High-Frequency Analysis of Financial Stability*

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Abstract

We study empirically efficiency and stability trade off in the design of large value payment systems using $500 trillion CAD of intraday transaction level data from Canadian Large Value Transfer System (LVTS). We develop measures of systemic risk and apply these measures to millions of LVTS payments during 2001-2014. LVTS showed stress during 2007-2009. The main source of fragility of the system are binding collateral and credit constraints that cause delays and rejections of payments. Unprecedented injection of liquidity by the Bank of Canada prevented a spillover of systemic risk to global systemically important payment and settlement systems.

Keywords: large value payment systems, financial stability, financial crisis, systemic risk, collateral constraints, credit constraints, Lehman's failure

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1 Introduction

Since the recent financial crisis, measuring systemic risk has become one of the main priorities in financial regulation. We develop new measures of systemic risk that utilize high-frequency data from large-value transfer systems. The measures utilize second-by-second information about bilateral credit limits (BCLs) and collateral constraints faced by participants in the payment systems. Collateral and credit limits are used to manage a risk of contagion caused by failure of one of the participants. Our main contribution is twofold. First, we argue that BCLs and collateral constraints in payment systems provide valuable information about the health of the financial system. Our systemic risk measures spike during 2007-2009, some starting to increase already in the second half of 2005. Second, we argue that a fragility exists in a financial system because of endogenous credit limits can be reduced for non-fundamental reasons. If banks cannot utilize BCLs, critical time-sensitive payments would be delayed or rejected. Failure of a payment system to process payments can cause contagion in other clearing and settlement systems that process daily transactions measured in trillions USD.[1] Because of the interconnectedness between a payment system and other systemically important clearing and settlement systems, risk in a payment system is systemic.[2] We apply our measures to \$500 trillion of payments in Canada's LVTS and find that, contrary to the current view, the payment system was under a significant stress in 2007-2009 and that some critical payments were rejected because of binding credit and/or collateral constraints faced by some of the largest financial institutions in the world.

To understand the risk of a payment system to stop processing critical payments, we need to understand the economic mechanism in the core of these systems. The goal of payment systems is to transfer large value, time-sensitive funds between financial institutions. These transfers involve all non-cash transactions (e.g. interbank loans, FX derivatives, exchange-traded securities, commercial transactions) that cannot be settled within a financial institution. The total value of payments settled by payment systems around the world totaled more than \$3.1 quadrillion USD in 2009.[3] LVTS in Canada is one of the largest large-value transfer systems in the world, with \$3.5 trillion Canadian dollars (CAD) of interbank payments in July 2016.[4]

[1]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`.

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

[3]See Table II.3 in The World Bank's "Payment Systems Worldwide: A Snapshot". The total value includes 111 countries with real-time gross settlement payment systems that were operations in 2009.

[4]Source: `https://payments.ca/about-us/our-systems/large-value-transfer-system/statistics/`.

LVTS participants adjust BCLs and collateral levels at second-by-second frequency. The role of the BCLs is to control interbank exposures to the risk that a sender of a payment fails to settle its net positions at the settlement time. The role of the collateral is to facilitate payments when banks cannot sent payments by utilizing BCLs granted to them by counterparties. If BCLs are all set to zero, then collateral is the only option to send payments. Even if BCLs are positive, they can be binding in some states of the world. Binding collateral constraints and BCLs reveal information about financial constraints of the participants, their counterparty risk and ability of a payment system to process payments. We use this information to infer about the health of the financial system in general and of the payment system in particular.

Mark Carney, the former governor of the Bank of Canada (BoC) said in March 2009 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. First, we validate our measures by showing that on the day when Lehman filed for bankruptcy and on the following day, LVTS experienced high number of rejected and delayed payments because of binding collateral or credit constraints of the participants. The fact that credit constraints were binding is a sign of high financial risk, but it is not a sign that the system is not functioning correctly because banks are expected to control counterparty risk by adjusting credit limits (Rochet and Tirole, 1996). In times of high risk, it is not surprising to observe rejected payments due to binding credit limits. However, we show that BCLs can be reduced and payments rejected for non-fundamental reasons. Specifically, we show that in May 2008, the system experienced a large number of rejected and delayed payments, caused by reductions of BCLs. The BCLs were reduced after one LVTS participant faced a multi-billion losses in U.S. sub-prime market. While it would be not surprising to see BCLs cut to this bank by other banks, our high-frequency data allows us to show that the chain reaction of BCLs reductions was initiated by the bank that suffered the loss. This bank cut BCLs to six other banks by 20% because it needed to reduce its exposures following the reduction in its capital. As a result of the BCL cuts, the LVTS experienced a large number of rejected and delayed payments as well as further reductions in BCLs. Given that the original reductions in BCLs were not towards a bank that suffered large losses, we argue that this is an evidence of a liquidity crisis in LVTS that is not driven by counterparty risk.

We identify three types of risks in a payment system: (1) the risk of binding credit limits, (2) the risk of binding collateral constraints, and (3) the risk of a transition from binding credit constraints to binding collateral constraints.[5] Our systemic risk measures capture these three types of risks.

We propose four risk measures. 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 slack in the collateral constraints and/or credit constraints. If the slack is zero, then any further payments are rejected. The third 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 fourth measure is a ratio of credit-based transactions (uncollateralized) relative to all transactions. When this ratio is close to one, it means that most of counterparties trust each other and are willing to bare the counterparty risk. As this ratio approaches zero, it means that there is a loss of trust and that banks transitioned to an equilibrium with only collateral.

To understand the need for collateral and credit limits, we need to understand the efficiency-stability trade-off in different designs of payment systems. On one side, a system needs to process payments at a low cost. On the other side, it needs to be safe. In deferred net settlement systems (DNS) all payments are accepted in real-time, but settled multilaterally based on the net position of each bank at the end of the day. This design makes a system efficient because of the multilateral netting, but it exposes banks to losses if some banks fail to settle. To manage exposures, DNS systems allow each bank to specify BCLs that determine the maximum net deficit that each counterparty can have with this bank. If a bank is not able to settle its net position, the loss is allocated to the surviving banks proportional to the highest credit limit they extended to the failed bank during the day. In addition to BCLs, participants also face a multilateral credit limit (MCL), which requires participants that their net debit position does not exceed some fraction of the aggregate BCLs granted to them.[6] Participants in a DNS system will not be able to send payments if they hit BCL or MCL constraints. Endogenous credit limits introduce fragility to the DNS system because banks can reduce BCLs at any point at time. If many reductions happen over a short period of time, a DNS system will fail to process payments, including critical payments to other systemically important clearing and settlement systems.

[5] Not all payments systems will face all three types of risk, but all three of them are present in LVTS.

[6] In LVTS, this fraction is 30%.

A real-time gross settlement system (RTGS) eliminates the counterparty risk by requiring the sender of a payment to pledge collateral equal to the value of the payment. This design makes a system to be resilient to bank failures, but banks do not benefit from multilateral netting of payments and they are required to use large amounts of collateral.[7] The risk of this system is that participants will face collateral constraints or reserves required for sending critical payments in a timely manner.

The benefit of using LVTS for our empirical analysis is that LVTS is a hybrid system. It was designed in 1999 to benefit from the efficiency of the DNS system and stability of the RTGS system. LVTS allows banks to chose whether to send a payment by pledging collateral (Tranche 1) or utilizing a bilateral credit limits extended to them by other banks (Tranche 2). As the only hybrid payment system, LVTS provides a unique opportunity to study risks associated both with RTGS and DNS features of a payment system. Moreover, given that LVTS can transition from a credit-based equilibrium to a collateral-based equilibrium endogenously, we can assess empirically the risk associated with these transitions.

