Poker," *working paper*, SSRN 2136871.

[10] Coulter, B., J.D. Shapiro and P. Zimmerman (forthcoming), "A Mechanism for Libor," *Review of Finance*.

[11] Diehl, C. (2013), "The LIBOR Mechanism and Related Games," *Center of Mathematical Economics Working Paper* No. 482.

[12] Duffie, D. and P. Dworczak (2014), "Robust Benchmark Design," *NBER Working Paper* 20540.

[13] Duffie, D. and J.C. Stein (2015), "Reforming Libor and other Financial-market Benchmarks," *The Journal of Economic Perspectives*, **29**, 191-212.

[14] Eisl, A., R. Jankowitsch and M.G. Subrahmanyam (2017), "The Manipulation Potential of Libor and Euribor," *European Financial Management,* forthcoming.

[15] Fershtman, C. and A. Pakes (2000), "A Dynamic Oligopoly with Collusion and Price Wars," *The RAND Journal of Economics*, **31**, 207-236.

[16] Fouquau, J. and P.K. Spieser (2015), "Statistical Evidence about LIBOR Manipulation: A "Sherlock Holmes" Investigation," *Journal of Banking & Finance*, **50**, 632-643.

[17] Furfine, C.H. (1999), "The Microstructure of the Federal Funds Market," *Financial Markets, Institutions & Instruments*, **8**, 24-44.

[18] Gandhi, P., B. Golez, J.C. Jackwerth, and A. Plazzi (2017), "Financial Market Misconduct and Public Enforcement: The Case of Libor Manipulation," *working paper*, SSRN 2342075 (R&R *Management Science*).

[19] Green, E.J., and R.H. Porter (1984), "Noncooperative Collusion under Imperfect Price Information," *Econometrica*, **52**, 87-100.

[20] Haltiwanger, J. and J.E. Harrington (1989), "The Impact of Cyclical Demand Movements on Collusive Behavior," *The RAND Journal of Economics*, **22**, 89-106.

[21] Kandori, M. (1991), "Correlated Demand Shocks and Price Wars During Booms," *The Review of Economic Studies*, **58**(1), 171-180.

[22] Kuo, D., D. Skeie and J. Vickery (2012), "A Comparison of LIBOR to other Measures of Bank Borrowing Costs," *working paper*, Federal Reserve Bank of New York.

[23] Kuo, D., D. Skeie, J. Vickery and T. Youle (2013), "Identifying Term Interbank Loans from Fedwire Payments Data," *Staff Report No. 603*, Federal Reserve Bank of New York.

[24] Monticini, A. and D.L. Thornton (2013), "The Effect of Underreporting on LIBOR Rates," *Journal of Macroeconomics*, **37**, 345-348.

[25] Rotemberg, J. and G. Saloner (1986), "A Supergame-theoretic Model of Price Wars during Booms," *The American Economic Review*, **76**, 290-407.

[26] Snider, C. and T. Youle (2012), "The Fix Is In: Detecting Portfolio Driven Manipulation of the LIBOR," *working paper*, SSRN 2189015.

[27] Vaughan, L. and G. Finch (2017), *The Fix: How Bankers Lied, Cheated and Colluded to Rig the Worlds' Most Important Number*, Wiley, Chichester.

