

Liquidity Push, Collateral Rush

Renaud Beaupain^{1,2,3}, Umur Cengiz^{*1,4}, and Gunther Wuyts⁴

¹IESEG School of Management, Lille, France

²Univ. Lille, Lille, France

³CNRS, Lille, France

⁴KU Leuven, Leuven, Belgium

January 15, 2026

Abstract

Quantitative easing programmes inject reserve liquidity into the banking system while withdrawing high-quality collateral from balance sheets, yet how this intervention reshapes intraday market dynamics remains largely unexplored. We investigate using unique tick-level data from MTS Cash and MTS Repo, matching Italian government bonds with their special-collateral repos at 15-minute intervals around the ECB's Pandemic Emergency Purchase Programme (PEPP). Our analysis reveals a striking duality: PEPP compresses bid-ask spreads and nearly doubles order-book depth in cash markets, yet elevates funding volatility and widens specialness premia in the repo segment. Vector Autoregressive models estimated separately before and during PEPP uncover a regime shift in cross-market transmission. Collateral-market shocks propagate more forcefully to cash-bond liquidity under the purchase programme, while cash-market depth feeds back more strongly into repo specialness. These amplified spillovers identify a channel through which central bank purchases can transmit repo-market stress into deteriorating cash-market conditions via collateral scarcity. Our findings carry implications for the design of asset purchase programmes and suggest that access to securities lending facilities is not enough to mitigate collateral-side distortions during large-scale asset purchases.

*Corresponding author: u.cengiz@ieseg.fr

1 Introduction

Since the global financial crisis on 2008, large-scale asset-purchase programmes (APPs) have moved from unconventional policy tools to the core of modern monetary policy. By compressing term premia and stabilising market functioning, successive rounds of quantitative easing have supported economic activity during episodes of acute stress (Sack et al., 2011; Joyce et al., 2010; Krishnamurthy and Vissing-Jorgensen, 2011; Altavilla et al., 2015). At the same time, a growing literature highlights an important balance-sheet trade-off resulting from such programmes. Central bank purchases add reserve liquidity to the banking system but withdraw high-quality collateral from private balance sheets while increasing collateral scarcity and repo specialness premia (Arrata et al., 2020; Corradin et al., 2020; D’Amico et al., 2018; Singh, 2014), with securities-lending facilities partly offsetting these effects (Baltzer et al., 2022). This duality requires a specific and granular data to confirm whether the QE program affecting the markets heterogeneously, where we want to tackle in this paper.

First a large empirical literature finds that central bank asset purchases improve liquidity in sovereign bond cash markets. For the euro area, evidence from the Eurosystem Public Sector Purchase programme (PSPP) indicates narrower bid ask spreads and higher volumes in sovereign bond cash markets (Bränder and Lovas, 2019), similarly Schlepper et al. (2020) show that bond level PSPP activity narrows quoted bid ask spreads and increased volumes, consistent with a portfolio rebalancing channel that lowers dealer inventory costs. Similar effects are documented for United States Treasuries under the Federal Reserve large scale asset purchases; for instance, Gagnon et al. (2016) report that on the run spreads contract by about one basis point on purchase days. These studies, however, measure benefits where bonds are traded, not where they are financed, hence leave the repo market out of their scope. while it is showed that outright purchases have been linked to wider scarcity premia in special collateral repos in the euro area and in other jurisdictions (Arrata et al., 2020; Corradin et al., 2020).

The benchmark model of collateral scarcity and repo specialness developed by Duffie (1996) links the spread between general-collateral and special-collateral rates to search frictions and limited deliverable supply. Empirically, Corradin et al. (2020) demonstrate that a one percentage point reduction in Bund free float increases the specialness premium by approximately 0.5 basis points, while securities lending facilities moderate though do not eliminate this effect according to Baltzer et al. (2022). The existing literature examines collateral scarcity predominantly in isolation and has not comprehensively assessed how the withdrawal of collateral through large scale purchase programmes alters shock transmission mechanisms between cash and repo markets. The theoretical framework of Brunnermeier and Pedersen (2009) demonstrates that funding constraints and market liquidity reinforce each other through liquidity spirals, suggesting that balance sheet policies can fundamentally restructure cross market transmission channels.

The collateral scarcity dimension is especially pronounced under the Pandemic Emergency Purchase programme (PEPP), announced on 18 March 2020 at the height of Covid 19 market stress, which authorised deviations from the capital key to address market fragmentation and transmission impairments and accumulated more than 1.7 trillion euro of public sector bonds by mid 2024.¹ The introduction of the Pandemic Emergency Purchase programme provides us a unique setting to examine collateral effects in the euro area context. Unlike previous asset purchase programmes that adhered strictly to the ECB’s capital key, the

¹ECB Press Release, 18 March 2020; Eurosystem balance sheet Bank (2020).

distribution formula based on each member state's shareholding in the ECB, the PEPP was designed with explicit flexibility to deviate from this constraint. This flexibility allowed the ECB to concentrate purchases in jurisdictions experiencing the most acute financial stress, particularly southern European sovereigns whose bond markets faced severe dislocation during the early phases of the pandemic. As illustrated in Figure 1, the deviation from capital key allocations was most pronounced in May 2020, with Italy receiving 21.64% of cumulative net purchases compared to its 16.02% capital key share, while France was allocated only 13.65% against its 20.00% capital key purchase allowance. By January 2022, as financial conditions normalised and net purchases approached their conclusion, the ECB had gradually rebalanced its holdings to align more closely with capital key proportions across member states. But the combination of elevated purchases and the deliberate deviation from capital key allocations in the meantime had pronounced effects on the availability of high-quality collateral in the repo market, with heterogeneous impacts across jurisdictions that varied according to the intensity of PEPP interventions in each sovereign bond market. Building on this theoretical insight, we conjecture that following the PEPP's concentration of substantial high quality collateral on the Eurosystem balance sheet, shocks originating in the collateral constrained repo segment transmitted more intensively to the cash market, thereby altering both the direction and magnitude of liquidity spillovers compared to the pre PEPP regime.

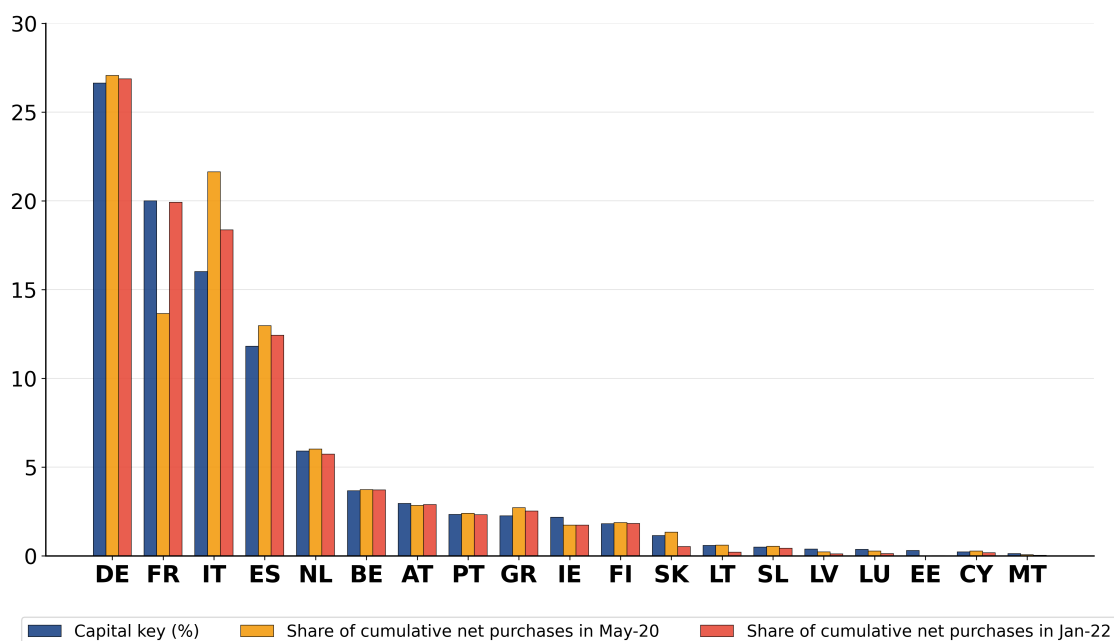


Figure 1: PEPP Purchases and Capital Key Deviations Across Euro Area Countries

This figure shows the distribution of Pandemic Emergency Purchase programme (PEPP) purchases across euro area member states compared to their ECB capital key shares. The blue bars represent each country's capital key percentage, which determines their standard allocation under conventional asset purchase programmes. The orange bars show the share of cumulative net PEPP purchases in May 2020. The red bars display the share of cumulative net purchases in January 2022, near the end of the PEPP net purchase period. *Source:* European Central Bank Statistical Data Warehouse, PEPP holdings of securities and ECB capital key.

The flexibility to deviate from capital key allowed the ECB to concentrate purchases in jurisdictions experiencing the most acute financial stress, where bond markets faced severe dislocation during the early phases of the pandemic. One of the key consequences of the PEPP was the substantial increase in excess

liquidity within the banking system (see Figure 2), as the ECB conducted large-scale asset purchases to support the economy during the COVID-19 pandemic. While the primary objective of these quantitative easing (QE) measures was to lower borrowing costs and stimulate economic activity, the combination of elevated purchases and the deliberate deviation from capital key allocations had pronounced effects on the availability of high-quality collateral in the repo market, albeit potential heterogeneous impacts across jurisdictions. At the end the PEPP program increases the excess liquidity on top of other APP, and potentially help the bond markets while potentially distorting repo markets with two separate channels, by making funding rich and collateral scarce.

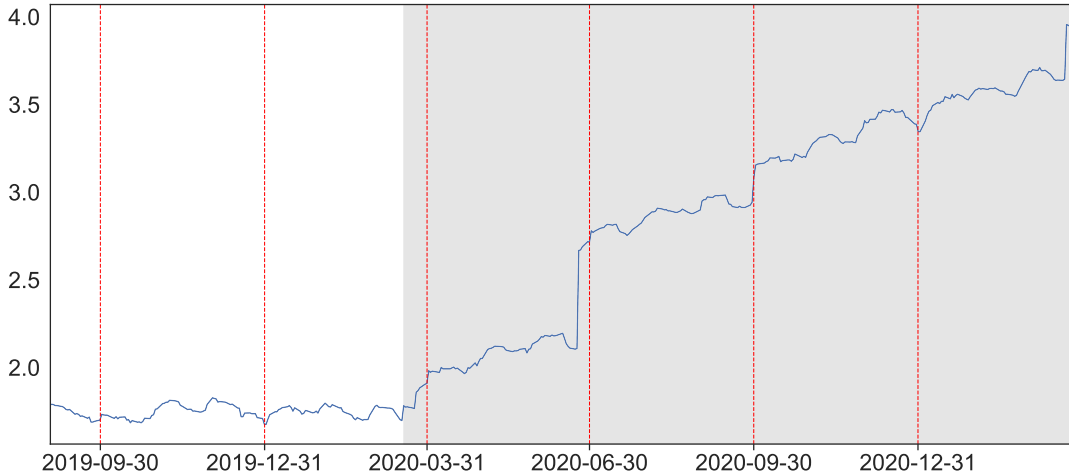


Figure 2: Daily Excess Liquidity in Euro Area

This figure displays the daily excess liquidity in the euro area, sourced from the European Central Bank’s (ECB) data warehouse. The excess liquidity levels are shown in trillion euros, with red lines marking the end of each quarter. The shaded area corresponds to the European Central Bank’s Pandemic Emergency Purchase programme (PEPP), which was announced on March 18, 2020.

Building on these insights, our empirical analysis is structured around two main objectives. First, does an asset-purchase programme such as the PEPP generate mixed effects, in the sense that it enhances liquidity in the sovereign-bond cash market while simultaneously draining liquidity in the corresponding special-collateral repo segment? Second, do the excess reserves and collateral scarcity created by large-scale public purchases amplify or alter within- and cross-market liquidity spillovers, in the spirit of Brunnermeier and Pedersen (2009), relative to the pre-PEPP regime? We focus on Italian government bonds because Italy experienced some of the largest deviations from capital-key allocations under the PEPP and because its sovereign market is one of the deepest and most actively traded in the euro area, making it a natural laboratory to study collateral scarcity and liquidity transmission.

We address these questions using a matched, tick-by-tick data set from the MTS platforms, the primary electronic interdealer venue for euro-area sovereign bond trading. For every Italian government bond, we link transactions on the MTS cash platform to the corresponding repo on the MTS repo market. The high-frequency granularity permits intraday construction of proportional quoted spreads, top-of-book depth, trading volume, trade count, and trade size in the cash market, together with analogous measures of trade count, trading volume, trade size, an Amihud-type illiquidity ratio, and repo specialness in the repo market.

Exploiting the regime shift created by the PEPP announcement, we estimate vector autoregressions (VARs) on two separate samples—Pre-PEPP and During-PEPP—and use the millisecond-level MTS records to trace how liquidity spillovers changed within and across the cash and repo markets.

Our main findings are threefold. *First*, relative to pre-PEPP conditions the programme helps to increase market liquidity in the sovereign-bond cash market by roughly 45% at the open and, on average, doubles top-of-book depth throughout the trading day, while it simultaneously increases the Amihud illiquidity ratio in special-collateral spot-next repos by about 14% and reduces afternoon repo volume by roughly one-third. These changes document a clear divergence between cash and repo-market reaction. *Second*, exploiting the fifteen-minute resolution of our data, we perform a slot-by-slot comparison of unconditional moments—means, medians and variances—for every liquidity and volatility measure. Our empirical tests reveal that the PEPP’s effects are time-dependent: cash-market spreads tighten most between 08:00 and 10:00 after PEPP, while repo illiquidity and specialness premia increases most in the final hour of trading consistent with the run of collateral at the end of the day. *Third*, impulse-response estimates reveal that, in the During-PEPP regime, funding-liquidity shocks propagate more strongly to cash-market depth, less strongly to quoted spread, and that shocks to cash depth feed back more forcefully into the repo specialness premium. Also, shocks from repo market is more profound in the cash market. The pattern aligns with the collateral scarcity that emerged after PEPP: shock transmission now shifts and primarily from the repo market and collateral supply (market depth) toward the cash market liquidity rather than the other way around.

The remainder of the paper is organised as follows. Section 2 sets out the institutional background and details the construction of our high-frequency variables from the data set covering both the cash and special-collateral repo segments. Section 3 presents the intraday patterns and empirical results that quantify how PEPP implementation affected liquidity and market activity in each market. Section 4 uses these findings in the Brunnermeier and Pedersen (2009) framework, estimating sample-specific spillover coefficients to show how PEPP changed the liquidity spillovers between the two MTS markets. Finally, section 5 concludes.

2 Institutional Background and Data Description

Starting from the mid-2000s, repurchase agreements (repos) have grown to become the primary source of short-term funding in euro-denominated markets (Comotto, 2024). During this period, the repo market has successfully navigated significant events such as the Global Financial Crisis (GFC) from 2007 to 2009 and the European sovereign debt crisis between 2011 and 2012. Moreover, the repo market played a crucial role in maintaining financial stability during the COVID-19 pandemic. In times of heightened volatility and market stress, such as the mass sell-offs in early 2020, the repo market’s ability to redistribute liquidity and provide access to high-quality collateral like government bonds proved vital (ICMA European Repo and Collateral Council (ERCC), 2020; European Central Bank, 2020b). During episodes of deteriorating funding conditions and surging volatility, repo markets acted as a stabilizing mechanism by allowing institutions to secure liquidity through collateralized lending. Given the shift from unsecured funding (which carries default risk) to secured markets, the repo market has become integral to liquidity redistribution and collateral management among financial institutions. This is especially relevant in Europe, where the bank-dominated economy relies heavily on secured funding, and consequently the European repo market is the largest in the

world (International Capital Market Association, 2021).

2.1 Institutional Background

The MTS repo platform operates in three sessions. From 07:00 to 07:45 CET, the Pre-Market lets participants enter, change, or cancel quotes, which are visible only to the submitting dealer. Trading then moves to the Open Market (07:45–18:45 CET), where banks, broker-dealers, and institutional investors execute repos through real-time electronic matching and all market activity halts in the Closed Market (18:45–07:00 CET). The MTS Cash market, designed for European government bonds, begins with a Pre-Market from 07:30 to 08:15 CET, permitting non-executed order entry and adjustment. Continuous trading occurs in the Open Market (08:15–17:30 CET), followed by a During-Market until 18:30 CET for reporting and confirming off-market trades ¹. ² Although all eligible Euro-area sovereign bonds can serve as collateral, repos backed by Italian collateral comprise 98 percent of our sample, these numbers are also in line with Dufour et al. (2020). Near all trades are centrally cleared via CCPs such as LCH Ltd, LCH SA, Cassa di Compensazione e Garanzia, and TACH.³

Table 1: Trading sessions on the MTS Cash and MTS Repo platforms

Platform	Session	Hours (CET)	Key functionality
MTS Cash	Pre-Market	07:30–08:15	Non-executable order entry and adjustment
	Open Market	08:15–17:30	Continuous trading in Italian (and other EU) government bonds
	During-Market	17:30–18:30	Reporting and confirmation of off-market deals
MTS Repo	Pre-Market	07:00–07:45	Quote entry/modify/cancel (visible only to submitting dealer)
	Open Market	07:45–18:45	Real-time electronic matching and execution of repo trades
	Closed	18:45–07:00	Trading disabled; blotters/statistics download only

2.2 Data and cleaning

Our matched dataset covers 382 business days from September 2019 to February 2021 and links Italian securities across the MTS cash platform and the MTS repo venue, spanning the onset of Covid 19 and the early phase of the ECB Pandemic Emergency Purchase programme (PEPP). We remove records with missing prices, rates, or volumes, and we discard trades flagged as suspended (Rossi and Vu, 2014; Dick and Mazzotta, 2009)⁴. We filter extreme return reversals that exceed 50% from one trade to the next, and we treat repo rates and bond prices that are more than five times the rolling 20 trade median as outliers.

