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Abstract

In August 2016, the Bank of England (BoE) announced a Corporate Bond Purchase Scheme (CBPS) to purchase up to £10 billion of sterling corporate bonds. To investigate the impact of these purchases on liquidity, we create a novel dataset that combines transaction-level data from the secondary corporate bond market with proprietary offer-level data from the BoE's CBPS auctions. Identifying the impact of central bank asset purchases on liquidity is potentially impacted by reverse causality, because liquidity considerations might impact purchases. But the offer-level data allow us to construct proxy measures for the BoE's demand for bonds and auction participants' supply of bonds, meaning that we can control for the impact of liquidity on purchases. Across a range of liquidity measures, we find that CBPS purchases improved the liquidity of purchased bonds.

Key words: Quantitative easing, market liquidity, market-making, corporate bonds.

JEL classification: G12, G23, E52, E58.

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1 Introduction

Quantitative easing (QE) has become a key component of the monetary policy toolkit since the global financial crisis. The aim of QE is typically to stimulate nominal spending and therefore increase inflation (Joyce et al., 2011b). But the introduction of a large, relatively price-insensitive buyer has the potential to significantly impact market functioning. Indeed, both policy makers and market participants have raised concerns that central bank asset purchases could lead to a deterioration in market liquidity. For example, in his 2012 Jackson Hole speech, Federal Reserve Chairman Bernanke argued that the Federal Reserve's large-scale asset purchases "could impair the functioning of securities markets" (Bernanke, 2012). Similarly, fund manager PIMCO reported that "the Street's capacity or willingness to provide liquidity has declined" after the ECB began its covered bond purchase programme in 2014 (Financial Times, 2015). Poor liquidity can increase financial stability risks, impede price discovery and lead to misallocation of resources. Understanding the impact of QE on liquidity is therefore of clear importance to the design of future policy interventions.

In theory, the impact of central bank asset purchases on liquidity could be positive or negative. On the one hand, asset purchases are likely to stimulate trading by inducing portfolio rebalancing. In addition, market participants have argued that the presence of a 'back-stop buyer' makes dealers more willing to hold larger bond inventories, and therefore facilitates market-making. On the other hand, asset purchases lead to a reduction in the quantity of bonds held by private investors, which could damage liquidity by increasing search frictions. Moreover, asset purchases by a relatively price-insensitive central bank might distort price signals, reducing the willingness of market participants to trade. The net effect of these channels is theoretically ambiguous and is likely to depend on the structure of the market and the design of the asset purchase programme.

This paper contributes to our understanding of these issues by providing evidence on the impact of the Bank of England's (BoE) Corporate Bond Purchase Scheme (CBPS) on the liquidity of sterling corporate bonds. In August 2016, following the UK's vote to leave the European Union, the BoE announced a package of monetary stimulus measures. This included a new scheme to purchase up to £10bn of sterling-denominated corporate bonds. The purchases were implemented between September 2016 and April 2017 via a series of auctions. The objective of the purchases was to impart monetary stimulus by lowering corporate bond yields, triggering portfolio rebalancing, and stimulating corporate bond issuance (Bank of England, 2016). But a potential unintended consequence was a reduction in market liquidity. This paper focuses on the impact of the CBPS on liquidity, rather than the overall macroeconomic impact.

Our analysis of the CBPS is based on a novel combination of two granular, proprietary datasets: transaction-level data on the corporate bond market and offer-level data from the CBPS auctions. We use the transaction-level data to compute a wide range of measures of market liquidity, including simple measures of trading activity such as total weekly trading volume, measures of transaction costs such as the effective spread, and measures of price impact such as the Amihud measure. We then use the offer-level data to estimate the impact of CBPS purchases on these liquidity measures.

In general, an important challenge to identifying the causal impact of central bank asset purchases on liquidity is that purchases are not randomly assigned across bonds. Instead, the purchase decisions of the central bank might be affected by liquidity considerations. For example, the central bank might focus purchases on less liquid bonds in an attempt to improve the liquidity of those bonds. Alternatively, the central bank might avoid purchasing illiquid bonds in order to reduce the risk on its own balance sheet. In either case, there would be a problem of reverse causality, with liquidity impacting purchases rather than purchases impacting liquidity. Importantly, this effect could go in either direction.

The design of the CBPS and the granularity of our dataset help us to reduce the magnitude of any estimation biases arising from reverse causality. In comparison to bilateral purchases, the auction design of the CBPS greatly reduces the discretionary nature of purchases. During the auctions, the auction participants submitted offers specifying the bonds that they were willing to sell to the BoE and the spreads (prices) at which they were willing to sell them. The offers can be viewed as expressions of the auction participants' supply of bonds. And ahead of each auction, the BoE set a reserve spread for each bond, i.e. a spread below which any offers would be rejected. The reserve spreads were based on risk management considerations and the BoE's various purchase targets and limits. The reserve spreads can be viewed as expressions of the BoE's demand for each bond. The CBPS purchases were then determined by the intersection of the BoE's demand and the auction participants' supply. Both of these might have been impacted by liquidity considerations. But the granularity of our offer-level dataset allows us to construct proxies for both the BoE's demand (using the reserve spreads) and auction participants' supply (based on their offers). These demand and supply proxies control for the potential impact of liquidity on purchases, and therefore reduce the magnitude of any reverse causality.

We begin by estimating the impact of the CBPS purchases on contemporaneous liquidity - that is, liquidity in the week following the auction. In our baseline regressions, our identification strategy is to estimate the impact of asset purchases on secondary market liquidity using a difference-in-differences approach, controlling for both the BoE's demand and auction participants' supply of eligible bonds. The treatment group is bonds that were purchased, and the control group is bonds that received offers in the auction but were not purchased (either because the offer spreads were below the BoE's reserve spreads or because binding purchase limits were hit).

We find that the CBPS purchases significantly improved the contemporaneous liquidity of purchased bonds relative to the control group, across a range of liquidity measures. For example, over the week following an auction, a typical purchase size of £5mn was associated with an increase in average trade size of around £0.57mn (compared to an average level of £0.81mn over the sample period), a reduction in the effective bid-ask spread of around 4.3 basis points (compared to an average of 26 basis points), and a reduction in the volatility associated with a £1mn trade of around 3.4 basis points (compared to an average of 26 basis points). These results appear consistent with a scenario in which the purchases provided dealers with confidence that they could sell bonds to the BoE if needed, and thereby increased dealers' willingness to intermediate trades. This is consistent with reports from participants in the sterling corporate bond market during the CBPS (Belsham et al., 2017; Financial News, 2017).

It is plausible that the impact on liquidity of the treated bonds spilled over to the control bonds due to investor portfolio rebalancing. In that case, the estimates above would be underestimates of the true effect. In order to obtain estimates that are less likely to be impacted by spillover effects, we repeat the analysis using two additional control groups that are less similar to the treatment group: sterling-denominated investment grade corporate bonds that were not eligible for the CBPS, and euro-denominated bonds issued by issuers who also issued eligible bonds. Using these additional control groups has the advantage that the results are less likely to be impacted by spillover effects; but the disadvantage that we are unable to control for demand and supply (because the bonds in these control groups were not eligible in the auctions). The results using these additional control groups are similar to the results using the benchmark control group.

The results above suggest that, in this case, the potential negative impact of QE on liquidity did not dominate. On the contrary, CBPS purchases had a significant positive impact on the liquidity of purchased bonds. This impact on liquidity does not appear to persist beyond one week: we find little evidence of any association between liquidity and lagged purchases. Similarly, when we compare the overall change in liquidity of bonds between the start and end of the scheme, we find no evidence that the liquidity of purchased bonds changed systematically relative to sterling bonds that were not purchased.

Related literature

Most studies of the financial market impact of QE have focussed on government bond markets: for example, D'Amico and King (2013); Breedon et al. (2012); Joyce and Tong (2012); Joyce et al. (2011a); McLaren et al. (2014); Gagnon et al. (2011).

Several studies have estimated the impact of central bank asset purchases on secondary market liquidity. The direction of the estimated effect varies across papers. Investigating asset purchase programmes in the euro area and UK, Beirne et al. (2011), Eser and Schwaab (2011), De Pooter et al. (2018) and Steeley (2015) find evidence that asset purchases improved liquidity. On the other hand, Kandrac (2013), Kandrac (2018), Han and Seneviratne (2018) and Kurosaki et al. (2015) find that asset purchase programmes in the US and Japan damaged liquidity. Some papers find mixed evidence within a single purchase programme. Christensen and Gillan (2017), Schlepper et al. (Forthcoming), Pelizzon et al. (2018), Iwatsubo and Taishi (2016) and Abidi and Miquel-Flores (2018) find that the direction of the effect varies over time or across liquidity measures. The mixed results across studies might reflect differences in the operational design of the asset purchase programmes, as well as the nature of the markets in which they were implemented. Indeed, Ferdinandusse et al. (2017) model the relationship between QE and liquidity theoretically and find that it is ambiguous.

An important challenge faced by the existing papers on this topic is reverse causality. If central bank purchase decisions reflect liquidity considerations, then existing estimates of the impact of QE on liquidity are likely to be biased. Indeed, Song and Zhu (2014) and Schlepper et al. (Forthcoming) both find evidence that purchase decisions are impacted by liquidity. Our key contribution relative to the existing empirical literature is to use granular offer-level data to control for the demand and supply factors that determine the purchases. This should reduce the magnitude of any reverse causality and therefore better identify the causal impact of the purchases on liquidity. To our knowledge, the only existing paper to use offer-level data to estimate the impact of QE auctions is Song and Zhu (2014), which studies the Federal Reserve's purchases of Treasury bonds. However, due to data constraints, that study only uses data on accepted offers. In contrast, we use data on all offers by CBPS auction participants (both rejected and accepted). This allows us to control for dealers' supply using information from the complete supply curve.

The remainder of this paper is organized as follows. Section 2 describes how the CBPS was implemented and discusses the channels through which it might have impacted liquidity. Section 3 describes the auction data and the data on secondary market transactions in the corporate bond market, and explains how we measure liquidity in that market. Section 4 investigates whether the initial announcement of the CBPS had an immediate impact on liquidity. Section 5 describes our approach to addressing reverse causality and reports our results regarding the effects of the CBPS on contemporaneous liquidity. Section 6 considers whether the purchases had any longer-term impacts on liquidity, and Section 7 concludes.

2 The Corporate Bond Purchase Scheme

2.1 Background to the CBPS

On 4 August 2016, following the UK's vote to leave the European Union, the Bank of England (BoE) announced a package of monetary stimulus measures. This included a reduction in Bank Rate, a new Term Funding Scheme, and an expansion of the BoE's programme of quantitative easing. The expansion of QE included both an increase in government bond purchases and a new Corporate Bond Purchase Scheme (CBPS).

The CBPS was authorised to purchase up to £10 billion of sterling-denominated investment grade corporate bonds over a period of 18 months. The purpose of the CBPS was "to impart monetary stimulus by lowering the yields on corporate bonds, thereby reducing the cost of borrowing for companies directly; by triggering portfolio rebalancing; and by stimulating new issuance of corporate bonds" (Bank of England, 2016, page vii). Impacting secondary market liquidity was not an explicit aim of the scheme.[1]

In order to be eligible for purchase, bonds had to be denominated in sterling, rated investment grade, and issued by firms that made "a material contribution to economic activity in the UK" (Bank of England, 2017). Bonds issued by banks, building societies, insurance companies and other financial sector entities regulated by the BoE or the UK Financial Conduct Authority were ineligible. More detailed eligibility criteria are provided in Bank of England (2017). A list of eligible bonds was first published on 12 September 2016, and this was updated regularly while purchases were ongoing.

Purchases began on 27 September 2016 and were conducted via auctions (discussed further below). The BoE announced that it had reached the £10bn target on 27 April 2017, at which point purchases ceased. During this seven-month period, the BoE purchased bonds at an average pace of £357mn per week. At the end of the purchase period, the BoE's holdings amounted to around 6% of eligible bonds, by market value. Since the completion of purchases, the BoE has continued to hold the stock of bonds. In August 2017, the BoE's Monetary Policy Committee (MPC) agreed that the BoE would reinvest cash flows from maturing bonds held under the CBPS back into eligible corporate bonds, with the first reinvestment operation expected to take place in 2019 H2. Further description of the CBPS and the composition of purchases is provided in Belsham et al. (2017).

[1] The BoE also purchased sterling corporate bonds in 2009, with the aim of improving market functioning during the intense financial market stress at the time (Fisher, 2010). The 2009 purchases were of a much smaller scale, with peak holdings of less than £2bn.

