Braving the Uncharted Sea:

Effects of the IOER – ON RRP Spread on the Federal Funds Market and Overnight Reverse Repurchase Facility

Harry Browne

Economics 491 and 492: The Senior Essay

Advisor: William English

April 4, 2018

Abstract

After quantitative easing flooded the Federal Reserve's balance sheet with trillions of dollars of excess reserves, the central bank lost the ability to manipulate interest rates with small amounts of open market operations. As such, it turned to an alternative strategy—using interest payments on excess reserves (IOER) supplemented by a new overnight reverse repurchase (ON RRP) facility. Open to a wider variety of counterparties, the ON RRP facility works in tandem with IOER to strengthen the federal funds rate's "floor," keeping it within its target range. This paper examines the effects of the IOER-ON RRP spread on volatility in the federal funds market and volumes at the ON RRP facility, finding that narrowing the spread by 10 basis points can decrease intraday volatility by as much as 5.8 bps while increasing facility size by just $185 billion. Given the facility's small size relative to pre-liftoff market expectations and its power to control volatility, the Federal Reserve should consider reducing the IOER-ON RRP spread from its current 25 bps setting to its historical minimum of 15 bps.

Particular thanks to William English, Antoine Martin, Jacob Faber, and Kevin Kiernan for their valuable input and advice.

Datasets used in the creation of this paper are available upon request.

1 Introduction

Though its pains have since subsided, the scars of the Global Financial Crisis will long remain. Sweeping regulations such as Dodd-Frank, enacted in response to the most significant economic upheaval since the Great Depression, have dramatically altered the regulatory landscape of the United States. The powers of supervisory institutions have been reshaped to more efficiently identify risks and prevent crises, while their heads have been united under the Financial Stability Oversight Council (FSOC) to provide better coordination and more effective action. Within this period of rebalancing, no institution has undergone a more profound change than the Federal Reserve (the Fed). Facing disaster and having lowered the federal funds rate to the effective lower bound, the Fed turned to quantitative easing—large-scale purchases of long-term securities—in an effort provide further assistance. As a direct result of these operations, the size of the Fed's balance sheet skyrocketed as banks and other financial institutions received trillions of dollars in exchange for their long-term assets. In this environment, the Fed's tried-and-true method of monetary policy—using open market operations to manipulate the supply of reserves and move short-term interest rates—became wholly ineffectual, as the supply grew well above the point where changes of a few billion dollars could sway interest rates. In response, the Fed began to use a new policy tool—the payment of interest on excess reserves (IOER). Statutory limitations denying certain institutions the ability to earn interest on reserves gave rise to an arbitrage opportunity in the federal funds market, yet due to its associated costs, the federal funds rate "leaked" below IOER, further threatening the Fed's ability to manage rates. To regain control, the Fed added a new, supplementary element to its monetary policy regime: the overnight reverse repurchase facility (ON RRP).

The ON RRP facility, which acts as a more widely-available proxy for IOER, has been in use for almost five years, undergoing a battery of tests and helping the Fed through its December 2015 rate increase—the first since the crisis—and several more since. Nevertheless, the facility remains far less understood than traditional monetary policy tools, as the academic research concerning it is still in its nascent stages. In order to improve calibration at the facility, an econometric analysis of how the relative settings of IOER and the ON RRP rate affect conditions both within the federal funds market and at the facility is needed. This paper provides such an analysis. These enquiries consider how the IOER-ON RRP spread affects the intraday and interday volatility of the federal funds rate as well as the volume of transactions that occur at the ON RRP facility daily, thereby allowing policy makers at the Fed to weigh rate control against the Fed's financial footprint. To achieve this goal, this paper consolidates a wide variety of data, including the daily distribution of trades in the federal funds market, daily rates and volumes at the ON RRP facility, and volumes of other Fed policy tools, such as term reverse repurchases and term deposits. It then employs ordinary least squares regressions to evaluate the efficacy and size of the new facility.

This paper's results reveal that the IOER-ON RRP spread can significantly affect volatility in the federal funds market and volumes at the ON RRP facility. Reductions in the spread by just 10 basis points (0.1 percent) can lead to a 5.8 bps decrease in funds rate volatility during a single business day, measured as the difference between the 99^{th} and 1^{st} percentile of traded rates. A similarly sized reduction can decrease volatility over five business days, measured as the standard deviation of the days' effective federal funds rates, by one basis point. Moreover, the costs of these reductions in terms of the Fed's financial footprint are not as high as might be feared, as a 10 basis point decrease in the spread would increase facility volumes by

just $185 billion. Considering that the average volume since December 2015 has stood around $125 billion and that market predictions of the volume were usually between $300 billion and $400 billion, this increase would keep the facility within previously expected sizes. Tests also show that term RRPs, which are used less frequently than their overnight counterparts, can reduce volumes at the ON RRP facility without great effect on market volatility.

Based on these results, the Fed should consider reducing the IOER-ON RRP spread from its current 25 bps setting to its historical minimum of 15 bps. This change should significantly lower volatility in the federal funds market without imposing a prohibitive increase in facility size. Low volatility is an important goal for the Fed, as it can improve policy communication and reduce uncertainty costs, creating more efficient markets. Additionally, this change should not create unacceptable financial risk as a potential drainer of liquidity during future financial crises, as the size of the facility would remain on the low end of expectations, roughly equivalent to the cap formerly imposed by the Fed to prevent exactly that phenomenon. Though a larger ON RRP facility may lead to a more substantial role in monetary policy for money market funds (MMFs), which are regulated by the Securities and Exchange Commission rather than the Fed, the creation of the FSOC allows the Fed to participate in their oversight, mitigating some risk.

The remainder of the paper continues as follows: Section 2 provides an in-depth discussion of the changes to Federal Reserve monetary policy that followed the Global Financial Crisis; Section 3 discusses the existing literature on the ON RRP facility and its effects on various financial markets; Section 4 presents the available data and explains the methodology of the econometric analyses; Section 5 reports the results of the regressions and tests residuals to ensure accurate results; Section 6 provides a policy recommendation based on the findings; Section 7 suggests opportunities for further research and concludes. Cited works can be found in

Appendix A, an additional analysis of the effect of the IOER-ON RRP spread on federal funds volumes in Appendix B, figures in Appendix C, descriptive statistics in Appendix D, main regression results in Appendix E, residual tests in Appendix F, the R code used to conduct the main analyses in Appendix G, and the R code for the federal funds volume analysis in Appendix H.

2 The Financial Crisis and the Changing Monetary Policy Landscape

The Federal Reserve, like many other central banks, conducts monetary policy by targeting a private interest rate set in the markets—the federal funds rate. Historically, the federal funds market primarily served as the conduit through which depository institutions could borrow and lend reserves overnight either to meet their legal requirements or to offload unneeded liquidity, and the Fed has long held the view that this rate transmits effectively to other private rates (Federal Reserve Bank of New York 2013). This type of overnight market features an atypical demand curve, as it is constrained by two factors—the rate the Fed offers at the discount window and the rate it pays on reserve balances. Consider a financial institution seeking a loan in the federal funds market. It will be unwilling to borrow at a rate appreciably higher than that offered at the Fed's discount window, which, if the institution is solvent, will always be available to it (Bernhardsen and Kloster 2010, 1). This effectively makes the discount rate a "ceiling" for overnight rates in the private market.[1] Likewise, consider an institution that wishes to lend in the federal funds market. It will be unwilling to accept any interest rate below that which it could receive by simply leaving its money at the Fed, making the interest rate on excess reserves (IOER) a "floor" (Bernhardsen and Kloster 2010, 1). Figure 1 represents supply and demand for

[1] To some degree, depository institutions may prefer to avoid borrowing from the discount window, worrying it might suggest instability at the firm to other market participants. This phenomenon, known as "stigma," can potentially result in some private borrowing at rates above the "ceiling."

reserves in the overnight market. The demand curve exhibits a distinctive “z shape;” as the price of reserves in the market decreases, there is increased demand for reserve balances, yet that price should never go above or below the Fed’s discount or IOER rates, respectively.

Despite the fact that the Fed takes no part in the individual transactions that occur in the federal funds market, it can use indirect influence to conduct policy using two frameworks—a “corridor” system or a “floor” system. As the monopolistic supplier of reserves, the Fed can unilaterally choose the quantity available to the market; as such, it is depicted as a vertical line in Figure 1. Naturally, the equilibrium point of the supply and demand curves determines the federal funds rate. If the supply of reserves is low enough, the equilibrium point will occur on the downward-sloping portion of the demand curve, represented by the curve labeled S1. In such an environment, small increases or decreases in the quantity of reserves—shifting S1 left or right—will correspond to decreases or increases in the federal funds rate. This setting is known as a corridor system, as the central bank operates within the corridor defined by its own lending and deposit rates. In contrast, if the supply of reserves is large, equilibrium occurs on the flat portion of the demand curve, represented by S2. Here, small changes to the quantity of reserves have no effect on the interest rate. Instead, the central bank can only raise or lower rates by moving the floor itself, either increasing or decreasing the interest rate it pays when it borrows from private institutions. As all activity in the market occurs at the bottom of the demand curve, this is referred to as a floor system.

For the vast majority of its history, the Federal Reserve operated within the corridor system. Prior to October 1, 2008, the Fed did not pay any interest on excess reserves held at the Federal Reserve Banks—that is, the deposit rate was zero (Board of Governors of the Federal Reserve System 2018). As such, before the Global Financial Crisis, banks attempted to hold only

the required amount of reserves and no more, minimizing excess reserves and providing a critical role for the federal funds market (Ihrig, Meade, and Weinbach 2015, 2). Figures 2 and 3 track the amount of excess reserves and the amount of total reserves, respectively, held by depository institutions at Federal Reserve Banks in the pre- and post-crisis periods. In November 2007, depository institutions held just $1.7 billion of excess reserves out of a total of $8.3 billion, placing the U.S. firmly within the corridor system (Federal Reserve Bank of St. Louis 2018a; Federal Reserve Bank of St. Louis 2018b). In this period, the Fed conducted monetary policy in a straightforward manner, directing the open market desk at the Federal Reserve Bank of New York to sell or purchase securities—permanently or through repo transactions—to and from private institutions (Ihrig, Meade, and Weinbach 2015, 5). In exchange for a security, the Fed would provide its counterparty with funds, thereby increasing the supply of reserves and lowering the federal funds rate, with the same process holding true in reverse. Given the low level of reserves in the system, these open market operations were a natural choice for the Fed and formed the backbone of American monetary policy for decades.

However, the events surrounding the Global Financial Crisis of 2007-08 forced the Fed into an environment it had never before faced. In December 2008, as the U.S. economy continued to contract, the Fed lowered its target for the federal funds rate to 0.00-0.25%, reaching the "effective lower bound" and preventing the Fed from lowering overnight rates any further.[2] In an effort to provide additional stimulus, on November 25, 2008, the Fed announced a plan to purchase up to $500 billion in agency mortgage-backed securities (MBS) and $100 billion of the direct obligations of government sponsored enterprises, amounts that were

[2] It may be possible to push rates somewhat below zero. For instance, the Swiss National Bank has recently experimented with slightly negative interest rates, but this has never been attempted in the United States. As currency pays a nominal rate of zero, rates far below zero are not feasible.

expanded to $1.25 trillion in agency MBS, $200 billion in direct obligations, and $300 billion in long-term Treasuries in March 2009 (Board of Governors of the Federal Reserve System 2008; Board of Governors of the Federal Reserve System 2009). These purchases, which represented the first steps in a process referred to as quantitative easing (QE), aimed to limit the supply of longer-term securities in the private sector, thereby further decreasing long-term interest rates. Two more rounds of QE followed suit, with $600 billion in purchases of longer-term Treasuries in 2010-11 and monthly purchases of $40 billion in agency MBS from September 2012 to October 2014 (Board of Governors of the Federal Reserve System 2010; Board of Governors of the Federal Reserve System 2012; Board of Governors of the Federal Reserve System 2014). While these purchases may have been a necessary step in quelling the economic storm that had embroiled the U.S. and the world at large, they carried a side effect that fundamentally altered the manner in which Fed could conduct monetary policy for the foreseeable future. By August 2014, total reserves at Federal Reserve Banks had swelled to a colossal $2.8 trillion, with $2.7 trillion of that figure in excess of requirements (Federal Reserve Bank of St. Louis 2018a; Federal Reserve Bank of St. Louis 2018b). This greater than 1,000-fold increase in excess reserves was more than enough to push the U.S. market for reserves onto the flat portion of the demand curve depicted in Figure 1. In the post-crisis environment, small changes to the supply of reserves would be an ineffective method of conducting monetary policy. As such, the Fed had to resort to a floor system.

Complicating the shift to a new system was a radical change in the post-crisis makeup of the federal funds market. Figure 4 shows the volume of trading in the market from the end of 2006—prior to the crisis—to the end of 2012. In the second quarter of 2007, $221.7 billion of loans were made in the federal funds market, more than half of which was created by domestic

bank holding companies, domestic standalone banks, and foreign entities (Federal Reserve Bank of New York, Undated, a). Yet by the fourth quarter of 2012, the size of the market had plummeted to $60.3 billion, with 73 percent of the loans extended by the Federal Home Loan Banks (FHLBs) (Federal Reserve Bank of New York, Undated, a). This dramatic shift had two causes. First, the Emergency Economic Stabilization Act of 2008 authorized the Fed to pay interest on depository institutions' excess reserves on October 1 of that year (Board of Governors of the Federal Reserve System 2018). In a market with abundant reserves and a central bank paying interest on the excess, depository institutions were almost entirely disincentivized from trading in the federal funds market. However, the authorization did not extend to government-sponsored enterprises (GSEs) such as the FHLBs (Afonso, Entz, and LeSueur 2013a). As such, the only way the FHLBs can earn a return on their reserves is to lend them in the federal funds market. Since GSEs cannot earn interest at the Fed, they are willing to lend below the supposed "floor rate." Primarily, their counterparts are foreign banks, which, being eligible for IOER, can borrow in the private market and deposit the funds at the Fed's higher rate as an arbitrage opportunity (Afonso, Entz, and LeSueur 2013b). Due to the requirements of the Federal Deposit Insurance Corporation and new rules resulting from the Basel III accords, these arbitrage opportunities feature significant costs, especially for domestic banks, that have kept the effective federal funds rate below IOER (Frost et al 2015, 5-6). Figure 5 tracks the IOER rate and the effective federal funds rate since 2010 and clearly shows that the effective federal funds rate has consistently fallen below IOER in recent years due to arbitrage costs.

Amid worries over the central bank's ability to control its target rate with a "leaky floor," the Federal Open Market Committee (FOMC) was briefed in July 2013 on the possibility of opening an overnight reverse repurchase (ON RRP) facility and agreed in September 2013 to

authorize the Federal Reserve Bank of New York to experiment with such operations (Federal Open Market Committee 2013a; Federal Open Market Committee 2013b). The ON RRP facility conducts "reverse repo" transactions, which function as a type of collateralized overnight loan to the Fed. Through the open market desk at the New York Fed—which previously had conducted all open market operations under the corridor system—the Fed sells a security to a counterparty in exchange for cash; under the contract, the Fed repurchases the security the next day at an increased price (Federal Reserve Bank of New York 2017). As such, ON RRPs are functionally the same as an overnight loan with a certain interest rate, collateralized by a security—specifically, Treasuries—from the Fed's System Open Market Account (Federal Reserve Bank of New York 2017). ON RRPs supplement the use of the primary tool—IOER, which is determined by the Board of Governors (Board of Governors of the Federal Reserve System 2017a). The key difference between the two tools is the broader list of counterparties eligible for ON RRP relative to IOER. Whereas IOER is only available to domestic depository institutions and U.S. branches of foreign banks, ON RRPs are additionally available to GSEs and money market funds (MMFs) (Federal Reserve Bank of New York 2013; Federal Reserve Bank of New York, Undated, b). By expanding the list of counterparties, the ON RRP facility supports the new monetary policy regime; the GSEs that drive the federal funds arbitrage market should be unwilling to lend below the ON RRP rate, thus providing a secondary, firmer floor under IOER.

Worries of an overlarge facility led the FOMC to impose limits on its terms. Generally, the ON RRP rate is specified by the FOMC in the implementation notes released following its meetings (Board of Governors of the Federal Reserve System 2017a). However, that rate can be altered based on an auction process if the total volume of bids exceeds the facility's "cap." In the event that investors seek an amount above the daily aggregate cap, the New York Fed ranks the

offers from that of the counterparty willing to accept the lowest rate to that of the counterparty demanding the highest, and it fulfills requests at the rate at which the cap is reached—the "stop-out" rate (Federal Reserve Bank of New York 2017). Such a situation is very uncommon, however, having occurred only once on September 30, 2014 (Federal Reserve Bank of New York, Undated, e). Moreover, no counterparty can receive more than the individual limit. Originally, transactions were limited to $1 billion per counterparty per day, which has since expanded to $30 billion; an aggregate cap of $300 billion per day was in place from September 2014 to December 2015 (Federal Open Market Committee 2013b; Federal Reserve Bank of New York 2017; Federal Open Market Committee 2014c; Federal Open Market Committee 2015c). Under these terms, the facility has been in continuous operation since its introduction in September 2013.

The open market desk at the New York Fed has conducted a number of experiments with this system, including changes to the spread between IOER and the ON RRP rate and in the individual and aggregate caps. Since the facility's creation, the appropriate IOER-ON RRP spread has been a matter of debate within the FOMC. The minutes of the June 2014 meeting reflect this, noting, "The appropriate size of the spread between the IOER and ON RRP rates was discussed, with many participants judging that a relatively wide spread—perhaps near or above the current level of 20 basis points—would support trading in the federal funds market and provide adequate control over market interest rates… A couple of participants suggested that adequate control of short-term rates might be accomplished with a very wide spread or even without an ON RRP facility" (Federal Open Market Committee 2014a). This tendency towards a wider spread and lower reliance on the facility is supported by the Fed's commitment to halt usage of overnight reverse repos following "normalization"—the Fed's ongoing process of

returning to an environment of higher interest rates and a smaller balance sheet (Board of Governors of the Federal Reserve System 2017b). Despite these sentiments, the Fed has not yet moved to reduce usage of the ON RRP facility.

In sum, the current Fed balance sheet represents an uncharted sea for policy makers. The effects of QE have upended the federal funds market, driving depository institutions out, replacing them with GSEs and foreign banks looking for an arbitrage opportunity, and bringing the U.S. into a "leaky floor" environment. The Fed has responded with a new facility designed to firm up the system, but its appropriate design remains unknown. This paper will attempt to provide clarity to that question and help guide the Fed forward on its post-crisis journey.

3 Literature Review

As the ON RRP facility is a recent creation, there are a number of gaps in the related literature, leaving a great deal of room for exploration. Within the existing research, however, the transmission of the ON RRP rate to private market rates is one of the better-studied aspects of the new monetary policy regime. Researching the period prior to "liftoff"—the December 17, 2015 rate increase, the first since Global Financial Crisis—Klee, Senyuz, and Yoldas examine data from 2001 to 2015 and find that the introduction of the ON RRP facility led interest rates in both secured and unsecured markets to move in greater tandem and that the private Treasury GC repo rate had become a strong predictor of both the federal funds rate and other private rates (Klee, Senyuz, and Yoldas 2016, 17). The authors also found that volatility in overnight markets, including the federal funds market, declined substantially following the creation of the ON RRP facility (Klee, Senyuz, and Yoldas 2016, 21). More recently, several researchers have examined rate transmission in the post-liftoff period. Ihrig, Meade, and Weinbach briefly look at market rates following liftoff, noting that "the variability of interest rates and trading volumes in money

markets have remained similar to what they were before the Fed's policy change" (Ihrig, Meade, and Weinbach 2016). Anderson, Ihrig, Meade, and Weinbach go a step further, showing that many overnight and term rates increased in the aggregate with the rate hike and that the daily distribution of rates remained similar (Anderson et al 2016). Anderson, Ihrig, Styczynski, and Weinbach perform a comparable analysis following the third rate increase (Anderson et al 2017). In a paper specifically about rate volatility, Senyuz and Tase examine how the introduction of ON RRPs affected both uncertainty and volatility in the private repo market, finding that uncertainty was diminished and volatility was mostly unaffected, except for at month- and quarter-end dates, when it decreased (Senyuz and Tase 2017). These studies, however, are insufficient to describe the ON RRP facility's effect on the federal funds rate. Klee, Senyuz, and Yoldas use an aggregated measure of volatility that fails to reveal an effect of the IOER-ON RRP spread. Moreover, the Ihrig and Anderson papers all fall short of providing full econometric analyses, such as the one provided by this paper, resorting instead to graphical interpretation. Senyuz and Tase do provide a regression analysis, but focus on the Treasury GCF market rather than the federal funds market. As such, there remains a need to investigate the IOER-ON RRP spread's effects on federal funds rate volatility, especially in the post-liftoff period.

In addition to the papers on rates, other studies have considered the ON RRP facility's effect on volumes. Anderson, Ihrig, Meade, and Weinbach argued that the December 2015 rate hike had little effect on either trade volumes in the federal funds market or take-up at the ON RRP facility (Anderson et al 2016). Anderson and Kandrac use a difference-in-difference approach to estimate how increases in the ON RRP caps—the per-counterparty limits on lending—affected take-up in the facility and volumes in other markets, finding that the facility tended to take investment away from the private repo market (Anderson and Kandrac 2016, 15).