We find that during 2001-2014, the LVTS retained an extremely high level of efficiency because almost 98% of the transferred value was utilizing credit-limits. However, we also observe instances of sharp declines in the fraction of credit-based transactions. The two worst declines at the system level happened in 2008 and 2009. At the individual bank level, we observe even more pronounced declines during the crisis period. These declines could happen because counterparties were not willing to grant large enough BCLs. Indeed, we document that starting the second half of 2005, banks became reluctant to provide large BCLs at the beginning of the day and preferred rather to adjust BCLs later in the day. This pattern is observed until the end of 2008. While there is a fair amount of intraday adjustments in BCLs, both up and down, it is very rare that banks change the beginning of the day BCL from one day to another.

Financial stability of LVTS is important for global financial stability. First, LVTS facilitates transactions of other systemically important financial systems, such as the CLS, SwapClear, CDCS, and CDSX.[8] When payments are delayed or rejected in LVTS it can cause financial contagion to other global banks via

[7]To improve efficiency of RTGS system, some central banks provide intraday overdrafts that would allow a bank to send payments even without having enough collateral, but these overdrafts expose central banks to default risk.

[8]CLS operates the largest multicurrency cash settlement system. In 2015, it settled on average $1.5 trillion USD of transactions daily. SwapClear provides clearing and compression services for interest rate derivatives. It clears on average $1 trillion USD notional per day. CDCS provides a central counterparty (CCP) service for all equity derivatives, index derivatives, and interest rate derivatives traded on the Montreal Exchange. In 2013, it cleared contracts with notional value of more than $30 trillion CAD. CDSX clears and settles eligible exchange-traded and over-the-counter equity, debt and money market transactions in Canada. In June 2016, it had $1.6 trillion CAD of confirmed trades. Similarly to LVTS, this system relies on intraday credit limits mechanism to control risk.

these systems. Second, liquidity shocks can spread to and from LVTS through international subsidiaries or parent companies of LVTS participants (Chapman and Damar, 2015).

Our paper is most closely related to the literature about systemic risk in payment systems.[9] This literature includes both theoretical and empirical papers. The main focus of the theoretical papers is on the efficiency and stability trade-offs in different system designs. Rochet and Tirole (1996), Freixas and Parigi (1998), and Kahn and Roberds (1998) study risk and efficiency trade-offs in RTGS and DNS systems. The main result is that a gross settlement system is resilient to contagion risk, but makes an extensive use of liquidity, while the net settlement system economizes on liquidity, but exposes banks to contagion. Temzelides and Williamson (2001) find that the payments system will work more efficiently if credit contracts and insurance contracts are an integral part of the relationship among the participants. Lester (2009) uses a general equilibrium model to study the frequency of interbank settlements. In his paper, more frequent settlements reduce risk, but are less efficient. Chakravorti (2000) studies how to minimize risk in a DNS system. Our approach to risk is different. Our measures assess to what extend a payment system is financially constrained to process payments. These constraints may not generate cascades of defaults in a payment system, but they affect other financial and real transactions in the economy.

The risk associated with binding collateral constraints or credit constraints has a strong theoretical foundation. Kiyotaki and Moore (1997) show how an economy can transition from non-binding collateral constraints to binding collateral constraints and that this transition can have a long-lasting effects on the economic activity. Kehoe and Levine (1993) model an economy without collateral, but with endogenous credit limits. Gu et al. (2013) show that this type of economy can have a non-stationary equilibrium with chaotic dynamics of credit limits that are not driven by fundamentals, but rather by beliefs about the future extensions of credit limits. If credit limits in a payment system are binding for non-fundamental reasons and/or banks do not have enough collateral, then payment system's capacity to process payments will be reduced, causing rejected payments and delays. We interpret these risk scenarios as a realization of a systemic risk.

We also contribute to the empirical literature that studies payment systems. The main focus of the empirical literature about systemic risk in payment networks has been mainly concerned with contagion effects of failure of a participant (Zhang and Hossfeld, 2010; Angelini et al., 1996). Our paper contributes to this literature by focusing on the risk that payments are rejected or delayed because of binding collateral

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

or credit constraints. Craig and Fecht (2011) study what drives banks decision to use European RTGS or DNS systems when they have access to both. For the period between January 2000 and September 2007, they do not find any evidence that access to both systems has a destabilizing substitution effect in their sample. They do find that higher transaction volume in the RTGS system leads to a rise in money market rates, while higher volume in the DNS system increases credit risk premium in the interbank loans market. Craig et al. (2015) use delays in the European RTGS system (TARGET2), to study whether some banks are involved in a strategic behavior of free riding on a liquidity provision of other banks. This paper is similar to our paper as it uses transaction-level data on payments, but it does not focus on systemic risk measures and does not study the fragility caused by endogenous credit limits.

Our paper is not the first to use LVTS data to study systemic risk, but existing studies do not utilize information from the intraday interaction between LVTS participants. Allen et al. (2013) assess the performance of Canadian banks during the financial crisis using LVTS data. They study whether changes in credit default swaps premiums on Canadian banks got reflected in the daily BCL levels. The main conclusion in this paper is that Canadian banks performed quite well during the crisis compared to their international counterparts, and that contrary to the elevated counterparty risk implied by market indicators, such as CDS prices, the BCL levels showed no significant changes during the crisis. This, in the authors' view implies that the LVTS participants did not perceive the counterparty and liquidity risk to be high during the crisis. The authors conclude that the intervention by the BoC during this period may have been overly aggressive and the $114 billion liquidity support provided to financial institutions in Canada during the crisis may have been sustained for too long. Our analysis shows that the LVTS had an elevated level of risk during the 2007-2009 period. Our findings lead us to a different conclusion because we use different measures of risk, such as the number of rejected payments, intraday payment flow and intraday changes in BCLs, while Allen et al. (2013) focus on interday changes in BCLs which are rare.[10] The duration of counterparty risk in LVTS system is measured in hours, not days. Therefore, low frequency measures are not able to track this risk. From a policy perspective, a flash crash in credit limits can trigger a chain of events that is more devastating than slow-moving changes in credit limits because participants and regulators do not have enough time to prepare for an abrupt transition from a credit-based system with a high level of trust to a collateral-based system with no trust. For LVTS this transition can be particularly damaging because banks do not hold as much collateral as they would hold if they knew that all payments need to be backed up by collateral. Embree and Taylor (2015) use

[10]In our sample, there are only 46 declines from one day to another in the beginning of the day BCLs.

LVTS payments from July to December 2013 to determine what amount of collateral would be needed to process these payments if LVTS was a fully collateralized RTGS system. Their findings suggest that some participants would experience collateral savings, while others would need more collateral than what they have pledged under the existing design. Given that the ex-post analysis of collateral requirements does not consider an abrupt and unexpected reduction in BCLs, it underestimates the collateral needed to maintain a normal level of operation in all states of the world. Moreover, for the system to operate normally in this stress scenario, not only the aggregate level of collateral matters, but also whether each participants has sufficient level of collateral to send its payments.[11] If all LVTS participants are required to hold enough excess collateral to be always able to send all the payment without relying on BCLs then LVTS would not provide any efficiency benefits from its multilateral netting.

Allen et al. (2016) make use of the LVTS data covering the period from April, 2004 to April, 2009 to study Canada's overnight interbank market during the crisis period. Their analysis suggests that leading up to the crisis, borrowers and lenders in the overnight market generally have equal bargaining power. However, during the crisis, borrowers experienced an increase in their bargaining power. The authors suggest that this outcome may be due to the LVTS system participants' wanting to shore up the interconnected troubled banks.