2.2 The CBPS auction mechanism

Purchases of corporate bonds were implemented via a series of multi-good reverse auctions. Each eligible bond was assigned to one of nine sectors based on the industrial sector of its issuer. There were three auctions per week, with each auction on a different day. Different sectors were included in different auctions so that each eligible bond was auctioned once per week. The design of the auctions took into account the relatively illiquid nature of the sterling corporate bond market (Salmon, 2017).

The auction participants were fourteen of the major dealers (market-makers) in the sterling corporate bond market. Dealers submitted offers to sell bonds to the BoE, and were able to submit multiple offers per bond. An offer consisted of a quantity and a price (expressed as a yield spread to the benchmark gilt for that bond), implying that the dealer was willing to sell the offer quantity at a spread less than or equal to the offer spread.

Before each auction, the BoE set a minimum spread (maximum price) for each bond, i.e. a reserve spread. Any offers below the reserve spread would be rejected. The reserve spread was unobserved by auction participants and reflected several factors. First, the BoE sought to purchase a portfolio of bonds that matched the proportion of total outstanding eligible bonds accounted for by different sectors (the 'sector key'). So if a sector was over-represented in the CBPS portfolio relative to the amount in issue, the reserve spreads for bonds in that sector would be increased in order to make offers against bonds in that sector relatively less attractive, and therefore slow down purchases. Similarly, if a sector was under-represented relative to the sector key, the BoE would reduce the reserve spreads for that sector to increase purchases. Second, the reserve spread reflected bond-level, issuer-level and sector-level purchase limits: if the BoE was close to reaching the purchase limits for a bond, it would increase the reserve spread for that bond to reduce the pace of future purchases. Third, the reserve spread reflected market-based and model-based indicators of the risk characteristics of the bond. The BoE reserved the right to adjust the reserve spread on the basis of any other information.

In addition to the sector targets and overall purchase limits, there were also purchase limits within an auction. The BoE would not purchase more than £10mn of a single bond in a single auction. And the total amount that the BoE would purchase in a given auction was determined on the basis of the quantity and quality of offers received.

The purchases were then determined according to the interaction of the offers, reserve spreads and purchase limits. Offers were ranked in order of attractiveness, taking into account the difference between the offer spread and the reserve spread. Offers would then be accepted in order of attractiveness until the auction purchase target was reached. Offers were allocated on a uniform spread basis, meaning that all successful offers for a bond were allocated at the same spread, with offers at the clearing spread pro-rated if necessary. Further detail on the auction process is available in Bank of England (2017).

While the main features of the auction process were published, auction participants were able to observe only limited information about the auction outcomes (beyond the outcomes of their own offers). The BoE published weekly data on total corporate bond holdings, with a one-week lag, and a monthly update of sector allocations relative to the sector key. But auction participants were unable to observe reserve spreads, holdings of individual bonds, or purchase limits. Therefore, from the perspective of participants, there was significant uncertainty regarding which of their offers would be accepted and rejected. A participant might submit offers for two different bonds that, from the perspective of the participant, are equally aggressive; but discover that one is accepted and the other is rejected on the basis of unobserved reserve spreads or purchase limits.

The auction mechanism used for the CBPS is in contrast to the manner in which many other central bank asset purchase programmes have been carried out.[2] For example, very few of the asset purchases by the Eurosystem have been implemented via auction. Instead, these programmes have typically been implemented via bilateral purchases in the primary and/or secondary markets. As explained in Section 5.1, the auction setting provides important advantages for identifying the causal impact of the CBPS on liquidity. This is because it enables us to observe (and therefore control for) the determinants of purchases with much greater granularity, thereby reducing concerns around the endogeneity of purchases.

2.3 The impact of the CBPS on yields, issuance and trading

The spreads of sterling-denominated investment grade corporate bonds fell sharply when the CBPS was announced (Figure 1), indicating that the policy came as a surprise to market participants. By comparing the spreads of eligible sterling bonds to the spreads of dollar and euro bonds issued by the same set of firms, Boneva et al. (2018) estimate that the announcement of the CBPS caused a reduction in eligible bond spreads of at least 13 basis points. Moreover, analysing the price reaction by bond characteristics, D'Amico and Kaminska (2019) show that the main channels through which market participants believed that the CBPS would affect corporate bond prices were likely to be linked to changes in net supply, rather than confidence or credit risk.

The CBPS appeared to have a significant impact on financing conditions. Gross issuance of sterling non-financial corporate bonds had been falling for several years prior to the introduction of the CBPS, which market participants ascribed to structural developments relating to the investor base (Elliott and Middeldorp, 2016). But sterling issuance increased substantially following the announcement of the CBPS (Figure 2). Market par-

[2]The BoE also uses auctions for its government bond QE purchases.

ticipants argued that the reduction in funding costs caused by the CBPS contributed to this increase in issuance (Belsham et al., 2017; Salmon, 2017).

Our transaction-level dataset (discussed in Section 3) allows us to investigate trading in the sterling corporate bond market during the CBPS purchase period. The sterling corporate bond market is an OTC market intermediated by around fourteen main dealer banks. The main investors in the market are insurance companies and asset managers. Since only dealers could participate directly in the CBPS auctions, if investors wished to sell bonds to the CBPS then they would need to sell them via dealers. This pattern is reflected in the transaction-level data. Figure 3, which is adapted from Mallaburn et al. (2019), shows net secondary market trading volume in eligible bonds by investor type (primary market trades and trades with the CBPS are excluded). Positive numbers indicate net buying volume while negative numbers indicate net selling volume. In the period between the announcement of the CBPS and the start of purchases, insurance companies and asset managers were net buyers of eligible bonds in the secondary market, while dealers were net sellers. But during the purchase period, the main investors had large net selling positions while dealers had large net buying positions, consistent with investors selling bonds to dealers so that dealers could sell the bonds on to the CBPS.[3]

The transaction-level data also allow us to analyse how dealers traded around the individual auctions. We split the week around each auction into two parts: a pre-auction period consisting of the two full days before the auction plus the part of the auction day before the open of the auction; and a post-auction period consisting of the two full days after the auction plus the part of the auction day after the close of the auction. For each dealer, we then compute their net secondary market trading volume in each bond in these two periods. Figure 4 shows averages (across dealers, bonds and auctions) of these pre- and post-auction net trading volumes for three groups of bonds: bonds that were eligible but that the dealer did not offer in the auction; bonds that the dealer offered unsuccessfully; and bonds that the dealer sold in the auction. Dealers could sell bonds to the CBPS out of their own inventories. Alternatively, they could offer to sell bonds that they did not already own, and if their offers were accepted, purchase the bonds in the secondary market in order to deliver them to the CBPS. The figure shows that dealers offered to sell to the CBPS bonds that they had bought in the run-up to the auction. But they primarily bought the bonds that they sold to the CBPS after the auction results were known. In part, this is likely to reflect dealers selling bonds on behalf of particular clients.

[3]This pattern reversed during December 2016. This is likely to reflect two factors. First, the BoE ran fewer auctions during December due to reduced liquidity around the Christmas period. Second, dealers might have been reducing bond inventories ahead of year-end in order to improve regulatory capital and leverage ratios.

2.4 How might the CBPS have impacted liquidity?

Market participants and academics have proposed several mechanisms by which central bank asset purchases could impact liquidity. In theory, the impact on liquidity could be positive or negative.

Stimulating trading: Central bank asset purchases involve market participants selling bonds in exchange for cash. But cash and bonds are imperfect substitutes, so the initial purchases are likely to stimulate further portfolio rebalancing (Joyce et al., 2011a). By stimulating trading, this portfolio rebalancing could also improve liquidity.

Back-stop buyer: Dealers take risk by holding bonds on their balance sheets as market-making inventory (Stoll, 1978). By providing a predictable source of demand for bonds, asset purchases can reduce the inventory risk faced by dealers. This might make them willing to hold larger inventories and could therefore facilitate market-making (Kandrac, 2018).

Search frictions: Absent new issuance, asset purchases lead to a reduction in the quantity of bonds held by private investors. If there are search frictions, then this could reduce trading by making it more difficult for investors to be matched (Ferdinandusse et al., 2017). And if it becomes more difficult for dealers to source specific bonds in the secondary market, then the costs and risks of market-making could increase, reducing dealers' willingness to intermediate trades (Kandrac, 2018). Moreover, a reduction in the quantity of a bond available for trading by private investors might deter market participation, leading to a thinner market and lower liquidity (Bolton and von Thadden, 1998).

Distorted price signals: Central bank asset purchases typically involve quantity targets, making the central bank relatively price-insensitive in its purchase decisions. Market participants have argued that this can distort price signals and therefore reduce the willingness of investors to trade (Financial Times, 2015).

Market participants in the sterling corporate bond market generally argued that the CBPS improved secondary market liquidity (Belsham et al., 2017). The key channel that they emphasised was that of the back-stop buyer: investors argued that predictable demand from the CBPS made dealers more willing to hold market-making inventory (Financial News, 2017). In this paper, we aim to estimate the impact of the CBPS on liquidity more formally.

3 Data

3.1 CBPS auction data

Our auction dataset includes the complete set of information determining CBPS purchases. We observe granular information on each individual offer submitted, including: the identity of the dealer, the ISIN (International Securities Identification Number) of the bond, the offer quantity, the offer spread, the quantity of the offer that was accepted, and the reason the offer was rejected (where applicable). We also observe the reserve spreads for each bond and each auction.

The dataset covers 82 auctions taking place over the lifetime of the scheme, from 27 September 2016 to 27 April 2017. Over that period, 364 bonds were eligible at some point, 306 of which were purchased at least once.

Table 1 reports descriptive statistics for the auction data. For bonds that received at least one offer in a given auction, the average sum of offer quantities was £9.2mn. For bonds that were purchased in a given auction, the average total purchase size was around £5mn. The maximum purchase amount of a single bond in a single auction was £10mn, equal to the purchase limit.

On average, the spread between the offer yields submitted in the auction and the average offer yield quoted in the secondary market was 1.25 basis points. This means that, on average, auction participants were offering to sell bonds to the BoE at lower prices than the prices that they were quoting to sell the same bonds to investors in the secondary market. This might have reflected competition between dealers induced by the auction process. Alternatively, it might have been because dealers were effectively selling bonds on behalf of their clients.

As discussed in Section 2.2, the auction allocations were also influenced by reserve spreads set by the BoE. The distribution of reserve spreads is shown in Figure 5 (the chart pools across bonds and auctions). The majority of reserve spreads were below the average market mid spread. However, in some cases the reserve spreads were set substantially higher than quoted market spreads in order to reduce the pace of purchases of particular bonds.

3.2 Corporate bond transaction data

To estimate liquidity measures for the corporate bond market, we use the transaction-level 'Zen' dataset maintained by the UK Financial Conduct Authority (FCA). This dataset includes transaction reports for all secondary-market trades by EEA-regulated firms in corporate bonds that are issued by UK firms, and all secondary-market trades by UK-regulated firms in any corporate bond. Since the large majority of the main dealers in the sterling corporate bond market are UK-regulated firms, the dataset should cover the majority of trading in sterling-denominated corporate bonds. And under the assumption that most trading in euro-denominated bonds involves EEA-regulated dealers or investors, the dataset should cover the majority of trading in euro-denominated bonds issued by UK firms.

Each transaction report includes the date, time, ISIN, quantity, price, the identity of the reporting firm, and (in most cases) the identity of their counterparty. The counterparty information allows us to match reports in cases where both counterparties report the trade. We drop trades that are implausibly large or small, or that have implausible reported prices. We also drop trades that occur within one week of the bond's announcement date (trading volumes are much higher in the week after a bond is announced, making this period unrepresentative of normal trading conditions in the bond).[4]

3.3 Liquidity measures

We estimate market liquidity at the bond level using the transaction-level Zen dataset. There is no single accepted liquidity measure for bond markets (Schestag et al., 2016). We therefore estimate a wide range of liquidity measures drawn from the academic literature. The measures are summarised briefly below and defined in Appendix A. We split the measures into three groups: measures of trading activity, measures of transaction costs, and measures of price impact.

Sterling and euro corporate bonds trade relatively infrequently, with around one trade per day on average in the Zen dataset, so we compute all liquidity measures at weekly frequency. We also winsorise several liquidity measures at 2.5% to reduce the impact of outliers.[5] Summary statistics for all of the liquidity measures are provided in Table 2 for the sample period January 2016 to December 2017.

Measures of trading activity. We compute four simple measures of trading activity: sterling trading volume, number of trades, average trade size, and number of 'block trades'. For these measures, higher numbers are likely to indicate better liquidity. We define a block trade to be one that is greater than £2mn, which is approximately the 90th percentile of the trade size distribution. As reported in Table 2, the average trade size of

[4]As discussed in Section 2.3, there was an increase in sterling corporate bond issuance after the CBPS was announced. Given that bonds trade most frequently shortly after they are issued, the increase in issuance is likely to have caused an increase in average trading volumes. Since we drop trades around the issuance date, this effect should not affect our analysis.

