Collusive Benchmark Rates Fixing

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Collusive Benchmark Rates Fixing[*]

Nuria Boot[†], Timo Klein[‡] and Maarten Pieter Schinkel[§]

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Abstract

Benchmark rates, such as Libor and Euribor, are proven vulnerable to manipulation. We analyze benchmark rate collusion, which is challenging due to varying and opposing trading interests of the subset of market participants that determine the rates. Our theory is based on two mechanisms. We define front running as information sharing that allows cartel members to optimally adjust their portfolios ahead of the market. To support the joint-profit maximizing rate, designated traders engage in costly manipulation of their submissions. We find that observed episodic recourse to independent quoting is part of a feasible continuous collusion equilibrium and that all panel members would want to participate in the scheme. Our model suggests that high rate volatility may be indicative of collusion. Further protocol reforms to broaden the class of transactions eligible for submission and to average over fewer middle quotes can unintentionally facilitate collusion.

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Keywords: benchmark rate, Libor, Euribor, IRD, banking, cartel

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

Benchmarks such as the Libor and Euribor, silver and gold fixes, and foreign exchange (forex) rates are proven vulnerable to manipulation.[2] They are determined on the basis of contributions by a small set of larger market participants, who also trade in the financial products that are valued on these rates and therefore have incentives to distort the benchmarks in a direction that is favorable to their financial interests. In the majority of the manipulation cases that came to light, the focus of investigation was on individuals who had tried to fraudulently direct the rate for gain on their own trading book, primarily within their own bank, or incidentally as a favor between a few rogue traders. However, benchmark manipulation is a lot more effective when done cooperatively and there have been several cartel proceedings.

In this paper we develop a theory of benchmark rate collusion. Conspiring to jointly rig a benchmark rate is challenging for the members of the panels that fix the rates, due to rapidly varying and often opposing trading interests. Contrary to conventional cartels, in which all members want to increase product prices, the interests of the panel members are typically not sufficiently aligned for them to agree even on

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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]See European Commission, "Antitrust: Commission fines banks €1.49 billion for participating in cartels in the interest rate derivatives industry," 4 December 2013 and Abrantes-Metz et al. (2012); Financial Conduct Authority, "Barclays fined £26m for failings surrounding the London Gold Fixing and former Barclays trader banned and fined for inappropriate conduct," 24 March 2015 and Caminschi and Heaney (2014); Financial Conduct Authority, "Final Notice to Citibank N.A.," 11 November 2014, "EU accuses eight banks of collusion in sovereign bond market", *Financial Times*, 31 January 2019 and Evans (2018).

the direction in which to manipulate a rate. Influencing a benchmark is complicated by the fact that most of them are based on only a subset of contributions, for example a trimmed average, or a median of observations collected during a given time window. Manipulation also can be costly when it requires engaging in transactions.

We show how a cartel in the fixing of benchmark rates can work, despite conflicting and time-varying interests. The panel members are exposed to the rate through their portfolios. They exchange inside information on their true unmanipulated contributions and their portfolio positions, which is then used to jointly agree on a target cartel rate and corresponding contributions for each cartel member. Subsequently, all participants can optimally adjust their own exposure positions to the new rate, which they know ahead of the market. We refer to this as 'front running'. The costs of manipulation are minimized and shared over time, so that each cartel member has a strictly positive expected payoff from participating in the scheme.

Benchmark rates collusion turns out fundamentally different from regular price fixing cartels, in which individual firms can have an incentive to freeride by not joining the (partial) cartel and enjoy the umbrella price effect. However, not participating in the collusive benchmark setting makes a panel member strictly worse off for two reasons. One is that the non-member would miss out on the information necessary to front run, which generates profits that are higher in expectation than the cost of collusion. In addition, the cartel would not take the outsider's (trading) interests into account when determining the rate. Collusion can also be more stable, the higher the number of panel members, as it reduces each individual member's impact on the rate upon deviation.

The model is tailored to the interest rate derivatives cartel infringements that the European Commission found.[3] The Libor and Euribor manipulations have also

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[3]European Commission, *Case A.39914—Euro Interest Rate Derivatives* and *Case AT.39861—*

extensively been investigated by the American and British authorities, albeit predominantly as fraud cases for misreporting in breach of the rates' code of conduct.[4] Reforms to the rate setting protocols have been proposed since. In particular, the submissions are to be based on a, particular and relatively small, subset of actual trades, so-called 'eligible' transactions. Our cartel theory applies both to the original rate setting procedure, as well as with these reforms implemented. Whereas before, manipulation entailed misreporting borrowing costs, in the revised procedures, it would be necessary to manipulate eligible transactions. We refer to it as 'eligible transactions rigging'.

Our model predicts rate patterns that can be used for screening. We find that benchmark collusion creates higher price variance in the benchmark over time, as movements in the rate are inside information to the members, hence potential for cartel trading profits. Also a high positive correlation between panel banks' transactions in the front-running window and the subsequent change in the published rate is indicative of coordinated manipulation. We furthermore find that broadening the class of transactions eligible for submission and averaging over fewer middle quotes can unintentionally make collusion more sustainable.

The paper is organized as follows. Section 2 sets out mechanisms and evidence of collusive Libor and Euribor fixing. In Section 3, related literature is reviewed. Section 4 lays out the model and presents existence and stability results. In Section 5, simulation exercises illustrate collusive rate patterns. In Section 6, we discuss several extensions of our model. Section 7 concludes, briefly discussing also how the theory applies to other benchmark fixings. The source code of a software that calculates optimal cartel strategies is given in an appendix.

Yen Interest Rate Derivatives. See Section 2 for details.

[4]For example Financial Services Authority, "Final Notice: Barclays Bank PLC," 27 June 2012.

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2 Collusion on the Libors and Euribors

The London Interbank Offered Rate (Libor) and the Euro Interbank Offered Rate (Euribor) are financial benchmarks that globally underlie enormous transaction values. They are key variables in portfolio and risk management decisions, as well as barometers of financial sector health. Between 370 trillion and 400 trillion U.S. dollars worth of interest rate derivatives, consumer credit and commercial loans—or over four times global GDP—are estimated to directly derive their value from these rates.[5]

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.[6] A member bank's quote is meant to reflect its opportunity costs of unsecured funds in the interbank market.[7] Each trading day morning, quotes are submitted to a central administrator, who discards the extremes, averages the middle range and publishes the new rates at a given time.[8] All the individual submissions are also published.[9]

Suspicion of manipulation of the fixings rose when, in the run up to 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.[10]

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

[6] The Libor panels are consistently formed by 11 to 16 banks. The Euribor panel consisted of 44 banks before the crisis, after which over half of them withdrew.

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

[8] The Libor quotes are submitted before 11:00 a.m. GMT. Of the middle 50% of the quotes, the average is taken, which is published at 11:45 hours. For the Euribor, this is 10:45 a.m. CET, 70% and 11:00 hours. The Libors used to be produced by the British Banking Association (BBA), but the process was transferred to ICE Benchmark Administration (IBA) in February 2014. The Euribor is published by the European Money Markets Institute (EMMI), formerly the Euribor-EBF.

[9] As of 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.

[10] 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.

Subsequent investigations focussed on incentives of individual contributing banks to appear more creditworthy during the 2007-2009 financial crisis by underreporting their true borrowing cost—so-called 'low-balling'.[11]

The panel banks also have strong incentives to manipulate submissions in order to enhance their portfolio results. The British Bankers Association (BBA), responsible for overseeing the rate setting process, knew that:

> "Many institutions set their Libors based on their derivative reset positions."[12]

Traders requested submissions aimed at benefiting their trading positions, illustrating how a bank with a net lending (borrowing) position would profit from a higher (lower) Libor or Euribor. Money market desks are in a position to know their banks' overall net exposure to the various rates and how they would gain or lose from changes in the rates.[13] The potential trading gains from even a small move in the rates are large.[14]

The design of the Libor and Euribor setting processes is conducive to collusion. The trimming of the highest and the lowest submissions allows an individual bank only a very limited effect on the rate, so that manipulation is most effective when done in cooperation between the panel banks.[15] The same known banks form the panels for

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[11]See Financial Services Authority, "Final Notice: Barclays Bank PLC," 27 June 2012, pages 25-26 and Abrantes-Metz et al. (2012).

