High-Frequency Analysis of Financial Stability*

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Abstract

Central banks maintain, supervise, monitor, and regulate national wholesale payment systems, which are the backbone of the financial system. In this paper, we study the efficiency and stability trade-off in the payment systems' design and derive implications for central banks' modernization efforts of these systems. We identify a new source of systemic risk due to binding credit or collateral constraints that result in delays and rejections of critical payments. To measure this risk, we develop novel high-frequency measures of financial stability that can be computed by regulators in real-time. We implement our measures using 500 trillion CAD of interbank payments in Canadian Large Value Transfer System (LVTS). We find that some of our measures spiked in the second half of 2005 and stayed high until March 2008, when the Bank of Canada started injecting liquidity to LVTS. Other measures showed stress in 2007-2009 when LVTS experienced an abnormal increase in delayed and rejected payments, including payments sent by banks to the Bank of Canada. The intraday analysis of bilateral credit limits (BCL) shows system's stress following the Lehman failure and following a large writedown on US subprime mortgage portfolio by one of the LVTS participants. High reciprocity in the provision of BCLs suggests that the systemic risk can materialize due to strategic (non-fundamental) considerations. Despite missing the warning signals, Bank of Canada, as part of a coordinated effort with other central banks, injected in 2008-2010 unprecedented amounts of liquidity by allowing banks to pledge risky collateral. Overall, the results suggest that central banks should use high-frequency analysis of wholesale payment systems to identify buildups of systemic risk and derive optimal real-time intervention.

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1 Introduction

Since the financial crisis, measuring systemic risk has been a main priority of financial regulators. One source of systemic risk rests in interbank payment systems. Such payment systems are the foundation of the global financial system. They are used to settle interbank loans, financial contracts, as well as securities transactions cleared via centralized exchanges and CCPs. Without such systems commercial transactions and international trade would halt, wages could not ultimately be paid, and taxes could not be collected. The systemic importance of large value payment systems is recognized by regulators, but what is the source of the systemic risk in these systems and how to measure it is not well understood.[1]

In this paper, we argue that the main risk of the payment system is that it will stop processing critical payments. We develop new measures of this systemic risk using high-frequency data from such a system. If the frequency of risk measurement is lower than the frequency at which the risk can materialize, then regulators can wrongfully conclude that the risk does not exist. Focusing on the wrong type of risk or measuring the right risk at the wrong frequency cause a delay in intervention, such as injection of liquidity. This delay is socially costly because given the unique role of payment systems in the financial system, a freeze in a large value payment system can spread to other local and global clearing and settlement systems in a matter of minutes.

We derive these high-frequency intraday systemic risk measures using information about daily and intraday credit limits, collateral constraints, payment flows, and rejected payments in the Canadian payment system. In particular, we focus on binding credit and collateral constraints as a source of systemic risk. We develop our high-frequency measures using half a *quadrillion* CAD of payments in Canadas interbank payment system the LVTS. Using these measures we find that LVTS was under stress in during the crisis period of 2007-2009. Some risk measures started signaling stress as early as the second half of 2005.

To understand the source of the risk in a payment system resulting from settlement of interbank payments, we need to understand fundamental efficiency-stability trade-off that exists in the design of these systems. The two main types of systems are Real-Time Gross Settlement (RTGS) systems

[1] According to the Bank for International Settlements, "Robust payment systems are a key requirement in maintaining and promoting financial stability" (BIS, 2001).

and Deferred Net Settlement (DNS) systems. In RTGS systems an interbank payment is settled in real-time on a gross basis. This results no counterparty risk since senders of a payment are required to pledge collateral or liquidity equal to the gross value of the payment. While there is no credit risk it does typically require enormous amounts of collateral given that these systems settle of quadrillions USD of payments annually.[2] Importantly, the mitigation of the counterparty risk in RTGS system does not mean that it eliminates systemic risk completely. We argue that the risk of RTGS system is that collateral constraints may bind, which could cause a delay or rejection of time critical payments.[3] These failures could cause corresponding failures, uncertainty or panic in other systemically important systems as they rely on RTGS to settle daily transactions measured in trillions USD.[4] In contrast, a DNS system only settles on a net basis at the end of the day.[5] This netting enables the system to achieve a high efficiency of collateral or liquidity usage, but it exposes banks to credit risk and losses if any banks fail to settle.

In this paper we utilize the unique features of Canadian LVTS. It is the only hybrid payment system in the world. It attempts to combine the efficiency of the DNS system and the stability of the RTGS system. LVTS allows banks to choose for every payment whether fully collateralize it like a RTGS system (using the so-called Tranche 1) or to ultimately settle it on a net basis using less collateral (using Tranche 2). To control counterparty credit risk in Tranche 2 participants extend bilateral credit limits (BCLs) to each other.[6]

LVTS provides a unique opportunity to study systemic risk of a payment system for several reasons. First, the hybrid nature of LVTS allows us to develop measures that are relevant for both an RTGS and a DNS, as well as measures that are unique to LVTS. Second, it is one of the largest payment systems in the world. Just to put it into perspective, LVTSs *daily* average value

[2]RTGS payments systems settled $3.1 quadrillion USD in 2009 across 111 countries (Table II.3 in The World Bank's "Payment Systems Worldwide: A Snapshot" report).

[3]Some central banks provide intraday overdrafts that would allow a bank to send payments even without having enough collateral. These overdrafts transfer the risk to the central bank.

[4]For example, in 2015, the CLS group relied on 18 payment systems around the world to settle a daily value of $1.5 trillion USD of FX transactions. Source: `https://www.cls-group.com`. CLS has loss-sharing agreements among surviving members that would be activated if there is a loss due to a member bank failing to make a payment Galati et al. (2002).

[5]An example of a DNS system is EURO1 payment system in Europe that processed €51 trillion of payments in 2017. Source: `https://www.ebaclearing.eu/media/azure/production/1824/eba-clearing-annual-report-2017_single-pages.pdf`.

[6]We explain the nature of LVTS and our data set in Section 2.

of transactions in 2018 was 7% larger than the *annual* value of all Bitcoin transactions in 2018.[7] Third, some of the largest banks in world are participants in LVTS. Therefore, LVTS allows us to analyze the constraints they face and how they perceive the counterparty risk of each other. Our analysis helps to study the systemic risks inherent in RTGS and DNS systems; which is an important factor in Canadas and other countries choice of a future payment system.

We propose three high-frequency risk measures to capture vulnerabilities we identified. The first measure captures the number and the value of payments that were rejected or delayed due to binding collateral or credit constraints. The second measure captures the volatility of the intraday adjustments in BCLs. These adjustments provide an indirect proxy for the size of the counterparty risk. If the risk is low, banks can manage risk by assigning high BCLs at the beginning of the day that do not require further adjustments. However, if the risk is high, banks will start with a low BCL at the beginning and will adjust later in the day if the risk does not materialize. The third measure is a ratio of credit-based transactions (uncollateralized) relative to all transactions. When this ratio is close to one, it means that the system operates using credit. If this measure is zero, it means that banks use only collateral-based payments. A sharp unanticipated transition from a credit-based to a collateral-based system is a source of risk because banks might not have enough collateral to make payments.

We use these measures to shed light on LVTS's performance over the period of 2003-2013. We show that the LVTS retained an extremely high level of efficiency because almost 98% of the transferred value was utilizing credit-limits. However, we also find that LVTS was under stress during the financial crisis. We show significant stress following Lehmans failure. Second, we find an instance of a "flash crash" in the first half of 2008. which would be impossible to identify without using high-frequency risk measures. We also identify two instances of sharp declines in the fraction of credit-based transactions relative to total transactions in 2008 and 2009. Our complimentary measure of rejected payments also spikes during this period. We document that starting the end of March of 2005, banks became reluctant to provide large BCLs at the beginning of the day and

[7] According to `http://www.blockchain.com`, the total value of Bitcoin transactions was $130 billion USD in 2018, which was higher than in any previous year. According to `https://payments.ca/about-us/our-systems/large-value-transfer-system/statistics/`, the daily average value of payments in LVTS was $181 billion CAD ($140 billion USD) in 2018.

preferred rather to adjust BCLs later in the day. This pattern is observed until March 2008, when the Bank of Canada (BoC) started to inject liquidity in the system as part of the coordinated efforts by central banks around the world.

The intervention did not seem to come as a response to the stress that LVTS experienced given that our measures were not available to the BoC to use at the time. Mark Carney, the governor of the BoC at the time stated that "...our payments system has functioned smoothly and reliably, despite the enormous shocks to our financial system over the past two years" (Carney, 2009). While LVTS did not collapse during the crisis, our measures show that it experienced a significant stress despite being not in the center of the crisis.

1.1 Related literature

Our paper is most closely related to the literature on systemic risk in payment systems.[8] The main focus is on understanding the efficiency and stability trade-offs in different system designs mentioned above. Rochet and Tirole (1996), Freixas and Parigi (1998), Kahn and Roberds (1998), and more recently Lester (2009) study risk and efficiency trade-offs in RTGS and DNS systems. The main conclusion of this literature is that (1) a gross settlement system is resilient to contagion risk but makes an extensive use of liquidity; (2)while deferring and netting settlement economizes on liquidity it exposes participating banks to contagion. Our approach to understanding systemic risk is different from the previous literature.

Our measures assess the extent to which a payment system is liquidity constrained in processing payments which itself can cause a crisis and builds on the ideas of Kiyotaki and Moore (1997) and related literature. These constraints may prevent direct cascades of defaults in a payment system like in Eisenberg and Noe (2001), but they affect other financial and real transactions in the economy by reducing available liquidity to other participants. This literature shows how an economy can transition from non-binding collateral constraints to binding collateral constraints or credit limits and that this transition can have a long-lasting effects on the economic activity. For example, Kehoe and Levine (1993) model an economy without collateral, but with endogen-

[8]Kahn and Roberds (2009) provides an excellent survey of this literature.

ous credit limits. Gu et al. (2013) show that this type of economy can have credit limits that are not driven by fundamentals, but by beliefs about the future extensions of credit limits. In our context, if credit limits in a payment system are binding and/or banks do not have enough collateral, then payment system's capacity to process payments will be reduced, causing rejected payments and delays. These rejections and delays are what we interpret as a realization of a systemic risk event and hence we bring the ideas of this literature into the context of payment systems efficiency-stability trade-off discussions.

We combine insights from this theoretical literature to develop new measures of systemic risk. A number of measures for systemic risk have been proposed since the financial crisis. They include the marginal expected shortfall of Acharya et al. (2010) and Acharya et al. (2012), (Adrian and Brunnermeier, 2016) CoVaR measure and (Brownlees and Engle, 2015) SRISK as a measure of bank's contribution to systemic risk. In all cases, these measures and the others surveyed by Bisias et al. (2012) rely on stock market data or other daily or lower frequency measurement. Our measures are different along three main dimensions. First, our measures are based on bank decisions, such as decisions to utilize excess collateral or to extend a credit limit to a counterparty. While stock prices aggregate noisy signals from millions of investors, our measures aggregate information from a small set of participants in a payment system that are some of the largest and most sophisticated financial institutions in the world. Second, our measures focus on the risks associated with binding collateral or credit constraints, as opposed to the risk associated with contagion and depreciation in asset prices. Third, to the best of our knowledge, our measures of systemic risk are the only one that can be computed in real-time and at second-by-second frequency.

2 LVTS

We use high-frequency data about LVTS to implement our measures of systemic risk. LVTS is the only systemically important payment system in Canada. It was designated as such on January 19, 1999.

Our data includes bilateral payment flows between LVTS participants, BCLs, pledged collateral, and rejected payments. Most of the data is available from January 2001 to August 2014. The total number of payments during this period is more than 74.4 million with a total value of \$500 trillion CAD. LVTS participants during our sample include the six largest Canadian banks, four subsidiaries of global financial institutions, four regional financial institutions, and the BoC.[9] In fiscal year 2015, the six largest Canadian banks had \$3.3 trillion of total assets, 354 thousand employees, and a market capitalization of \$351 billion, while the four parent companies of the subsidiaries had \$6.9 trillion of total assets, 501 thousand employees, and a market capitalization of \$475 billion.[10]. The regional financial institutions are much smaller than the big six banks, with total assets of \$112 billion in 2015.[11] LVTS is a tiered system in which a small number of banks are direct participants and a large number of local and global banks use the direct participants to send and receive payments on their behalf.[12]

We use high-frequency LVTS data which is generated and maintained by Payments Canada. Our empirical analysis focused mainly on three datasets (i) the number of rejected payments experienced by each participant (ii) the bilateral credit limits granted and received by all LVTS participants (iii) the cumulative payment flows in a day. All these data are available on a transaction-by-transaction basis and are time-stamped. This gives us the ability to assess the provision and receipt of BCLs on a second-by-second basis. In total, the rejected payments dataset has over 6,200 observations, the BCL dataset has over 770,000 observations, and payment flows dataset has well over a million records. The BCL dataset provides information on the value of credit granted by a participant to all other participants for every day that a participant is active in the LVTS. The majority of LVTS participants have been active in the system for well over 3,000 days. The rejected payments data provide information on a daily basis on the number and type of rejected payments experienced by each participant. Finally, the payment flow data provide information

[9]For convenience, we refer to all private participants as banks.

[10]The six Canadian banks are Toronto-Dominion Bank, Royal Bank of Canada, Bank of Nova Scotia, Bank of Montreal, Canadian Imperial Bank of Commerce, and the National Banks of Canada. The parent companies are HSBC, State Street, Bank of America, and BNP Paribas. The market capitalization is computed as of January 1, 2015. Source: Capital IQ.

[11]These include La Caisse Centrale Desjardins Du Qubec, ATB Financial, Laurentian Bank of Canada, and Central 1 Credit Union.

[12]There are 57 indirect participants listed on the Payments Canada's website in 2019, including some of the largest banks in the world (UBS, Deutsche Bank, Citibank, J.P. Morgan Chase, Mizuho Bank, Société Générale, US Bank). The tiered structure of LVTS is similar to the structure of CHIPS, UK's large value payment system, which has 16 direct participants.

on the payments sent and received by each participant with details about the counterparty, the type of the payment (collateralized or uncollateralized), whether it is a jumbo payment (more than $100 million CAD), time the payment was submitted and when it passed risk controls. For some transactions we also know whether the payment was sent on behalf of the bank itself or on behalf of a customer.

The proper flow of payments in the LVTS is supported by posted collateral and BCL between participants. For a payment to be made, it needs to pass the LVTS's automated risk controls that ensure that a direct participant sending a payment has sufficient collateral or credit limits at the time of a transaction, otherwise, the payment is rejected. If participant(s) experience sufficient number of rejected payments, it can cause a grid lock in the LVTS intraday through disruptions in payment flows. This is because participants rely on incoming payments as a source of intraday liquidity and base their payments decision on it. Since LVTS also performs settlement function for other financial systems, including a number of systemically important systems, on designated-time basis, the result of a LVTS freeze can significantly harm broader economic activity.

At the start of each day, participants make the decision about how much collateral they pledge and what BCL they are willing to grant to all other participants.[13] The collateral is pledged to the BoC and is held in a participant's settlement account. The pledged collateral can be used for two purposes. First, banks can allocate part of the collateral to support their collateralized payments. Second, banks are required to back up their BCLs with collateral equal to a system wide percentage (30%) of the largest BCL. Participants have the ability to post additional collateral during the day or withdraw collateral which is in excess of what they allocated for collateralized payments and for support of the granted BCLs.[14] If a participant decides to increase BCL intraday to its largest recipient, it needs to post additional collateral. On the other hand, if the BCL granted is decreased intraday, the granting participant cannot retrieve the posted collateral that day. Each collateralized payment received (sent), replenishes (depletes) a participant's collateral by an equal amount. It is also important to note that participants are not required to grant BCL to other participants and hence each participant has the ability to force all others to send it payments using

[13]Arjani and McVanel (2006) provide a detailed summary of the LVTS procedures.