Our paper is also related to empirical studies that use LVTS data to better understand the characteristics of the interbank network in Canada.[12] Bech et al. (2010) use the difference between a stationary distribution of payment flows that implied by daily BCLs and the actual daily payment flows to identify which banks delay payments in 2005-2006. While the focus of this paper is on the cross-sectional properties of the delays across banks, our paper focuses on the measures of systemic risk that can identify periods of system-wide stress.

This paper also belongs to the literature that develops measures of systemic risk. This high growing literature came into existence after the recent financial crisis was undetected by the existing risk indicators. Bisias et al. (2012) provide a survey of 31 systemic risk indicators. Acharya et al. (2010) focus on high-frequency marginal expected shortfall (MES) as a systemic risk measure. MES is defined as the expected return of a bank conditional on the market realizing a return in the tail of the empirical distribution.

[11] A similar argument is made by Di Maggio and Tahbaz-Salehi (2015) for non-payment systems. They build a theoretical model to show that financial systems intermediation capacity crucially depends on the distribution of collateralizable assets among financial institution as opposed to their aggregate amount.

[12] For a comprehensive review of this literature see Chapman et al. (2011).

Acharya et al. (2012) calculate capital shortfall of individual institutions conditional on market stress. Adrian and Brunnermeier (2016) propose a systemic risk measure, $\Delta CoVaR$, which is defined as the change in the value at risk of the financial system conditional on an institution being under distress relative to its median state. Brownlees and Engle (2015) introduce SRISK as a measure of bank's contribution to systemic risk. It is based on the capital shortfall of a bank conditional on a severe market decline. All these measures rely on stock market data. Our measures are different along several 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 many investors, our measures aggregate information from a small set of participants in a payment system who 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.

One of our main results is to show that LVTS experienced stress after Lehman's failure. Afonso et al. (2011) find that following Lehman's bankruptcy, risky banks faced higher spreads and borrowed 1% less than usual in the Fed funds market. Copeland et al. (2014) document that the tri-repo market experienced a large decline in short-term collateralized funding during the crisis. The adjustment of the intensive and extensive margins when there is a spike in risk are somewhat expected. We document stress in a payment system during the crisis that is not explained by fundamental increase in a counterparty risk.

The paper is organized as follows. Section 2 provides information about LVTS and how it controls risk using collateral and credit limits. Section 3 provides a detailed methodology used to develop indicators of systemic risk. In section 4, we apply our systemic risk measures to LVTS. We derive policy implications that arise from our analysis in Section 5. Section 6 concludes.

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, even before it started its operation because it was clear that when operational, LVTS will be capable of triggering disruptions and shocks within the financial system, not just domestically but even internationally.[13] The decision to designate the LVTS as systemically important was due in large part to the expectation that (i) it will be processing large value of individual payments (ii) it will process significant value of aggregate payments on a daily basis (iii) participants will require significant resources to support LVTS payments and (iv) the LVTS will interact with other major clearing and settlement systems (Goodlet, 2001).

Our data includes bilateral payment flows between LVTS participants, BCLs, pledged collateral, and rejected payments. Most of the data are 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 more than $500 trillion CAD. For rejected payments, we have data up to May 2015. LVTS participants during our sample include the six largest Canadian banks, four subsidiaries of global financial institutions, four regional financial institutions, and the BoC.[14] For convenience, we refer to all private participants as banks. 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.[15]. The regional financial institutions are much smaller than the big six banks, with total assets of $112 billion in 2015.[16] All other financial institutions send and receive large value payments in Canada by using intermediation services of one of the LVTS participants.

We use high-frequency LVTS data which is generated and maintained by the Canadian payments Association (CPA). 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 is time-stamped giving 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

[13]The Governor of the Bank of Canada at the time, Gordon Thiessen, sent a notice to the CPA on January 19, 1999 notifying that the LVTS will be designated under Section 4 of the *Payment Clearing and Settlement Act.*

[14]We exclude payment flows to and from the BoC in our analysis. We also exclude from the sample two participants who joined LVTS after the financial crisis period.

[15]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.

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

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 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 grid lock 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.[17] 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.[18] 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

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

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

required to grant BCL to other participants and hence each participant has the ability to force all others to send it payments using 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

For our measures, we use data on rejected payments, changes in standing BCL, and intraday payment flows. Below we discuss each of the measures in more details. We explain these measures using LVTS as an example because LVTS is a hybrid system that encompasses both RTGS and DNS payment systems.

3.1 Tightness of Collateral and Credit Constraints

Our systemic risk measures capture how constrained each bank and the system as a whole. When constraints start to bind, it means that the throughput of the payment is reduced. Inability to send payments imposes a systemic risk because of the time-sensitive nature of the payments processed by a large value payment systems and because of the dependence of other clearing and settlement systems on a payment system.

The first constraint is on the net debit position in collateralized payments:

$$T1RISK_t(i) \equiv T1C_t(i) - \sum_{j=1}^{n-1} (P_t(i,j,1) - P_t(j,i,1)) \geq 0 \tag{1}$$

- $T1C_t(i)$ - collateral apportioned by i for Tranche 1 as of time t.
- $P_t(i,j,k)$ - total payments sent by i to j using Tranche $k = \{1,2\}$ by time t.
- $T1RISK_t(i)$ - measures bank i's slack in collateral constraint at time t.

Equation (1) implies that if a participant has no collateral apportioned to Tranche 1 (T1) payments, the only way for it to send a T1 payment is if the total T1 payment it has received from all other participants exceeds the total that it has sent.

There are two constraints on payments sent via Tranche 2 (T2). The first constraint is between a pair of banks:

$$T2RISK_t(i,j) \equiv BCL_t(j,i) - (P_t(i,j,2) - P_t(j,i,2)) \geq 0 \tag{2}$$

- $BCL_t(j,i)$ - bilateral credit limit granted by j to i as of time t.

- $T2RISK(i,j)_t$ - measures bank i's slack in credit constraint for sending payments to bank j at time t.

The second credit constraint is bank-specific:

$$T2RISK_t(i) \equiv NDC_t(i) - \sum_{j=1}^{n-1} (P_t(i,j,2) - P_t(j,i,2)) \geq 0 \tag{3}$$

where

- $NDC_t(i) = 0.3 \sum_{j=1}^{n-1} BCL_t(j,i)$ - net debit cap limits each bank's max net debit position

- $T2RISK_t(i)$ measures bank i's slack on a credit constraint against all other banks.

We can use $T1RISK_t(i)$ to infer collateral constraints of each bank, while $T2RISK_t(i)$ and $T2RISK_t(i,j)$ proxy for credit constraints of each bank against other banks and against each counterparty.

3.2 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 ratio can be easily computed for Canadian payment system because banks can choose whether to send each transfer using T1 or T2. So the measure is simply $T2ratio = \frac{T2}{T1+T2}$, where T1 (T2) here stands for the total value of payments sent using Tranche 1 (Tranche 2).

To compute this ratio for other countries requires combining data from RTGS and DNS systems. Moreover, this measure can be applied to the financial system as a whole. With access to the relevant data, the ratio is computed as the aggregate value of all uncollateralized transactions (e.g. Fed funds) divided by the the value of all collateralized interbank loans (e.g. repo contracts) and uncollateralized transactions.

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. 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.

3.3 Rejected and Delayed Payments

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

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 sign of stress. However, stress can be present because the constraints are very tight, even if they are not violated. That is why the rejected payments measure combined with the tightness of the constraints provide a better picture of systemic risk. 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 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. A delay in LVTS can cause failures in settlement of these systems.