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

[13]UBS instructed its traders 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. Tom Hayes, a convicted derivatives trader for UBS and later Citigroup, stated at his trial that he had acted on the instructions of his employer. An internal document titled 'Publishing Libor Rates', containing such instructions, was recovered from the communal drive at UBS. Vaughan and Finch (2017), page 23 and 154.

[14]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 Bet, and Profit, on Libor," *Wall Street Journal*, 10 January 2013.

[15]In theory, any group that is strictly larger than the fraction trimmed on either side can have an unbounded effect on the rate. For example a group of 5 in a 16-bank Libor panel, or a group of 4 in

long periods of time and follow each others' submissions closely. Monitoring adherence to a collusive agreement is easy from the published rates alone, which facilitates the implementation of punishment strategies to stabilize against unilateral defection.

The manipulation cases gave ample indication of more widespread communication and coordination of for-profit manipulation strategies.[16] The U.K. Financial Service Authority (FSA) concluded that Barclays had acted in concert with other banks.[17] The U.S. Commodity Futures Trading Commission (CFTC) found that:

> "Libor was routinely being gamed by the banks that set it."[18]

Several antitrust cases have been brought for benchmark rate collusion. The European Commission established cartel violations in breach of Article 101 TFEU in interest rate derivatives against nine of the panel banks for record fines.[19] The U.S. Department of Justice's Antitrust Division, which was involved in the fraud investigations, did not prosecute for collusion. However, several private antitrust damages actions have been brought. Seminally, the Court of Appeals for the Second Circuit in Manhattan ruled that Libor manipulation could constitute price-fixing as

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the current 20-bank Euribor panel. In practice, extreme quoting will raise suspicion of manipulation, whereas a larger group in coordination can influence the rate more smoothly.

[16]For example U.S. Department of Justice, "Statement of Facts, Non-prosecution Agreement: Barclays Bank PLC," 26 June 2012, and Commodity Futures Trading Commission, "Order Instituting Proceedings: Barclays Bank PLC," 27 June 2012. Similar documents exist for Deutsche Bank, Lloyds, Rabobank, RBS and UBS.

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

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

[19]See European Commission, *Case AT.39914—Euro Interest Rate Derivatives* and European Commission, *Case AT.39861—Yen Interest Rate Derivatives*, two hybrid settlements of 4 December 2013, involving Barclays, Deutsche Bank, Société Générale, RBS, UBS, JP Morgan, Citigroup and RP Martin (broker); probition decisions in both cases, of respectively 7 December 2016 against Crédit Agricole, HSBC and JPMorgan Chase, and 4 February 2015 against broker ICAP for facilitating collusion (later on, this decision was partially annuled by the European Court of Justice); European Commission, *Case AT.39924—Swiss Franc Interest Rate Derivatives*, two prohibition decisions on 21 October 2014, one against RBS and JP Morgan on derivatives based on the Swiss franc Libor and one against RBS, UBS, JP Morgan and Crédit Suisse for bid-ask spreads charged on Swiss Franc interest rate derivatives.

a *per se* antitrust violation under Section 1 of the Sherman Act.[20]

The workings of such financial benchmark rate cartels are not obvious, however. Due to often opposite exposure positions, some banks gain from an increase in the rate, while the others gain from a decrease. Moreover, the position a trader or bank faces on any given day is uncertain and largely stochastic. For a bank, it is the sum total of a vast number of transactions done by various trading desks worldwide. Around a kernel of longer-term contracted money in- and outflows, exposure positions are largely driven by positions in over-the-counter (OTC) derivatives that are highly volatile. This means banks' exposure positions regularly flip back and forth between negative and positive.

Furthermore, rate manipulation is costly, especially after the reforms. Previously, there was no clearly prescribed method for panel members to determine their Libor and Euribor submissions. The misreporting of their true borrowing costs was a form of cheap lying, with really only the risk of too unusual quotes raising suspicion with clients or the authorities. The reforms prescribe that a submission is to be the volume weighted average rate of eligible transactions executed during the last day.[21] In the case of Libor, also transactions closer to 11 a.m. are to receive a higher weight in the quote.[22] If a cartel were to attempt to move the rate, it would need to do substantial and timed actual transactions in line with the submitted rate rather than the going rate, which is potentially suboptimal.

Two complementary mechanisms facilitate collusion. First, designated traders

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[20] *In re: LIBOR-Based Financial Instruments Antitrust Litigation*, No. 13-3565, 2nd Circuit, 23 May 2016. Initially, the Federal Court of New York had ruled that the Sherman Act would not apply to the Libor setting mechanism, which it deemed a cooperative rather than competitive process. *In re: LIBOR-Based Financial Instruments Antitrust Litigation*, No. 935 F. Supp. 2d 666, 29 March 2013.

[21] ICE Benchmark Administration, "ICE LIBOR Evolution Report," 25 April 2018 and European Money Markets Institute, "The Path Forward to Transaction-based Euribor," 21 June 2016.

[22] ICE Benchmark Administration, "ICE LIBOR Evolution Report," 25 April 2018, page 10.

engage in eligible transactions rigging: they submit cartel quotes supported by manipulated transactions. By having only some of its members manipulate, in turns, the cartel minimizes and spreads the costs of its manipulation. Also, eligible transactions could (partly) be matched between cartel members, with no net cost to the cooperative.

Obviously, prior to the reforms, when the rates were not transaction-based, there was no need for panel banks to engage in eligible transactions rigging. Hence, no direct evidence of this mechanism can be expected from the cases investigated under the old regime. However, as detailed above, the Libor and Euribor panel banks misreported their true borrowing costs when submitting quotes regularly, and with information and objectives that are in line with eligible transactions rigging.

In the second mechanism, all cartel members benefit from front running. The cartel creates inside information for its members on what the future rate will be, before it is published. This information allows cartel members not only to increase their trading profits at the expense of other market participants, but also to better align their interests by creating more beneficial portfolio positions. Front running involves some direct transaction costs, trade risks and liquidity constraints, but is mostly lucrative.

There is ample evidence of front running.[23] The European Commission describes how:

> "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

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[23]Vaughan and Finch (2017), on page 114 quote Hayes explaining to another submitter by email: "If we know ahead of time we can position and scalp the market."

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publicly known/available information on the trading positions."[24]

Further findings of traders' strategies to adjust trading exposure on behalf of their banks with an eye to the cash-flows expected to be received are given in the Commission's prohibition decisions.[25] Without OTC data, which is proprietary to banks, it is not possible to examine the extent or magnitude of this trading position alignment.

A third characteristic of benchmark rate collusion is that the cartel may alternate days of collusive quoting with days of individual quoting. Regularly, the panel banks agreed not to coordinate behavior, when interests were too diverging. One example of a failed attempt to coordinate submissions is that of a Euribor submitter who was unable to accommodate another trader's request due to opposing interests.[26] In another, a Lloyds submitter explained to two new colleagues making the Yen Libor submissions that:

"We usually try and help each other out. .. but only if it suits .. .!"[27]

There was consensus that although coordination would not be possible in 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:

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[24]European Commission, *Case A.39914—Euro Interest Rate Derivatives*, settlement decision of 4 December 2013, recital 32.

[25]See the *EIRD* prohibition decision of 7 December 2016, at recitals 130 and 384 amongst others; and the *YIRD* prohibition decision of 4 February 2015, recital 89.

[26]A submitter who was asked to submit 3-month Euribor "at the ceiling" explained that he could not do so because: "long swaps need it low." Transcript of conversations on 28 March 2008 in U.S. Department of Justice, "Statement of Facts, Deferred Prosecution Agreement: Rabobank," 29 October 2013, page 37.

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

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."'[28]

Despite the cost of collusion, the potential for cartel profits is large. Currently, the class of eligible transactions is only a small subset of all trades benchmarked against the rate.[29] The volume of OTC derivates trades alone, which are not eligible, is a factor ten higher than all the other asset classes that make up the panel banks' total exposure positions to the benchmark rates combined.[30] Basing submissions on more actual trades would increase the cost of manipulation. A further reform considered is to discard more of the highest and lowest quotes.[31]

3 Related Literature

The emerging literature on benchmark rate manipulation 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

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[28]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.