[5]We winsorise round-trip cost, Roll, effective spread, interquartile range, Amihud, and volatility-over-volume.

CBPS-eligible bonds is around £0.81mn, and eligible bonds trade on average around 4.4 times per week. As shown in Figure 6, the measures of trading activity exhibit substantial volatility but no clear trend over the sample period. The measures of trading activity are cruder than the measures of transaction costs and price impact. But their simplicity means that they can be estimated more reliably than the other measures, with fewer missing observations.

Measures of transaction costs. We also compute four measures of transaction costs. These can be interpreted as transaction-based estimates of the bid-ask spread. Specifically, we estimate the effective spread (Hong and Warga, 2000), the Roll measure (Roll, 1984), the round-trip cost (Goldstein et al., 2007), and the interquartile range of traded prices (Han and Zhou, 2011). For these measures, higher numbers indicate worse liquidity. These measures suggest that the average transaction-based bid-ask spread of eligible bonds is between 25 and 45 basis points (Table 2). As shown in Figure 7, all four of these measures indicate that the liquidity of eligible bonds and ineligible sterling investment grade bonds improved over the period during which CBPS purchases occurred.

Measures of price impact. Finally we compute two measures of price impact: the Amihud measure (Amihud, 2002), and a simple implementation of the volatility-over-volume measure of Fong et al. (2017). For these measures, higher numbers indicate worse liquidity. The Amihud measure indicates that, on average, a £1mn trade moves the price of eligible bonds by around 83 basis points. Meanwhile, volatility-over-volume suggests that an increase in trading volume of £1mn increases price volatility by around 26 basis points (Table 2). As with the measures of transaction costs, both measures of price impact suggest that the liquidity of eligible bonds and ineligible sterling bonds improved substantially over the CBPS purchase period (Figure 8).

While the majority of these measures indicate that liquidity in the sterling corporate bond market improved as CBPS purchases took place, we cannot conclude that this improvement was driven by the CBPS. Multiple other factors might have been impacting corporate bond liquidity during this period (e.g. the BoE's other monetary policy actions, investor perceptions of developments in the UK-EU negotiations, and the ECB's Corporate Sector Purchase Programme). We therefore rely on weekly cross-sectional variation across bonds to identify the impact of the CBPS purchases, as explained in Section 5.

4 Announcement effects

Before estimating the impact of the purchases on liquidity, we investigate whether the announcement of the policy itself had a direct impact on liquidity. Specifically, we estimate the following cross-sectional regression:

$$\Delta \text{Liquidity}_b = \mu + \beta \text{Eligible}_b + \phi' Z_b + \epsilon_b, \tag{1}$$

where $\Delta\text{Liquidity}_b$ is the liquidity of bond b in the calendar week after the announcement (8 – 12 August) minus the liquidity in the calendar week before the announcement (25 – 29 July); and Z_b is a set of bond-level control variables measured prior to the announcement: amount outstanding, credit rating, residual maturity, residual maturity squared, industry fixed effects, yield spread to the reference government bond, and amount outstanding of gilts with a similar residual maturity.

The variable of interest is Eligible_b, which is an indicator variable equal to one for bonds that were eligible for purchase by the CBPS and zero otherwise. Although the list of eligible bonds was not published at the time of the announcement, the main eligibility criteria were published, and Boneva et al. (2018) show that the spreads of eligible bonds fell significantly more than the spreads of ineligible sterling bonds after the announcement, indicating that investors were to a large extent able to predict which bonds would be eligible. We consider two control groups: sterling-denominated investment grade bonds that were never eligible (bonds issued by banks and insurance companies are excluded), and euro-denominated bonds issued by firms who had also issued eligible bonds.

The results are summarised in Table 3, and more detailed results are reported in the online appendix. There is evidence of significantly increased trading activity in eligible bonds relative to euro-denominated bonds. This might have reflected investor positioning ahead of the purchase period, as illustrated in Figure 3. However the estimated coefficients on the transaction cost and price impact measures are statistically insignificant in most cases, suggesting that the initial announcement did not cause an immediate change in the costs of trading. We now turn to the question of whether the purchases impacted liquidity.

5 Impact of CBPS purchases on contemporaneous liquidity

5.1 Addressing reverse causality

Identifying the impact of CBPS purchases on liquidity is challenging because the purchases were not randomly assigned across bonds. Instead, they were determined by the intersection of the BoE's demand and auction participants' supply. But both of these could have been affected by liquidity. For example, auction participants might have been more likely to submit offers for less liquid bonds because it would be more costly to sell them in the secondary market. And the purchase targets and risk management considerations underlying the BoE's reserve spreads (see Section 2) might have made it more or less willing to purchase illiquid bonds. In either case, there would be a problem of reverse causality, with liquidity impacting purchases rather than purchases impacting liquidity. Importantly, this effect could go in either direction. As discussed in Section 1, similar considerations apply to other episodes of central bank asset purchases that have been studied in the literature.

Our granular offer-level auction dataset offers novel ways to reduce the magnitude of any reverse causality. If liquidity impacted CBPS purchases, then this impact must have come via auction participants' supply (as expressed by their offers) or the BoE's demand (as expressed by its reserve spreads). But we are able to control for both of these. We observe all of the individual offers by market participants to sell bonds to the BoE, and can therefore use this information to construct bond-level proxies for the strength of auction participants' supply in each auction. Specifically, we construct two such proxies, one based on quantity (the total nominal quantity of the bond offered in the auction, summed across all auction participants) and one based on price (the volume-weighted average spread between the offer yields in the auction and the offer yield prevailing in the market). Similarly, we use the BoE's bond-level reserve spread as a proxy to control for the strength of its demand for the bond. By including these demand and supply proxies in our regressions, we are able to control for the two potential channels of reverse causality and should therefore reduce any bias arising from reverse causality. This argument is set out formally in Appendix B.

As explained more precisely in Section 5.2, our analysis is based on difference-in-differences regressions of liquidity on CBPS purchases. The regressions are estimated at auction frequency (eligible bonds were auctioned once per week). The bond-level treatment variable is the nominal amount purchased in the auction. So the treatment group consists of bonds that were purchased in the auction, and bonds can be treated multiple times because they can be purchased in multiple auctions. For robustness, we use four different control groups.

In our benchmark regressions, the control group consists of bonds that received offers in the auction but were not purchased, either because the offer spread was below the reserve spread or because purchase limits were reached. Since the control group consists of eligible bonds, we are able to control for demand and supply as described above. Note that bonds frequently move between the treatment group and this control group depending on whether they have CBPS offers accepted. That is, treatment status is determined within each auction, and bonds in the treatment group on one date are likely to be in the control group on other dates. The identifying assumption is that - in the absence of purchases, and conditional on demand and supply - the liquidity of purchased bonds would have moved in line with the liquidity of this control group: the 'parallel trends' assumption. This is very plausible, given that the BoE's eligibility criteria ensured that the bonds in the treatment and control groups had similar characteristics in terms of credit rating, sector and geographical focus.[6]

Our second control group is a subset of the first. It consists of bonds that received offers in the auction in which the offer spread was greater than the reserve spread (that is, attractive to the BoE) but were not purchased because auction or issuer purchase limits were reached within the auction. Given that these offers were at attractive prices, it would have been particularly difficult for auction participants to predict that they would be rejected. Including this control group acts as a robustness test against the possibility that auction participants were using sophisticated bidding strategies that are not well approximated by our two proxy variables for supply.

The bonds in the two control groups discussed above are likely to be close substitutes to the bonds in the treatment group. This has the advantage that the parallel trends assumption is likely to hold. However, it also raises the possibility that the impact of purchases on the treatment group 'spills over' to the control group: investors who have sold bonds to the CBPS might rebalance their portfolios into bonds in the control group, and this might mean that the CBPS purchases also indirectly impact the liquidity of control bonds.[7] In order to obtain estimates that are less likely to be impacted by these spillover effects, we repeat the analysis using two control groups that are less similar to the treatment group: sterling-denominated investment grade corporate bonds that were never eligible for the CBPS, and euro-denominated bonds issued by issuers who had also

[6]The parallel trends assumption cannot easily be visually inspected for this control group, given that bonds frequently move between the treatment and control groups.

[7]Note that spillover effects on control bonds might be expected to be in the same direction as the direct effect on treated bonds, meaning that our difference-in-differences estimates might be expected to be underestimates of the true effect.

issued eligible bonds.

We can use Figures 6, 7 and 8 to assess how well the parallel trends assumption holds for these two additional control groups by observing trends in the liquidity measures prior to the start of CBPS purchases. Over the pre-CBPS period, most of the liquidity measures for eligible bonds and ineligible sterling bonds move relatively closely together, providing support for the parallel trends assumption. The figures provide less support for the parallel trends assumption in the case of the euro control group, which might reflect differences in the investor base.

5.2 Baseline regression specification

For our baseline results, we run staggered difference-in-differences regressions at the bond-auction level. Each regression uses data for bonds in a treatment group and bonds in a control group, and takes the following form:

$$\text{Liquidity}_{bt} = \alpha_b + \mu_t + \beta \text{PurchasedAmount}_{bt} + \kappa X_{bt}^{\text{Demand}} + \delta' X_{bt}^{\text{Supply}} + \epsilon_{bt}, \quad (2)$$

where:

- Liquidity_{bt} is a measure of secondary market liquidity for bond b in the week starting on the date of auction t.
- α_b and μ_t are bond and auction fixed effects.
- $\text{PurchasedAmount}_{bt}$ is the total nominal quantity of bond b purchased in auction t, denominated in sterling millions. Note that this is a continuous treatment variable.
- X_{bt}^{Demand} is the BoE's reserve spread for bond b in auction t, which we use as a proxy variable for the BoE's demand for the bond.
- X_{bt}^{Supply} is a vector of two variables summarising the supply by auction participants of bond b in auction t: the total nominal quantity offered in the auction (summed across all auction participants); and the volume-weighted average spread between auction participants' offer yields and the average offer yield quoted in the secondary market.

We run separate regressions for different liquidity measures and different control groups. In each case, the treatment group consists of bonds for which $\text{PurchasedAmount}_{bt}$ is greater than zero, i.e. bonds that were purchased in auction t. We consider four different control groups (as discussed in Section 5.1):

- **Offer:** Bonds that were eligible in auction t and received offers, but were not purchased (either because the offer spreads were below the reserve spread or because purchase limits were reached).

- **Limit:** Bonds that were eligible in auction t and received offers in which the offer spread was greater than the reserve spread, but were not purchased (because purchase limits were reached). This is a subset of the previous control group.

- **Sterling:** Sterling-denominated investment grade corporate bonds that were never eligible. Bonds issued by banks and insurance companies are excluded.

- **Euro:** Euro-denominated bonds issued by issuers who had also issued eligible bonds.

Eligible bonds were auctioned once per week, but different bonds were auctioned on different weekdays depending on the sector of the issuer. So for eligible bonds (i.e. the treatment group and the first two control groups), the regressions only use data from auctions in which the bond was eligible. And we estimate the liquidity measures using trades in the week starting on the day that the bond was auctioned (excluding the period on the auction day before the close of the auction). This is to ensure that the liquidity measures are responding to actual purchases, rather than moving in anticipation of the auctions.

Our third and fourth control groups consist of ineligible bonds. We match each of these bonds to auctions based on the sector of the issuer. We then estimate the liquidity measures for these bonds in the same way as for eligible bonds, i.e. using trades in the week starting on the day of the auction to which the bond was matched. Since these bonds are ineligible, purchased amount is always equal to zero, and the demand and supply proxies are unobserved and are therefore excluded from the regressions.

The coefficient of interest is β. This provides an estimate of the impact of CBPS purchases on the liquidity of purchased bonds in the week following the auction.

Standard errors are double-clustered at the bond and auction levels.

5.3 Baseline results

Our results are summarised in Table 4, with more detailed results reported in the online appendix. The results for the first control group are shown in column (1). We find that, in response to a £1mn increase in the amount purchased, the number of weekly trades increased by around 0.3 and the weekly trading volume increased by around £0.7mn. These effects are likely to be partly mechanical, reflecting the design of the auctions.[8]

[8] The main holders of sterling corporate bonds are asset managers and insurers (see Section 2), who were not eligible to participate directly in the auctions. In order to sell bonds to the BoE, these investors

However, the other measures of trading activity also suggest that the CBPS purchases improved liquidity. Following a typical purchase of £5mn, the average trade size increased by around £0.57mn (compared to an average of £0.81mn for eligible bonds over the sample period), and the number of 'block trades' (trades larger than £2mn) increased by around 0.46 (compared to an average of 0.45).