3.4 Bilateral Credit Limits

DNS systems provide a unique opportunity to infer participant's credit risk conditions based on BCLs extended to it by all other participants.

Using standing BCL data both at an aggregate and participant-by-participant levels, we identify day(s) where a participant or a collection of participants reduced the beginning of the day or intraday

BCL to another participant. Such reductions can signify spikes in the counterparty risk. Moreover, it is possible to infer increased risk if banks are not willing to increase a BCL to a counterparty even when this counterparty approaches credit limit constraints. Moreover, it is possible that a bank reduces BCL to counterparties not because their risk increases, but because the grantor of BCLs experiences stress and needs to reduce its risk exposure to others.

In times of low counterparty risk, we do not expect banks to update BCLs frequently. It is enough for them to set a sufficiently large BCL in the morning and keep constant during the day. However, in times of high uncertainty, we should expect more frequent adjustments in BCLs. Therefore, the volatility of intraday adjustments in BCLs can be used an indirect measure of systemic risk. Formally, we define the difference between the end of the day BCLs and the beginning of the day BCLs as $\Delta BCL = \sum\sum BCL_T(i,j) - \sum\sum BCL_0(i,j)$. This difference is computed using all $n(n-1)$ BCLs extended by n banks to $n-1$ counterparties. The standard deviation of ΔBCL over a window shows the level of uncertainty this period.

4 Application of the Systemic Risk Measures to LVTS

Using the data and methodology described in the previous sections, we apply our measures to LVTS in this section. It allows us to validate the measures and to take a closer look at how the LVTS performed before, during and after the crisis.

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, it allows us to validate that our risk measures indeed capture counterparty risk and are sensitive to the stress in the financial system. Second, we want to study whether Lehman's failure affected a payment system.

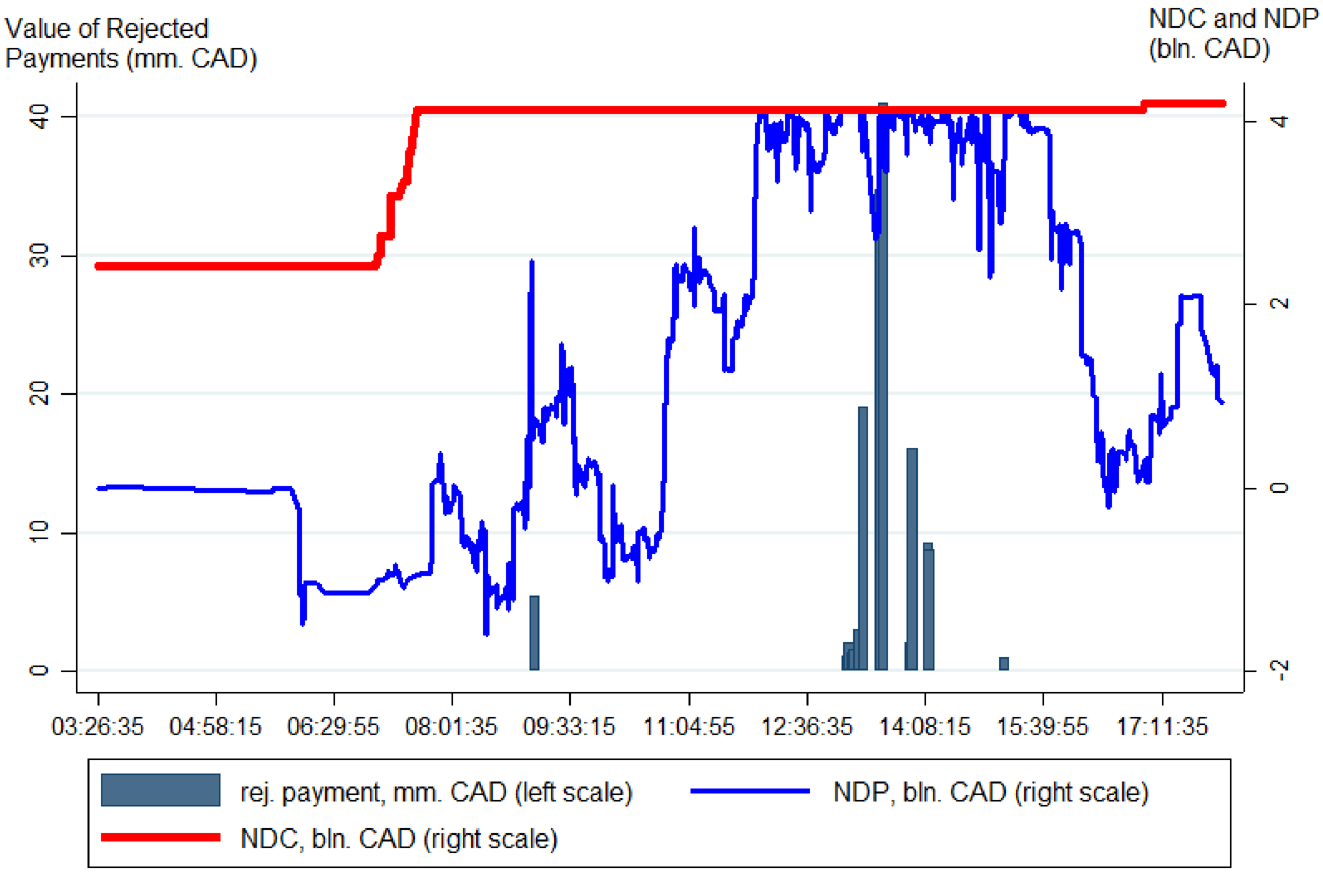
We find that our measures do capture risk on the day of Lehman's failure and the following day. On September 15, 2008 at 8:06am, Bank H's four payments with a total value of $160 million CAD to three other banks are rejected because of violation of risk controls.[19] Then at 11:20am, a T1 payment of $324 million CAD sent by Bank I is queued because of the binding collateral constraint and settled with delay. This was the only delayed T1 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 it 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, September 16th, 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 violation of a credit limit with one counterparty. Other rejections took place after 3:10pm because of violations of multilateral credit limits. 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. This slack is captured by our risk measure $T2Risk_t(B)$, which is defined in equation 3. 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 there was no elevation in the counterparty risk, other banks would have

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

increased their BCLs to Bank B, as did Bank E later in the day, and it would avoid the rejections.

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.

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. Bank F also experienced binding credit constraints because it had a \$1.7B payment that was settled with a delay at 1:30pm.

On one side, we are the first to show that Lehman's failure caused disruptions not only in financial markets, but also in the most fundamental part of the financial system–the payments system. On the other side, it might not be surprising to observe binding credit limits during this time given that the role of BCLs is to control the counterparty risk, which increased after Lehman's failure. However, there are reasons why these rejections are not a result of an optimal risk management at the system level.

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. As long as banks do not internalize fully other banks' welfare and counterparty risk in their decision to grant a BCL, binding multilateral constraint are not optimal.

Second, the fact that not only T2, but also T1 payments were rejected raises a concern because the system is supposed to be able to process payments using T1, 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 fact that Bank E increased BCL to Bank B, when other banks were refusing to increase BCLs to this bank, could signal that rejected payments were happening for non-fundamental reasons. If Bank E's decision reflects the true level of counterparty risk of Bank B, other banks should have increased their BCLs as well. There are alternative explanations to this increase. A moral hazard explanation would suggest that Bank E is willing to increase its BCL because any potential losses from the failure of Bank B are allocated proportional to BCLs provided by all banks. By increasing the BCL, Bank B is able to receive $200 million more of payments, but would loose only part of that amount if Bank B fails. This explanation would still suggest that BCLs are adjusted in LVTS for non-fundamental reasons. Alternatively, banks could have different views about the level of the counterparty risk. This heterogeneity could explain differences in the BCL cuts across counterparties of Bank B. However, but it is unlikely to explain why one bank would increase a BCL when we know that day after Lehman's failure the risk should not be decreasing. It is also possible that the risk of failure of Bank B dropped significantly from 2pm, when payments were rejected, to 5pm, when the BCL was increased. If that is the case, it provides further justification for using high-frequency risk measures developed in this paper.

