Collateral Choice*

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Abstract

I provide the first systematic analysis of *collateral choices* in one of the main short-term funding markets, the repurchase agreement (repo) market. Repos establish a natural connection between short-term and long-term funding markets as long-term bonds serve as collateral in short-term funding trades. In general collateral repos, the borrower can choose which bond he posts as collateral out of a predefined list. In the aggregate, on-the-run bonds are more likely to be delivered than cheapest-to-post securities, which is surprising given that the former are more expensive. I rationalize those findings in a theoretical framework that links the repo to the bond market. My results are relevant for explaining different bond market patterns.

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Funding markets are crucial for the efficient allocation of money and financial securities as well as for preserving financial stability. Short-term funding markets provide financing for financial institutions and can be used to obtain securities, while long-term funding markets allow governments and firms to finance long-term investments and manage debt sustainably. The two markets are connected by a secured, short-term funding instrument, the repurchase agreement (repo), which is a short-term loan between banks collateralized by long-term assets such as government bonds. Since the Global Financial Crisis, activity has moved towards the secured market, the repo is now the major short-term funding source. From an intermediation perspective, banks operate as maker makers for long-term bonds while they use short-term funding trades to manage and finance their portfolio. I exploit this linking in my paper. More precisely, I study the use of government bonds as collateral in short-term funding trades to improve our understanding of the *interconnection* between short-term and long-term funding markets and to see whether *frictions* in short-term funding markets impact long-term bond market dynamics.

The repo is the main money market instrument, understanding its dynamics is important for several reasons. First, repo rates are the key benchmark for the implementation of monetary policy. Second, the allocation of liquidity is central to the financial system and frictions in it can have spillover effects impacting financial stability.[1]. And third, money market rates are often used as a reference for real-sector lending rates such as mortgages or derivatives. The asset being used as collateral in a repo can be a particular government bond ("special repo") or any bond from a predefined basket ("general collateral" or "GC repo").[2] Surprisingly little is known about borrowers' collateral choices in the GC segment. This is different from other markets such as futures, where the "cheapest-to-deliver" concept was developed. In this paper, I study those collateral choices.

I first focus on the European market which provides the ideal laboratory to analyze collateral choices. It is a centrally cleared market that eliminates concerns such as counterparty risk, bargaining power, and banking relationships which exist in bilateral, over-the-counter

[1]See, for example, Brunnermeier and Pedersen (2009) and Gorton and Metrick (2012).

[2]A special repo is also referred to as a "specific" repo in the United States.

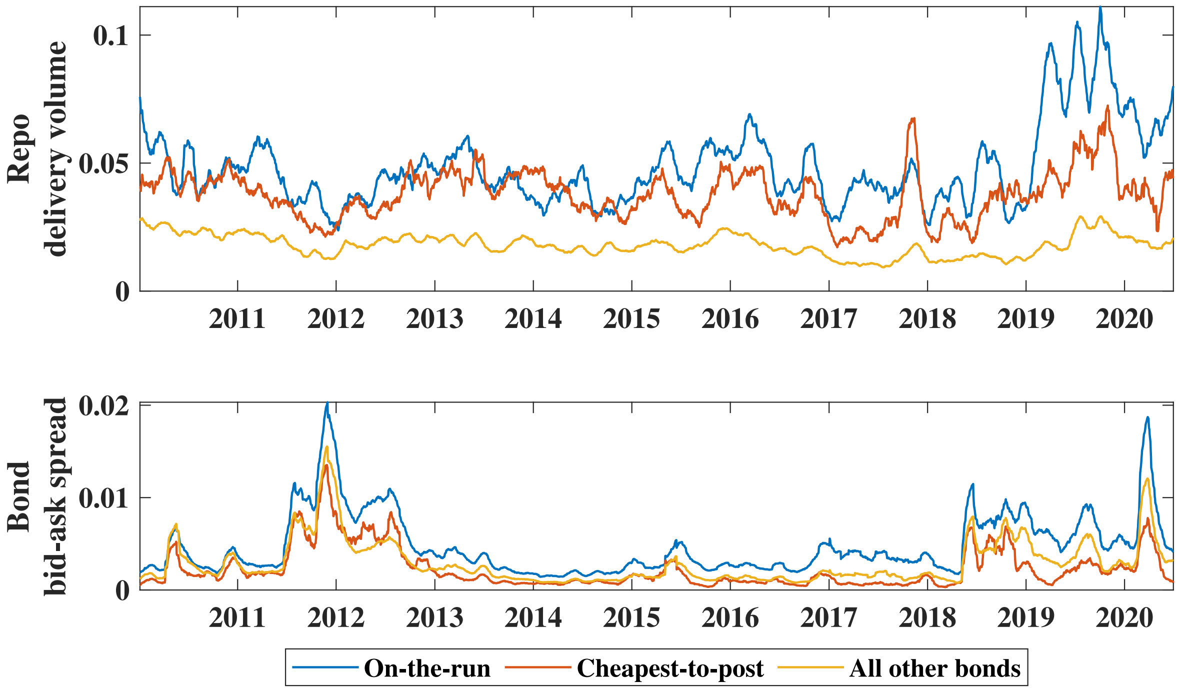


Figure 1 depicts (i) the daily delivery volume of a bond into GC repos relative to its outstanding volume, and (ii) the relative bid-ask spread. The results are depicted for OTR bonds (blue), CTP securities (orange), and all other bonds (yellow).

Figure 1: Repo delivery volumes and bond bid-ask spread

(OTC) markets. Figure 1 depicts repo delivery volumes and bond market bid-ask spreads for (i) the most recently issued, "on-the-run" (OTR) government bond (blue line), (ii) the "cheapest-to-post" (CTP) bond (orange line), and (iii) an average across all other bonds (yellow line). OTR bonds are more likely to be chosen as collateral than CTP bonds, which is surprising since posting OTR bonds is more costly (e.g., Krishnamurthy, 2002). In fact, ex ante, the expectation is that bonds less valuable than the OTR bond are parked in GC trades since the borrower could refinance himself at a significantly lower rate in the special segment using the OTR bond (Duffie, 1996). This points towards frictions such as search cost in short-term funding trades which prevent the intermediary from accessing special trades entirely so that he also needs to rely on general collateral refinancing. This creates cost for which the intermediary wants to get compensated. He does so by charging transaction cost in the bond market, which are a common measure of bond market liquidity.

Studying collateral choices in detail, I find that banks' willingness to post bonds as collateral in GC trades depends on collateral availability (quantity) and opportunity cost (price). Collateral availability relates to variations in the net supply of collateral assets and asset scarcity. I find that the intensity of bond deliveries declines in the auction cycle and is smaller for bonds targeted by quantitative easing (QE).

Collateral opportunity cost is the second driver of collateral choice. The cheapest-to-post idea is a new concept developed in this paper. I identify the CTP bond, which is the bond with the highest special repo rate of all bonds that are eligible to be posted as collateral. Conceptually, the CTP bond minimizes the borrowers' opportunity cost. Consistent with this, I find that the GC delivery volume of a bond is highest for low levels in the opportunity cost and decreases as it gets more expensive to post a security. This is consistent with the idea that borrowers take more effort to post a bond into a special trade at a lower rate if the benefit of doing so is higher.

Looking at the joint effect, I find that OTR bonds (with the highest availability) are more likely to be posted than CTP bonds (with the lowest opportunity cost). For example, when bonds with high opportunity cost are delivered, those are likely to be OTR securities. The opportunity costs for OTR bonds are economically meaningful as they go up to 50bps. In line with Keane (1996), I show that OTR bonds become increasingly special until the next auction. Repo deliveries reverse this pattern. Inspired by the safe asset literature, I also consider the level of short-term rates. Nagel (2016) theorizes that the convenience benefits of assets are more valuable in a high interest rate environment. Consistent with this idea, I find that the delivery volume of OTR bonds is lower in a high interest rate environment when the superior liquidity services of OTR bonds are more valuable.

I then extend my analysis to the U.S. Treasury market, which confirms that the economic intuition derived from the euro area also applies to the U.S. setting. The borrower in a repo trade always has the option of posting the OTR bond into a GC *or* special trade. If the borrower posts the OTR bond into a GC trade at a higher rate instead of benefiting from the lower special rate, then this can be considered a measure of frictions and market inefficiencies. I show that the share of OTR bonds posted into GC versus special trades depends on the opportunity cost. In the U.S. market, borrowers rely more heavily on special trades, which points towards the idea that frictions are less pronounced.

I introduce a theoretical framework that explains the use of OTR bonds in GC repos and relates it to the bond market for the collateral.[3] My framework is based on Stoll (1978) and considers an inventory model with a dealer who is a market maker for government bonds. The dealer holds OTR bonds in excess in his inventory to distribute them to investors over time. In the meantime, he uses repos to finance his portfolio. The dealer can access the GC and special segments; however, the use of special repos is limited due to cost related to search and settlement frictions. By holding the inventory and having to finance it, the dealer faces financing and opportunity cost for which he requires compensation. The dealer's resulting cost function predicts that the bid-ask spread charged to his clients in the bond market increases with the size of the dealer's portfolio of OTR bonds and with the OTR opportunity cost. In line with the theoretical predictions, I show that *tomorrow's* bid-ask spread tends to be higher when *today's* GC delivery volumes and *today's* collateral opportunity cost are higher.

My results are important for understanding the systematically important role of *financial intermediaries.* Market makers provide a service to governments by subscribing to government bond auctions, as they ensure demand and thus price certainty. Market makers are also important to clients, as they are fulfilling an important financial intermediation role. My results also have (intermediary) *asset pricing* implications. Transaction costs in the bond market are time-varying; I show that collateral choices in the repo market are one reason for this. At first, it seems surprising that OTR bonds can have higher bond market spreads in spite of higher trading volumes. At the same time, the proposed mechanism is intuitive. Market makers need to hold OTR inventories, which is costly, in particular, when frictions prevent dealers from accessing the special segment and benefiting from lower refinancing rates. My results suggest that stronger frictions could translate into different bond pricing patterns. A prominent pattern, the on-the-run / off-the-run phenomenon, materializes in

[3]Related studies include, for example, Krishnamurthy (2002), Huh and Infante (2021), and Bartolini et al. (2011).

different forms when funding choices are different, which provides an explanation for the lack of the OTR premium in the euro area. Lastly, my results are important for *monetary policy*, as they suggest frictions in the money market, which is important given the repo market's key role in the monetary policy transmission (Ballensiefen et al., 2022).

My analysis mainly contributes to two strands of the literature. First, I contribute to the literature on short-term funding markets and the choice of the collateral asset. Our understanding of which and why safe assets are pledged as collateral in short-term funding markets if the borrower is presented with a choice is very limited. I complement the existing literature by analyzing borrowers' collateral choices and determine what characteristics make bonds more likely to be used as collateral.[4]

Second, I contribute to the literature focusing on the linkage between short-term and long-term funding markets.[5] I provide an extension of the theoretical framework in Stoll (1978) to incorporate a dealer's funding decision and explain how this relates to the market liquidity for the collateral. Related to my study is the literature on auction cycles.[6]

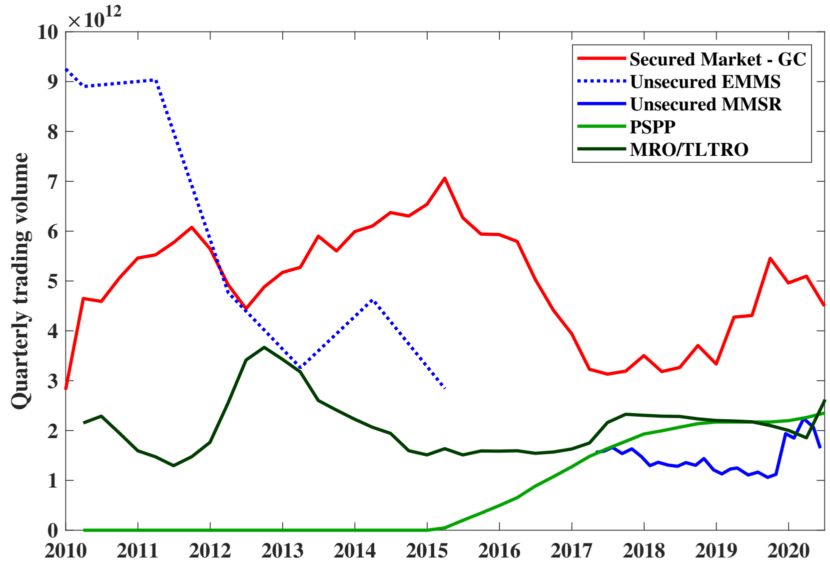
1. Setting

I start by explaining the main characteristics of the repo market and my data.