[28] Youle, T. (2014), "How Much Did Manipulation Distort the Libor?," *working paper*, University of Minnesota.
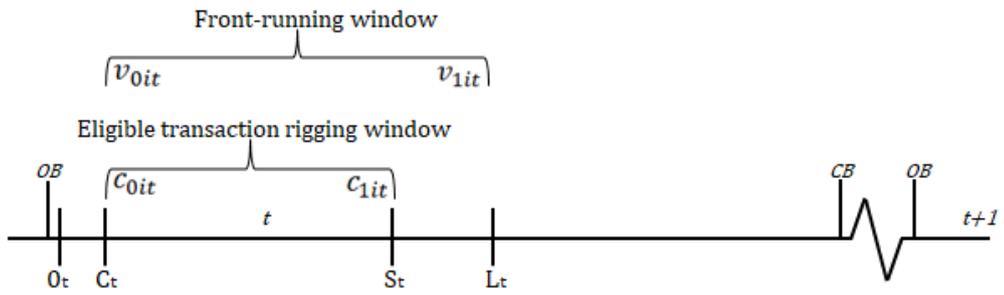
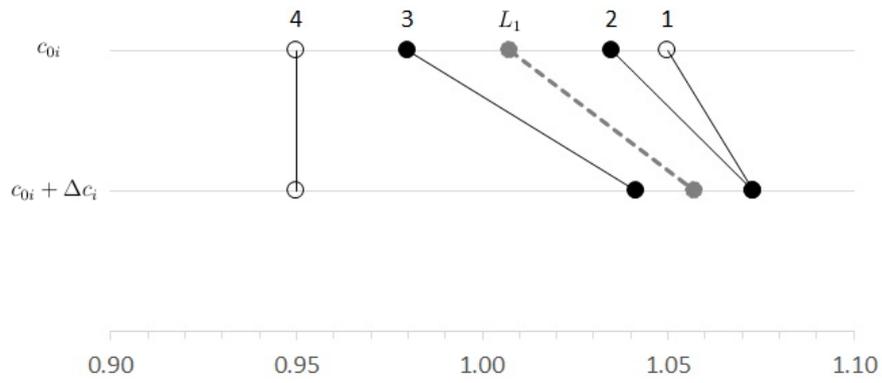Figure 1: A trading day in the life of Libor.

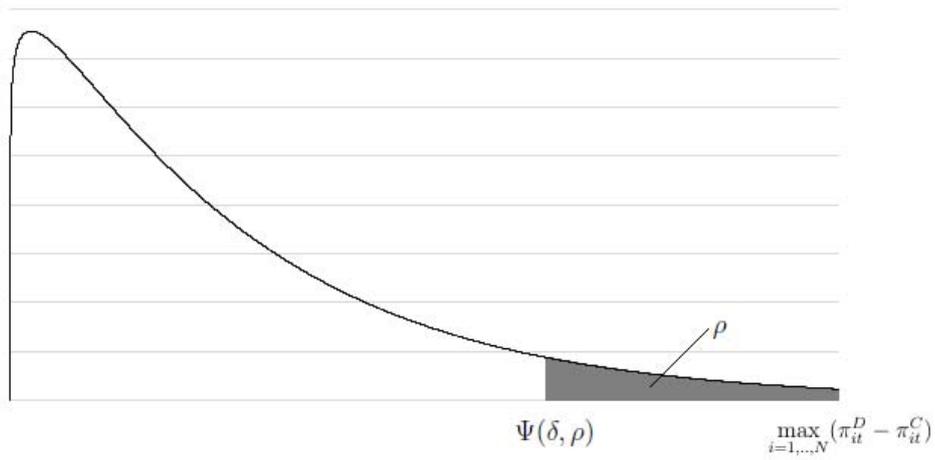Figure 2: Panel bank 1, not in $\mathcal{T}$, engaging in collusive eligible transactions rigging.

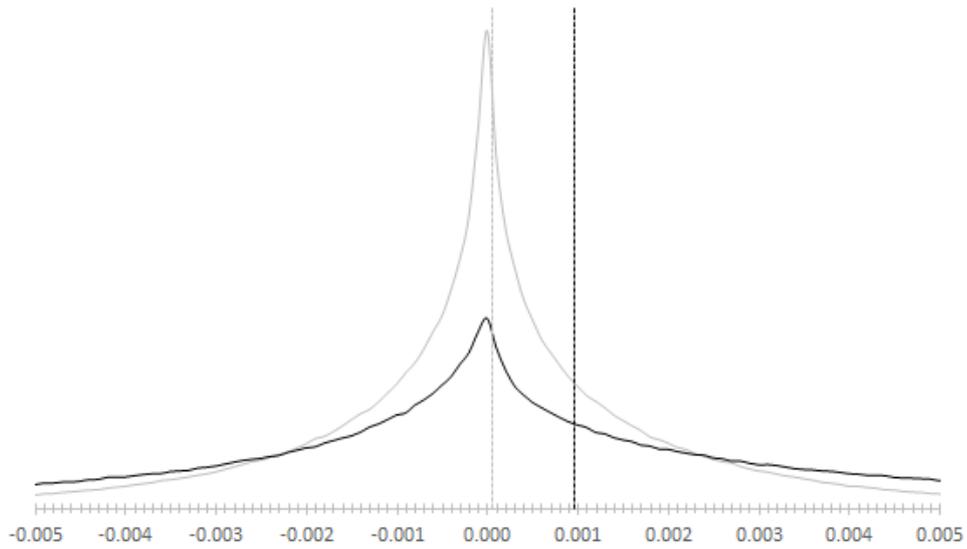Figure 3: Cartel break-up probability defined by the payoff-differential distribution.