Based on the analysis of LVTS during Lehman's failure we reach two main conclusions. First, Lehman's failure allows us to validate our risk measures. Second, 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 Lehman was not a participant in the system. That means that the shock of Lehman's failure propagated to the most critical infrastructure of the financial system.

In the next section we provide a direct evidence for non-fundamental stress in LVTS during the financial crisis.

4.2 Flash Crash in May 2008

Besides days right after Lehman's failure, there are several other days during 2007-2009 when LVTS was under stress. We focus on a particular day in May 2008 because it provides us with an insight about the source of fragility of a systemically important payment system. All three stress indicators; namely, rejected payments, bilateral credit limits and cumulative payments flow, point to high levels of stress on this day. We refer to this episode as Flash Crash because it lasted only several days, and any monthly, quarterly or annual measure of risk would not be able to identify this period of stress.

The trigger for the Flash Crash was a multi-billion USD write-down by Bank A related to US subprime 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 there is a high level of reciprocity in bank decisions to grant BCLs to counterparties. If we were to observe BCL reductions at lower frequency, we could wrongfully conclude that Banks L, C and F were cutting BCLs to Bank A as a result of its write-down that could suggest that it has higher credit risk than what they previously thought. While that explanation would be natural, our high-frequency data allows us to reject this reverse causality because we clearly see that Bank A was the first one to cut credit limits. This behavior helps us to identify a case that BCL reductions can be initiated by the bank that experiences losses and these reductions are done 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 unlikely that Bank A reduced exposures only 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 $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.[20] 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, ten T2 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 T1 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.

To find out if the day following the write-down was unique from intraday payment flows perspective, we analyze the intraday payment flows' data for all LVTS participants. As shown in Figure 2, we find that aggregate T1 payment flows on this day experienced a significant disruption, whereby large value of T1 payments were sent much earlier in the day.

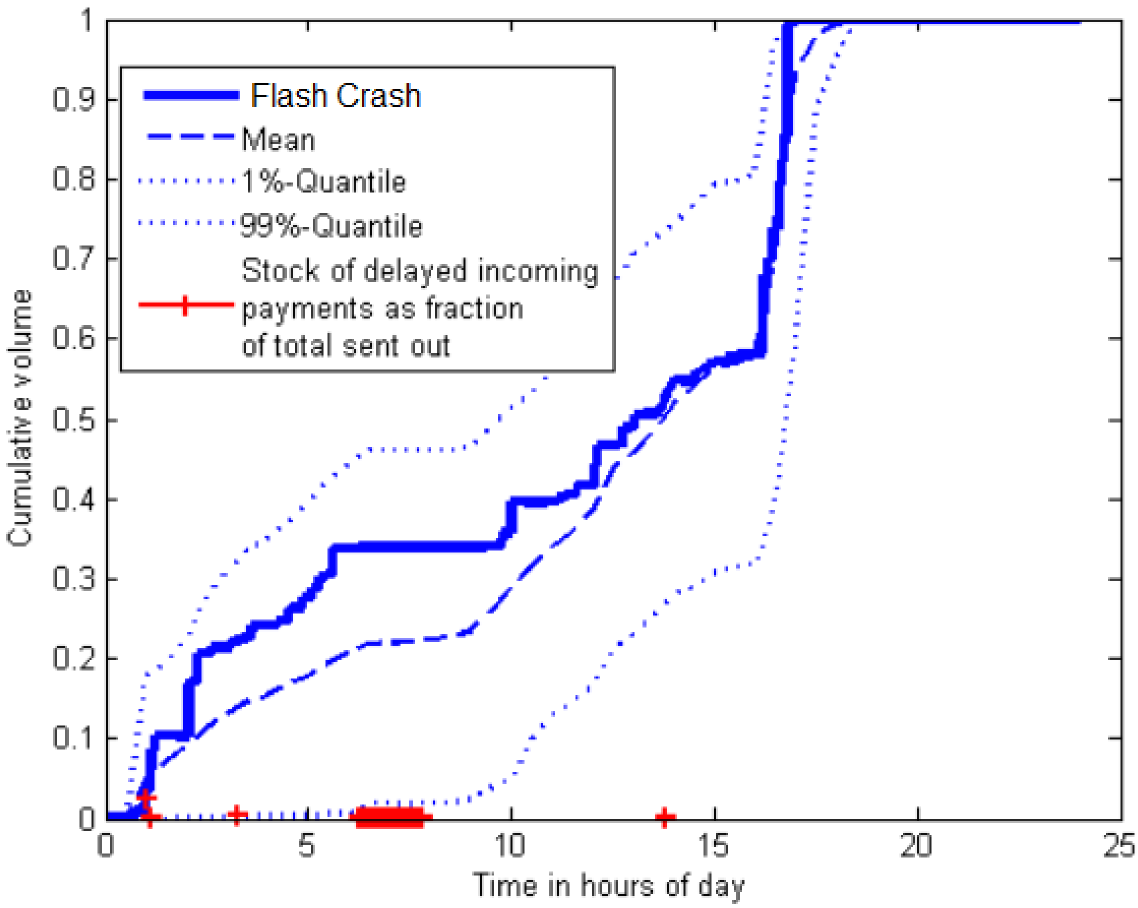
The T1 payment flows were skewed due to the fact that Bank B and Bank I significantly increased their T1 volumes early on in the day (see figures 3 and 4). While we are not certain why these two participants increased their T1 flows significantly earlier on in the day, one hypothesis is that the two 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. We could expect that it to switch sending payments using collateral via Tranche 1. However, according to Figure 5, during the Flash Crash, Bank H significantly changed its T1 (liquidity intensive stream) payment flows and did not send any T1 payments until late afternoon.

The transition from credit-based payments to collateral-based payments is the source of fragility in LVTS. So far we showed that the aggregate T1 payments were sent earlier than usual during the Flash