[29]Libor quotes are to be supported by transactions in unsecured deposits, commercial paper, and certificates of deposit, where the submitting bank received funding from specified counterparties. ICE Benchmark Administration, "ICE LIBOR Evolution Report," 25 April 2018, pages 15-17. For Euribor, only transactions of unsecured cash deposits from specified counterparties traded in the wholesale unsecured money markets are eligible. European Money Markets Institute, "The Path Forward to Transaction-based Euribor," 21 June 2016, pages 4-6.

[30]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. Financial Stability Board, "Market Participants Group on Reference Rate Reform, Final report," March 2014, page 243.

[31]EMMI reform proposals 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. The Libors are still based on the average of the middle 50% of the quotes.

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 financial 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. 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 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,

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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 protocol changes to reduce the risk of manipulation collusion, 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. (2017) 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.

Our paper relates to the literature on collusion with heterogeneity in players and market conditions in repeated games. In benchmark rate setting, heterogeneity between banks stems from their time-varying interests, both in their exposure position and true borrowing costs, which is different from other types of heterogeneity that have been modeled in the cartel literature. As a result, some cartel members prefer a higher rate and others a lower one. When firms have different costs, capacity constraints or product varieties, they may prefer different levels of the cartel price increase, but never want a decrease.[32] Heterogeneity in discount factors affects firms' ability to collude on higher prices.[33]

As during booms in Rotemberg and Saloner (1986), extreme portfolio positions or true borrowing costs in our model may give one or more panel banks incentives to deviate. However, in our model there is no fallback strategy from which no cartel

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[32]Heterogeneity in costs is studied by, among others, Harrington (1991) and Rothschild (1999); in capacities in Davidson and Deneckere (1990) and Compte et al. (2002); and in product differentiation in Ross (1992) and Osterdal (2003). Although there may not be a common collusive price when the firms differ widely, Harrington (2016) establishes that a minimum price always exists.

[33]See Harrington (1989) and Obara and Zincenko (2017).

member has incentive to deviate, as competitive pricing is in Rotemberg and Saloner (1986). In their model, by getting sufficiently close to competitive pricing levels, continuous collusion can be assured.

We show stability of an equilibrium as in Fershtman and Pakes (2000), which is broadly consistent with the evidence of the panel temporarily reverting to independent quoting if agreeing on a collusive submission is not possible for the period.[34] Whenever at least one bank would have an incentive to deviate, there is episodic recourse to non-cooperative quoting. Such 'price wars' are short-run unprofitable, as in Green and Porter (1984), but they are an integral part of the collusive strategy and not punishment. In our model, 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).

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. As a result, when the number of banks in the panel is larger, it is harder for each individual bank to move the rate and, thus, less attractive to deviate, which makes the benchmark cartel easier to sustain. A similar mechanism also makes average bid auctions, where the winning bid is the one closest to a trimmed average bid, more susceptive to collusion, as found in Conley and Decarolis (2016). A benchmark cartel creates negative externalities for non-members, which induces the grand coalition, as in Yi (1995).[35] That is, the cartel is externally stable in the sense of D'Aspremont et al. (1983) only if all banks in the panel participate.

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[34] We are indebted to Joe Harrington for suggesting this equilibrium concept.

[35] We are indebted to Richard Gilbert for suggesting this property of a standard setting cartel.

4 A Model of Benchmark Rate Collusion

We develop a model for one Libor, as representative for the various benchmark rates that are set for different maturities on a daily basis. For the main model, we abstract from some of the details of the rate setting process, such as a heavier weighing of transactions closer to the submission deadline and the administrator's discretion to discard contributions, which are not essential to the analysis and straightforward to include in practical collusion.

In Section 4.1 we outline the per-period stage game and associated strategies under independent behavior, collusion, and deviation. In Section 4.2 a first-best continuous collusion strategy is formulated, as well as a more straightforward episodic break-up strategy for which the existence of a stable cartel is established. Several benchmark cartel properties follow in Section 4.3, which are relevant for assessing (potential) reforms.

4.1 Stage Game

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. Eligible transactions, which the reforms require, are not part of a bank's exposure to the benchmark rate. The true borrowing costs of bank i on the day are c_{0it}. 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 $(c_{11t}, ..., c_{1Nt})$. After the reforms, the panel banks need to show all their transactions in the eligible category and can only submit a rate that is on the whole consistent with this subset of its trades. Therefore, 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 will refer to choice variables Δc_{it} and Δv_{it} as 'eligible transactions rigging' and 'front running' respectively, which can be either positive or negative.

It is reasonable to assume that panel banks can always find counterparties for their intended trades in these vast and liquid markets. Front running takes place at the going prices, while for eligible transactions rigging a panel bank proposes terms that would be preferred by the unsuspecting outsider. If need be, members can carry out offsetting transactions within the cartel, either to generate free eligible transactions at the desired rate, or to bring portfolio exposure positions more in line—although the latter does not increase overall cartel profits.

The new interbank rate L_t is determined as the trimmed average of all N quotes.[36] 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,

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[36]Note that volume- and time-weights can straightforwardly be accommodated for in the composition and timing of the Δc_{it}'s. Similarly, the model can easily be modified to EMMI's proposed change that would calculate each bank's contribution to the Euribor individually, based only on all its raw eligible transactions data. See European Money Markets Institute, "The Path Forward to Transaction-based Euribor," 21 June 2016, pages 5 and 12.

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

Since the majority of financial contracts, such as swaps, futures, and corporate loans, have linear payouts to the rate, bank i's gains $(i = 1, ..., N)$ from changes in the rate from the current to the next trading day are

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

where $C \left(\Delta c_{it}, \Delta v_{it} \right)$ are any costs associated with bank-specific changes in exposure and rate, assumed strictly convex in both Δc_{it} and Δv_{it}.[37] Extreme adjustments are constrained by the risk of raising suspicion of manipulation increasing in the degree of front running and eligible transactions rigging, which carry their own specific costs.

Both v_{0it} and c_{0it} are assumed to be independent and identically distributed, each according to a symmetric and commonly known continuous distribution, with $E \left[v_{0it} \right] = 0$ and $E \left[c_{0it} \right] = L_{t-1}$. The zero mean assumption 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. $E \left[c_{0it} \right] = L_{t-1}$ reflects that Libor is a main signal to creditors, who would not know about any manipulation. The mean is assumed to be equal across panel banks, which are all global systemically important banks. Shocks to the panel banks' respective opportunity costs of funds are assumed to be non-persistent. Under these assumptions, the panel members' optimization problems are static, because only the difference to the current rate

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[37] This assumption 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. 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 $C''_{\Delta v_{it} \Delta v_{it}}(\cdot) \times C''_{\Delta c_{it} \Delta c_{it}}(\cdot) - C''_{\Delta v_{it} \Delta c_{it}}(\cdot)^2 > 0$.

matters, not its absolute level.

4.1.1 Independent Quoting

If panel banks formulate their contributions independently, as they are supposed to, 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 in 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 $t = 1, ..., \infty$.

However, following the banking code of conduct is not individually optimal. Instead, each bank is induced to independently engage in some amount of front running and eligible transactions rigging, maximizing own expected gains in the benchmark-setting:

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

This form of manipulation is unilateral, under the assumption that the other panel members may similarly manipulate. 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.