A deeper exploration of market volumes in the period following the ON RRP facility's creation is certainly needed. Anderson et al (2016) focuses only on one event—liftoff—rather than the four years since the facility's creation, leaving many unanswered questions. Moreover, though Anderson and Kandrac study a longer period, the key variation examined is changes in the facility's caps, as opposed to the IOER-ON RRP spread, which is of interest here.

While the aforementioned papers have examined realized market trends, there has been a great deal of data-driven modeling done since ON RRPs were first used as well. Armenter and Lester create an elegant model that seeks to answer many of the questions relevant to this paper, predicting that it is the spread between IOER and ON RRP, not their absolute levels, that determines take-up of ON RRP and the effective federal funds rate (Armenter and Lester 2016, 19). Anderson and Huther create a model of individual take-up in the ON RRP facility, which is similar to one of the goals of this paper, predicting that it is affected by the spread between ON RRP and market repo rates (Anderson and Huther 2016, 20). Of course, these models do not replace the need for a full regression analysis. Though Armenter and Lester's predictions match well with the post-liftoff data, their model is calibrated using only a very small dataset from the fourth quarter of 2015 and therefore does not factor in the experimental period from 2013-14 (Armenter and Lester 2016, 15-18). Likewise, Anderson and Huther do not comment on how ON RRP takeup will be affected by the spread between the IOER and ON RRP rates.

Other papers have tended to be more theoretical, especially those that were developed contemporaneously with the creation of the ON RRP facility. Clouse, Ihrig, Klee, and Chen model the economy by examining the interactions of several sectors' balance sheets, finding that decreases in the IOER-ON RRP spread will lead to an increase in ON RRP usage and a decrease in volume in the federal funds market (Clouse et all 2014, 22). Martin, McAndrews, Palida, and

Skeie also dive into the debate surrounding the facility, arguing that a full-allotment ON RRP facility may lead to lower volatility than a capped facility (Martin et al 2013, 20). While these findings are extremely similar to those sought in this paper, the works are based on theory as opposed to data due to the time of their writing. As such, there is room to explore these questions again in a more quantitative manner.

Lastly, there have been a number of papers that have addressed this issue with neither empirical evidence nor modeling, relying on argument alone. Though they do not provide the data analysis necessary to calibrate an ON RRP facility, these papers have been frequently cited by other authors and form the foundations of debate on this issue. Frost, Logan, Martin, McCabe, Natalucci, and Remache provide the most notable example, as their paper extensively covers the different benefits and pitfalls an ON RRP facility might have, including the effects of the IOER-ON RRP spread. It explains that as the spread grows, use of the facility will shrink, hindering its ability to control the federal funds rate, but that too large a facility might allow "flights-to-quality" during a financial panic, depleting market liquidity (Frost et al 2015, 18-22). Ihrig, Meade, and Weinbach support a wide IOER-ON RRP spread for similar reasons, arguing that a 25-basis point spread would be effective yet not cause instability (Ihrig, Meade, and Weinbach 2015, 22). On the contrary, Gagnon and Sack argue for no spread at all between IOER and ON RRP, contending that a system in which the Fed completely forgoes targeting the federal funds rate would lead to all interest rates being set in the market relative to IOER and ON RRP in a natural, predictable manner (Gagnon and Sack 2014, 7-8). Though not rigorous enough to lead to policy decisions, these papers give critical context to any conclusions drawn from the data.

Based on the state of the existing literature, an empirical investigation of the effect that the IOER-ON RRP spread has on federal funds rate volatility and ON RRP take-up is both novel

and necessary. Few authors have considered federal funds rate volatility, and none have empirically examined how it responds to the IOER-ON RRP spread. Likewise, the papers that have been written on take-up at the ON RRP facility have not factored in the effects of the IOER-ON RRP spread as well. Most importantly, many of these papers have not yet accounted for the effects of the FOMC's rate hikes that have occurred since December 2015. As such, this paper will provide important information useful to the effort to design an ideal ON RRP facility.

4 Data and Methodology

There are a wide variety of methods to measure the volatility of the federal funds rate, two of which will be employed in this paper. First, the paper examines intraday volatility—the distribution of rates in trades occurring on one business day. On any given day, financial institutions borrow and lend reserves in the federal funds market either directly to their counterparties or through brokers, and each transaction occurs at a privately negotiated interest rate. As such, a feasible measure of intraday volatility is the difference between the daily highest and lowest interest rates. A smaller range would indicate that trading was less volatile, and vice versa. The Federal Reserve Bank of New York publishes data on the federal funds market daily, yet a change in calculation methodology has imposed a challenge. Beginning on March 1, 2016, the bank, which had previously published a volume-weighted mean Effective Federal Funds Rate (EFFR), standard deviation, and daily highs and lows taken from a survey of brokered transactions, began publishing a volume-weighted median EFFR with 1^{st}, 25^{th}, 75^{th}, and 99^{th} percentile values taken from both brokered transactions and those directly between counterparties (Federal Reserve Bank of New York 2016). While the mean and median values are similar, they are not identical and cannot be considered perfect substitutes; the spread of the median over the mean varied wildly during the Global Financial Crisis, and has varied mildly

since, particularly on quarter-end dates (Federal Reserve Bank of New York 2015a, 3-4). In preparation for this shift, the New York Fed provided a history of the daily median and percentiles with a statement concerning the methodology change, with the historical data running from January 3, 2005 to June 17, 2015 (Federal Reserve Bank of New York 2015b). Unfortunately, that dataset was not extended to the March 2016 switch in methodology, creating a missing period from June 18, 2015 through February 29, 2016—a stretch that includes December 2015's liftoff. A request for the missing data under the Freedom of Information Act was granted only in part and did not yield the desired data.[3] The alternative to using this data, however, would be to use only the mean values, which were discontinued in March 2016, before several more rate increases over the ensuing two years. Therefore, it was decided to use the difference between the 99th and 1st percentile values as the measure of intraday volatility, combining the historical data with the New York Fed's regular updates (Federal Reserve Bank of New York, Undated, c). This choice resulted in 879 business days since the ON RRP facility's creation for which complete data were available.

Interday volatility—the distribution of trades over the course of multiple business days—is also examined. First, the data set is divided into a series of multi-day periods of constant length during which the relevant covariates remain fixed. Then, the standard deviation of the median EFFR is taken for each period. Given the aforementioned missing data, it was possible to construct 119 five-business day periods from September 2013 to December 2017 during which only the median EFFR changed. While this is a decrease in the number of observations, it remains more than sufficient to provide worthwhile results.

[3] Email with the Corporate Secretary's Office of the Federal Reserve Bank of New York, March 26, 2018.

In addition, this paper investigates the factors affecting volumes at the ON RRP facility. The New York Fed conducts its reverse repurchase activities under the label of "temporary open market operations," transacting with securities in the Fed's System Open Market Account (SOMA) (Federal Reserve Bank of New York 2017). Results of these operations have been published daily since the facility's creation on September 23, 2013, on the New York Fed's website (Federal Reserve Bank of New York, Undated, e). These details include the number of participating counterparties, the total volume of transactions proposed and accepted, and the offered rate.

There are a number of factors that could influence these measures of volatility and volumes, of which the IOER-ON RRP spread is of particular interest. The FHLBs and other government-sponsored enterprises engage in the federal funds market primarily due to their inability to receive interest on excess reserves. In this environment, GSEs have a choice on how to best receive a return on their reserves: lend them to arbitrage-seeking foreign banks in the federal funds market, or lend them to the Fed at the ON RRP facility. As the rate offered at the ON RRP facility increases relative to IOER, investors would find the elevated ON RRP rate more attractive. As such, when the IOER-ON RRP spread decreases, one should expect to see greater volumes at the ON RRP facility as the GSEs seek a higher, safer return. Moreover, it should be expected that volatility in the federal funds rate would decrease with a narrower spread; as the rate should remain below IOER due to the FDIC and Basel III costs associated with arbitrage, and as it should remain above ON RRP due to that facility's openness to a wider variety of counterparties, a tighter IOER-ON RRP spread will force the private transactions of the federal funds market to occur in a smaller range of interest rates, thereby reducing volatility in the aggregate. Data on the IOER rate is available from the Federal Reserve Economic Data

arm of the St. Louis Fed, which, when combined with the daily ON RRP rate available at the New York Fed, can be used to construct a daily measure of the IOER-ON RRP spread (Federal Reserve Bank of St. Louis 2018d).

In addition to the IOER-ON RRP spread, there are several other factors that must be considered. A key concern of the FOMC during its 2015 meetings was whether or not liftoff—the first increase of both IOER and ON RRP—would be successful in raising the effective federal funds rate. In the first two meetings of that year, the participants received staff briefings on the subject, noting in January, "[P]articipants generally agreed that it was very important for the commencement of policy firming to proceed successfully. Consequently, most were prepared to take the steps necessary to ensure that the federal funds rate traded within the target range established by the Federal Open Market Committee (FOMC)" and using similar language in March (Federal Open Market Committee 2015a; Federal Open Market Committee 2015b). In theory, however, the absolute levels of ON RRP and IOER should matter less than their relative settings. Armenter and Lester showed that the changes to rates and volumes that occurred at liftoff were driven entirely by the increase in the IOER-ON RRP spread, not the increase in level (Armenter and Lester 2016, 19). Moreover, since most trading in the federal funds market today occurs due to the arbitrage opportunity provided by IOER, the federal funds rate should be bid up as IOER is increased. Data on the federal funds target range was compiled from the Board of Governors website (Board of Governors of the Federal Reserve System 2017d).

The Fed provides two further alternatives for institutions seeking to earn a return on their excess funds—term deposits and term RRPs. As it sees fit, the Fed offers term deposits at the term deposit facility (TDF). When available, financial institutions eligible to receive IOER can choose to move funds from their reserve accounts into term deposits, which offer higher interest

rates in exchange for keeping funds for longer periods, often a week (Board of Governors of the Federal Reserve System 2017c). Likewise, the Fed also from time to time offers term reverse repurchase operations, which are open to the same set of counterparties as ON RRP transactions, though the repurchase of the security occurs after multiple business days (Federal Reserve Bank of New York 2017). The terms of TDF transactions—rate, maturity, and maximum allotment—are decided beforehand by the Fed and announced; for term RRPs, the maximum allotment and maturity are fixed while rate is determined at auction (Board of Governors of the Federal Reserve System 2017c; Federal Reserve Bank of New York 2017). As these operations are alternatives for institutions seeking to lend funds overnight, they could drain volumes at the ON RRP facility. Moreover, term RRPs could attract GSEs away from the federal funds market, reducing the supply of funds and raising rates closer to IOER, thereby decreasing volatility. However, these operations are relatively infrequent and may well prove statistically insignificant. Data on TDF operations for 2017 is available through the facility's website, which includes the date offered, rate offered, amount accepted, and maturity date; activities prior to 2017 are similarly available through the facility's archive (Board of Governors of the Federal Reserve System 2017c; Board of Governors of the Federal Reserve System 2017e). Term RRP volumes and rates are available through the New York Fed's website (Federal Reserve Bank of New York, Undated, e). This paper's dataset uses the daily volumes held at each facility as a covariate, as volume is a more accurate indicator of their usage than their interest rates.

Calendar effects must also be considered. Following the Basel III accords, United States regulators agreed to calculate firms' supplementary leverage ratios based on daily averages over a given quarter (Board of Governors of the Federal Reserve System, Federal Deposit Insurance Corporation, and Office of the Comptroller of the Currency 2014). Under this method of

calculation, domestic financial institutions are subject to a constant cost of borrowing in the federal funds market, as each loan increases their leverage ratio and will be reflected in the quarterly average regardless of when the borrowing occurred. However, many foreign banks are regulated differently. In Europe, banks are required to calculate their leverage ratios quarterly either as the mean of the three month-end ratios or simply as the quarter-end ratio (Official Journal of the European Union 2014, 8). As such, European banks do not endure a constant cost of leverage and can borrow as much as needed in the federal funds market on most days. However, on month- and quarter-end dates, European banks leave the federal funds market in favor of safer assets to appear less risky (Klee, Senyuz, Yoldas 2016, 10). This process is known as "window dressing." As the European banks temporarily abandon the arbitrage opportunity, it should be expected that the GSEs would settle for greater amounts of ON RRP transactions on month- and quarter-end dates. Moreover, volatility in the federal funds market should increase, as rates at the bottom of the 99^{th}-1^{st} percentile spread fall as the foreign banks seeking arbitrage temporarily avoid the market (Federal Reserve Bank of New York 2015a, 4).

A change in the regulation of MMFs provides a further consideration. In 2014, the SEC announced an alteration to the rules governing prime and municipal MMFs to be implemented in October 2016, forcing them to use the market values of their securities to calculate net asset value (NAV), as opposed to the historical standard NAV of $1 per share, as well as to impose gates or fees on redemptions during crises (Cipriani, La Spada, and Mulder 2017, 1-3). Government MMFs were unaffected by the new regulations and continued to use a fixed NAV without additional gates or fees, making them more money-like relative to prime and municipal MMFs and causing investors to move their funds out of the latter and into the former beginning in November 2015 (Cipriani, La Spada, and Mulder 2017, 3). Such a policy change has

enormous bearing on the ON RRP facility; between September 23, 2013 and September 29, 2017, MMFs on average accounted for 86.1 percent of the daily volume of the facility's trades (Federal Reserve Bank of New York 2018). Since government MMFs represent such a large fraction of trades at the facility, an exogenous increase in their use should strengthen the floor created by the ON RRP rate, reduce volatility, and boost volumes at the facility.

Tables 1 and 2 provide summary statistics for the available data, which was taken between September 23, 2013 and December 7, 2017 with a gap between June 18, 2015 and March 1, 2016, and Histograms 1-3 describe the distributions of the dependent variables. The distribution of the 99^{th}-1^{st}-percentile spread is skewed left with a mean of 21.5 basis points. As evidenced from Histogram 1, the dataset contains a wide variety of values for the spread, with large clusters around 10, 15, 20, and 25 basis points and outliers as large as 40. The five-business day standard deviation of EFFR displays less variability due to there being fewer data points, each representing multiple days; most observations take a value of zero, indicating that the effective federal funds rate was constant across all five days, yet there are still almost two dozen periods for which there was non-zero volatility. Volumes at the ON RRP facility widely varied across the data set. The mean volume at the ON RRP facility is $115.4 billion, as the bulk of business days involved around $100 billion worth of trades, with a few outlier month- and quarter-end days rising above $400 billion. In addition, of the 879 business days and 119 five-business day periods analyzed in this dataset, 433 and 49 occurred prior to liftoff, respectively. These nearly even splits between observations before and after interest rates began to rise renders this data particularly useful for investigating the overall efficacy of the ON RRP facility and the IOER-ON RRP spread.

This paper uses ordinary least squares (OLS) regressions to capture the effects of the IOER-ON RRP spread on the measures of volatility and volumes. To capture the spread's effect on intraday volatility, a regression of the following form is used:

$$P_i = c + a_1 S_i + a_2 T_i + a_3 TDF_i + a_4 TRRP_i + a_5 M_i + a_6 Q_i + a_7 R_i$$
$$a_8(TDF_i \times R_i) + a_9(TRRP_i \times R_i) + a_{10}(M_i \times R_i) + a_{11}(Q_i \times R_i) + e_i$$

In this equation, the dependent variable, P_i, is the 99th-1st-percentile spread on day i. c is a constant, and the terms denoted with the letter "a" are the coefficients of the independent variables. e_i is the residual term, which should be random and distributed normally about zero. S_i is the primary covariate, representing the daily IOER-ON RRP spread. T_i represents the FOMC's target for the federal funds rate; as the committee sets a 25 basis point-wide span for its objective, T_i simply assumes the value of the midpoint of that range. TDF_i and $TRRP_i$ represent the daily volume of funds held at the Fed's Term Deposit Facility and the Term Reverse Repurchase Facility, respectively. Q_i is a dummy variable that takes a value of 1 on the last business day of each quarter; M_i is a second dummy that indicates month-end dates that are not also quarter-end dates. Likewise, R_i is a dummy variable that takes a value of 1 on each day since November 1, 2015, in order to capture the effects of MMF reform. Lastly, the regression includes interactive terms between the MMF reform dummy and the TDF volume, term RRP volume, and calendar effects, as the exogenous increase in government MMF investment may well affect the way funds utilize term deposits and term reverse repos as well as their actions on month- and quarter- end dates. Due to the missing data from June 2015 to February 2016, the data set does not contain a point within the post-MMF reform era at which the IOER-ON RRP

spread changes, nor does it contain a point before MMF reform at which the target rate changes. As such, the interactive effects cannot be expanded to those two covariates.

To examine interday volatility, the following regression design is employed:

$$SD_f = c + a_1 S_f + a_2 T_f + a_3 TDF_f + a_4 TRRP_f + a_5 R_f + a_6 (TDF_f \times R_f) + e_f$$

SD_i represents the standard deviation of the median EFFR in a given five-business day period, *f*. The remaining covariates are defined as in the intraday regression, yet they are taken over the relevant period; the periods were defined in the dataset such that none of the covariates changed values within the five days. The calendar effects, *M* and *Q*, are not included as none of the five-business day periods included a month-end date. In each of the 49 observations occurring after November 2015, term RRPs took a value of zero, eliminating the need for an interactive term between term RRPs and the MMF reform dummy.

For the ON RRP volume regression, a methodology almost identical to that of the intraday volatility regressions is used. It is of the form:

$$V_i = c + a_1 S_i + a_2 T_i + a_3 TDF_i + a_4 TRRP_i + a_5 M_i + a_6 Q_i + a_7 R_i$$
$$a_8 (TDF_i \times R_i) + a_9 (TRRP_i \times R_i) + a_{10} (M_i \times R_i) + a_{11} (Q_i \times R_i) + e_i$$

where V_i indicates he volume of trades at the ON RRP facility on day *i*.

To ensure the validity of these results, the residuals of each regression will be examined by plotting them as a histogram. A key assumption of ordinary least squares regression is that the residuals—the difference between the actual and predicted values—are independently and identically distributed in accordance with the normal distribution. If this assumption is true, the histograms should display the distinctive “bell curve” shape, making it possible to visually gauge the soundness of these regressions.

Additionally, it would be beneficial to examine how the IOER-ON RRP spread affects volumes in the federal funds market. To completely understand the size of the Fed's financial footprint, it is important to know the degree to which the ON RRP facility attracts funds out of the private overnight market. Unfortunately, the switch from using brokered transactions to all transactions creates a particularly large problem for such an analysis. Whereas it was possible for the New York Fed to provide data for the median EFFR and its percentiles prior to the change, the Fed tracked only brokered volumes prior to March 1, 2016 and only total volumes after. Under these conditions, a very strong assumption is necessary to perform an analysis—that effects on brokered volumes transmit perfectly linearly to total volumes. If such a hypothesis held, it would be possible to extrapolate pre-change results into the post-change period. As this assumption is much stronger than those used in examining volatility or ON RRP facility volumes, this fourth analysis is conducted and discussed separately in Appendix B. The results of this test were not in line with expectations and at times contradictory, indicating that the key assumption was faulty, that data error was present, or both.

5 Results

Table 3 reports the results of the OLS regression of the daily 99^{th}-1^{st}-percentile EFFR spread onto to the IOER-ON RRP spread with controls. Seven of the eleven covariates are statistically significant at the five percent level—the IOER-ON RRP spread, the target federal funds rate, the month- and quarter-end dummy variables, the MMF reform dummy, and each of the interactive terms between MMF reform and the calendar effect dummies. The effect of the IOER-ON RRP spread is extremely significant, yielding a coefficient of 0.581 with a standard error of just 0.120. This result indicates that a 10 basis point reduction in the IOER-ON RRP spread would decrease the difference between the 99^{th} and 1^{st} percentile values by 5.8 basis

points. The range of observed values of the 99th-1st-percentile spread in the dataset is only 33 bps and the average spread is 21.5 bps, thus a reduction of 5.8 bps would be relatively large.

The federal funds rate target is extremely significant as well, with a coefficient of -0.99. This result is unexpected. As most transactions in the federal funds market facilitate the IOER arbitrage opportunity, theory suggests the IOER-ON RRP spread should have the predominant effect on trading, especially given that the two rates have moved together with each rate hike in this dataset. A potential explanation for this phenomenon comes from Figure 6, which separates the 99th and 1st percentiles and tracks them over time against the ON RRP rate. From the facility's inception to mid-2015, the 1st percentile value often fell below ON RRP, indicating that the Fed's reverse repurchase operations had not fully succeeded in creating a firm floor. However, in 2016 following liftoff, the 1st percentile fell below ON RRP infrequently and did not do so following further rate increases in December 2016, March 2017, and June 2017. It may be that each rate hike bolsters the credibility of the ON RRP facility, making it a firmer floor for the 1st percentile value and thereby reducing the daily spread. However, it is worth noting that the calculation change that occurred in March 2016 may also be the cause of this result. In Figure 6, the fluctuations that occur in both the 99th and 1st percentile rates are larger following the data gap. Recall that the source of the data changed from brokered transactions before the gap to all transactions after; if brokered transactions occur under fundamentally different circumstances than those without brokers, there could be some mismatch between the historical and current percentile data. MMF reform had a pronounced effect on intraday volatility, reducing the spread by 5.6 bps. Month- and quarter-end dates increased intraday volatility by 1.9 and 2.9 bps, respectively, with those values rising to 7.5 and 9.4 following MMF reform. As expected, neither the TDF facility nor term RRP operations had a significant effect on intraday volatility, likely

due to the Fed's infrequent employment thereof. By far, the IOER-ON RRP spread had the most significant effect on the daily 99^{th}-1^{st}-percentile spread, suggesting that adjustments to the former could be a powerful tool to decrease intraday volatility in the federal funds market.