[4]Literature on the GC repo segment includes, for example, Longstaff (2004), Bartolini et al. (2011), Mancini, Ranaldo, and Wrampelmeyer (2016), and Boissel et al. (2017). Papers focusing more on special repos, for instance, include Duffie (1996), Jordan and Jordan (1997), Buraschi and Menini (2002), Krishnamurthy (2002), D'Amico, Fan, and Kitsul (2018), Arrata, Nguyen, Rahmouni-Rousseau, and Vari (2020), Infante (2020), Corradin and Maddaloni (2020), and Ranaldo, Schaffner, and Vasios (2021). Song and Zhu (2019) analyze a different notion of collateral choice by focusing on the "to-be-announced" market for mortgage-backed securities.

[5]Seminal work linking the bond and repo market includes Duffie (1996), Krishnamurthy (2002), and Vayanos and Weill (2008). More recent studies include, for example, Fontaine and Garcia (2012), Chen et al. (2019), Huh and Infante (2021), and D'Amico and Pancost (2022). Brunnermeier and Pedersen (2009) model the reinforcement of market and funding liquidity. Related literature focuses on the impact of dealers' funding cost on asset prices, for example, He and Krishnamurthy (2013), Rytchkov (2014), Adrian, Boyarchenko, and Shachar (2017), and He, Kelly, and Manela (2017), and asset liquidity, for example, Comerton-Forde et al. (2010), Andersen, Duffie, and Song (2019), and Goldstein and Hotchkiss (2020).

[6]Work focusing on the repo market goes back to Keane (1996) and includes, for example, Lou et al. (2013), D'Amico et al. (2018), and Sigaux (2018). Related literature on the impact of asset supply on the bond market includes, for example, Brandt and Kavajecz (2004), Pasquariello and Vega (2009), Krishnamurthy and Vissing-Jorgensen (2012), D'Amico and King (2013), Krishnamurthy and Vissing-Jorgensen (2015), Beetsma et al. (2016), Beetsma et al. (2018), and Eisl et al. (2019). Other papers, such as Klingler and Sundaresan (2020), look at auction results from a demand perspective.



The figure depicts the quarterly trading volumes in the secured and unsecured market segments as well as the total cumulative Public Sector Purchase Program (PSPP) purchases and volumes of the European Central Bank's (ECB) main refinancing operations (MRO) and targeted longer-term refinancing operations (TLTRO). The data for the secured market refer to the total general collateral repo trading volume. The data for the unsecured market stem from the Euro Money Market Survey (EMMS) until 2015 and from the Money Market Statistical Reporting (MMSR) thereafter. To be conservative, I sum reported borrowing and lending activity in the unsecured market, which may entail double-counting. The data on PSPP purchases and refinancing operations are from the ECB. All data are in euro.

Figure 2: Different market turnovers

1.1 Repo market infrastructure

In a repo contract, two counterparts exchange cash for collateral (first leg) for a predefined period with a fixed repurchase obligation (second leg). Repos are a form of short-term borrowing, as collateral is typically sold on an overnight basis. The motive for entering into a repo trade can either be to obtain funding or collateral. The repo market, therefore, serves a dual role: it represents the main market for banks to obtain short-term funding and rebalance their portfolios. While a large body of literature has analyzed the special segment with seminal work going back to Duffie (1996), I investigate which bond the borrower chooses to post as collateral if presented with a choice in GC repos.

I start my analysis by studying the European repo market, which is the largest repo market in the world (ICMA, 2021). Figure 2 depicts trading volumes in the two main euro area money market segments: the red line depicts trading volumes in GC repos and the blue line depicts volumes in the unsecured money market. The repo market is clearly the main money market segment; in particular, an increase in risk aversion after the Global Financial Crisis and European Sovereign Debt Crisis has shifted bank activity towards the secured segment (European Central Bank, 2018). To put the importance of the repo market into perspective, repo trading volumes exceed cumulative bond purchases by the European Central Bank (ECB) under the largest euro area QE program, the Public Sector Purchase Program (PSPP), as depicted by the light green line, or the ECB's main refinancing operations (MRO) and targeted longer-term refinancing operations (TLTRO), as depicted by the dark green line. Overall, the GC repo market is now the predominant euro area money market in which banks operate. It is highly representative of banks' funding and portfolio reallocation decisions and thus the ideal laboratory in which to study short-term funding market collateral choices.

Four characteristics of the European repo market infrastructure are noteworthy:[7] First, the most common collateral assets are government bonds whose supply and demand varies depending on auctions, reopenings, and QE purchases. Second, repos are euro-denominated and the usual term types are Overnight (ON), Tomorrow-Next (TN), and Spot-Next (SN), indicating purchase dates tonight, tomorrow, and the day after tomorrow, respectively, and the repurchase date 1 day thereafter. Third, it mostly operates through central counterparties (CCP) that interpose themselves between each lender and borrower.[8] Through novation, a CCP acts as a clearinghouse and applies the same collateral and (credit) risk policies to all market participants. And fourth, the core segment is the interbank market in which banks trade anonymously via centralized electronic order book platforms. All those characteristics allow me to eliminate many confounding factors to collateral choices such as currency and counterparty risk, thus buttressing the measurement accuracy of my results. It also ensures that borrower-level characteristics and bank reputation do not affect funding cost and collateral choices.

[7]More detailed information about the European repo market infrastructure can be found in, for example, Mancini, Ranaldo, and Wrampelmeyer (2016), Nyborg (2016), Bank for International Settlements (2017), and European Central Bank (2018).

[8]CCPs account for more than two-thirds of the total repo market turnover (European Central Bank, 2018).

Table 1: Breakdown of the repo data

	Transactions (in million)	Volume (in euro trillion)	Transactions (share in %)	Volume (share in %)
General collateral euro repos	1.57	77.94	100.00%	100.00%
Overnight	0.40	15.29	25.13%	19.62%
Tomorrow-next	0.65	30.39	41.61%	38.99%
Spot-next	0.42	24.70	26.41%	31.69%
Other term types	0.11	7.57	6.85%	9.71%
OTR in GC and special			100.00%	100.00%
OTR GC volumes	0.33	17.94	24.14%	44.37%
OTR special volumes	1.04	22.49	75.86%	55.63%

The table shows the breakdown of the repo data. My data includes GC repos denominated in euros. The upper part breaks down the universe of GC repos traded on the MTS platform by repo term. The lower part compares volumes of OTR deliveries into GC trades with special trading volumes for OTR securities.

1.2 Data

I observe a unique data set of GC repo trades for the period from January 2010 to June 2020. My sample comprises about 70% of all euro area GC repo trades and 38% of the traded volume. For each transaction, I observe the trade date, the term, the trade volume, the rate, the GC basket, the bond being delivered as collateral identified by the ISIN, and the aggressor type. I also employ data on special repo trades to connect collateral choices in the GC segment to special repo rates of the bonds being pledged as collateral.

Table 1 provides a summary of my data. In total, I observe more than 1.5 million GC trades totalling more than 75 trillion euro in trading volume. In my analysis, I include all trading days, however, to ensure robustness, I exclude quarter-end and end-of-ECB maintenance period days in additional tests.[9] All transactions are euro repos executed via a CCP

[9] On quarter- and year-end days as well as on end-of-ECB maintenance period days, window dressing impacts repo rates (Ranaldo, Schaffner, and Vasios, 2021). As further robustness checks, I also remove observations in the 99th percentile of CTP spreads for on-the-run and off-the-run bonds. The results are virtually unchanged in all those specifications.

and more than 93% of the trades are overnight trades of term types ON, TN, and SN.[10] My sample covers a sizeable percentage of the European market transactions and the near-total universe of all Italian repo trades (Corradin and Maddaloni, 2020). For the main part of my analysis, I, therefore, focus on Italian trades, for which I have almost complete coverage. However, I show that my results are fully consistent for other euro area countries such as Germany and France. I then extend my analysis to the U.S. Treasury market, which ensures the general validity of my analysis. Each government bond type has its own dedicated GC basket.[11] This ensures that all bonds eligible to be delivered into a basket have the same bond type characteristics and thus guarantees that delivery patterns are not driven by, for example, different regulatory treatment.[12]

The borrower in a repo trade always has the option of posting a security into the GC or special segment. In my sample, 44% of the OTR repo trading volume is in the GC segment, compared to 56% in the special segment. This means that OTR volumes in the GC and special segment are comparable, which confirms the importance of the GC market. I return to the comparison between the GC market and the special segment when I relate my results to the U.S. Treasury market.

On each day and for each bond, I compute the daily number and volume of trades for which that bond served as collateral in GC trades. I complement this data with results on auctions and reopenings, which allows me to determine the OTR status and the remaining time for which a bond serves as an OTR bond. I also classify bonds into *eligible* and *noneligible* for QE purchases depending on whether they fulfilled the purchasing provisions that were valid at a specific point in time.[13] This allows me to measure the number of days a bond has been

[10]I include all term types in my analysis to ensure the general validity of my results. However, my results are fully consistent if I only consider ON, TN, and SN repos in my analysis.

[11]A summary of the bond characteristics is provided in the Internet Appendix.

[12]For example, all euro area government bonds in my sample qualify as high-quality liquid assets (HQLA) in terms of the liquidity coverage ratio (LCR) requirement for banks.

[13]The ECB has constituted implementation provisions to limit market impacts and distortions of bond purchases under the Public Sector Purchase Program, the largest of the QE programs implemented in the Eurosystem. These provisions specify the conditions under which the ECB (via local central banks) is allowed to purchase government bonds: they contain (i) a maturity restriction that specifies the minimum and maximum remaining maturity of a security, (ii) a yield restriction that states that the yield of a security needs to be above the ECB's deposit facility rate (DFR), and (iii) a restriction limiting the purchase of bonds to those denominated in euros. Over time, the ECB has adjusted and modified the initial implementation provisions.

eligible for QE to capture scarcity effects.[14] Finally, I add haircut information for each bond based on the ECB's collateral framework.[15] To capture collateral opportunity cost, I derive a daily list of bonds that are eligible to be pledged as collateral into a GC basket. Based on this list, I determine, for each GC trade, the CTP bond that is the bond with the highest special repo rate of all bonds that are eligible to be delivered into a particular basket.[16]

To connect the collateral choices in the repo market to the bond market for the collateral, I obtain the corresponding set of tick-by-tick, intraday bond quotes and trades.[17] Finally, I complement my bond data with investor holding information from Bloomberg, which allows me to calculate the bond-level buy-and-hold investor share.[18]

I complement my euro area sample with repo data for 2 and 10-year OTR U.S. Treasury securities. I use data from the Fed's Primary Government Securities Dealers Reports (Form FR 2004), which requires primary dealers in U.S. government bonds to report weekly repo activity in OTR U.S. Treasury securities. The U.S. primary dealer market is the U.S. repo market most closely resembling the euro area repo market setup.