The measures of transaction costs also indicate that CBPS purchases improved liquidity. A typical purchase of £5mn was associated with a reduction in the effective spread of around 4.3 basis points (compared to an average of 26 basis points) and a reduction in the Roll measure of the bid-ask spread of 1.8 basis points (compared to an average of 41 basis points). The estimated coefficients on the other measures of transaction costs (round-trip cost and interquartile range) are statistically insignificant.

We also find that the CBPS reduced the price impact of trades. Following a £5mn purchase, the Amihud measure falls by 4.1 basis points (compared to an average of 83 basis points), and the volatility-over-volume measure falls by around 3.4 basis points (compared to an average of 26 basis points).

The results using the other three control groups, shown in columns (2)-(4) of Table 4, are very similar.

Overall these results indicate that the CBPS purchases improved the liquidity of purchased bonds in the week following the auction. This suggests that the positive channels from asset purchases to liquidity discussed in Section 2.4 outweighed the negative channels in this case. This is consistent with reports from market participants in the sterling corporate bond market. The key channel that they emphasised was that of the back-stop buyer: predictable demand from the CBPS made dealers more willing to hold market-making inventory and intermediate trades (Belsham et al., 2017; Financial News, 2017).

5.4 Robustness tests

We perform two tests to address the possibility that there is remaining reverse causality from liquidity to purchases, even after controlling for demand and supply (results available upon request). First, we re-estimate our baseline regressions, but use liquidity in the week before the auction as the dependent variable (rather than liquidity in the week after the auction). For most liquidity measures, there is no significant relationship between pre-auction liquidity and amount purchased. However for some liquidity measures (trading volume, average trade size and round-trip cost), we find evidence that the CBPS was more likely to purchase bonds that were *less* liquid prior to the auction. This suggests

would have to ask dealers to submit offers on their behalf. If the offer were accepted, then the investor would sell the bond to the dealer so that the dealer could deliver it to the CBPS. This would lead to an increase in the number of trades and volume of trading directly.

that our finding that purchases improved liquidity is unlikely to be driven by reverse causality. Second, we estimate our baseline regressions including the lagged dependent variable as an additional control variable, using the system GMM estimator of Blundell and Bond (1998). The results from this test are generally similar to our baseline results, although statistical significance is reduced for some liquidity measures. The reduction in statistical significance could reflect a reduction in efficiency arising from the instrumental variables approach. The coefficient on the lagged dependent variable is generally small and statistically insignificant, indicating that it is not an important omitted variable.

We perform three further robustness tests (results available upon request). First, we re-estimate the baseline regressions for the first two control groups, but exclude the proxy variables for demand and supply. Second, we scale the treatment variable (purchased amount) by amount outstanding, to allow for the possibility that the effect of purchases depends on the quantity of the bond in issue. Third, we repeat the analysis using the common correlated effects estimator of Pesaran (2006), which controls for unobserved common shocks to both purchases and liquidity. The results from all of these robustness tests are similar to our baseline results.

5.5 Heterogeneous effects

In this subsection we investigate whether the effects estimated in Section 5.3 varied across bonds or across time.

In recent years, market participants have argued that there has been a reduction in the liquidity of corporate bonds in general (Committee on the Global Financial System, 2014) and sterling corporate bonds in particular (Elliott and Middeldorp, 2016; Financial Conduct Authority, 2017). Market participants and policymakers have raised the concern that the reduction in liquidity has been larger for less liquid bonds: that is, that there has been a 'bifurcation' in liquidity across bonds (Dudley, 2016). We therefore investigate how the impact of the CBPS varied across bonds according to their liquidity prior to the scheme: did the CBPS contribute to or lean against any bifurcation in liquidity?

To address this question, we introduce interaction terms to extend our baseline specification to the following regression:

$$\begin{aligned}
\text{Liquidity}_{bt} &= \alpha_b + \mu_t + \beta \text{PurchasedAmount}_{bt} \\
&+\phi \left(\text{PurchasedAmount}_{bt} \times \text{Pre-CBPS liquidity}_b\right) \\
&+\kappa X_{bt}^{\text{Demand}} \\
&+\gamma \left(X_{bt}^{\text{Demand}} \times \text{Pre-CBPS liquidity}_b\right) \\
&+\delta' X_{bt}^{\text{Supply}} \\
&+\psi' \left(X_{bt}^{\text{Supply}} \times \text{Pre-CBPS liquidity}_b\right) + \epsilon_{bt},
\end{aligned} \tag{3}$$

where Pre-CBPS liquidity_b is defined as the level of liquidity for bond b in the week before the announcement of the CBPS, and all other variables are defined as above. Pre-CBPS liquidity_b is demeaned.

The coefficient of interest is ϕ, which provides an estimate of how the impact of CBPS purchases on liquidity varied with the level of pre-CBPS liquidity.

The results for this regression are summarised in Table 5, and a full set of results is reported in the online appendix. As before, different columns relate to different control groups. For all dependent variables, positive coefficients on the interaction term would indicate that CBPS purchases improved liquidity more for bonds that were already more liquid (consistent with bifurcation), while negative coefficients would indicate that the CBPS had more beneficial impacts on the liquidity of less liquid bonds. We find that almost all estimated coefficients on the interaction between purchases and pre-CBPS liquidity are statistically insignificant.

As an additional test of the bifurcation hypothesis, we estimate how the impact of the CBPS purchases varied according to credit rating. These regressions take the same form as equation (3), except that we replace the variable Pre-CBPS liquidity_b with an ordinal numeric variable representing the bond's average credit rating across the three major rating agencies. Again, the estimated coefficient on the interaction term is statistically insignificant in nearly all cases (results available upon request).

Overall, these results do not indicate that the impact of the CBPS differed systematically across purchased bonds.

The strength of the channels from asset purchases to liquidity discussed in Section 2.4 is likely to depend on time-varying factors such as the expected time until completion of the scheme. We therefore estimate whether the size of the impact of purchases on liquidity established in Section 5.3 varied over the lifetime of the scheme. To that end, we estimate the following regression:

$$\begin{aligned}
\text{Liquidity}_{bt} &= \alpha_b + \mu_t + \beta \text{PurchasedAmount}_{bt} \\
&+ \phi \left(\text{PurchasedAmount}_{bt} \times \text{Trend}_t\right) \\
&+ \kappa X_{bt}^{\text{Demand}} \\
&+ \gamma \left(X_{bt}^{\text{Demand}} \times \text{Trend}_t\right) \\
&+ \delta' X_{bt}^{\text{Supply}} \\
&+ \psi' \left(X_{bt}^{\text{Supply}} \times \text{Trend}_t\right) + \epsilon_{bt},
\end{aligned} \tag{4}$$

where Trend_t is a linear time trend variable at weekly frequency (defined to be zero at the midpoint of the purchase period).

The results are summarised in Table 6 and the online appendix. For the measures of trading activity (number of trades, trading volume, average trade size and number of block trades), the estimated coefficient on the interaction between purchased amount and the time trend is generally negative and significant. This indicates that the positive impact of CBPS purchases on trading activity decreased over the purchase period. For the other liquidity measures, the estimated coefficient on the interaction term is statistically insignificant for most control groups.

The reduced impact on trading activity might have reflected a weakening in the backstop buyer channel over the course of the scheme. As the CBPS approached its £10bn purchase target, the future time period over which dealers would be able to sell excess inventory to the CBPS reduced. Therefore the reduction in inventory risk associated with the CBPS might have dissipated, potentially reducing the positive impact of the CBPS on dealers' willingness to intermediate trades.

6 Longer-term impact

The results in Section 5 indicate that CBPS purchases improved the liquidity of bonds in the week immediately following the purchase. We now turn to the question of whether the purchases had any longer-lasting impacts on liquidity. We approach this question in two ways. First we consider whether the initial impact persisted beyond the first week. Then we investigate whether there were 'stock effects' from total CBPS purchases.

6.1 Persistence of the initial impact

In order to test whether the contemporaneous impact persisted beyond the first week, we add the first lag of purchases to regression (2). This results in the following specification:

$$\begin{aligned} \text{Liquidity}_{bt} &= \alpha_b + \mu_t + \beta \text{PurchasedAmount}_{bt} \\ &\quad + \phi \text{PurchasedAmount}_{b,t-1} \\ &\quad + \kappa X_{bt}^{\text{Demand}} + \delta' X_{bt}^{\text{Supply}} + \epsilon_{bt}. \end{aligned} \tag{5}$$

The results are summarised in Table 7 and reported in full in the online appendix. The estimates suggest that the impact of purchases on liquidity was short-lived. In most cases, the coefficient on the first lag of purchases is statistically insignificant and much smaller than the coefficient on contemporaneous purchases.

6.2 Stock effects

Our second approach is based on comparing how the liquidity of bonds changed between the start and end of purchases. We run cross-sectional regressions of the following form:

$$\Delta \text{Liquidity}_b = \mu + \beta \text{TotalPuchasedAmount}_b + \phi' Z_b + \kappa' \Delta X_b + \epsilon_b, \tag{6}$$

where $\Delta\text{Liquidity}_b$ is the liquidity of bond b in the week after purchases were completed minus the liquidity in the week before the CBPS was announced. The primary variable of interest is $\text{TotalPurchasedAmount}_b$, which is defined as the total quantity of bond b purchased by the CBPS over the entire purchase period. We include two sets of bond-specific control variables: Z_b and ΔX_b. Z_b consists of variables measured just prior to the announcement of the CBPS: amount outstanding, credit rating, residual maturity, residual maturity squared, industry fixed effects, yield spread to reference gilt, and amount outstanding of gilts with a similar residual maturity (specifically, gilts with a residual maturity within two years of the residual maturity of bond b). ΔX_b consists of variables computed over the duration of the scheme: change in credit rating, change in amount outstanding of gilts with a similar residual maturity, and BoE QE purchases of gilts with a similar maturity.

The treatment group is bonds that were purchased during the CBPS period. We consider two control groups: bonds that were eligible but never purchased, and ineligible sterling investment grade corporate bonds (bonds issued by banks and insurance companies are excluded).

The results are summarised in Table 8, with more detailed results reported in the online appendix. In almost all cases, the estimated impact of total purchases on liquidity is statistically insignificant. This suggests that the liquidity effects of the CBPS did not extend beyond the active phase of purchases. In other words - and following the terminology of D'Amico and King (2013) - we find that the CBPS had 'flow effects' on bond liquidity, but that there were no 'stock effects' arising from the BoE's total holdings of corporate bonds. This is consistent with the 'back-stop buyer' channel discussed in Section 2.4: the CBPS might have supported liquidity by providing a committed buyer to the market, but this impact did not persist once CBPS purchases were completed.

In this respect, our findings are in line with Christensen and Gillan (2017), who study the impact of the Federal Reserve's purchases of TIPS on liquidity premia during QE2. They find that TIPS liquidity premia fell during the program, but that the effects dissipated towards the end of the purchases. This led them to conclude that, although QE programs can improve financial market functioning through a liquidity channel, the liquidity effects are only sustained as long as QE purchases are ongoing and expected to continue.

7 Discussion and conclusions

In August 2016, the Bank of England's Monetary Policy Committee announced a Corporate Bond Purchase Scheme (CBPS) to purchase up to £10bn of sterling corporate bonds. The objective of the purchases was to impart monetary stimulus by lowering corporate bond yields, triggering portfolio rebalancing, and stimulating corporate bond issuance. But a potential unintended consequence was an impact on market liquidity. To estimate whether the purchases did indeed impact liquidity, we create a novel dataset by combining transaction-level data from the corporate bond market with proprietary offer-level data from the CBPS auctions.

Identifying the impact of central bank asset purchases on liquidity is plagued with endogeneity concerns, particularly the possibility of reverse causality. For example, if the central bank aims to purchase more or less liquid bonds, then liquidity will be impacting purchases as well as purchases impacting liquidity. But the auction design of the CBPS and the granularity of our offer-level dataset offer novel ways to alleviate this reverse causality problem. In particular, we are able to control for the impact of liquidity on purchases by constructing proxy variables for auction participants' supply of bonds (based on their offers in the auctions) and the BoE's demand for bonds (based on the reserve prices that it set ahead of the auctions).