4.1.2 Collusive Quoting

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 $\mathcal{T}$. As a result, there is an incentive to coordinate behavior. If the panel colludes, it is

assumed that the baseline values (c_{0it}, v_{0it}) for all $i = 1, ..., N$ are shared. The cartel members jointly determine a joint-profit-maximizing new Libor, front running and eligible transactions rigging strategies. Each cartel member is instructed to submit a certain quote, with (if any) eligible transactions to carry out and what the front running strategy is that optimally exposes it to the future rate. [38]

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 rate. Suppose that at time 0_t, shortly into day t, all banks learn their private values c_{i0t} and v_{i0t}.[39] 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, and communicated to 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.[40] The window for front running remains open until publication of the rate at

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[38]Given the generality of cost functions $C_i(\Delta c_{it}, \Delta v_{it})$, in which the cost of eligible transactions rigging and front run can interact ($C''_{\Delta v_{it} \Delta c_{it}}(\cdot)$ is non-zero), all members need to be instructed about their optimal front running strategy. If these cost components are separable ($C''_{\Delta v_{it} \Delta c_{it}}(\cdot) = 0$, as assumed in Section 5), front running is individually rational and cartel members need to be told only which eligible transactions to do and how to quote. While each panel bank is expected to each period make a submission, the benchmark setting protocols do allow that a panel member bank may exceptionally not submit a quote. In theory, this provides the cartel with an option to instruct particular members to "not submit a quote" and, as such, avoid manipulation costs. However, there is no evidence that supports quote skipping as part of the collusive strategy. If it were, this would alter incentives to defect, as analyzed in Section 4.2.

[39]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 takes place around the clock worldwide and unforeseen events or market-moving news 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.

[40]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

11:55 a.m. (L_t), which then no longer is inside information to the cartel members.[41]

<div align="center">FIGURE 1 HERE</div>

Given the shared information v_{0it} and c_{0it} on all banks $i = 1, ..., N$, the joint-profit-maximizing 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.[42] 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.[43] Since objective function (4) is strictly convex, this optimum is unique. ∎

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 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. As a result, for this symmetric setup, no explicit side-payments are necessary. Note that the 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, as it minimizes the

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[43]See, for example, Brinkhuis and Tikhomirov (2005), pages 210-211.

cartel's total eligible transactions rigging costs. Which banks are included in the trimmed range $\mathcal{T}$ 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 all 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. All banks report their position and rate simultaneously, without knowledge of those of the other panel members. While each bank sees whether its own drawing(s) may be extreme values relative to the distribution, what matters for determining whether it is beneficial to misreport is the complete picture of positions and rates, which no member has before reporting. A motive for lying could be to try to avoid cost of collusion, by pretending to have relatively high borrowing costs, or to increase the probability of the cartel moving the rate in the direction favorable to the bank by overstating its exposure position. However, reporting other than its 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 have had with the truth. In order for the lies not to be discovered, the bank would have to subsequently behave according to the (costlier) cartel instructions.

4.1.3 Defection

Certain combinations of drawings of portfolio positions and rates lead to joint-profit maximizing cartel instructions that give one or more panel banks incentive to unilaterally deviate from the cartel agreement. 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 in two ways: by reducing the upward manipulation of L_t, foregoing the costs of its eligible transactions rigging, and from the lower resulting L_t that is more favorable to the defecting bank. Since the defecting bank knows that the rate will be different from what was agreed, it can front run lucratively for the period on all market participants, including also the other panel banks that are defected against.

To be able to deviate profitably, a bank i needs to be able to impact the rate sufficiently by deviating, which depends on its c_{0it} value relative to the rates of the other panel members. In addition, that bank's portfolio position v_{0it} needs to be sufficiently extreme for the deviant unilateral manipulation to be profitable beyond its costs.

On the basis of the shared information, each bank will consider whether and by how much it would be better off if it defected and maximized its own profits instead, given that all other cartel members do follow the cartel instructions. Note that no cartel member has an incentive to defect from the cartel prior to sharing

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the private information. Not only would it forego valuable information if it did and is $E\left[\pi^C\right] > E\left[\pi^{BN}\right]$, also can no bank know only on the basis of its own private information whether it is in an extreme position relative to all other cartel members that may incentivize it to defect after having received the cartel instructions. For this reason we can focus on defection from the rate setting cartel.

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. A bank not in the trimmed range $\mathcal{T}$ 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 rate is published, all the cartel members can immediately infer from it whether there has been defection from the collusive eligible transactions rigging strategies. Previously, when all the banks' submissions were published together with the rate, which bank had defected was instantly public as well. Note that, while it is not obviously observable 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.

4.2 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). 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 $T \to \infty$, stop sharing information and revert to independent quoting, so that $E \left[V^P \right] = \sum_{t=0}^{\infty} \delta^t E \left[\pi^{BN} \right]$. The grim trigger strategy is credible, since the Bayesian Nash punishment is a sub-game perfect equilibrium. However, the cartel would also

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.

4.2.1 Continuous Collusion

The optimal cartel strategy would be continuous collusion, as in Rotemberg and Saloner (1986), 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 an incentive to unilaterally manipulate and front run, using the information that has been exchanged. Thus, portfolio position-specific stable collusive actions need to be determined every day anew.

Finding common ground in the 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 submissions no longer needs to be in the same order as the baseline transaction rates, the proof of Proposition 1, which relies on the absence of cross-overs, thereby significantly reducing the strategy space, no longer holds. Also note that one cartel member incurring higher manipulation costs to allow another a 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 very high—it is equal to the necessary high number of small bins to the power $2N$, the dimensionality of the choice variables.[44] It would be prohibitively complex for the cartel to determine the continuous collusion strategy within the short time span.

4.2.2 Episodic Break-up

The evidence obtained in the various government investigations suggests that the panel banks exchanged information on a continuous basis, but occasionally decided not to coordinate the rates when interests were not aligned. This is consistent with the much simpler cartel strategy in Fershtman and Pakes (2000), in which as part of

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[44]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 $300^{2\times16}$, or approximately 10^{80} cases—which is of the same order of magnitude as the number of atoms that are in the universe.

ongoing collusion it is agreed episodically to break-up coordination. The benchmark cartel is feasible using this episodic break-up 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. In case at least one panel bank would deviate, all banks revert to non-cooperative contributions for that period. The cartel is continuous in that each period information is shared, but also breaks up episodically during 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. However, note 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 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 $E\left[\pi^C\right]$ on not. Since break-up occurs at extreme value positions that the panel bank(s) can exploit with their shared information, it may 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 $\rho = 0$ cannot 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, since the distribution from which the base-line values are drawn is continuous. ∎

For reasonable assumptions on the underlying stochastics, the cartel always exists to at least 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.[45]

4.2.3 The Collusive Coalition

Essentially, a panel bank benefits from participating in the benchmark cartel in two ways. It shares in the information on all other cartel members' strategies and the new rate prior to becoming public knowledge, which allows it to front run, which is strictly profitable. In addition, by submitting its own private information, it ensures that the cartel takes the bank's trading interest into account in formulating the collusive manipulation strategy. Thus, no panel bank in the know about the existence of benchmark collusion would not want to participate in the scheme.

Suppose that all N panel banks know that there exists a benchmark cartel that consists of a coalition of $M \leq N$ of the panel banks. Not participating in the partial benchmark cartel means not sharing in the information that all cartel members exchange. The (partial) cartel maximizes the joint-profits of its members. We call a coalition of panel banks colluding on the benchmark *internally* stable if no coalition member has an incentive to leave the coalition to act on its own. A coalition is *externally* stable if no individual panel bank outside the partial cartel has an incentive to join the coalition.

Maintaining perfect monitoring, we then have the following result.

Proposition 3 *Only a full-panel cartel is both internally and externally stable.*

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[45] As noted, alternatively the cartel may instruct banks with an incentive to deviate from the joint-profit maximizing strategy to skip a quote and so forego the manipulation costs. If the instruction "do not submit a quote" is part of the cartel strategy space, the cartel may be able to come closer to first-best than in episodic break-up equilibrium. However, it would require a complete recalculation of the cartel strategy, which may induce other panel members to defect, the accommodation of whom can in turn involve the original member again. Each member bank would then need to consider a probability ρ that it would not submit on each given day, associated with a different cartel profit than for the other panel members. Computing the equilibrium actions remains prohibitively complex. The strategy option also introduces a form of side-payments by cartel cost reallocation.