[14]The system wide percentage was increased by the CPA Board of Directors from 24% to 30% on May 1, 2008.

collateral. A participant can make the decision of not granting BCL to all other participants at any time during the day or at the start of each day. In practice, participants generally roll over the previous day's standing bilateral credit limit to the next day. Moreover, typically there is significant reciprocity in BCL granting, whereby participants grant BCL amount to other participants in the amount equal to what they receive from them. This reciprocity has been noted in literature (see Bech et al. (2010) and Allen et al. (2013)).

LVTS participants also have the ability to increase BCL intraday and the only time this increase impacts their collateral requirement is if it exceeds their previous largest BCL granted. The reduction in the BCL granted intraday, even if it is for the largest receiver, does not reduce a participant's collateral requirement.

The LVTS Tranche 2 is considered a survivor-pay model. The settlement risk in the LVTS results from the fact that it is a DNS system. While all payments are final and irrevocable, settlement happens at the end of the day on a multilateral net basis and a participant's inability to fund its net negative position exposes the surviving participants to settlement risk. Tranche 1 does not create any settlement risk because each payment is backed dollar-for-dollar against a participant's collateral. By its design, LVTS must settle at the end of the day, even in the event of a single or multiple default. In case of a single default, surviving participants make final settlement possible by contributing in the amount corresponding to their share of the largest BCL granted to the defaulting participant during the day. As an example, if a defaulting participant had a net negative position of $100 million (after taking into account its own posted collateral), and another participant; Participant A, granted it $300 million in BCL, while all the remaining participant granted the defaulting participant a total of $700 million in BCL, then participant A's relative contribution to BCL is 30%. As a result, it will have to contribute $30 million towards the total shortfall of $100 million. A surviving participant's contribution is based on the highest intraday BCL it grants, thus reducing the BCL intraday does not affect a participant's relative contribution, but can avoid further accumulation of losses. A participant can request additional BCL from another participant, but there is no obligation on that participant to oblige. As long as the BCL increase does not result in the new BCL exceeding the grantor's largest BCL for the day, it has no implication on grantor's collateral needs, but it does increase grantor's contribution to a final settlement pool in case of default.

3 Systemic Risk Measures

In this section, we present our high-frequency risk measures.[15] Our risk measures can be computed at the system level, at the bank level or between any pair of banks. Our main focus is on the aggregate measures because they provide a system-wide measure of risk. Bank-level measures can help to study stress experienced by a particular bank, which is also important for financial stability because some of the participants are systemically important financial institutions (SIFIs). The pairwise analysis is useful to study the network effects that exist in the payment system.

3.1 Rejected and Delayed Payments

Depending on the type of the payment system, payments are rejected if collateral or/and credit-limits are binding. If a payment system puts a payment in a queue when it cannot be processed immediately, this payment is processed with a delay once the constraint stops to be binding. In LVTS, only jumbo payments (above \$100 million CAD) can be queued if they violate collateral constraints or credit limits. If a payment stays in a queue for too long, it is eventually rejected.

Our rejected payments measure is the system-level and bank-level number and value of rejected payments that happen because of violations of collateral or credit constraints. When a payment is rejected, it is a potential sign of stress in the system because the whole goal of the system is to process payments. The risk is especially high if the same bank experiences multiple rejected payments during the same day and/or multiple banks experience rejected payments on the same day.

Even if payments are only delayed, it is a sign of binding constraints. A severe stress exists if many payments with high value are delayed on the same day. Settlement and clearing systems that rely on LVTS have a very specific time window when all the payments need to be made. Figure

[15] Some measures can be applied to all payment systems, while others are specific to a particular system design.

11 in the Online Appendix provides details about the times when different clearing and settlement systems use LVTS during the day. A delay in LVTS during these time windows can cause failures in settlement of other systemically important systems.

3.2 Bilateral Credit Limits

If banks adjust BCLs based on their estimates of risk of each counterparty, then BCL changes should provide a valuable high-frequency information about stress in the payment system.[16] BCLs are set initially at the beginning of the day, these are refereed to as standing BCLs in LVTS. Banks can adjust them any time during the day.

We derive two risk measures to extract information about the perceived system-wide counterparty risk. The first measure computes the difference between the aggregate end of the day BCL minus the beginning of the day BCL.[17] Formally,

$$\Delta BCL_t = \sum_{i=1}^{n} \sum_{j \neq i} BCL_t^T(i,j) - \sum \sum BCL_t^0(i,j) \tag{1}$$

where $BCL_t^T(i,j)$ is the end of the day BCL extended to bank j by bank i on day t, $BCL_t^0(i,j)$ is the beginning of the day BCL extended by bank i to bank j on day t. The aggregate measure utilizes all $n(n-1)$ BCLs extended by n banks to $n-1$ counterparties. The second measure computes volatility of ΔBCL_t over a 30-days rolling window.[18]

The economic intuition for these two measures is as follows. When the counterparty risk is low and the system functions normally, banks can set high BCLs that do not need to be adjusted. If the risk is high, they will start with a low level of BCL and will increase it later on during the day as they see that the counterparty risk has not materialized yet.[19] In LVTS, if a counterparty fails, surviving banks allocate the net loss generated to the system proportional to the largest BCL they extended to this counterparty, not the latest one. Therefore, starting with a high BCL and reducing

[16]Federal Reserve requires participants in DNS systems to set credit limits conservatively, taking into consideration other exposures to the counterparty. Banks are also required to monitor changes in financial condition of counterparties on a regular basis. If changes are identified, steps should be taken to change bilateral credit limits. See Section VII (C) in `https://www.federalreserve.gov/paymentsystems/files/psr_guide.pdf`.

[17]We also study changes in the standing BCLs, but they change very rarely.

[18]Both measures can be also computed at the bank level and a pair-wise level.

[19]This is similar to the argument that rolling over short-term loans is less risky than providing a long-term loan.

it later in the day if the risk spikes is not the same as starting with a low BCL and increasing it later in the day if the risk does not spike. We expect that the during times of alleviated risk, ΔBCL measure is positive and significantly higher than during the normal times. The volatility of the changes in the aggregate BCL would be alleviated if banks face high uncertainty and as a result make more frequent adjustments in BCLs.

3.3 Fraction of Credit-based Transactions

Decisions of banks to send payments by utilizing credit limits or by utilizing collateral provide information about which constraints are binding. We can summarize these decisions as a fraction of credit-based payments to all payments.

This measure is specific for LVTS system because only in this system banks can choose whether to send each payment using Tranche 1 or Tranche 2.[20] The measure is $T2ratio = \frac{T2}{T1+T2}$, where T1 (T2) here stands for the total value of payments sent using Tranche 1 (Tranche 2). We also compute this measure at the bank level.

If the $T2ratio$ is close to 1, it means that the system operates at high level of trust that allows to overcome need for costly collateral.[21] As the ratio starts to drop, it signals that the trust evaporates and counterparties require collateral. A fast transition of $T2ratio$ from high to low constitutes risk, especially if banks are unprepared to absorb this shock.[22]

4 Application of the Systemic Risk Measures to LVTS

In this section we apply our high-frequency measures to study systemic risk in LVTS before, during, and after the financial crisis.

[20]For countries with two separate systems, one RTGS and one DNS systems, it could be possible to apply this measure by combing data from these two systems.

[21]The collateral pledged by the provider of a BCL is much smaller than what it would require to send the payment using collateral.

[22]If banks always have enough collateral to absorb this shock, then there is no efficiency benefit from using credit in the system.

4.1 Lehman's Failure

We start with the analysis of LVTS on September 15th and 16th, 2008. Lehman Brothers was not one of the participants in LVTS, so its failure on September 15th 2008 does not generate direct losses in LVTS, but it could generate stress because of high uncertainty about direct and indirect exposures that LVTS banks had to Lehman. By analyzing the effects of Lehman's failure on LVTS we aim to achieve two goals. First, we want to study whether Lehman's failure has affected a payment system. Second, it allows us to validate that our risk measures indeed capture risk in the way that we anticipate.

We find that our measures do capture risk on the day of Lehman's failure and the following day. On September 15, 2008 at 8:06am, Bank H's four payments with a total value of $160 million CAD to three other banks are rejected because of violation of risk controls.[23] Then at 11:20am, a Tranche 1 payment of $324 million CAD sent by Bank I is queued because of the binding collateral constraint and settled with delay. This was the only delayed Tranche 1 payment in September 2008. Two payments of $1.5 billion CAD sent by Bank B are delayed due to binding credit constraints at 11:39am and at 4:51pm. One payment of $1.46 billion CAD that was sent by Bank F at 11:40am was settled with delay because of the binding credit constraints. Bank E also faced binding credit constraints at 4:26pm because its payment of $229 million CAD was also delayed. Overall, we document that four banks faced credit or collateral constraints on the day of Lehman's failure, with one bank experiencing multiple rejected payments.

On the next day after Lehman's failure, the day when A.I.G. has nearly collapsed, the stress in LVTS continued. Bank B experienced 32 rejected payments to seven other banks totaling $163 million CAD. The first rejection was at 9:05am because of a violation of a BCL. This payment was processed 1 hour and 13 minutes later. Other rejections took place between 13:07:26 and 15:10:08 because of violations of multilateral credit limits. It is important to notice that 29 rejections took place during the two hour window from 13:00 to 15:00 when the CLS payments are settled, which are some of the most critical payments LVTS is processing.[24]

[23]To preserve the confidentiality, we use randomly assigned letters to refer to individual banks.

[24]Other payments are processed during this window as well. In general, there is not information about the purpose of each payment, it can only be sometimes inferred based on its time.

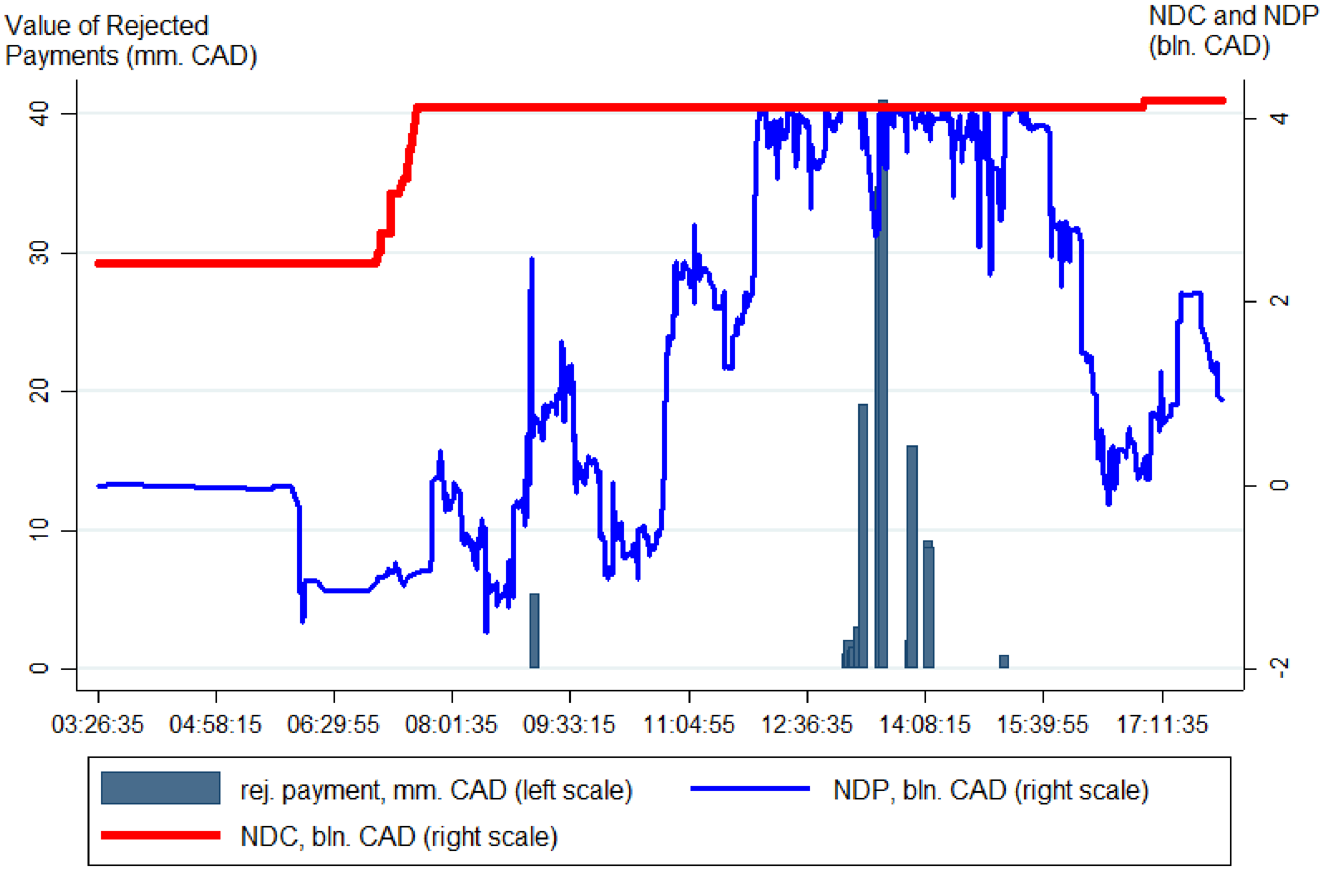
Figure 1 shows how these rejections happened at a second-by-second frequency. The red line in this figure shows the evolution of the net debit cap (NDC) of Bank B, which is equal to 30% of the sum of BCLs extended to Bank B by counterparties on September 16, 2008. Most of the increase the NDC takes place in the morning around 7-8am, when more participants start their daily activity and grant standing BCL. However, on this day we see an additional increase during the afternoon. This increase reflects an increase of $200 million CAD in the BCL provided by Bank E to Bank B at 4:57pm. Without this increase, Bank B's credit constraint against Bank E would be binding and it would not be able to send payments to Bank E.

The blue line in Figure 1 shows the second-by-second evolution of the net debit position (NDP) of Bank B during the day, which is the difference between the payments sent by Bank B to other banks and payments sent by other banks to Bank B. The difference between the NDC and the NDP is the slack that Bank B has for its multilateral credit constraints. The figure clearly shows how Bank B's NDP hits NDC in the afternoon of September 16th. When it happens, we see that payments start to be rejected. Moreover, it is clear from the figure that the constraints were binding for a significant time, which explains why Bank B experienced an extremely large number of rejected payments on this day. It is important to emphasize the the NDC is endogenous and evolves based on the decision of Bank B's counterparties. If other banks would have increased their BCLs to Bank B, as did Bank E later in the day, it would avoid the rejections.

Besides rejected payments, Bank B also experienced delays in jumbo payments in the afternoon of September 16th. Specifically, Bank B experienced delays in settlement of three payments of $1.6B, $1.1B and $102M CAD to three different banks because of the binding credit limits. These delays happened at 1:30pm, 2:25pm and 3:09pm respectively. Again, notice that all three delayed payments were during the CLS window. Bank F also experienced binding credit constraints because it had a $1.7B payment to Bank B that was settled with a delay at 1:30pm.