Table 4 reports the results of the interday volatility regression, which uses the five-business day EFFR standard deviation as a dependent variable. Again, the IOER-ON RRP spread produced the largest effect; results show that a 10 basis point reduction in the spread would lead to a one basis point reduction in the five-day standard error. Likewise, MMF reform had a significant effect, reducing the standard error by half a basis point. Surprisingly, term RRPs were significant at the one-percent level; each additional $100 billion at the facility increases the standard error for the period by a basis point. This is in contrast to expectations, which suggest that as such investments become available, GSEs should shift towards term RRPs, reducing the supply of federal funds. This, in turn, should raise the federal funds rate closer to IOER, reducing volatility. This result may be a product of the infrequent use of the term RRP facility, which may have led to slightly skewed results. Despite this concern, the magnitude of the effect is extremely small, as expected, and is overshadowed by the effect of the IOER-ON RRP spread.

The results of the regression of ON RRP volumes are reported in Table 5. Once more, the IOER-ON RRP spread had the most significant, positive effect on volumes. A 10 basis point reduction in the spread increases activity at the ON RRP facility by $180.5 billion, indicating that the institutions that typically transact at the facility—GSEs and MMFs, primarily—see it as a more enticing opportunity when its rate increases relative to IOER. The federal funds rate target is again significant, with each 25 basis point increase resulting in just over an $11 billion increase in activity. This too could be due to the increase in the facility's credibility with each rate hike. Term RRPs, despite their comparative disuse, are significant detractors of ON RRP

volumes, with every additional billion dollars of term RRPs decreasing ON RRPs by $422 million. MMF reform naturally increases ON RRP volumes by $82.5 billion, as it led to a movement of funds to government MMFs, which are extremely active at the facility. Month- and quarter-end dates increase facility usage by $34.8 and $159.8 billion in normal times, respectively, as foreign banks depart the federal funds market in order to obtain lower leverage ratios ahead of financial reporting, forcing GSEs to settle for ON RRPs instead.

Histograms 4-6 display the residuals for each of the three regressions. For the results of these regressions to hold, the histograms must display the typical "bell curve" shape of the normal distribution, centered at zero. Histogram 4, tracking the residuals from the intraday volatility regression, certainly fits this criterion. The histogram peaks at zero and slopes away on either side, with only a very small number of outliers. Histogram 5, the interday volatility residuals, is less distinct due to the smaller number of observations, yet the bulk is again centered at zero, with slightly fewer on each side, and a small number of larger residuals in both directions. Histogram 6, for the ON RRP volume, displays a classic bell curve shape, sloping away on each side with a very small tail on the right containing only a few observations. These three histograms suggest that the regression results are likely accurate.

6 Discussion

Even in the wake of a successful liftoff, the FOMC has remained ambivalent about the use of the ON RRP facility. The minutes of the January 2016 meeting note, "[P]articipants reiterated that the Committee expects to phase out the facility when it is no longer needed to help control the federal funds rate… nearly all indicated a preference for waiting a couple of months or longer before making operational adjustments to the facility, in part so that the Federal Reserve could gain additional experience with its policy implementation tools" (Federal Open

Market Committee 2016a). This intention to eventually retire the ON RRP facility was reiterated in March 2016, with meeting participants expressing reluctance to use term RRPs as well (Federal Open Market Committee 2016b). However, despite these sentiments, the facility remains in use for now.

Among the largest of the Fed's concerns is that the ON RRP facility will force the central bank to leave a bigger footprint in financial markets, which could create stability risks. During periods of stress, financial institutions naturally shift investment towards safer assets, of which ON RRPs are one (Frost et al 2015, 20). The risk is that investors will favor transacting at the ON RRP facility rather than lending to private counterparties, decreasing market liquidity and amplifying a crisis (Frost et al 2015, 20). These concerns have been frequently referenced at FOMC meetings with general agreement among participants that the facility's size must therefore be limited (Federal Open Market Committee 2014b; Federal Open Market Committee 2014c). Today, there is a $30 billion per counterparty daily maximum at the ON RRP facility, and from September 2014 to December 2015, there was a $300 billion facility-wide cap (Federal Reserve Bank of New York 2017; Federal Open Market Committee 2014c; Federal Open Market Committee 2015c). Despite the removal of the aggregate cap, the continued existence of the per-counterparty limit and the tentative language used in FOMC meetings indicates considerable resistance towards a large ON RRP facility.

Additionally, there is the worry that a permanent ON RRP facility will solidify the role of MMFs in monetary policy. Since MMFs pool shareholder resources and invest them with other financial market participants, strains on an MMF could lead to it withdrawing its funds wholesale, creating a larger, quicker run than might happen if individuals lent directly to banks (Cipriani, Martin, and Parigi 2013). Such a phenomenon, which occurred in 2008 and 2011, has

the potential to augment financial crises, making MMFs potentially risky actors to include in monetary policy transmission (Cipriani, Martin, and Parigi 2013). Moreover, the Fed does not directly regulate MMFs; rather, the Securities and Exchange Commission (SEC) oversees them under the Investment Company Act of 1940 (U.S. Securities and Exchange Commission 2013). Naturally, the Fed prefers to rely on those institutions it supervises directly, such as traditional depository institutions, and would be cautious of affording such importance to MMFs.

Yet, many of these hesitations are based on speculation, not history. The facility is not now, nor has it ever been, very large. Eight times a year since 2014, the New York Fed conducted the Survey of Market Participants (SMP), soliciting opinions on central bank policy from a list of financial institutions as diverse as Credit Suisse, Vanguard, Microsoft, and the Teacher Retirement System of Texas (Federal Reserve Bank of New York, Undated, f). From June 2014 to December 2015, one survey question asked for the institutions' expectations for the aggregate use of the ON RRP facility immediately after liftoff, later expanding the question to one year and three years after liftoff. Figures 7-9 track the 25th percentile, median, and 75th percentile of the responses each time the question was posed. Over the year and a half before the Fed's December 2015 rate increase, the median expectation for the period immediately after liftoff varied predominantly between $300 and $500 billion. Over the same period, the 25th percentile expectation never dipped below $200 billion, and expectations increased across the board in late 2015. Expectations for a year after liftoff were steadier in the run-up, with a median of about $400 billion and a 25th percentile of just over $200 billion. For the period three years after liftoff, market participants median expectation was that the ON RRP facility would be sized at roughly $300 billion with a 25th percentile of just under $200 billion. Across the board, market participants expected ON RRP use to be in the hundreds of billions of dollars; 75th percentile

estimates often rose above $700 billion. Yet, hindsight shows that these expectations were almost entirely unfounded. Figure 10 tracks the size of the ON RRP facility daily from liftoff on December 17, 2015 to December 7, 2017. Volumes at the facility have predominantly been under $200 billion, with exceptions occurring around typically volatile quarter-end dates. The mean volume during the post-liftoff period for the facility was $125.3 billion; excluding quarter-end dates, the figure drops to $121.2 (Federal Reserve Bank of New York, Undated, e). Even in an environment with no market-wide cap, activity at the ON RRP facility has barely reached market participants' 25th percentile expectations, let alone the median or 75th percentile values. In fact, when the aggregate cap was in place, the facility reached it only once on September 30, 2014, the final day of the third quarter of that year (Federal Reserve Bank of New York, Undated, e). Despite the FOMC's fears of a creating too large a footprint in private markets, the facility has billions of dollars worth of room to grow relative to both market expectations and the Fed's previous size limits—room that could be used to improve financial conditions.

The creation of the Financial Stability Oversight Council (FSOC) could mollify some risks associated with MMFs as well. The FSOC brings together leaders from all the major financial regulators in the United States, including the Chairman of the SEC and the Chairman of the Board of Governors of the Federal Reserve, in order to unify their identification of and response to potential financial stresses (U.S. Department of the Treasury 2017). Through its Chairman's participation in FSOC, the Fed would be privy to information concerning MMF risks and would be able to assist in their regulation, which could help the Fed and other regulators stave off runs. Moreover, the SEC has clearly shown a readiness to tighten MMF regulations as it has required prime and municipal MMFs to impose gates and fees on redemptions during crises, further reducing the risk of runs (Cipriani, La Spada, and Mulder 2017, 3). With better cross-

department cooperation after the passing of Dodd-Frank and a proven willingness to regulate, there is now less risk associated with using MMFs in monetary policy transmission.

At the same time, there are benefits to a less volatile federal funds market, both to the Fed and market participants. If a central bank's target rate is particularly volatile, investors may have a more difficult time recognizing policy objectives (Borio 1997, 91-2). It is critical that market participants understand the Fed's goals in order for the federal funds rate to effectively transmit to longer-term private rates; if the federal funds rate is too volatile, investors could mistake rate changes for shifts in policy or become altogether less sensitive to policy changes when they actually occur (Borio 1997, 91-2). Moreover, lower uncertainty in markets could allow financial institutions to better project future prices, reducing any costs of associated hedging. In order for markets to operate as smoothly as possible, financial institutions must be able to accurately interpret intended policy changes and avoid uncertainty costs, both of which become more difficult in highly volatile environments.

Given these concerns, the Fed should consider reducing the IOER-ON RRP spread by 10 basis points to its historical minimum of 15 bps, as such a setting would give the Fed significantly greater interest rate control without creating an unduly large footprint. As Table 3 shows, a 10 basis point reduction in the spread would reduce the 99^{th}-1^{st}-percentile difference by 5.8 bps on average. In 2017, while the IOER-ON RRP spread remained a quarter of a percent, the mean value for the 99^{th}-1^{st}-percentile difference was 14.9 bps; moving to a 15 point spread therefore has the potential to bring this measure of intraday volatility into the single digits, significantly reducing market uncertainty. Table 4 indicates that such a reduction would also decrease the five-business day EFFR standard deviation by a full basis point. These sizeable reductions come at an acceptable cost. As Table 5 reveals, a 10 basis point reduction in the

IOER-ON RRP spread would only increase ON RRP facility volumes by $185 billion on average. Added to the post-liftoff average, this yields a total facility size of about $310 billion, a value below market participants' median expectations for the periods immediately and one year after liftoff and generally in line with their expectations for three years after—a date that will not arrive until December 2018. Moreover, this volume barely exceeds the aggregate cap in place from September 2014 to December 2015, indicating that the Fed should not view it as a significant threat to financial stability. Reducing the spread in this manner would not surprise financial institutions; it would merely match their expectations and create a more stable private market. Alternatively, the Fed could consider reducing the spread by a smaller amount. Figure 11 displays the effects various IOER-ON RRP spreads would have on intraday volatility and ON RRP facility volume. A setting of 20 bps—5 bps smaller than the current spread—would only increase facility size by about $100 billion dollars, though it would provide a more modest decrease in intraday volatility. However, given the significant amount of room the facility has to grow, a setting that more meaningfully reduces volatility would likely be preferable.

If these risks were still unacceptable, increased use of term RRPs could help reduce the financial stability risks. Tables 3 and 4 reveal that term RRPs have a very small effect on federal funds rate volatility. However, every $10 billion dollars of term RRPs reduces the size of the ON RRP facility by $4.2 billion. While the net size of the Fed's balance sheet would rise, risks to financial stability would be reduced due to the unique nature of term RRPs. As the FOMC noted in January 2015, the Fed has more control with these operations, as it sets the date, term, and maximum volume exogenously, and the interest rate could be determined through an auction, none of which are typically the case for ON RRPs (Federal Open Market Committee 2015a). In

times of stress, the Fed could increase its term RRP offerings and pull funds away from ON RRPs, providing both safe assets and greater stability to the private sector.

The Fed's steadfast commitment to the future elimination of the ON RRP facility and its ongoing process of balance sheet reduction indicate its desire to use a methodology as similar as possible to its pre-crisis techniques. In an industry where mistakes can cost billions of dollars, it is natural that the Fed wishes to fall back on established practices. Even as it uses the ON RRP facility, the Fed has preferred to stick to convention, as the January 2015 FOMC minutes note, "With regard to the potential use of other tools, several participants noted that the IOER and ON RRP rates should be set at the top and bottom, respectively, of the target range for the federal funds rate. To deviate from such a structure would complicate communications about the policy framework and therefore should be avoided if possible" (Federal Open Market Committee 2015a). Five years ago, when the facility was in its earliest stages, this argument may have held, as the floor system for monetary policy was new and not fully understood by both policy makers and market participants. Today, however, is a new day. The financial sector has returned to strength, and market participants have grown used to the presence of the ON RRP facility. Moving the ON RRP rate away from the bottom of the FOMC's target range, especially if announced in advance, is unlikely to confuse investors at this point. Though it may be elegant and simple to match IOER and ON RRP to the top and bottom of the Fed's target range, a decrease in the IOER-ON RRP spread would be a strong, vital signal that the bank is firmly committed to creating effective policy and reducing preventable uncertainty costs.

7 Conclusion

The results of this paper help provide a roadmap for Federal Reserve in these unprecedented conditions, yet further research is necessary to achieve an even clearer vision for

the future. Only once has the IOER-ON RRP spread been changed simultaneously with an increase in the federal funds target range, as the spread increased from 20 to 25 bps during December 2015's liftoff. Due to the missing federal funds data from the New York Fed, the eight-month period from June 2015 through February 2016 went unexplored in this paper. These analyses must be extended to that period when the data is available, so the Fed might be able to consider potential positive or negative side effects of simultaneous changes. Additionally, the ON RRP facility remains relatively new, and as such, many settings of the IOER-ON RRP spread have not been attempted in practice. Continued experimentation at the facility could expand this dataset, leading to more accurate results and quelling many remaining doubts about its proper calibration.

The events of 2007 and 2008 that befell the United States financial system and the world at large called into question economic concepts and practices that had previously been treated as gospel. Nowhere was this shift more potent than in the Federal Reserve's monetary policy regime. Decades of experience conducting open market operations in a market of scarce reserves became moot as quantitative easing flooded the system with excess reserves almost two thousand times larger than at any point in previous history. To regain control over the system, the Fed created the overnight reverse repurchase facility, expanding the list of counterparties allowed to invest funds directly with the central bank. This facility has been an overwhelming success. Indicators discovered by this paper show that increasing the ON RRP rate relative to the rate of interest paid on excess reserves is a powerful tool in the Fed's arsenal, capable of decreasing volatility in the federal funds market both within and across days. Despite this power, the Fed has remained wary of over-reliance, fearing that too large volumes at the facility could exacerbate financial crises when they occur and cement the role of money market funds in

monetary policy. Yet, the ON RRP facility has proven significantly smaller than even more conservative market participants predicted, both with and without limits on its size, and the creation of the FSOC has reduced the risk associated with MMFs. As the Fed continues to use the federal funds rate as its primary target, and therefore has a vested interest in promoting stability in that market, now is the time to raise the ON RRP rate by 10 basis points relative to IOER. Such a move has the potential to meaningfully reduce volatility in the federal funds market without overly enlarging the Fed's footprint. The post-crisis world remains complex and mysterious, but with five years of experience under its belt and a thorough understanding of its tools at hand, the Fed should play a more active role in stabilizing it.

Appendix A: Works Cited

Afonso, Gara, Alex Entz, and Eric LeSueur. 2013a. “Who’s Lending in the Fed Funds Market?” Liberty Street Economics. Accessed February 21, 2018. http://libertystreeteconomics.newyorkfed.org/2013/12/whos-lending-in-the-fed-funds-market.html.

Afonso, Gara, Alex Entz, and Eric LeSueur. 2013b. “Who’s Borrowing in the Fed Funds Market?” Liberty Street Economics. Accessed February 21, 2018. http://libertystreeteconomics.newyorkfed.org/2013/12/whos-borrowing-in-the-fed-funds-market.html.

Anderson, Alyssa and Jeffrey Huther. 2016. “Modelling Overnight RRP Participation.” Finance and Economics Discussion Series 2016-023. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/feds/2016/files/2016023pap.pdf.

Anderson, Alyssa G. and John Kandrac. 2016. “Monetary Policy Implementation and Private Repo Displacement: Evidence from the Overnight Reverse Repurchase Facility.” Finance and Economics Discussion Series 2016-096. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/feds/2016/files/2016096pap.pdf.

Anderson, Alyssa, Jane Ihrig, Ellen Meade, and Gretchen Weinbach. 2016. "What Happened in Money Markets After the Fed's December Rate Increase?" FEDS Notes. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/notes/feds-notes/2016/what-happened-in-money-markets-after-the-feds-december-rate-increase-20160222.html.

Anderson, Alyssa, Jane Ihrig, Mary-Frances Styczynski, and Gretchen Weinbach. 2017. "How Have the Fed's Three Rate Hikes Passed Through to Selected Short-term Interest Rates?"

FEDS Notes. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econres/notes/feds-notes/how-have-the-feds-three-rate-hikes-passed-through-to-selected-short-term-interest-rates-20170602.htm.

Armenter, Roc and Benjamin Lester. 2016. "Excess Reserves and Monetary Policy Implementation." Working Paper 15-35/R. Federal Reserve Bank of Philadelphia. https://www.philadelphiafed.org/-/media/research-and-data/publications/working-papers/2015/wp15-35r.pdf?la=en.

Bernhardsen, Tom and Arne Kloster. 2010. "Liquidity Management System: Floor or Corridor?" Staff Memo No. 4. Norges Bank. http://www.norges-bank.no/globalassets/upload/publikasjoner/staff-memo/2010/staff_memo_042010.pdf.

Board of Governors of the Federal Reserve System, Federal Deposit Insurance Corporation, and Office of the Comptroller of the Currency. 2014. "Agencies Adopt Supplementary Leverage Ratio Final Rule." Joint Press Release. Accessed March 17, 2018. https://www.federalreserve.gov/newsevents/pressreleases/bcreg20140903b.htm.

Board of Governors of the Federal Reserve System. 2008. "Federal Reserve Announces It Will Initiate a Program to Purchase the Direct Obligations of Housing-Related Government-Sponsored Enterprises and Mortgage-Backed Securities Backed by Fannie Mae, Freddie Mac, and Ginnie Mae." Press Release. Accessed February 16, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20081125b.htm.

Board of Governors of the Federal Reserve System. 2009. "FOMC Statement." Press Release. Accessed February 16, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20090318a.htm.

Board of Governors of the Federal Reserve System. 2010. “FOMC Statement.” Press Release. Accessed February 16, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20101103a.htm.

Board of Governors of the Federal Reserve System. 2012. “Federal Reserve Issues FOMC Statement.” Press Release. Accessed February 16, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20120913a.htm.

Board of Governors of the Federal Reserve System. 2014. “Federal Reserve Issues FOMC Statement.” Press Release. Accessed February 16, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20141029a.htm.

Board of Governors of the Federal Reserve System. 2017a. “Implementation Note Issued March 15, 2017.” Press Release. Accessed March 17, 2018. https://www.federalreserve.gov/newsevents/pressreleases/monetary20170315a1.htm.

Board of Governors of the Federal Reserve System. 2017b. “FOMC Communications related to Policy Normalization.” Policy Normalization. Accessed February 21, 2018. https://www.federalreserve.gov/monetarypolicy/policy-normalization.htm.

Board of Governors of the Federal Reserve System. 2017c. “Term Deposit Facility.” Policy Tools. Accessed February 25, 2018. https://www.federalreserve.gov/monetarypolicy/tdf.htm.

Board of Governors of the Federal Reserve System. 2017d. “Open Market Operations.” Policy Tools. Accessed March 3, 2018. https://www.federalreserve.gov/monetarypolicy/openmarket.htm.

Board of Governors of the Federal Reserve System. 2017e. “Term Deposit Facility - Archive.” Policy Tools. Accessed March 3, 2018. https://www.federalreserve.gov/monetarypolicy/tdf_archive.htm.

Board of Governors of the Federal Reserve System. 2018. “Interest on Required Reserve Balances and Excess Balances.” Policy Tools. Accessed February 16, 2018. https://www.federalreserve.gov/monetarypolicy/reqresbalances.htm.

Borio, Claudio E.V. 1997. “The Implementation of Monetary Policy In Industrial Countries: A Survey.” Bank for International Settlements. Accessed March 17, 2018. https://www.bis.org/publ/econ47.pdf.

Cipriani, Marco, Antoine Martin, and Bruno Maria Parigi. 2013. “The Fragility of an MMF-Intermediated Financial System.” Liberty Street Economics. Accessed March 17, 2018. http://libertystreeteconomics.newyorkfed.org/2013/12/the-fragility-of-an-mmf-intermediated-financial-system.html.

Cipriani, Marco, Gabriele La Spada, and Philip Mulder. 2017. “Investors’ Appetite for Money-Like Assets: The Money Market Fund Industry after the 2014 Regulatory Reform.” Staff Reports No. 816. Federal Reserve Bank of New York. https://www.newyorkfed.org/medialibrary/media/research/staff_reports/sr816.pdf?la=en.