Proof. Let $E\left[\pi^{CM}\right]$ be the expected profit of each member of an M-member cartel. A panel member that is not in the collusive coalition has no specific information about true rates and positions—yet it would not trade with any of the members of the partial benchmark cartel, which it knows are more informed sellers by inside information. The outsider therefore obtains $E\left[\pi^{BN}\right]$. For each member of the cartel the per-period profits from colluding satisfy:

$$E\left[\pi^{C1}\right] < \ldots < E\left[\pi^{CM}\right] < \ldots < E\left[\pi^{C(N-1)}\right] < E\left[\pi^{CN}\right],$$

since the more members the cartel has, the larger the expected per-period profits because the cartel's influence on the rate and its accuracy of predicting it—and thereby its ability to front run—increases in the number of members. Since by definition

$$E\left[\pi^{BN}\right] = E\left[\pi^{C1}\right],$$

expected profits of continued collusion are strictly higher than those of acting independently. Similarly, because it improves banks' accuracy in predicting the rate, the per-period expected profits of playing Nash with only the information of a subset of banks are strictly larger than the Bayesian Nash profits. That is:

$$E\left[\pi^{BN}\right] = E\left[\pi^{N1}\right] < \ldots < E\left[\pi^{NM}\right] < \ldots < E\left[\pi^{N(N-1)}\right] < E\left[\pi^{NN}\right],$$

where the first superscript N refers to 'Nash'.

Therefore, for any break-up probability $0 \leq \rho \leq 1$ and any $M \geq 2$

$$E\left[\pi^{BN}\right] < (1-\rho)E\left[\pi^{CM}\right] + \rho E\left[\pi^{NM}\right],$$

where $E\left[\pi^{CM}\right]$ is conditional on there being no break-up and $E\left[\pi^{NM}\right]$ on there being a break-up.

From this, it follows that any cartel with more than one member is *internally stable*: The expected sum of discounted profits of being in an M-member cartel is larger than the expected sum of discounted profits of being outside an $(M-1)$-member cartel for every bank i. Similarly, no cartel with less than $M = N$ members is *externally stable*: The expected sum of discounted profits of being inside an $(M+1)$-cartel is strictly larger than the expected sum of discounted profits of being outside an M-member cartel for every bank i and for all $M < N$. ∎

Ex ante no cartel member has an incentive to unilaterally leave the cartel, because it would lose both its interests being taken into account by the (remaining) cartel and inside information on the future rate needed to front run. Further, unless all panel banks are part of the cartel, there would always be an outsider willing to join. If there is collusive manipulation of the benchmark rates and all panel banks know it, the grand coalition can be expected to be involved.

It is not necessarily so that a cartel of N members also yields the highest expected cartel profits among all possible cartel sizes. While the expected per-period profit of colluding—conditional on there not being a break-up—is larger for larger cartel sizes, the effect of cartel size on the break-up probability ρ is ambiguous. How overall expected profits of the cartel are affected by its number of member M depends therefore on a trade-off. In a smaller cartel, on the one hand, the interests of a member with a sizeable exposure position get a relatively higher weight in determining the cartel strategy, so that a larger member is more likely to benefit from the cartel strategy. On the other hand, collusive profits are likely to be lower with less information about the future rate.

Note that for a partial cartel monitoring of adherence to a partial-panel cartel from the published rate only is no longer straightforward, since it also depends on the submissions of the independent panel banks. Only if enough banks are part of the cartel is deviation somewhat constrained by the risk that because of it, the resulting rate will be outside of the range that it should have been in if all cartel member obeyed.[46] However, defection will still become apparent with the publication of individual submissions.

4.3   Benchmark Cartel Properties

A closed-form, analytical solution of the episodic break-up equilibrium using the primitives of the stage game cannot be formulated. This is because the profits do not have a closed-form solution, since they are functions of the (ordered) distribution of all baseline values. This section discusses properties specific to benchmark collusion.

One way to consider the original protocols is as having very low eligible transactions rigging costs. How this affects the cartel equilibrium depends on specifics of the case: in general both the costs of collusion and of defection decrease, so that the net effect on cartel steadiness (ρ) is ambiguous. If defection profits increase, it causes the cartel to break up constantly, to the point of being merely an exchange of information to play Nash rather than Bayesian Nash.

The introduction of transaction-based submissions increased manipulation costs, which on the one hand make defection less attractive, so that higher extreme value positions can be sustained without the cartel having to break up. On the other

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[46]It is possible to tell defection from the published rate only if there are at most $\frac{N-\mathcal{T}}{2}$ panel members outside of the collusive coalition, so that a maximum possible rate—when all outsiders quote above the highest cartel submission—and a minimum possible rate—when all outsiders quote below the lowest cartel submission—can be established. With that many outsiders, the resulting rate without deviation will at least (at most) be an average of some of the lower (upper) quotes of the collusive coalition. A lower (higher) published rate would mean that at least one bank deviated.

hand, higher manipulation costs also reduce cartel profits, thus making collusion less attractive. Yet even if break-ups occur less often, the cartel would be manipulating the rates less extremely when manipulation costs are higher. Therefore, while likely reducing the extent of manipulation, broadening the class of eligible transactions can have increased the frequency of collusive quoting.

Further reforms to decrease 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 also 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 collusion, if it were feasible.

Under the assumptions made, the benchmark rate time-series would fluctuate around a fixed mean, since the probabilities of higher and lower drawings are equal. The theory does predict that the variance under collusion is larger than under independent quoting. The 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.

No specific patterns in the volume of eligible transactions are predicted. The requirement is that banks submit their entire log of trades completed during the 24 hours since the previous submission deadline in the category of eligible transactions. A bank's submitted rate is to match the transaction weighted average of the rates against which it made its eligible trades. While a bank wants to minimize the costly eligible transactions that are completed against the intended future rate, not the current rate, the eligible transactions category also contains regular trades that may be carried out at going prices. The more of the latter, the more costly manipulated trades the bank would need to place against them in order to maintain the average rate it is instructed to submit. Thus, the effect of manipulation on eligible transactions trade volume depends crucially on the (unknown) normal trade pattern, which may also have spikes and variation in volume during the day, month, and year.

In front running, the theory does predict a clear pattern. Periods of collusion would 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 published 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 larger trading volumes or lower front-running costs. To be effective, however, a correlation screen requires a complete picture or

unbiased sample of all bank transactions in the window.

5 Collusive Rate Patterns

To illustrate our benchmark collusion theory 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 $L_0 = 1$.[47]

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 100000 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

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[47]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}.

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.[48] Portfolio exposure adjustment is more than 20 times higher under the cartel. 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.

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.[49]

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[48]$E[\pi^{BN}] \approx 0.000024$, $\sigma_{BN} \approx 0.00274$; $E[\pi^C] \approx 0.000898$, $\sigma_C \approx 0.00679$; $E[\pi^N] \approx 0.000218$, $\sigma_N \approx 0.00283$. Note that the payoff increase from collusion is only less than three percent smaller from Bayesian Nash than honest quoting—which is zero.

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

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 reduces 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 when eligible transactions rigging is punitively costly (α very high), the banks collude only to exchange information and front run individually. The published benchmark rate is unaffected. There is no incentive to deviate in that case, so that the cartel never breaks up. In the other extreme case, when the cost of quote submission are very low, the cartel breaks up almost all of the time but continues to exchange information for individual front running purposes (ρ approaches one when α goes to zero).

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 then 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.[50]

<center>FIGURE 6 HERE</center>

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.

The intraday variance patterns (or quote dispersion) in the banks' submissions are not statistically different between the regimes, either for the full panel or the banks that determine the rate.[51] 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 that quote their true rate.[52] 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 it is more likely that a decreased intraday variance is found.

The interday variance (or volatility) of the interbank rate over a certain time window does result in distinct differences in some of the runs. Figure 7 shows the

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

[51]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.

[52]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.

<center>41</center>

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 optimal Bayesian Nash apart 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.[53] Note that the underlying cause of the volatility is eligible transactions rigging, not the occasional break-up in and of itself—as volatility is larger when no break-up occurs.

FIGURE 7 HERE

Further, the average absolute change in the interbank rate is significantly different between the break-up and full collusion regimes.[54] Moreover, within the collusion period it is significantly higher in no break-up than during break-up.[55] These markers are robust against changes in the length of the rolling window. Nevertheless, while increase volatility is in line with our theory, in a substantial number 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

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[53]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.

[54]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.

[55]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.

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.[56] On the 5-day volatility in Figure 7, 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.[57]

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

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[56]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).