Figure 4: Frequency payoffs for Monte Carlo simulation independent quoting (grey, $E[\pi^{BN}] \approx 0.000024$) and collusive quoting (black, $E[\pi^C] \approx 0.000898$).
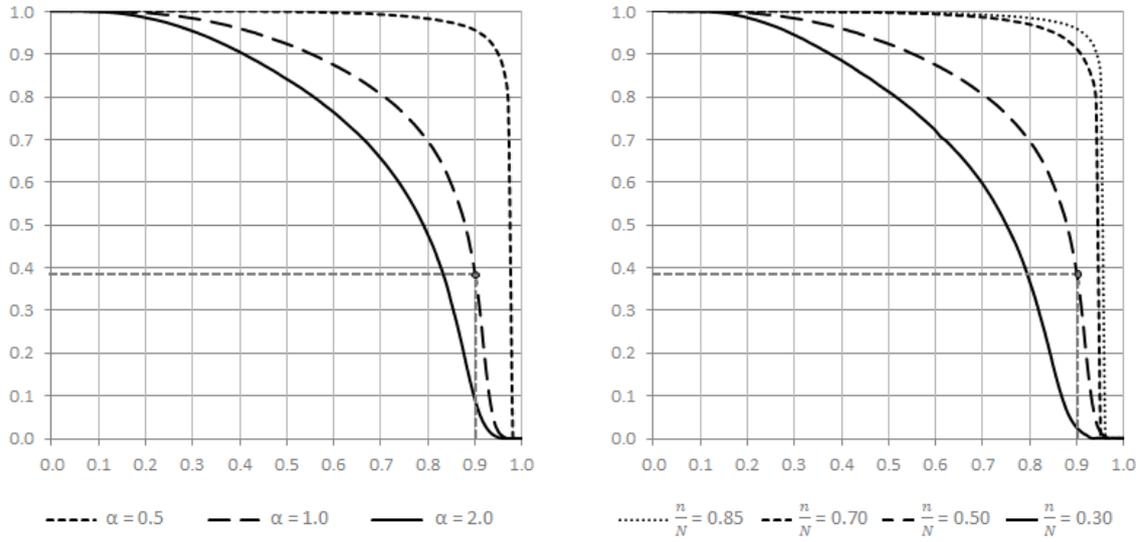
Figure 5: Cartel break-up probability ρ as a function of discount rate δ for different α's (left-panel) and $\mathcal{T}$'s (right-panel).