2. Drivers of collateral choice

Figure 1 highlights that OTR bonds and CTP securities are most likely to be delivered as collateral into GC trades, pointing towards collateral availability and opportunity cost as

[14]Time since eligibility is a continuous variable that increases by 1 day if bond i on day t was eligible for purchase under the PSPP. If a bond was eligible in the past but is not at the moment, the variable keeps its value.

[15]The ECB collateral framework (https://www.ecb.europa.eu/paym/coll/assets/html/list-MID.en.html) provides a reference for individual bonds' haircut levels. The economics of central bank collateral frameworks have been discussed in, for example, Nyborg (2016).

[16]My results are robust if I determine the CTP bond based on yesterday's special repo rate.

[17]I employ data from the MTS cash market, which is the largest interdealer trading network for European government bonds; liquidity is ensured by active market-making and a quote-driven electronic limit order book. Related studies that have used this data include, for example, Pelizzon et al. (2016) and Corradin and Maddaloni (2020). For my analysis, I focus on the cross-section of sovereign bonds that are posted as collateral into GC trades. On each day, I compute the volume-weighted average mid-quote, bid-ask spread, and amounts quoted at the best bid and ask, as well as the volume-weighted average transaction price and transaction cost.

[18]I derive quarterly bond holding information by institution for 10-year government bonds during the first 3 years after the initial auction. I classify an institution as a buy-and-hold investor if it reduces its position in less than a third of all observations. My results are robust to alternative classifications. For each bond and for each quarter after the initial auction, I calculate a bond's buy-and-hold investor share as the sum of the positions held by buy-and-hold investors over the total coverage in the database.

the two main drivers of collateral choice. I start by analyzing different aspects of collateral availability and opportunity cost separately before looking at their interplay.

2.1 Collateral availability

Collateral availability refers to the net supply of collateral assets (*quantity*). Auction cycles are a first source of variation in the supply of government debt impacting money and bond markets (e.g., Keane, 1996; Krishnamurthy and Vissing-Jorgensen, 2012; Lou et al., 2013; D'Amico et al., 2018; Sigaux, 2018; Huh and Infante, 2021). A second form of variation stems from scarcity induced by QE (e.g., Arrata et al., 2020; Corradin and Maddaloni, 2020). Asset scarcity is the counterpart to collateral availability; while auctions increase the availability, central bank asset purchases reduce it.

Figure 3 illustrates those aspects of collateral availability. Figure 3a plots the repo delivery volume of a bond against its issuance size, separately for initial auctions (orange crosses) and reopenings (blue circles). [19] The delivered volume is measured as the *cumulative* volume of a bond posted into GC repo trades over the first 90 days after an auction relative to the bond's outstanding volume.[20] It is clearly apparent that the delivery volume increases with the auction size. For example, the cumulative delivery volume after initial auctions is about 200% (400%) of the outstanding volume for an auction size of euro 2 billion (10 billion). The effect is consistent for reopenings, although the effect is stronger after initial auctions due to their larger issuance size. The results also highlight the importance of repo delivery volumes relative to the issuance size.

Figure 3b looks more closely at the delivery patterns during the first 90 days after an auction; it graphs the *daily* volume delivered (relative to the outstanding volume) against the time since the last auction, again separately for initial auctions (orange crosses) and reopenings (blue circles). Three patterns stand out: the delivery volume (i) is higher for initial auctions than for reopenings, (ii) decreases in the days after an initial auction or

[19] Delivery volumes are standardized by the issuance for ease of comparison.

[20] The results are consistent if the delivery volume is measured over a different horizon of, for example, 30 or 60 days.

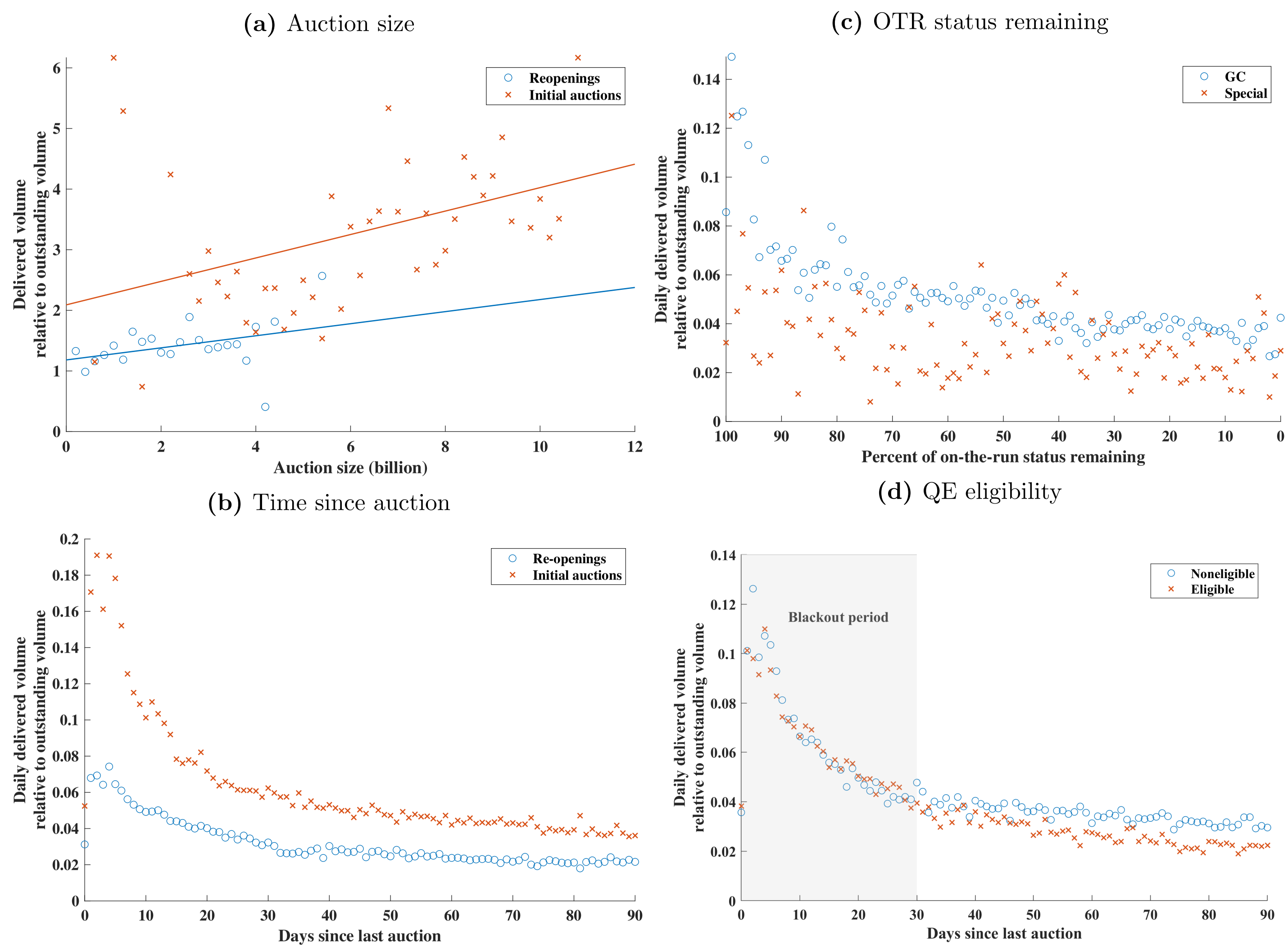


Figure 3a depicts the cumulative delivery volume of a bond into GC trades during the first 90 days after its auction relative to the total outstanding volume. Figure 3b depicts the daily delivered volume of a bond into GC trades relative to its outstanding volume on each of the first 90 days after the auction. Both graphs differentiate between initial auctions (orange crosses) and reopenings (blue circles). Figure 3c depicts the daily delivered volume of a bond relative to its outstanding volume in the GC market (blue circles) as well as the OTR trading volume in the special repo market (orange crosses) in relation to the remaining OTR status. Figure 3d depicts the daily delivered volume of a bond in GC trades relative to its outstanding volume for each of the first 90 days after the initial auction or reopening by differentiating between bonds eligible (orange crosses) and noneligible (blue circles) for PSPP purchases.

Figure 3: Aspects of collateral availability

reopening, and (iii) peaks again around reopenings. For example, daily delivery volumes are about 20% of the outstanding volume for delivery dates close to the initial auction; those volumes drop to around 6% 1 month after the initial auction. Around reopenings, the delivery volume peaks again at about 8%. The results are in line with the interpretation that OTR deliveries are due to funding needs from primary dealers who received OTR securities in the auction and hold them in their portfolio; or to put differently, OTR bonds are highly available in the dealers' portfolio and can be used as collateral for refinancing.

Figure 3c is developed in a similar spirit; it depicts the daily volume delivered against the remaining time for which a bond serves as the OTR (blue circles).[21] The results are consistent: The delivery volume of newly issued, OTR government bonds peaks at the auction and decreases as the OTR bond gets closer to turning off-the-run. The figure also displays OTR trading volumes in the special repo market (orange crosses). OTR deliveries into GC trades and special trading volumes for OTR bonds are comparable in size, which is surprising since the borrower could refinance himself at a significantly lower rate by posting OTR bonds into special repos (Duffie, 1996). This hints towards frictions in special repo trades that lead borrowers to also post OTR bonds as collateral in GC rates at the higher GC rate.

In contrast to government bond auctions, which are a source of supply of collateral assets, central bank asset purchase programs have led to asset scarcity and a corresponding reduction in collateral availability. Figure 3d graphs the volume delivered against the time since the last auction, separately for QE eligible bonds (orange crosses) and bonds that are not eligible for QE purchases (blue circles). For the first 30 days after a government bond auction, delivery volumes are similar between eligible and noneligible bonds, which is in line with an initial blackout period for central bank purchases (grey shaded area). However, for periods more than 1 month after the auction, bonds that are not eligible for QE are delivered about one-and-a-half times as often as QE eligible bonds. Those results are consistent with the idea that central banks target QE eligible bonds, which leads to their scarcity. Among other things, this reduces their availability in the dealers' portfolio to serve as collateral in repo trades.

[21] I display the percentage of the OTR status remaining since government bonds with different tenors follow different auction cycles and thus serve as the OTR bond for different time periods.

2.2 Opportunity cost

Collateral opportunity cost (*price*) is the second driver of collateral choice, it measures the price of posting different bonds into different repo trades. For example, posting a bond like the OTR in a GC repo that is in high demand in the special segment due to its convenience benefits is costly as rates on special repos that earmark the specific collateral are often lower than prevailing GC rates (Ballensiefen and Ranaldo, 2022). A bank, therefore, faces opportunity cost for the delivery of a special collateral bond into a GC repo.[22] Economically, if a bank post a special collateral bond into GC repos at the higher GC rate, then this points towards frictions such as search cost in the special segment which prevent the bank from benefiting from the lower special rates.

For my analysis, I compute two measures of collateral opportunity cost:

$$CTP\ spread_{i,t} = reporate^{special}_{CTP,t} - reporate^{special}_{i,t} \tag{1}$$

$$Repo\ specialness_{i,t} = reporate^{GC}_{basket,t} - reporate^{special}_{i,t}. \tag{2}$$

Equation (1) computes the "CTP spread" as the difference in special repo rates between the CTP bond of a given GC basket and bond i, which was delivered as collateral into that basket. The CTP spread measures the opportunity cost of delivering bond i as collateral into a GC repo as opposed to the CTP bond. Equation (2) computes the "repo specialness" measure as the difference between the GC repo rate of the basket in which a security is posted as collateral and the special repo rate of the delivered bond i. This spread measures the opportunity cost of engaging in a GC trade as opposed to a special repo trade.[23] The

[22]The opportunity cost relates to the utility a borrower forgoes during the time between the purchase and repurchase when he delivers a bond as collateral into a GC trade. A repo represents a sale and repurchase of the collateral asset, that is, the lender becomes the legal owner of the collateral at the purchase date. Still, while the buyer of the collateral is the owner of the bond during the term of the repo, the borrower retains the risk of the bond, as he has agreed to buy it back at the repurchase date. Any income arising from the bond during the term of the repo (e.g., coupon payments) is, therefore, transferred to the borrower. Hence, any foregone utility must stem from the collateral's safety and liquidity attributes, also referred to as convenience benefits (Gorton, 2017).