[57]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 $E\left[c_{0it}\right] = L_{t-1}$. Upward (downwards) manipulation is followed by a higher (lower) baseline value draw in the next period, which combines with the collusive variance. If we used 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. However, this would require dynamic optimization.

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, the exact moment of information exchange (C_t)—that is, the opening of the front-running window—will not be known outside the cartel. Furthermore, other transactions that classify as eligible can 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 needed 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 currently not publicly available.

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.

Finally note that screening for increased intraday variance patterns may deter manipulation if panel banks are aware of this, also when imperfect. 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 lose 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 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. Although 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 desks or traders cartel maximizing joint profits on their liquid trading books only, and not their employer banks' overall exposures.

We assume that panel banks' opportunity costs of funds fluctuate around a common 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 it additionally 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 exten-

sions 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 in which banks are supposed to pay the eligible transactions rigging costs, for which there is some evidence.[58] Break-up periods may be longer if it takes time to get trading books incentives aligned again and find a stable cartel strategy. Thus, while the literature extends Rotemberg and Saloner (1986), dynamic collusive benchmark rates fixing is left for future research.

The daily rates can alternatively be assumed drawn from an unmanipulated mean, in particular a daily rate that follows from honest reporting only. If manipulation was indeed widespread and commonly known, possibly the initiated financial institutions accounted as well for an actual borrowing standard that would have followed from honest reporting only–like 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 been contaminated by the Libor manipulations. If such a shadow Libor existed and were the mean of the distribution of banks' true borrowing costs, panel members' manipulation today would affect their ability to profitably manipulate tomorrow, which also would introduce dynamic optimization.

We model manipulation costs equally 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

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[58]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."

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.

No side-payments are necessary for maintaining collusion, since, due to the symmetry of the model, all cartel members have the same positive expected profits from participating. Explicit transactions between the panel banks or more sophisticated forms of side-payments, 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, can further facilitate collusive manipulation by internal alignment of interests. Note however that they do not increase cartel profits, since the panel's overall net portfolio position generally revolves around zero—while incurring transaction costs. Wash trades or doing offsetting eligible transactions between cartel members can reduce manipulation costs, the effect of which on cartel stability is ambiguous. These, as well as skipping a quote, may be made part of a more sophisticated cartel strategy that comes closer to continuous collusion by periodically alleviating members with strong defection incentives.

7 Concluding Remarks

Our cartel theory shows that it is possible to operate a benchmark rates cartel, despite interests typically not being aligned—and without a need for side-payments. We tailor our model to Euribor and Libor and model two mechanisms that reinforce each other in facilitating benchmark collusion: front running and eligible transactions rigging—or, pre-reform, simple misreporting of borrowing costs. By creating inside information, panel banks are in a position to take a more favorable exposure position to the upcoming rate, while reducing conflicting interests in their trading books. Some cartel banks need to engage in eligible transactions rigging, placing transactions at rates required to allow the cartel to justify the collusively optimal quotes.[59] Even though the cost of this may exceed the member's cartel gains in those periods, average expected collusion payoff is much higher than under independent quoting. Consistent with the evidence found, the benchmark collusion 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 provide incentives to deviate. It paints a picture of panel banks that, in multi-market contacts over a variety of financial products linked to different maturities and currencies, sometimes meet short-term inside liquidity demands at a small loss, in order to maintain longer-term banking relationships and to benefit from larger outside business gains.

We find that all panel banks in the know about the cartel would want to be part of it. The coordinated manipulation cases so far investigated suggest rather that

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[59]Also after transition to the Secured Overnight Funding Rate (SOFR), which is based on a larger volume of transactions but otherwise comparable to the Libor and Euribor, the system remains vulnerable to coordinated manipulation. 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.

one or several smaller subsets of traders may have colluded, possibly unbeknownst to part of the panel—in which case these outsiders may also have been victims of the collusion. However, to form subcoalitions, a wider exchange of private information within the panel would be necessary to establish where are the common interests. Also, monitoring adherence to agreements within smaller groups would be difficult. In any event, among those knowing, coordination would be full in the sense of our theory.

Alternatively, after the full-panel cartel shared information, collusion in (rotating) subcoalitions could be part of the continuous collusion strategy. This would allow the cartel to avoid manipulation costs and break-ups, as banks with an unfavorable position that would otherwise have incentives to defect, could skip a period of cartel participation. Such extensions of the cartel strategy space, however, introduce incentives to falsely report and freeride on a partial cartel that we leave for further study.

While sharing all private information allows determining collusive strategies and playing Nash during break-ups, it also has the unattractive feature that it facilitates defection. To avoid this, the colluding banks could employ an independent administrator who collects the information, runs the cartel software, and only then provides personal instructions on quotes to be submitted and front-running. Organizing the cartel this way would reduce the incentives to deviate—break-up profits would be Bayesian Nash instead of Nash. However, there is no hard evidence that such an administrator existed.[60]

The collusion leaves no obvious traces in neither benchmark patterns over time,

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[60]A broker from ICAP was nicknamed 'Lord Libor' for sending a daily email with Libor predictions at 7 a.m. GMT to more than a hundred traders and brokers, including representatives of almost all of the Libor panel banks. See Vaughan and Finch (2017), page 29. However, the EU General Court partly annulled the Commission's decision that implicated ICAP in the *EIRD* case.

nor in intraday variance in the quotes. It does markedly increase the volatility in quotes between trading days—as opposed to price variance decreases that are commonly found in regular cartels. On this basis, we propose volatility screens to monitor submissions for periods of collusive manipulation. To the extent that sufficient transactions data is available, these could be supplemented with tests for suspiciously strong positive correlations between rate and portfolio changes.

The primary victims of the collusion are the counterparties on whom the cartel members rolled off their unwanted portfolio positions, including central banks, non-panel banks, institutional investors, pension funds, non-bank corporations and branches of the government.[61] While this may largely have been rent shifting, the manipulations may also have induced different borrowing behavior, impacting the efficient allocation of resources in countless underlying markets. Moreover, the manipulation scandals affected the benchmarks' trustworthiness as foundations of value and signals of underlying risks. This will likely have had consequences for financial market stability.[62]

In the assessment of antitrust damages, a key question is whether the counterfactual quotes should be the true rates or individual expected profit-maximizing Bayesian Nash quotes. A benchmark cartel could claim to its defense that any antitrust damage would have to be assessed incremental to the already independently distorted rates, which would be lower than the damage relative to honest quoting.

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. A small number of banks

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[61]See European Commission, *Case A.39914—Euro Interest Rate Derivatives*, prohibition decision of 7 December 2016, recital 130.

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

account for the bulk of transactions on the platform that are used to calculate the rates. '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.

A key difference in forex is that the same set of transactions to manipulate the rate, is also part of a bank's exposure position. Evans (2018) models competitive forex trading around the fix and suggests that the anomalies found in the data could be explained by collusion. Other possible applications include front running 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. Duffie and Stein (2015) and Duffie et al. (2018) show that widening the set of eligible transactions reduces the scope for individual manipulation. However, with respect to collusion, we find that it has an ambiguous effect. On the one hand, widening the set of eligible transactions increases manipulation costs, thereby lowering collusive profits. On the other hand, it also reduces defection gains which has a positive 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.