Clouse, Jim, Jane Ihrig, Elizabeth Klee, and Han Chen. 2014. “The Federal Reserve’s Tools for Policy Normalization in a Preferred Habitat Model of Financial Markets.” Finance and Economics Discussion Series 2014-83. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/feds/2014/files/201483pap.pdf.

Federal Open Market Committee. 2013a. “Minutes of the Federal Open Market Committee: July 30-31, 2013.” Accessed February 21, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20130731.htm.

Federal Open Market Committee. 2013b. “Minutes of the Federal Open Market Committee: September 17-18, 2013.” Accessed February 21, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20130918.htm.

Federal Open Market Committee. 2014a. “Minutes of the Federal Open Market Committee: June 17-18, 2014.” Accessed February 21, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20140618.htm.

Federal Open Market Committee. 2014b. “Minutes of the Federal Open Market Committee: July 29-30, 2014.” Accessed March 5, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20140730.htm.

Federal Open Market Committee. 2014c. “Minutes of the Federal Open Market Committee: September 16-17, 2014.” Accessed March 5, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20140917.htm.

Federal Open Market Committee. 2015a. “Minutes of the Federal Open Market Committee: January 27-28, 2015.” Accessed February 25, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20150128.htm.

Federal Open Market Committee. 2015b. “Minutes of the Federal Open Market Committee: March 17-18, 2015.” Accessed February 25, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20150318.htm.

Federal Open Market Committee. 2015c. “Minutes of the Federal Open Market Committee: December 15-16, 2015.” Accessed March 5, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20151216.htm.

Federal Open Market Committee. 2016a. “Minutes of the Federal Open Market Committee: January 26-27, 2016.” Accessed March 5, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20160127.htm.

Federal Open Market Committee. 2016b. “Minutes of the Federal Open Market Committee: March 15-16, 2016.” Accessed March 5, 2018. https://www.federalreserve.gov/monetarypolicy/fomcminutes20160316.htm.

Federal Reserve Bank of New York. 2013. “Federal Funds and Interest on Reserves.” FedPoint. Accessed February 15, 2018. https://www.newyorkfed.org/aboutthefed/fedpoint/fed15.html.

Federal Reserve Bank of New York. 2015a. “Technical Note Concerning the Methodology for Calculating the Effective Federal Funds Rate.” Accessed March 3, 2018. https://www.newyorkfed.org/medialibrary/media/markets/EFFR-technical-note-070815.pdf.

Federal Reserve Bank of New York. 2015b. “Statement Regarding the Calculation Methodology for the Effective Federal Funds Rate and Overnight Bank Funding Rate.” Statement. Accessed March 3, 2018. https://www.newyorkfed.org/markets/opolicy/operating_policy_150708.html.

Federal Reserve Bank of New York. 2016. “Statement Regarding the Implementation of Planned Changes to the Effective Federal Funds Rate and Publication of the Overnight

Bank Funding Rate." Operating Policy. Accessed March 3, 2018. https://www.newyorkfed.org/markets/opolicy/operating_policy_160106.

Federal Reserve Bank of New York. 2017. "FAQs: Reverse Repurchase Agreement Operations." Markets & Policy Implementation. Accessed February 21, 2018. https://www.newyorkfed.org/markets/rrp_faq.html.

Federal Reserve Bank of New York. 2018. "Reverse Repo Data by Counterparty Type Since 9/23/2013 (Data updated as of 09/30/2017)." Temporary Open Market Operations: Historical Data. Accessed March 2, 2018. https://apps.newyorkfed.org/markets/autorates/temp.

Federal Reserve Bank of New York. Undated, a. "Fed Funds Lending (2006-2012)." Accessed February 21, 2018. https://www.newyorkfed.org/fed-funds-lending/index.html.

Federal Reserve Bank of New York. Undated, b. "Reverse Repo Counterparties." Accessed March 17, 2018. https://www.newyorkfed.org/markets/rrp_counterparties.html.

Federal Reserve Bank of New York. Undated, c. "Federal Funds Data Historical Search." Accessed March 3, 2018. https://apps.newyorkfed.org/markets/autorates/fed-funds-search-page.

Federal Reserve Bank of New York. Undated, d. "Federal Funds Data." Accessed March 3, 2018. https://apps.newyorkfed.org/markets/autorates/fed%20funds.

Federal Reserve Bank of New York. Undated, e. "Temporary Open Market Operations Historical Search." Accessed March 3, 2018. https://apps.newyorkfed.org/markets/autorates/tomo-search-page.

Federal Reserve Bank of New York. Undated, f. "Survey of Market Participants." Accessed March 5, 2018. https://www.newyorkfed.org/markets/survey_market_participants.html.

Federal Reserve Bank of St. Louis. 2018a. “Excess Reserves of Depository Institutions.” Federal Reserve Economic Data. Accessed February 16, 2018. https://fred.stlouisfed.org/graph/?g=ixZq.

Federal Reserve Bank of St. Louis. 2018b. “Reserve Balances with Federal Reserve Banks.” Federal Reserve Economic Data. Accessed February 16, 2018. https://fred.stlouisfed.org/graph/?g=jhIu.

Federal Reserve Bank of St. Louis. 2018c. “Effective Federal Funds Rate and Interest Rate on Excess Reserves.” Federal Reserve Economic Data. Accessed February 21, 2018. https://fred.stlouisfed.org/graph/?g=ixZe.

Federal Reserve Bank of St. Louis. 2018d. “Interest Rate of Excess Reserves.” Federal Reserve Economic Data. Accessed March 3, 2018. https://fred.stlouisfed.org/series/IOER.

Frost, Josh, Lorie Logan, Antoine Martin, Patrick McCabe, Fabio Natalucci, and Julie Remache. 2015. “Overnight RRP Operations as a Monetary Policy Tool: Some Design Considerations.” Finance and Economics Discussion Series 2015-010. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/feds/2015/files/2015010pap.pdf.

Gagnon, Joseph E. and Brian Sack. 2014. “Monetary Policy with Abundant Liquidity: A New Operating Framework for the Federal Reserve.” Policy Brief Number PB14-4. Peterson Institute for International Economics. https://piie.com/sites/default/files/publications/pb/pb14-4.pdf.

Ihrig, Jane E., Ellen E. Meade, and Gretchen C. Weinbach. 2015. “Monetary Policy 101: A Primer on the Fed’s Changing Approach to Policy Implementation.” *Board of Governors*

of the Federal Reserve System Finance and Economics Discussion Series 2015 (047). https://www.federalreserve.gov/econresdata/feds/2015/files/2015047pap.pdf.

Ihrig, Jane, Ellen Meade, and Gretchen Weinbach. 2016. "The Federal Reserve's New Approach to Raising Interest Rates," FEDS Notes. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/notes/feds-notes/2016/the-federal-reserves-new-approach-to-raising-interest-rates-20160212.html.

Klee, Elizabeth, Zeynep Senyuz, and Emre Yoldas. 2016. “Effects of Changing Monetary and Regulatory Policy on Overnight Money Markets,” Finance and Economics Discussion Series 2016-084. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econresdata/feds/2016/files/2016084pap.pdf.

Martin, Antoine, James McAndrews, Ali Palida, and David Skeie. 2013. “Federal Reserve Tools for Managing Rates and Reserves.” Staff Reports No. 642. Federal Reserve Bank of New York. https://www.newyorkfed.org/medialibrary/media/research/staff_reports/sr642.pdf.

Official Journal of the European Union. 2014. “Commission Implementing Regulation (EU) No 680/2014 of 16 April 2014.” Accessed March 17, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0680&qid=1521403003139&from=EN.

Senyuz, Zeynep and Manjola Tase. 2017. "Overnight Reverse Repurchase (ON RRP) Operations and Uncertainty in the Repo Market." FEDS Notes. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/econres/notes/feds-notes/overnight-reverse-repurchase-operations-and-uncertainty-in-the-repo-market-20171019.htm.

U.S. Department of the Treasury. 2017. “About FSOC.” Financial Stability Oversight Council. Accessed March 17, 2018. https://www.treasury.gov/initiatives/fsoc/about/Pages/default.aspx.

U.S. Securities and Exchange Commission. 2013. “The Laws That Govern the Securities Industry.” Fast Answers. Accessed March 17, 2018. https://www.sec.gov/answers/about-lawsshtml.html#invcoact1940.

Appendix B: Federal Funds Market Volume Analysis

Due to the Federal Reserve Bank of New York's March 2016 change in calculation methodology, an exploration of federal funds volumes presents far more significant challenges than previous analyses. Critically, the New York Fed switched its data source from federal funds brokers to the FR 2420 Report of Selected Money Market Rates, which tracks all transactions in the federal funds market, both brokered and non-brokered (Federal Reserve Bank of New York 2015b). While this change created issues for prior analyses, they were endurable; the New York Fed published a history of median and percentile data, which, though imperfect, allowed for an investigation of volatility. However, it did not publish a history of the total market volume, nor did it continue to publish the brokered volumes after March 1, 2016. As such, that date represents an unavoidable discontinuity, before which federal funds volume data is simply a different variable than after. However, an analysis still may be attempted if one strong assumption is made—that changes to brokered volumes transmit to total volumes in a perfectly linear manner that does not change over time. If this assumption holds, then it is possible to run two regressions, one before the discontinuity and one after, and combine the results.

The first of the two regressions uses data between September 23, 2013 and February 29, 2016 and is of the form:

$$\log(BV_i) = c + a_1 S_i + a_2 T_i + a_3 TDF_i + a_4 TRRP_i + a_5 M_i + a_6 Q_i + a_7 R_i$$

$$a_8(TDF_i \times R_i) + a_9(TRRP_i \times R_i) + a_{10}(M_i \times R_i) + a_{11}(Q_i \times R_i) + e_i$$

where $\log(BV_i)$ indicates the log of the daily brokered volumes in the federal funds market. Logarithms are used so that regression coefficients represent changes in percent terms, rather than in billions of dollars. If it is assumed that brokered data transmits linearly to total data, then an increase of, say, five percent to brokered volumes should correspond to an increase of five

percent in total volumes, and vice versa. The covariates are the same as those used in the previous analyses. The second regression uses data following March 1, 2016 and takes the form:

$$\log(TV_i) = c + a_1 T_i + a_2 TDF_i + a_3 TRRP_i + a_4 M_i + a_5 Q_i + e_i$$

where $\log(TV_i)$ indicates the log of the total volume of federal funds transactions, both those involving brokers and those directly between counterparties. Note that several covariates are missing. As the IOER-ON RRP spread last changed during liftoff in December 2015 and the MMF reform dummy takes a value of one for every day after November 2015, there is no variation in either variable to exploit in this regression.

It is expected that as the IOER-ON RRP spread shrinks, volumes in the federal funds market will decrease. As ON RRP becomes relatively more attractive to investors, they should theoretically move their funds out of the private market and into the Fed. In contrast, the target for the federal funds rate should not have an effect. As most trades in the federal funds market are part of the IOER arbitrage opportunity, increases of the target and IOER rate should cause the federal funds rate to be bid up in a corresponding manner, rendering the market no more or less attractive than it was prior to the rate hike. Term deposits and term RRPs should reduce volumes in the federal funds market, as they represent alternative investment opportunities, reducing the number of market participants. However, their infrequent use may render coefficients statistically insignificant. Lastly, MMF reform is expected to decrease volumes in the federal funds market, as it led to outflow from prime and municipal MMFs into government MMFs, which can only invest in government securities and not the federal funds market.

The available data on federal funds volumes comes from the New York Fed. The reserve bank has regularly published total market volumes since March 2016 through its website (Federal Reserve Bank of New York, Undated, c). Though it did not previously publish volumes

at all, it has since released a history of brokered federal funds volumes dating back to October 2006 (Federal Reserve Bank of New York, Undated, d). The brokered data is used to preform the first regression, and the regularly updated record of total volumes is used for the second.

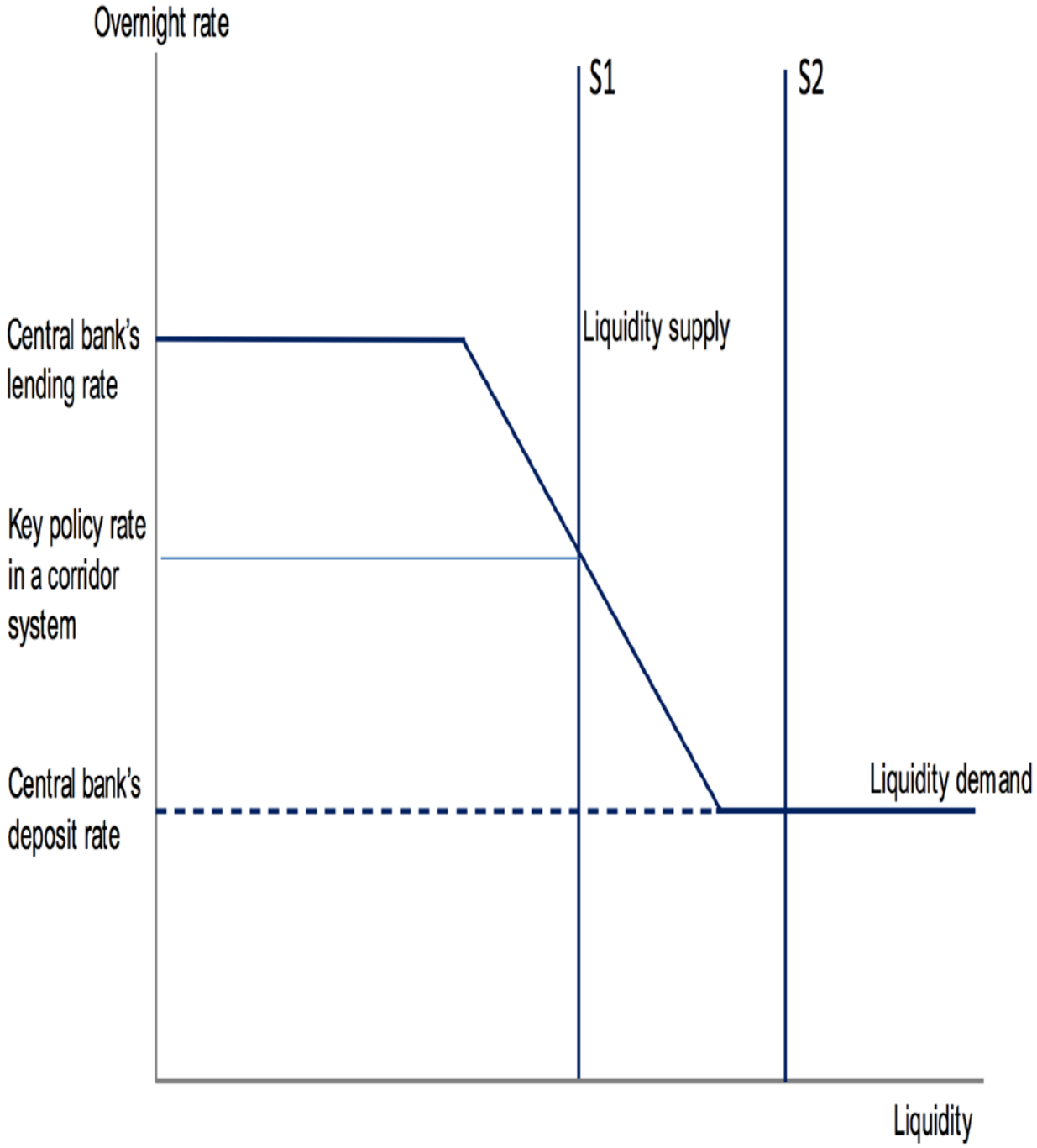
Table 6 reports the results of the regression using brokered data. Surprisingly, the IOER-ON RRP spread is statistically insignificant. This could have a number of causes. It may be that investors sensitive to the IOER-ON RRP spread—those seeking an arbitrage opportunity—avoid using brokers due to the extra fees. Alternatively, it is possible that there was not enough variation in the IOER-ON RRP spread to achieve accurate results. Another surprise is that increases in the target range significantly decrease brokered volumes in the federal funds market; a one-percentage point increase in the target is shown to reduce volumes by 22.3 percent. This is counterintuitive, as the target should have little effect on volumes. However, there was only one rate increase in the period covered by this regression, occurring just a few days before the change in calculation methodology. With an extended data set with more changes to the target rate, more accurate results may have been produced. Moreover, term RRPs significantly increase brokered volumes, with each additional $100 billion leading to three percent more transactions in the private market. This too is surprising, yet the infrequent use of the facility may have led to skewed results. Month- and quarter-end dates produce the only expected effect, reducing volumes by 15.6 percent and 66.3 percent, respectively, as foreign banks avoid the market to alter their leverage ratios ahead of regulatory examination. Taken together, it seems that this regression suffers from incomplete data, faulty assumptions, or both.

Table 7, which reports the results of the total volume regression, confirms the presence of these issues. In a complete reversal, this regression indicates that a one-percentage point rise in the target increases total volumes by 39.2 percent. It is possible that the smaller number of

observations in this period accounts for this difference, yet it is more likely that the assumption that brokered volumes transmit linearly to total volumes is false. Another difference is that term RRPs become insignificant in this period. The only consistent result is that calendar effects remain significant and negative. These striking changes further suggest data set issues. As a final test, the residuals are plotted in Histograms 7 and 8. Residuals from the brokered volume regression generally follow the normal curve, indicating that the errors may be independently and identically distributed from the normal distribution, yet those of the total volume regression are much more varied. This may indicate that the discontinuous federal funds volume data is ill suited for an OLS regression, bringing these results into greater question. Due to these serious concerns, meaningful policy insights should not be taken from these results.

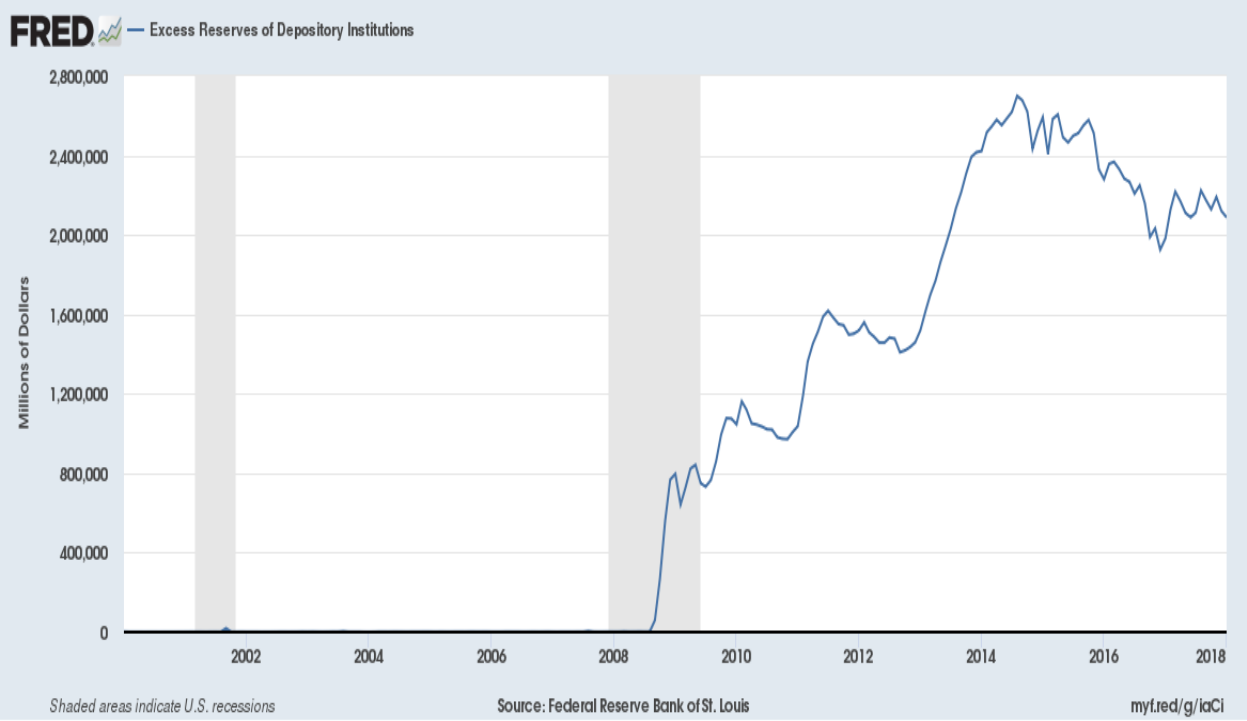
Appendix C: Figures

Figure 1: The Market for Reserves in a Floor and Corridor System



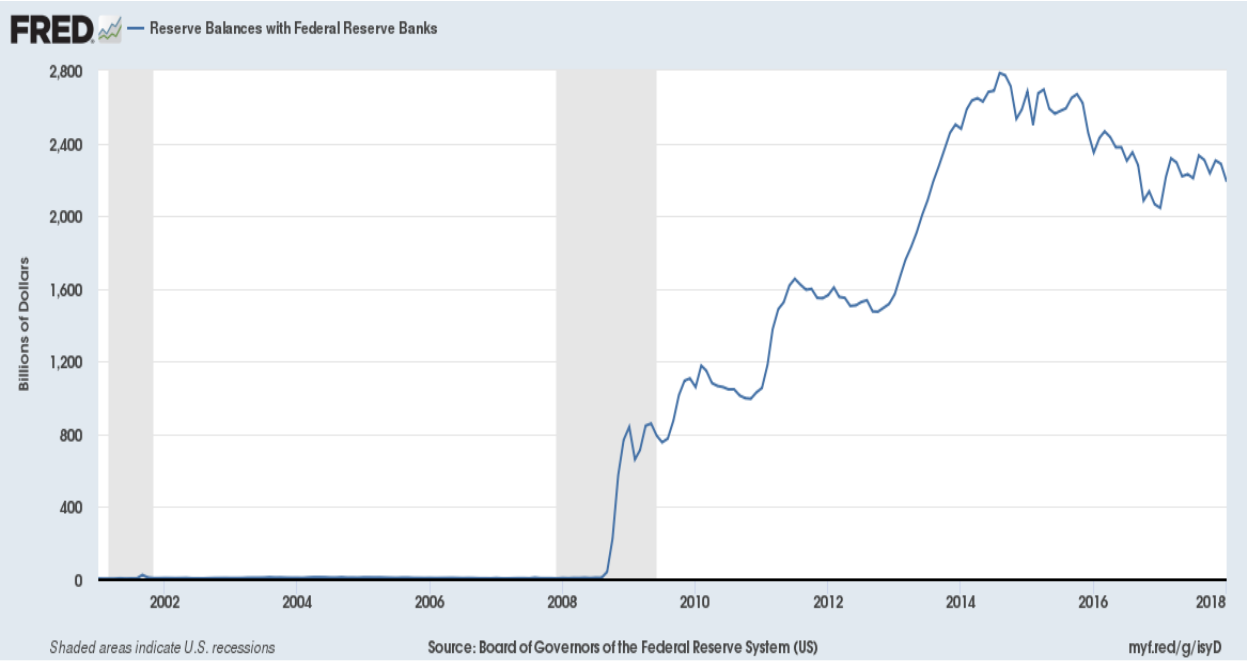
Source: Bernhardsen and Kloster 2010, 6.