After all filters, we retain 948,072 repo executions, 484,091 cash bond trades, and roughly 400,000,000 two sided quotes, each time stamped to the millisecond in Central European Time (CET). The collateral set comprises 182 Italian bonds, mainly Buoni del Tesoro Poliennali (BTPs), Certificati di Credito del Tesoro (CCTs), and Certificati del Tesoro Zero Coupon (CTZs). Italian securities account for more than 95% of

²For a detailed discussion of the MTS Cash market’s structure and its implications for bond-market liquidity, see Cheung et al. (2005).

³The euro interbank repo market relies heavily on CCP clearing and is mainly accessed through Eurex Repo, BrokerTec, and MTS; see Mancini et al. (2016); Schaffner and Senner (2019).

⁴Suspensions may arise from duplicate reporting, execution errors, or violations of participant limits.

daily collateral value, with German and French bonds making up the remainder. By term, spot next (SN) trades account for about 64% of market volume, tomorrow next (TN) for about 25%, and overnight (ON) for about 6%, which is in line with ECB survey figures (European Central Bank, 2020a).

To minimize collateral heterogeneity, our baseline analysis focuses on special collateral spot next (SN) repos that use Italian bonds. This focus is economically motivated. First, spot next is the modal tenor in our data and therefore provides a representative view of the repo market. Concentrating on special collateral spot next Italian repos therefore reduces variation in both collateral characteristics and term-structure effects, which strengthens identification for our intraday liquidity measures and subsequent intraday analysis. In addition, the special spot next segment plays a central role in financing short positions in euro-area government bonds. Cash trades in these bonds settle on a $T + 2$ basis, while special spot next repos also settle at $T + 2$ and mature at $T + 3$; a trader who sells a bond short for $T + 2$ delivery can borrow the security in a spot next repo and then reverse the position at $T + 3$. This alignment with the cash-market settlement cycle makes special spot next repos the natural instrument for sourcing collateral to cover short positions and for linking cash and repo trades, so that our focus on this segment ensures that the intraday measures we construct capture the main channel through which short-selling pressures feed into repo specialness and liquidity (see, e.g., Duffie, 1996; Dufour et al., 2020; Corradin et al., 2020; International Capital Market Association, 2019). Second, Italy is the second largest sovereign issuer in the euro area, with a deep cash market whose collateral nonetheless becomes special around coupon periods and during Eurosystem purchase operations (Corradin et al., 2020).

2.3 Market Liquidity and Quality Measures

Table 2 lists the variables used in the empirical analysis and aligns cash measures with their repo counterparts. We consider two groups. *Liquidity metrics*: in the cash segment we use the proportional quoted spread (PQS^C) and top-of-book depth ($DEPTH^C$), which capture tightness and available volume at the best quotes. In the repo segment we use an Amihud-type price impact measure (PI^R), defined as the absolute change in the funding rate per unit of traded volume, and the specialness premium ($SPEC^R$), measured as the general collateral rate minus the special collateral rate (in basis points), which increases with collateral scarcity. *Market quality metrics*: in both segments we track trading volume (VOL^R, VOL^C), trade count ($TRADES^R, TRADES^C$), average trade size ($SIZE^R, SIZE^C$), and realised intraday volatility (RV^R, RV^C). Volumes and trade counts measure trading intensity and market participation, average trade size proxies immediacy demand and market capacity, and realised volatility summarises intraday uncertainty that informs risk limits and inventory management.

Market liquidity and market-quality metrics. This section presents the variables used to measure market liquidity and trading activity in both the cash and repo segments. The metrics are designed to capture different facets of market quality, including transaction costs, market depth, price impact, and trading intensity. Throughout, n indexes bonds (collateral), d trading days, i the 15-minute intraday intervals within a day, and t the one-second snapshots contained in each interval, consistent with the formal definitions in the subsequent subsections.

For both markets, we construct bond-level liquidity and trading-activity measures on a 15-minute intraday

Table 2: Core metrics

Dimension	Cash market metrics	Repo market metrics	Economic interpretation
Market quality metrics			
Trading volume	VOL^C	VOL^R	Aggregate activity in the interval; trading intensity.
Trade count	$TRADES^C$	$TRADES^R$	Number of executions; proxy for participation.
Trade size	$SIZE^C$	$SIZE^R$	Average size per trade; immediacy demand and capacity.
Realised volatility	RV^C	RV^R	Intraday price or rate uncertainty informing risk limits and quotes.
Market liquidity metrics			
Proportional quoted spread	PQS^C	—	Tightness of the cash market (round-trip execution cost).
Market depth	$DEPTH^C$	—	Volume available at best bid and ask; capacity to absorb order flow.
Amihud illiquidity	—	PI^R	Repo rate impact per euro traded in the special-collateral segment.
Repo specialness	—	$SPEC^R$	Collateral-driven funding premium in special repo.

grid. Trading hours differ across platforms: on MTS Cash, the open-market session runs from 08:15 to 17:30 CET, preceded by a non-executable pre-market phase and followed by a During-Market reporting session; on MTS Repo, the open-market session extends from 07:45 to 18:45 CET, with a pre-market phase from 07:00 to 07:45 and no trading overnight (Table 1). To ensure that every 15-minute interval corresponds to a period in which both markets are simultaneously open to electronic trading, we focus on the overlapping daytime window from 08:15 to 17:30 CET. This common grid is used to construct all bond-day-interval liquidity and trading-activity series that enter the empirical analysis, including the VAR specifications discussed below.

The 15-minute sampling frequency follows standard practice in high-frequency studies of euro-area sovereign bond markets and ECB purchase programmes, where intraday yield changes at 15-minute intervals are used to identify the immediate price impact of policy announcements and interventions (Ghysels et al., 2017). From a measurement perspective, 15-minute intervals strike a balance between capturing the rich intraday dynamics of both cash and repo markets and accumulating a sufficient number of trades and quote updates within each interval to obtain reliable estimates of spreads, depths, volumes, and realised volatility. Shorter intervals would increase noise and the incidence of empty bins, while much longer intervals would blur the timing of liquidity and funding shocks that are central to our analysis.

All variables are first constructed at the one-second level and then aggregated to 15-minute intervals. On the cash side, for each bond-day-interval (n, d, i) , we obtain $VOL_{n,d,i}^C$, $TRADES_{n,d,i}^C$, and $SIZE_{n,d,i}^C$ by aggregating per-second transaction volumes and trade counts; we compute $PQS_{n,d,i}^C$ and $DEPTH_{n,d,i}^C$ from one-second best-bid and best-ask quotes and their associated depths; and we define realised variance and realised volatility, $RVAR_{n,d,i}^C$ and $RV_{n,d,i}^C$, from high-frequency midquote changes, following the realised-volatility literature (Andersen et al., 2001, 2003; Hansen and Lunde, 2006). On the repo side, we analogously construct

$VOL_{n,d,i}^R$, $TRADES_{n,d,i}^R$, and $SIZE_{n,d,i}^R$ from special-collateral repo transactions; define $RVAR_{n,d,i}^R$ and $RV_{n,d,i}^R$ from one-second changes in special-collateral repo rates; and build additional funding-liquidity measures such as repo specialness $SPEC_{n,d,i}^R$ and the price-impact proxy $PI_{n,d,i}^R$, which adapt the Amihud-type illiquidity idea to rate changes. The construction follows standard practice in intraday liquidity and realised-volatility measurement and is designed to allow consistent comparisons across markets (O'Hara, 1995; Glosten and Milgrom, 1985; Huang and Stoll, 1997; Stoll, 2000; Chordia et al., 2001, 2002).

On the cash side, we focus on six core variables that are standard in market microstructure and map directly into our empirical analysis: proportional quoted spread $\left(PQS_{n,d,i}^C\right)$, top-of-book depth $\left(DEPTH_{n,d,i}^C\right)$, trading volume $\left(VOL_{n,d,i}^C\right)$, trade count $\left(TRADES_{n,d,i}^C\right)$, average trade size $\left(SIZE_{n,d,i}^C\right)$, and realised volatility $\left(RV_{n,d,i}^C\right)$. Proportional quoted spread provides a unit-free proxy for transaction costs faced by an impatient trader and embeds adverse-selection and inventory considerations borne by liquidity suppliers (Glosten and Milgrom, 1985; Huang and Stoll, 1997; Stoll, 2000). Top-of-book depth measures the quantity that can be executed immediately at the best prices and therefore reflects immediacy and the market's capacity to absorb order flow with limited price impact (Kyle, 1985; O'Hara, 1995). Measures of trading activity such as volume, number of trades, and average trade size summarize participation, market attention, and immediacy demand; they comove with liquidity provision and the cost of transacting (Chordia et al., 2001, 2002). Realised volatility constructed from high-frequency midquote returns provides a nonparametric gauge of intraday price uncertainty that informs dealers' risk limits and hence quoted tightness (Andersen et al., 2001, 2003; Hansen and Lunde, 2006).

On the repo side, the corresponding measures $VOL_{n,d,i}^R$, $TRADES_{n,d,i}^R$, $SIZE_{n,d,i}^R$, $RV_{n,d,i}^R$, $SPEC_{n,d,i}^R$, and $PI_{n,d,i}^R$ provide the repo-market counterpart to our cash-market liquidity metrics. Trading volume, number of trades, and average trade size capture the intensity and composition of special-collateral activity in the spot-next segment, while realised volatility of special-collateral rates summarizes short-horizon uncertainty in repo pricing and the tightness of trading conditions (cf. Brunnermeier and Pedersen, 2009). Specialness $SPEC_{n,d,i}^R$ measures the premium of general-collateral over special-collateral funding for a given bond and thus reflects collateral scarcity, search frictions, and rehypothecation demand in the specials market (Duffie, 1996; Jordan and Jordan, 1997; Mancini et al., 2016). The price-impact proxy $PI_{n,d,i}^R$ adapts Amihud-type ideas to repo-rate changes and quantifies how sensitive special-collateral rates are to order flow (Amihud, 2002). Taken together, these repo-side variables characterise liquidity conditions in the special-collateral repo segment and determine the effective cost at which dealers and end-investors can obtain secured funding against a given bond.

Cash Market Measures All cash-market variables are constructed at the one-second frequency and then aggregated to 15-minute intervals. Let n index bonds (collateral), d trading days, i intraday 15-minute intervals within day d , and $t = 1, \dots, T$ the one-second timestamps within interval i . For bond n , day d , interval i , and second t , let $V_{n,d,i,t}^C$ denote the total cash-market transaction volume (in that bond) occurring in that second, and let $TRADES_{n,d,i,t}^C$ denote the corresponding number of trades in that second. The per-second totals are thus

$$V_{n,d,i,t}^C \geq 0, \quad (1)$$

$$TRADES_{n,d,i,t}^C \in \{0, 1, 2, \dots\}, \quad (2)$$

so that $V_{n,d,i,t}^C = 0$ and $\text{TRADES}_{n,d,i,t}^C = 0$ when no trade occurs in second t . We aggregate these one-second variables over t to obtain our 15-minute trade-based measures at the bond-day-interval level:

$$\text{VOL}_{n,d,i}^C = \sum_{t=1}^T V_{n,d,i,t}^C, \quad (3)$$

$$\text{TRADES}_{n,d,i}^C = \sum_{t=1}^T \text{TRADES}_{n,d,i,t}^C. \quad (4)$$

Trade size in interval (n, d, i) is then defined as total volume per trade:

$$\text{SIZE}_{n,d,i}^C = \begin{cases} \frac{\text{VOL}_{n,d,i}^C}{\text{TRADES}_{n,d,i}^C}, & \text{if } \text{TRADES}_{n,d,i}^C > 0, \\ 0, & \text{if } \text{TRADES}_{n,d,i}^C = 0, \end{cases} \quad (5)$$

so that $\text{SIZE}_{n,d,i}^C$ equals the average trade size whenever at least one trade occurs in the interval and is set to zero otherwise.

For each bond n , day d , interval i , and second t , we record the best bid quote $BQ_{n,d,i,t}^C$, the best ask quote $AQ_{n,d,i,t}^C$, and their corresponding depths $Q_{n,d,i,t}^{b,C}$ and $Q_{n,d,i,t}^{a,C}$. The midquote is defined as

$$MQ_{n,d,i,t}^C = \frac{1}{2}(AQ_{n,d,i,t}^C + BQ_{n,d,i,t}^C). \quad (6)$$

For a given 15-minute interval i on day d , with $t = 1, \dots, T$ indexing the one-second snapshots contained in that interval, we compute time-weighted average liquidity measures by simple averaging over the T seconds (e.g. Chordia et al., 2001; Goyenko et al., 2009):

$$\text{PQS}_{n,d,i}^C = \frac{1}{T} \sum_{t=1}^T \frac{AQ_{n,d,i,t}^C - BQ_{n,d,i,t}^C}{MQ_{n,d,i,t}^C}, \quad (7)$$

$$\text{DEPTH}_{n,d,i}^C = \frac{1}{T} \sum_{t=1}^T \frac{1}{2}(Q_{n,d,i,t}^{a,C} + Q_{n,d,i,t}^{b,C}). \quad (8)$$

The proportional quoted spread $\text{PQS}_{n,d,i}^C$ is expressed in basis points after the calculation. Market depth $\text{DEPTH}_{n,d,i}^C$ represents the average depth available at the best quotes, capturing the liquidity supplied by market makers (Foucault et al., 2023).

Following the high-frequency realised-volatility literature (e.g. Andersen et al., 2001, 2003), we define the one-second *midquote* change (within a given day) as

$$\Delta MQ_{n,d,i,t}^C = MQ_{n,d,i,t}^C - MQ_{n,d,i,t-1}^C, \quad (9)$$

whenever both $MQ_{n,d,i,t}^C$ and $MQ_{n,d,i,t-1}^C$ are observed inside regular trading hours. This choice of using midquote changes is consistent with the market microstructure literature that employs midquote returns to mitigate bid-ask bounce (e.g. Bandi and Perron, 2006). Let $\mathcal{T}_{n,d,i} \subseteq \{1, \dots, T\}$ denote the set of seconds in

interval i that fall within regular trading hours. The realised variance over interval i is then

$$\text{RVAR}_{n,d,i}^C = \sum_{t \in \mathcal{T}_{n,d,i}} (\Delta MQ_{n,d,i,t}^C)^2, \quad (10)$$

and realised volatility is defined as

$$\text{RV}_{n,d,i}^C \equiv \sqrt{\text{RVAR}_{n,d,i}^C}. \quad (11)$$

Repo Market Measures

Repo-market variables are defined analogously at the one-second level and then aggregated to 15-minute intervals. We again use n for the bond (collateral), d for the trading day, i for the 15-minute interval, and $t = 1, \dots, T$ for the one-second snapshots within interval i . For each bond n , day d , interval i , and second t , let $V_{n,d,i,t}^R$ denote the total special-collateral spot-next repo volume traded in that second, and let $\text{TRADES}_{n,d,i,t}^R$ denote the corresponding number of trades. Let $r_{n,d,i,t}^{\text{SC}}$ denote the (per-second) volume-weighted average special-collateral rate (in decimals) when trading occurs in second t . Per-second totals are thus

$$V_{n,d,i,t}^R \geq 0, \quad (12)$$

$$\text{TRADES}_{n,d,i,t}^R \in \{0, 1, 2, \dots\}, \quad (13)$$

so that $V_{n,d,i,t}^R = 0$ and $\text{TRADES}_{n,d,i,t}^R = 0$ when no trade occurs in second t . In that case, the one-second transaction rate $r_{n,d,i,t}^{\text{SC}}$ is left undefined and does not contribute to the realised-variance and price-impact calculations below. When at least one trade occurs in second t (i.e., $V_{n,d,i,t}^R > 0$), the volume-weighted average special-collateral rate is given by the standard definition of a per-second VWAP rate and we denote it by $r_{n,d,i,t}^{\text{SC}}$. We also observe the corresponding one-second general-collateral rate $r_{d,i,t}^{\text{GC}}$.