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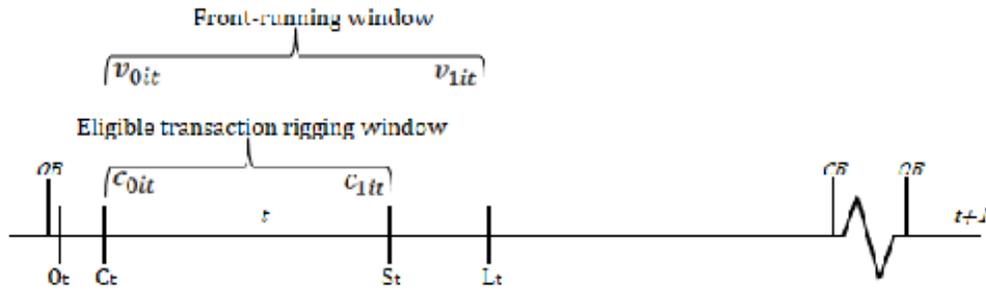
Figure 1: A trading day in the life of Libor.
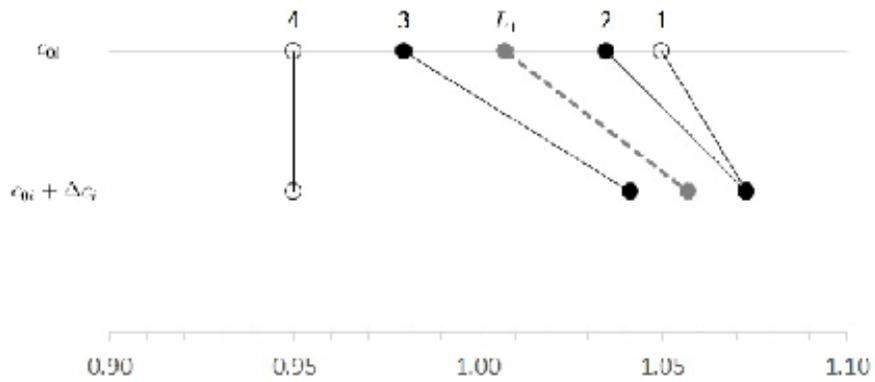
Figure 2: Panel bank 1, not in $\mathcal{T}$, engaging in collusive eligible transactions rigging.
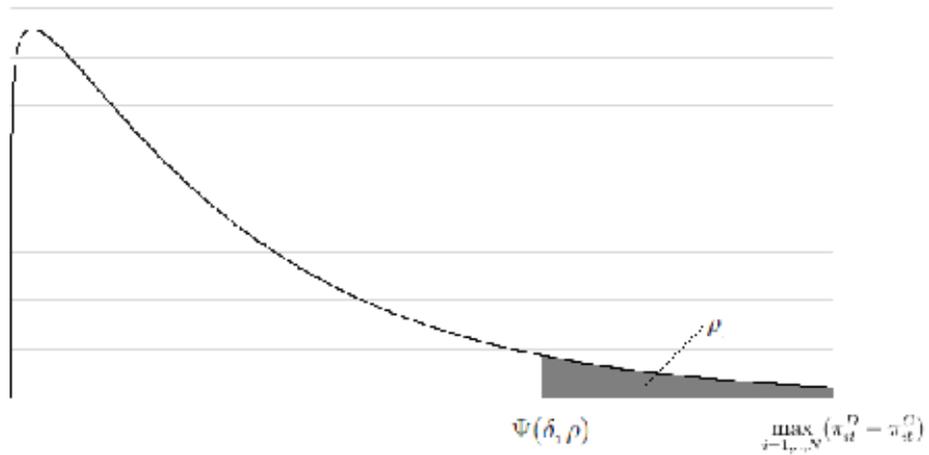
Figure 3: Cartel break-up probability defined by the payoff-differential distribution.
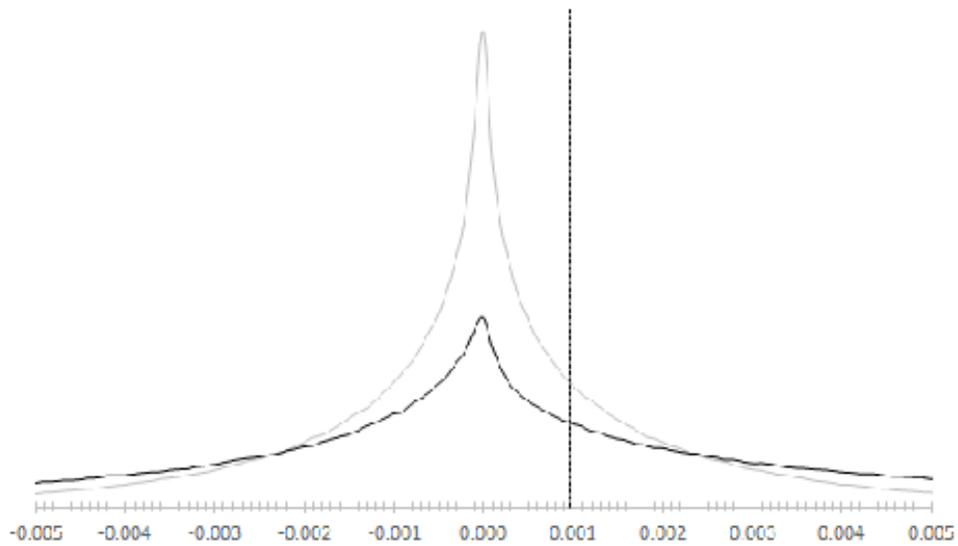
Figure 4: Frequency payoffs for Monte Carlo simulation independent quoting (grey, $E[\pi^{BN}] \approx 0.000024$) and collusive quoting (black, $E[\pi^{C}] \approx 0.000898$).
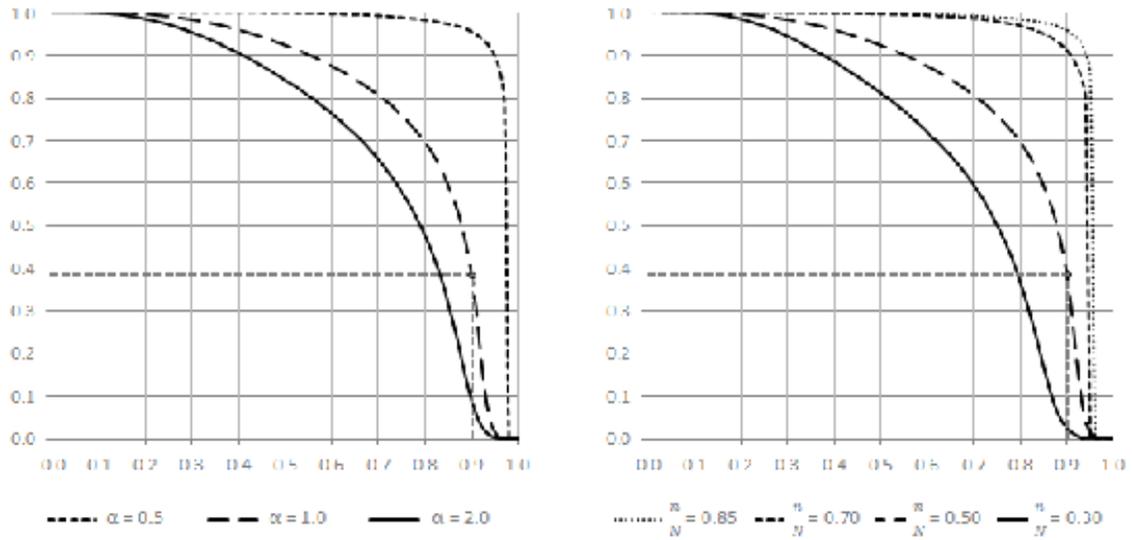
Figure 5: Cartel break-up probability ρ as a function of discount rate δ for different α's (left-panel) and $\mathcal{T}$'s (right-panel).
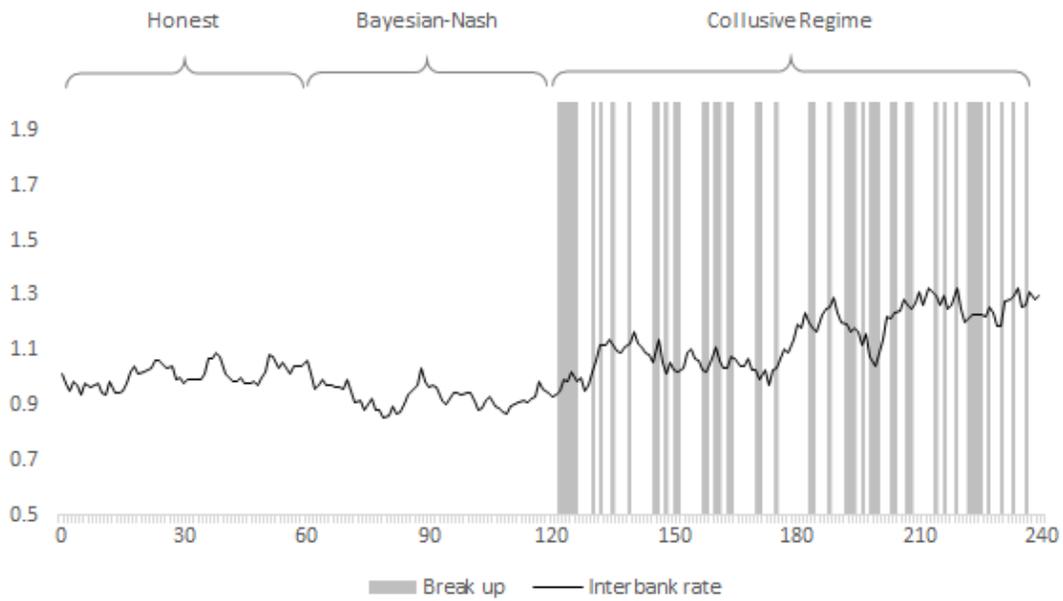
Figure 6: Simulated benchmark rate under honest and Bayesian Nash independent quoting and collusion.
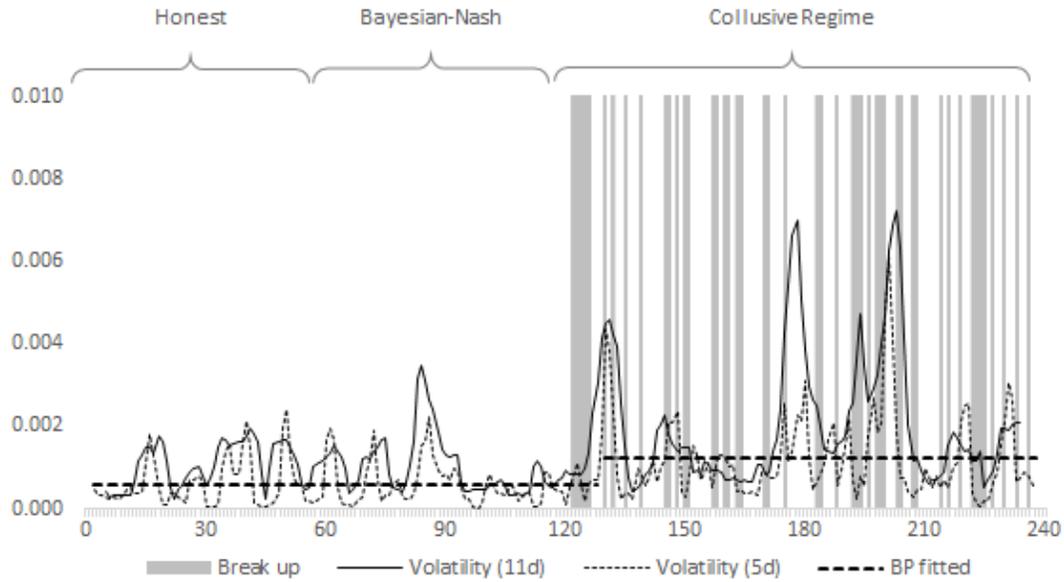
Figure 7: Volatility in quotes, 11-day and 5-day rolling window, including 5-day
Bai-Perron structural break test results.
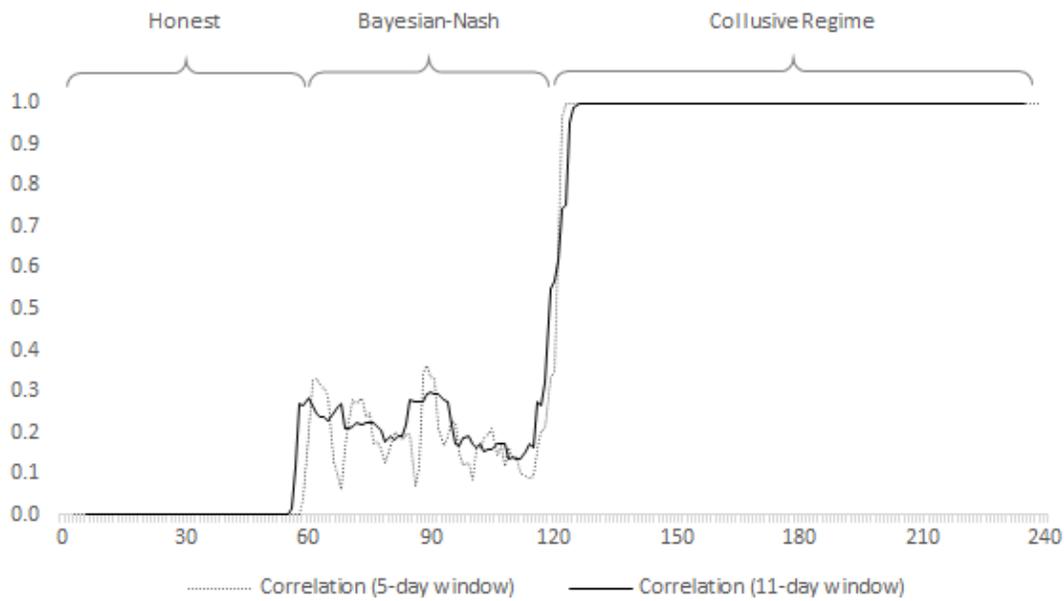
Figure 8: Correlation between changes in the interbank rate and in portfolio
positions, 5-day and 11-day rolling window.