Figure 2: Excess Reserves of Depository Institutions, January 1, 2001-January 1, 2018



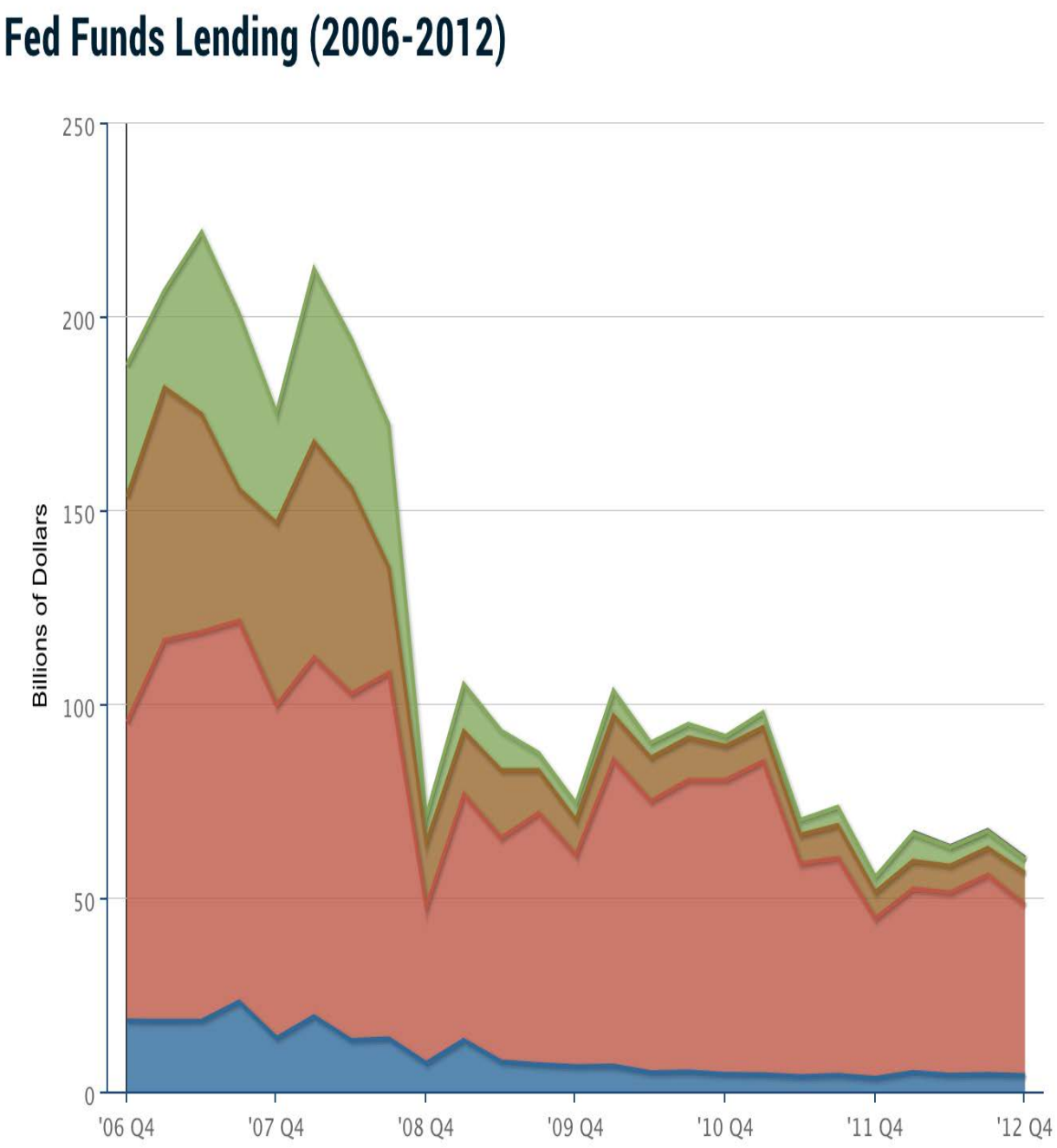
Source: Federal Reserve Bank of St. Louis 2018a.

Figure 3: Total Reserves of Depository Institutions, January 1, 2001-January 1, 2018



Source: Federal Reserve Bank of St. Louis 2018b.

Figure 4: Trading Volumes in the Federal Funds Market By Lender Type, 2006-2012

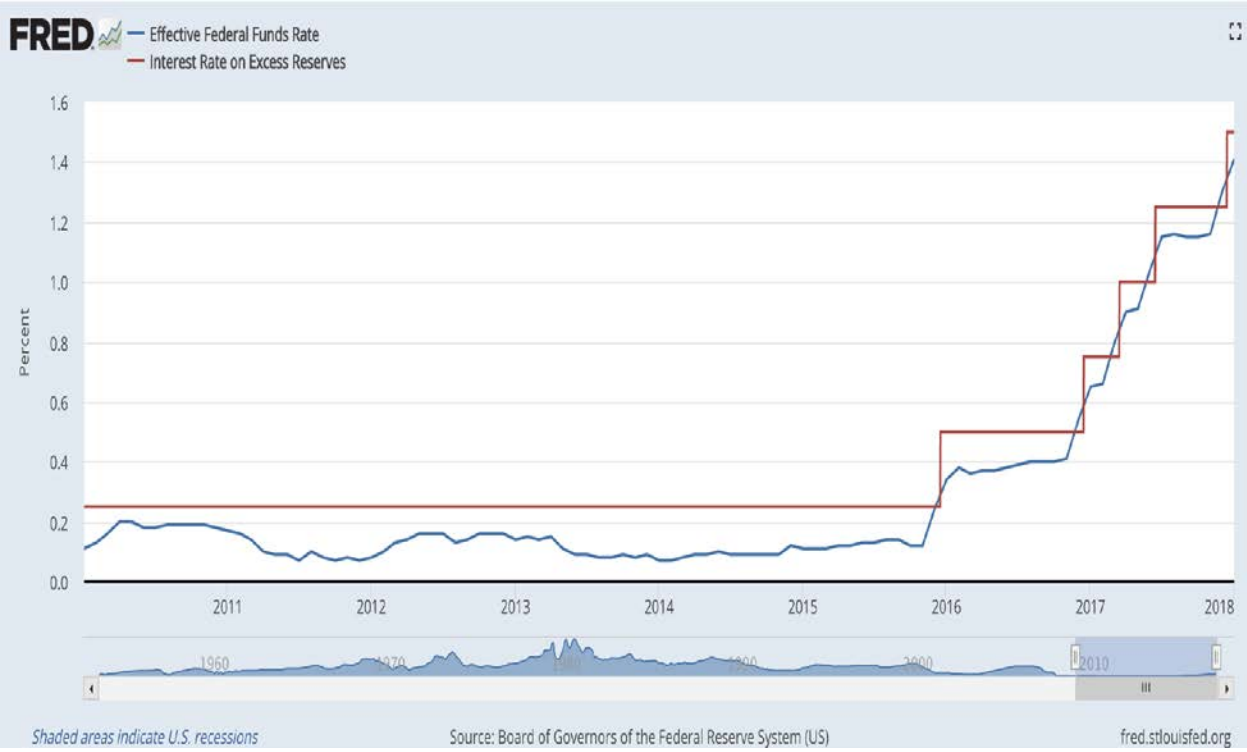


Green – Foreign Entities, Brown – Domestic Bank Holding Companies,

Red – Federal Home Loan Banks, Blue – Domestic Standalone Banks

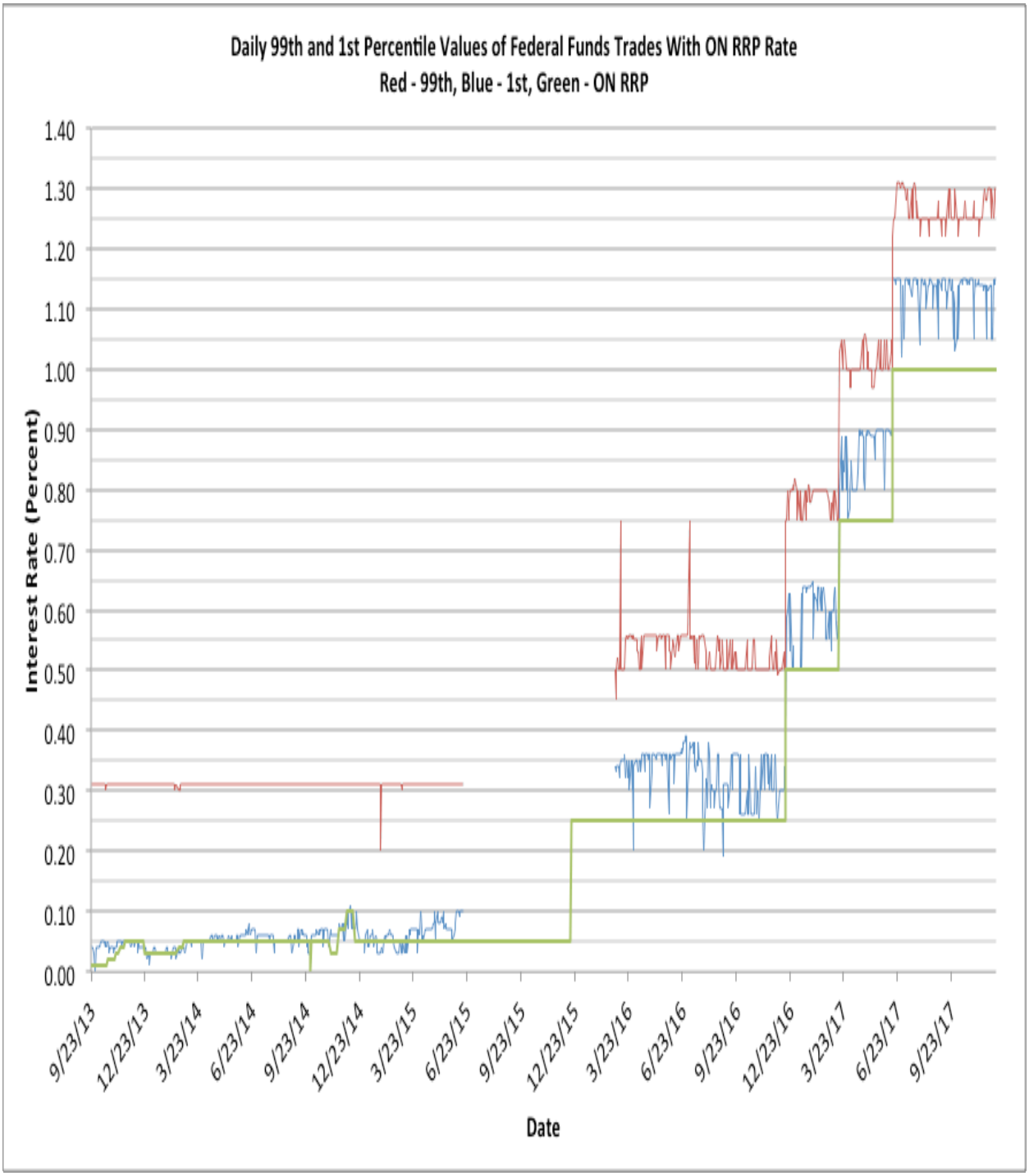
Source: Federal Reserve Bank of New York, Undated, a.

Figure 5: IOER and Effective Federal Funds Rate, January 1, 2010-January 1, 2018



Source: Federal Reserve Bank of St. Louis 2018c.

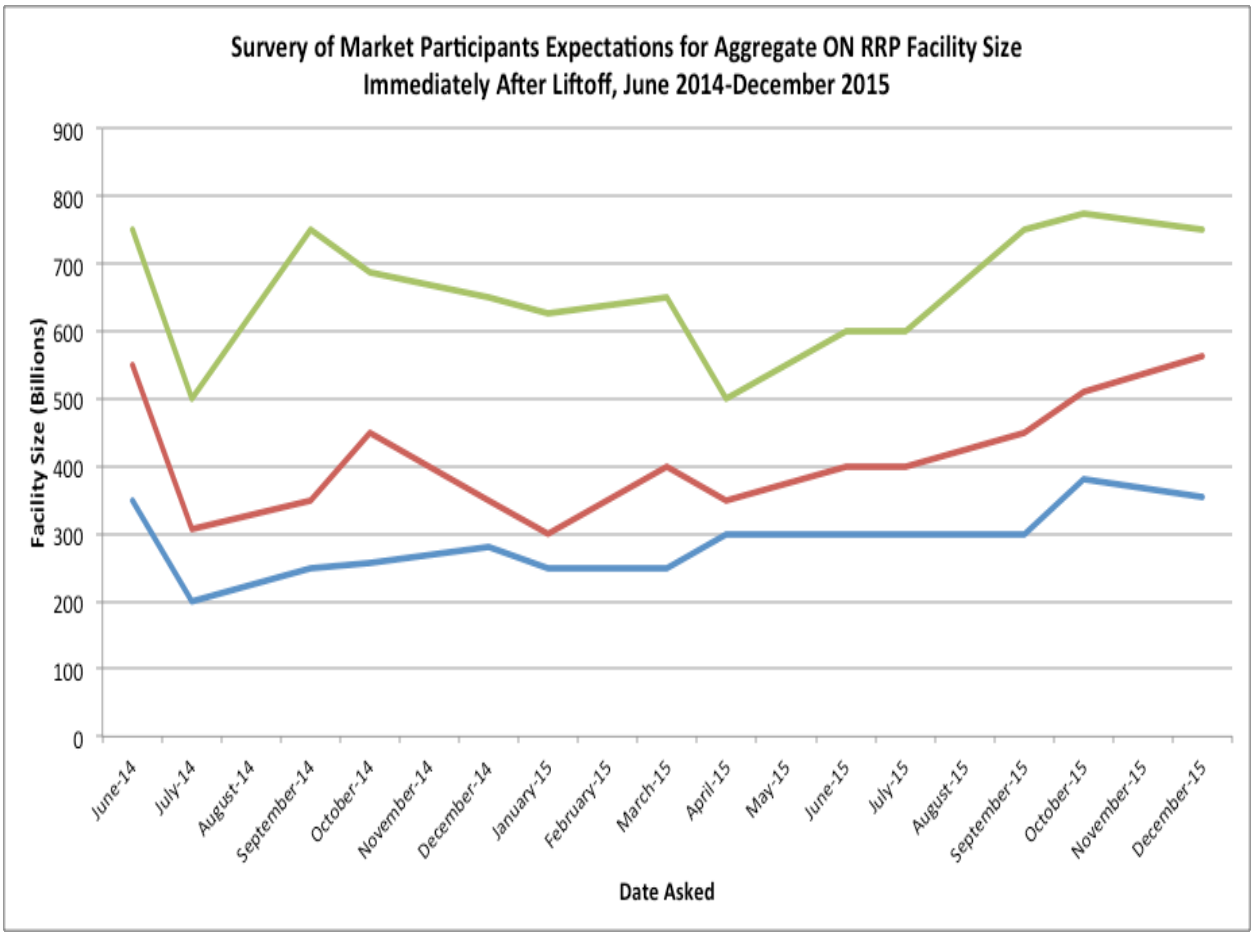
Figure 6: 99th and 1st Percentile Values of the Daily Federal Funds Traded Rates with ON RRP, September 23, 2013–December 7, 2017



Source: Federal Reserve Bank of New York 2015b; Federal Reserve Bank of New York, Undated, c; Federal Reserve Bank of New York, Undated, e.

Figure 7: Survey of Market Participants Expectations for Aggregate ON RRP Facility Size Immediately After Liftoff, June 2014 – December 2015

Green – 75th Percentile, Red – Median, Blue – 25th Percentile

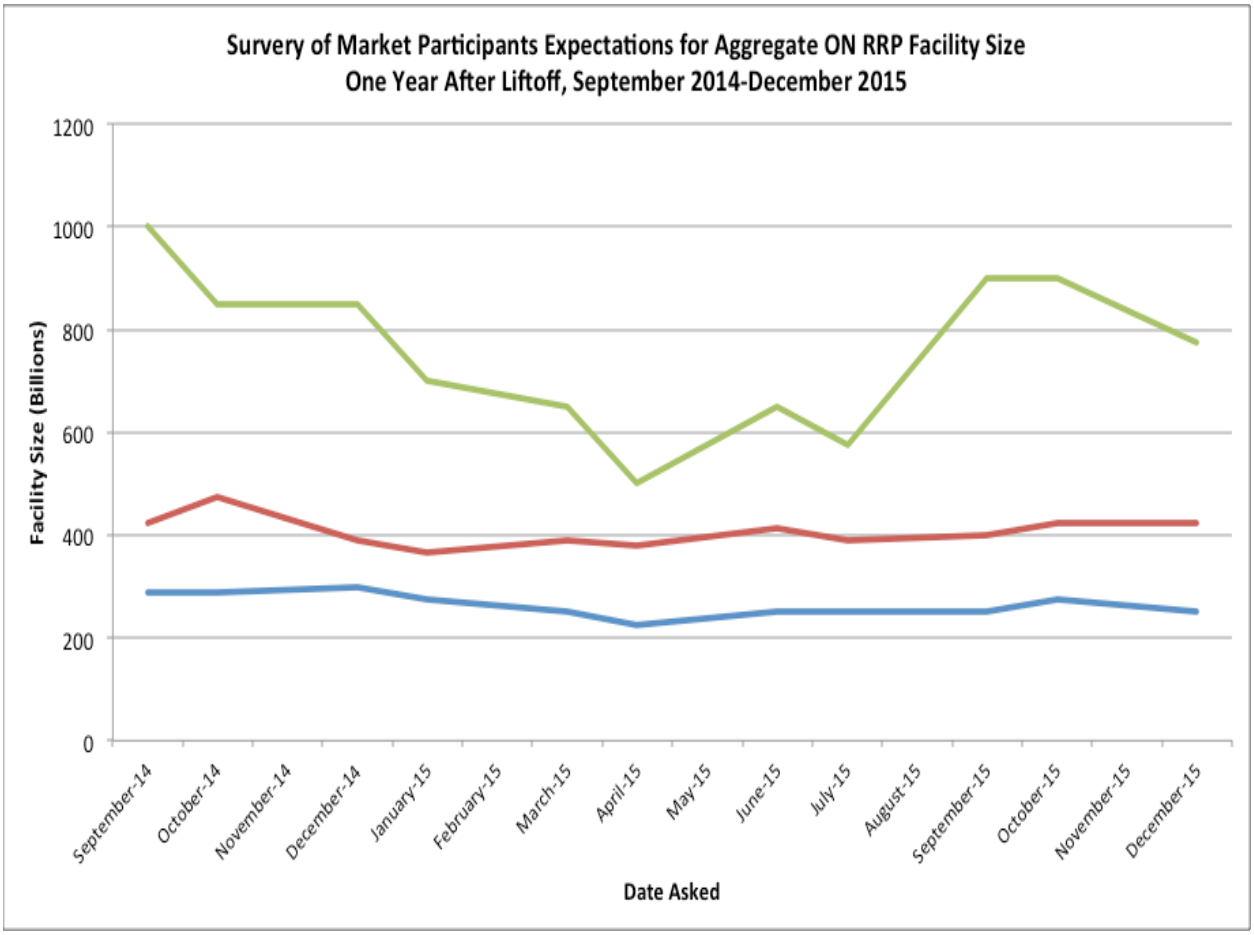


Source: Federal Reserve Bank of New York, Undated, f.