Discussion. We show that Lehman's failure caused disruptions in the most fundamental part of the financial system–a payments system. A number of interest facts arise from this analysis. First, only one rejection on September 16th was due to a binding BCL. Other rejections were due to violations of multilateral credit limits, which depend on the BCLs provided by all banks. Second,

Figure 1: **Lehman's Failure and Bank B's Binding Credit Limits**



This figure shows second-by-second evolution of Bank B's net debit position (blue line, right scale in billions CAD) and multilateral credit constraint (red line, right scale in billions CAD) on September 16, 2008, the next day after Lehman's failure. Blue bars represent the value of each rejected payments (left scale, million CAD). The first rejected payment is due to violation of a bilateral credit limit, other rejected payments happened because of violation of multilateral credit limits.

the fact that not only Tranche 2, but also Tranche 1 payments were rejected raises a concern because the system is supposed to be able to process payments using Tranche 1, whenever credit constraints start to bind. If both credit and collateral constraints are binding that constitutes a serious risk to LVTS and to other systems that depend on it. Third, the $200 million BCL increase day after Lehman's failure by Bank E to Bank B is important. It is unlikely that Bank B's credit risk has dropped at 16:57:37 and that only Bank E has noticed it and made an appropriate adjustment. It is even less likely that the credit risk drop coincided with a need of Bank B to send large payments to Bank E. We see that Bank B sent to Bank E 1.5 billion CAD using Tranche 2 at 17:02:42 (5 minutes after the BCL increase). Bank B also sent to Bank E three payments of 513M, 103M, and 585M using Tranche 1 between 16:31 to 17:02:42, making it more difficult to send the 1.5B payment via Tranche 1 as well. A more likely explanation for the increase in the BCL is that Bank E wanted to relax the binding constraint so that it can receive the payments, despite the fact that the counterparty risk has actually increased after Lehman's failure. This example highlights a potential moral hazard problem in the provision of BCLs due to the explicit bail-in mechanism in LVTS. When Bank E increases a BCL by 200 million CAD, it does not mean that it commits to cover 200 million CAD of losses in case of default. The losses are allocated proportional to the BCLs granted. As a result, while Bank E is able to get its 1.5B from Bank B, other banks would have needed to pay at least part of this amount in case of Bank B' failure.

Based on the analysis of LVTS during Lehman's failure we reach two main conclusions. First, the indirect effects of Lehman's failure were much deeper than has been thought before. We document stress in LVTS on September 15th and September 16th, even though neither Lehman nor the A.I.G. were direct participants in LVTS. That means that the shock of Lehman's failure propagated to the most critical infrastructure of the financial system. Second, Lehman's failure allows us to validate our risk measures.

In the next section we provide additional evidence for the presence of stress in LVTS in 2008.

4.2 Flash Crash in 2008

In this subsection, we study a Flash Crash that took place in LVTS in the first half of 2008.[25] We refer to this episode as a Flash Crash because it lasted only several days, and any monthly, quarterly or annual measure of risk would not be able to identify it.

The trigger for the Flash Crash was a multi-billion USD write-down by Bank A related to US sub-prime market. In the morning of the next day, this bank cut standing BCL to six other banks (C,H,J,F,K and L) by 20%. There are only 46 reductions in standing BCL by all banks between January 2001 and August 2014, and six BCL reductions on one day are unprecedented. These reductions triggered further reductions in BCL in the next two days. Bank L reduced standing BCL to Bank A on the next day and Banks C and F reduced standing BCLs to Bank A on the second day. All further reductions were also at 20%, which suggests that these three banks reciprocated to the 20% reduction by Bank A, rather than responded to the write-down. If they were responding to the write down, they would not necessarily reduce BCLs by exactly the same percentage. Our high-frequency data allows us to see that Bank A was the first one to cut credit limits, providing additional evidence that the three BCL cuts by banks L, C and F were responding to the BCL cut by bank A and not to the writedown. It suggests that BCL reductions can be initiated by a bank that experiences losses with a goal to reduce exposures to counterparties in the LVTS. With a smaller capital base, Bank A needed to reduce its risk exposures, to raise capital or both. It is possible that Bank A reduced exposures not only in LVTS, but other risk-adjustments is harder to identify in real-time. For example, if Bank A decided to reduce business lending, it would take much longer to see it in the data. So by monitoring on the behavior of banks in LVTS we can measure directly how constrained are they.

Bank H, one of the six banks that saw their BCLs reduced in the morning, experienced 30 rejected payments between 1:14pm and 1:52pm due to binding credit constraints. This is the highest number of rejections during one day. The total number of rejected payments experienced by Bank H during the 3,653 days of the sample is 233, indicating high significance of the 30 rejections. The total standing BCL granted to Bank H went down by 0.84% or $42 million (from

[25] We do not report the exact date of the Flash Crash to preserve anonymity of the banks.

$5.03 billion to $4.99 billion). This reduction in the BCL was the result of Bank A reducing the standing BCL to Bank H by 20% ($40 million) of the total it typically grants to Bank H and as a result, the BoC reducing the standing BCL to Bank H by $2 million.[26] The reduced aggregate standing BCL of Bank H was sustained until May 21st, 2009.

Another sign of stress during the Flash Crash was a large number of payments with delayed settlement because of binding credit limits. In total, 10 Tranche 2 payments by Banks B, F and H with a total value of $7.5B CAD were delayed by 10 minutes on average. Bank H experienced the longest delay of 38 minutes when it sent a payment of $500 million CAD. The following day, Bank G hits collateral constraints and its Tranche 1 payment of $894M CAD is queued and eventually rejected. Six other banks hit credit constraints and 22 payments of $15B in total are settled with an average delay of 8 minutes, one payment is queued and eventually rejected. Figure 12 in the Online Appendix shows that these delays are abnormal for LVTS comparing to other days within the same month and to the same month in 2013.

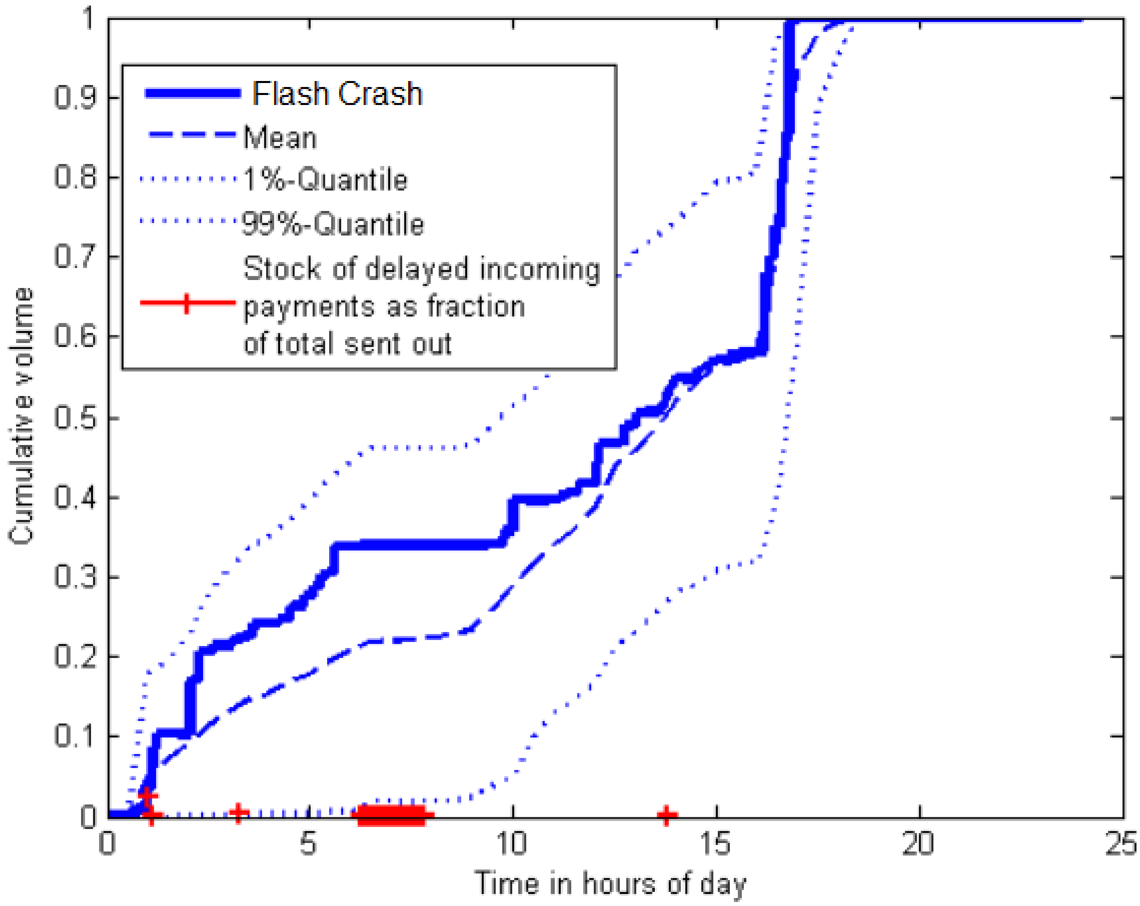
To study whether the day following the write-down was unique from the intraday payment flows perspective, we analyze the intraday payment flows' data for all LVTS participants. As shown in Figure 2, we find that aggregate Tranche 1 payment flows on this day experienced a significant disruption, whereby large value of Tranche 1 payments were sent much earlier in the day.

The Tranche 1 payment flows were skewed due to the fact that Bank B and Bank I significantly increased their Tranche 1 volumes early on in the day (see figures 3 and 4). While we are not certain why these two participants increased their Tranche 1 flows significantly earlier on in the day, one hypothesis is that the two anticipated the impending liquidity shortage resulting from BCL reduction that day and decided to flush the system with significant liquidity to prevent a liquidity crisis. As Allen et al. (2016) suggested, this behavior is also self-serving because of exposures in the Canadian interbank market.

During the Flash Crash, Bank H experienced high number of rejected payments. According to Figure 5, during the Flash Crash, Bank H also significantly delayed its Tranche 1 payment flows and did not send any Tranche 1 payments until late afternoon.

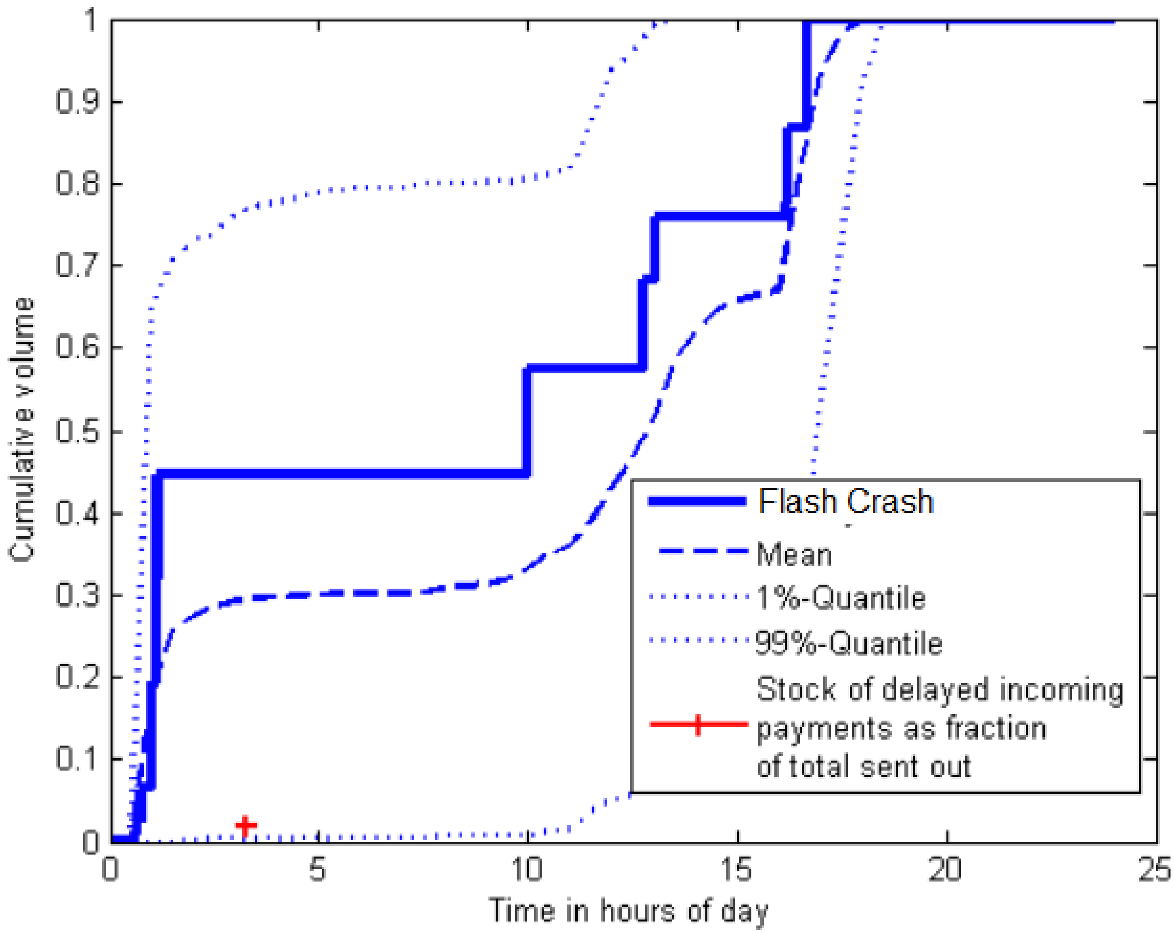
[26] In the LVTS, the Bank of Canada's BCL to a participant is calculated as 5% of the sum of the BCLs established for a participant by all other participants.

Figure 2: **Typical daily Tranche 1 payments flow of all participants compared to payments flow during the Flash Crash**



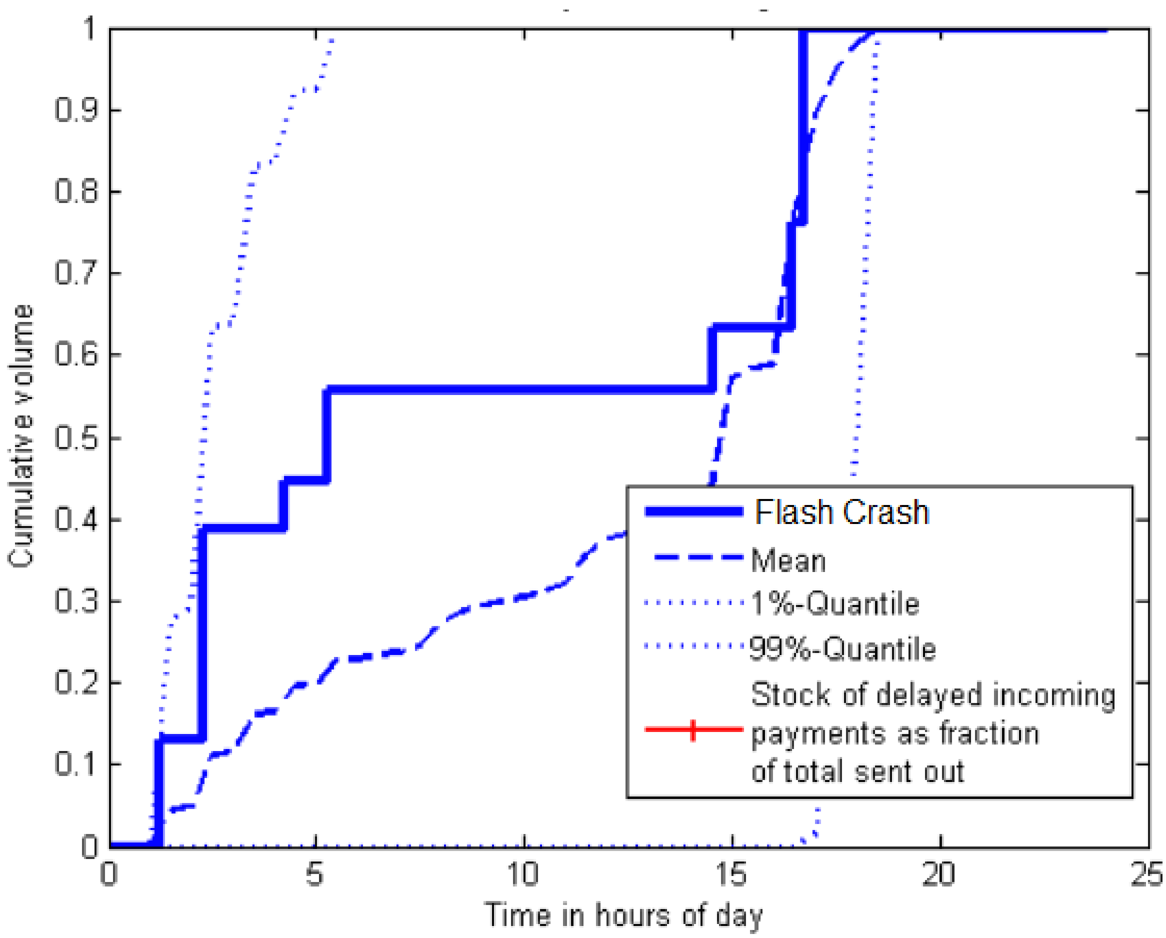
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow in the LVTS based on the empirical distribution between January 1, 2001 and August 30, 2014. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The total value of Tranche 1 payments sent by all LVTS participants by 10:00 during the Flash Crash was well in excess of 30% of the total value sent that day.