We aggregate these one-second variables over t to obtain 15-minute trade-based measures at the bond-day-interval level:

$$\text{VOL}_{n,d,i}^R = \sum_{t=1}^T V_{n,d,i,t}^R, \quad (14)$$

$$\text{TRADES}_{n,d,i}^R = \sum_{t=1}^T \text{TRADES}_{n,d,i,t}^R. \quad (15)$$

Trade size in interval (n, d, i) is then defined as total volume per trade:

$$\text{SIZE}_{n,d,i}^R = \begin{cases} \frac{\text{VOL}_{n,d,i}^R}{\text{TRADES}_{n,d,i}^R}, & \text{if } \text{TRADES}_{n,d,i}^R > 0, \\ 0, & \text{if } \text{TRADES}_{n,d,i}^R = 0, \end{cases} \quad (16)$$

so that $\text{SIZE}_{n,d,i}^R$ equals the average trade size whenever at least one trade occurs in the interval and is set to zero otherwise.

Following realised-variance conventions (e.g. Andersen et al., 2001, 2003), we define the one-second rate

change (within a given day) as

$$\Delta r_{n,d,i,t}^{\text{SC}} \equiv r_{n,d,i,t}^{\text{SC}} - r_{n,d,i,t-1}^{\text{SC}}, \quad (17)$$

whenever both $r_{n,d,i,t}^{\text{SC}}$ and $r_{n,d,i,t-1}^{\text{SC}}$ are observed inside regular trading hours. Let $\mathcal{T}_{n,d,i}^R \subseteq \{1, \dots, T\}$ denote the set of one-second timestamps in interval i for which these rate changes are well defined and fall within regular trading hours. The realised variance over interval i is then

$$\text{RVAR}_{n,d,i}^R = \sum_{t \in \mathcal{T}_{n,d,i}^R} (\Delta r_{n,d,i,t}^{\text{SC}})^2, \quad (18)$$

and realised volatility is defined as

$$\text{RV}_{n,d,i}^R \equiv \sqrt{\text{RVAR}_{n,d,i}^R}. \quad (19)$$

Adapting the Amihud illiquidity idea to repo-rate changes (Amihud, 2002), we define for each second with trading activity in the special-collateral market

$$\iota_{n,d,i,t} \equiv \frac{|\Delta r_{n,d,i,t}^{\text{SC}}|}{V_{n,d,i,t}^R} \quad \text{for } V_{n,d,i,t}^R > 0, \quad (20)$$

where $V_{n,d,i,t}^R$ is the traded volume in that second. Let $\mathcal{T}_{n,d,i}^{R,\text{trade}} \subseteq \{1, \dots, T\}$ denote the set of seconds in interval i for which $V_{n,d,i,t}^R > 0$ (that is, at least one special-collateral trade occurs). The interval-level price impact is

$$\text{PI}_{n,d,i}^R = \frac{1}{|\mathcal{T}_{n,d,i}^{R,\text{trade}}|} \sum_{t \in \mathcal{T}_{n,d,i}^{R,\text{trade}}} \iota_{n,d,i,t}, \quad (21)$$

whenever $|\mathcal{T}_{n,d,i}^{R,\text{trade}}| > 0$; intervals with no trades are excluded from the price-impact sample.

Finally, at the one-second level, specialness is

$$s_{n,d,i,t}^R \equiv r_{d,i,t}^{\text{GC}} - r_{n,d,i,t}^{\text{SC}}, \quad (22)$$

whenever both rates are observed. Let $\mathcal{T}_{n,d,i}^{R,\text{spec}} \subseteq \{1, \dots, T\}$ denote the set of seconds in interval i for which $s_{n,d,i,t}^R$ is well defined. The 15-minute specialness measure is the simple time average over these seconds:

$$\text{SPEC}_{n,d,i}^R \equiv \frac{1}{|\mathcal{T}_{n,d,i}^{R,\text{spec}}|} \sum_{t \in \mathcal{T}_{n,d,i}^{R,\text{spec}}} s_{n,d,i,t}^R. \quad (23)$$

Thus, $\text{SPEC}_{n,d,i}^R$ is a 15-minute aggregation of the per-second specialness premium $r^{\text{GC}} - r^{\text{SC}}$, which follows the standard definition of special collateral premia in Duffie (1996); Jordan and Jordan (1997); Mancini et al. (2016).

Data aggregation

We construct all variables in two stages. First, we aggregate one-second observations into 15-minute measures at the bond, day and interval level (Level 2). Second, we aggregate these bond-level measures across bonds to obtain market-level series (Level 3).

Building on the 15-minute bond, day, and interval measures $\text{PQS}_{n,d,i}^C$, $\text{VOL}_{n,d,i}^C$, $\text{VOL}_{n,d,i}^R$, $\text{TRADES}_{n,d,i}^C$,

TRADES $_{n,d,i}^R$, SIZE $_{n,d,i}^C$, SIZE $_{n,d,i}^R$, RV $_{n,d,i}^C$, RV $_{n,d,i}^R$, DEPTH $_{n,d,i}^C$, PI $_{n,d,i}^R$, and SPEC $_{n,d,i}^R$ defined above, we introduce two further aggregation levels.

Level 2: Market-level aggregation across bonds

For each trading day d and 15-minute interval i , let $\mathcal{N}_{d,i}$ denote the set of bonds for which PQS $_{n,d,i}^C$ is observed, and let $N_{d,i} \equiv |\mathcal{N}_{d,i}|$. The market-level cash proportional quoted spread is

$$\text{PQS}_{d,i}^C = \frac{1}{N_{d,i}} \sum_{n \in \mathcal{N}_{d,i}} \text{PQS}_{n,d,i}^C. \quad (24)$$

All cash and repo measures are constructed in the same way, by replacing PQS $_{n,d,i}^C$ with the relevant interval-level variable and averaging across bonds at each day-interval pair (d, i) .

Level 3: Aggregation across days

To study intraday patterns, we average the market-level series across days. Let $d = 1, \dots, D$ index trading days, and let PQS $_{d,i}^C$ be the market-level spread defined above. The average intraday pattern of the cash proportional quoted spread at interval i is

$$\text{PQS}_i^C = \frac{1}{D} \sum_{d=1}^D \text{PQS}_{d,i}^C. \quad (25)$$

The same aggregation across days is applied to all other market-level variables; the expression above provides the generic form of the day-aggregation step.

Units and reporting conventions

Proportional quoted spreads PQS C , repo specialness SPEC R , and realised volatilities RV C and RV R are reported in basis points. Trade counts TRADES C and TRADES R are unitless.

Quantity-based variables are scaled versions of the raw trade-size and depth fields in the data. In the cash market, trading volume VOL C , average trade size SIZE C , and quoted depth DEPTH C are reported in units of 1,000,000 of the underlying trade-size quantity; that is, we divide the raw quantity by 1,000,000 before reporting. In the repo market, trading volume VOL R , average trade size SIZE R , and any repo depth measure DEPTH R (if used) are reported in units of 10,000,000 of the underlying trade-size quantity, so we divide the raw quantity by 10,000,000.

These conventions affect only the reporting and scaling of the variables; the underlying definitions remain as given in Table 2.

We observe that, within each market segment, trading volume, trade count, and average trade size move very tightly together. In the cash market, VOL C and TRADES C have a correlation of 0.92, and both are positively related to SIZE C (with $\text{corr}(\text{VOL}^C, \text{SIZE}^C) = 0.91$ and $\text{corr}(\text{TRADES}^C, \text{SIZE}^C) = 0.27$). In the repo market, VOL R and TRADES R are almost collinear ($\text{corr} = 0.96$) and both load very strongly on SIZE R (with $\text{corr}(\text{VOL}^R, \text{SIZE}^R) = 0.95$ and $\text{corr}(\text{TRADES}^R, \text{SIZE}^R) = 0.90$). These comovements indicate a high degree of redundancy in the activity block and raise concerns about multicollinearity in the VAR specification.

Table 3: Correlation Matrix (Cash & Repo, market-level, Pearson)

	VOL^C	$TRADES^C$	$SIZE^C$	RV^C	PQS^C	$DEPTH^C$	VOL^R	$TRADES^R$	$SIZE^R$	RV^R	PI^R
$TRADES^C$	0.92										
$SIZE^C$	0.91	0.27									
RV^C	-0.21	-0.17	-0.18								
PQS^C	-0.19	-0.18	-0.10	0.65							
$DEPTH^C$	0.33	0.27	0.31	-0.40	-0.23						
VOL^R	0.04	0.00	0.12	0.01	0.24	0.32					
$TRADES^R$	0.04	-0.01	0.13	0.01	0.25	0.32	0.96				
$SIZE^R$	0.05	0.01	0.12	0.02	0.24	0.30	0.95	0.90			
RV^R	0.07	0.04	0.11	0.03	0.17	0.22	0.60	0.65	0.59		
PI^R	-0.01	-0.01	-0.02	0.04	-0.01	-0.04	-0.14	-0.11	-0.16	0.23	
$SPEC^R$	0.08	0.08	0.05	0.00	0.00	0.12	-0.03	-0.02	-0.05	0.40	0.34

Notes: This table reports Pearson correlation coefficients between market-level liquidity and market-quality measures in the cash and repo segments, computed from fifteen-minute aggregates. VOL^C and VOL^R denote trading volume in the cash and repo markets; $TRADES^C$ and $TRADES^R$ are trade counts; $SIZE^C$ and $SIZE^R$ are average trade sizes; RV^C and RV^R are realised volatilities of mid-yields (cash) and repo rates; PQS^C is the proportional quoted spread in the cash market; $DEPTH^C$ is top-of-book depth; PI^R is the Amihud-type price impact in the special-collateral repo segment; and $SPEC^R$ is the repo specialness premium. All variables are constructed at the bond-day-interval level and then averaged across bonds to obtain market-level series before computing correlations.

To keep the model parsimonious and to avoid over-weighting trading activity, we therefore retain trading volume as the representative activity measure in each segment and drop trade count and average trade size from the VAR and from the subsequent analysis in the paper.

3 PEPP Effect on Intraday Liquidity Patterns

The ECB’s Pandemic Emergency Purchase Programme (PEPP), announced late on 18 March 2020, was the first facility that explicitly allowed the Eurosystem to deviate from the capital key in sovereign-bond purchases.⁵ While the Public-Sector Purchase Programme (PSPP) launched in March 2015 was guided by the Eurosystem capital key, where any country-level over- or under-weights had to be temporary and cancel out over time,⁶ the Pandemic Emergency Purchase Programme (PEPP), announced on 18 March 2020, introduced an explicit flexibility clause. Under this clause, purchase flows may fluctuate over time, across asset classes and among jurisdictions, allowing sizeable and potentially persistent deviations from the capital-key benchmark whenever required to counter market fragmentation.⁷ Consequently, PEPP is the first capital-key programme whose legal design openly permits deliberate, policy-driven departures from the benchmark country weights; earlier facilities such as the PSPP could deviate only for operational or liquidity reasons and were required to revert toward the capital key in the medium run. The programme therefore offers a quasi-natural break for testing how central-bank interventions reshape the microstructure of the spot-next repo segment at high frequency. Our objective in this subsection is to gauge whether (and how fast) the intraday liquidity profile of Italian special-collateral repos adjusted once the PEPP came into force.

⁵See Arrata et al. (2020); Ranaldo et al. (2021) for evidence that large-scale asset purchases tighten collateral markets.

⁶European Central Bank, Implementation aspects of the public sector purchase programme (PSPP), Frankfurt am Main, 5 March 2015. <https://www.ecb.europa.eu/mopo/liq/html/pspp.en.html>

⁷European Central Bank, “ECB announces €750 billion Pandemic Emergency Purchase Programme (PEPP)” Press release, 18 March 2020. https://www.ecb.europa.eu/press/pr/date/2020/html/ecb.pr200318_1-3949d6f266.en.html

To descriptively show the PEPP-effect. We divide the cleaned panel at the cut-off date

$$\text{Pre-PEPP : Date} < 18 \text{ Mar } 2020, \quad \text{During-PEPP : Date} \geq 18 \text{ Mar } 2020,$$

and denote the two subsamples by $\mathcal{S}^{\text{pre}}$ and $\mathcal{S}^{\text{During}}$, respectively. For every date-time interval t we compute the aggregated mean for both $\bar{X}_t^{\text{pre}}$ and $\bar{X}_t^{\text{During}}$, the two intraday curves.

Across 15-minute trade intervals, the cash market displays well-known intraday regularities: trading activity is front-loaded after the open, eases around midday, and strengthens into the close; realized volatility (RV^C) exhibits a mild hump; proportional quoted spreads (PQS^C) tighten rapidly after the first few intervals and remain low; and top-of-book depth (DEPTH^C) rises from thin early books to a higher midday plateau. Relative to the pre-PEPP period, the during-PEPP curves shift in patterns consistent with improved liquidity: trading volume (VOL^C) and trade count (N^C) are higher at most intervals (with the largest gains near the open and late afternoon), average trade size (SIZE^C) is modestly larger through the mid-session, PQS^C is persistently lower after 09:00, and DEPTH^C is higher throughout the day. The shape of RV^C remains broadly similar across regimes while preserving the intraday pattern, while level differences are comparatively small. Overall, the during-PEPP profile features tighter quotes and thicker books alongside stronger trading intensity, indicating a level improvement in liquidity rather than a change in timing.

Across 15-minute trade intervals, the repo market displays a stable intraday profile: trading volume (VOL^R) and trade count (N^R) jump after the open, ease around midday, and rise into the close; average trade size (SIZE^R) tends to increase through the session; realized volatility (RV^R) spikes early and moderates before firming late; and the Amihud price impact (PI^R) is highest near the open and late afternoon, with repo specialness (SPEC^R) positive throughout. Relative to the pre-PEPP sample (blue), the during-PEPP curves (red) show broadly similar timing but different levels: VOL^R , N^R , and SIZE^R are largely comparable to pre-PEPP across most intervals, whereas both PI^R and RV^R are higher for much of the day, particularly around the morning and late-day peaks. SPEC^R is systematically higher during PEPP. Overall, the during-PEPP pattern indicates a higher market volatility with lower liquidity and stronger collateral scarcity without a drastic change in trading intensity.

3.1 Intraday pattern differences

After comparing the graphs for pre- and during- asset purchasing programme, now we assess statistically whether the PEPP programme altered each repo- and cash-market indicator, we compare the pre- and during- PEPP samples along three statistical dimensions. First, we test for a shift in means with the Welch unequal-variance t -test, which remains valid when the two subsamples have different variances and different sizes. Second, we examine changes in dispersion by applying the Brown–Forsythe version of Levene’s test, which is based on absolute deviations from the group medians and is robust to non-normal tails. The p -values obtained for the mean, median, and standard-deviation comparisons are reported for every metric in Table 4.

Descriptive Statistics

Across all dimensions, cash–market liquidity improves markedly in the PEPP period. Proportional quoted spreads PQS^C narrow and depth DEPTH^C expands, with differences that are economically large and

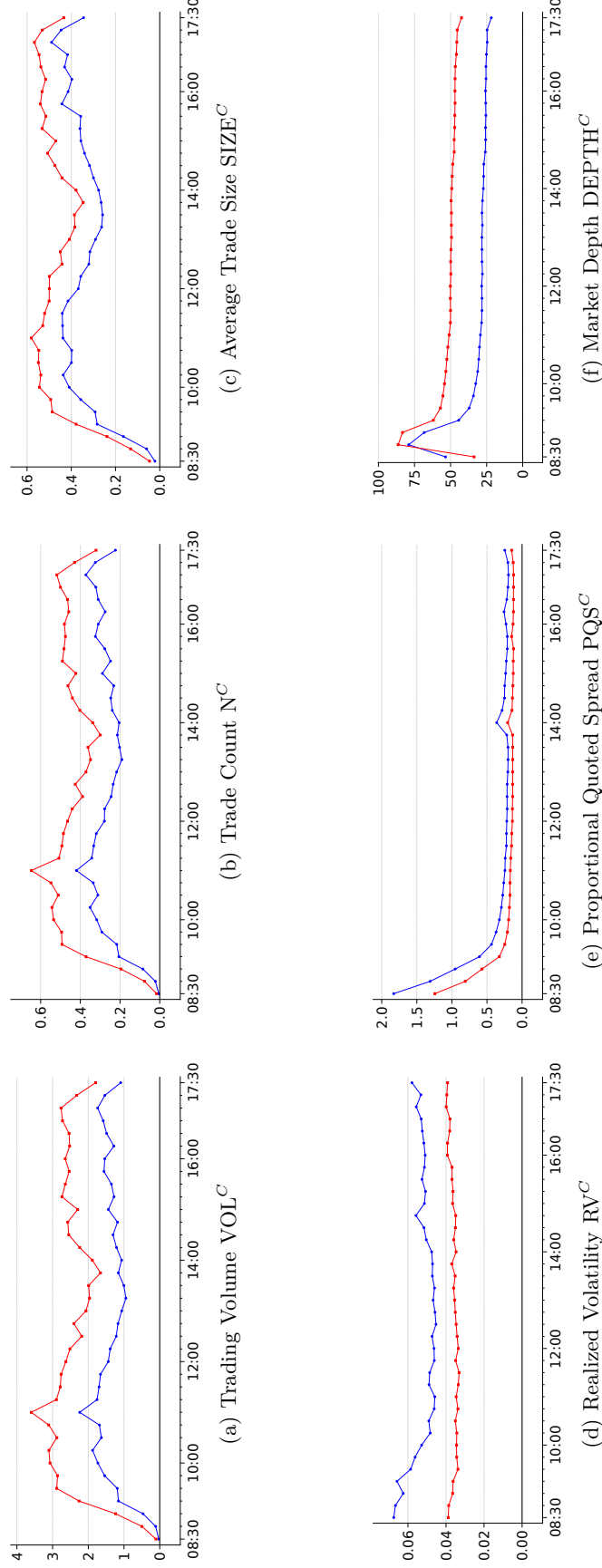


Figure 3: Cash Market Measures

Note: Each panel displays the intraday mean of the indicated liquidity proxy for the **pre-PEPP** sample (blue circles) and the **during-PEPP** sample (red squares). The split date for the subsamples is 18 March 2020, the announcement of the ECB's Pandemic Emergency Purchase programme. Variable definitions follow those in Fig. 2.