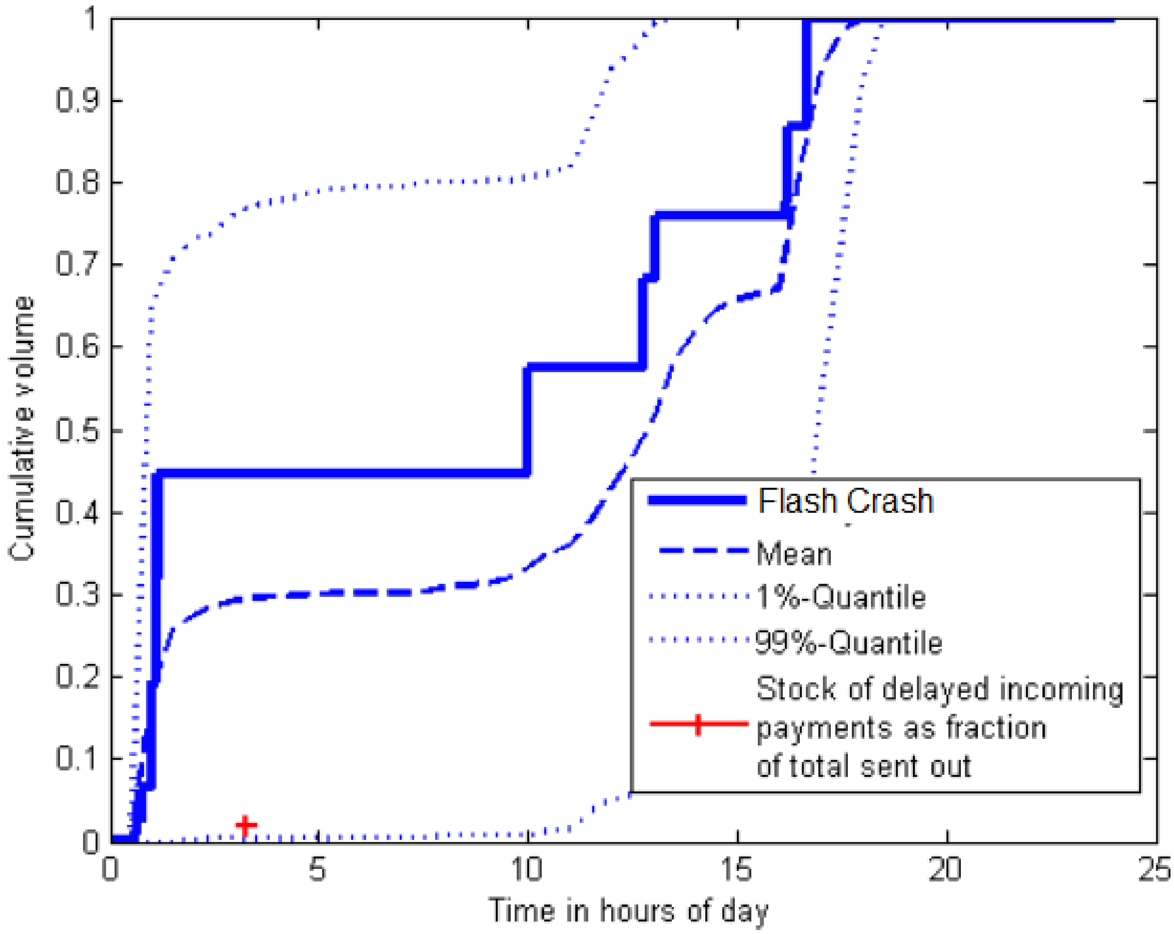
[20]In the LVTS, the Bank of Canada's BCL to a participant is calculated as 5% of the sum of the BCLs established for a participant by all other participants.

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



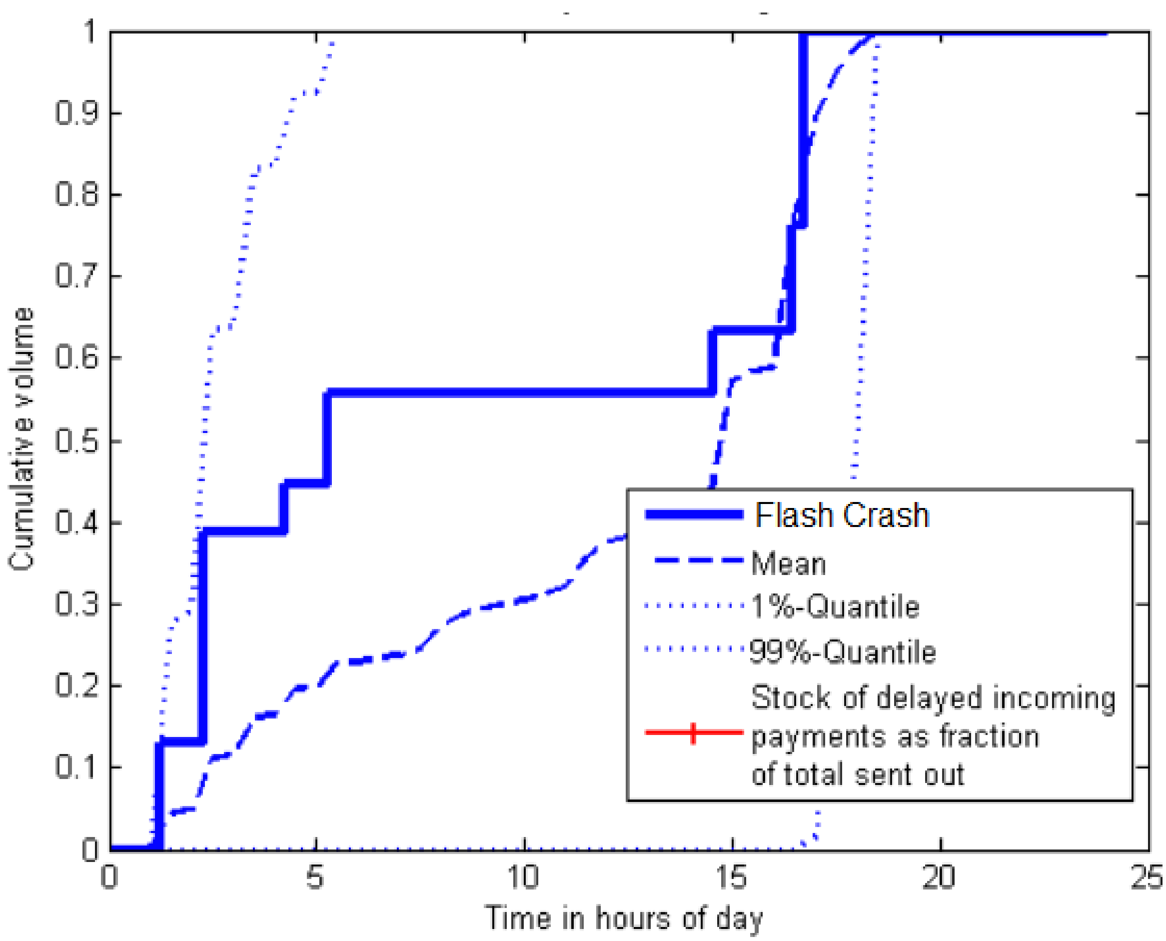
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow in the LVTS based on the empirical distribution between January 1, 2001 and August 30, 2014. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the 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**



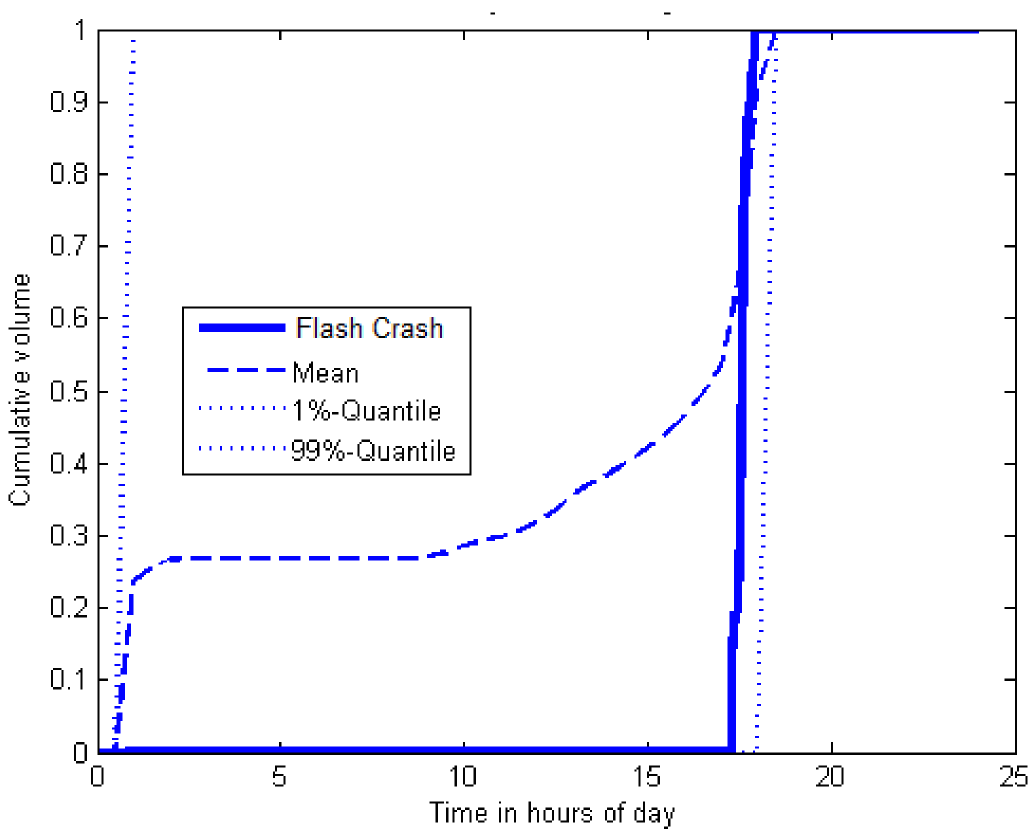
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank B. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The total value of Tranche 1 payments sent by Bank B by 10:00 on the 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.