Figure 3: **Typical daily Tranche 1 payments flow of Bank B compared to its payments flow during the Flash Crash**



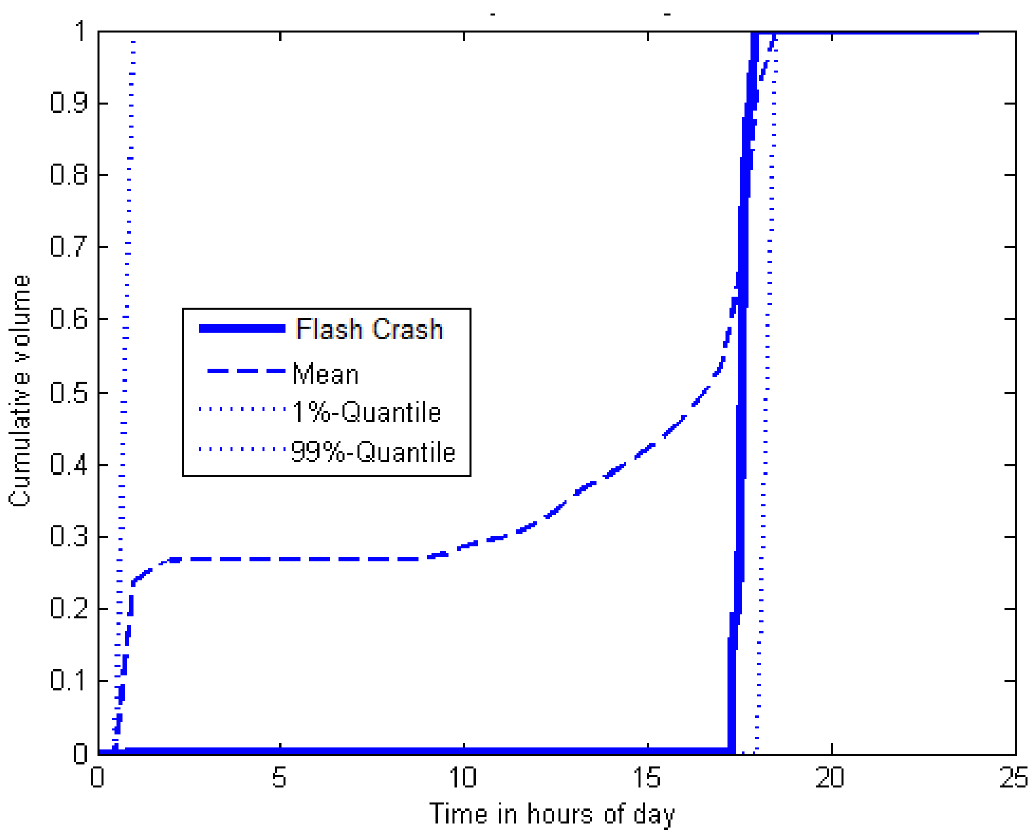
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank B. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The total value of Tranche 1 payments sent by Bank B by 10:00 on the day of the Flash Crash was well in excess of 40% of the total value sent that day. This was significantly higher than its mean.

Figure 4: **Typical daily Tranche 1 payments flow of Bank I compared to its payments flow during the Flash Crash**



The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank B. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The total value of Tranche 1 payments sent by Bank I by 10:00 during the Flash Crash was well in excess of 50% of the total value sent that day. This was significantly higher than its mean.

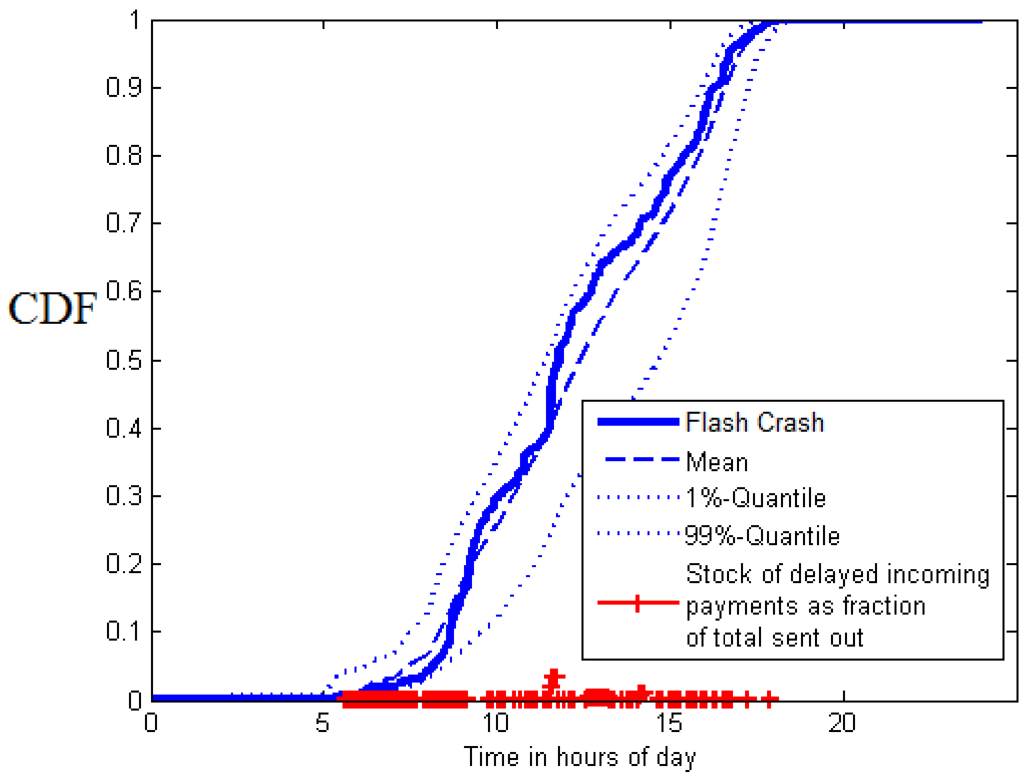
Figure 5: **Typical daily Tranche 1 payments flow of Bank H compared to its payments flow during the Flash Crash**



The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank H. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The figure shows that during the Flash Crash, Bank H did not send any payments until late afternoon. This is a significant delay compared to what had typically been the case.

The transition from credit-based payments to collateral-based payments is the source of fragility in LVTS. So far we showed that the aggregate Tranche 1 payments were sent earlier than usual during the Flash Crash. Now we show that the Tranche 2 payments were sent later than normal during the Flash Crash. Figure 6 shows that at the beginning of the day, the aggregate Tranche 2 payments were sent much later than usual. The solid blue line represents the fraction of the value of Tranche 2 payments sent by a given time during the Flash Crash. This line touches the 99th percentile (dashed line on the right) in the morning. It means that only in 1% of the days in the sample, Tranche 2 payments were sent as late as in the morning of the Flash Crash. Figure 6 also shows that there were many instances of binding credit constraints marked in red.

Figure 6: **Typical daily Tranche 2 payments flow of all banks compared to the payments flow during the Flash Crash**



The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 2 cumulative payments flow of all banks. The dashed line provides the mean and the solid line provides the flow of Tranche 2 payments during the Flash Crash. There is a delay in sending payments in the morning of the Flash Crash. Red marks show instances of delays between a time that a payment is submitted and the time when it is settled.

During the Flash Crash, Bank A reduced BCLs by the same percentage point (20%) to six banks. As shown in figures 15-17 in the Online Appendix, some of the involved banks significantly changed their Tranche 1 payment flows on this day whereby they refrained from sending Tranche 1 payments until much later in the day.

During days 3-4 since the multi-billion write-down, LVTS was still experiencing stress. One jumbo Tranche 1 payment is queued and rejected. In total, 27 Tranche 2 jumbo payments of $19B are queued and delayed, 1 queued and rejected. Bank J temporary increases standing BCL to Bank B by 167% potentially helping it to deal with the disruption in the normal flow of liquidity.

Discussion. LVTS stress during the Flash Crash episode is captured by several risk indicators. Most importantly, this stress was caused by reductions in BCLs that were not driven by higher counterparty risk. The availability of high-frequency data is critical for identification. With lower frequency data, we could wrongfully conclude that Banks C, F and L cut BCLs to Bank A by 20% because it has become more risky following the multi-billion write-down. We can also rule out an alternative explanation that Bank A initiated the BCL reductions because it anticipated that Banks C, F and L would cut its BCL in the coming days. This explanation does not explain why would Bank A also cut BCLs to three other banks (H, J and K). These banks did not cut BCLs to Bank A and Bank A did not increase BCLs to these banks to the original level after the Flash Crash. Therefore, we conclude that the Flash Crash is a clear example of stress in a payment system triggered by BCL reductions.

Next, we examine the time-series of the our risk measures before, during, and after the global financial crisis period.

4.3 Fraction of credit-based payments

Table 1 reports summary statistics for the period around the crisis (2003-2013). On average, there are 5.3 million payments per year valued at $38.2 trillion CAD. The vast majority of payments (98.5%) utilize credit limits and only 1.5% are processed using collateral. If we exclude payments to and from the BoC, then the volume of credit-based payments increases to 99.87%. The average $T2ratio$ is 0.84, meaning that the system on average is very efficient in terms of collateral usage with 84% of the total value processed relies on Tranche 2. This fraction increases to 97.56% if we exclude payments to and from the BoC. Most of the payments are below $100 million CAD (98.44%), but jumbo payments constitute almost 62% of the total value of payments. Most of the payments are sent in LVTS on behalf of the customers of LVTS participants (63%), but these payments are only 22% of the total value. It means that 78% of the total value of payments are sent on behalf of the banks that are direct participants in LVTS.

Table 1: **Summary Statistics**

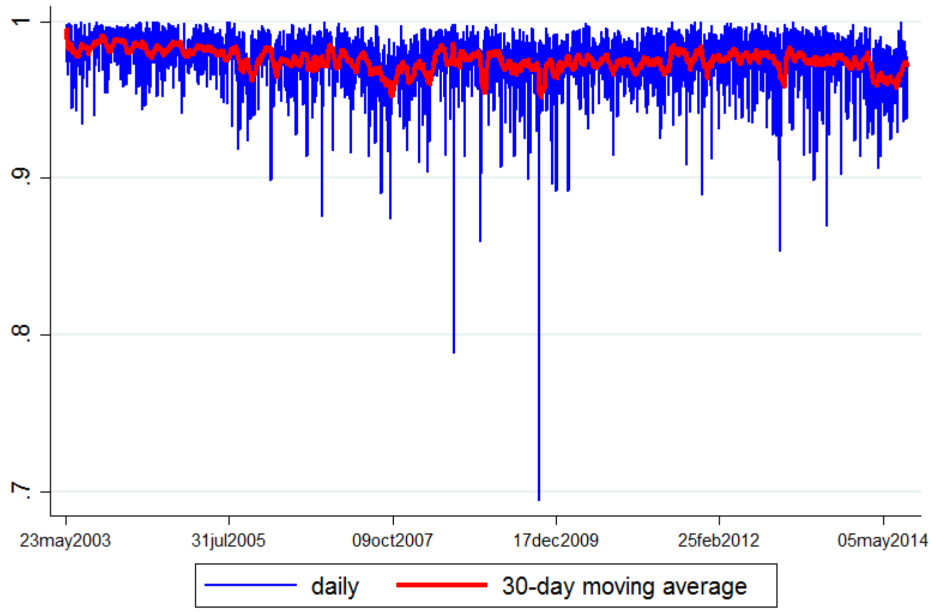
	Mean (2003 - 2013)
Annual volume (million)	5.5
Tranche 2, %	98.50
Tranche 2 w/o BoC, %	99.87
Jumbo, %	1.55
Non-jumbo, %	98.44
Customer, % ('13-'14)	63.37
Bank, % ('13-'14)	36.63
Annual value (trillion CAD)	38.2
Tranche 2, %	84.26
Tranche 2 w/o BoC, %	97.56
Jumbo, %	61.86
Non-Jumbo, %	38.13
Customer, % (2013-2014)	22.17
Bank, % (2013-2014)	77.83

In Figure 7, we can see the evolution of the $T2ratio$ over time at a daily frequency. Overall, we do not see permanent transitions from credit-based to collateral based transactions that last for a significant period of time. Most of the days, the system maintains high level of bilateral trust with more than 98% of payments are transferred using Tranche 2.

However, there are a number of sharp declines in the fraction of Tranche 2 payments during the financial crisis. The largest drop is on September 23, 2009, when the $T2ratio$ drops to 0.7. The second-largest decline was observed on August 4, 2008, when $T2ratio$ drops to 0.79. The red line reports a 30-days moving average of the $T2ratio$. It shows that monthly frequency of monitoring the system is too low because the risk of transitioning to collateral-based system can materialize within a day.

In Table 2, we report results of a time series regression of aggregate daily $T2ratio$. The table

Figure 7: **Daily fraction of credit-based transactions ($T2ratio$)**



This figures plots the aggregate value of credit-based payments (Tranche 2) to total payments (Tranche 1 and Tranche 2) on each day. The sample is from January 2003 to August 2014. The red line is a 30-day moving average of the daily $T2ratio$. We exclude payments to and from the BoC in this calculation. The weight of each bank's $T2ratio$ in the the aggregate measure is equal to the total value of payments sent by this bank to other banks on each day.

shows that the T2ratio was significantly lower on August 4th 2008 and September 23rd 2009. In all specifications, the t-stat is more than 100 for September 23rd 2009 dummy and more than 16 for August 4th 2008 regardless whether we control for the volume of payments on this day, the fraction of jumbo payments, whether it was a Civic holiday when some banks are closed, or use year fixed effects. When we add a dummy for the crisis period (2007-2009), we do not see any difference in the aggregate $T2ratio$. It highlights the nature of risk in the system. The transition from high efficiency with T2ratio close to 1 to a system when banks suddenly need to use only collateral can happen within a day. Low frequency monitoring will not be able to capture this sudden transition.