[23]The decision to use a GC trade instead of a special repo trade involves subtle differences. In a GC trade, the borrower can choose which bond he delivers as collateral until the first leg is settled. By contrast, a borrower already commits to deliver a specific collateral in a special trade at the trade date of the repo trade.

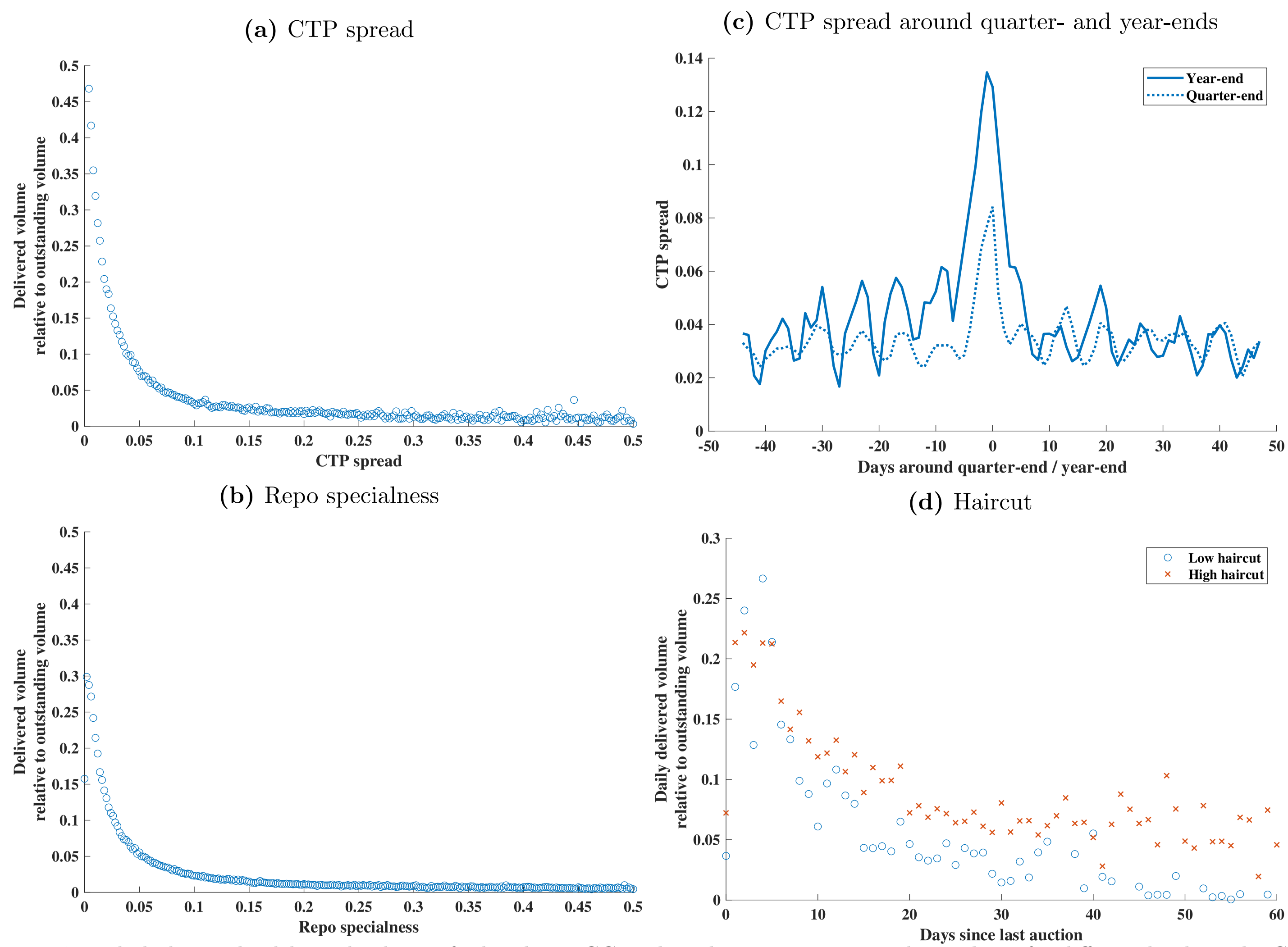
economic intuition behind both measures is the same; the opportunity cost of posting a bond into a GC repo is higher for bonds that carry larger convenience benefits and thus are more special. Or to put differently, in the spirit of Bartolini et al. (2011), the CTP bond is the one maximizing the collateral rent of a basket, which is not maximized by posting a bond other than the CTP bond. Hence, if bonds other than the CTP bond are posted into GC trades, then this points towards inefficiencies in the collateral choice.

Figure 4 displays those aspects of collateral opportunity cost. Figure 4a plots the relative delivery volume of a bond into GC repos for different levels in the CTP spread. The delivery volume peaks for CTP spreads close to zero and decreases in the CTP spread as the collateral opportunity cost increase. Figure 4b presents consistent results for repo specialness as the alternative measure of collateral opportunity cost. Both results are consistent with the idea that borrowers take more effort to find a lending counterparty to post a bond into a special trade at a lower rate if the benefit of doing so is higher.

Looking at the CTP spread on reporting dates creates an interesting perspective as those days create exogenous short-term funding rate variation in the euro area.[24] Figure 4c illustrates the CTP spread for the 50 days prior to and after quarter-ends (dotted blue line) and year-ends (straight blue line). At quarter-ends, the CTP spread increases to about 8bps; at year-ends, the increase is even stronger to about 14bps. The spikes in the CTP spread on quarter- and year-end reporting days can be considered a measure of *collateral stress*, as the opportunity cost of posting bonds into GC trades is higher on those dates when borrowers can benefit from lower special funding rates.

A bond's haircut is another aspect of collateral opportunity cost. The idea here is that bonds with higher haircuts have a lower fungibility and (re-)pledgeability, thus they are less special in the repo market and have lower collateral opportunity cost. Figure 4d graphs the daily volume delivered against the time since the last auction, separately for bonds with high

[24]Ranaldo, Schaffner, and Vasios (2021) show that the introduction of the leverage ratio rules under the Basel III framework disincentivizes the borrowing demand at quarter- and year-end periods when the leverage ratio is calculated. The Basel III rules imply that borrowing cash through a repo expands the balance sheet of financial intermediaries and thus reduces the leverage ratio, whereas lending cash via a repo does not.



Figures 4a and 4b depict the delivered volume of a bond into GC trades relative to its outstanding volume for different levels in the CTP spread and in repo specialness. Figure 4c depicts the CTP spread for the 50 days prior to and after the quarter-ends (dotted blue line) and year-ends (straight blue line). Figure 4d depicts the daily delivered volume of a bond relative to its outstanding volume for the first 60 days after the initial auction, separately for bonds with high (i.e., daily haircut above average haircut, orange crosses) and low haircuts (i.e., daily haircut below average haircut, blue circles). For illustrative purposes, Figure 4d only includes medium- and long-term bonds.

Figure 4: Aspects of collateral opportunity cost

(orange crosses) and low haircuts (blue circles).[25] The results confirm that intuition as the delivery volume tends to be higher for high-haircut bonds.

2.3 Combined effects

I then want to understand the interplay of collateral availability and opportunity cost. Figure 5 provides several illustrations of it. Figure 5a plots the delivery volume for different levels in the CTP spread, as we have seen before, but now separately for OTR government bonds (orange crosses) and their off-the-run counterparts (blue circles). We clearly see that if bonds with high CTP spreads are delivered, those are likely to be OTR securities. The CTP spreads for OTR securities are economically meaningful as they go up to 50bps; this means that borrowers accept significant opportunity cost to post OTR bonds into GC repos. Still, also for OTR securities, the delivery intensity declines with the opportunity cost. This nicely illustrates both aspects of collateral choice: the generally declining delivery volumes with a bond's repo specialness point towards the role of collateral opportunity cost, as borrowers increase their effort to fund themselves at lower special rates when the cost of not doing so are high; still, the relatively higher delivery volumes of OTR securities into GC trades for higher levels in the CTP spread highlight the role of collateral availability and frictions in the collateral choice, which prevent borrowers from entirely posting OTR bonds into special trades.

Developed in a similar spirit, Figure 5b shows the delivery volume of a bond into GC repos (blue circles) and its repo specialness (orange crosses) relative to the position in the auction cycle. Consistent with Keane (1996), clear cyclical patterns emerge as OTR bonds become increasingly special throughout the auction cycle. Repo deliveries reverse this pattern; they decline in the repo specialness of the delivered security. This means that borrowers have more incentive to find a counterparty to post OTR bonds into special repos when the benefit of doing so increases.[26] Figure 5c complements this view by showing that OTR deliveries are

[25] At each point in time, I classify a newly issued security into a bond with a high (low) haircut depending on whether its haircut is above (below) the average haircut of newly issued securities.

[26] In a repo squeeze, banks post a substantial portion of their OTR bond holdings into GC trades at a higher GC rate instead of using the less expensive special rate. The goal of this trading strategy is to increase the