Across a range of transaction-based liquidity measures, we find that CBPS purchases improved the liquidity of purchased bonds in the week following the purchase. This impact on liquidity does not appear to persist beyond one week: we find little evidence of any association between liquidity and lagged purchases. Similarly, when we compare the overall change in liquidity between the start and end of the scheme, we find no evidence that the liquidity of purchased bonds changed systematically compared to sterling bonds that were not purchased. In other words, we find that the CBPS had positive 'flow effects' on bond liquidity, but that there were no 'stock effects' on liquidity arising from the BoE's total holdings of corporate bonds (D'Amico and King, 2013).

That said, Figures 7 and 8 do show substantial improvements in the liquidity of sterling corporate bonds - both eligible and ineligible - over the lifetime of the scheme. We cannot conclude that these improvements were driven by the CBPS, because multiple other factors might have been impacting corporate bond liquidity during this period. But one possibility is that portfolio rebalancing caused by the scheme contributed to a generalised improvement in liquidity across the entire sterling corporate bond market. This would be consistent with D'Amico and Kaminska (2019), who find evidence of price spillover effects of the CBPS in the case of highly rated bonds with similar characteristics.

Our results have important policy implications. Policymakers and market participants have repeatedly raised concerns that asset purchases could have the unintended consequence of causing a deterioration in liquidity. Our results provide evidence that, in the case of the CBPS, the purchases caused an improvement, rather than a deterioration, in liquidity. While our empirical tests are not designed to sharply differentiate between the different channels through which asset purchases can impact liquidity, the results appear consistent with a scenario in which the purchases provided dealers with confidence that they could sell bonds to the BoE if needed, and thereby increased dealers' willingness to intermediate trades. It seems plausible that this channel was strengthened by the fact that the purchases were implemented via auction, which gave dealers more influence over which bonds were bought, compared to an operational design in which the central bank purchases bonds bilaterally.

The CBPS was a monetary policy tool, and did not have an explicit objective of improving market liquidity. However, since the financial crisis, policymakers and academics have paid increased attention to the question of whether, and under what conditions, the central bank should act as 'market-maker of last resort' (MMLR) in markets suffering a reduction in liquidity (Bank for International Settlements, 2014). The results in this paper indicate that asset purchases conducted via auction can improve the liquidity of corporate bond markets and therefore have implications for the design of any future MMLR operations.

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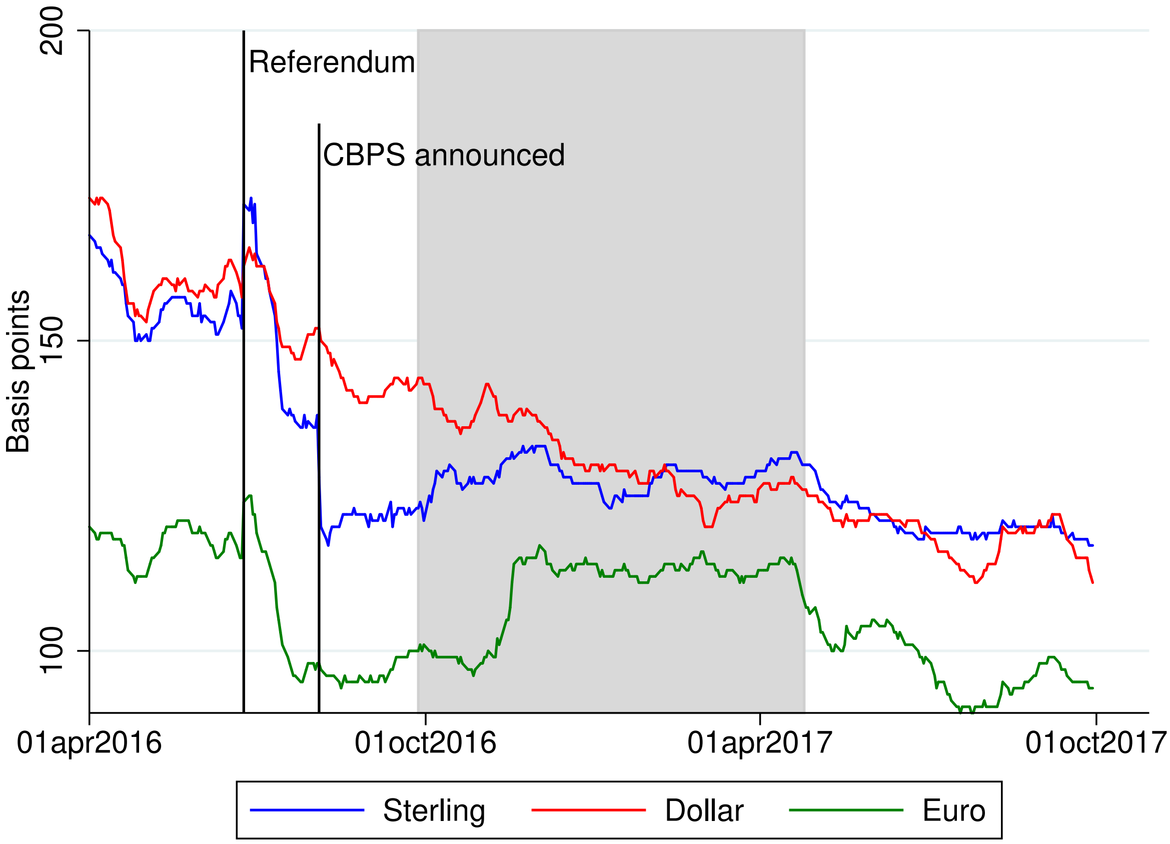
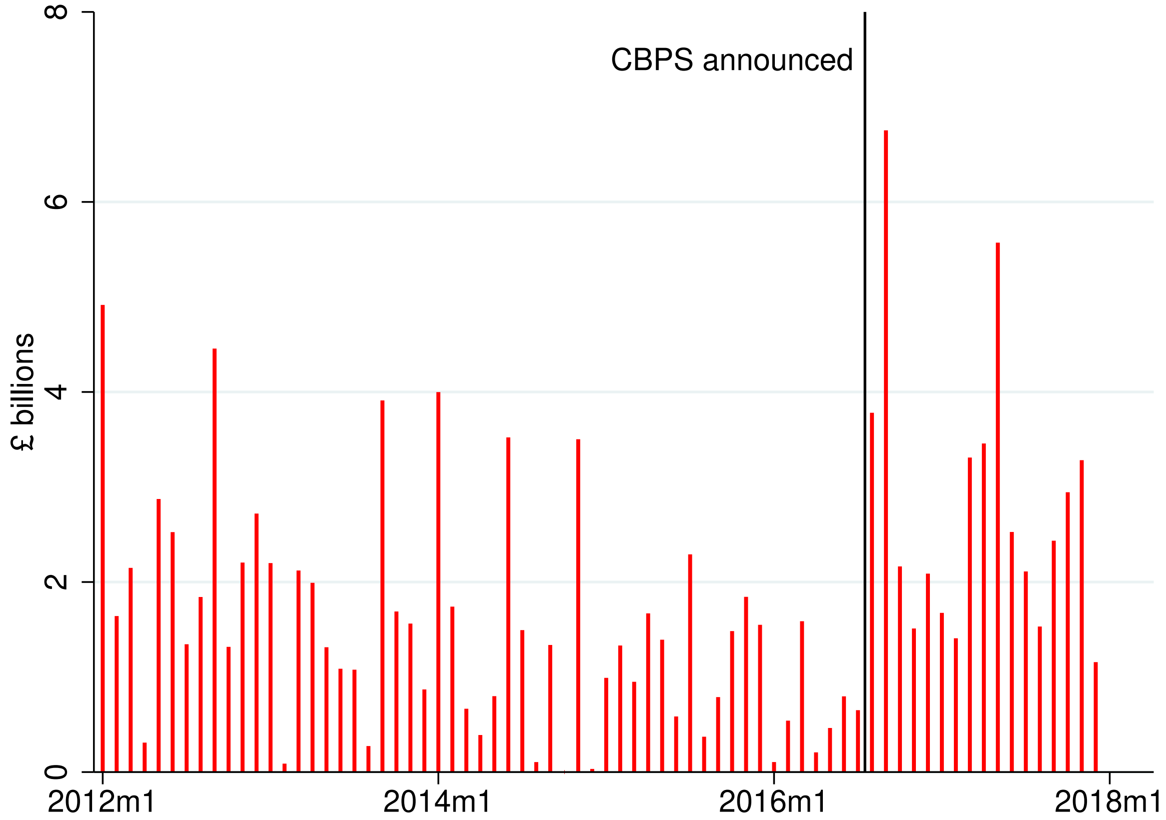
Figure 1: Corporate bond spreads



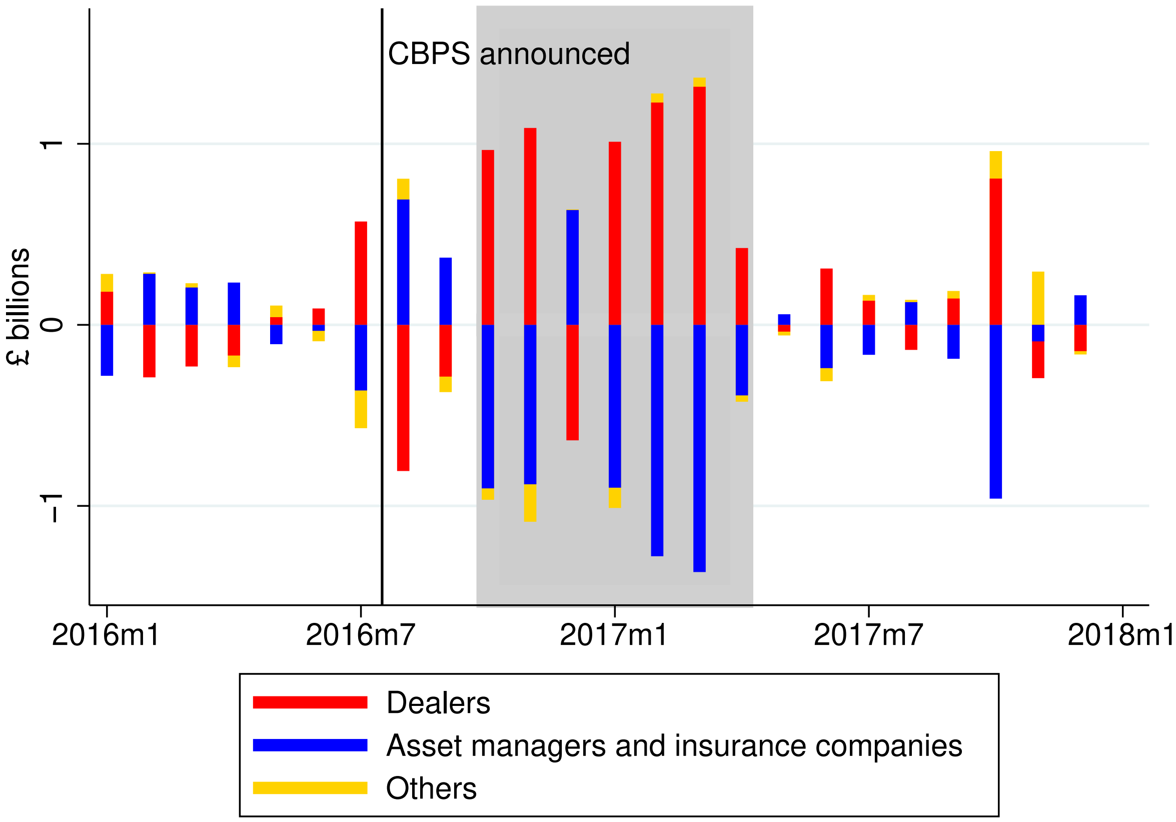
Notes: The chart shows option-adjusted spreads for investment grade non-financial corporate bonds. The shaded region shows the period of CBPS purchases.
Source: Bank of America.