Figure 8: Survey of Market Participants Expectations for Aggregate ON RRP Facility Size

One Year After Liftoff, September 2014 – December 2015

Green – 75th Percentile, Red – Median, Blue – 25th Percentile

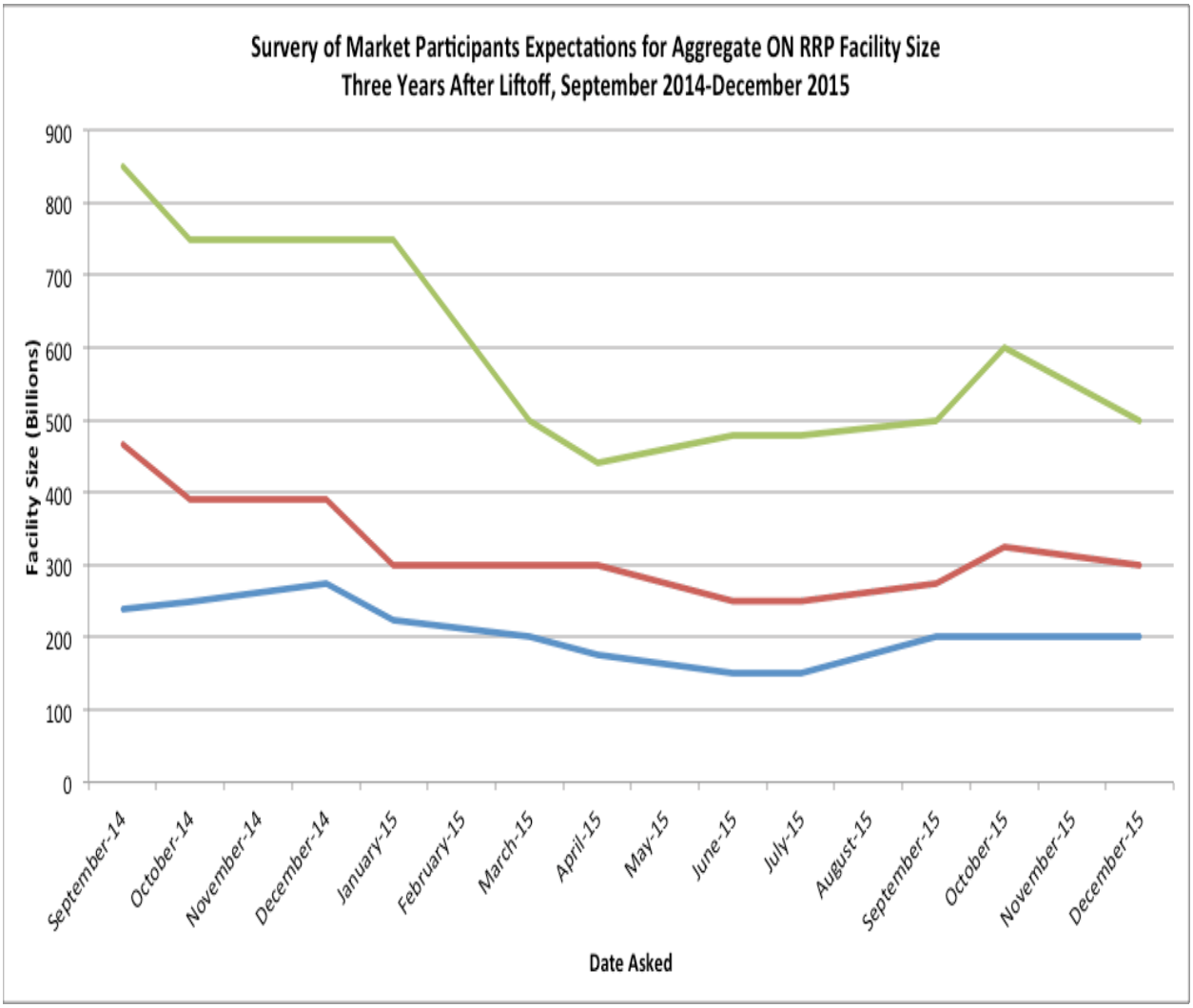


Source: Federal Reserve Bank of New York, Undated, f.

Figure 9: Survey of Market Participants Expectations for Aggregate ON RRP Facility Size

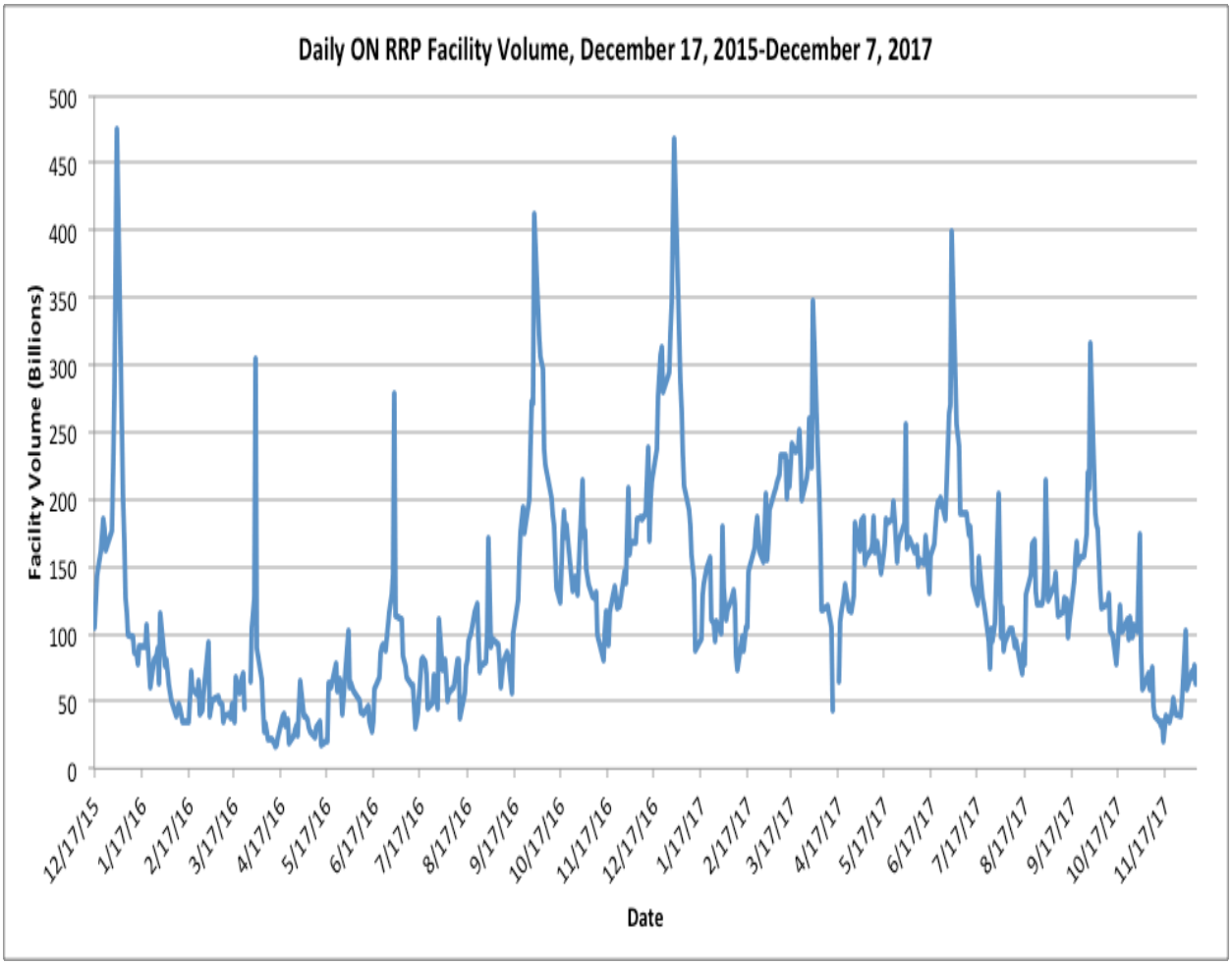
Three Years After Liftoff, September 2014 – December 2015

Green – 75th Percentile, Red – Median, Blue – 25th Percentile



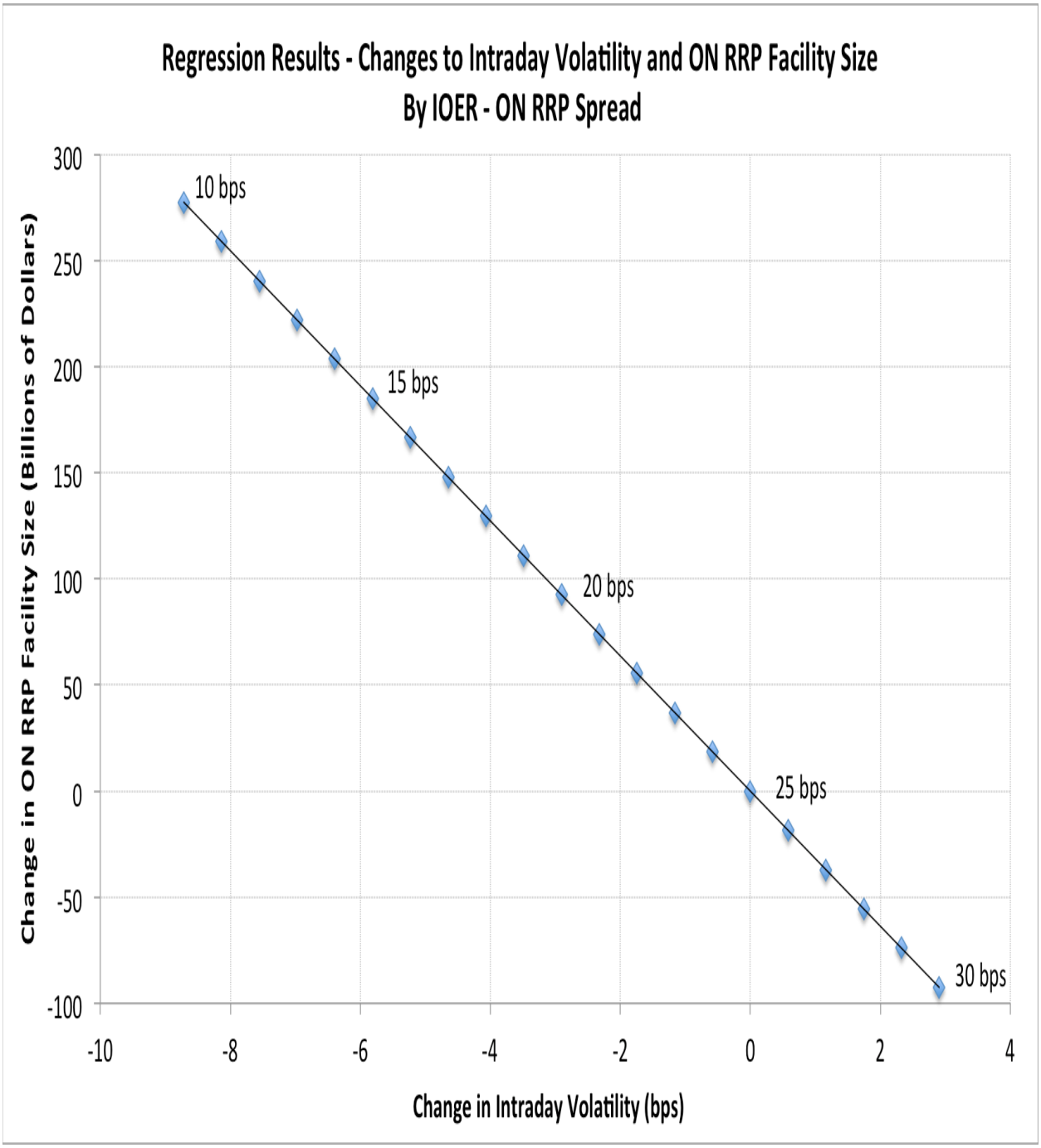
Source: Federal Reserve Bank of New York, Undated, f.

Figure 10: ON RRP Facility Volume, December 17, 2015-December 7, 2017



Source: Federal Reserve Bank of New York, Undated, e.

Figure 11: Predicted Changes to Intraday Volatility and ON RRP Facility Size By IOER-ON RRP Spread



Appendix D: Summary Statistics

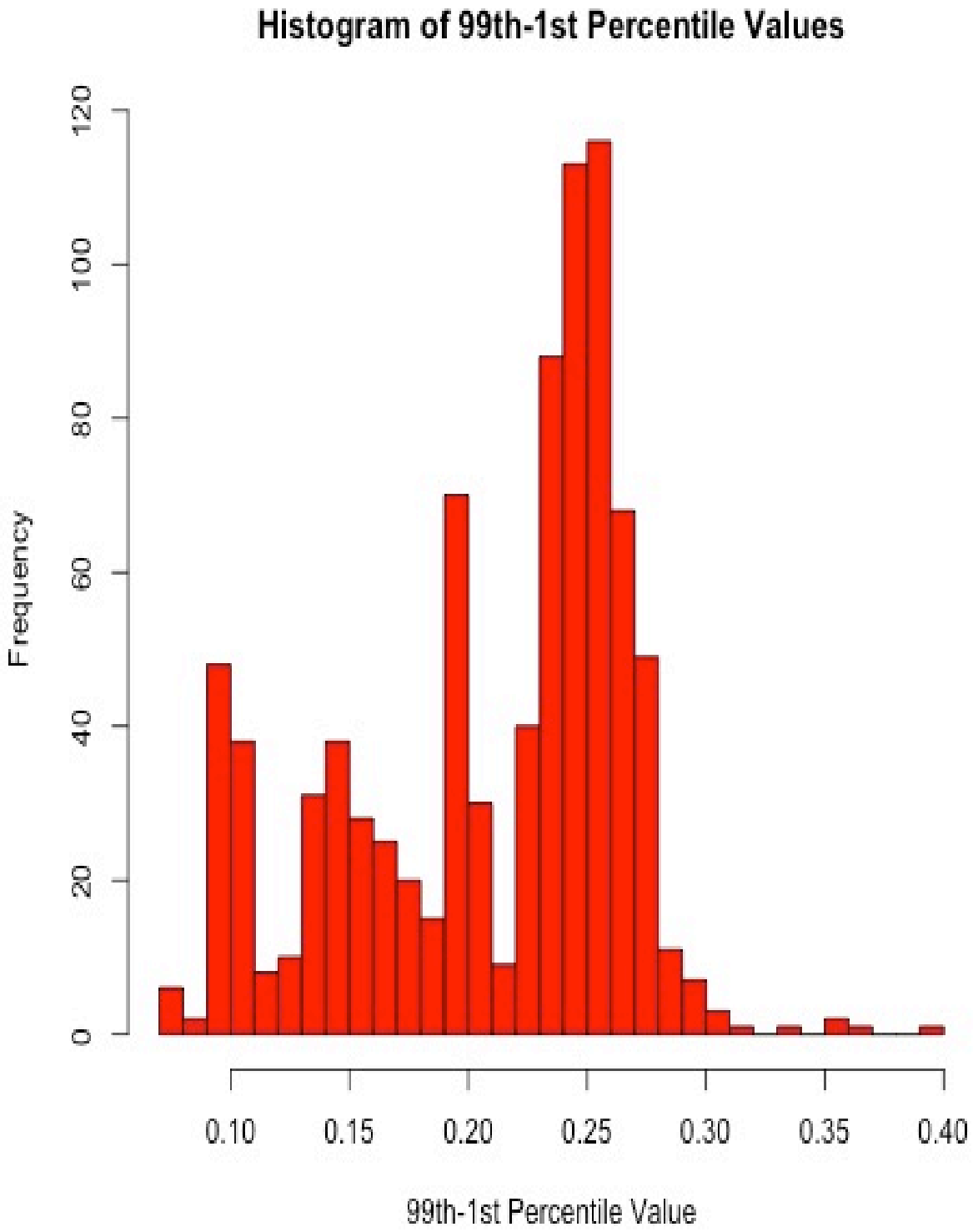
Table 1: Summary Statistics for Daily-Measured Variables

Statistic	N	Mean	St. Dev.	Min	Max
Effective Federal Funds Rate	879	0.402	0.389	0.030	1.160
99th-1st Percentile Spread	879	0.215	0.058	0.070	0.400
1st Percentile EFFR	879	0.361	0.390	0.000	1.150
99th Percentile EFFR	879	0.575	0.344	0.200	1.310
IOER-ON RRP Spread	879	0.227	0.025	0.150	0.250
ON RRP Rate	879	0.307	0.343	0.000	1.000
Federal Funds Rate Target	879	0.414	0.361	0.130	1.130
ON RRP Facility Volume (Billions)	879	115.393	66.728	0.350	468.360
Term RRP Volume (Billions)	879	4.905	24.563	0.000	225.590
Term Deposit Volume (Billions)	879	33.961	101.973	0.000	736.870

Table 2: Summary Statistics for 5-Day-Measured Variables

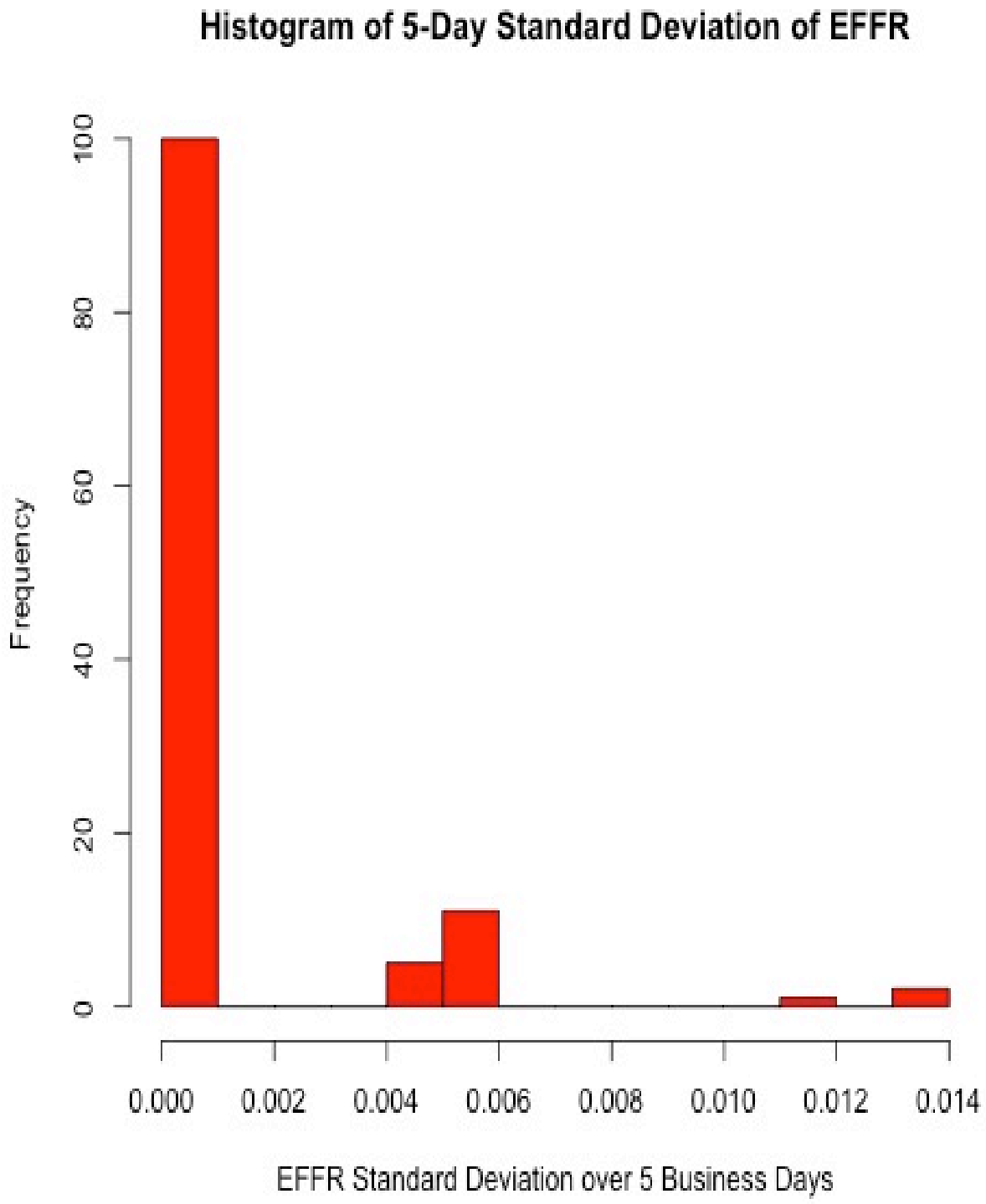
Statistic	N	Mean	St. Dev.	Min	Max
Five-Day Standard Deviation of EFFR	119	0.001	0.003	0.000	0.010
IOER-ON RRP Spread	119	0.232	0.023	0.200	0.250
Target Federal Funds Rate	119	0.456	0.368	0.130	1.130
ON RRP Rate	119	0.344	0.352	0.010	1.000
Term RRP Volume (Billions)	119	2.143	12.514	0	100
Term Deposit Volume (Billions)	119	10.014	44.584	0.000	404.150