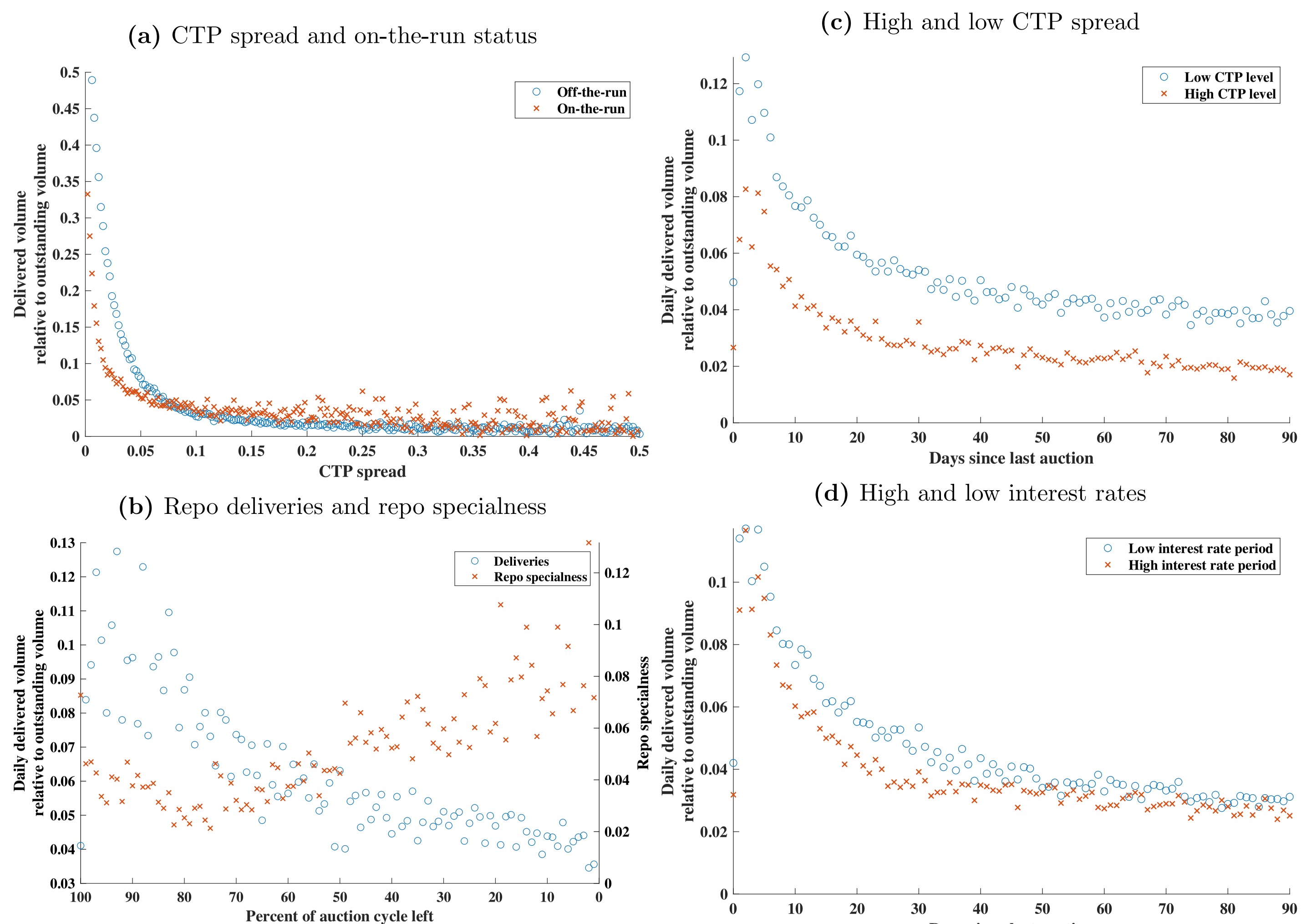


Figure 5a depicts the delivered volume of a bond into GC trades relative to its outstanding volume for different levels in the CTP spread, separately for on-the-run (orange crosses) and off-the-run securities (blue circles). Figure 5b depicts the daily delivered volume of a bond relative to its outstanding volume (blue circles) and the repo specialness of the delivered security (orange crosses) relative to the position in the auction cycle. Figures 5c and 5d depict the daily delivered volume of a bond relative to its outstanding volume for the first 90 days after the initial auction or reopening by differentiating between bonds with high (i.e., CTP spread above the average CTP spread over the sample period, orange crosses) and low levels of CTP spread (i.e., CTP spread below the average CTP spread over the sample period, blue circles), respectively during high (i.e., positive rate on the ECB's main refinancing operations (MRO), orange crosses) and low interest rate periods (i.e., non-positive rate on the ECB's MRO, blue circles) .

Figure 5: Aspects of collateral opportunity cost

lower during periods when CTP spreads are higher.

Inspired by the safe asset literature, I also consider the level of short-term interest rates. The borrower in a repo forgoes the convenience benefits of the bond, which he posts as collateral. Nagel (2016) shows that the value of those convenience benefits depends on the level of short-term rates. His main finding is that the liquidity premium provided by near-money assets is more valuable in a high interest rate environment. The utility loss of posting OTR bonds, which carry the highest liquidity attributes, into GC repos, therefore, depends on the level of short-term interest rates. Figure 5d shows the daily repo delivery volume during the first 90 days after the auction, separately for periods with high (orange crosses) and low interest rates (blue circles). Consistent with Nagel (2016), the delivery intensity of OTR bonds is lower in a high interest rate environment when the superior liquidity services of OTR bonds are more valuable.

2.4 Empirical estimation

For the empirical analysis, I formalize the graphical intuition in a set of panel regressions. The main variable of interest is the volume delivered of a bond into GC repos, which I measure as a bond's daily delivery volume over its outstanding volume ("Delivery volume"). I relate the delivery volume to different aspects of collateral availability and collateral opportunity cost, as depicted in Table 2. All regressions include basket-month-term fixed effects and standard errors clustered at the bond level.

Baseline: Column (1) serves as the baseline. To capture collateral availability, I employ a bond's issuance volume at the preceding auction or reopening ("Auction size") and the time since the preceding auction or reopening ("Time since auction," measured in logs), both variables interacted with a dummy for initial auctions ($D^{Initial}$); the dummy $D^{OnTheRun}$ that is equal to one for OTR bonds; and the time for which a bond has been eligible for QE purchases ("Time since QE eligibility" or "TSE," measured in logs). To capture collateral

specialness of the bond with the idea of profiting from it at a later point. However, in my data, I observe that OTR volumes in both segments, the GC and special segment, decline in the repo specialness, which counters this idea and alleviates any concerns around the concept of repo squeeze for my analysis.

opportunity cost, I add a dummy that equals one for the CTP bond (D^{CTP}) and the CTP spread ("CTP spread").

Collateral availability: The delivery volume follows the auction cycle and is impacted by asset scarcity. Four patterns stand out: First, the delivery volume increases with the auction size; all else equal, a 10-billion-euro increase in the auction size increases a bond's daily delivery volume (relative to its outstanding volume) by about 1.4 percentage points for initial auctions (0.3 percentage points for reopenings). Second, the delivery volume decreases in the time since the last auction. For example, an increase in the time since the initial auction by 1 percentage point relates to a decrease in the delivery volume by 4.1 percentage points; the effect is again stronger for initial auctions than for reopenings. Third, the delivery volume tends to be 0.7 percentage points higher for OTR bonds. And fourth, bonds eligible for central bank asset purchasing programs have a lower delivery volume. In economic terms, an increase in the time during which a bond is eligible for QE purchases by 1 percentage point is associated with a 0.7 percentage points lower delivery volume. Those results are consistent with the idea that a greater availability bonds in banks' portfolios implies a larger need to post those securities as collateral in GC funding trades.

Collateral opportunity cost: The CTP bond has, all else equal, a 0.3 percentage points higher delivery volume. In addition, the delivery volume decreases in the CTP spread. If the CTP spread increases by 1 percentage point, the delivery volume decreases by 0.3 percentage points. This means that if the opportunity cost to post a bond increases (i.e., the bond's specialness increases), its delivery volume into GC repos decreases. Column (2) employs the repo specialness measure ("Repo specialness") instead of the CTP spread and confirms the results. Those results are consistent with the idea that banks take greater effort to post CTP bonds into GC repos or to place bonds into special trades at the cheaper special rate if the benefit of doing so is greater.

Interaction: Columns (3)–(5) provide different specifications of the baseline setup to analyze the joint impact of collateral availability and opportunity cost. Column (3) interacts the CTP spread with the OTR dummy to analyze the different sensitivities of on-the-run

Table 2: Collateral availability and opportunity cost

	(1) Delivery volume b/t	(2) Delivery volume b/t	(3) Delivery volume b/t	(4) Delivery volume b/t	(5) Delivery volume b/t
Auction size	0.026	0.035*	0.029	0.027	0.041**
	(1.483)	(1.864)	(1.601)	(1.539)	(2.116)
Auction size $\cdot D^{Initial}$	0.144***	0.150***	0.144***	0.145***	0.154***
	(5.081)	(5.247)	(5.062)	(5.104)	(5.818)
Time since auction	−0.143***	−0.140***	−0.149***	−0.144***	−0.182***
	(−3.281)	(−3.121)	(−3.378)	(−3.288)	(−3.818)
Time since auction $\cdot D^{Initial}$	−4.100***	−4.262***	−4.112***	−4.118***	−4.036***
	(−14.034)	(−14.479)	(−13.919)	(−14.080)	(−12.905)
$D^{OnTheRun}$	0.708***	0.711***	0.868***	0.790***	0.946***
	(9.795)	(9.693)	(9.532)	(9.994)	(7.015)
Time since QE eligibility	−0.691***	−0.718***	−0.654***	−0.657***	−0.244***
	(−9.226)	(−9.475)	(−8.688)	(−8.924)	(−5.731)
D^{CTP}	0.265***	0.390***	0.245***	0.324***	0.388***
	(9.409)	(13.321)	(9.210)	(11.815)	(11.717)
CTP spread	−0.294***		−0.236***		
	(−15.978)		(−12.076)		
Repo specialness		−0.591***			
		(−10.990)			
$D^{OnTheRun}\cdot$ CTP spread			−0.573***		
			(−10.373)		
$D^{HighCTP}$				−0.227***	
				(−14.026)	
$D^{OnTheRun} \cdot D^{HighCTP}$				0.237***	
				(3.620)	
$D^{HighInterest}$					−0.379***
					(−6.982)
$D^{OnTheRun} \cdot D^{HighInterest}$					0.282***
					(3.351)
N	611,444	611,444	611,444	611,444	613,392
R^2	0.256	0.252	0.258	0.258	0.190
FE	Yes	Yes	Yes	Yes	Yes

The table reports the results examining the impact of different aspects of collateral availability and opportunity cost on the delivery volume into GC repo trades. The dependent variable is a bond's daily delivery volume over its outstanding volume in percentage points. Auction size depicts a bond's issuance volume at the preceding auction or reopening in euro billion, time since auction denotes the time since the preceding auction or reopening in logs, $D^{Initial}$ equals one for initial auctions, $D^{OnTheRun}$ equals one if a bond is the OTR bond, time since QE eligibility refers to the time since QE eligibility in logs, D^{CTP} equals one if a bond is the CTP bond, CTP spread and repo specialness are the two measures of collateral opportunity cost, $D^{HighCTP}$ equals one if the CTP spread is above the average CTP spread over the sample period, and $D^{HighInterest}$ equals one for periods when the ECB's MRO rate is positive. All regressions include basket-month-term fixed effects (regression (5) includes basket-term fixed effects) and standard errors clustered at the bond level. Data include GC repo trades from January 2010–June 2020. t-statistics are in parentheses. *p ¡ .1; **p ¡ .05; ***p ¡ .01.

and off-the-run bonds to changes in collateral opportunity cost. While, all else equal, OTR bonds have a higher delivery volume than their off-the-run counterparts, OTR bonds are also more sensitive to changes in the CTP spread. Column (4) illustrates this mechanism in more detail: it exchanges the CTP spread for a dummy that is equal to one for deliveries with high CTP spreads ($D^{HighCTP}$) and also includes its interaction with the OTR dummy. The results confirm that delivery volumes in general and OTR deliveries in particular are lower when CTP spreads are higher. Column (5) extends the basic framework and additionally includes a dummy variable to capture high interest rate periods ($D^{HighInterest}$); I also include the interaction of the interest rate dummy with the OTR dummy. In line with Nagel (2016), the results show that OTR deliveries are lower during high interest rate periods when the superior liquidity benefits provided by OTR bonds are more valuable.

To gain additional insight into borrowers' collateral choices, Table 3 extends my analysis by looking at different aspects of collateral availability in more detail. Column (1) shows the baseline specification for reference. Column (2) exchanges the auction size variable with the ratio of the issuance volume over the total outstanding debt held by financial institutions. The idea here is that a larger auction size relative to the total outstanding debt held by financial institutions implies a greater need for banks to diversify their portfolio holdings. The results confirm this intuition. An increase in the relative auction size is accompanied by an increase in delivery volumes; the effect is more pronounced for initial auctions than for reopenings. Column (3) replaces the OTR dummy with the remaining time outstanding during which a bond serves as the OTR ("On-the-run remaining"). It shows that a 10% decrease in the remaining time for which a bond serves as the OTR is associated with a 0.2 percentage points lower delivery volume, hinting towards a lower availability of that bond in the banks' portfolio.[27]

Column (4) introduces a dummy that is equal to one for bonds that have been purchased by the ECB under the PSPP and have, afterwards, been made available for the Eurosystem's

[27]The OTR dummy captures, on average, the higher delivery volume of OTR bonds during the entire OTR period, while the continuous variable capturing the remaining OTR time highlights that the delivery volume of OTR bonds tends to peak around auction days and decrease thereafter.