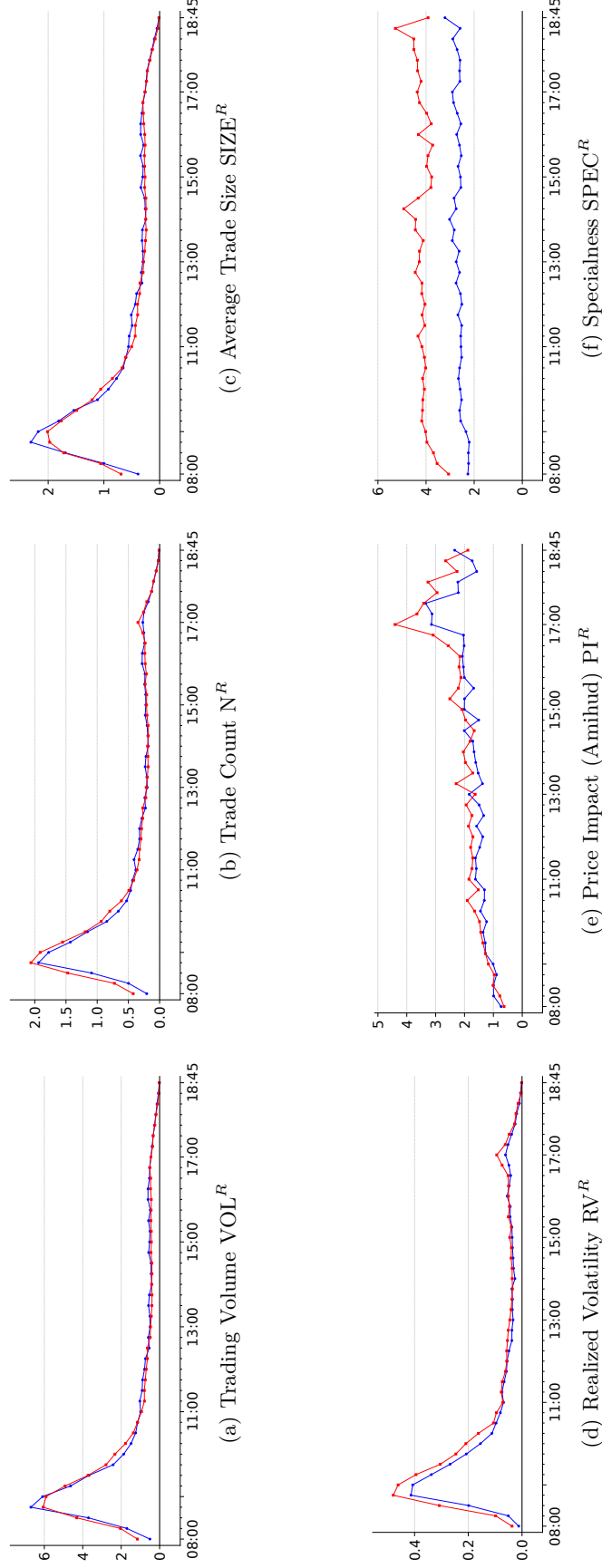


Figure 4: Repo Market Measures

Note: Each panel displays the intraday mean of the indicated repo-market proxy for the **pre-PEPP** sample (blue circles) and the **during-PEPP** sample (red squares). The split date for the subsamples is 18 March 2020 (PEPP announcement). Variable definitions follow those in Fig. 2.

Table 4: Pre- vs. During-PEPP summary statistics

Variable	Means			Standard deviations		
	Pre	During	$t(\bar{X})$	Pre	During	$F(SD)$
VOL^C	17.07	25.26	-34.47***	12.79	14.62	150.74***
$TRADES^C$	3.33	4.48	-32.21***	2.00	2.11	43.46***
$SIZE^C$	4.57	5.08	-19.68***	1.39	1.42	8.69***
RV^C	0.05	0.04	14.89***	0.06	0.06	39.78***
PQS^C	0.35	0.21	14.61***	0.65	0.48	16.09***
$DEPTH^C$	31.42	51.10	-68.37***	17.73	21.36	1198.65***
VOL^R	1.18	1.18	-0.28	1.77	1.77	0.46
$TRADES^R$	0.41	0.44	-6.32***	0.50	0.55	9.65***
$SIZE^R$	0.56	0.54	3.86***	0.65	0.61	7.04***
RV^R	0.08	0.10	-8.63***	0.15	0.18	15.43***
PI^R	1.69	1.99	-6.53***	2.49	3.52	19.50***
$SPEC^R$	2.63	4.15	-27.95***	2.29	4.52	77.21***

Notes: Cash proportional quoted spread PQS^C , cash and repo realised volatility RV^C and RV^R , and repo specialness $SPEC^R$ are expressed in basis points (bps). The columns labelled $t(\bar{X})$ and $F(SD)$ report the test statistics for Welch's unequal-variance t test (differences in means) and the Brown-Forsythe F test (differences in variances), respectively. All tests are conducted on deseasonalised series, after removing systematic intraday patterns. ***, **, and * denote 1%, 5%, and 10% significance, respectively.

statistically precise: all tests on means and dispersions reject equality at the 1% level. Trading activity also strengthens along several margins. Both total volume and the number of trades (VOL^C and $TRADES^C$), as well as average trade size ($SIZE^C$), increase significantly, again with strong rejections across t and F tests on deseasonalised series. Realised volatility in the cash market RV^C also declines in a statistically highly significant way. Although levels are already very low in both periods, the further reduction in volatility is consistent with an improvement in market quality: prices move within a narrower range while trading becomes more active and order books deepen. Overall, the combination of tighter spreads, greater depth, higher trading activity, and lower volatility points to a clear strengthening of cash-market liquidity during the PEPP period.

In contrast, the special-collateral repo segment displays clear signs of strain during the PEPP period. Transaction-cost and price-impact proxies, in particular the Amihud measure PI^R and realised volatility RV^R , both rise with highly significant differences in means and variances, pointing to a deterioration in repo-market liquidity. The collateral premium $SPEC^R$ registers the most pronounced adjustment: all tests overwhelmingly reject equality across regimes, consistent with a substantial and statistically very robust increase in specialness under PEPP. Activity indicators in the repo market move more moderately. Aggregate volumes remain essentially unchanged on average, but the trading pattern shifts towards a larger number of smaller transactions: the number of trades increases slightly whereas average trade size declines, with both changes statistically significant. Overall, the evidence is consistent with a regime in which cash-market liquidity improves sharply, while the corresponding special-collateral repo market becomes more fragile and segmented.

Cash Market Intraday significance

To complement the descriptive intraday profiles, we formally test whether the pre- versus During-PEPP differences at each 15-minute slot are statistically significant. For both cash-market volume and realized volatility, we take the full bond $\times$ day cross-section in each interval and compare pre- and During-PEPP distributions using Welch’s t -test for means, the Mann–Whitney z -test for medians, and the Brown–Forsythe F -test for variances. This step allows us to distinguish visually small but systematic shifts from noise, and to identify which parts of the trading day exhibit robust changes in the level, incidence, and dispersion of our measures.

Table 5 indicates that the PEPP announcement coincides with a strong and pervasive increase in cash–market trading activity. For virtually all 15-minute intervals, average volumes (VOL^C) are higher during PEPP, and Welch unequal-variance t -tests reject equality of means at conventional significance levels throughout the trading day. The increase is not concentrated at specific times: volumes are already elevated at the open, remain materially higher through the late morning and early afternoon, and persist into the final hour. Brown-Forsythe tests further show that the dispersion of market-wide volume across days generally increases during PEPP, implying not only higher typical trading activity but also greater day-to-day variability in aggregate activity at a given time of day.

In parallel, cash-market realised volatility (RV^C), measured in basis points, is lower during PEPP across the intraday profile. The reduction is visible from the open and persists through the late morning, early afternoon, and into the close, with Welch tests indicating statistically significant declines in a large share of 15-minute intervals. In addition, Brown-Forsythe tests rarely reject equality of variances, implying that for the dispersion of RV^C across days at a given time of day, the variance of realised volatility remains broadly similar across two samples. Taken together, the results point to during PEPP, intraday price variability is systematically lower, whereas the dispersion of intraday volatility across days remains broadly unchanged.

Table 6 shows a pronounced During-PEPP compression of proportional quoted spreads across virtually the entire trading day. Welch tests for equality of means reject the null in almost all intraday intervals, indicating systematically tighter PQS C during the programme. Only a very small number of late-midday slots fail to exhibit a statistically significant difference, and even there spreads remain at very low levels in both regimes. Tests for equality of variances point to broadly similar dispersion in the time-series of market-wide spreads across regimes in the early part of the day, followed by a more frequent rejection of variance equality in the afternoon in a direction consistent with a more stable spread environment during the PEPP. Overall, the evidence points to a regime shift towards uniformly narrower and more stable cash-market quoted spreads under the PEPP.

For top-of-book depth, the table indicates a substantial and broad-based improvement in liquidity conditions aligned with other market activity and liquidity measures. With the exception of a short initial window at the very start of trading and one early-morning interval, mean Depth C is significantly higher during the PEPP in every intraday slot, with test statistics uniformly rejecting equality of means. Brown–Forsythe tests likewise reject equality of variances in most intervals, reflecting a marked change in the time-series variability of market-wide depth across days once the programme is in place. Taken together, the depth results signal a regime in which dealers systematically post thicker books at the best quotes throughout the day, while the altered variance pattern suggests that the day-to-day profile of market-wide depth is also

Table 5: Pre- versus During-PEPP Cash-Market Volume and Realized Volatility

Time	Cash-Market Volume (VOL ^C)						Cash-Market Realized Volatility (RV ^C)					
	Means and <i>t</i> -test			SDs and <i>F</i> -test			Means and <i>t</i> -test			SDs and <i>F</i> -test		
	Pre	During	<i>t</i> ($\bar{X}$)	Pre	During	<i>F</i> (SD)	Pre	During	<i>t</i> ($\bar{X}$)	Pre	During	<i>F</i> (SD)
08:30	0.021	0.083	−4.05***	0.062	0.225	10.20***	0.068	0.039	3.44***	0.067	0.094	3.91**
08:45	0.070	0.394	−7.92***	0.110	0.622	35.88***	0.067	0.039	3.53***	0.065	0.089	3.15*
09:00	0.308	0.961	−8.61***	0.434	1.032	47.21***	0.062	0.037	3.22***	0.073	0.079	3.29*
09:15	0.766	1.724	−7.64***	0.979	1.464	24.99***	0.066	0.036	3.86***	0.073	0.068	6.87***
09:30	0.762	2.235	−10.17***	0.745	2.031	42.06***	0.059	0.034	3.17***	0.082	0.056	4.14**
09:45	0.998	2.197	−8.55***	0.985	1.753	35.39***	0.056	0.034	3.11***	0.070	0.057	3.57*
10:00	1.097	2.356	−8.63***	0.990	1.861	39.15***	0.053	0.035	2.67***	0.068	0.057	1.97
10:15	1.226	2.389	−7.04***	1.265	1.958	22.75***	0.048	0.034	2.14**	0.063	0.058	1.05
10:30	1.059	2.195	−8.36***	0.949	1.708	23.15***	0.049	0.035	2.16**	0.059	0.063	0.67
10:45	1.074	2.389	−8.26***	0.952	2.139	27.61***	0.046	0.034	2.14**	0.051	0.060	0.54
11:00	1.432	2.739	−6.74***	1.422	2.364	21.85***	0.046	0.035	1.99**	0.052	0.054	0.21
11:15	1.116	2.214	−7.68***	1.028	1.767	31.80***	0.049	0.034	2.76***	0.056	0.046	1.68
11:30	1.113	2.118	−6.65***	1.290	1.622	17.55***	0.049	0.033	2.80***	0.054	0.047	1.93
11:45	1.054	2.134	−7.59***	0.986	1.794	31.02***	0.046	0.035	2.12**	0.051	0.046	0.55
12:00	0.913	2.015	−9.30***	0.778	1.534	39.58***	0.046	0.034	2.30**	0.056	0.044	1.16
12:15	0.884	1.924	−8.14***	0.846	1.647	28.34***	0.047	0.034	2.22**	0.056	0.055	1.17
12:30	0.783	1.678	−7.68***	0.675	1.581	24.79***	0.045	0.035	1.67*	0.063	0.052	0.62
12:45	0.755	1.840	−9.25***	0.680	1.592	52.97***	0.046	0.035	1.84*	0.057	0.049	0.94
13:00	0.690	1.587	−8.09***	0.759	1.408	31.05***	0.047	0.036	1.62	0.071	0.053	1.02
13:15	0.620	1.505	−8.10***	0.666	1.458	25.74***	0.046	0.036	1.63	0.061	0.052	0.60
13:30	0.645	1.538	−7.52***	0.789	1.528	26.50***	0.047	0.035	2.01**	0.061	0.046	1.87
13:45	0.736	1.269	−5.04***	0.827	1.234	10.18***	0.047	0.037	1.40	0.065	0.072	0.54
14:00	0.687	1.448	−6.53***	0.827	1.448	23.69***	0.048	0.035	2.29**	0.053	0.051	1.86
14:15	0.791	1.715	−7.53***	0.817	1.580	23.38***	0.050	0.036	2.36**	0.061	0.050	2.22
14:30	0.861	1.970	−6.86***	1.166	1.994	18.24***	0.052	0.035	2.55**	0.067	0.049	3.05*
14:45	0.770	1.987	−8.15***	0.942	1.966	26.45***	0.056	0.035	3.27***	0.066	0.047	5.65**
15:00	0.919	1.758	−6.99***	0.888	1.458	19.21***	0.051	0.036	2.60**	0.057	0.046	1.78
15:15	0.822	2.096	−9.44***	0.813	1.810	42.48***	0.051	0.036	2.33**	0.060	0.054	1.11
15:30	0.854	2.011	−9.70***	0.807	1.523	50.28***	0.053	0.037	2.55**	0.063	0.048	1.70
15:45	0.982	1.924	−7.81***	0.855	1.502	27.57***	0.051	0.037	2.25**	0.064	0.053	1.31
16:00	0.974	2.016	−8.58***	0.849	1.524	27.47***	0.051	0.039	1.58	0.062	0.081	0.10
16:15	0.811	1.938	−9.60***	0.718	1.563	48.49***	0.052	0.039	2.04**	0.052	0.064	0.14
16:30	0.942	1.950	−7.67***	0.856	1.708	23.04***	0.053	0.038	2.49**	0.053	0.057	0.54
16:45	0.996	2.079	−7.78***	0.846	1.859	32.47***	0.053	0.038	2.68***	0.053	0.053	1.02
17:00	1.095	2.078	−8.00***	0.824	1.574	24.92***	0.056	0.040	2.21**	0.058	0.080	0.37
17:15	0.973	1.771	−7.21***	0.771	1.392	20.10***	0.053	0.040	2.20**	0.046	0.074	0.08
17:30	0.703	1.373	−7.25***	0.661	1.145	23.51***	0.058	0.039	2.78***	0.055	0.075	1.12

Notes: Means and standard deviations are computed including zero-activity intervals. The $t(\bar{X})$ columns report Welch's unequal-variance *t*-tests for equality of pre- versus during-PEPP means. The *F*(SD) columns report Brown–Forsythe *F*-tests for equality of variances (based on absolute deviations from the median). Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; absence of a superscript indicates non-significance. VOL^C is measured in million units, and RV^C in basis points (bps).

reshaped by the programme rather than liquidity gains being confined to a limited set of dates.