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);
```

```matlab
PCol = fpayoff(V0,C0,N,n,L0,a,b,CStrategy);

% Deviation payoffs
PDev = zeros(N,1);
for i = 1:N
 Cj = CStrategy; DCj(:,i)=[]; C0j = C0; C0j(:,i)=[];
 fOwnProfit = @(DD)-((V0(1,i)+DD(2,i))*(trimmean(horzcat(C0(1,i)+...
   DD(1,i),C0j+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 (100000 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$^{\circledR}$ 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 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.
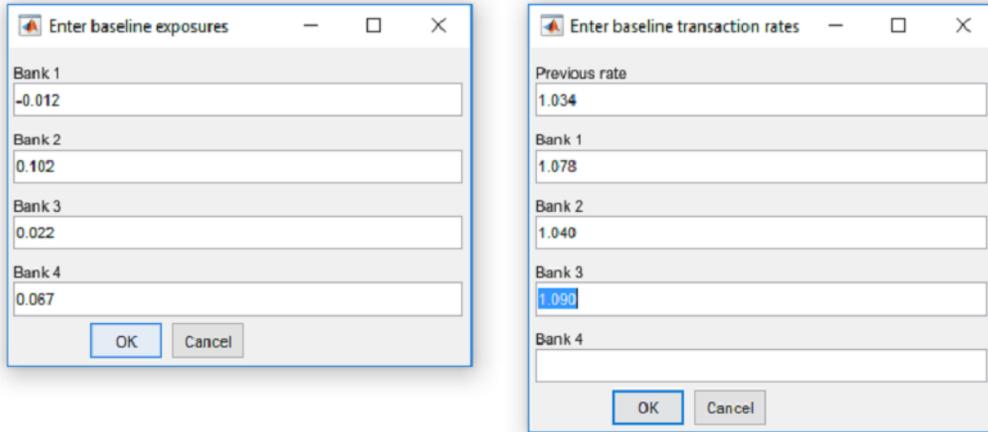

Figure A1: Baseline exposure and eligible transaction rate prompts (for $N = 4$).

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.
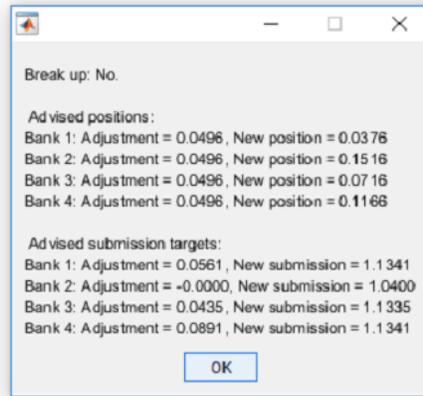

Figure A2: Exchange of information and cartel instructions (for $N = 4$).

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.