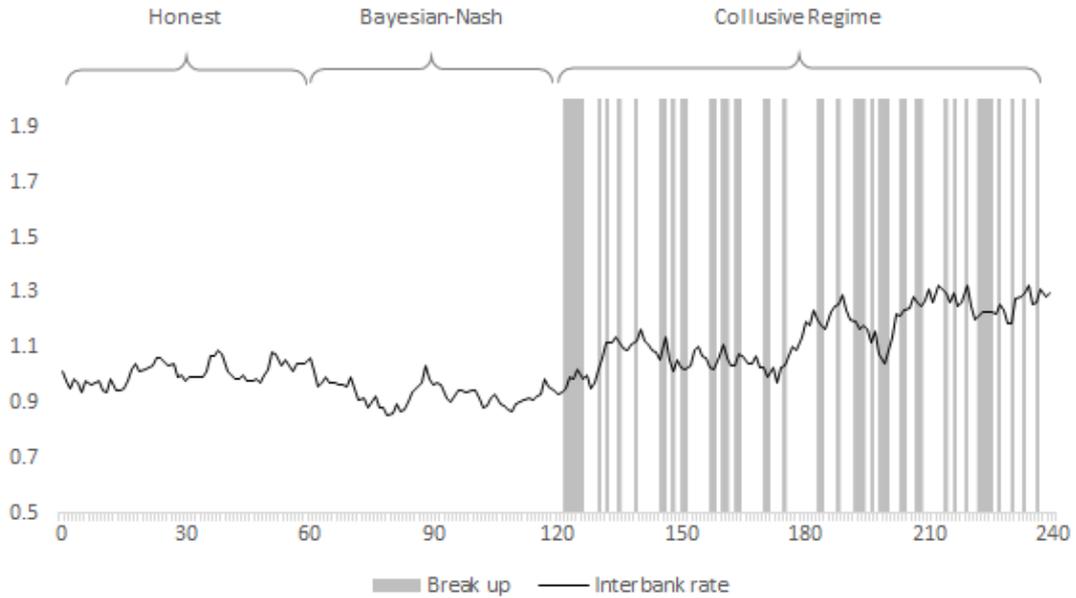
Figure 6: Simulated benchmark rate under honest and Bayesian-Nash independent quoting and collusion.
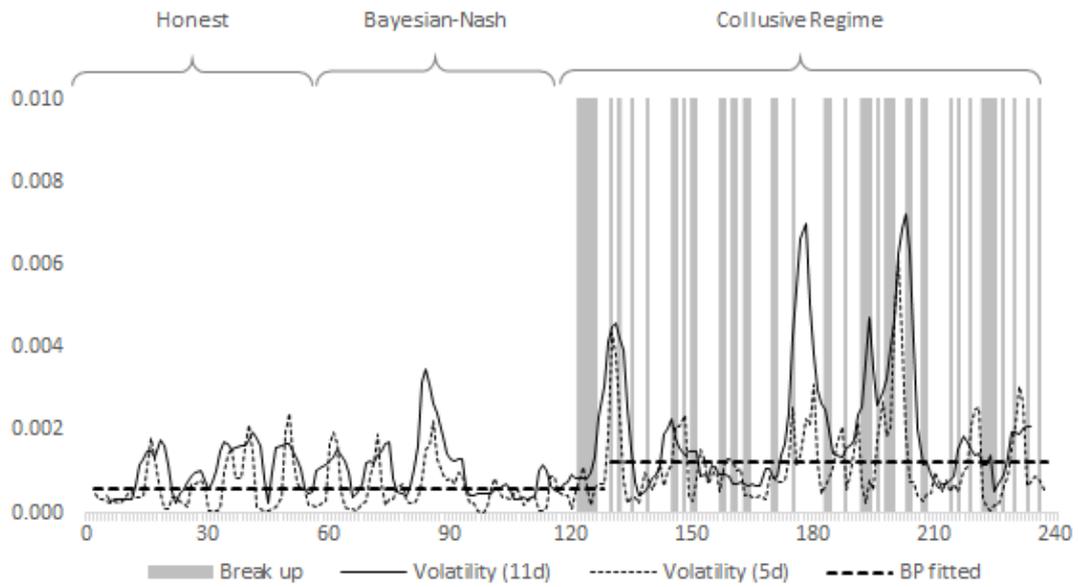
Figure 7: Volatility in quotes, 11-day and 5-day rolling window, including 5-day Bai-Perron structural break test results.
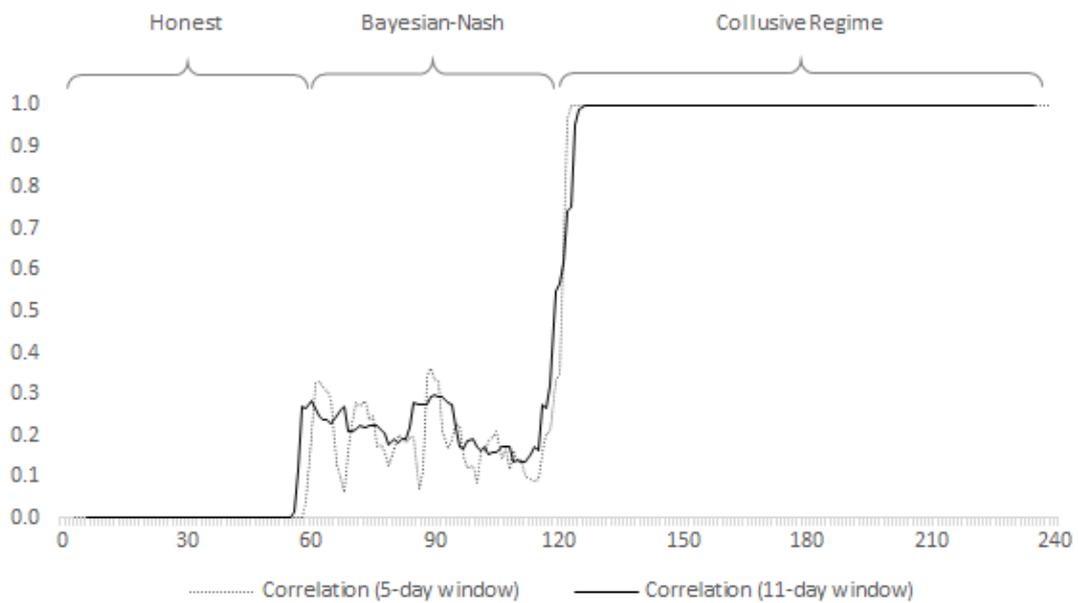