Overall, Tables 5 and 6 provide consistent intraday evidence that the PEPP coincides with a broad-based improvement in cash-market liquidity conditions. Trading activity intensifies markedly throughout the day, with market-wide volumes higher in virtually every 15-minute interval and with greater day-to-day dispersion in volume, while realised volatility is systematically lower across the intraday profile and its day-to-day variability at a given time of day remains largely unchanged. At the same time, quoted liquidity improves

Table 6: Pre- versus During-PEPP Cash-Market Proportional Quoted Spread and Depth

Time	Proportional Quoted Spread (PQS ^C , bps)						Depth (Depth ^C)					
	Means and <i>t</i> -test			SDs and <i>F</i> -test			Means and <i>t</i> -test			SDs and <i>F</i> -test		
	Pre	During	<i>t</i> ($\bar{X}$)	Pre	During	<i>F</i> (SD)	Pre	During	<i>t</i> ($\bar{X}$)	Pre	During	<i>F</i> (SD)
08:30	1.830	1.243	4.52***	1.115	1.369	1.46	53.501	33.694	5.07***	43.701	17.866	87.86***
08:45	1.310	0.810	4.84***	0.917	1.047	3.15*	79.037	86.360	-1.59	43.123	42.943	0.25
09:00	0.953	0.571	4.39***	0.798	0.839	4.51**	68.247	83.315	-4.26***	31.026	36.263	2.25
09:15	0.607	0.324	4.61***	0.609	0.511	8.19***	44.344	61.969	-8.13***	17.714	24.075	9.10***
09:30	0.436	0.247	3.74***	0.520	0.379	4.46**	37.145	57.022	-12.04***	12.234	19.833	25.16***
09:45	0.370	0.209	3.32***	0.481	0.400	3.25*	34.139	55.303	-14.16***	9.872	19.150	42.13***
10:00	0.324	0.192	3.11***	0.430	0.325	3.16*	32.561	54.204	-15.09***	8.948	18.849	47.54***
10:15	0.295	0.180	2.90***	0.403	0.300	3.15*	31.195	53.236	-15.88***	8.007	18.743	66.63***
10:30	0.275	0.172	2.87***	0.370	0.267	3.29*	30.429	52.567	-16.16***	7.908	18.501	65.32***
10:45	0.261	0.171	2.49**	0.343	0.330	1.75	29.972	51.872	-16.33***	7.502	18.286	69.61***
11:00	0.244	0.168	2.17**	0.331	0.329	1.18	29.314	51.017	-16.32***	7.135	18.346	73.23***
11:15	0.241	0.161	2.11**	0.365	0.325	1.18	28.497	50.095	-16.62***	7.174	17.788	72.17***
11:30	0.223	0.151	2.29**	0.308	0.271	1.08	28.218	50.022	-16.93***	7.019	17.693	72.14***
11:45	0.223	0.148	2.45**	0.296	0.270	1.51	28.192	50.128	-17.28***	7.032	17.364	74.43***
12:00	0.218	0.138	2.63***	0.304	0.247	2.20	28.450	50.115	-17.22***	6.979	17.197	75.70***
12:15	0.213	0.138	2.65***	0.281	0.233	1.80	27.923	49.830	-17.27***	6.877	17.457	70.38***
12:30	0.214	0.134	2.63***	0.310	0.226	2.12	28.199	49.939	-17.19***	6.802	17.435	68.78***
12:45	0.213	0.135	2.46**	0.323	0.235	1.97	28.209	49.745	-17.26***	6.739	17.186	70.53***
13:00	0.203	0.135	2.50**	0.270	0.225	1.34	28.263	49.344	-17.22***	6.716	16.786	65.72***
13:15	0.200	0.134	2.59**	0.249	0.216	1.32	27.934	49.422	-17.68***	6.640	16.686	63.66***
13:30	0.200	0.134	2.61***	0.254	0.206	1.73	28.187	49.399	-17.78***	6.455	16.425	70.34***
13:45	0.218	0.136	2.42**	0.365	0.215	2.64	27.871	49.601	-18.01***	6.350	16.736	75.77***
14:00	0.362	0.205	0.93	1.859	0.829	0.76	27.265	49.188	-17.75***	6.534	17.102	78.81***
14:15	0.285	0.144	1.77*	0.919	0.246	2.85*	27.066	48.854	-18.11***	6.379	16.655	83.25***
14:30	0.250	0.137	2.34**	0.546	0.190	4.20**	26.958	48.486	-17.86***	6.562	16.563	79.11***
14:45	0.247	0.131	2.72***	0.488	0.163	5.99**	25.940	47.480	-17.92***	6.424	16.605	85.11***
15:00	0.234	0.126	3.01***	0.402	0.160	6.74***	25.728	47.500	-18.06***	6.283	16.759	86.81***
15:15	0.225	0.126	2.78***	0.397	0.169	5.44**	25.772	47.146	-17.85***	6.272	16.629	88.87***
15:30	0.210	0.122	2.93***	0.330	0.165	5.28**	25.535	47.047	-18.37***	6.178	16.230	78.52***
15:45	0.210	0.150	1.69*	0.322	0.356	0.51	25.660	46.890	-17.86***	6.241	16.495	75.78***
16:00	0.229	0.129	2.22**	0.498	0.232	3.19*	25.813	46.946	-17.75***	6.351	16.452	76.36***
16:15	0.258	0.123	2.32**	0.663	0.198	5.06**	25.429	46.881	-18.29***	6.280	16.194	74.74***
16:30	0.218	0.123	2.74***	0.382	0.187	4.67**	25.474	46.718	-18.30***	5.979	16.146	78.71***
16:45	0.201	0.122	2.76***	0.308	0.177	3.62*	25.123	45.966	-18.07***	6.016	16.030	83.23***
17:00	0.194	0.122	2.73***	0.281	0.171	3.09*	24.612	45.643	-18.18***	5.954	16.124	84.96***
17:15	0.202	0.126	2.60**	0.310	0.184	3.00*	24.697	45.362	-17.57***	6.235	16.277	80.25***
17:30	0.246	0.149	2.81***	0.355	0.258	2.95*	21.771	42.413	-17.82***	5.411	16.492	104.30***

Notes: Means and standard deviations are computed including all intervals. The $t(\bar{X})$ columns report Welch's unequal-variance *t*-tests for equality of pre- versus during-PEPP means. The *F*(SD) columns report Brown-Forsythe *F*-tests for equality of variances (based on absolute deviations from the median). Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; absence of a superscript indicates non-significance. PQS^C is measured in basis points (bps), and Depth^C follows the depth.

on both price and quantity margins: proportional quoted spreads compress across almost the entire trading day and appear, particularly in the afternoon, to evolve in a more stable manner, while top-of-book depth increases strongly and pervasively across intraday slots. These patterns point to a regime shift in which trading becomes more active and order books thicker at tighter quotes, accompanied by lower intraday price variability, consistent with smoother price discovery and enhanced market resilience during the PEPP period.

Repo Market Intraday Pattern Significance

In the repo market, we proceed analogously and formally assess whether the pre- versus post-PEPP differences at each 15-minute slot are statistically meaningful. For every interval and for each repo variable—trading volume (VOL^R), realized volatility (RV^R), Amihud price impact (PI^R) and repo specialness ($SPEC^R$)—we use the full bond $\times$ day cross-section and compare the pre- and post-PEPP distributions by means of Welch’s t -test (means), the Mann–Whitney z -test (medians) and the Brown–Forsythe F -test (variances). This framework helps us distinguish persistent, systematic shifts from mere sampling variation and to identify precisely which parts of the repo trading day experience robust changes in the level, incidence and dispersion of funding activity, volatility, price impact and scarcity premia.

Table 7 documents a pronounced shift in the *timing* of repo-market activity between the pre- and during-PEPP samples. Trading volume (VOL^R) is strongly front-loaded during PEPP, with a materially more active opening phase and statistically significant differences concentrated in the first part of the session. As the day progresses, the regime contrast becomes less uniform: several late-morning and early-afternoon intervals display higher activity in the pre-PEPP period, consistent with a partial redistribution of trading away from midday once PEPP is in place. In the late afternoon and into the close, average volumes converge and tests rarely reject equality of means. Overall, the evidence is best read as a re-timing of repo trading intensity toward the open during PEPP, rather than a broad-based increase in volume throughout the day.

Realized volatility (RV^R) exhibits an even clearer regime change. Volatility is significantly higher during PEPP at the start of the session, indicating that price formation in repo rates becomes more variable precisely when trading activity is most concentrated. Beyond the opening window, RV^R generally remains elevated during PEPP across a wide range of intraday intervals, with additional statistically significant differences emerging around midday and again toward the end of the trading day. The pattern therefore points to a PEPP environment characterised by persistently higher intraday variability in repo rates, with particularly pronounced increases around the open and in the late-afternoon window, consistent with heightened sensitivity of repo pricing to funding and collateral-demand imbalances at these times.

Table 8 indicates that the impact of PEPP on special-collateral repo liquidity operates primarily through *collateral scarcity* rather than through a uniform deterioration in trading conditions. For the Amihud price-impact measure (PI^R), differences between the pre- and post-PEPP periods are heterogeneous across the intraday profile. In the early morning, average PI^R is broadly comparable across regimes, and the corresponding Welch tests typically do not reject equality of means. Statistically significant increases in PI^R appear in selected late-morning and early-afternoon intervals, and become more pronounced closer to the end of the session, where the post-PEPP price impact rises sharply in several late-day bins. This pattern is consistent with price-impact effects being state- and time-dependent: when balance-sheet usage, collateral substitution, and funding needs accumulate intraday, marginal special-collateral trades tend to move repo rates more strongly in the post-PEPP regime.

Repo specialness ($SPEC^R$, bps) exhibits a much clearer and more persistent regime shift. Across virtually the entire trading day, mean $SPEC^R$ is higher in the post-PEPP sample, with Welch tests rejecting equality of means in most intraday intervals, including the open, the core of the session, and the late afternoon. Moreover, Brown-Forsythe tests reject equality of variances more frequently for $SPEC^R$ than for PI^R , particularly in several afternoon and late-day bins, pointing to more variable scarcity premia across days once the programme is in place. Taken together, the evidence suggests that post-PEPP repo conditions are characterised by a persistent elevation in collateral scarcity (higher $SPEC^R$) and episodic spikes in price impact (PI^R) that are

Table 7: Pre- versus During-PEPP Repo-Market Volume and Realized Volatility

Time	Repo-Market Volume (VOL^R)						Repo-Market Realized Volatility (RV^R)					
	Means and t -test			SDs and F -test			Means and t -test			SDs and F -test		
	Pre	During	$t(\bar{X})$	Pre	During	$F(SD)$	Pre	During	$t(\bar{X})$	Pre	During	$F(SD)$
08:00	0.506	1.158	-10.09***	0.382	0.871	38.76***	0.012	0.037	-7.31***	0.026	0.040	24.53***
08:15	1.702	2.033	-2.74***	1.080	1.227	0.55	0.068	0.131	-7.85***	0.057	0.100	21.05***
08:30	3.688	4.292	-3.09***	1.809	1.880	0.44	0.251	0.393	-5.16***	0.169	0.366	2.20
08:45	6.672	6.033	2.19**	2.793	2.666	0.39	0.501	0.583	-2.58**	0.255	0.357	1.03
09:00	6.060	5.888	0.73	2.102	2.404	1.98	0.518	0.593	-2.15**	0.312	0.348	1.34
09:15	4.618	4.894	-1.17	2.295	2.061	1.60	0.471	0.539	-1.82*	0.341	0.382	0.01
09:30	3.661	3.704	-0.20	2.127	1.826	3.33*	0.396	0.445	-1.23	0.325	0.445	0.01
09:45	2.408	2.776	-2.45**	1.452	1.329	0.11	0.326	0.378	-1.06	0.481	0.426	0.06
10:00	1.862	2.311	-3.56***	1.183	1.194	1.34	0.252	0.333	-2.96***	0.223	0.304	1.03
10:15	1.479	1.769	-2.57**	0.997	1.157	2.50	0.205	0.270	-2.45**	0.190	0.333	0.65
10:30	1.239	1.360	-1.33	0.849	0.869	0.01	0.185	0.203	-0.94	0.189	0.161	0.07
10:45	1.135	1.145	-0.12	0.858	0.742	0.02	0.163	0.188	-1.77*	0.128	0.136	0.89
11:00	0.984	0.937	0.68	0.656	0.639	0.03	0.154	0.161	-0.43	0.140	0.168	0.06
11:15	1.022	0.785	2.73***	0.921	0.593	3.35*	0.160	0.163	-0.18	0.132	0.212	0.24
11:30	0.904	0.790	1.62	0.691	0.606	1.83	0.144	0.155	-0.67	0.147	0.166	0.15
11:45	0.881	0.741	2.07**	0.658	0.588	1.07	0.132	0.141	-0.61	0.099	0.188	0.42
12:00	0.780	0.691	1.57	0.524	0.537	0.00	0.119	0.136	-1.67*	0.082	0.123	3.83*
12:15	0.732	0.631	1.48	0.705	0.523	1.44	0.114	0.133	-1.34	0.125	0.138	0.55
12:30	0.539	0.629	-1.66*	0.446	0.597	1.34	0.091	0.123	-2.89***	0.105	0.102	1.72
12:45	0.580	0.487	1.54	0.647	0.394	5.15**	0.091	0.118	-2.03**	0.084	0.174	1.57
13:00	0.494	0.442	0.51	0.442	0.400	0.93	0.087	0.111	-2.12**	0.085	0.128	2.68
13:15	0.502	0.396	1.79*	0.396	0.346	2.95*	0.086	0.101	-1.62	0.084	0.095	0.84
13:30	0.573	0.528	3.47***	0.528	0.359	9.90***	0.082	0.098	-1.99**	0.061	0.097	6.24**
13:45	0.528	0.454	2.99***	0.454	0.364	6.92***	0.089	0.096	-0.85	0.081	0.082	0.13
14:00	0.408	0.416	-0.18	0.408	0.412	0.02	0.068	0.104	-4.67***	0.059	0.089	12.31***
14:15	0.438	0.396	0.93	0.422	0.432	0.02	0.081	0.092	-1.25	0.079	0.088	4.18**
14:30	0.442	0.400	1.08	0.342	0.397	0.09	0.090	0.100	-1.00	0.099	0.105	2.08
14:45	0.566	0.444	2.30**	0.552	0.383	5.77**	0.091	0.107	-1.56	0.073	0.131	1.58
15:00	0.518	0.427	2.05**	0.452	0.352	5.55**	0.093	0.114	-1.64	0.077	0.167	2.32
15:15	0.498	0.432	1.54	0.432	0.332	2.33	0.093	0.110	-2.12**	0.069	0.096	3.36*
15:30	0.573	0.453	2.45**	0.520	0.342	8.40***	0.108	0.122	-1.30	0.100	0.111	2.25
15:45	0.483	0.439	0.99	0.415	0.424	0.42	0.111	0.116	-0.56	0.092	0.102	0.10
16:00	0.601	0.431	3.29***	0.563	0.305	14.40***	0.124	0.128	-0.34	0.104	0.111	0.01
16:15	0.598	0.469	2.39**	0.555	0.409	5.20**	0.119	0.130	-1.11	0.086	0.099	3.24*
16:30	0.527	0.465	1.32	0.473	0.376	4.68**	0.111	0.142	-2.15**	0.098	0.187	2.08
16:45	0.516	0.506	0.22	0.408	0.408	0.01	0.123	0.172	-3.35***	0.091	0.195	4.91**
17:00	0.449	0.449	0.00	0.401	0.320	2.34	0.166	0.239	-4.59***	0.130	0.179	3.40*
17:15	0.389	0.361	0.85	0.316	0.302	0.36	0.146	0.167	-1.67*	0.118	0.125	2.30
17:30	0.333	0.336	-0.10	0.307	0.356	0.12	0.114	0.140	-2.54**	0.085	0.118	2.30
17:45	0.264	0.248	0.50	0.284	0.290	0.95	0.082	0.088	-0.86	0.071	0.083	0.79
18:00	0.197	0.185	0.48	0.228	0.268	0.26	0.062	0.075	-1.41	0.064	0.107	1.33
18:15	0.134	0.103	1.58	0.205	0.152	4.48**	0.036	0.042	-0.87	0.051	0.086	0.12
18:30	0.063	0.036	2.19**	0.133	0.075	6.52**	0.017	0.015	0.48	0.038	0.027	0.27
18:45	0.016	0.014	0.42	0.051	0.035	0.21	0.007	0.007	0.24	0.027	0.020	0.07

Notes: Means and standard deviations are computed from two-step aggregated day-level series. For each day and 15-minute interval, we first take the simple average across all bonds, and then compute pre- and during-PEPP moments across days. The $t(\bar{X})$ columns report Welch's unequal-variance t -tests for equality of pre- versus during-PEPP means. The $F(SD)$ columns report Brown-Forsythe F -tests for equality of variances (based on absolute deviations from the median). Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; absence of a superscript indicates non-significance. VOL^R denotes the repo trading volume aggregated to the market level from bond-level observations, and RV^R is the repo realized volatility.

concentrated at intraday times when funding and inventory constraints are more likely to bind.