The same ratio can be also computed at a bank level. Figures 18 and 19 in the Online Appendix, plot the $T2ratio$ for two individual banks. These figures shows that these banks experienced a sharp declines in their $T2ratio$ during the financial crisis period. These episodes of a sharp transition from credit-based to collateral-based payments cannot be detected by a 30-days moving average calculation of this measure (the red line in the plot) suggesting that daily and

Table 2: Time series regression results for T2ratio

	(1)	(2)	(3)	(4)
August 4th, 2008	-0.187***	-0.187***	-0.193***	-0.185***
	(0.001)	(0.011)	(0.012)	(0.011)
September 23rd, 2009	-0.281***	-0.273***	-0.269***	-0.273***
	(0.001)	(0.002)	(0.002)	(0.002)
Volume		-0.001***	-0.001***	-0.001***
		(0.000)	(0.000)	(0.000)
Civic holiday		-0.043***	-0.049***	-0.043***
		(0.013)	(0.014)	(0.013)
Jumbo fraction		-0.117***	-0.141***	-0.111***
		(0.023)	(0.029)	(0.021)
2007-2009 dummy				-0.001
				(0.001)
Constant	0.976***	1.073***	1.087***	1.070***
	(0.001)	(0.015)	(0.020)	(0.014)
Year FE	No	No	Yes	No
Observations	2804	2804	2804	2804
R^2	0.118	0.228	0.251	0.229

The dependent variable is an aggregate $T2ratio$ that measures the ratio of credit-based payments to all payments during 2003-2013. Volume measures the number of payments processed on this day (in thousands). 2007-2009 dummy is 1 during these three years. Civic holiday is a dummy variable equal to one if the date falls on a Civic holiday in Canada. Jumbo fraction is the share of jumbo payments in the total payments on this day. August 4th, 2008 and September 23rd, 2009 are dummies to test whether the T2ratio was statistically lower on these two days when there was the largest drop on the ratio. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are clustered by year and appear in parentheses.

intraday monitoring are needed to see these transitions happen.

4.4 Rejected Payments Results

We first use the number of rejected payments in LVTS due to violations of collateral or credit constraints as a measure of stress. During the crisis in 2007, the number of payments that were rejected in the LVTS due to a transaction's failure in meeting LVTS risk control more than doubled to over 550 transactions compared to a six-year trailing average of 211. We show that the increase in these types of rejected payments was even more dramatic for a selected LVTS participants. In one case, the incidence of rejected payments increased eight fold in 2007, compared to its six-year trailing average. All in all, 6 out of the 14 LVTS participants saw an increase in these types of rejected payments in 2007 compared to their historical averages. By 2009, these types of rejected payments went down to pre-crisis levels.

When a direct LVTS participant enters payment instructions in the LVTS, the payment can get rejected for a number of reasons. In total, there are 15 reasons for a payment rejection.[27] Since 2001, only 9 of these 15 rejection types have been observed in the data.

During the period from January 2001 to May 2015, a total of 20,994 payments have been rejected. The most common reason for payment rejection is when a sending LVTS participant enters a wrong date in the payment instruction (this was the case for 65% of rejected payments). Two other more common reasons are when a sender misses the cutoff time for sending payments (18% occurrence) and when a payment gets rejected because it fails to meet LVTS risk control (13%). Jumbo payments are not rejected immediately, but are queued for 65 minutes and then are rejected if collateral or credit constraints are not relaxed during this period. These rejections constitute 3% of the rejected payments. The remaining five reasons have only been observed 1% of the time and similar to the top two reasons are very mechanical in nature. Out of all the reasons of payment rejection, only two reflect risk in the payment system. The first is when a payment gets immediately rejected because it fails risk controls (herein after referred as FRC). The second is when a payment is rejected after spending some time in the queue. These two reasons constitute 16% of all rejected payments.

Figure 8 shows the number of rejected payments due to binding credit or collateral constraints on an annual basis. This plot includes both outright rejections and rejections that took place after a delay. The number of rejected payments peaks in 2007. The number of rejected payments in 2007 is three times higher than the average annual number of rejected payments pre-crisis. Table 3 provides a detailed summary about the rejected payments. From this table we learn that both the number of non-Jumbo payments that violated risk controls and the number of Jumbo payments that got first delayed and then rejected spiked in 2007. Most of these payments were rejected due to binding credit constraints. In 2007, LVTS experienced the largest number of both Jumbo and non-Jumbo rejected payments.

Table 3 also reports the value of rejected payments. In total from 2003 to 2013, $204 billion CAD of payments were rejected because of binding credit or collateral constraints. The largest value of rejected payments was in 2007. In this year the value of rejected payments reached $40.5

[27] These reasons are explained more fully in the LVTS Web Solution User Guide Annex 3, Version 1.0 - 2013-04-05.

billion CAD, which is more than 2.5 times the average annual value of rejected payments pre-crisis. Banks faced the highest value of rejected payment in 2007 in all types of rejected payments—intimidate rejections, rejections after a delay, Tranche 1, Tranche 2, Jumbo, non-Jumbo.

The evidence presented in Figure 8 and Table 3 might suggest that it is sufficient to monitor systemic risk at the annual frequency. This would be a wrong conclusion for two reasons. First, rejected payments are not equally spread throughout the year, they are clustered around several days. Second, we present conditional results given that we know that LVTS did not freeze during the financial crisis. Intraday monitoring of rejected payments does allow regulators to see that one or more banks are not able to send payments due to binding credit or collateral constraints, and as such, offering an opportunity to intervene if deemed necessary. The annual frequency results show that the risk was alleviated during the crisis, but an intervention at this frequency of measurement could come one year later than needed.

Our data allows us also to study rejected payments by every bank to every other banks. Ultimately, the most critical rejected payments are payments to the BoC. These payments include settlement of FX derivatives, repayment of loans, payments to BoC's clients, which are the Government of Canada, other central banks, the Canada Deposit Insurance Corporation (CDIC), Clearing and Depository Services Inc. (CDS), International Monetary Fund (IMF), and the Bank for International Settlements (BIS). Table 4 reports that the largest number of rejected payments to the BoC was in 2009. Rejected payments to the BoC in 2009 constituted 69% of all rejected payments in this year, more than three times higher than the average in 2003-2006. Moreover, most of the rejected payments to the BoC in 2009 were Tranche 1 payments (80%), meaning that they were caused due to binding collateral constraints. The vast majority (95%) of the 200 rejected payments to the BoC in 2009 were non-Jumbo payments. In total, almost $8 billion CAD of payments to the BoC were rejected in 2009, with almost equal split between Tranche 1 and Tranche 2 payments. While banks can send payments to the BoC using Tranche 2, the BCL is not actively managed by the BoC, but is set to 5% of the aggregate BCL received from other participants. The fact that the BoC cannot control BCLs that it extends to other participants can explain some of the Tranche 2 rejected payments.

Combining results in Table 3 and Table 4 we learn that both credit and collateral constraints were more binding in 2007-2009 than during the period before or after the crisis. Besides validating our systemic risk measures, the results also provide insights about the source of risk. First, we can identify whether the rejections are caused by credit or collateral constraints. Second, we find that Tranche 2 payments to the BoC are rejected because of the BCL decisions of other banks because BoC's BCLs granted to other banks follows a mechanical rule of 5% from the aggregate BCLs granted by other participants to a given bank.

Figure 8: **Total annual number of rejected payments**

The figure shows the annual total number of rejected payments that were rejected because of binding credit or collateral constraints. The observations cover the period from January 2003 to December 2013.

In the cross-section, the distribution of the number of FRC instances has a fat-tail, but not for all. There exists a group of participants who have experienced an extreme number of rejected payments. In the case of two participants, this extreme number of FRC has been 129x and 155x their median level. Table 6 in the Online Appendix reports the median and the maximum number of rejected payments in cross-section of banks for days when at least one rejection took place. The conditional median for all banks is one rejection (the unconditional is zero). The extremely high number of FRC is a very rare event. Such one-time extreme events are difficult to predict

Table 3: **Summary of Rejected Payments**

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
						Volume					
Total	131	314	197	265	688	319	290	105	121	106	123
Expired	10	37	61	41	78	46	47	33	42	51	24
Rejected	121	277	136	224	610	273	243	72	79	55	99
Tranche 1	0	15	16	42	13	11	168	8	10	12	28
Tranche 2	129	298	180	221	673	308	121	97	111	94	95
Jumbo	12	38	62	43	80	46	47	33	42	51	24
Non-Jumbo	119	276	135	222	608	273	243	72	79	55	99
						Value (mm. CAD)					
Total	5,933	18,025	19,957	20,503	40,467	16,529	21,380	13,917	12,827	24,488	10,005
Expired	2,284	9,475	15,811	11,548	30,921	13,045	13,944	11,573	10,617	22,798	7,733
Rejected	3,649	8,550	4,146	8,954	9,546	3,484	7,436	2,343	2,211	1,690	2,272
Tranche 1	0	1,424	1,366	2,633	6,595	4,440	5,141	876	1,750	5,658	2,406
Tranche 2	4,154	15,601	18,370	15,513	32,605	12,089	16,239	13,041	11,078	18,830	7,599
Jumbo	4,062	10,475	16,032	13,905	32,188	13,045	13,944	11,573	10,617	22,798	7,733
Non-Jumbo	1,870	7,550	3,925	6,598	8,279	3,484	7,436	2,343	2,211	1,690	2,272
Mean	45	57	101	77	59	52	74	133	106	231	81
Median	7	13	50	28	3	4	32	50	48	97	16

This table reports a summary of all rejected payments between January 2003 and December 2013. The top panel reports the volume and the bottom panel reports the value in million of CAD. Expired payments are jumbo payments that were queued initially because of the binding credit and collateral constraints and eventually got rejected. Rejected payments are non-Jumbo payments that were rejected without queuing. Tranche 1 are payments that were rejected due to violations of collateral constraints. Tranche 2 are payments that were rejected due to violations of bilateral or multilateral credit limits. Jumbo are rejected payments that are more than $100 million CAD.

Table 4: **Summary of Rejected Payments to the Bank of Canada**

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
					Volume						
Total	23	46	37	86	38	42	200	21	29	36	40
Expired	0	13	16	14	15	12	11	12	11	21	7
Rejected	23	33	21	72	23	30	189	9	18	15	33
Tranche 1	0	12	10	38	4	5	161	6	7	8	14
Tranche 2	21	33	26	46	32	37	38	15	22	28	26
Jumbo	2	14	17	16	17	12	11	12	11	21	7
Non-Jumbo	21	32	20	70	21	30	189	9	18	15	33
					Value (mm. CAD)						
Total	2,517	5,813	5,398	10,355	8,505	3,822	7,988	5,323	3,844	11,587	3,237
Expired	0	3,167	4,365	4,977	6,412	2,745	3,014	5,072	3,011	11,071	2,229
Rejected	2,517	2,646	1,033	5,378	2,094	1,077	4,974	252	833	516	1,008
Tranche 1	0	1,307	991	1,999	2,091	677	4,032	790	646	3,497	684
Tranche 2	739	3,506	4,186	6,000	5,148	3,145	3,955	4,533	3,199	8,090	2,553
Jumbo	1,778	4,167	4,586	7,333	7,679	2,745	3,014	5,072	3,011	11,071	2,229
Non-Jumbo	739	1,646	812	3,022	827	1,077	4,974	252	833	516	1,008
Mean	109	126	146	120	224	91	40	253	133	322	81
Median	37	62	92	54	81	43	26	110	70	163	31

This table reports a summary of rejected payments to the Bank of Canada between January 2003 and December 2013. The top panel reports the volume and the bottom panel reports the value in million of CAD. Expired payments are jumbo payments that were queued initially because of the binding credit and collateral constraints and eventually got rejected. Rejected payments are non-Jumbo payments that were rejected without queuing. Tranche 1 are payments that were rejected due to violations of collateral constraints. Tranche 2 are payments that were rejected due to violations of bilateral or multilateral credit limits. Jumbo are rejected payments that are more than $100 million CAD.

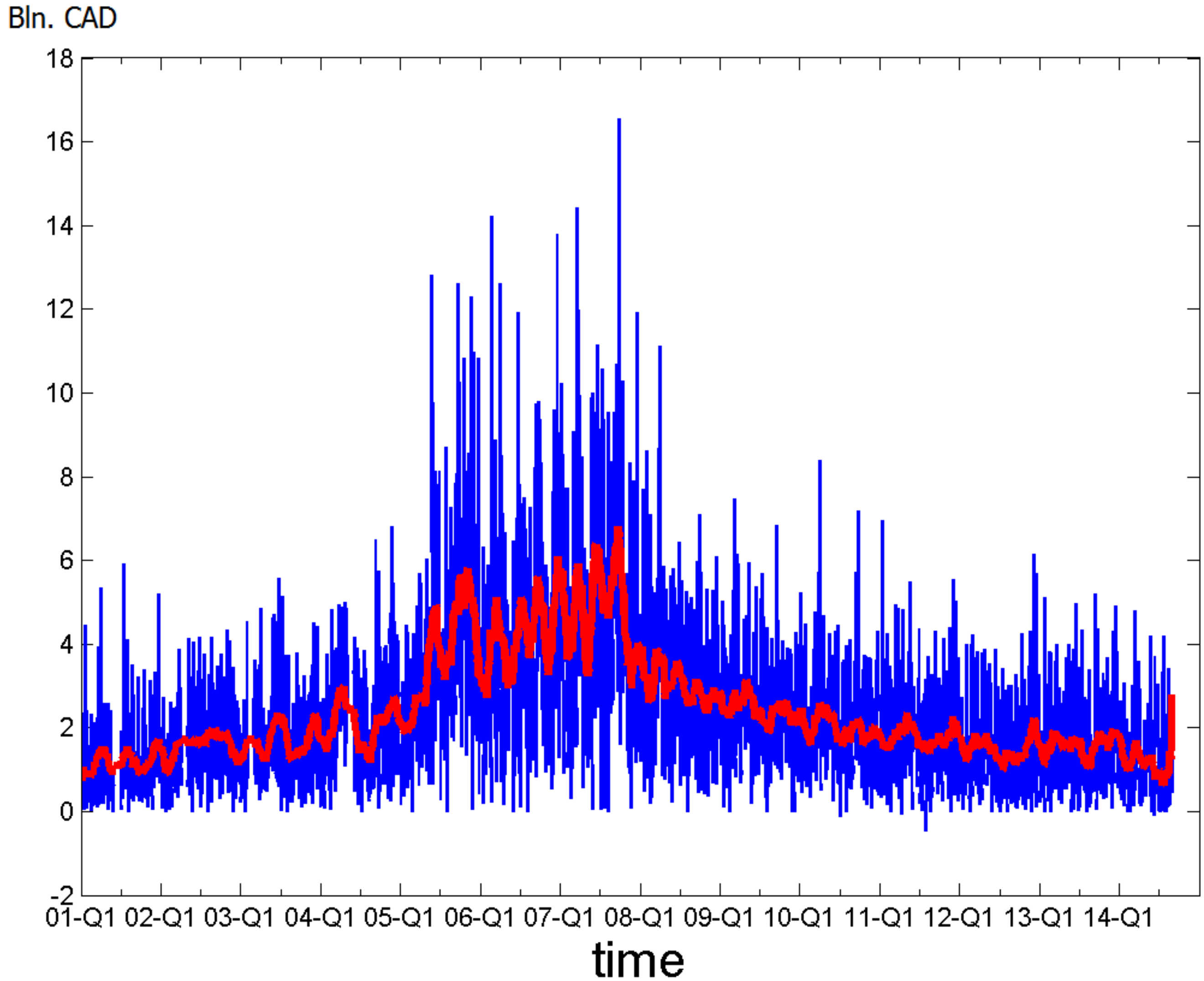
using historical data and a participant may or may not have appropriate contingencies in place to deal with such an event, leading to intraday payment delays or a freeze altogether. The fact that a participant experiences such a high incidence of FRC in a single day suggests to us that it is unlikely to have taken such an event into account when allocating its collateral or in managing its intraday liquidity.

In the case of the two participants that experienced an extreme FRC in one day, we find that the extreme-value day was preceded by relatively calm days. For example, one of the two participants faced a single day FRC of 129 (this took place on a Tuesday, January 23rd, 2007). During the entire week preceding this day, this participant did not experience a single FRC. Similarly, the other participant which saw a single-day FRC of 155 (on Tuesday, September 29, 2009), had not experienced a FRC in almost two months.