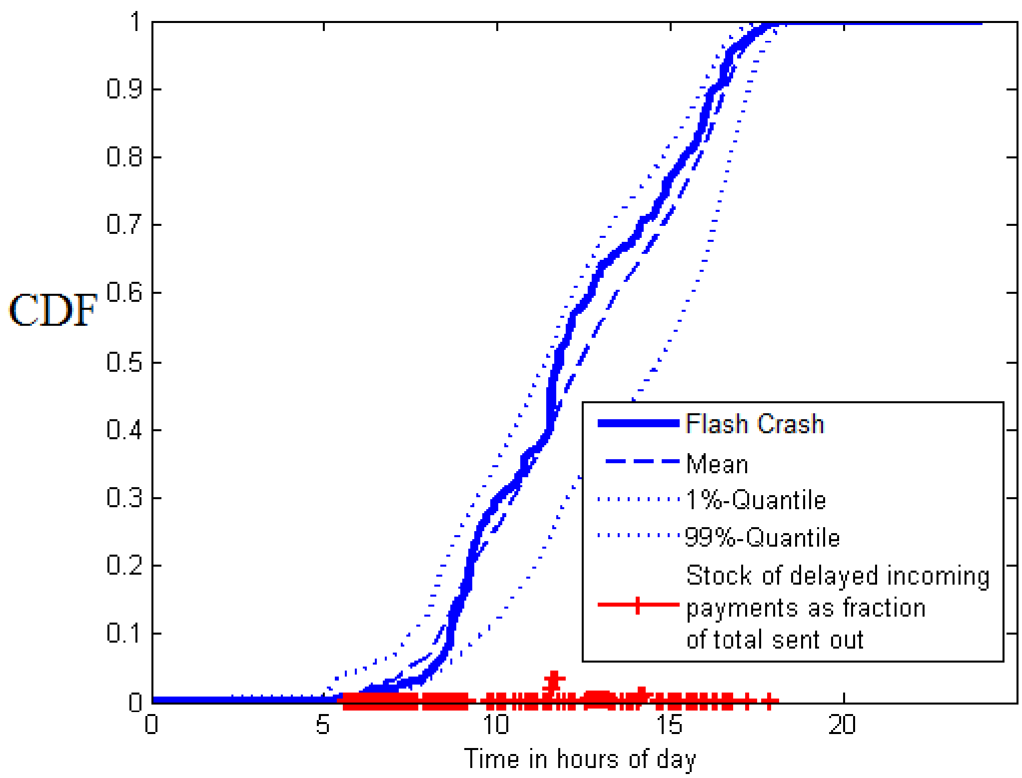
Figure 5: **Typical daily Tranche 1 payments flow of Bank H compared to its payments flow during the Flash Crash**



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.

Crash. Now we show that the T2 payments were sent later than normal during the Flash Crash. Figure 6 shows that at the beginning of the day, the aggregate T2 payments were sent much later than usual. The solid blue line represents the fraction of the value of T2 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, T2 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 28-30 in Appendix, some of the involved banks significantly changed their T1 payment flows on this day whereby they refrained from sending T1 payments until much later in the day.

In light of overlapping evidence of LVTS vulnerability from the three stress indicators; rejected payments, BCL and intraday payment flows, we conclude that there were two days in May 2008 when LVTS was under significant stress. Most importantly, this stress was caused by reductions in BCLs that were not driven by higher counterparty risk. We refer to these reductions as not driven by fundamentals. 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 non-fundamental BCL reductions.

Next, we apply our risk measures to the whole sample.

4.3 Fraction of credit-based payments

Table 1 reports the average volume and value of payments in LVTS.[21] On average, there are 5.4 million payments per year valued at $36 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 because only 16% of payments require collateral.[22] 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 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 value of payments are sent on behalf of the banks who are direct participants in LVTS.

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 almost 98% of value transferred using Tranche 2.

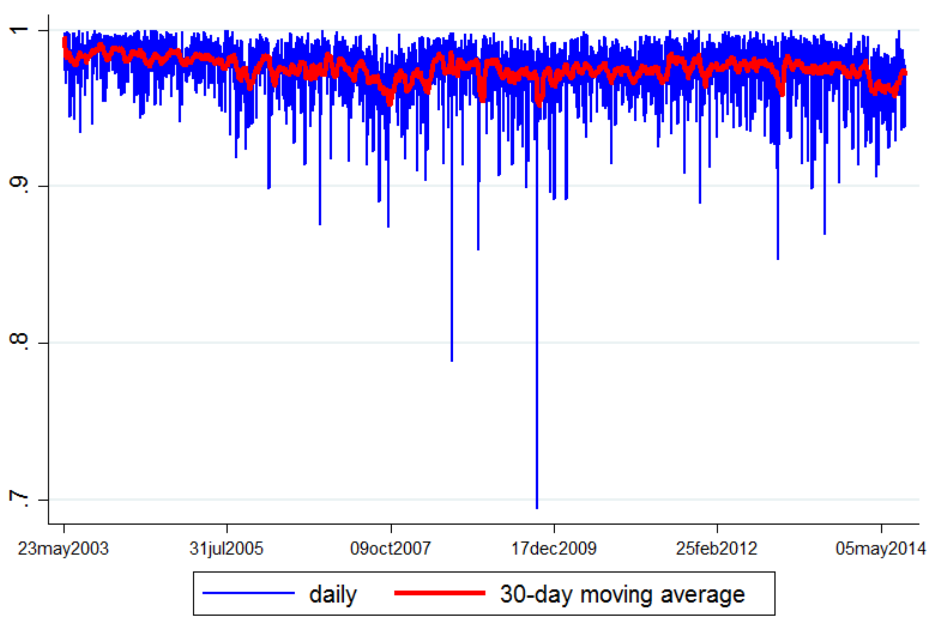
[21] A detailed summary statistics for the latest period (Jan. 2013 to Aug. 2014) appears in Table 5 in the Appendix.

[22] In this table we include also payments sent and received by the BoC. Given that most of transactions between private banks and the BoC are done using collateral, the efficiency of the system for payments between private banks is even higher.