Table 8: Pre- versus Post-PEPP Repo-Market Amihud Price Impact and Specialness

Time	Repo Amihud Price Impact (PI^R)						Repo Specialness ($SPEC^R$, bps)					
	Means and t -test			SDs and F -test			Means and t -test			SDs and F -test		
	Pre	Post	$t(\bar{X})$	Pre	Post	$F(SD)$	Pre	Post	$t(\bar{X})$	Pre	Post	$F(SD)$
08:00	0.734	0.630	0.69	1.488	0.935	2.92*	2.261	3.062	-3.30***	2.051	1.977	0.00
08:15	0.992	0.778	1.04	2.320	0.849	3.98**	2.233	3.542	-3.58***	1.844	4.483	0.54
08:30	0.998	1.011	-0.12	0.957	1.167	0.82	2.240	3.693	-4.28***	1.697	4.249	1.06
08:45	0.890	0.968	-1.33	0.391	0.749	3.01*	2.206	3.963	-5.32***	1.640	4.244	1.33
09:00	1.009	1.173	-1.76*	0.717	1.095	1.75	2.341	4.019	-5.43***	1.601	4.026	1.23
09:15	1.276	1.276	0.00	1.080	1.100	0.03	2.561	4.179	-5.33***	1.652	3.973	1.51
09:30	1.282	1.362	-0.62	1.129	1.325	0.04	2.604	4.147	-4.99***	1.764	4.050	1.12
09:45	1.357	1.437	-0.63	1.208	1.194	0.89	2.524	4.134	-5.67***	1.585	3.796	2.04
10:00	1.233	1.480	-1.78*	0.878	1.821	2.62	2.583	4.070	-4.74***	2.163	3.869	0.81
10:15	1.448	1.654	-1.24	1.392	1.817	1.86	2.654	4.141	-4.42***	2.035	4.445	1.29
10:30	1.313	1.904	-2.73***	1.042	3.082	4.68**	2.605	4.013	-4.42***	2.263	3.915	1.34
10:45	1.309	1.525	-1.50	1.222	1.559	1.72	2.522	4.069	-4.44***	2.382	4.383	1.65
11:00	1.623	1.847	-0.89	2.058	2.814	0.75	2.549	4.171	-4.36***	2.496	4.755	1.94
11:15	1.592	1.740	-0.53	1.858	3.655	0.27	2.560	4.334	-4.54***	2.670	4.961	2.62
11:30	1.621	1.712	-0.46	1.710	2.089	0.51	2.519	4.051	-4.33***	2.260	4.621	2.97*
11:45	1.475	1.788	-1.12	2.310	3.118	0.56	2.676	4.166	-3.42***	2.884	5.601	1.99
12:00	1.366	1.709	-1.54	1.845	2.458	1.40	2.512	4.045	-3.86***	2.588	5.150	2.04
12:15	1.582	1.861	-0.99	2.520	2.906	0.54	2.570	4.178	-3.97***	2.732	5.174	1.67
12:30	1.336	1.741	-2.24**	1.367	2.160	2.29	2.753	4.169	-3.32***	3.381	4.905	0.85
12:45	1.496	1.944	-1.65*	1.503	3.718	1.32	2.608	4.449	-4.78***	2.401	5.071	3.82*
13:00	1.838	1.631	0.45	5.102	2.215	0.37	2.747	4.280	-4.04***	2.564	4.818	4.44**
13:15	1.377	2.290	-1.70*	1.694	7.998	1.52	2.625	4.271	-4.04***	2.890	5.038	2.87*
13:30	1.528	1.716	-0.76	2.491	1.977	0.42	2.909	4.116	-3.27***	2.329	4.840	2.60
13:45	1.612	1.971	-1.25	2.967	2.085	0.51	2.826	4.444	-3.39***	2.831	6.368	1.38
14:00	1.669	2.040	-1.36	2.320	2.897	0.89	3.023	4.432	-3.01***	4.084	4.832	0.80
14:15	1.712	1.808	-0.43	1.891	2.342	0.55	2.748	4.925	-4.20***	2.324	7.436	4.04**
14:30	2.010	1.664	1.37	2.409	2.264	2.24	2.836	4.327	-4.09***	2.345	4.761	2.92*
14:45	1.509	1.965	-2.15**	1.659	2.470	3.85*	2.553	3.798	-5.27***	2.234	2.175	3.06*
15:00	2.006	2.087	-0.16	5.451	3.483	0.01	2.570	3.767	-4.71***	2.070	2.826	2.13
15:15	2.002	2.509	-1.12	3.735	4.956	0.37	2.670	3.976	-4.52***	2.240	3.360	1.61
15:30	1.683	2.214	-2.27**	1.517	3.026	3.01*	2.536	3.919	-5.81***	1.797	2.827	2.08
15:45	2.007	2.125	-0.50	2.218	2.200	0.02	2.610	3.727	-4.81***	1.947	2.522	3.02*
16:00	2.040	2.189	-0.51	2.563	3.029	0.06	2.726	4.318	-2.65***	2.684	8.601	0.89
16:15	2.074	2.160	-0.31	2.460	2.741	0.03	2.552	3.782	-6.00***	1.928	1.882	2.33
16:30	2.014	2.564	-1.45	3.081	4.242	1.73	2.705	3.974	-6.01***	1.525	2.578	2.34
16:45	2.036	3.086	-4.01***	1.622	3.456	5.43**	2.858	4.271	-4.37***	1.915	4.322	1.68
17:00	3.145	4.405	-3.00***	3.106	5.056	1.80	2.906	4.366	-5.75***	2.589	1.935	0.00
17:15	3.124	3.647	-1.24	3.678	4.311	0.52	2.594	4.208	-8.61***	1.691	1.840	0.47
17:30	3.348	3.413	-0.11	4.562	6.438	0.03	2.606	4.350	-7.65***	2.092	2.174	1.08
17:45	2.215	2.950	-1.63	2.502	6.022	1.64	2.587	4.361	-8.01***	1.571	2.662	10.88***
18:00	2.231	3.266	-1.63	3.144	8.591	1.00	2.709	4.506	-5.68***	1.798	4.105	2.64
18:15	1.578	2.260	-2.19**	2.220	3.278	3.03*	2.890	4.508	-3.36***	2.028	6.323	2.04
18:30	1.734	2.651	-1.93*	2.469	4.293	2.56	2.585	5.274	-3.30***	1.656	9.044	3.54*
18:45	2.340	1.885	0.75	2.791	2.469	0.19	3.214	3.915	-1.43	2.125	2.336	0.00

Notes: Means and standard deviations are computed from two-step aggregated day-level series. For each day and 15-minute interval, we first take the simple average across all bonds, and then compute pre- and post-PEPP moments across days. The $t(\bar{X})$ columns report Welch's unequal-variance t -tests for equality of pre- versus post-PEPP means. The $F(SD)$ columns report Brown-Forsythe F -tests for equality of variances (based on absolute deviations from the median). Significance codes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$; absence of a superscript indicates non-significance. PI^R is the repo Amihud price-impact measure; $SPEC^R$ denotes repo specialness measured in basis points (bps).

Overall, Tables 7 and 8 jointly point to a PEPP-era repo market in which *scarcity dynamics* become more central to intraday trading conditions. While trading activity and realized volatility exhibit a non-uniform re-timing across the session, the most pervasive shift is the sustained rise in repo specialness, consistent with a structurally higher scarcity premium for specific collateral after PEPP. In parallel, the Amihud price-impact evidence indicates that market became illiquid during PEPP. the effect is more pronounced in late-day intervals especially around cash market and repo market closing when funding pressures, balance-sheet constraints, and collateral allocation frictions are more likely to bind market participants. Intraday patterns are consistent with a post-PEPP environment in which central-bank intermediation coincides with tighter effective availability of special collateral, producing persistently higher scarcity premia and episodically stronger volume-to-rate transmission in the special repo segment.

4 Liquidity spillovers for pre-PEPP and during PEPP

Liquidity spillovers represent the transmission of liquidity shocks across markets and asset classes, where disturbances in one market propagate to affect liquidity conditions in related markets. In the context of sovereign bond markets, these spillovers manifest through two primary channels: the direct transmission between cash and repo markets for the same security, and the cross-sectional spillovers across different sovereign issuers. The interaction between repo market liquidity the ease with which market participants can obtain financing, the ease with which securities can be traded—creates a bilateral feedback mechanism where shocks in one market amplify conditions in the other. When funding constraints tighten in the repo market, investors’ ability to intermediate in the cash market deteriorates, reducing market liquidity and widening bid-ask spreads. Conversely, deteriorating market liquidity in the cash market increases the cost and difficulty of unwinding positions, thereby straining funding liquidity as collateral becomes more difficult to value and finance. This bidirectional relationship intensifies during periods of market stress, when both dimensions of liquidity tend to deteriorate simultaneously, creating adverse feedback loops that can compromise market functioning.

Previous studies have highlighted the impact of central bank asset purchase programmes on collateral scarcity and market functioning. Arrata et al. (2020) find that QE measures can lead to significant scarcity effects in the bond market, affecting the price and availability of securities. Similarly, Schlepper et al. (2020) demonstrate that the ECB’s asset purchases have had notable effects on repo specialness and market liquidity conditions. Baltzer et al. (2022) further discuss how the Eurosystem’s collateral framework interacts with monetary policy operations, influencing liquidity in financial markets. The excess liquidity resulting from the PEPP intensifies these spillover dynamics by fundamentally altering the collateral landscape. As the central bank absorbs high-quality government bonds from the market, the reduction in the supply of eligible collateral intensifies repo specialness—the premium paid for borrowing specific securities in the repo market. This scarcity effect operates through multiple channels: first, by increasing competition for scarce securities, thereby elevating specialness premia; second, by forcing market participants to substitute toward less liquid or less preferred collateral, thereby fragmenting liquidity across the collateral pool; and third, by amplifying the sensitivity of repo rates to idiosyncratic shocks in individual securities. As specialness increases, liquidity frictions are exacerbated in both the repo and cash markets, potentially amplifying the bilateral feedback loop between funding liquidity and market liquidity. The PEPP’s flexibility to deviate from

the ECB’s capital key subscription structure—allowing disproportionate purchases of bonds from countries under greater market pressure—may have heterogeneous effects on spillover dynamics across sovereign issuers, with potentially stronger scarcity effects in jurisdictions where PEPP purchases were most concentrated. This propagation channel suggests that the PEPP may have modified the magnitude, persistence, and cross-sectional heterogeneity of spillover effects between funding and market liquidity by fundamentally altering the collateral scarcity dynamics that govern repo market functioning.

Given these considerations, our analysis examines how liquidity spillovers change with the introduction of an additional asset purchase programme that allows deviations from the capital key and how market liquidity dynamics evolve in the periods before and during the implementation of the PEPP. Specifically, the empirical framework assesses whether the excess liquidity introduced by the PEPP amplifies spillover effects through increased collateral scarcity. To this end, separate vector autoregression (VAR) models are estimated for the pre-PEPP and during-PEPP periods. As in the previous section, Granger causality tests are employed to identify the directionality of relationships between key variables, and impulse response functions are used to evaluate the dynamic effects of shocks over time.

Sample Construction and Period Definitions. To investigate how liquidity spillovers between repo and cash–bond markets evolved with the implementation of the PEPP, we estimate separate VARs for two distinct periods: Pre-PEPP (before 18 March 2020) and During-PEPP (from 18 March 2020 onwards).

Our market-level dataset is constructed from high-frequency bond-level liquidity measures sampled at 15-minute intervals. For each variable, we aggregate across all bonds in our sample by taking the simple cross-sectional mean at each timestamp, yielding representative market-level series. Because repo and cash markets operate on different trading schedules,⁸ we restrict the sample to the common trading window when both are simultaneously open (08:30–17:30 CET), ensuring our spillover analysis is not contaminated by non-overlapping trading hours.

To investigate how liquidity spillovers between the repo and cash–bond markets evolved with the implementation of the PEPP, we estimate separate vector autoregressions (VARs) for two distinct periods: Pre-PEPP (before 18 March 2020) and During-PEPP (from 18 March 2020 onwards). Our market-level dataset is constructed from high-frequency bond-level liquidity measures sampled at 15-minute intervals. For each variable, we aggregate across all bonds in our sample by taking the simple cross-sectional mean at each timestamp, yielding representative market-level series for repo trading volume (VOL^R), repo realized volatility (RV^R), repo Amihud illiquidity (PI^R), repo specialness ($SPEC^R$), cash-market trading volume (VOL^C), cash realized volatility (RV^C), proportional quoted spread in basis points (PQS^C), and top-of-book depth ($DEPTH^C$). Because repo and cash markets operate on different trading schedules, we restrict the sample to the common trading window when both are simultaneously open, 08:30–17:30 CET,⁹ so that our spillover analysis is not include non-overlapping trading hours.

VAR Identification Strategy and Causal Ordering

To identify structural shocks in our vector autoregression framework, we employ a recursive Wold causal ordering that separately characterizes intra-market and cross-market transmission mechanisms. Within the

⁸The repo market operates from 08:00 to 18:45, while the cash bond market trades from 08:30 to 17:30.

⁹The repo market operates from 08:00 to 18:45, while the cash bond market trades from 08:30 to 17:30. We use the intersection of these periods.

cash-bond market, we follow the market microstructure framework of Kyle (1985) and Easley and O'Hara (1992) by ordering variables from information-driven volatility shocks to price adjustments (proportional quoted spreads) to quantity responses (market depth and trading volume), reflecting the sequential process through which dealers update quotes in response to uncertainty and inventory risk. For the repo segment, we place specialness premium first in the ordering, consistent with Duffie (1996) and Jordan and Jordan (1997), who demonstrate that collateral scarcity shocks originate from supply frictions in the special-collateral market and subsequently propagate to transaction costs and trading activity. Regarding cross-market spillovers, while the canonical view suggests repo-to-cash causality (Corradin et al., 2020; Huh and Infante, 2020), we explicitly account for bidirectional transmission by incorporating the regulatory constraint imposed by Article 13 of EU Regulation 236/2012, which mandates that short sellers secure collateral through reverse repo transactions prior to executing cash-market sales. This institutional feature creates a structural repo-to-cash channel that intensifies under collateral scarcity, precisely the condition induced by large-scale central bank asset purchases. Our identification strategy therefore tests whether the PEPP-driven withdrawal of high-quality collateral strengthened this reverse transmission mechanism, manifesting in stronger impulse responses from repo specialness and illiquidity shocks to cash-market depth and spreads in the During-PEPP regime. To ensure robustness, we verify that our main results remain qualitatively unchanged across alternative Cholesky orderings and supplement the analysis with generalized impulse response functions that are invariant to variable ordering (Pesaran and Shin, 1998).

Structural shocks are identified by a recursive (Cholesky) decomposition of the reduced-form VAR residuals. Our *baseline* specification orders cash-market variables first and repo variables second, reflecting the institutional feature of EU short-selling regulation (Regulation 236/2012, Article 13), which requires short sellers to pre-borrow or locate collateral via reverse repo before executing cash-market sales. In this “Cash $\rightarrow$ Repo” ordering, the endogenous vector is

$$\mathbf{Y}_t^{\text{Cash}} = (\text{VOL}_t^C, \text{RV}_t^C, \text{PQS}_t^C, \text{DEPTH}_t^C, \text{VOL}_t^R, \text{RV}_t^R, \text{PI}_t^R, \text{SPEC}_t^R)'$$

Shocks to cash-market liquidity are thus allowed to have contemporaneous effects on repo-market conditions, while repo shocks affect cash variables only with a lag. This captures the mechanism whereby increased selling pressure and changing execution costs in the cash market tighten collateral conditions and amplify specialness premia in the repo segment.

As a robustness check, we also consider the conventional “Repo $\rightarrow$ Cash” ordering, which embodies the view that funding conditions drive secondary-market liquidity. In this alternative specification,

$$\mathbf{Y}_t^{\text{Repo}} = (\text{VOL}_t^R, \text{RV}_t^R, \text{PI}_t^R, \text{SPEC}_t^R, \text{VOL}_t^C, \text{RV}_t^C, \text{PQS}_t^C, \text{DEPTH}_t^C)',$$

so that structural shocks to repo liquidity and specialness can contemporaneously affect cash-market variables, while the reverse impact operates with a lag. Comparing impulse responses across these two recursive schemes allows us to assess the robustness of our spillover estimates and to gauge the relative importance of cash-to-repo versus repo-to-cash transmission channels before and during the PEPP.

Our empirical strategy incorporates several robustness features. First, by estimating VARs under two alternative causal orderings, we verify that key spillover findings are not artifacts of a particular identification scheme. Second, the use of intraday time dummies controls for systematic patterns in liquidity provision

throughout the trading day, isolating the component of variation relevant for cross-market transmission. Third, the BIC-based lag selection ensures that our models capture the relevant dynamic structure without overfitting but we also confirm that usage of AIC-based lag selection do not change the main results. Finally, by computing IRFs over a long horizon, of one and half day, we assess both immediate and persistent transmission effects, distinguishing temporary liquidity disruptions from sustained liquidity shifts.