4.5 Bilateral Credit Limits Results

In this section, we investigate the behavior of aggregate BCL adjustments. In Figure 9 we plot the difference between the end of the day and the beginning of the day BCL granted by banks to each other (ΔBCL). The highest intraday adjustments in intraday BCLs are observed during 2007-2008, however the increase in the measure started at the end of May 2005. Banks provided up to an additional $16B CAD of BCLs to counterparties between beginning of the day and the end of the day. The fact that they preferred to delay the BCL to later in the day suggests that they faced elevated levels of counterparty risk during this period. In Figure 13 in the Online Appendix, we report the levels of the aggregate BCL at the beginning of the day (standing BCL) and the end of the day (cycle BCL) separately. The standing BCL is higher in the post-crisis period than during 2007, but the cycle BCL during 2007 is as high as the post-crisis standing BCL levels. The question is why banks would not increase the standing BCLs in 2007 like they did in 2013 of they see that they need more capacity to process payments? We argue that banks were reluctant to provide high standing BCL during the crisis because they were concerned about the counterparty risk and preferred not the take too much risk at the beginning of the day. The ΔBCL measure goes back to the normal levels only at the end of March 2008, when the BoC starts to inject

Figure 9: **Intraday BCL Adjustments** (ΔBCL)



This figure plots daily ΔBCL (blue) and a 30-days moving average of the daily measure (red) during Jan. 2001 - Aug. 2014.

liquidity in LVTS.[28]

Figure 14 in the Online Appendix shows the rolling standard deviation of the intraday changes in the BCLs. The highest volatility of ΔBCL is observed during the financial crisis. This measure of risk is going to be low when the difference between the standing BCL and the cycle BCL stays the same over the short-term. It will spike if banks vary the intraday BCL adjustments across days. Such variation signals high uncertainty that requires continuous risk management.[29]

In Table 5, we report results of a time series regression of aggregate daily ΔBCL. In specification (1), we see that between the end of May 2005 and the end of March 2008 banks provided on average 2.4 billion CAD more BCLs at the end of the day relative to the beginning of the day. This is more than one standard deviation of the measure for 2003-2013, which is 2 billion CAD. In specification (2), we see that there is a strong negative correlation between the fraction of credit-based payments ($T2ratio$) and ΔBCL. Low $T2ratio$ and high ΔBCL both are signs of higher risk. The volume of payments seem to be uncorrelated with the ΔBCL, unless we put year FE. A high fraction of Jumbo payments is positively correlated with ΔBCL, suggesting that banks need to increase BCL if a large Jumbo payment is incoming via Tranche 2. ΔBCL is 2 billion smaller during Civic holidays, but it is not significant when we add year FE. In specification (3), the unreported year FE dummies are all positive in 2005, 2006 and 2007, but are negative for 2003 and 2008-2013. Even after we control for year FE, ΔBCL is higher by 0.9 billion CAD between May 25th 2005 and March 31st 2008 as can be seen in specification (4). Overall, the results confirm the conclusions based on Figure 9 that this risk indicator started to increase two years prior to the beginning of the crisis. Whether it can be used as a leading indicator in the future is difficult to say, but it does seem to be a useful measure for regulators to monitor.

[28] We provide more details about BoC intervention in section 5.

[29] While it is not clear what triggered banks' decisions to start delaying provision of BCLs to their counterparties at the second half of 2005, it could have been related to banks' exposure to asset-back commercial paper (ABCP) a market for which had grown drastically from 2004 to 2006, but has resulted eventually in large losses to banks. Source: `https://www.bankofcanada.ca/wp-content/uploads/2010/04/fsr_0603.pdf`.

Table 5: Time series regression results for ΔBCL

	(1)	(2)	(3)	(4)
May 25 2005 - March 31 2008	2.406***	1.704***		0.891**
	(0.284)	(0.230)		(0.307)
T2ratio		-22.380***	-20.822***	-20.254***
		(4.542)	(3.930)	(3.890)
Volume		0.006	0.115***	0.114***
		(0.018)	(0.023)	(0.023)
Jumbo fraction		13.532***	19.141***	18.397***
		(2.736)	(3.140)	(2.667)
Civic holiday		-2.073***	0.432	0.360
		(0.352)	(0.626)	(0.529)
Constant	1.991***	14.923***	8.794**	6.275*
	(0.144)	(4.416)	(3.407)	(3.172)
Year FE	No	No	Yes	Yes
Observations	2726	2615	2615	2615
R^2	0.269	0.384	0.446	0.454

The dependent variable is an aggregate ΔBCL that measures at the daily frequency the difference between beginning of the day and end of the day aggregate BCL provided by all banks to their counterparties during 2003-2013. Volume measures the number of payments processed on this day (in thousands). May 25 2005 - March 31 2008 dummy is 1 during this period. Civic holiday is a dummy variable equal to one if the date falls on a Civic holiday in Canada. Jumbo fraction is the share of jumbo payments in the total payments on this day. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are clustered by year and appear in parentheses.

5 Policy Implications

Despite LVTS's designation as a systemically important system, the nature of the systemic risk of LVTS is not well understood. BoC's framework for assessment of systemic risk in the banking sector in Canada (Gauthier et al., 2012) does not account for LVTS risks that we study in this paper. Basel III guidance for intraday liquidity monitoring tools, adopted by the Canadian Office of the Superintendent of Financial Institutions in 2014, does not address these risks either.[30] Basel III (BCBS April 2013, para 30-36) specifies four stress scenarios that banks should use to assess liquidity risk (i) own financial stress, (ii) counterparty stress, (iii) a customer banks stress, and (iv) market-wide credit or liquidity stress. These stress scenarios do not account for a possibility of rejected or delayed payments due to binding credit or collateral constraints. We argue that a freeze in interbank payment system constitutes systemic risk because of the effect on other clearing and settlement systems.

[30] http://www.osfi-bsif.gc.ca/Eng/Docs/LAR_chpt6.pdf.

We identify a number of stress scenarios that could lead to rejected payments. First, an increase in the counterparty risk should trigger adjustments in BCL provisions. We see these adjustments have started to take place starting the second half of 2005. Second, bank's own risk can push it to reduce BCLs to its counterparties. We see an example of this behavior during the Flash Crash scenario. Moreover, counterparties have incentives to reciprocate to such BCL reduction.[31] Third, in LVTS banks have exposure to a failed bank even if they have not sent/received any payment to/from this counterparty because losses are allocated proportional to BCL provision. That can trigger changes in BCL because there is moral hazard in provision of mutual insurance. We provide some evidence that is consistent with this channel on September 16th 2008, day after Lehman's failure. We also discuss that the spike in rejected payments towards the BoC in 2009 could be driven by the fact that BoC does not have control over BCLs that it provides to other participants.

All these scenarios would not cause if banks can always send payments using collateral. However, we document that 98% of value in LVTS is transferred via credit channel. Sudden transitions from credit-based to collateral-based payments, like the one on September 23 2009, are rare. These sudden transitions are by themselves constitute an important risk scenario not accounted for in Basel III guidance. This scenario is important from the financial stability perspective because banks are not expecting it to happen often. If banks were required to hold excess collateral sufficient to absorb this sudden transitions then it would jeopardize the efficiency benefits of LVTS over RTGS system.[32]

With all the above risk scenarios, a question arises why LVTS has not shown even more severe stress than what we find. One possible answer could be the intervention by the BoC. During the crisis period, the BoC made several changes in qualification of assets that are accepted for collateral in LVTS. These was done as part of a coordinated effort by central banks around the world and not a response to a risk build-up in LVTS. If such build-up existed, as our measures suggest, it stayed unnoticed to regulators (Carney, 2009). Below we discuss the direct interventions by the

[31]Three out of six banks reciprocated during the Flash Crash scenario and reduced BCLs by exactly the same amount.

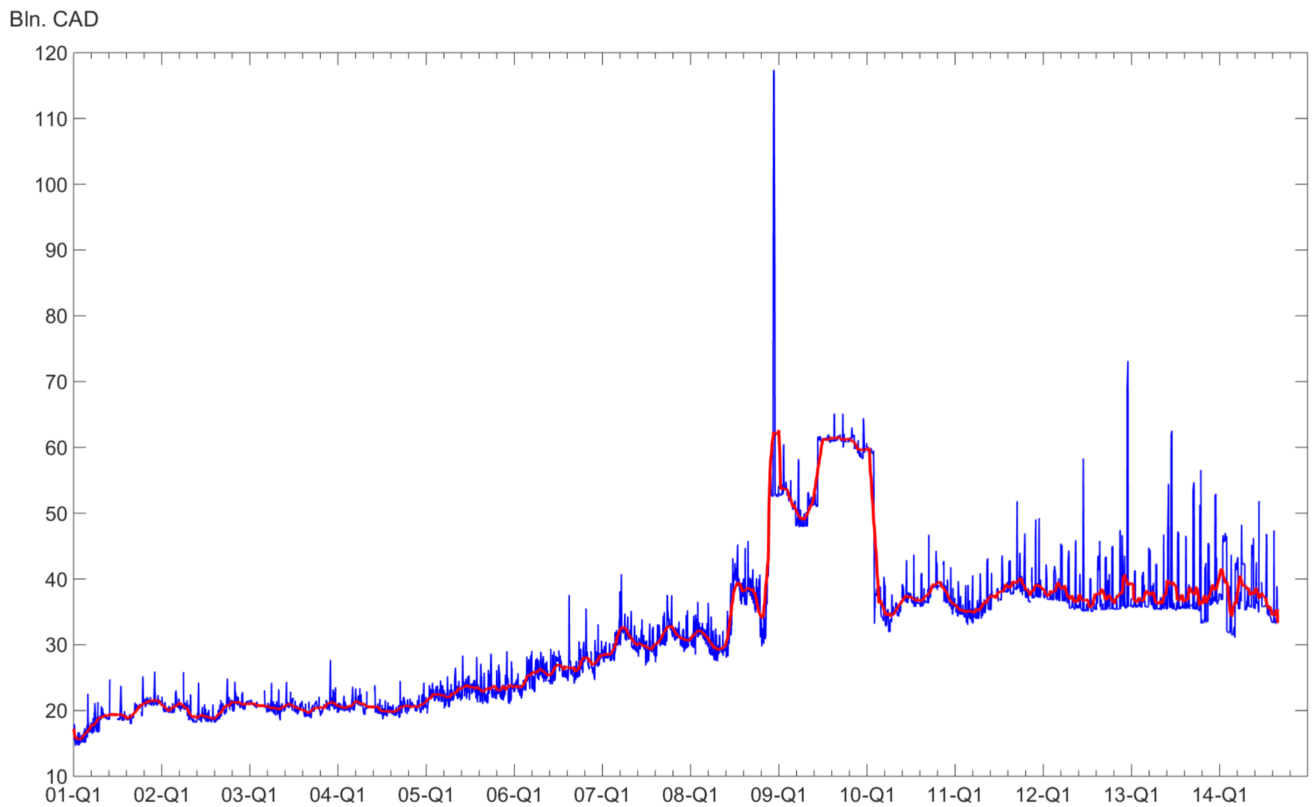
[32]Theoretically, a sudden reduction in BCLs and a transition to collateral-based payments does not need to be a result of a spike in counterparty risk or a transition between two equlibria. It could be a path in a non-stationary equilibrium in provision of credit (Gu et al., 2013).

BoC during the crisis.

In March 2008, the BoC expended the class of acceptable collateral for the first time during the crisis period. For example, the ABCP products were included in the list of the acceptable collateral. interestingly, this corresponds to the decline in the intraday BCLs changes risk measure that spiked in the second half of 2005.

Then in June 2008, the BoC started to accept U.S. Treasuries as a collateral in LVTS. The largest change was in October 2008, when the BoC started to accept all CAD denominated non-mortgage loan portfolios (NMLP). This policy lasted until March 2010. In February 2009, investment-grade corporate bonds entered the list of eligible collateral. Overall, the LVTS system experienced an unprecedented injection of liquidity during the crisis due to BoC intervention.

Figure 10: **Aggregate Amount of Pledged Collateral in LVTS**



The blue line is the aggregate daily value of the pledged collateral in LVTS in billion CAD. The red line is a 30-day moving average.

Above interventions have affected the eligible collateral at LVTS. In Figure 10, we plot the aggregate amount of pledged collateral in LVTS for the whole sample. The average daily collateral is \$29 billion CAD in the whole sample. At the middle of December 2008, this value reached \$117 billion. Without taking a stand on whether the intervention was optimal, we report a significantly smaller number of rejected payments in 2008 than in 2007.[33]

In addition to the injection of liquidity by reducing the quality of the acceptable collateral, the BoC performed a number of other interventions that affected LVTS and its direct participants. During December 2007-July 2008, BoC used purchase and resale agreements (PRAs) to inject liquidity. The PRAs were resumed in September 2008.

Moreover, on May 1st 2008, BoC increased the system wide percentage in LVTS from 24% to 30%. Effectively, It increased the throughput of credit-based payments (Tranche 2) by 25%. In addition, in November 2008 BoC offered a term loan facility for LVTS direct participants that can be secured using NMLP.

While evaluation of the BoC policies during the crisis is beyond the scope of this paper, the fact that our risk measures are all within a normal range after 2009 is consistent with the notion that these interventions helped to address the stress in the system and that without such broad intervention the system's ability to process payments would be jeopardized.[34]

Our research has a number of policy implications. First, we have shown that the high frequency LVTS data exhibited noticeable changes during the crisis period and in advance of the broad scale intervention by the BoC that followed. As such, our opinion is that the LVTS data should be utilized more fully and frequently to identify early indicators of financial stress. This type of analysis can also better equip the regulators and system operator to deal with a flash crash type scenario in the LVTS, triggered by chain events starting with cuts to credit limits. These events are more devastating than slow-moving changes in credit limits because participants and regulators do not have enough time to prepare for the system's transition away from credit-based payments. Second, our research has discovered risk scenarios, which should be integrated in the stress testing

[33]While a low quality collateral increases the risk that the BoC faces in case a default in LVTS happens exactly when the value of the collateral drops, this risk is faced completely by the central bank and not by the participants. This risk is also different from the systemic risk caused by a freeze in the payment system, which is the risk that our risk measures aim to capture.

[34]Bernanke (1990) studies the role played by clearing and settlement systems and of the payment system in US during the stock market crash of October 1987. The crash was more severe because the Fedwire (US RTGS payment system) was shut down during several critical hours on October 20th due to a programming glitch. The paper concludes that "Federal Reserve played a vital role in protecting the integrity of the clearing and settlements system during the crash."

of the LVTS. The scenarios to consider are the tail risks associated with high FRC, reduction of aggregate BCL and impact on participant liquidity due to significant changes in payment flows. Lastly, our research is one of the very few to look into the actual payment system performance during the crisis. This will enable policy makers domestically and globally in assessing their own performance during the crisis and identifying opportunities for improvement.

6 Conclusion

In this paper, we have argued that high-frequency data about payments, collateral, and credit limits in payment systems are useful in measuring systemic risk. These systems transfer annually quadrillions USD of large, time sensitive payments between financial institutions. As such, policy-makers have long recognized that they are critical to the functioning of the economy (Greenspan, 1996). Therefore, these systems are regulated due to their systemically important nature. We argue that using the information about their operations is useful to measure systemic risks.

This comes from the fact that actions taken by direct participants in a large value payments system reflect both their own financial condition (e.g., availability of collateral and utilization of credit limits) and their perception about the conditions of other participants (e.g., provision of credit limits). Besides the high-frequency information about external conditions of the participants, real-time information is produced about the ability of a payment system to process payments. The failure of these systems to perform their fundamental role of payments processing is itself a novel source of systemic risk.

All existing systemic risk measures do not capture this threat due to the high-frequency at which the risk can materialize; despite the threat that a payment systems failure presents for the economy. In this paper, we analyzed the threats that exist in payment systems. We then proposed a set of high-frequency measures to monitor these threats. Finally, we applied these measures a data set that covers half a quadrillion CAD of payments in the Canadian high-value payment system the LVTS.