Histogram 1: Daily 99th-1st-Percentile EFFR Values, September 23, 2013-December 7, 2017

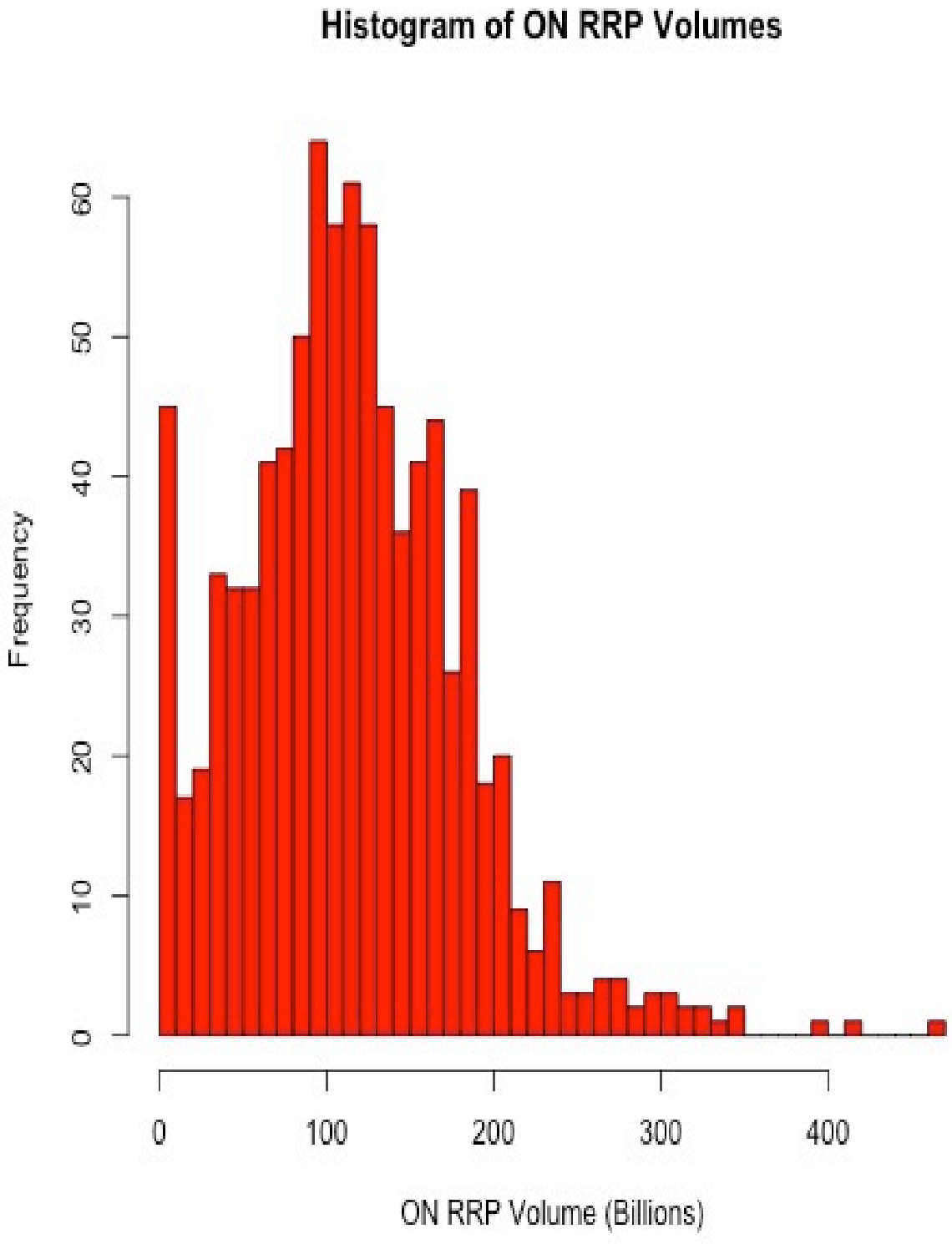


Histogram 2: Five-Day Standard Deviation of EFFR,

September 23, 2013-December 7, 2017



Histogram 3: Daily ON RRP Facility Volumes, September 23, 2013-December 7, 2017



Appendix E: Regression Analyses

Table 3: Intraday Volatility Regression Results

OLS Regression - Daily 99th-1st Percentile FFR Spread on IOER-ON RRP Spread with Controls

	Dependent variable:
	Daily 99th-1st Percentile Spread in FF Market
IOER-ON RRP Spread	0.581***
	(0.120)
Target FFR	-0.099***
	(0.005)
TDF Facility Volume (Billions)	-0.00000
	(0.00001)
Term RRP Volume (Billions)	-0.00000
	(0.00005)
End of Month Dummy	0.019**
	(0.009)
End of Quarter Dummy	0.029**
	(0.012)
MMF Reform Dummy	-0.056***
	(0.006)
Month End-MMF Reform Interaction	0.075***
	(0.012)
Quarter End - MMF Reform Interaction	0.094***
	(0.017)
TDF Volume - MMF Reform Interaction	0.0001
	(0.0001)
Term RRP Volume - MMF Reform Interaction	0.001
	(0.001)
Constant	0.149***
	(0.025)
Observations	879
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 4: Interday Volatility Regression Results

OLS Regression - Five Day Variance of Median FFR on IOER-ON RRP Spread with Controls

	Dependent variable:
	Five Day Variance of Median Federal Funds Rate
IOER-ON RRP Spread	0.104^{***}
	(0.029)
Target FFR	-0.001
	(0.001)
TDF Facility Volume (Billions)	-0.00001
	(0.00001)
Term RRP Volume (Billions)	0.0001^{***}
	(0.00002)
MMF Reform Dummy	-0.005^{***}
	(0.001)
TDF Volume - MMF Reform Interaction	-0.00000
	(0.00002)
Constant	-0.020^{***}
	(0.006)
Observations	119
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 5: ON RRP Facility Volume Regression Results

OLS Regression - Daily ONRRP Facility Volume on IOER-ON RRP Spread with Controls

	Dependent variable:
	Daily ON RRP Facility Volume (Billions)
IOER-ON RRP Spread	-1,850.006***
	(213.479)
Target FFR	44.175***
	(8.479)
TDF Facility Volume (Billions)	0.019
	(0.022)
Term RRP Volume (Billions)	-0.422***
	(0.082)
End of Month Dummy	34.825**
	(15.398)
End of Quarter Dummy	159.815***
	(22.151)
MMF Reform Dummy	82.521***
	(11.262)
Month End-MMF Reform Interaction	12.327
	(21.768)
Quarter End - MMF Reform Interaction	76.998**
	(30.931)
TDF Volume - MMF Reform Interaction	-0.300
	(0.249)
Term RRP Volume - MMF Reform Interaction	-1.311
	(0.913)
Constant	472.949***
	(44.261)
Observations	879
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 6: Brokered Federal Funds Volume Regression Results, Pre-March 2016

OLS Regression - Log of Brokered Daily Federal Funds Volume on IOER-ON RRP Spread with Controls, Pre-March 2016

	Dependent variable:
	Log of Brokered Daily Federal Funds Market Volume
IOER-ON RRP Spread	0.321
	(0.395)
Target FFR	-0.223*
	(0.129)
TDF Facility Volume (Billions)	-0.0001
	(0.00004)
Term RRP Volume (Billions)	0.0003**
	(0.0001)
End of Month Dummy	-0.156***
	(0.026)
End of Quarter Dummy	-0.663***
	(0.038)
MMF Reform Dummy	0.047**
	(0.021)
Month End-MMF Reform Interaction	0.126*
	(0.069)
Quarter End - MMF Reform Interaction	0.334***
	(0.120)
TDF Volume - MMF Reform Interaction	0.001**
	(0.001)
Term RRP Volume - MMF Reform Interaction	84.125**
	(41.898)
Constant	3.636***
	(0.072)
Observations	607
Note:	*p<0.1; **p<0.05; ***p<0.01

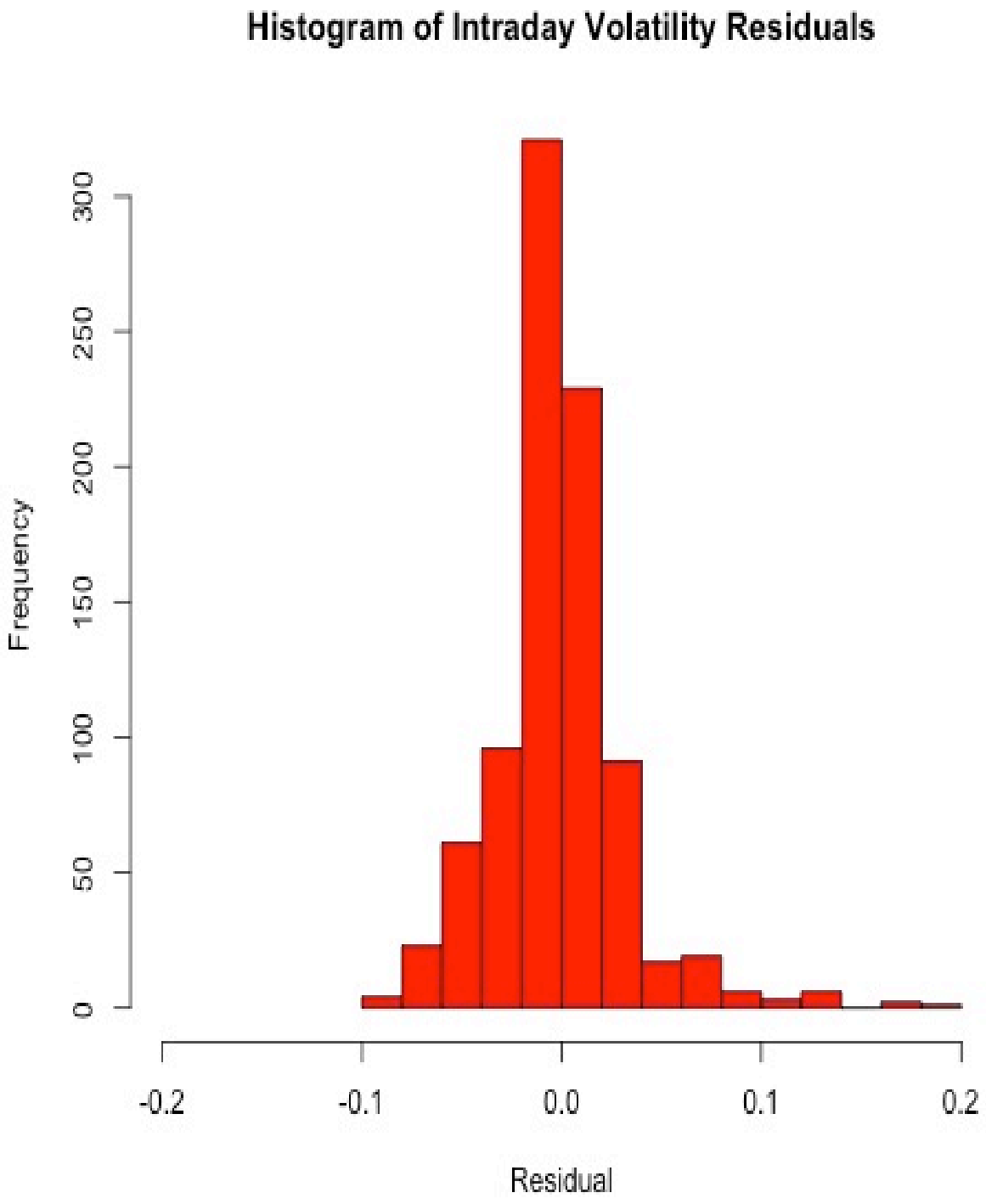
Table 7: Total Federal Funds Volume Regression Results, Post-March 2016

OLS Regression - Log of Total Daily Federal Funds Volume on Target FFR with Controls, Post-March 2016

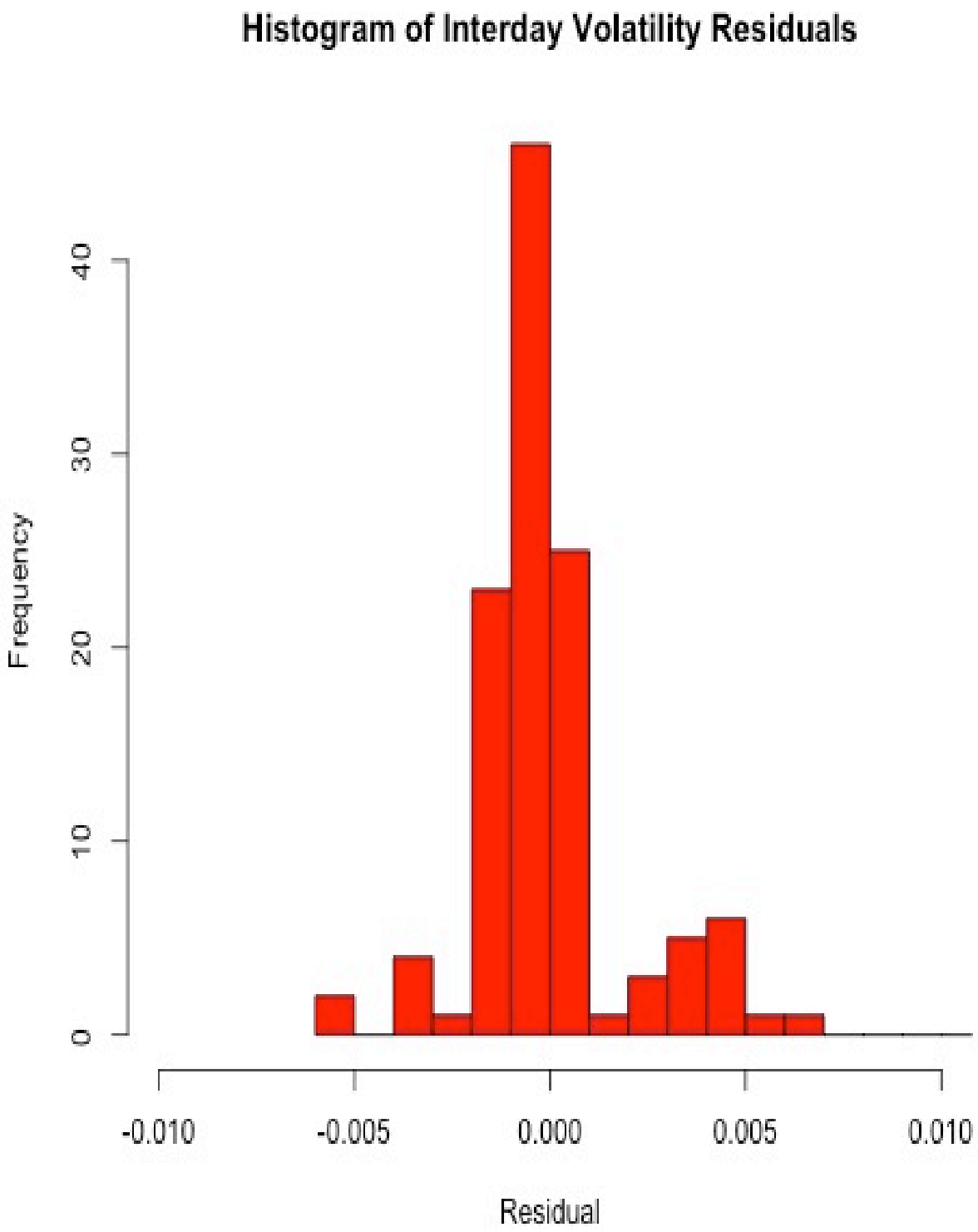
	Dependent variable:
	Log of Total Daily Federal Funds Market Volume
Target FFR	0.392***
	(0.012)
TDF Facility Volume (Billions)	0.00004
	(0.0003)
Term RRP Volume (Billions)	-0.001
	(0.001)
End of Month Dummy	-0.049**
	(0.022)
End of Quarter Dummy	-0.238***
	(0.030)
Constant	4.061***
	(0.009)
Observations	446
Note:	*p<0.1; **p<0.05; ***p<0.01

Appendix F: Residual Analyses

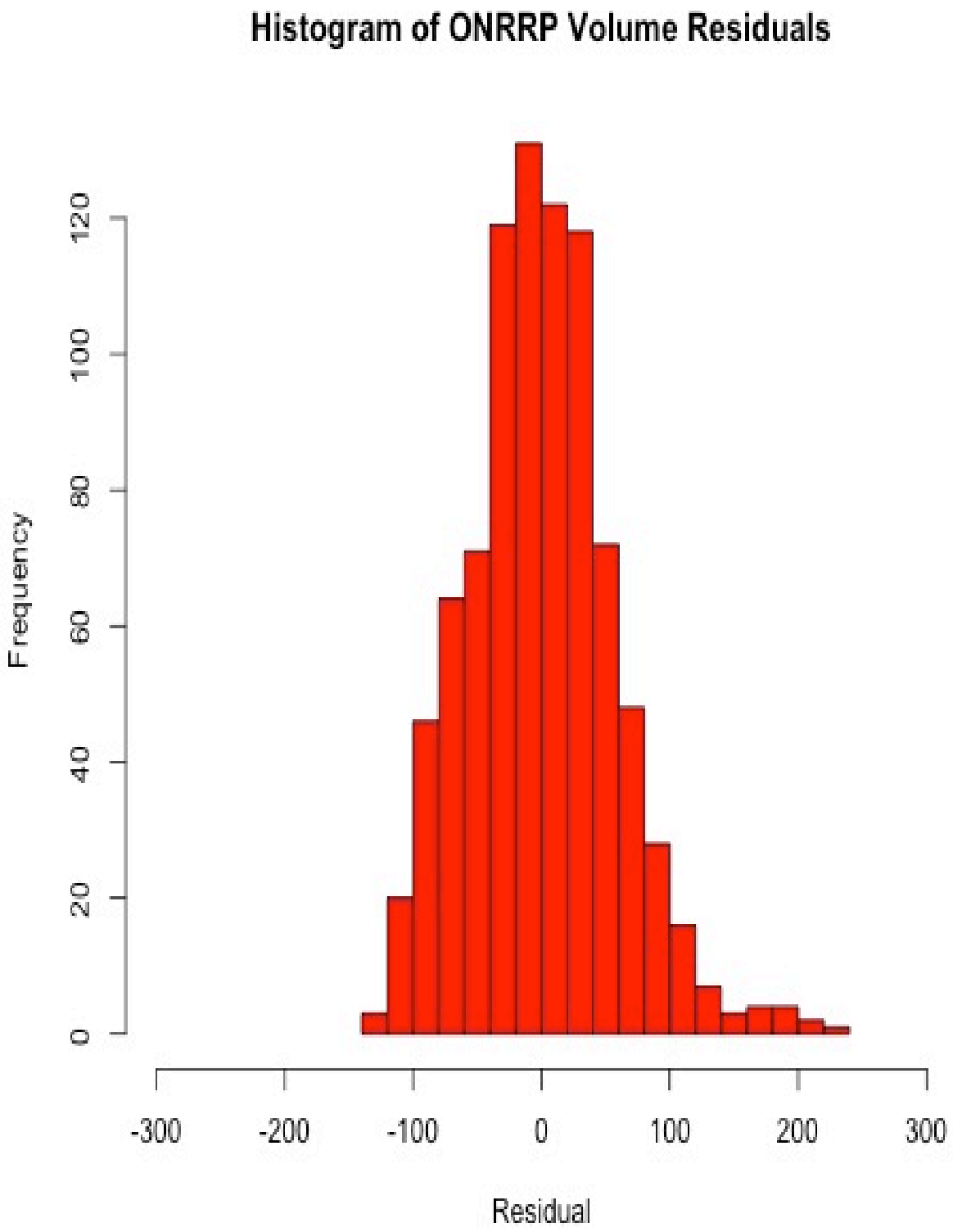
Histogram 4: Residuals from Intraday Volatility Regression