Table 9: Pairwise Granger causality

	VOL^C	RV^C	PQS^C	$DEPTH^C$	VOL^R	RV^R	PI^R	$SPEC^R$
Panel A: Pre-PEPP								
VOL^C	—	0.299	3.945***	2.423*	0.242	0.483	0.279	4.139***
RV^C	0.668	—	17.502***	13.291***	1.073	0.017	1.051	2.594*
PQS^C	0.507	89.135***	—	7.675***	1.335	3.066**	1.370	0.766
$DEPTH^C$	1.119	26.178***	1.264	—	1.051	0.228	4.754***	2.011
VOL^R	2.025	3.332**	0.200	9.666***	—	1.788	1.678	3.314**
RV^R	0.802	0.344	5.662***	0.633	134.163***	—	0.514	5.381***
PI^R	1.709	2.402*	2.053	0.878	1.033	8.359***	—	83.799***
$SPEC^R$	0.872	0.112	0.834	0.203	1.162	54.588***	11.396***	—
Panel B: During-PEPP								
VOL^C	—	1.076	5.189***	33.863***	2.271*	1.476	1.024	0.455
RV^C	1.268	—	25.418***	5.877***	0.519	0.083	0.772	0.571
PQS^C	2.862**	239.739***	—	3.818***	1.045	0.858	0.562	0.875
$DEPTH^C$	5.555***	2.382**	66.552***	—	1.147	0.408	0.763	0.127
VOL^R	2.399**	4.434***	27.810***	3.917***	—	2.068*	6.758***	1.154
RV^R	1.417	1.486	6.782***	0.677	122.025***	—	24.419***	26.206***
PI^R	3.191**	0.282	0.476	1.274	0.494	16.054***	—	46.709***
$SPEC^R$	0.768	1.198	9.634***	0.544	2.677**	46.474***	25.771***	—

Notes: Entries report F-statistics for the null that the column variable does not Granger-cause the row variable, based on VARs with BIC-selected lag length and intraday time-of-day dummies. Panel A uses $p = 3$ (Pre-PEPP) and Panel B uses $p = 4$ (During-PEPP). VOL^C , RV^C , PQS^C , and $DEPTH^C$ denote cash-market volume, realised volatility, proportional quoted spread, and depth; VOL^R , RV^R , PI^R , and $SPEC^R$ denote repo-market volume, realised volatility, Amihud price impact, and specialness. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Within each market, the Granger results point to substantial internal feedback at intraday horizons, but the structure differs across subsamples. In the cash market, the tightest interactions are among realised volatility RV^C , spreads PQS^C , and depth $DEPTH^C$. In the pre-PEPP period, PQS^C and $DEPTH^C$ predict subsequent trading activity VOL^C , while RV^C strongly forecasts both PQS^C and $DEPTH^C$, and depth in turn helps to forecast future spreads. By contrast, cash volume plays a more limited role as a driver of other cash-market variables in this subsample. On the repo side, the system is anchored by a strong liquidity–scarcity nexus: realised volatility RV^R and specialness $SPEC^R$ are mutually predictive, and both variables also forecast the Amihud price impact PI^R , where PI^R captures how strongly repo rates respond to trading volume. Price impact, in turn, predicts specialness, consistent with a repo market in which scarcity premia and trade-induced rate movements reinforce each other at short horizons.

Cross-market linkages show that the cash and repo markets do not evolve independently, but the direction of predictability changes across regimes. In the pre-PEPP sample, repo-market conditions carry meaningful predictive content for cash-market liquidity. In particular, repo specialness predicts cash trading activity and also has some forecasting power for cash volatility, while repo price impact predicts subsequent cash depth and repo realised volatility predicts cash spreads. By comparison, cash-to-repo spillovers are more

selective before PEPP: cash depth and cash volatility predict repo trading activity, and cash spreads predict repo realised volatility, but cash variables provide little systematic predictive power for repo specialness in this period. Overall, the pre-PEPP cross-market pattern is consistent with collateral scarcity and repo liquidity frictions propagating into cash-market order-book resilience, with feedback from cash to repo mainly operating through repo activity and volatility rather than through scarcity premia.

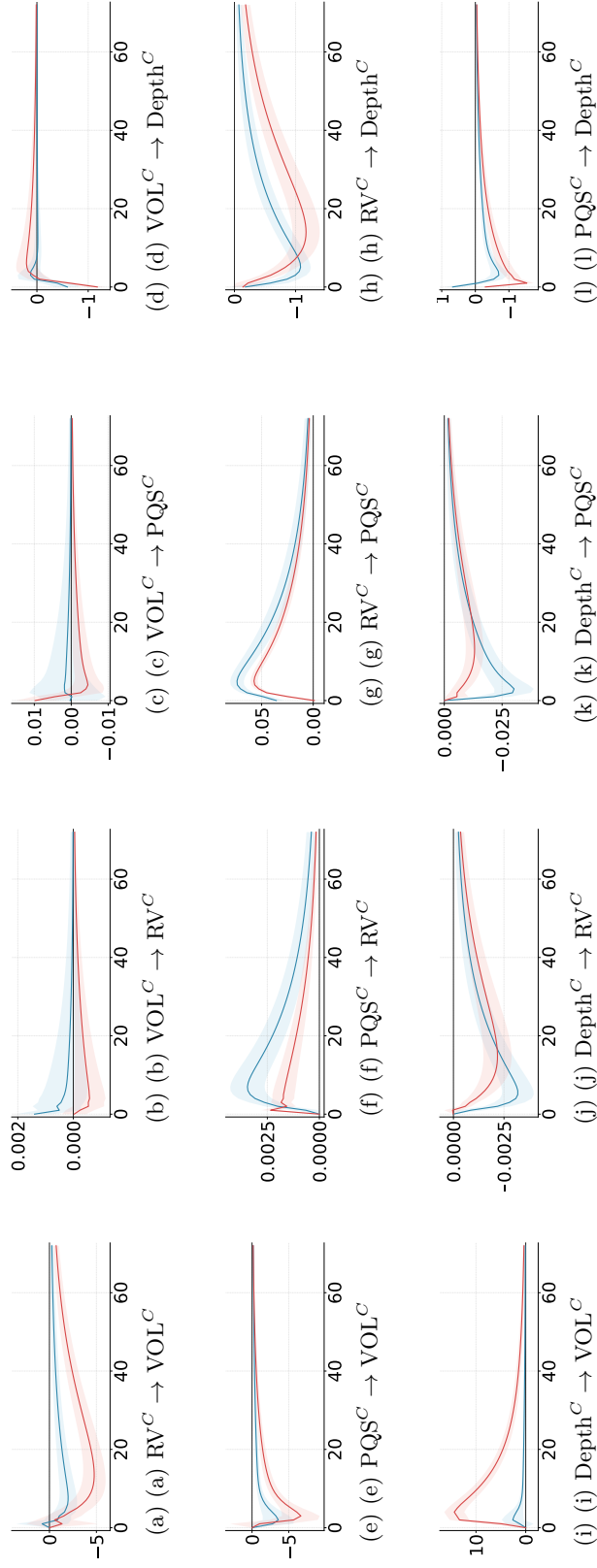
During PEPP, the architecture of predictability shifts toward stronger cash-to-repo transmission and a denser internal cash-market feedback loop. Within the cash market, VOL^C becomes an active component of the system: volume, spreads, depth, and volatility exhibit more pervasive two-way predictability, consistent with faster intraday adjustment between trading intensity and order-book conditions. Across markets, cash liquidity indicators (especially PQS^C , $DEPTH^C$, and RV^C) forecast repo trading activity VOL^R , and cash spreads in particular predict both repo realised volatility and repo specialness, indicating that cash-market liquidity and uncertainty are closely tied to collateral scarcity dynamics during PEPP. Cash volume also helps to forecast repo price impact, suggesting that heightened trading pressure in the cash market is associated with stronger trade-volume-driven rate impacts in the special repo segment. In contrast, repo-to-cash predictability becomes more limited in this subsample, with the most robust reverse link running from repo activity to cash activity. Taken together, the evidence indicates a regime shift toward tighter integration in which cash-market liquidity conditions play a more prominent leading role for repo-market liquidity and scarcity during PEPP, while repo variables contribute less systematically to forecasting cash-market order-book conditions.

Figure 5 shows that the cash market is characterised by strong and rapid within-market feedbacks between order-book conditions and trading intensity. Shocks to proportional quoted spreads PQS^C immediately widen spreads further, compress depth $DEPTH^C$, and raise both volume VOL^C and realised volatility RV^C , consistent with a temporary deterioration in market liquidity followed by a gradual mean reversion within roughly 20–30 intervals. As expected Depth innovations work in the opposite direction: a positive shock to $DEPTH^C$ tightens PQS^C and decreases subsequent volatility, while also attracting additional trading volume. Volume and volatility shocks in turn propagate back to both PQS^C and $DEPTH^C$, indicating that trading activity and order-book quotes adjust jointly rather than in isolation. Across almost all impulse–response pairs, the during-PEPP responses (red) are noticeably larger in magnitude than their pre-PEPP counterparts (blue), suggesting that the same cash-market shock induces stronger short-run adjustments in spreads, depth, and volatility once the PEPP is in place.

Figure 6 documents a clear transmission of cash–market shocks to repo–market liquidity conditions. Innovations in cash-market spreads and depth (PQS^C and $DEPTH^C$) generate pronounced and short-lived responses in repo trading volume VOL^R , realised volatility RV^R , Amihud price impact PI^R , and specialness $SPEC^R$, while shocks to cash volume and volatility have more muted effects. In particular, a widening of PQS^C or a fall in $DEPTH^C$ is followed by higher PI^R and $SPEC^R$, indicating that a temporary deterioration in cash–market liquidity is accompanied by tighter and more fragile conditions in the special–collateral repo segment. Across most impulse–response pairs the red lines (during–PEPP regime) are larger in magnitude than the blue lines (pre–PEPP), especially for responses of PI^R and $SPEC^R$. This suggests that, once the PEPP is in place, cash–market order–book shocks are transmitted more forcefully to repo–market illiquidity, consistent with an amplification of the collateral channel in periods of abundant central–bank reserves.

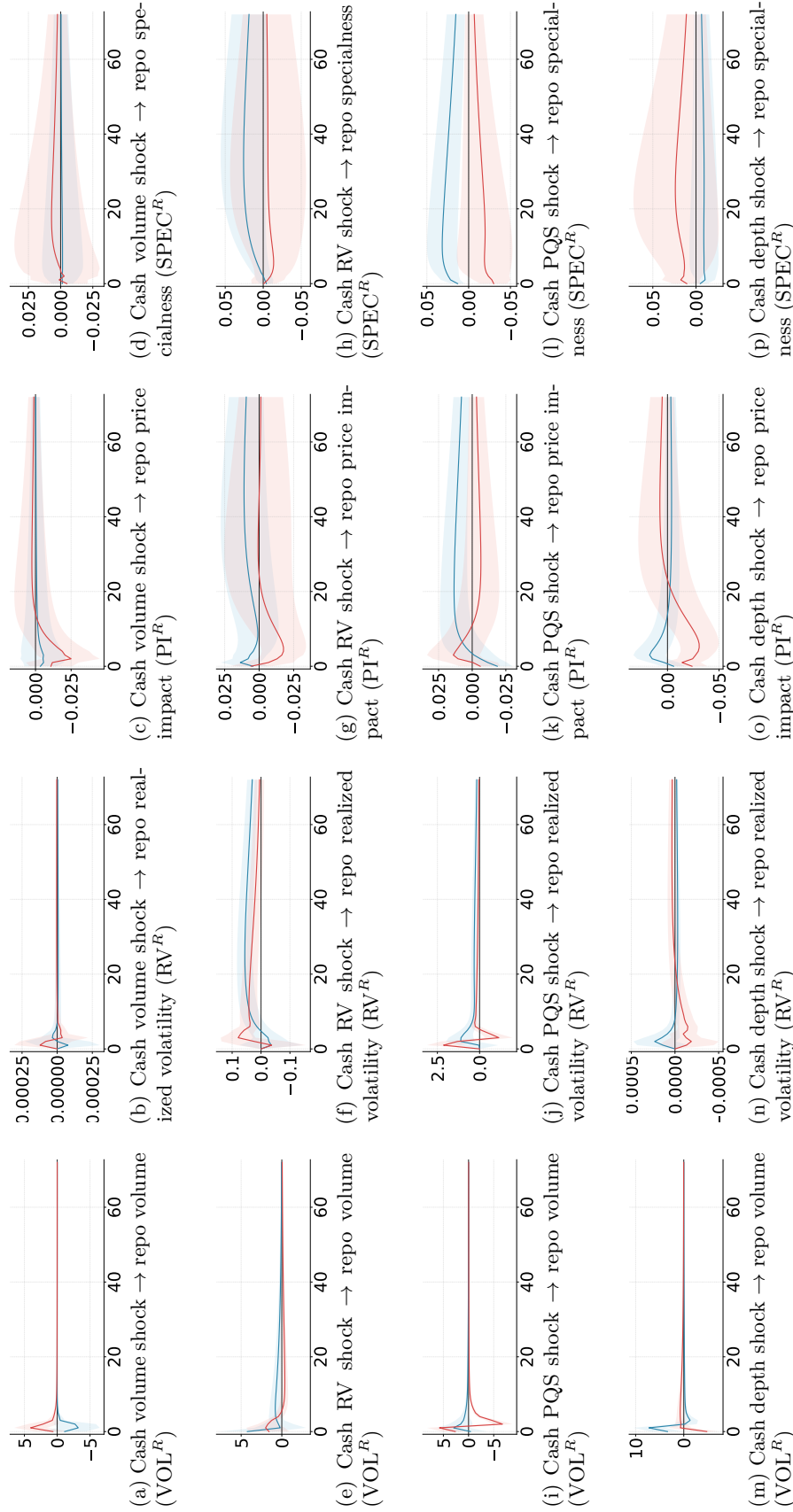
Figure 7 illustrates the reverse spillover channel, tracing how shocks originating in the special collateral repo segment propagate to cash market liquidity. Innovations in repo trading activity (VOL^R) have only limited

Figure 5: Cash-market impulse response functions (cash shocks to cash variables)



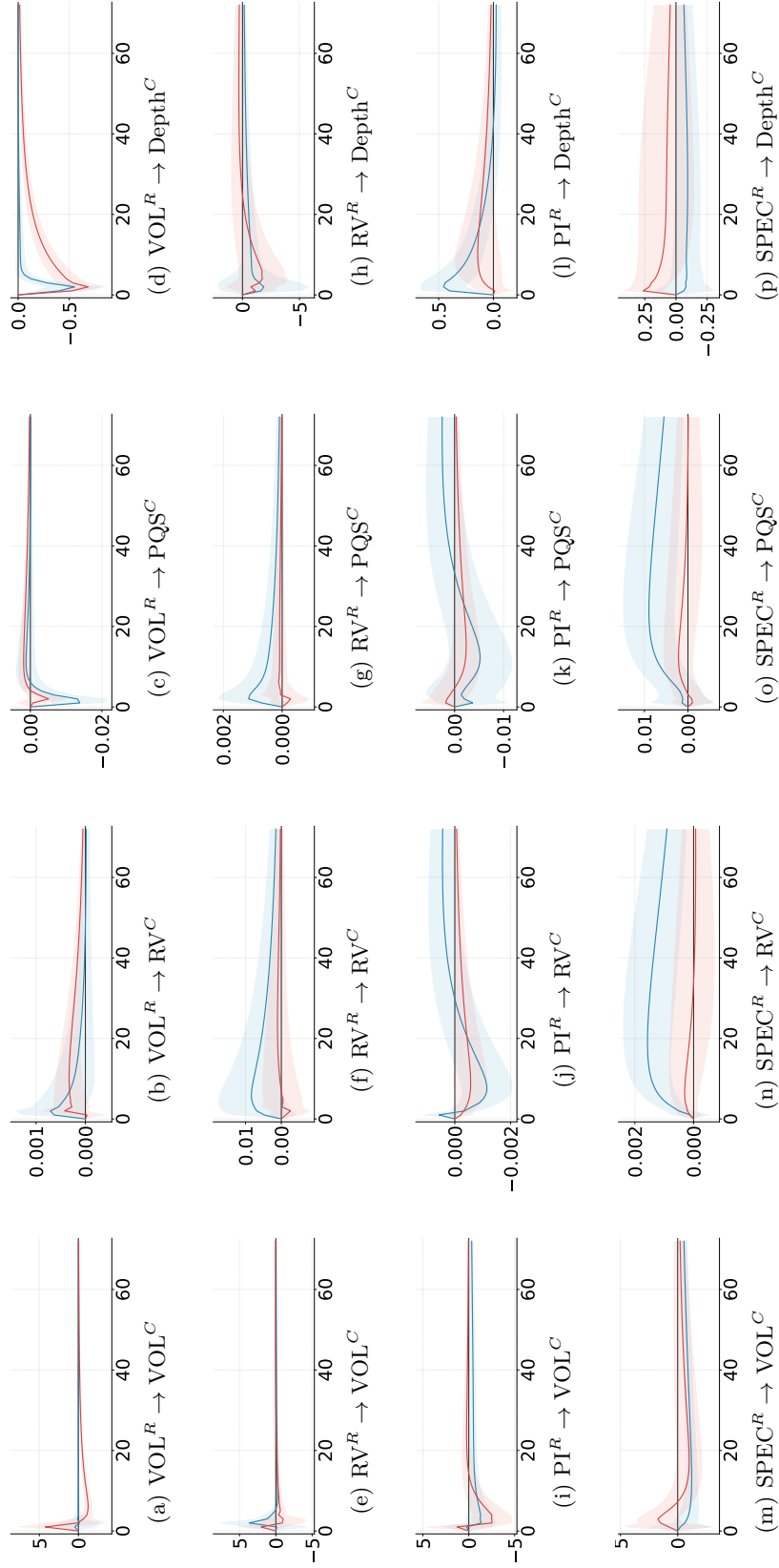
Notes: Each panel reports an orthogonalized impulse response from a VAR in cash-market variables (VOL^C , RV^C , PQS^C , $DEPTH^C$), estimated on 15-minute data and including time-of-day dummies as exogenous controls. The VAR is estimated separately on the pre-PEPP and During-PEPP subsamples. In every subfigure, the first variable in the caption provides a one-standard-deviation shock, and the second variable provides the response. The solid blue (red) line shows the pre-PEPP (During-PEPP) response; shaded regions (where visible) denote approximate 95% confidence bands. Horizons on the horizontal axis are measured in 15-minute steps, and the vertical axis uses the original units of each series.