Figure 2: Sterling corporate bond issuance



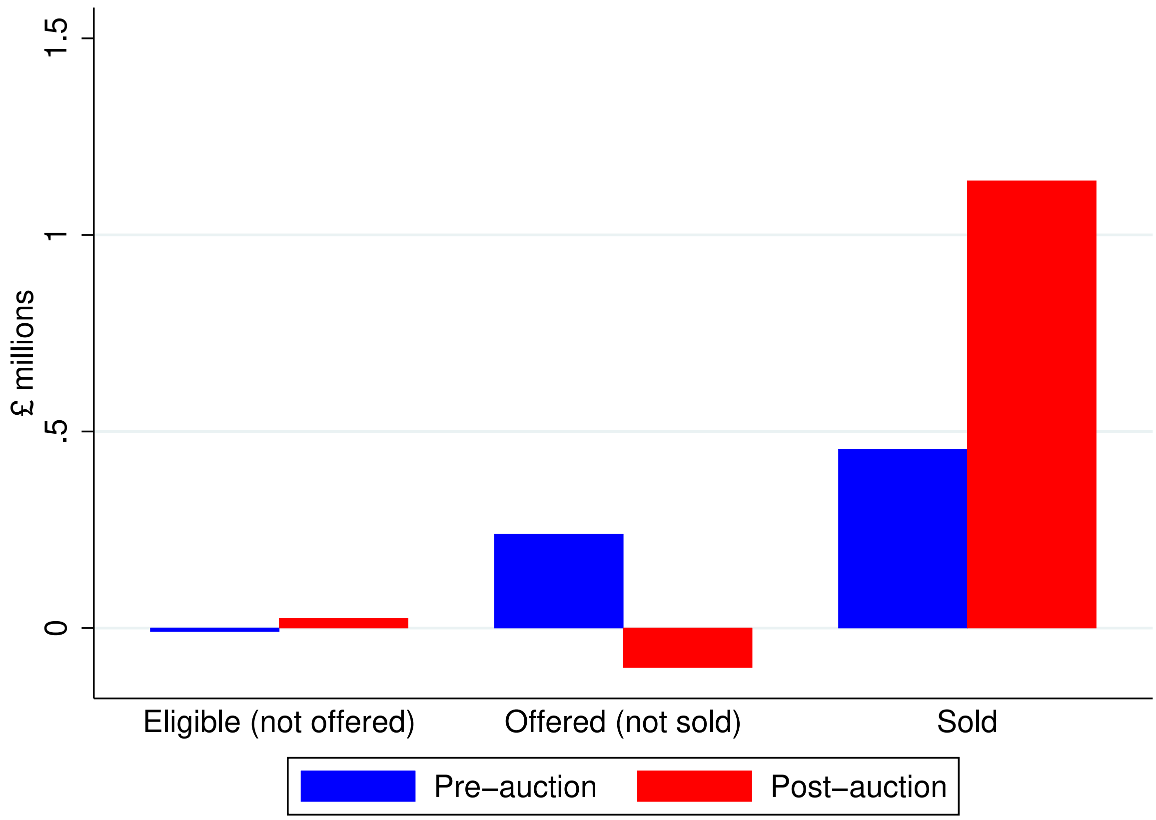
Notes: The chart shows monthly gross issuance of sterling-denominated investment grade non-financial corporate bonds.
Source: Thomson Reuters.

Figure 3: Net trading in eligible corporate bonds



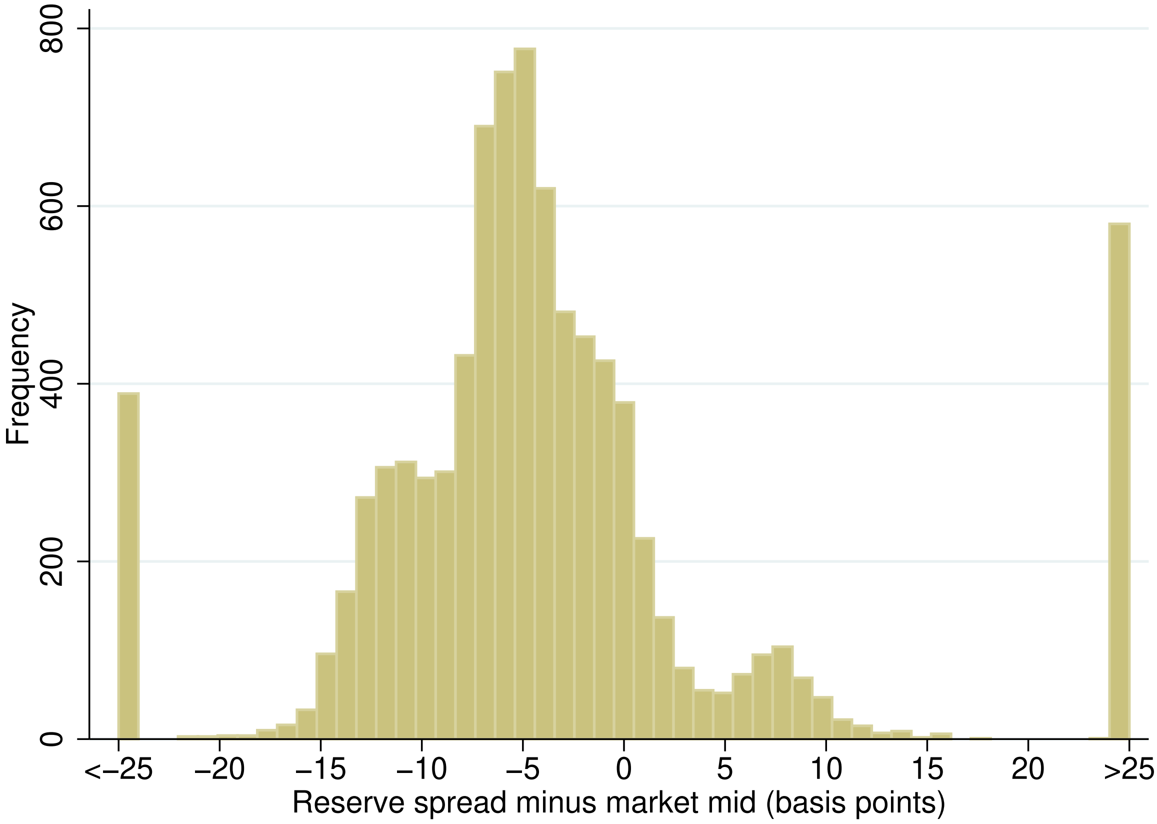
Notes: The chart shows monthly net secondary market trading volumes in bonds that were eligible for the CBPS, estimated using the transaction-level Zen dataset. Primary market trades and trades with the CBPS itself are excluded. Positive numbers indicate net buying volume while negative numbers indicate net selling volume. The shaded region shows the period of CBPS purchases.

Figure 4: Dealer trading behaviour around the auctions



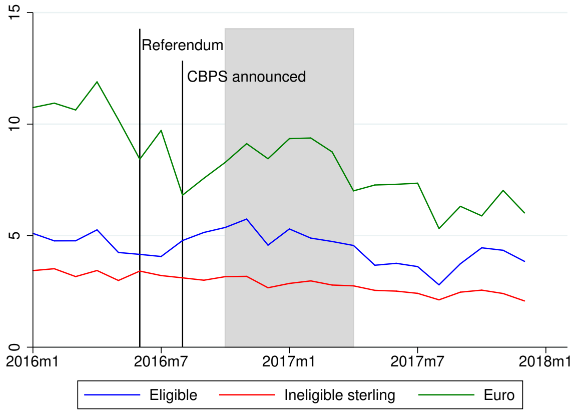
Notes: The chart shows average net secondary market trading volumes by CBPS participants (dealers) in the days around the auctions, estimated using the transaction-level Zen dataset. Primary market trades and trades with the CBPS itself are excluded. Positive numbers indicate net buying volume while negative numbers indicate net selling volume. 'Pre-auction' refers to the two full days before the auction plus the part of the auction day before the open of the auction. 'Post-auction' refers to the two full days after the auction plus the part of the auction day after the close of the auction. 'Eligible (not offered)' refers to bonds that were eligible in the auction but that the dealer did not offer in the auction. 'Offered (not sold)' refers to bonds that the dealer unsuccessfully offered in the auction. 'Sold' refers to bonds that the dealer sold in the auction.

Figure 5: Distribution of reserve spreads

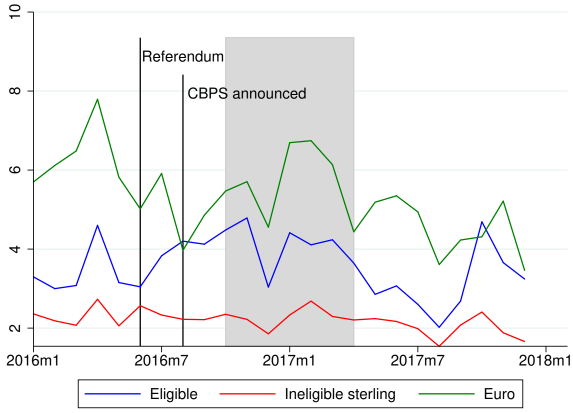


Notes: The chart is a histogram of the reserve spreads set by the Bank of England ahead of CBPS auctions. Quoted market mid spreads have been subtracted from the reserve spreads. Spreads greater than 25 basis points have been allocated to the highest bin, and spreads less than -25 basis points have been allocated to the lowest bin.

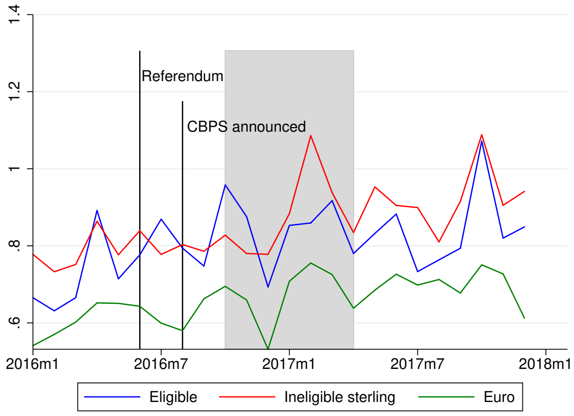
Figure 6: Measures of trading activity



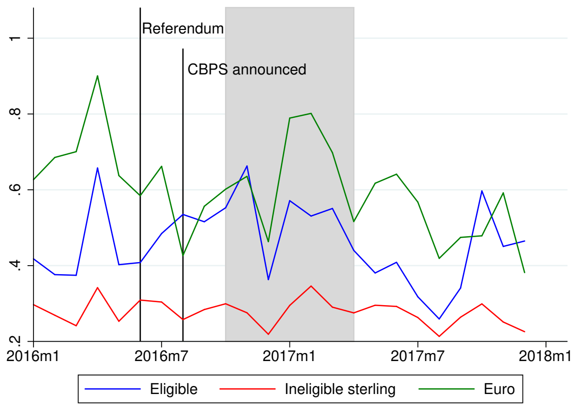
(a) Number of trades per week



(b) Weekly trading volume (£mn)



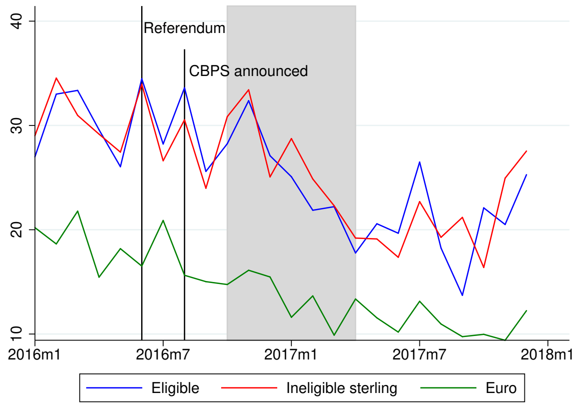
(c) Average trade size (£mn)



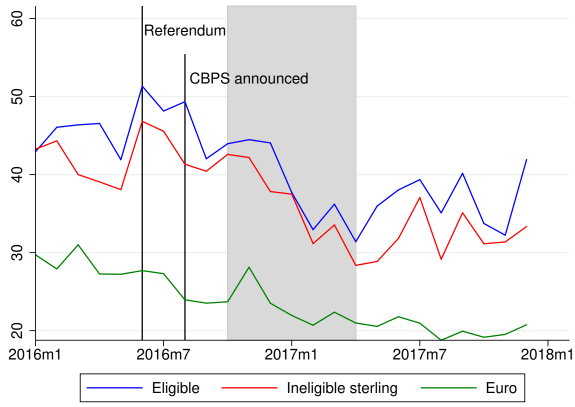
(d) Number of block trades per week

Notes: The charts show liquidity measures for the corporate bond market estimated using the transaction-level Zen dataset. The measures are computed for individual bonds at weekly frequency, then averaged across bonds within a group. The charts show monthly averages. 'Eligible' refers to bonds that were at some point eligible for the CBPS. 'Ineligible sterling' refers to sterling-denominated investment grade corporate bonds that were never eligible for the CBPS (bonds issued by banks and insurance companies are excluded). 'Euro' refers to euro-denominated bonds issued by issuers who had also issued eligible bonds. The shaded region shows the period of CBPS purchases. Higher numbers indicate better liquidity. Definitions of the measures are provided in Appendix A.