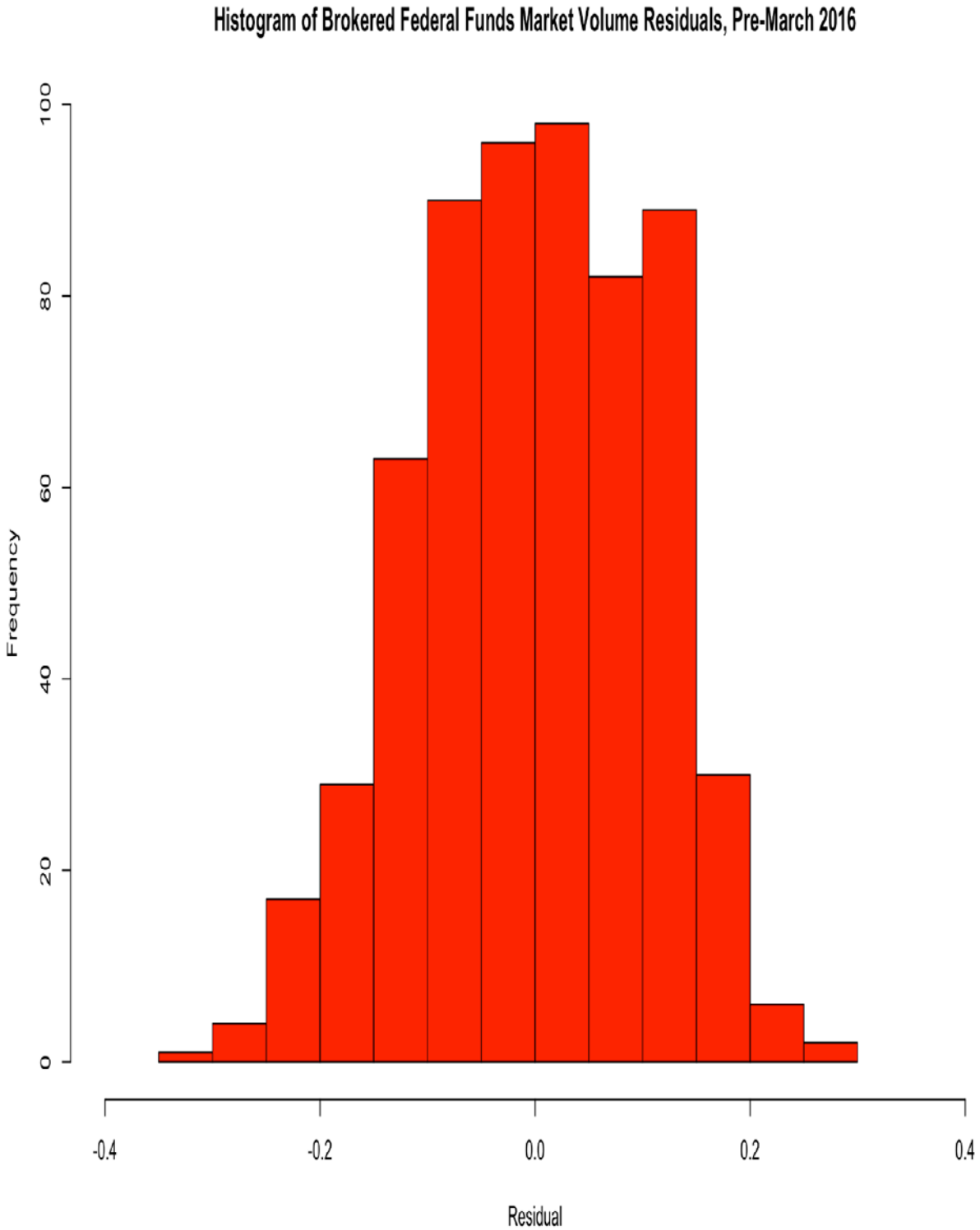
Histogram 5: Residuals from Interday Volatility Regression



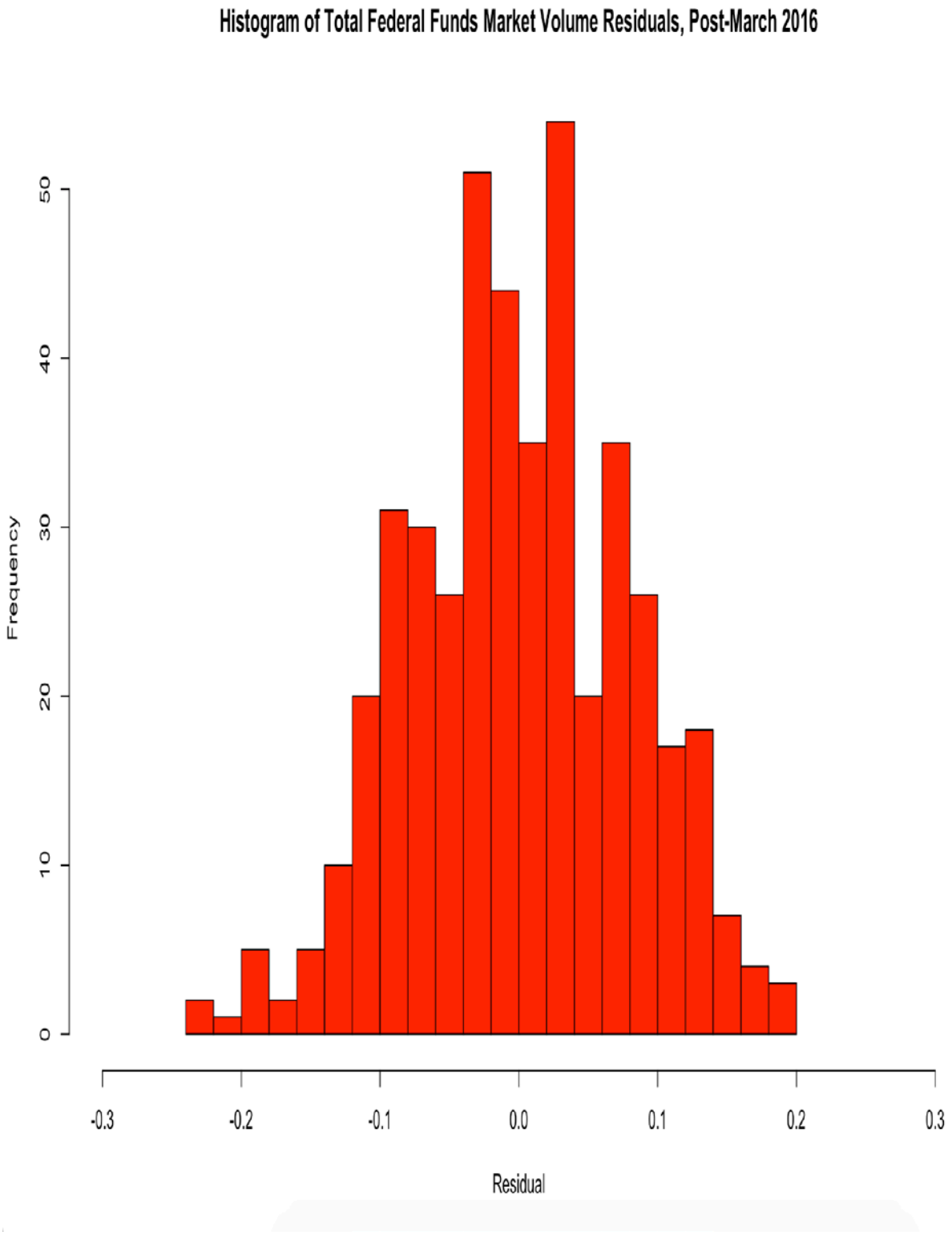
Histogram 6: Residuals from ON RRP Facility Volume Regression



Histogram 7: Residuals from Brokered Federal Funds Volumes Regression



Histogram 8: Residuals from Total Federal Funds Volumes Regression



Appendix G: R Markdown Code – Main Analysis

```
# Setting working directory and opening libraries
setwd("~/Documents/Yale Classes Documents/Senior Essay/Data")
library(stargazer)

##
## Please cite as:

##  Hlavac, Marek (2015). stargazer: Well-Formatted Regression and Summary Statistics Tables.

##  R package version 5.2. http://CRAN.R-project.org/package=stargazer

# Defining data sets from excel
data1 <- read.csv("Data1.csv", stringsAsFactors = FALSE)
data2 <- read.csv("Data2.csv", stringsAsFactors = FALSE)

# Dropping N/A from data1
data1 <- data1[complete.cases(data1),]

# Dropping days that had no ON RRP transactions
data1 <- subset(data1, !(data1$Index == 143 &
                         data1$Index == 383 &
                         data1$Index ==894))

# Dropping days between June 18, 2015 and February 29, 2016
# New York Fed has not provided median data for these dates
data1 <- subset(data1, !(data1$Index >= 436 &
                         data1$Index <= 610))

# Dropping days with N/A in the ON RRP rate column
data1 <- subset(data1, !(data1$ON_RRP_Rate == "#N/A"))

# Converting to matrices, ensuring variables are numeric
data1 <- data.matrix(data1, rownames.force = FALSE)
data2 <- data.matrix(data2, rownames.force = FALSE)

## Warning in data.matrix(data2, rownames.force = FALSE): NAs introduced by
## coercion

# Defining relevant variables

## Dependent Variables
Intraday_Volatility <-data1[,5]
Interday_Volatility <- data2[,8]
ONRRP_Volume <- data1[,8]

## Controls
IOER_ONRRP_Spread <- data1[,16]
Target_FFR <- data1[,6]
Term_RRP_Volume <- data1[,11]
Term_Deposit_Volume <- data1[,13]
MMF_Reform_Dummy <- data1[,20]
Month_End <- data1[,21]
Quarter_End <- data1[,22]

Interday_IOER_ONRRP_Spread <- data2[,7]
Interday_Target_FFR <- data2[,2]
Interday_Term_RRP_Volume <- data2[,4]
Interday_Term_Deposit_Volume <- data2[,5]
Interday_MMF_Reform_Dummy <- data2[,9]

# Creating descriptive statistics tables using Stargazer
stargazer::stargazer(data1[,c(2,5,3,4,16,7,6,8,11,13)],
                     covariate.labels = c("Effective Federal Funds Rate",
                            "99th-1st Percentile Spread",
                            "1st Percentile EFFR",
```

```
                              "99th Percentile EFFR",
                              "IOER-ON RRP Spread",
                              "ON RRP Rate",
                              "Federal Funds Rate Target",
                              "ON RRP Facility Volume (Billions)",
                              "Term RRP Volume (Billions)",
                              "Term Deposit Volume (Billions)"),
                      summary = TRUE,
                      type = "html",
                      out = "Data1.html")

stargazer::stargazer(data2[,c(8,7,2,3,4,5)],
                      covariate.labels = c("Five-Day Standard Deviation of EFFR",
                              "IOER-ON RRP Spread",
                              "Target Federal Funds Rate",
                              "ON RRP Rate",
                              "Term RRP Volume (Billions)",
                              "Term Deposit Volume (Billions)"),
                      summary = TRUE,
                      type = "html",
                      out = "Data2.html")

# Creating histograms of select descriptive statistics

jpeg("Hist_Desc_99_1.jpeg")
hist(data1[,5], main = "Histogram of 99th-1st Percentile Values",
     xlab = "99th-1st Percentile Value", col = "red", breaks = 40)
dev.off()

jpeg("Hist_Desc_ONRRP_Volume.jpeg")
hist(data1[,8], main = "Histogram of ON RRP Volumes",
     xlab = "ON RRP Volume (Billions)", col = "red", breaks = 40)
dev.off()

jpeg("Hist_Desc_EFFR_5DaySD.jpeg")
hist(data2[,8], main = "Histogram of 5-Day Standard Deviation of EFFR",
     xlab = "EFFR Standard Deviation over 5 Business Days", col = "red", breaks = 10)
dev.off()

# Defining main regressions
Intraday_Volatility_Reg <- lm(Intraday_Volatility ~ IOER_ONRRP_Spread +
                                      Target_FFR +
                                      Term_Deposit_Volume +
                                      Term_RRP_Volume +
                                      Month_End +
                                      Quarter_End +
                                      MMF_Reform_Dummy +
                                      MMF_Reform_Dummy*Month_End +
                                      MMF_Reform_Dummy*Quarter_End +
                                      MMF_Reform_Dummy*Term_Deposit_Volume +
                                      MMF_Reform_Dummy*Term_RRP_Volume)
Interday_Volatility_Reg <- lm(Interday_Volatility ~ Interday_IOER_ONRRP_Spread +
                                      Interday_Target_FFR +
                                      Interday_Term_Deposit_Volume +
                                      Interday_Term_RRP_Volume +
                                      Interday_MMF_Reform_Dummy +
                                      Interday_MMF_Reform_Dummy*Interday_Term_Deposit_Volume)
ONRRP_Volume_Reg <- lm(ONRRP_Volume ~ IOER_ONRRP_Spread +
                                     Target_FFR +
                                     Term_Deposit_Volume +
                                     Term_RRP_Volume +
                                     Month_End +
                                     Quarter_End +
                                     MMF_Reform_Dummy +
                                     MMF_Reform_Dummy*Month_End +
                                     MMF_Reform_Dummy*Quarter_End +
                                     MMF_Reform_Dummy*Term_Deposit_Volume +
                                     MMF_Reform_Dummy*Term_RRP_Volume)
```

```r
# Residual Tests

## Creating residual variables
Residual_Intra <- residuals(Intraday_Volatility_Reg)
Residual_Inter <- residuals(Interday_Volatility_Reg)
Residual_ONRRP <- residuals(ONRRP_Volume_Reg)

## Creating residual histograms
jpeg("Hist_Residual_Intra.jpeg")
hist(Residual_Intra, main = "Histogram of Intraday Volatility Residuals",
     xlab = "Residual", col = "red", breaks = 20, xlim = c(-0.2, 0.2))
dev.off()

jpeg("Hist_Residual_Inter.jpeg")
hist(Residual_Inter, main = "Histogram of Interday Volatility Residuals",
     xlab = "Residual", col = "red", breaks = 20, xlim = c(-0.01, 0.01))
dev.off()

jpeg("Hist_Residual_ONRRP.jpeg")
hist(Residual_ONRRP, main = "Histogram of ONRRP Volume Residuals",
     xlab = "Residual", col = "red", breaks = 20, xlim = c(-300, 300))
dev.off()


# Creating regression tables with Stargazer
stargazer::stargazer(Intraday_Volatility_Reg, type = "html",
                     title = "OLS Regression - Daily 99th-1st Percentile FFR Spread on IOER-ON RRP Spread
with Controls",
                     align= TRUE,
                     covariate.labels = c("IOER-ON RRP Spread",
                                          "Target FFR",
                                          "TDF Facility Volume (Billions)",
                                          "Term RRP Volume (Billions)",
                                          "End of Month Dummy",
                                          "End of Quarter Dummy",
                                          "MMF Reform Dummy",
                                          "Month End-MMF Reform Interaction",
                                          "Quarter End - MMF Reform Interaction",
                                          "TDF Volume - MMF Reform Interaction",
                                          "Term RRP Volume - MMF Reform Interaction"),
                     dep.var.labels = "Daily 99th-1st Percentile Spread in FF Market",
                     keep.stat = "n",
                     omit = "factor",
                     out = "Intraday_Volatility_Reg_Stargazer.html")

stargazer::stargazer(Interday_Volatility_Reg, type = "html",
                     title = "OLS Regression - Five Day StDev of Median FFR on IOER-ON RRP Spread with
Controls",
                     align= TRUE,
                     covariate.labels = c("IOER-ON RRP Spread",
                                          "Target FFR",
                                          "TDF Facility Volume (Billions)",
                                          "Term RRP Volume (Billions)",
                                          "MMF Reform Dummy",
                                          "TDF Volume - MMF Reform Interaction"),
                     dep.var.labels = "Five Day StDev of Median Federal Funds Rate",
                     keep.stat = "n",
                     omit = "factor",
                     out = "Interday_Volatility_Reg_Stargazer.html")

stargazer::stargazer(ONRRP_Volume_Reg, type = "html",
                     title = "OLS Regression - Daily ONRRP Facility Volume on IOER-ON RRP Spread with
Controls",
                     align= TRUE,
                     covariate.labels = c("IOER-ON RRP Spread",
                                          "Target FFR",
                                          "TDF Facility Volume (Billions)",
                                          "Term RRP Volume (Billions)",
                                          "End of Month Dummy",
```

```
                                "End of Quarter Dummy",
                                "MMF Reform Dummy",
                                "Month End-MMF Reform Interaction",
                                "Quarter End - MMF Reform Interaction",
                                "TDF Volume - MMF Reform Interaction",
                                "Term RRP Volume - MMF Reform Interaction"),
          dep.var.labels = "Daily ON RRP Facility Volume (Billions)",
          keep.stat = "n",
          omit = "factor",
          out = "ONRRP_Volume_Reg_Stargazer.html")
```

Appendix H: R Markdown Code – Federal Funds Volume Analysis

```
# Setting working directory and opening libraries
setwd("~/Documents/Yale Classes Documents/Senior Essay/Data")
library(stargazer)

##
## Please cite as:

##  Hlavac, Marek (2015). stargazer: Well-Formatted Regression and Summary Statistics Tables.

##  R package version 5.2. http://CRAN.R-project.org/package=stargazer

FFdata1 <- read.csv("Data1.csv", stringsAsFactors = FALSE)
FFdata2 <- read.csv("Data1.csv", stringsAsFactors = FALSE)
# Dropping N/A from data1
FFdata1 <- FFdata1[complete.cases(FFdata1),]
FFdata2 <- FFdata2[complete.cases(FFdata2),]

# Dropping days that had no ON RRP transactions
FFdata1 <- subset(FFdata1, !(FFdata1$Index == 143 &
                           FFdata1$Index == 383 &
                           FFdata1$Index ==894))
FFdata2 <- subset(FFdata2, !(FFdata2$Index == 143 &
                           FFdata2$Index == 383 &
                           FFdata2$Index ==894))
# Dropping days with N/A in the ON RRP rate column
FFdata1 <- subset(FFdata1, !(FFdata1$ON_RRP_Rate == "#N/A"))
FFdata2 <- subset(FFdata2, !(FFdata2$ON_RRP_Rate == "#N/A"))

# Converting to matrices, ensuring variables are numeric
FFdata1 <- data.matrix(FFdata1, rownames.force = FALSE)
FFdata2 <- data.matrix(FFdata2, rownames.force = FALSE)

FFdata1 <- subset(FFdata1, !(FFdata1[,17] >= 611))
FFdata2 <- subset(FFdata2, !(FFdata2[,17] <= 610))

# Defining variables

FF_Volume1 <- FFdata1[,9]
logFF_Volume1 <- log(FF_Volume1)
IOER_ONRRP_Spread1 <- FFdata1[,16]
Target_FFR1 <- FFdata1[,6]
Term_RRP_Volume1 <- FFdata1[,11]
Term_Deposit_Volume1 <- FFdata1[,13]
MMF_Reform_Dummy1 <- FFdata1[,20]
Month_End1 <- FFdata1[,21]
Quarter_End1 <- FFdata1[,22]

FF_Volume2 <- FFdata2[,9]
logFF_Volume2 <- log(FF_Volume2)
IOER_ONRRP_Spread2 <- FFdata2[,16]
Target_FFR2 <- FFdata2[,6]
Term_RRP_Volume2 <- FFdata2[,11]
Term_Deposit_Volume2 <- FFdata2[,13]
MMF_Reform_Dummy2 <- FFdata2[,20]
Month_End2 <- FFdata2[,21]
Quarter_End2 <- FFdata2[,22]

# Regression creation
FF_Volume_Reg1<- lm(logFF_Volume1 ~ IOER_ONRRP_Spread1 +
                     Target_FFR1 +
                     Term_Deposit_Volume1 +
                     Term_RRP_Volume1 +
                     Month_End1 +
                     Quarter_End1 +
                     MMF_Reform_Dummy1 +
```

```
                    MMF_Reform_Dummy1*Month_End1 +
                    MMF_Reform_Dummy1*Quarter_End1 +
                    MMF_Reform_Dummy1*Term_Deposit_Volume1 +
                    MMF_Reform_Dummy1*Term_RRP_Volume1)

FF_Volume_Reg2<- lm(logFF_Volume2 ~ Target_FFR2 +
                    Term_Deposit_Volume2 +
                    Term_RRP_Volume2 +
                    Month_End2 +
                    Quarter_End2)

# Stargazer
stargazer::stargazer(FF_Volume_Reg1, type = "html",
                    title = "OLS Regression - Log of Brokered Daily Federal Funds Volume on IOER-ON RRP S
pread with Controls, Pre-March 2016",
                    align= TRUE,
                    covariate.labels = c("IOER-ON RRP Spread",
                                         "Target FFR",
                                         "TDF Facility Volume (Billions)",
                                         "Term RRP Volume (Billions)",
                                         "End of Month Dummy",
                                         "End of Quarter Dummy",
                                         "MMF Reform Dummy",
                                         "Month End-MMF Reform Interaction",
                                         "Quarter End - MMF Reform Interaction",
                                         "TDF Volume - MMF Reform Interaction",
                                         "Term RRP Volume - MMF Reform Interaction"),
                    dep.var.labels = "Log of Brokered Daily Federal Funds Market Volume",
                    keep.stat = "n",
                    omit = "factor",
                    out = "FF_Volume_Reg1.html")

stargazer::stargazer(FF_Volume_Reg2, type = "html",
                    title = "OLS Regression - Log of Total Daily Federal Funds Volume on Target FFR with
Controls, Post-March 2016",
                    align= TRUE,
                    covariate.labels = c("Target FFR",
                                         "TDF Facility Volume (Billions)",
                                         "Term RRP Volume (Billions)",
                                         "End of Month Dummy",
                                         "End of Quarter Dummy"),
                    dep.var.labels = "Log of Total Daily Federal Funds Market Volume",
                    keep.stat = "n",
                    omit = "factor",
                    out = "FF_Volume_Reg2.html")

# Residuals

FFResidual_1 <- residuals(FF_Volume_Reg1)
FFResidual_2 <- residuals(FF_Volume_Reg2)


jpeg("Hist_FFResidual1.jpeg")
hist(FFResidual_1, main = "Histogram of Brokered Federal Funds Market Volume Residuals, Pre-March 2016",
     xlab = "Residual", col = "red", breaks = 20, xlim = c(-0.4, 0.4))
dev.off()

jpeg("Hist_FFResidual2.jpeg")
hist(FFResidual_2, main = "Histogram of Total Federal Funds Market Volume Residuals, Post-March 2016",
     xlab = "Residual", col = "red", breaks = 20, xlim = c(-0.3, 0.03))
dev.off()
```