Figure 6: Cash-market shocks to repo-market impulse response functions



Notes: Each panel reports an orthogonalized impulse response from a VAR in cash- and repo-market variables with 15-minute data, estimated separately on the pre-PEPP and During-PEPP subsamples and including time-of-day dummies as exogenous controls. In every subfigure, the cash-market variable named in the caption provides a one-standard-deviation shock, and the repo-market variable provides the response. The solid blue (red) line shows the pre-PEPP (During-PEPP) response; shaded areas (where visible) denote approximate 95% confidence bands. Horizons on the horizontal axis are measured in 15-minute steps; the vertical axis uses the original units of each series.

Figure 7: Repo-market shocks to cash-market impulse response functions



Notes: Each panel reports an orthogonalized impulse response from a VAR in repo- and cash-market variables with 15-minute data, estimated separately on the pre-PEPP and During-PEPP subsamples and including time-of-day dummies as exogenous controls. In every subfigure, the repo-market variable named in the caption provides a one-standard-deviation shock, and the cash-market variable provides the response. The solid blue (red) line shows the pre-PEPP (During-PEPP) response; shaded areas (where visible) denote approximate 95% confidence bands. Horizons on the horizontal axis are measured in 15-minute steps; the vertical axis uses the original units of each series.

and short lived effects on cash market variables, whereas shocks to repo illiquidity, captured by realised volatility RV^R , Amihud price impact PI^R and specialness $SPEC^R$, generate more pronounced reactions. In particular, positive PI^R and $SPEC^R$ shocks are followed by modest increases in cash market spreads PQS^C and realised volatility RV^C , alongside slight declines in depth $DEPTH^C$, consistent with the idea that stressed funding and collateral conditions weaken secondary market liquidity. Overall, the repo $\rightarrow$ cash responses are weaker and less persistent than the cash $\rightarrow$ repo spillovers documented in Figure 6, but the red impulse response paths, which correspond to the PEPP period, tend to dominate the blue pre PEPP paths, especially for shocks in PI^R and $SPEC^R$. This pattern suggests that the introduction of the PEPP amplifies the transmission of repo market stress to cash market liquidity, in line with a stronger collateral channel in the presence of large central bank purchases.

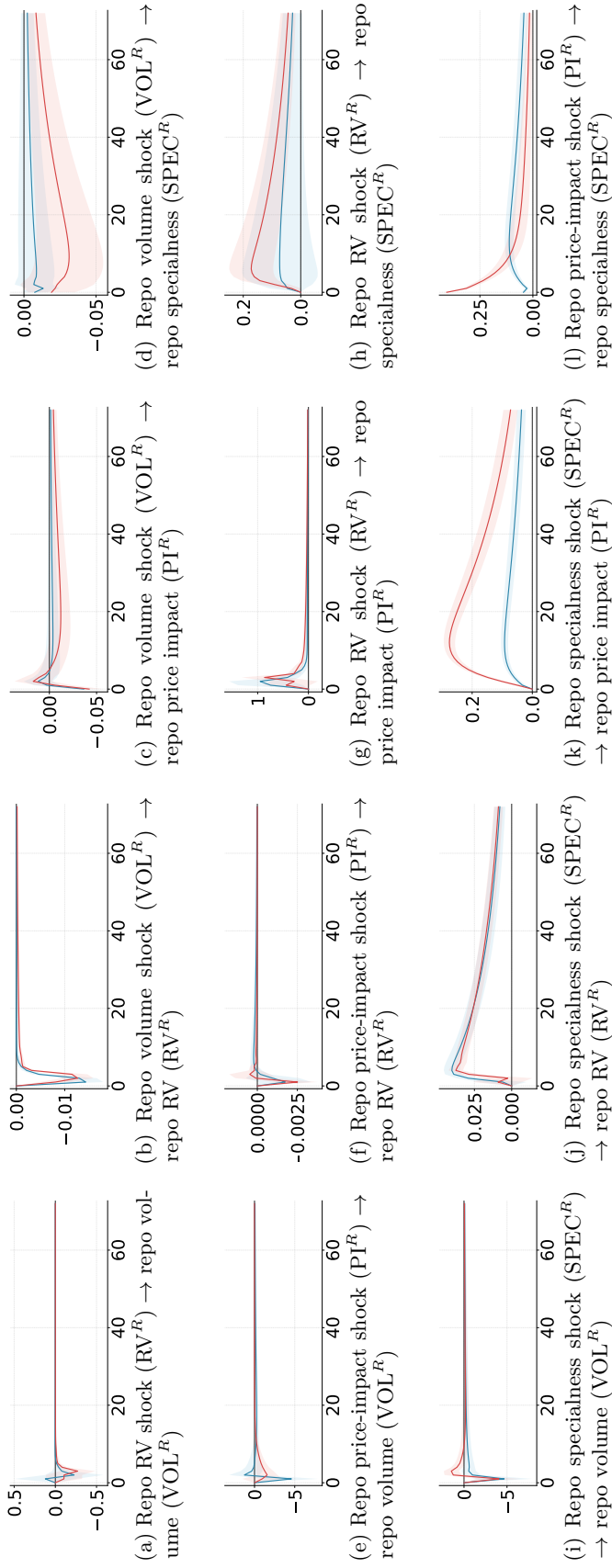
Figure 8 summarises the transmission of shocks within the repo market. A positive innovation to repo trading activity VOL^R has only a modest and short lived effect on its own future path and on the other repo variables, which indicates that temporary bursts in activity do not generate persistent changes in repo illiquidity. In contrast, shocks to realised volatility RV^R and Amihud price impact PI^R produce large and persistent responses in both RV^R and PI^R , with the responses in the PEPP period (red lines) systematically exceeding those in the earlier regime (blue lines). Shocks to specialness $SPEC^R$ also raise PI^R and RV^R markedly, again with stronger and more durable effects under PEPP. Overall, the figure shows that volatility, price impact, and collateral scarcity reinforce one another more strongly within the special collateral segment once PEPP is in place, consistent with an amplification of funding and collateral constraints inside the repo market.

5 Conclusion

This paper provides an intraday view of how the ECB’s Pandemic Emergency Purchase Programme (PEPP) reshaped liquidity in the Italian sovereign bond market and its associated special-collateral repo segment. Using millisecond-level data aggregated to 15-minute intervals, we jointly track trading activity, price impact, quoted spreads, order-book depth, and repo specialness across cash and repo markets. The descriptive evidence reveals a stark asymmetry. In the cash market, proportional quoted spreads narrow, top-of-book depth increases markedly, and trading volume rises throughout the trading day. In the repo market, by contrast, realized volatility and Amihud price impact become larger, specialness premia move persistently higher, and trading activity concentrates more heavily in the early part of the session. PEPP thus appears to improve immediate trading conditions in the cash market while tightening collateral constraints in the special-collateral repo segment.

Our VAR-based spillover analysis sharpens this picture. Estimating separate VARs before and during PEPP, with the cash-to-repo ordering as benchmark and the repo-to-cash ordering as robustness, we show that funding–market shocks and liquidity shocks increasingly propagate across segments after the programme’s launch. Shocks to repo illiquidity and specialness exert stronger and more persistent effects on cash-market depth and spreads in the PEPP regime, while cash-market depth feeds back more strongly into repo specialness. These patterns are consistent with a regime in which central-bank purchases absorb a significant share of high-quality collateral, making the locate constraint more binding for short sellers and increasing the strategic

Figure 8: Repo-market shocks to repo-market impulse response functions



Notes: Each panel reports an orthogonalized impulse response from a VAR including only repo-market variables (volume VOL^R , realized volatility RV^R , Amihud price impact PI^R , and repo specialness $SPEC^R$), using 15-minute data and time-of-day dummies as exogenous controls. The repo variable named first in each caption provides a one-standard-deviation shock, and the second variable provides the response. Solid blue (red) lines depict pre-PEPP (During-PEPP) responses; shaded bands, where visible, indicate approximate 95% confidence intervals. Horizons on the horizontal axis are measured in 15-minute steps, and the vertical axis is in the original units of each series. Self-responses (a variable's response to its *own* shock) are omitted from this figure and reported only in the individual IRF output.

value of special collateral for intermediaries.

From a policy perspective, our results highlight an important duality between asset purchases as a tool to stabilise secondary-market liquidity and their collateral-side effects in the secured funding market. While PEPP succeeded in compressing yields and improving cash-market liquidity, it also contributed to a tighter and more volatile special-collateral repo environment. This suggests that large-scale purchase programmes are more effective and less distortionary when they are accompanied by active securities lending, collateral swaps, or other measures that recycle scarce collateral back into the market. More broadly, our findings underscore that assessments of unconventional monetary policy should incorporate funding-market frictions and collateral scarcity, not only cash-market price and volume measures.

Finally, the paper opens several avenues for future research. One natural extension is to study heterogeneous effects across maturities and issuer segments, or to contrast Italian bonds with other large sovereigns in the euro area. Another is to embed our empirical results in a structural model of intermediaries that jointly choose cash-market quotes and repo positions under balance-sheet and collateral constraints. Such work would help quantify welfare and distributional implications of purchase programmes and inform the design of policy frameworks that support market functioning without causing collateral scarcity.

References

- Altavilla, C., Carboni, G., and Motto, R. (2015). Asset purchase programmes and financial markets: lessons from the euro area. Technical report, ECB Working paper.
- Amihud, Y. (2002). Illiquidity and stock returns: Cross-section and time-series effects. *Journal of Financial Markets*, 5(1):31–56.
- Andersen, T. G., Bollerslev, T., Diebold, F. X., and Ebens, H. (2001). The distribution of realized stock return volatility. *Journal of Financial Economics*, 61(1):43–76.
- Andersen, T. G., Bollerslev, T., Diebold, F. X., and Labys, P. (2003). Modeling and forecasting realized volatility. *Econometrica*, 71(2):579–625.
- Arrata, W., Nguyen, B., Rahmouni-Rousseau, I., and Vari, M. (2020). The scarcity effect of qe on repo rates: Evidence from the euro area. *Journal of Financial Economics*, 137(3):837–856.
- Baltzer, M., Schlepper, K., and Speck, C. (2022). The eurosystem’s asset purchase programmes, securities lending and bund specialness. *Deutsche Bundesbank Discussion Paper*.
- Bandi, F. M. and Perron, B. (2006). Long memory and the relation between implied and realized volatility. *Journal of Financial Econometrics*, 4(4):636–670.
- Bank, E. C. (2020). Ecb recalibrates its monetary policy instruments. Press release, 10 December 2020.
- Bränder, P. and Lovas, A. (2019). Repo specialness and the information content of treasury collateral. Technical Report 19-16, Swiss Finance Institute.
- Brunnermeier, M. K. and Pedersen, L. H. (2009). Market liquidity and funding liquidity. *Review of Financial Studies*, 22(6):2201–2238.
- Cheung, Y. C., De Jong, F., and Rindi, B. (2005). Trading european sovereign bonds: the microstructure of the mts trading platforms. Technical report, ECB working paper.
- Chordia, T., Roll, R., and Subrahmanyam, A. (2001). Market liquidity and trading activity. *The journal of finance*, 56(2):501–530.
- Chordia, T., Roll, R., and Subrahmanyam, A. (2002). Order imbalance, liquidity, and market returns. *Journal of Financial Economics*, 65(1):111–130.
- Comotto, R. (2024). European repo market survey. number 47 – conducted june 2024. Technical report, International Capital Market Association (ICMA), Zurich. Semi-annual survey of the European repo market.
- Corradin, S., Maddaloni, A., and Quéralt, J. (2020). The importance of being special: Repo markets during distress. *Journal of Financial Economics*, 137(2):392–414.
- D’Amico, S., Fan, R., and Kitsul, Y. (2018). The scarcity value of treasury collateral: Repo-market effects of security-specific supply and demand factors. *Journal of Financial and Quantitative Analysis*, 53(5):2103–2129.

- Dick, C. and Mazzotta, S. (2009). Liquidity filtering and bond microstructure. Working Paper 1095, European Central Bank.
- Duffie, D. (1996). Special repo rates. *Journal of Finance*, 51(2):493–526.
- Dufour, A., Marra, M., Sangiorgi, I., and Skinner, F. S. (2020). Explaining repo specialness. *International Journal of Finance & Economics*, 25(2):172–196.
- Easley, D. and O’Hara, M. (1992). Time and the process of security price adjustment. *The Journal of Finance*, 47(2):577–605.
- European Central Bank (2020a). Euro money market statistical data release. <https://www.ecb.europa.eu>. Accessed 14 May 2025.
- European Central Bank (2020b). Financial stability review, may 2020. European Central Bank publication.
- Foucault, T., Pagano, M., and Röell, A. (2023). *Market Liquidity: Theory, Evidence, and Policy*. Oxford University Press.
- Gagnon, J. E. et al. (2016). Quantitative easing: An underappreciated success. *PIIE Policy Brief*, 16(43):1–7.
- Ghysels, E., Idier, J., Manganelli, S., and Vergote, O. (2017). A high-frequency assessment of the ECB securities markets programme. *Journal of the European Economic Association*, 15(1):218–243.
- Glosten, L. R. and Milgrom, P. R. (1985). Bid, ask and transaction prices in a specialist market with heterogeneously informed traders. *Journal of Financial Economics*, 14(1):71–100.
- Goyenko, R. Y., Holden, C. W., and Trzcinka, C. A. (2009). Do liquidity measures measure liquidity? *Journal of financial Economics*, 92(2):153–181.
- Hansen, P. R. and Lunde, A. (2006). Realized variance and market microstructure noise. *Journal of Business & Economic Statistics*, 24(2):127–161.
- Huang, R. D. and Stoll, H. R. (1997). The components of the bid-ask spread: A general approach. *Review of Financial Studies*, 10(4):995–1034.
- Huh, Y. and Infante, S. (2020). Bond market intermediation and the role of repo. Finance and Economics Discussion Series 2017-003, Board of Governors of the Federal Reserve System. Revised version.
- ICMA European Repo and Collateral Council (ERCC) (2020). The european repo market and the covid-19 crisis. Technical report, International Capital Market Association. ERCC report on market performance, accessibility, settlement efficiency, and collateral management during Feb–Apr 2020.
- International Capital Market Association (2019). What is ‘short selling’ and what is the role of repo? *Frequently Asked Questions on Repo*, Question 30. ICMA European Repo and Collateral Council.
- International Capital Market Association (2021). European repo market survey no. 41 – conducted 9 june 2021. Technical Report 41, International Capital Market Association (ICMA).
- Jordan, B. D. and Jordan, S. D. (1997). Special repo rates: An empirical analysis. *The Journal of Finance*, 52(5):2051–2072.

- Joyce, M., Lasaosa, A., Stevens, I., and Tong, M. (2010). The financial market impact of quantitative easing. Technical report, Bank of England working paper.
- Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). The effects of quantitative easing on interest rates: channels and implications for policy. Technical report, National Bureau of Economic Research.
- Kyle, A. S. (1985). Continuous auctions and insider trading. *Econometrica*, 53(6):1315–1335.
- Mancini, L., Ranaldo, A., and Wrampelmeyer, J. (2016). The euro interbank repo market. *The Review of Financial Studies*, 29(7):1747–1779.
- O’Hara, M. (1995). *Market Microstructure Theory*. Blackwell Publishers, Oxford (UK) and Cambridge (USA).
- Pesaran, M. H. and Shin, Y. (1998). Generalized impulse response analysis in linear multivariate models. *Economics Letters*, 58(1):17–29.
- Ranaldo, A., Schaffner, P., and Vasios, M. (2021). Regulatory effects on short-term interest rates. *Journal of Financial Economics*, 141(2):750–770.
- Rossi, A. and Vu, T. (2014). Realized volatility in fixed-income markets. *Journal of Empirical Finance*, 29:367–381.
- Sack, B., Gagnon, J., Raskin, M., and Remache, J. (2011). The financial market effects of the federal reserve’s large-scale asset purchases. Technical report, Bank for International Settlements (BIS); Banca d’Italia/Central Bank of Italy.
- Schaffner, P. and Senner, F. (2019). Euro repo trading and the rise of electronic platforms. *Journal of Financial Market Infrastructures*, 7(3):1–30.
- Schlepper, K., Hofer, H., Riordan, R., and Schrimpf, A. (2020). The market microstructure of central bank bond purchases. *Journal of Financial and Quantitative Analysis*, 55(1):193–221.
- Singh, M. (2014). Financial plumbing and monetary policy. IMF Working Paper WP/14/111, International Monetary Fund.
- Stoll, H. R. (2000). Presidential address: friction. *The Journal of finance*, 55(4):1479–1514.