Table 3: Aspects of collateral availability

	(1) Baseline b/t	(2) Relative auction size b/t	(3) OTR status b/t	(4) Securities lending b/t	(5) Low demand b/t
Auction size	0.026	0.173	0.035*	0.032*	0.011
	(1.483)	(1.337)	(1.763)	(1.797)	(0.412)
Auction size $\cdot D^{Initial}$	0.144***	1.155***	0.069***	0.139***	0.123***
	(5.081)	(5.972)	(2.600)	(4.839)	(3.140)
Time since auction	−0.143***	−0.141***	−0.108***	−0.160***	−0.123**
	(−3.281)	(−3.275)	(−2.731)	(−3.573)	(−2.527)
Time since auction $\cdot D^{Initial}$	−4.100***	−4.106***	−3.855***	−4.115***	−4.160***
	(−14.034)	(−14.157)	(−14.066)	(−14.044)	(−15.510)
$D^{OnTheRun}$	0.708***	0.707***		0.699***	0.715***
	(9.795)	(9.804)		(9.724)	(10.025)
On-the-run remaining			0.017***		
			(12.010)		
Time since QE eligibility	−0.691***	−0.678***	−0.647***	−0.650***	−0.703***
	(−9.226)	(−9.133)	(−9.309)	(−8.052)	(−8.893)
$D^{SecuritiesLending}$				−0.535**	
				(−2.573)	
$D^{LowDemand}$					0.139***
					(2.763)
D^{CTP}	0.265***	0.264***	0.236***	0.262***	0.274***
	(9.409)	(9.364)	(8.813)	(9.352)	(8.807)
CTP spread	−0.294***	−0.294***	−0.309***	−0.293***	−0.298***
	(−15.978)	(−15.922)	(−15.840)	(−16.192)	(−15.190)
N	611,444	611,444	611,444	611,444	539,726
R^2	0.256	0.257	0.276	0.258	0.254
FE	Yes	Yes	Yes	Yes	Yes

The table reports the results examining the impact of different aspects of collateral availability on the delivery volume into GC repo trades. The dependent variable is a bond's daily delivery volume over its outstanding volume in percentage points. Auction size depicts a bond's issuance volume at the preceding auction or reopening in euro billion; in column (2), auction size is defined as the ratio of a bond's issuance volume at the preceding auction or reopening over the total debt outstanding held by financial institutions. Time since auction denotes the time since the preceding auction or reopening in logs, $D^{Initial}$ equals one for initial auctions, $D^{OnTheRun}$ equals one if a bond is the OTR bond and on-the-run remaining measures the remaining time outstanding for which a bond is the OTR bond, time since QE eligibility refers to the time since QE eligibility in logs, $D^{SecuritiesLending}$ equals one if a bond is eligible for the Eurosystem's securities lending facility, $D^{LowDemand}$ equals one for the lowest quartile in the bid-to-cover ratio at auctions and reopenings, D^{CTP} equals one if a bond is the CTP bond, and CTP spread refers to the measure of collateral opportunity cost. All regressions include basket-month-term fixed effects and standard errors clustered at the bond level. Data include GC repo trades from January 2010–June 2020. t-statistics are in parentheses. *p ¡ .1; **p ¡ .05; ***p ¡ .01.

securities lending facility ($D^{SecuritiesLending}$). The goal of securities lending was to allow market participants to source specific securities temporarily and to reduce the cost of acquiring good quality collateral. In the context of my analysis, bonds eligible for securities lending have, all else equal, a 0.5 percentage points lower delivery volume. Those results are consistent with my idea: market participants need to hold lower inventories of bonds eligible for securities lending, hence, repo delivery volumes are lower as well. Lastly, inspired by Klingler and Sundaresan (2020), I introduce a dummy for low demand auctions ($D^{LowDemand}$) in column (5). The dummy is equal to one for auctions and reopenings in which the bid-to-cover ratio is in the lowest quartile. The idea here is that a lower bid-to-cover ratio indicates a lower demand for specific bonds by investors. Market makers, therefore, need to hold those bonds for an extended period of time in their portfolios until they reallocate them. As a result, low-demand bonds have, all else equal, 0.1 percentage points higher delivery volume.

2.5 Internal robustness

My results show that aspects of collateral availability and opportunity cost jointly play a role in explaining collateral choices. To analyze the *internal* robustness of my results, I replicate my analyses (i) by introducing different control variables,[28] (ii) by estimating the regression with the delivery volume in logs, (iii) by considering different fixed effect combinations and standard error clustering, and (iv) by employing a sample without quarter-end and end-of-ECB maintenance period trading days as well as by accounting for outliers. The effect of collateral availability and opportunity cost on the delivery volume remains statistically and economically consistent across all specifications. (Results are reported in

[28]I introduce the bond bid-ask spread and bond tenor as additional controls on the bond level and I account for the cheapest-to-deliver bond in the futures market. I also consider additional economic variables as controls. First, I employ the debt-to-GDP ratio to account for overall asset supply, in line with Krishnamurthy and Vissing-Jorgensen (2012). Second, I include the price on 10-year CDS spreads as a measure of the overall sovereign risk level. More public debt creates uncertainty, which raises default risk premia (Liu, Schmid, and Yaron, 2019), so that collateral quality deteriorates with weak sovereign resources (He, Krishnamurthy, and Milbradt, 2019) and the government's inability to back its borrowing with taxation (Krishnamurthy and Vissing-Jorgensen, 2015). When a sovereign bond bears a convenience premium that is uncertain and adversely affected by risk, it becomes a quasi-safe asset (Ballensiefen and Ranaldo, 2022). Finally, I consider the ECB's purchases under the PSPP, as those purchases reduced the overall supply of government debt, consistent with Arrata et al. (2020) and Corradin and Maddaloni (2020).

the Internet Appendix.)

I also replicate my analysis for other euro area countries such as Germany and France. The results (also reported in the Internet Appendix) are fully consistent, which ensures that my analysis also speaks for other markets, such as the German "safe haven" market, which is the safe asset in the euro area. In line with the trade-off between collateral availability and opportunity cost, OTR bonds in Germany are also more likely to be posted as collateral into GC trades. This effect, however, is smaller than in my main sample, as the opportunity cost in the German funding market is higher, hence, borrowers take greater effort to place OTR bonds into special trades.

2.6 External relevance

To highlight the *external* relevance of my results, I complement my euro area sample with repo data for 2 and 10-year OTR U.S. Treasury securities. This allows me to compare repo collateral choices in the U.S. market compared to the euro area.

The borrower in a repo trade always has the option of posting the OTR bond into a GC *or* special trade. If the borrower posts the OTR bond into a GC trade at a higher rate instead of benefiting from the lower special rate, then this can be considered a measure of search frictions and market inefficiencies. To measure this, I calculate the ratio of OTR postings into GC trades relative to special trades for OTR bonds ("GC to Special ratio"). The same intuition as before applies; the dealer is more likely to post OTR bonds into GC trades when the collateral opportunity cost is lower. Confirming this intuition, Figure 6 graphs the GC to special ratio against the repo specialness measure for my main euro area sample (green) and for U.S. Treasuries (blue). I observe that the share of GC financing is higher when the opportunity cost of doing so is lower. The U.S. Treasury bond is the world's quintessential safe asset (e.g., He et al., 2019). As a result, repo specialness is highest in the U.S. market and the share of OTR postings into GC trades is smaller. Still, even for U.S. Treasuries, the intensity of OTR postings into GC trades increases as the opportunity cost get lower. This confirms that the economic intuition derived in this paper applies more generally to other

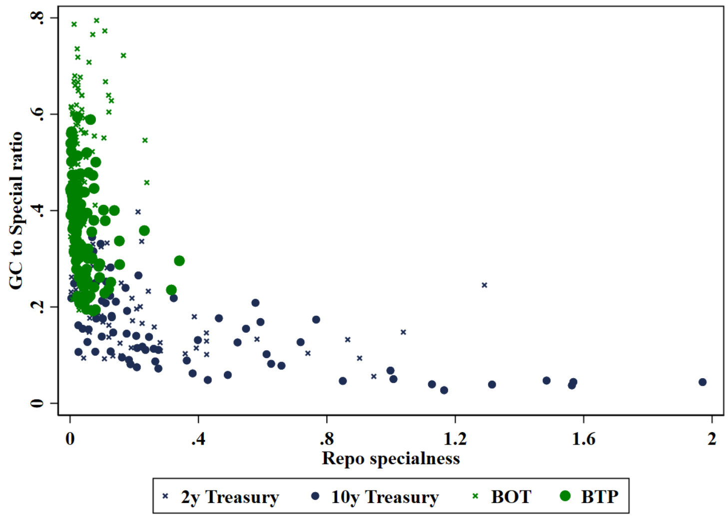


Figure 6: Repo financing shares in the United States vs the euro area

money markets, such as the U.S. Treasury market. Overall, in the U.S. market, borrowers rely more heavily on special trades which points towards the idea that search frictions are less pronounced and collateral choices are more efficient.

3. Theoretical implications

In the second part of this paper, I provide a theoretical framework related to market makers and their inventory holdings, which connects short-term funding market collateral choices with long-term bond market dynamics. My model is inventory-based (e.g., Stoll, 1978; Amihud and Mendelson, 1980; Ho and Stoll, 1981; Ho and Stoll, 1983);[29] it rationalizes borrowers' collateral choices and links them to the underlying bond market for the collateral.[30]

[29] Besides inventory cost, asymmetric information is the second, classic friction in the market microstructure literature to explain differences in intermediation cost (e.g., Glosten and Milgrom, 1985; Kyle, 1985). In my framework, I abstract from asymmetric information between the dealer and other market participants, as government bonds are less prone to asymmetric information than, for example, equities.

[30] One important reference is Krishnamurthy (2002), who provides a framework that connects the repo market to the bond market for the collateral. In his setup, the *lender* in special repos has a demand for a specific bond, which explains the higher repo specialness of newly issued, OTR U.S. Treasuries. Other related studies include, for example, Jordan and Jordan (1997), Buraschi and Menini (2002), D'Amico et al. (2018), and Corradin and Maddaloni (2020). Huh and Infante (2021) consider a cross-temporal perspective and arrive at the conclusion that bond market liquidity is lower when specialness is high due to the associated cost of intermediation.

3.1 Intuition

I consider a dealer for government bonds. This dealer participates in government bond auctions, the *primary* market for government debt, to establish a portfolio of newly issued, OTR securities. By participating in these auctions, the dealer builds up an inventory of bonds, which allows him (i) to meet the demand of *secondary* market investors who are not able to participate in primary auctions ("distribution phase"), and (ii) to perform future market-making obligations ("market-making phase").[31]

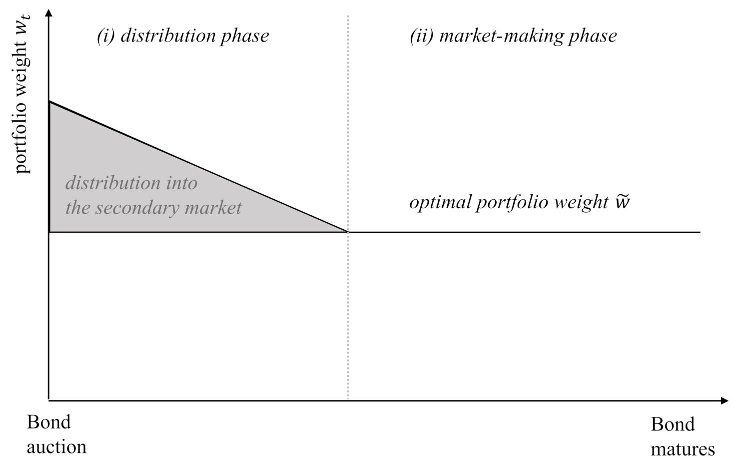


Figure 7: Illustration of optimal time-dependent portfolio weights

Illustrating this mechanism, Figure 7 shows the market maker's portfolio weight in newly issued, OTR bonds over time relative to the optimal portfolio weight. The dealer has a time-independent, optimal portfolio share in OTR bonds ($\tilde{w}$), which allows him to balance the investors' regular order flow. However, during the distribution phase, the dealer's actual portfolio share in OTR bonds (w_t) is above the optimal level, as he holds additional OTR bonds. The share declines over time as the dealer distributes part of his inventory into the

[31]Dealers that are market makers have obligations to subscribe in government bond auctions and trading volumes in the secondary market. Thus, they are required to offer sufficient amounts to meet the demand of secondary market investors who are not able to participate in primary auctions. Commonly, the market makers' obligations are defined by evaluation criteria set by the Treasury, which monitors that specialists participate in primary auctions, in secondary market trading, and in the repo market. An essential requirement for maintaining specialist status in government bonds is the allocation in primary auctions.