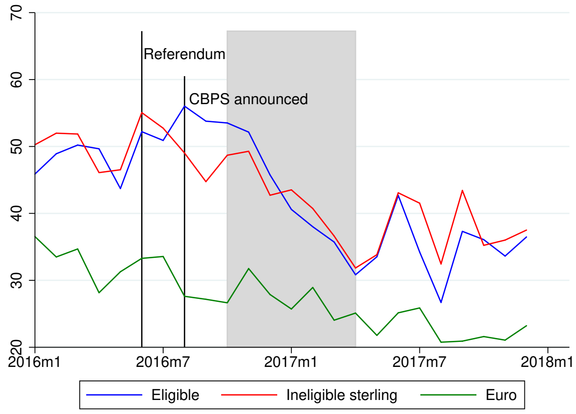
Figure 7: Measures of transaction costs



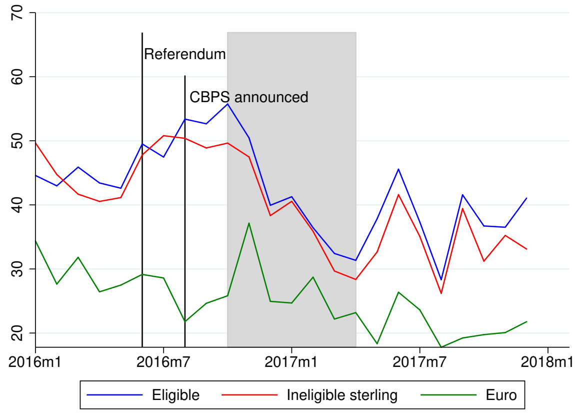
(a) Effective spread (bps)



(b) Roll (bps)



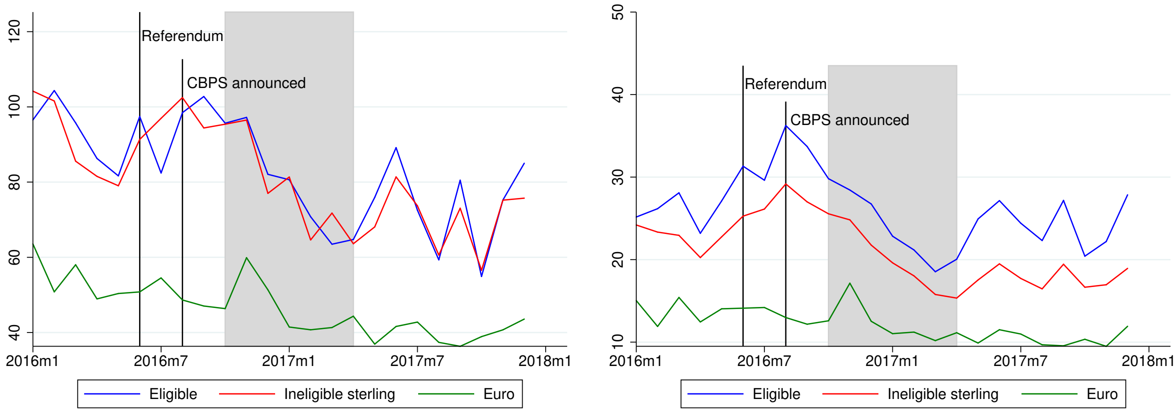
(c) Round-trip cost (bps)



(d) Interquartile range (bps)

Notes: The charts show liquidity measures for the corporate bond market estimated using the transaction-level Zen dataset. The measures are computed for individual bonds at weekly frequency, then averaged across bonds within a group. The charts show monthly averages. 'Eligible' refers to bonds that were at some point eligible for the CBPS. 'Ineligible sterling' refers to sterling-denominated investment grade corporate bonds that were never eligible for the CBPS (bonds issued by banks and insurance companies are excluded). 'Euro' refers to euro-denominated bonds issued by issuers who had also issued eligible bonds. The shaded region shows the period of CBPS purchases. Higher numbers indicate worse liquidity. Definitions of the measures are provided in Appendix A.

Figure 8: Measures of price impact



(a) Amihud (bps)

(b) Volatility-over-volume (bps)

Notes: The charts show liquidity measures for the corporate bond market estimated using the transaction-level Zen dataset. The measures are computed for individual bonds at weekly frequency, then averaged across bonds within a group. The charts show monthly averages. 'Eligible' refers to bonds that were at some point eligible for the CBPS. 'Ineligible sterling' refers to sterling-denominated investment grade corporate bonds that were never eligible for the CBPS (bonds issued by banks and insurance companies are excluded). 'Euro' refers to euro-denominated bonds issued by issuers who had also issued eligible bonds. The shaded region shows the period of CBPS purchases. Higher numbers indicate worse liquidity. Definitions of the measures are provided in Appendix A.

Table 1: CBPS auction data summary statistics

Statistic	N	Mean	Min	Pctl(25)	Median	Pctl(75)	Max	St. Dev.
Total offer amount (GBP mn)	4,275	9.164	1.000	3.000	6.300	12.100	78.600	9.027
Average offer spread (bps)	4,275	1.251	−62.000	−0.048	1.600	3.333	25.000	4.634
Total purchased amount (GBP mn)	1,622	4.827	0.100	2.000	4.000	8.000	10.000	3.294

Notes: The table shows summary statistics from the offer-level CBPS auction dataset. One observation refers to a bond-auction pair. 'Total offer amount' is the total quantity of a single bond offered by auction participants in a single auction, in nominal terms. 'Average offer spread' is the volume-weighted average spread between auction participants' offer yields and the average offer yield quoted in the secondary market. 'Total purchased amount' is the total quantity of a single bond purchased in a single auction, in nominal terms. The summary statistics for total offer amount and average offer spread are computed using observations where there was at least one offer for the bond in the auction. The summary statistics for total purchased amount are computed using observations where the bond was purchased in the auction.

Table 2: Liquidity measure summary statistics

Statistic	N	Mean	Median	St. Dev.
Eligible bonds				
Number of trades	36,042	4.423	3	6.122
Trading volume (GBP mn)	36,042	3.532	0.936	7.194
Average trade size (GBP mn)	27,383	0.809	0.477	1.107
Number of block trades	36,042	0.454	0	1.107
Effective spread (bps)	14,724	25.832	18.133	42.771
Roll (bps)	14,781	40.904	25.149	47.262
Round-trip cost (bps)	7,079	44.075	31.563	39.237
Interquartile range (bps)	22,498	42.617	29.320	41.695
Amihud (bps)	20,063	83.290	44.081	103.904
Volatility-over-volume (bps)	14,781	25.948	15.035	30.054
Ineligible sterling investment grade bonds				
Number of trades	52,166	2.814	0	6.877
Trading volume (GBP mn)	52,166	2.159	0.000	6.354
Average trade size (GBP mn)	20,161	0.856	0.496	1.363
Number of block trades	52,166	0.273	0	0.939
Effective spread (bps)	11,437	25.823	18.480	41.108
Roll (bps)	11,614	37.455	24.137	42.492
Round-trip cost (bps)	6,200	44.143	32.900	37.487
Interquartile range (bps)	16,769	40.294	27.270	40.588
Amihud (bps)	15,459	81.759	44.259	101.042
Volatility-over-volume (bps)	11,614	21.187	12.176	25.904
Euro-denominated bonds issued by eligible issuers				
Number of trades	56,659	8.148	4	14.424
Trading volume (GBP mn)	56,659	5.230	1.313	11.141
Average trade size (GBP mn)	39,896	0.658	0.443	0.891
Number of block trades	56,659	0.593	0	1.535
Effective spread (bps)	25,432	14.322	9.984	29.151
Roll (bps)	29,930	23.704	14.896	28.692
Round-trip cost (bps)	15,671	27.657	19.197	26.542
Interquartile range (bps)	36,570	25.081	16.308	27.537
Amihud (bps)	32,176	46.322	26.641	61.798
Volatility-over-volume (bps)	29,930	12.149	6.956	17.327

Notes: The table shows summary statistics of liquidity measures for the corporate bond market estimated using the transaction-level Zen dataset. The measures are computed at weekly frequency for the sample period January 2016 to December 2017. Definitions of the measures are provided in Appendix A.

Table 3: Announcement effects

	Control group	
Dependent variable	Sterling	Euro
Number of trades	0.223	2.940
	0.792	0.052
Trading volume (GBP mn)	0.860	4.515
	0.387	0.003
Average trade size (GBP mn)	-0.073	0.240
	0.674	0.064
Number of block trades	0.119	0.448
	0.429	0.029
Effective spread (bps)	5.249	23.418
	0.623	0.002
Roll (bps)	2.431	-8.237
	0.804	0.194
Round-trip cost (bps)	35.026	-13.335
	0.062	0.177
Interquartile range (bps)	1.515	4.841
	0.836	0.349
Amihud (bps)	-14.982	-15.670
	0.519	0.306
Volatility-over-volume (bps)	-2.788	-6.002
	0.609	0.095

Notes: The table shows estimates of β from equation (1). p-values are shown beneath the coefficient estimates, and are computed using heteroskedasticity-robust standard errors. Full regression results are shown in the online appendix.

Table 4: Impact of CBPS purchases on contemporaneous liquidity

	Control group			
Dependent variable	Offer	Limit	Sterling	Euro
Number of trades	0.289	0.246	0.385	0.389
	0.000	0.000	0.000	0.000
Trading volume (GBP mn)	0.739	0.776	0.978	0.978
	0.000	0.000	0.000	0.000
Average trade size (GBP mn)	0.114	0.142	0.145	0.144
	0.000	0.000	0.000	0.000
Number of block trades	0.091	0.090	0.108	0.110
	0.000	0.000	0.000	0.000
Effective spread (bps)	-0.854	-0.850	-0.950	-0.887
	0.022	0.078	0.085	0.086
Roll (bps)	-0.357	-0.693	-0.537	-0.407
	0.067	0.044	0.172	0.292
Round-trip cost (bps)	0.097	-0.951	-0.469	-0.265
	0.820	0.139	0.248	0.502
Interquartile range (bps)	0.203	0.006	-0.042	0.342
	0.359	0.987	0.889	0.293
Amihud (bps)	-0.828	-2.080	-2.742	-2.301
	0.092	0.001	0.000	0.001
Volatility-over-volume (bps)	-0.684	-0.877	-0.941	-0.847
	0.000	0.000	0.000	0.000

Notes: The table shows estimates of β from equation (2). p-values are shown beneath the coefficient estimates, and are computed using standard errors double-clustered at the bond and auction levels. Full regression results are shown in the online appendix.

Table 5: Heterogeneity of impact by pre-CBPS liquidity

	Control group			
Dependent variable	Offer	Limit	Sterling	Euro
Number of trades	-0.004	-0.005	0.006	0.005
	0.490	0.553	0.484	0.532
Trading volume (GBP mn)	0.000	-0.001	0.002	0.001
	0.974	0.889	0.690	0.795
Average trade size (GBP mn)	0.012	0.016	-0.004	-0.006
	0.394	0.296	0.790	0.696
Number of block trades	-0.001	-0.003	0.004	0.003
	0.943	0.781	0.451	0.527
Effective spread (bps)	-0.019	-0.009	-0.016	-0.017
	0.072	0.443	0.234	0.185
Roll (bps)	0.004	0.008	-0.001	0.002
	0.674	0.501	0.949	0.875
Round-trip cost (bps)	0.011	-0.002	-0.010	-0.006
	0.359	0.926	0.512	0.695
Interquartile range (bps)	0.004	0.000	0.003	-0.001
	0.513	0.949	0.761	0.910
Amihud (bps)	-0.004	-0.002	-0.014	-0.017
	0.532	0.806	0.238	0.171
Volatility-over-volume (bps)	-0.004	-0.005	-0.009	-0.012
	0.526	0.513	0.338	0.230

Notes: The table shows estimates of ϕ from equation (3). p-values are shown beneath the coefficient estimates, and are computed using standard errors double-clustered at the bond and auction levels. Full regression results are shown in the online appendix.

Table 6: Variation in contemporaneous impact over time

	Control group			
Dependent variable	Offer	Limit	Sterling	Euro
Number of trades	-0.009	-0.006	-0.010	-0.009
	0.069	0.333	0.071	0.114
Trading volume (GBP mn)	-0.022	-0.021	-0.018	-0.017
	0.002	0.011	0.002	0.004
Average trade size (GBP mn)	-0.004	-0.003	-0.004	-0.003
	0.002	0.083	0.001	0.003
Number of block trades	-0.002	-0.003	-0.002	-0.002
	0.014	0.041	0.004	0.005
Effective spread (bps)	0.048	0.056	0.041	0.004
	0.235	0.353	0.369	0.914
Roll (bps)	-0.005	-0.082	0.002	-0.044
	0.838	0.066	0.936	0.048
Round-trip cost (bps)	0.009	0.077	-0.064	-0.140
	0.844	0.259	0.168	0.001
Interquartile range (bps)	-0.001	-0.027	-0.039	-0.132
	0.953	0.391	0.118	0.000
Amihud (bps)	0.029	-0.034	0.057	-0.099
	0.647	0.652	0.358	0.098
Volatility-over-volume (bps)	0.029	0.011	0.012	-0.030
	0.056	0.515	0.247	0.040

Notes: The table shows estimates of ϕ from equation (4). p-values are shown beneath the coefficient estimates, and are computed using standard errors double-clustered at the bond and auction levels. Full regression results are shown in the online appendix.