Figure 8: Correlation between changes in the interbank rate and in portfolio positions, 5-day and 11-day rolling window.

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A A MATLAB® Cartel Routine

The following MATLAB® script calculates the optimal cartel strategies. Each bank inputs its daily baseline values, with which the software derives the optimal collusion and deviation strategies and their associated payoffs. The routine also determines whether all of the N cartel stability conditions hold, and dictates break-up as a strategy to all cartel members when one or more do not. The script provides all banks with the exact front running and eligible transactions rigging strategies. The kernel is provided below—for the condensed case of $N = 4$.

```
% Parametric assumptions
N = 4; % Number of panel banks
n = 2; % Share of banks within trimmed range
a = 1; % Eligible Transactions Rigging cost parameter
b = 1; % Front Running cost parameter
sc = 0.1; % Standard deviation transaction rates
sv = 0.1; % Standard deviation exposure
delta = 0.9; % Discount rate

% Derive critical cut-off level Psi
psi = fpsi[N,n,a,b,sv,sc,delta];

%% Step 1:  Prompt input baseline values
dlg_title = 'Enter baseline exposures'; num_lines = 1;
prompt = {'Bank 1','Bank 2','Bank 3','Bank 4'};
defaultans = {'','','',''};
V0 = str2double(inputdlg(prompt,dlg_title,num_lines,defaultans,'on'))';

dlg_title = 'Enter baseline transaction rates'; num_lines = 1;
prompt = {'Previous interbank rate',Bank 1','Bank 2','Bank 3','Bank 4'};
defaultans = {'','','','',''};
C0 = str2double(inputdlg(prompt,dlg_title,num_lines,defaultans,'on'))';

%% Step 2:  Calculate collusion and deviation payoffs
% Collusion payoffs
fJointProfit = @(DC)-((sum(V0)+sum(DC(2,:)))*(trimmean(C0+DC(1,:),...
  n/N*100)-L0)-a*(sum(DC(1,:).^2))-b*(sum(DC(2,:).^2)));
CStrategy = fminunc(fJointProfit,zeros(2,N),options);
PCol = fpayoff(V0,C0,N,n,L0,a,b,CStrategy);

% Deviation payoffs
PDev = zeros(N,1);
for i = 1:N
```

```
Cj = CStrategy; DCj(:,i)=[]; COj = C0; COj(:,i)=[];
fOwnProfit = @(DD)-((V0(1,i)+DD(2,i))*(trimmean(horzcat(C0(1,i)+...
  DD(1,i),COj+DCj(2,:)),n/N*100)-L0)-a*(DD(1,i).^2)-b*(DD(2,i).^2));
DStrategy = fminunc(fOwnProfit,zeros(2,N),options);
PDev(i,1) = fpayoffc(V0,C0,N,n,L0,a,b,CStrategy,DStrategy,i);
end

%% Step 3:  Check whether constraints hold and produce output
if PDev - PCol <= psi
msgbox(sprintf(['Break-up:  No.',...
'\n\n Advised positions:',...
'\nBank 1:  Adjustment = %.4f, New position = %.4f',...
'\nBank 2:  Adjustment = %.4f, New position = %.4f',...
'\nBank 3:  Adjustment = %.4f, New position = %.4f',...
'\nBank 4:  Adjustment = %.4f, New position = %.4f',...
'\n\n Advised submission targets:',...
'\nBank 1:  Adjustment = %.4f, New submission = %.4f',...
'\nBank 2:  Adjustment = %.4f, New submission = %.4f',...
'\nBank 3:  Adjustment = %.4f, New submission = %.4f',...
'\nBank 4:  Adjustment = %.4f, New submission = %.4f'],...
CStrategy(1,1), V0(1)+CStrategy(1,1), ...
CStrategy(1,2), V0(2)+CStrategy(1,2), ...
CStrategy(1,3), V0(3)+CStrategy(1,3), ...
CStrategy(1,4), V0(4)+CStrategy(1,4), ...
CStrategy(2,1), C0(1)+CStrategy(2,1), ...
CStrategy(2,2), C0(2)+CStrategy(2,2), ...
CStrategy(2,3), C0(3)+CStrategy(2,3), ...
CStrategy(2,4), C0(4)+CStrategy(2,4)));

else
msgbox('Break-up:  Yes.')
end
```