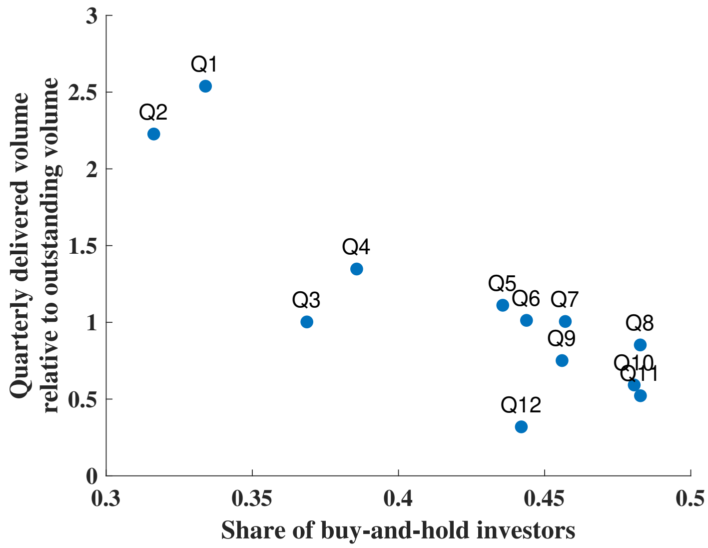


Figure 8 depicts the quarterly delivered volume of a bond into GC trades relative to the share of buy-and-hold investors; the figure illustratively includes data for 10-year government bonds.

Figure 8: Delivery volume and buy-and-hold investor share

secondary market; during the market-making phase, the optimal portfolio weight is reached. One can think of the dealer's inventory as holding two portfolios: an optimal portfolio represented by the *optimal* portfolio weight $\tilde{w}$ and an additional *trading* portfolio of "excess" OTR bonds during the distribution phase.

This intuition is consistent with, for example, Fleming and Rosenberg (2008), who estimate that primary dealers in U.S. Treasuries disseminate part of their auction purchases after the auction but also retain a substantial position until redemption. They argue that this mainly creates inventory risk since adverse selection risk is small. Building on this, Figure 8 depicts a bond's GC repo delivery volume relative to the buy-and-hold investor share for the first 12 quarters following the initial auction. The results confirm that the share of buy-and-hold investors increases over time. For example, the share increases from about 30% in the first quarter after the auction to about 50% 2 years after the auction. A higher buy-and-hold investor share suggests lower holdings of that bond in the market maker's portfolio; this leads to a lower need to post those securities as collateral in short-term funding trades and is, thus, reflected in lower repo delivery volumes.[32]

3.2 Model

My framework builds on Stoll (1978), who introduces an inventory model in which the representative agent is a dealer (market maker). The dealer in my setup is a market maker for government bonds.[33] As a market maker, the dealer provides bond quotes to investors who are looking to sell a bond (at the market maker's bid price) or buy a bond (at the market maker's ask price). The dealer adjusts his quotes in response to an unexpected and uneven order flow. The spread between the bid and ask quote compensates the dealer for his cost C_i. One can think of those costs as inventory cost, which reflect, for example, the cost for the dealer's balance sheet and the corresponding funding cost of the inventory (e.g., Duffie, 2018).

The dealer enters the period with wealth W_0. His optimal portfolio choice involves investing a share k into the optimal portfolio (yielding a return $\tilde{R}_e$) and the remaining share $(1-k)$ into cash holdings (earning the risk-free rate r_f).

Over time, the dealer participates in government bond auctions. Based on the auction allotments, the dealer holds an additional trading portfolio in newly issued, OTR government bonds.[34] As the market maker needs to participate in government bond auctions to retain his market-making status, he receives a certain allocation, which I consider to be exogenous. The true value of these "excessive" OTR holdings in the trading portfolio is denoted with Q_{OTR}; the return of the OTR holdings is denoted with $\tilde{R}_{OTR}$.

[32] A different way to illustrate this is to look at trading volumes in the bond market. In the Internet Appendix, I depict the trading volume in government bonds relative to the time since the last auction. The results confirm that trading volumes in the bond market are highest around auctions and decrease thereafter. This is consistent with the idea of market makers distributing auction allocations to secondary market, buy-and-hold investors after the auction.

[33] The model introduced in Stoll (1978) is not specific to a certain asset class, while my application focuses on the bond market.

[34] For expositional simplicity, I assume that the dealer only holds OTR securities in his trading portfolio.

Repo market funding

The dealer needs to finance his portfolio. In my setup, he does so via the repo market.[35] Repos are the most common vehicle for financing and rebalancing portfolios due to their short-term nature; dealers can stop rolling over overnight repos once they find a buyer for the bonds in the inventory (e.g., Bartolini et al., 2011; Eisl et al., 2019; Macchiavelli and Zhou, 2021). The dealer's decision to post a bond as collateral into a repo trade is, however, costly as the dealer needs to pay the repo financing cost and forgoes the utility flows of the repo collateral (Ballensiefen and Ranaldo, 2022).

The dealer has the option of placing bonds into GC *or* special repos. I denote the share placed in the special segment by $\theta_{Special}$ and the share posted in the GC segment by 1-$\theta_{Special}$. The financing cost for the dealer is lower when he posts bonds into special repos, where he can earn the repo specialness ($R_{Special} < R_{GC}$). The repo specialness is a function of the demand from lenders for collateral assets, which tends to be higher for securities such as U.S. Treasury bonds that are used by investors to invest liquidity and manage interest rate risk.

However, the market maker faces a cost for relying on special repo trades related to search cost of finding a suitable lending counterparty. Additional costs relate to different settlement cycles between GC and special repo trades.[36] These cost $\psi(\theta_{Special})$ read as follows:

$$\psi(\theta_{Special}) = a\theta^{b}_{Special} \tag{3}$$

The marginal cost increase in the share refinanced via special repo trades, with the increase being exponential.

The marginal cost have to be balanced against the repo specialness, which the market

[35]This is different from Stoll (1978), in which the dealer refinances himself at the risk-free rate. The repo market is the closest equivalent to a "true" risk-free rate and the primary market for portfolio reallocations.

[36]ON repos trade in the GC segment, while the special repo market is more liquid for SN repos. If the market maker "excessively" uses special repo trades, he faces the risk of being locked into repo trades when unexpected liquidity needs or investor trading in the bond market arise. GC repo trades have the advantages of superior liquidity, high trading volumes, and low price impact compared to special repo trades. For reference, I depict the ratio in trading volumes between the GC segment and the special segment for OTR securities relative to the time since the initial auction in the Internet Appendix. Overall, the GC trading volume surpasses that of special trades for OTR securities by about 5 times around auctions and by about 10 times 1 month after the auction, thus highlighting that GC repos are the more liquid option.

maker can earn by posting OTR bonds into special repo trades. This leads to the first order condition for the optimal repo funding shares:

$$\frac{\partial\psi(\theta_{Special})}{\partial\theta_{Special}} = ab\theta_{Special}^{(b-1)} = OC_i. \tag{4}$$

Solving for the optimal $\theta^*_{Special}$ leads to:

$$\theta^*_{Special} = (\frac{OC_i}{ab})^{\frac{1}{b-1}} \tag{5}$$

The optimization considerations can also be illustrated graphically as shown in Figure 9.

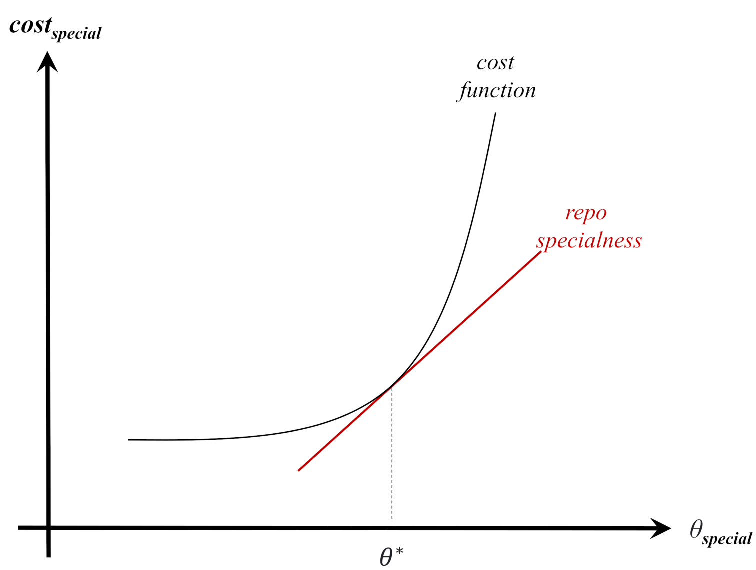


Figure 9: Optimal repo funding shares

The funding cost for the market maker in the repo market based on the optimal repo funding shares reads as:

$$R_F = \theta_{Special}R_{Special} + (1 - \theta_{Special})R_{GC}. \tag{6}$$

By defining the opportunity cost OC_i as repo specialness (see Equation 2), it follows that

$$R_F = R_{GC} - \theta_{Special} OC_i. \tag{7}$$

Equilibrium

The model is based on a one-period setting during which one trade occurs. The dealer's terminal wealth based on the initial portfolio is denoted with $\tilde{W}^*$, the terminal wealth after the trade with $\tilde{W}$. The dealer maximizes his expected utility. This implies that for the dealer to provide quotes and engage in a transaction, the compensation from the trade must offset the utility loss associated with the dealer holding the trading portfolio and, therefore, deviating from his optimal portfolio. The expected utility of the terminal wealth based on the initial portfolio must, therefore, be the same as the expected utility of the terminal wealth of the new portfolio after the transaction, which is the initial portfolio altered by the trade.[37] More formally:

$$EU(\tilde{W}^*) = EU(\tilde{W}). \tag{8}$$

The dealer's end-of-period, terminal wealth from the initial portfolio (comprised of the optimal portfolio, the risk-free investment, and the OTR bonds in the trading portfolio) without any trade occurring reads as follows:

$$\tilde{W}^* = W_0[1 + \underbrace{k\tilde{R}_e}_{\substack{return\\optimal\\portfolio}} + \underbrace{(1-k)r_f}_{\substack{return\\risk\text{-}free\\investment}} + \underbrace{\frac{Q_{OTR}}{W_0}(\tilde{R}_{OTR} - OC_i)}_{\substack{return\\trading\\portfolio}} - \underbrace{\frac{Q_{OTR}}{W_0}R_F}_{\substack{financing\\cost}}]. \tag{9}$$

The dealer earns the return on his optimal portfolio investment, the cash return, and the return on the OTR bond holdings in the trading portfolio. However, since the dealer posts his excessive OTR bonds into repo trades, the return on his trading portfolio is reduced by the forgone convenience yield valued OC_i. In addition, the dealer needs to pay the repo

[37] "Terminal" in this case refers to the end of the one period during which a trade occurs.

financing cost.[38]

I define $\tilde{W}^* = W_0[1 + \tilde{R}^*]$, in which $\tilde{R}^*$ depicts the overall return on the dealer's initial portfolio.