Table 7: Impact of lagged CBPS purchases on liquidity

	Control group			
Dependent variable	Offer	Limit	Sterling	Euro
Number of trades	0.053	0.058	0.031	0.037
	0.244	0.324	0.539	0.477
Trading volume (GBP mn)	0.068	0.075	0.037	0.042
	0.328	0.291	0.617	0.562
Average trade size (GBP mn)	0.003	0.004	0.006	0.009
	0.697	0.684	0.613	0.449
Number of block trades	0.011	0.011	0.003	0.004
	0.355	0.323	0.817	0.761
Effective spread (bps)	0.110	-0.043	-0.149	-0.064
	0.704	0.919	0.698	0.873
Roll (bps)	0.502	0.554	0.403	0.610
	0.104	0.155	0.353	0.124
Round-trip cost (bps)	0.226	0.371	0.778	0.921
	0.517	0.461	0.122	0.058
Interquartile range (bps)	-0.020	-0.079	0.066	0.281
	0.935	0.805	0.869	0.531
Amihud (bps)	-0.132	-0.860	-1.274	-0.975
	0.791	0.169	0.062	0.144
Volatility-over-volume (bps)	0.197	0.159	0.360	0.436
	0.225	0.311	0.077	0.048

Notes: The table shows estimates of ϕ from equation (5). p-values are shown beneath the coefficient estimates, and are computed using standard errors double-clustered at the bond and auction levels. Full regression results are shown in the online appendix.

Table 8: Stock effects

Dependent variable	Control group: Eligible	Control group: Sterling
Number of trades	0.008	-0.006
	0.809	0.807
Trading volume (GBP mn)	-0.040	-0.067
	0.208	0.006
Average trade size (GBP mn)	0.001	-0.001
	0.929	0.775
Number of block trades	-0.005	-0.009
	0.298	0.022
Effective spread (bps)	-0.011	0.386
	0.983	0.269
Roll (bps)	0.134	0.075
	0.814	0.823
Round-trip cost (bps)	1.126	-0.859
		0.544
Interquartile range (bps)	-0.117	-0.121
	0.625	0.492
Amihud (bps)	-0.627	-0.845
	0.439	0.122
Volatility-over-volume (bps)	-0.030	0.024
	0.931	0.909

Notes: The table shows estimates of β from equation (6). p-values are shown beneath the coefficient estimates, and are computed using heteroskedasticity-robust standard errors. Full regression results are shown in the online appendix.

A Definitions of liquidity measures

We compute ten liquidity measures using the transaction-level Zen dataset. All measures are computed at the individual bond level. Since corporate bonds trade relatively infrequently, the measures are computed at weekly frequency.

Number of trades. Number of trades within the week.

Trading volume. Total trading volume within the week, denominated in £mn.

Average trade size. Average trade size, denominated in £mn.

Number of block trades. Number of trades with a market value greater than or equal to £2mn, which is approximately the 90th percentile of the trade size distribution.

Effective spread. The effective spread is used by Hong and Warga (2000), among others, as an estimate of the average bid-ask spread. We compute this measure as the volume-weighted average price in trades where a dealer is selling to a non-dealer, minus the volume-weighted average price in trades where a dealer is buying from a non-dealer, divided by the volume-weighted average price across all trades. The units are basis points. To compute this measure, we require there to be at least one sell trade and one buy trade within the week.

Roll. Roll (1984) shows that under certain assumptions, the effective bid-ask spread is equal to two times the square root of the negative of the first-order serial covariance of returns. For a given bond and a given week, define r_i to be the return on the ith trade. We then compute the Roll measure as

$$Roll = 2\sqrt{\max\left\{0, -\text{cov}\left(r_i, r_{i-1}\right)\right\}}.$$

The units are basis points. We only compute this measure for weeks with at least four trades.

Round-trip cost. Following Goldstein et al. (2007), we estimate the round-trip cost of trading a bond as an additional measure of the bid-ask spread. Specifically, we search for instances in which a given dealer buys a bond from a non-dealer, and then the same dealer sells the same bond to a different non-dealer within the same week (or vice versa). We then find the dealer's return on this chain of transactions. The units are basis points.

Interquartile range. As an alternative estimate of the bid-ask spread, Han and Zhou (2011) use the interquartile range of traded prices, divided by the average price. The units are basis points. We require at least two trades within the week to compute this measure.

Amihud. Amihud (2002) measures liquidity as the ratio of absolute return to trading volume. This measure is intended to capture the price impact of trading. Following Dick-Nielsen et al. (2012), we compute the Amihud measure at the level of individual trades, then average over the trade-level values each week to obtain a measure at weekly frequency. More precisely, for a given bond and a given week, define r_i to be the return and Q_i to be the trade size (in £mn) of the ith trade, and define N to be the number of trades. We then compute the Amihud measure as

$$Amihud = \frac{1}{N-1} \sum_{i=2}^{N} \frac{|r_i|}{Q_i}.$$

The units are basis points. We require at least two trades within the week to compute this measure. We exclude trades smaller than £100k since these can introduce significant noise.

Volatility-over-volume. As an additional measure of price impact, we use the volatility-over-volume measure of Fong et al. (2017). For a given bond and a given week, let σ^2 be the variance of traded prices and let V be the total trading volume (in £mn). We then compute volatility-over-volume as

$$VoV = \sqrt{\frac{\sigma^2}{V}}.$$

The units are basis points, and we only compute this measure for weeks with at least four trades.

B Econometric model

We provide an econometric justification for our benchmark model. We suppose that liquidity is determined by the following equation:

$$L_{bt} = \alpha_b + \mu_t + \beta P_{bt} + \delta^\intercal Z_{bt} + e_{bt}, \tag{7}$$

where L_{bt} denotes the liquidity of bond b in period t, P_{bt} denotes auction purchases, and $Z_{bt} \in \mathbb{R}^{k_z}$ is a vector of latent signals about liquidity observed by market participants but not by the econometrician. We suppose that purchases are determined by demand and supply factors, so that

$$P_{bt} = a_b + c_t + \theta^\intercal X_{bt} + u_{bt}, \tag{8}$$

where $X_{bt} = (D_{bt}^\intercal, S_{bt}^\intercal)^\intercal \in \mathbb{R}^{k_x}$. The demand and supply measures are themselves driven by the latent liquidity factor, i.e.,

$$X_{bt} = \omega_b + \phi_t + BZ_{bt} + v_{bt}. \tag{9}$$

Here, α_b, μ_t, a_b, c_t, ω_b, and ϕ_t are unobserved bond-specific and time-specific fixed effects whose relations with other variables are not restricted in any way. Because Z_{bt} is not observed, the usual difference-in-differences estimator of liquidity L_{bt} on purchases P_{bt} would be inconsistent. The model shares some similarities with Pesaran (2006), except that the latent factors in our case vary over both bonds and time in an unspecified way.

Suppose that $k_x = k_z = k$ and that B is of full rank.[9] In this case, we may write

$$Z_{bt} = B^{-1}\left(X_{bt} - v_{bt} - \omega_b - \phi_t\right),$$

and hence substituting into (7) we obtain

$$L_{bt} = \alpha_b^* + \gamma_t^* + \beta P_{bt} + d^\intercal X_{bt} + e_{bt}^*, \tag{10}$$

where $e_{bt}^* = e_{bt} - \delta^\intercal B^{-1} v_{bt}$ is a linear combination of e_{bt} and v_{bt}, while α_b^* and γ_t^* are linear combinations of the fixed effects from the liquidity equation, the demand equation, and the supply equation. Taking double differences (across b and t), we obtain

$$\begin{aligned} \widetilde{L}_{bt} &= \beta \widetilde{P}_{bt} + d^\intercal \widetilde{X}_{bt} + \widetilde{e}_{bt}^* \\ \widetilde{P}_{bt} &= \theta^\intercal \widetilde{X}_{bt} + \widetilde{u}_{bt} \\ \widetilde{X}_{bt} &= B\widetilde{Z}_{bt} + \widetilde{v}_{bt}, \end{aligned} \tag{11}$$

[9] This is only for exposition; the argument also works provided $\text{rank}(B) \geq k_z$, i.e., more X than Z.

where $\widetilde{L}_{bt} = \Delta\Delta L_{bt}$, $\widetilde{P}_{bt} = \Delta\Delta P_{bt}$, etc. Note that $\widetilde{e}^*_{bt}$ contains $\widetilde{v}_{bt}$, which is correlated with $\widetilde{X}_{bt}$ and $\widetilde{P}_{bt}$, the included variables in (11), the equation of interest. This is like the classical measurement error problem: since X is an imperfect measure of Z, it usually leads to biased OLS coefficients (Aigner et al., 1984). However, because P is only driven by L through Z, this effect can be eliminated, at least as far as the main effect of interest, using the partitioned regression formula. Let $E_L(Y|X)$ denote the best linear predictor of a random variable Y by a random variable X. We have

$$E_L(\widetilde{L}_{bt}|\widetilde{X}_{bt}) = \beta E_L(\widetilde{P}_{bt}|\widetilde{X}_{bt}) + d^\intercal \widetilde{X}_{bt} + E_L(\widetilde{e}^*_{bt}|\widetilde{X}_{bt}),$$

using the linearity of the operator $E_L(\cdot|\cdot)$. Subtracting from (11) we obtain

$$\widetilde{L}_{bt} - E_L(\widetilde{L}_{bt}|\widetilde{X}_{bt}) = \beta \left(\widetilde{P}_{bt} - E_L(\widetilde{P}_{bt}|\widetilde{X}_{bt})\right) + \left(\widetilde{e}^*_{bt} - E_L(\widetilde{e}^*_{bt}|\widetilde{X}_{bt})\right).$$

Now, since $\widetilde{P}_{bt} - E_L(\widetilde{P}_{bt}|\widetilde{X}_{bt}) = \widetilde{u}_{bt}$, provided $E_L(\widetilde{e}_{bt}, \widetilde{v}_{bt}, \widetilde{X}_{bt}|\widetilde{u}_{bt}) = 0$, the slope of the best linear predictor of $\widetilde{L}_{bt} - E_L(\widetilde{L}_{bt}|\widetilde{X}_{bt})$ by $(\widetilde{P}_{bt} - E_L(\widetilde{P}_{bt}|\widetilde{X}_{bt}))$ is β. Therefore, for identification of β it suffices that the following unconditional moment conditions are satisfied:

$$E\left(\widetilde{e}_{bt} \times \widetilde{u}_{bt}\right) = 0 \quad (12)$$

$$E\left(\widetilde{v}_{bt} \times \widetilde{u}_{bt}\right) = 0 \quad (13)$$

$$E\left(Z_{bt} \times \widetilde{u}_{bt}\right) = 0. \quad (14)$$

In practice, we construct the OLS estimator of β from (11) by the partitioned regression formula

$$\widehat{\beta} = \left(\mathcal{P}^\intercal \mathcal{M}_x \mathcal{P}\right)^{-1} \mathcal{P}^\intercal \mathcal{M}_x \mathcal{L} = \beta + \left(\mathcal{P}^\intercal \mathcal{M}_x \mathcal{P}\right)^{-1} \mathcal{P}^\intercal \mathcal{M}_x \mathcal{E}^*,$$

where $\mathcal{P}$ is the $nT \times 1$ vector containing the observations $\widetilde{P}_{bt}$, $\mathcal{L}$ is the $nT \times 1$ vector containing the observations $\widetilde{L}_{bt}$, while

$$\mathcal{M}_x = I_{nT} - \mathcal{X}(\mathcal{X}^\intercal \mathcal{X})^{-1}\mathcal{X}^\intercal,$$

where $\mathcal{X}$ is the $nT \times k$ matrix containing the observations $\widetilde{X}_{bt}$. Here, $\mathcal{E}^*$ is the $nT \times 1$ vector containing the observations $\widetilde{e}^*_{bt}$. The partialling out by $\mathcal{M}_x$ removes the source of correlation between the error term in (11) and the included variables.

The moment conditions (12) - (14), along with technical conditions (that are standard in the difference-in-differences literature) to ensure laws of large numbers and central limit theorems, guarantee the large sample approximations we use in the paper. The estimates of d are not particularly meaningful as they involve a number of underlying parameters (these estimates will be affected by the measurement error bias anyway).