Given the parameters of the rate setting process, the cut-off value Ψ is found in routine `fpsi` that simulates a sufficient amount of daily payoff values in case of Bayesian-Nash, Collusion, Defection and Nash (100.000 times in the simulation in the paper), such that fixed point ρ can be identified with sufficient precision. The Bayesian-Nash strategies are found by calculating the expected baseline values of the other $N-1$ banks and for each bank separately using the `fminunc` function in MATLAB$^{\textregistered}$ under the assumption that the calculated expected baseline values hold for the other banks. Nash strategies following break-up are found by each bank consecutively maximizing its own payoff function, repeated for a sufficient number of

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rounds. Banks respond to each other for up to 24 rounds, after which either a non-cooperative equilibrium in pure strategies is reached, or none is concluded to exist, in which case the outcome of round 24 is taken as the mixed-strategy equilibrium drawing.

In Step 1, at 0_t in the morning, all cartel members report their baseline drawings, exposures v_{0i} and eligible transactions rate c_{0i}, which are entered as inputs in the prompt as shown in the screens below.

Figure A1: Baseline exposure and eligible transaction rate prompts (for $N = 4$).

In Step 2, the script subsequently derives the optimal cartel strategies, using the fminunc function. Taking V0 as the $1 \times N$ vector of baseline exposures and C0 as the $1 \times N$ vector of baseline eligible transaction rates, the code minimizes the objective function ObjFunc along the $2 \times N$ choice matrix DC, which represents the front running choice variables (first row) and eligible transactions rigging choice variables (second row). Note that ObjFunc is specified as the negative of the sum of the individual payoff functions, which is subsequently minimized. Output CStrategies are the optimal cartel strategies. Plugging these into the individual payoff functions provides each bank's cartel profits. This is done in the routine fpayoff. Similarly, the defection payoffs are found by maximizing own payoffs given that other banks adhere to cartel strategy.
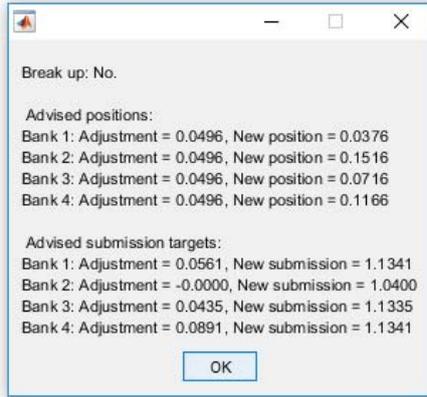
Figure A2: Exchange of information and cartel instructions (for $N = 4$).

Finally, in Step 3 it is checked whether the difference between the defection payoff and collusion payoff of each bank is below the critical cut-off value Ψ. The cartel instructions of all members are given to each, together with all shared information, as in the screen. Note that all banks optimally adjust their positions by the same amount, independent of their initial portfolio position, because manipulation costs are quadratic and profits linear, the same for all banks. If none of the banks has a payoff differential above Ψ, a collusive quote is scripted ('Break-up: No.'), including which strategies each bank should implement. If at least one bank has a payoff differential above Ψ, all banks receive the notification that collusive optimization is not stable ('Break-up: Yes.'), instructing them to revert to one-period static Nash.