A payment system cannot process payments if collateral and/or credit constraints are binding. Our measures utilize banks intraday decisions about BCLs, rejected payments due to risk controls violations, and the fraction of payments that are facilitated by bilateral trust as opposed to requiring costly collateral.

The empirical application of our measures shows that, despite the common view, LVTS did experience stress during 2007-2009. In fact, some of our risk indicators increased as early as the second half of 2005 highlighting that they may be useful as early warning signals; although more work is needed to develop this idea.

First, we show that day after Lehmans failure, LVTS experienced large number of rejected payments and delays in payments totaling billions of CAD. To the best of our knowledge, this is the first empirical evidence that Lehmans failure triggered stress in a payment system. Second, we show that over a period of four days in the first half of 2008, LVTS faced a significant stress, which was caused by a multi-billion loss in the US sub-prime market by one of the direct participants. We refer to this episode as a "Flash Crash" because it lasted only several days. Our second-by-second analysis shows that during the Flash Crash, the system experienced multiple reductions in bilateral credit limits, $23 billion CAD of delayed payments of rejected payments and abnormal delays in the intraday payment flows.

Our system-wide measures show a sharp increase in 2007 in the number of rejected payments due to risk control violations. There was also a spike in the number of rejected payments that were sent to the BoC in 2009. In addition, there was one day in 2008 and one day in 2009 when the aggregate ratio of credit-based transactions collapsed. Fortunately, the system recovered the following day and there was no long-term effect on bilateral trust in the system. Maybe the most interesting empirical finding is that banks started to delay intraday provision of BCLs in the second half of 2005. We capture it by looking on the aggregate value of BCLs at the end of the day versus the beginning of the day. The volatility of the intraday BCL provisions increased in the second half of 2005 as well. This increase in volatility is a possible sign of higher uncertainty that was forcing banks to monitor counterparty risk more closely. These two risk measures stayed at the elevated levels until the end of March 2008, when the BoC started to inject liquidity to LVTS. Interestingly, while BoC liquidity injection could have been crucial for LVTS, it was done as part of a coordinated effort by central banks around the world to inject liquidity in response to the financial crisis. With high-frequency measures, such as ours, a response to this payment system stress may have happened sooner.

As several countries, including Canada, are undergoing payment system modernization projects, the efficiency-stability trade-off in the design of payment systems will be of continued high relevance. Our results suggest that it is important to understand vulnerabilities in existing and future payment systems and to monitor them for these vulnerabilities in real-time because the consequence of a payments freeze can be the instigator of another financial crisis.

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7 Online Appendix

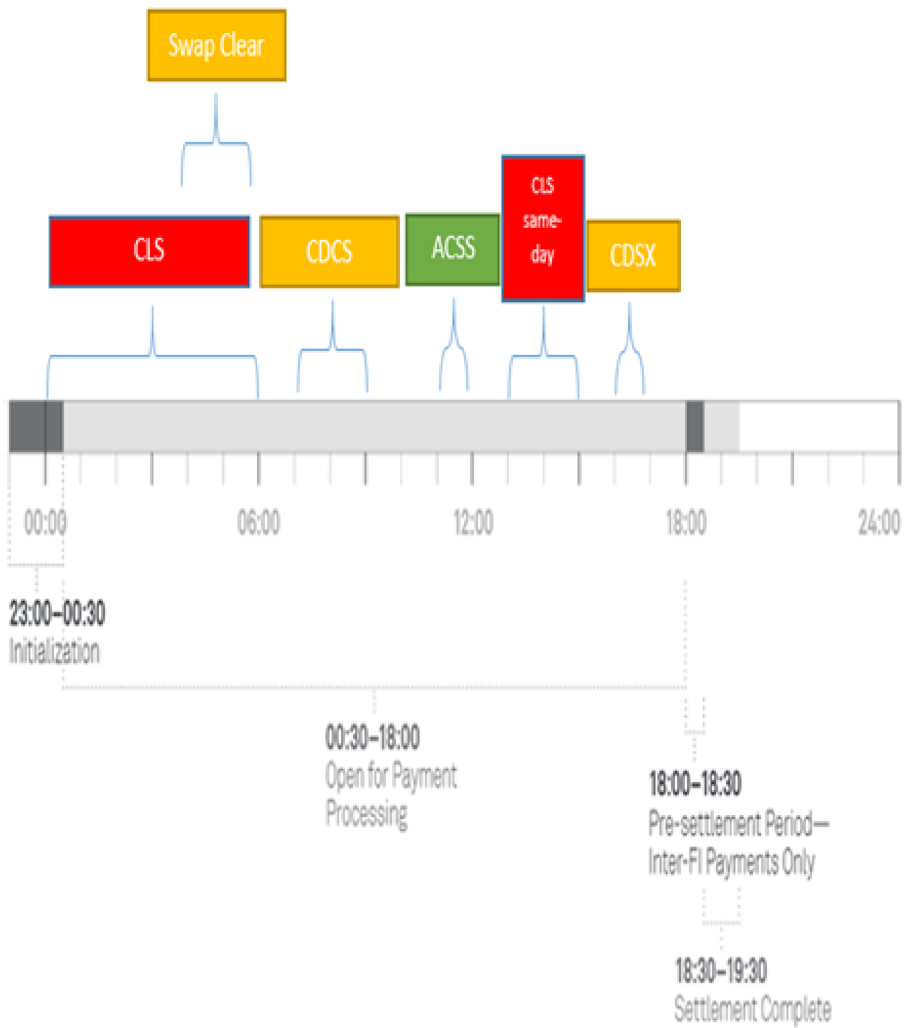
7.1 Additional Tables

Table 6: **Conditional median and maximum number of rejected payments by bank (Jan 2001 - May 2015)**

Bank	Median	Max
Bank A	1	33
Bank B	1	155
Bank C	1	16
Bank D	1	7
Bank E	1	5
Bank F	1	5
Bank G	1	6
Bank H	1	30
Bank I	1	129
Bank J	1	5
Bank K	1	37
Bank L	1	3
Bank M	1	10
Bank N	1	11

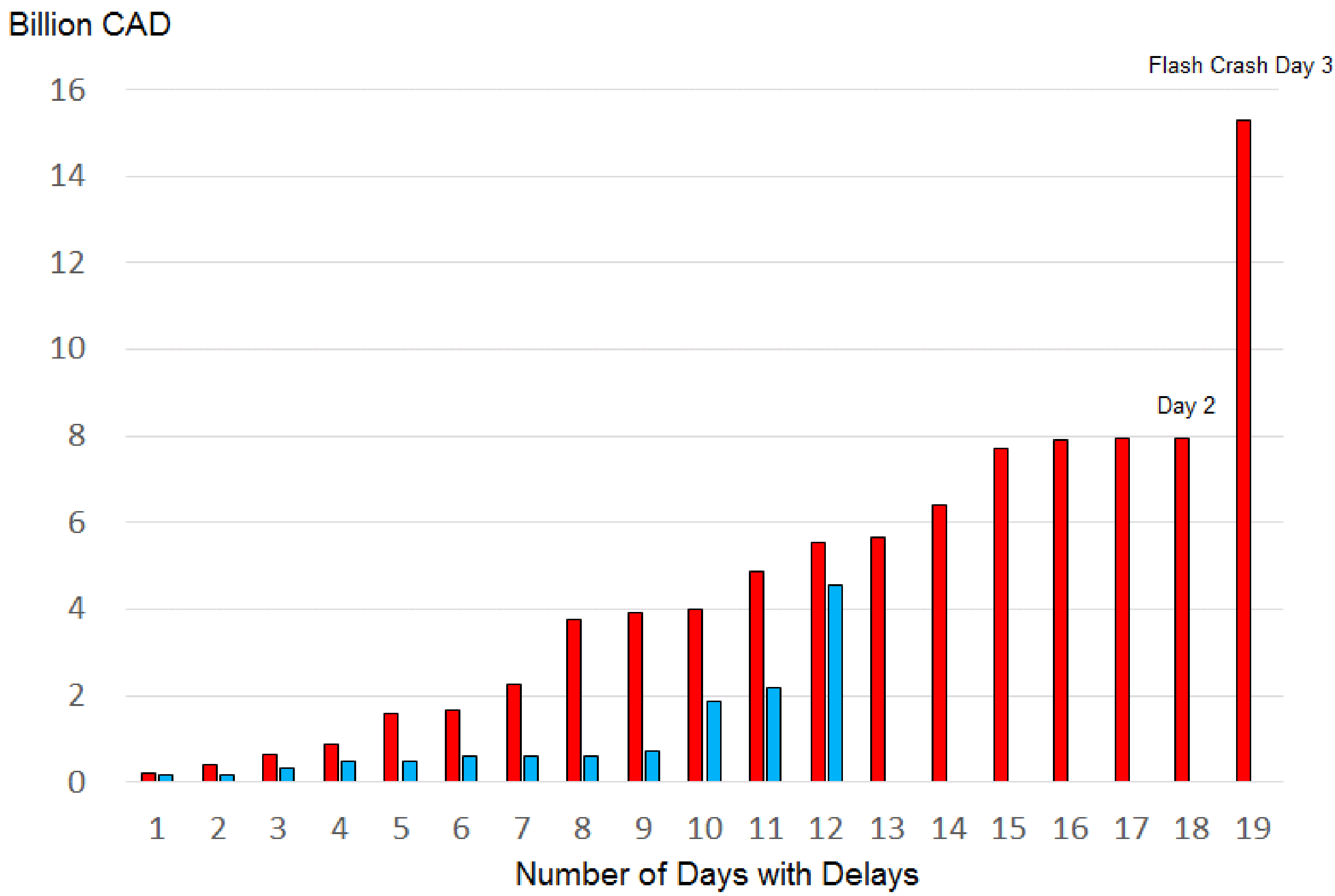
7.2 Additional Figures

Figure 11: Timing of LVTS usage by clearing and settlement systems



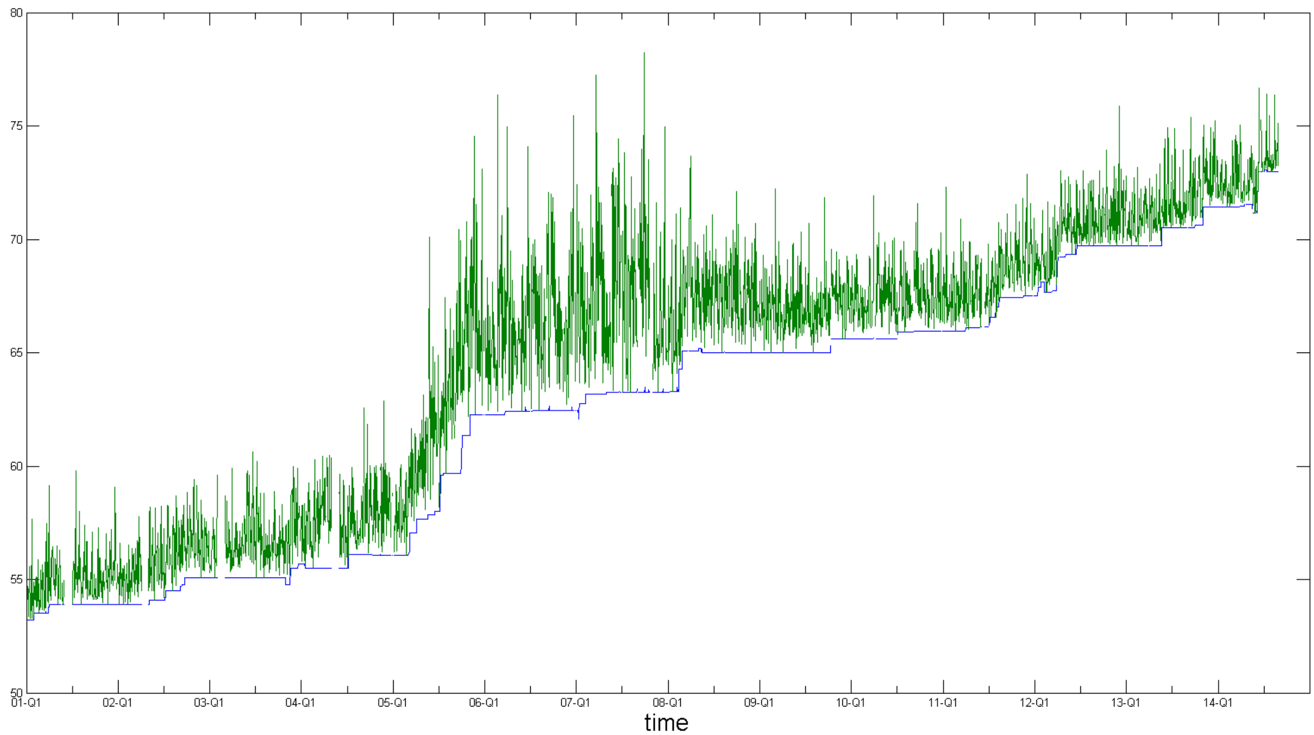
The figure shows time windows when other critical systems rely on LVTS. Delays in payments can result in failure to settle these systems. CLS operates the largest multicurrency cash settlement system. CDCS provides a central counterparty (CCP) service for all equity derivatives, index derivatives, and interest rate derivatives traded on the Montreal Exchange. CDSX clears and settles eligible exchange-traded and over-the-counter equity, debt and money market transactions in Canada. ACSS is Automated Clearing Settlement System for clearing retail payments in Canada. With the exception of ACSS, all these systems are designated as systemically important.

Figure 12: Value of Delayed Payments in the month of the Flash Crash vs same month in 2013



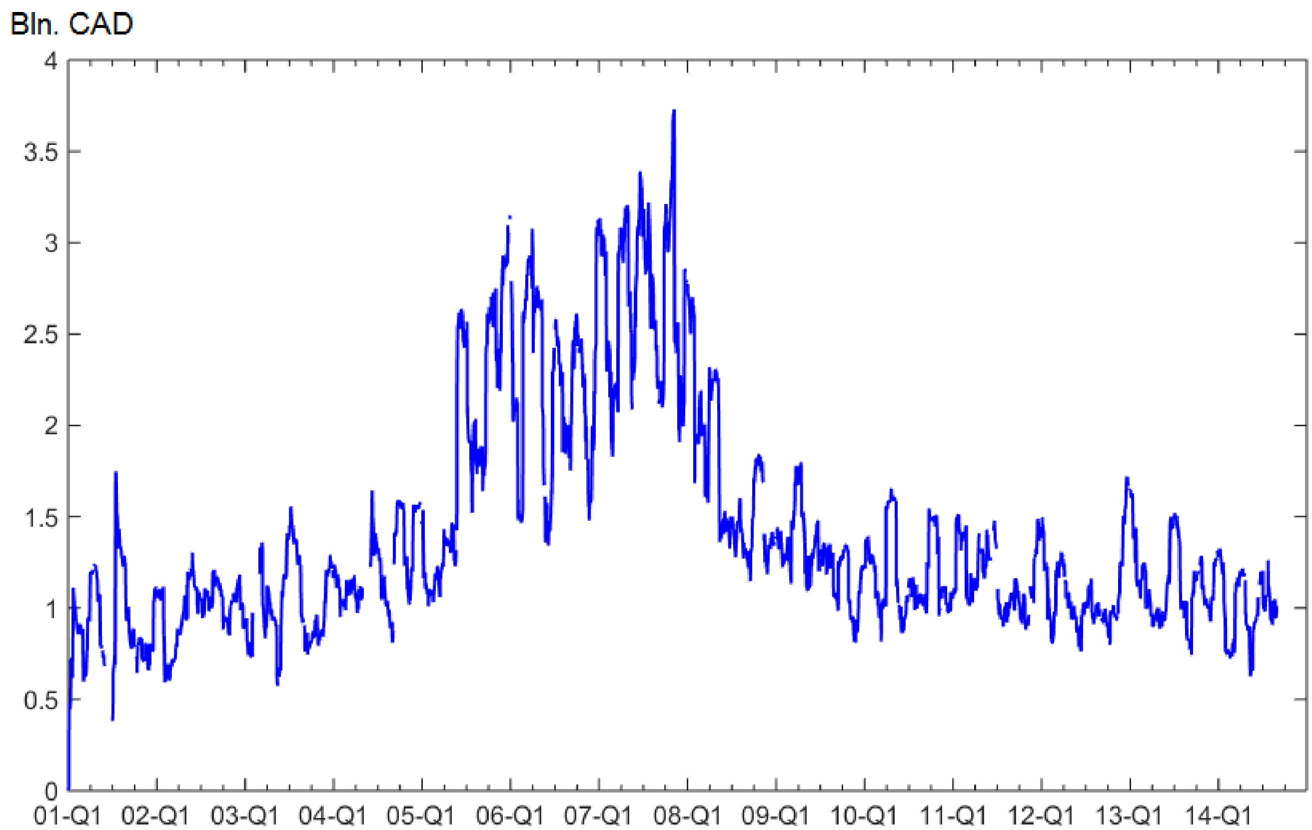
The figure shows that the amount and the value of delayed payments during the Flash Crash was abnormal both comparing to other days during the same month (red bars) and comparing to the delays during the same month in 2013 (blue bars). Day 2 corresponds to the day after a participant announced a multi-billion loss on sub-prime mortgages in US. Day 3 is the following day. All days are sorted by the amount of delayed payments within the same month.