The dealer's end-of-period, terminal wealth of the new portfolio after a trade (comprised of the initial portfolio, the change in the trading portfolio, and the financing cost of the new trade) reads as follows:

$$\tilde{W} = W_0(1 + \underbrace{\tilde{R}^*}_{\substack{return\\initial\\portfolio}}) + \underbrace{Q_i(1 + \tilde{R}_{OTR} - OC_i)}_{\substack{change\\return}} - \underbrace{(Q_i - C_i)(1 + R_F)}_{\substack{change\\financing\\cost}}. \tag{10}$$

Q_i indicates the value of the additional OTR bond in the trading portfolio (assuming the dealer buys an additional OTR bond).[39] The dealer earns the OTR return on this position but forgoes the convenience yield of the bond, which he posts into a repo trade. In addition, the dealer needs to finance the value of the new bond less any cost C_i, which he charges to the investor. C_i is endogenously determined in the model; the dealer sets C_i such that Equation 8 is fulfilled.

I assume that the dealer is subject to an exponential utility function with constant absolute risk aversion (CARA) of the following form:

$$U(W) = -e^{-aW}, \tag{11}$$

in which a denotes the coefficient of absolute risk aversion.[40] Under the assumption that W is normally distributed with $\sim \mathcal{N}(\mu, \sigma^2)$, we know that:

$$EU(W) = E(W) - \frac{1}{2}a\mathrm{Var}(W). \tag{12}$$

[38]The returns on the optimal portfolio and on the OTR holdings in the trading portfolio are stochastic, while the funding cost is deterministic, as the GC rate and the opportunity cost are known at the beginning of the period.

[39]Positive values of Q_i indicate purchases by the dealer (from the investor), while negative values indicate sales to the investor.

[40]The Arrow–Pratt measure of relative risk aversion z is defined as $z = a \cdot W_0$.

Thus, from Equation (8) follows:

$$E(\tilde{W}^*) - \frac{1}{2}a\text{Var}(\tilde{W}^*) = E(\tilde{W}) - \frac{1}{2}a\text{Var}(\tilde{W}). \tag{13}$$

The dealer's cost function can be derived by inserting the specifications for the dealer's terminal wealth from the initial portfolio and the new portfolio after the trade into Equation (13).[41] Solving for C_i leads to:

$$C_i = \frac{\frac{1}{2}aQ_i^2\text{Var}(\tilde{R}_{OTR}) + aQ_iQ_{OTR}\text{Var}(\tilde{R}_{OTR}) + Q_iOC_i(1 - \theta_{Special})}{(1 + R_{GC} - \theta_{Special}OC_i)}. \tag{14}$$

Equation (14) reflects the cost that the dealer charges the investor for a trade in the bond market. It incorporates the aspects of collateral availability and collateral opportunity cost into the dealer's decision problem. The model implies that the dealer's cost of intermediation increases with the size of the trading portfolio Q_{OTR} (inventory risk as the dealer's holdings deviate further from his optimal portfolio) and with the collateral opportunity cost of each bond i (due to the higher forgone utility of posting the bond into a repo trade) interacted with the share funded via GC repos at the higher GC rate. The intuition is that as long as the dealer can access the special segment at the lower special rate, the foregone convenience of the bond is offset by the financing benefit. If, however, frictions prevent the dealer from entirely accessing the special segment, then this increases the dealer's cost of intermediation due to higher GC financing cost.[42]

3.3 Bond market estimation

I use my repo and bond data to provide empirical support for the theoretical predictions. The main variable of interest is a bond's relative bid-ask spread charged by the dealer. I employ the bid-ask spread at time *t+1* so that I can relate *today*'s repo collateral choices to *tomorrow*'s bid-ask spread quoted in the bond market. To capture the dealer's repo market

[41] The model derivation is presented in the Internet Appendix.

[42] The conclusions also hold for the relative bid-ask spread. The derivation is presented in the Internet Appendix.

Table 4: Bond market spread

	(1)	(2)	(3)	(4)	(5)
	Relative spread *t+1*	Relative spread *t+1*	Relative spread *t+1*	Relative spread *t+1*	Relative spread *t+1*
	b/t	b/t	b/t	b/t	b/t
Delivery volume	1.010**				0.879**
	(1.976)				(2.356)
Repo specialness		0.406***			0.252***
		(4.912)			(5.003)
$Var(\tilde{R}_i)$			0.240***		0.224***
			(13.977)		(13.604)
Quoted depth difference				2.877***	2.963***
				(3.426)	(4.329)
N	253,521	256,944	289,034	289,073	253,521
R^2	0.633	0.633	0.715	0.594	0.736

The table reports the regression results examining the impact of different cost measures on the quoted relative spread in bond markets. The dependent variable is a bond's log of tomorrow's relative bid-ask spread at *t+1*. Delivery Volume denotes a bond's daily delivery volume into GC trades over its outstanding volume in percentage points, repo specialness refers to the measure of collateral opportunity cost, $Var(\tilde{R}_i)$ denotes the variance of the bond's return, and quoted depth difference denotes the difference in the volume offered at the best ask minus the volume offered at the best bid. All regressions include basket-month fixed effects and standard errors clustered at the bond level. Data include repo transactions and bond quotes for the period January 2010–June 2020. *t*-statistics are in parentheses. *p ¡ .1; **p ¡ .05; ***p ¡ .01.

activity, I employ delivery volumes into GC trades to mimic the size of the trading portfolio and the repo specialness measure to capture collateral opportunity cost.[43] As implied by the model, I also control for the variance of the bond return and the quoted depth difference.

Table 4 reports the results of the panel regressions of the relative bid-ask spread ("Relative spread") on the delivery volume ("Delivery volume") in column (1), on the repo specialness measure ("Repo specialness") in column (2), on the variance of the bond return ($Var(\tilde{R}_i)$) in column (3), on the quoted depth difference ("Quoted depth difference") in column (4), and

[43] I match the repo delivery volumes to the corresponding bond quotes depending on the settlement conventions.

on the combined effect in column (5).[44]

Column (1) confirms that a bond's bid-ask spread at time *t+1* increases in *today*'s repo delivery volumes; the effect is almost one-to-one. Column (2) highlights that a bond's bid-ask spread at time *t+1* also increases in *today*'s bond opportunity cost. If the repo specialness of a bond increases by 1 percentage point, the relative spread charged tomorrow increases by 0.4 percentage points. Columns (3) and (4) show that the bid-ask spread is higher for more volatile bonds (higher inventory risk) and for bonds with larger differences in the quoted depth (unbalanced portfolio). Finally, column (5) confirms the statistical significance and economic magnitude in the multivariate setting.

The results are consistent with the idea that higher holdings of OTR bonds in the trading portfolio (which are posted into GC repo trades to finance and diversify the portfolio) and higher bond opportunity cost (which the dealer faces by not being able to make optional collateral choices) are associated with higher bond market spreads.

4. Implications

The concept of liquidity is usually broadly defined. Bond market liquidity is often measured via the bid-ask spread; other measures include, for example, the trading volume. Table 5 reports the relative bid-ask spread and the daily bond trading volume for the on-the-run bond and its off-the-run counterparts, separately for different bond types, for my euro area sample. On average, the bid-ask spread is higher for OTR bonds. The difference in bid-ask spreads is statistically significant for medium- and longer-term bonds, while spreads are not statistically different for short-term bonds, which are less suitable for buy-and-hold investors and for which market makers are willing to hold larger inventories (e.g., Naik and Yadav, 2003 and Fleming and Rosenberg, 2008). Still, while OTR bonds feature higher bid-ask spreads, they also have higher daily trading volumes.

At first, it seems surprising that OTR bonds have higher bond market spreads in spite of higher trading volumes. At the same time, my results provide an explanation for it as they

[44] All regressions include basket-month fixed effects and standard errors clustered at the bond level.

Table 5: Liquidity measures for on-the-run and off-the-run bonds

	(1) Short-term	(2) Medium-term	(3) Medium-term floating	(4) Long-term	(5) Long-term inflation-linked
Bid-ask spread					
On-the-run	0.45	0.33	0.14	0.54	0.78
Off-the-run	0.45	0.28	0.12	0.35	0.54
Difference	−0.00	−0.05***	−0.02***	−0.19***	−0.24***
	(−0.16)	(−24.11)	(−3.74)	(−36.07)	(−6.95)
Daily bond trading quantity (mm)					
On-the-run	142.0	15.2	110.0	62.7	42.6
Off-the-run	61.9	14.2	51.7	28.9	28.3
Difference	−80.2***	−1.0***	−58.7***	−33.8***	−14.3***
	(−55.50)	(−3.48)	(−32.27)	(−73.97)	(−19.98)

The table reports the relative bid-ask spread in percentage points and the daily bond trading quantity in millions for on-the-run and off-the-run bonds for five different bond types: short-term bonds are Treasury bills, medium-term bonds are zero-coupon bonds, medium-term floating-rate bonds are Treasury certificates indexed to a floating benchmark, long-term bonds are Treasury bonds, and long-term inflation-indexed bonds are Treasury bonds linked to inflation. The difference is defined as the off-the-run less the on-the-run value. Data include bond quotes and trades for the period January 2010–June 2020. *t*-statistics are in parentheses. *p ¡ .1; **p ¡ .05; ***p ¡ .01.

connect short-term funding market collateral choices with long-term bond market dynamics.[45] Market participants are willing to pay a premium to obtain certain assets, for example, the OTR bond, which features superior liquidity benefits in the form of larger trading volumes. Market makers, by contrast, need to hold inventories of OTR bonds to cater to the needs of their clients, which creates a cost for which they want to get compensated. If dealers' short-term funding choices are more inefficient due to frictions, as in the euro area, then this creates additional cost for which they want to get compensated in the form of higher bid-ask spreads. As a result, higher GC repo delivery volumes and higher collateral opportunity cost lead to a higher bond bid-ask spread in the cross-section. In the U.S., by contrast, dealers can more easily finance their inventory of OTR bonds at the lower special rate (see Figure 6), which explains why U.S. OTR bonds feature lower bid-ask spreads than their off-the-run counterparts (as documented in, for example, Pasquariello and Vega, 2009).

As Amihud and Mendelson (1991) highlight, lower bid-ask spreads are associated with greater liquidity, which leads to the emergence of the on-the-run / off-the-run phenomenon in U.S. Treasury securities (see, for example, Krishnamurthy, 2002). My results provide *suggestive* evidence that short-term funding market inefficiencies help us explain, why there is no on-the-run / off-the-run phenomenon in markets outside the U.S such as the euro area. My analysis highlights that policies to improve short-term funding collateral choices by mitigating search frictions, such as an increase in transparency and the introduction of market making structures in short-term funding markets, can make collateral choices more efficient, thereby improving bond market liquidity.

5. Conclusion

The novelty of my study is in analyzing borrowers' refinancing behavior and collateral choices in the main short-term funding market, the repo market. In GC repos, the borrower

[45] Huh and Infante (2021) analyze the relation between repo market specialness and the bond market liquidity of the underlying collateral. They develop a theoretical model that suggests that over time (and for the same asset) a higher repo market specialness can lead to lower bond market liquidity as intermediaries face higher costs. Broadening their view, my focus is on the cross-section of assets.

can choose which bond he posts as collateral out of a predefined list. In the aggregate, OTR bonds are more likely to be delivered as collateral than CTP securities, which is surprising given that the former are more expensive and could be posted in special trades at significantly lower borrowing rates. Those results point towards frictions in short-term funding collateral choices, which are more pronounced in markets outside the U.S. I incorporate the results into a theoretical framework that links the funding decision to the bond market for the collateral. My results provide an explanation for different bond market patterns.

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