Figure 13: **Cycle and Standing Aggregate BCL**



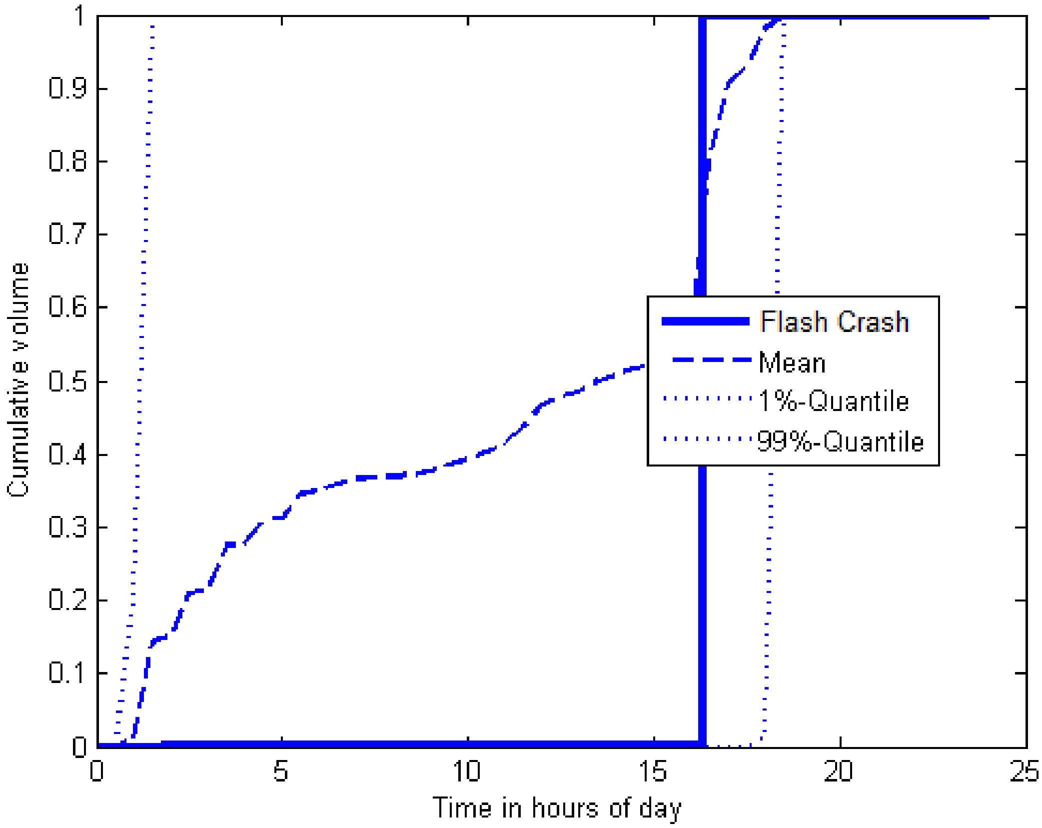
This figure presents aggregate standing BCL at the beginning of the day (blue) and aggregate cycle BCL at the end of the day (green) measured in billions of CAD at daily frequency between January, 2001 and August 2014.

Figure 14: **Volatility of Intraday BCL Adjustments**



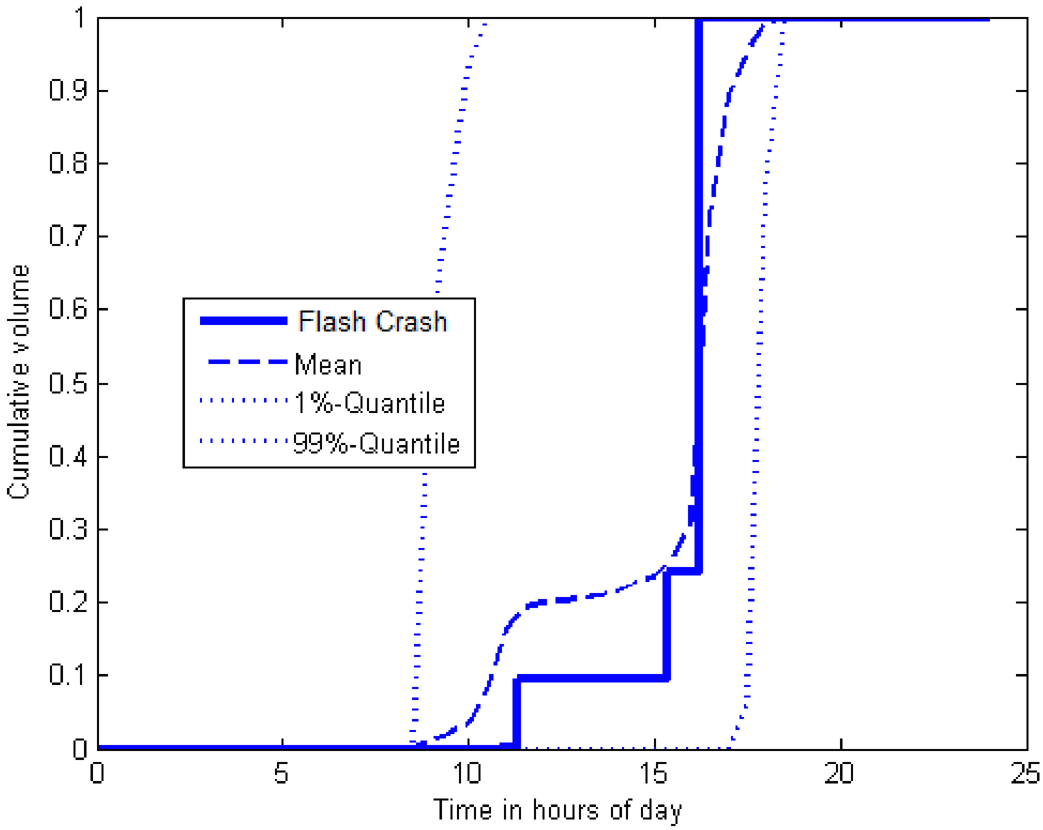
This figure plots 30-days rolling standard deviation of ΔBCL for Jan. 2001 - Aug. 2014.

Figure 15: Typical daily Tranche 1 payments flow of Bank A compared to its payments flow during the Flash Crash



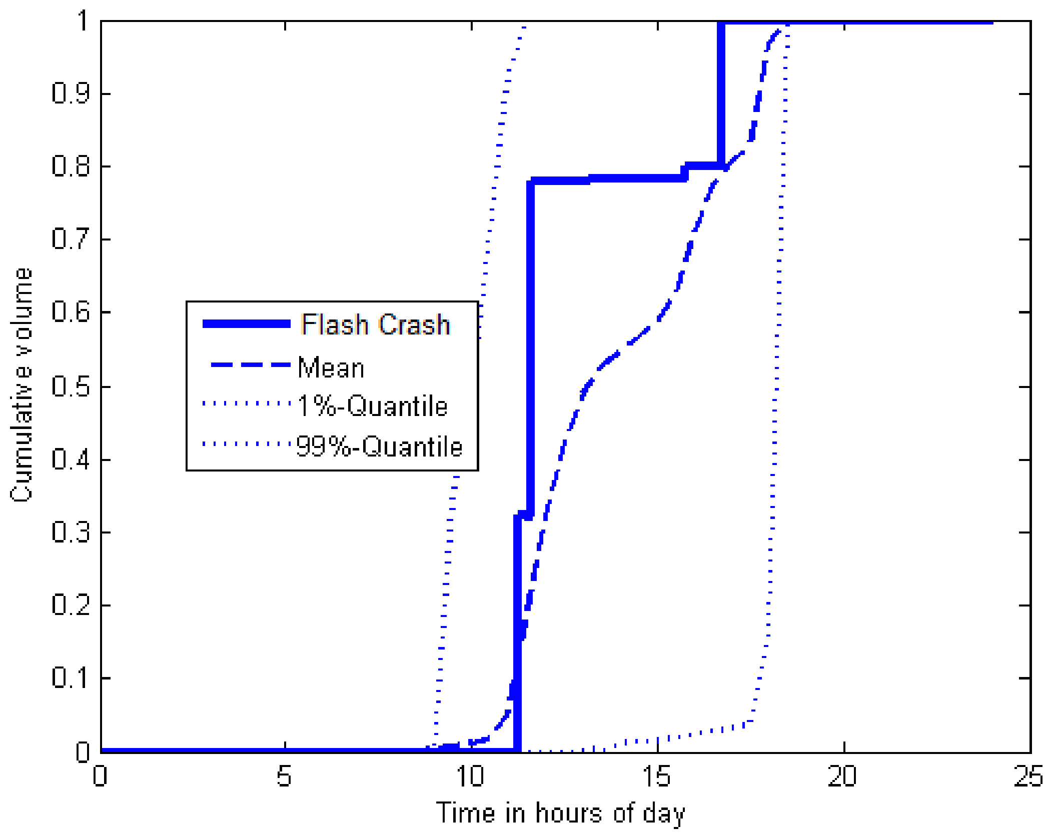
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank A. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The figure shows for most part of the day during the Flash Crash, Bank A was well below its average payments flow.

Figure 16: Typical daily Tranche 1 payments flow of Bank C compared to its payments flow during the Flash Crash



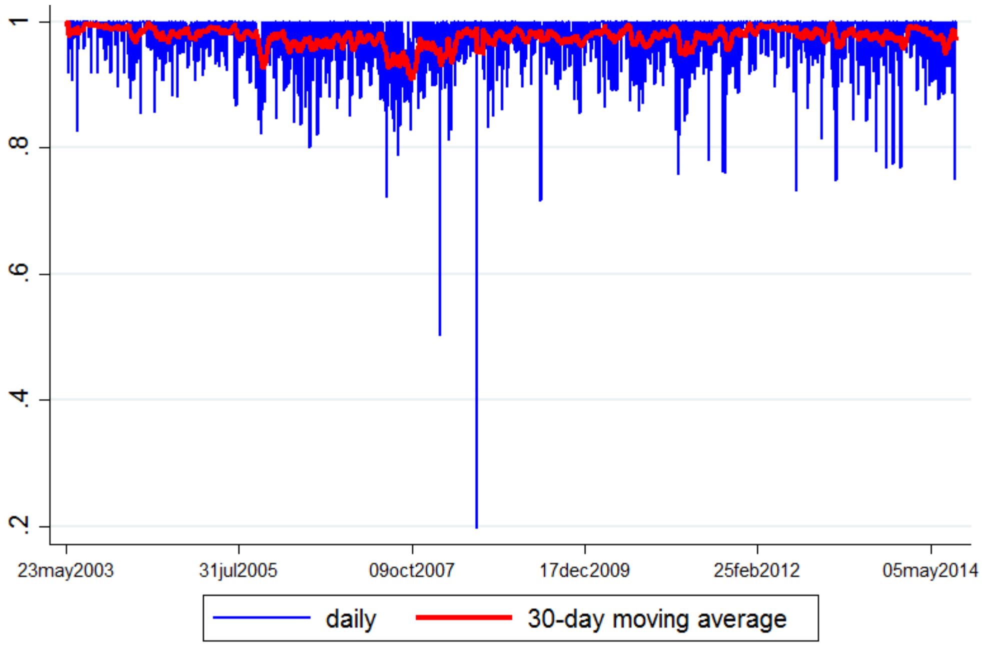
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank C. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The figure shows for most part of the day during the Flash Crash, Bank C was well below its average payments flow.

Figure 17: Typical daily Tranche 1 payments flow of Bank J compared to its payments flow during the Flash Crash



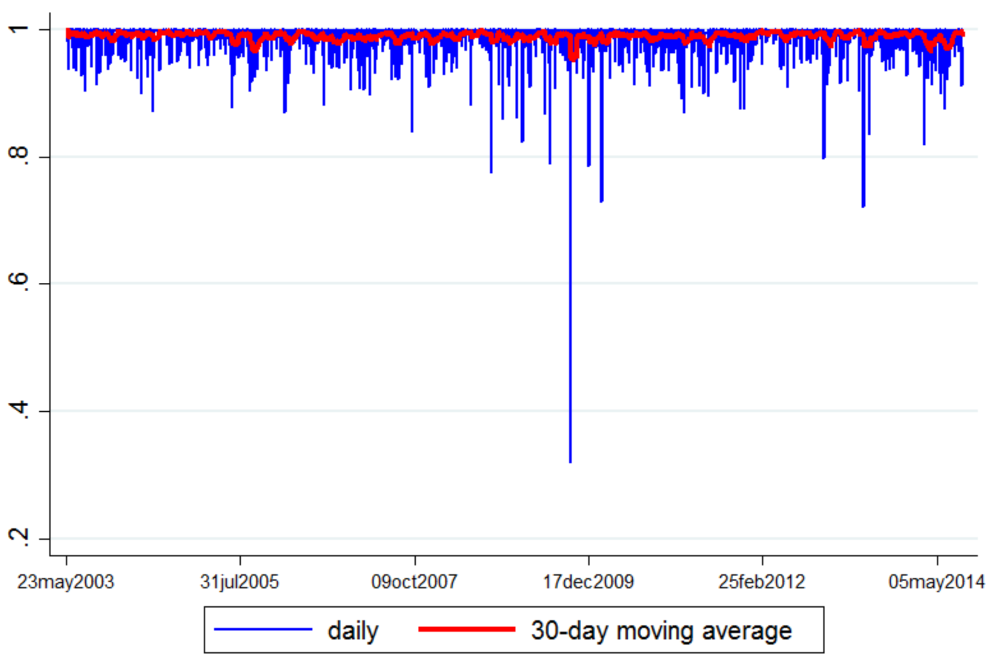
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank J. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The figure shows for example that during the Flash Crash, the total value of Tranche 1 payments sent by Bank J by late morning was well in excess of the average value.

Figure 18: $T2ratio$ **for Bank 1)**



This figures plots the $T2ratio$ (the fraction of credit-based payments that use Tranche 2) for bank 1 between January 2003 and August 2014. The red line is a 30-day moving average of the daily $T2ratio$. We exclude payments to the BoC for this calculation.

Figure 19: $T2ratio_i$ **for Bank 2)**



This figures plots the $T2ratio$ (the fraction of credit-based payments that use Tranche 2) for bank 2 between January 2003 and August 2014. The red line is a 30-day moving average of the daily $T2ratio$. We exclude payments to the BoC for this calculation.