Table 1: **Summary Statistics**

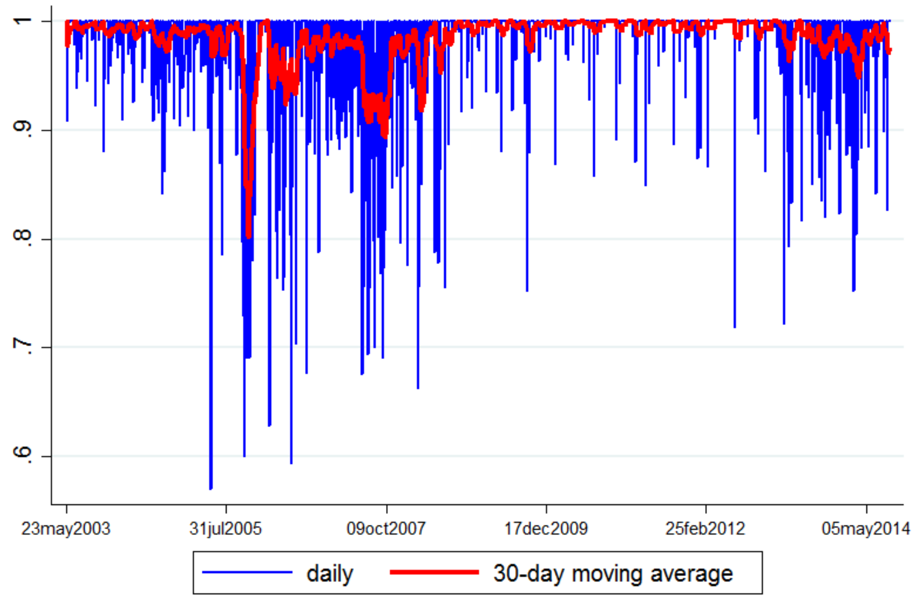
	Mean (2003 - 2013)
Annual volume (million)	5.39
T2, %	98.50
T2 w/o BoC, %	99.87
Jumbo, %	1.55
Non-jumbo, %	98.44
Customer, % ('13-'14)	63.37
Bank, % ('13-'14)	36.63
Annual value (trillion CAD)	35.91
T2, %	84.26
T2 w/o BoC, %	97.56
Jumbo, %	61.86
Non-Jumbo, %	38.13
Customer, % (2013-2014)	22.17
Bank, % (2013-2014)	77.83

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



This figures plots the aggregate value of credit-based payments (T2) to total payments (T1 and T2) 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.

Figure 8: **Bank A's daily fraction of credit-based transactions** ($T2ratio$)



This figures plots the value of credit-based payments (T2) sent by Bank A to total payments (T1 and T2) sent by the bank 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 the BoC for this calculation.

However, there are a number of sharp declines in the fraction of T2 payments during the financial crisis. The largest drop is on September 23, 2009, when the $T2ratio$ is 0.7. The second-largest decline was observed on August 4, 2008, when $T2ratio$ is 0.79. Despite that we see stress in the system during the crisis, we do not see a complete evaporation of trust and a transition to 100% collateral-based payments. It might not be surprising that there was no sharp and prolonged transition to T1 payments during the crisis because the crisis was not centered in Canada. However, it does not mean this transition cannot happen in the future. Monitoring the $T2ratio$ in real time would allow to see this transition happening before banks run out of collateral to process the normal flow of payments.

The same ratio can be also computed at a bank level. In Figure 8, we plot the $T2ratio$ for Bank A. This figure shows that Bank A reduced the fraction of T2 payments during the crisis period and even before it. On some of the days during the crisis period, the bank sent up to 70% using collateral. There were also days in 2005, when the $T2ratio$ for this bank fell to 60%, but these episodes were not as prolonged as the one during the crisis as can be seen from the 30-days moving average calculation of this measure (the red line in the plot). Later, we will try to identify specific events that could have caused the stress experienced by Bank A.

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.[23] 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 9 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 peaked in 2007. The number of rejected payments in 2007 is three times higher than the average annual number of rejected payments pre-crisis. Table 2 provides a detailed

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

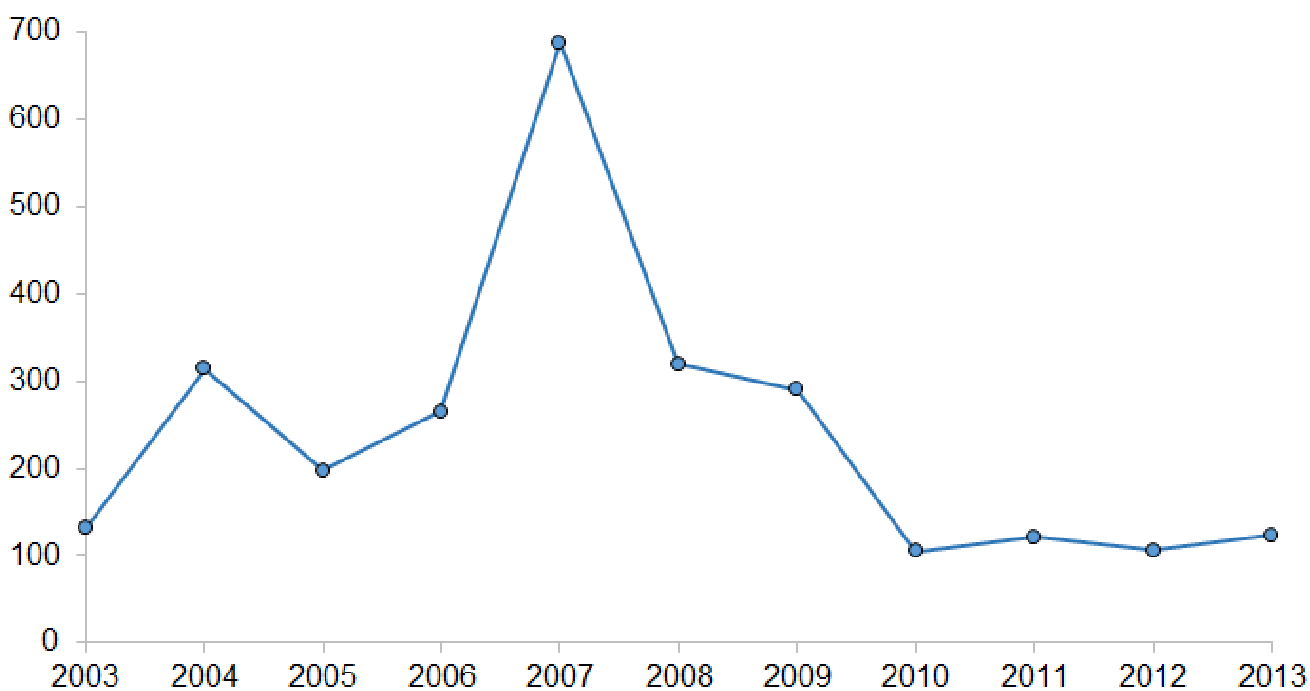
summary about the rejected payments. From this table we learn that both the number of non-Jumbo payments that violated risk controls and the number of Jumbo payments that got first delayed and then rejected spiked in 2007. Most of these payments were rejected due to binding credit constraints. In 2007, LVTS experienced the largest number of both Jumbo and non-Jumbo rejected payments.

Table 2 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 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, T1, T2, Jumbo, non-Jumbo.

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 3 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 T1 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 T1 and T2 payments. While banks can send payments to the BoC using T2, the BCL is not actively managed by the BoC, but is determined by the aggregate BCL provided that each bank receives from other participants. When banks set BCLs, they do not internalize the counterparty risk faced by the BoC. Neither they internalize the welfare losses from binding credit constrains that cause rejected T2 payments to the BoC. Therefore, we conclude that the $45 billion CAD of rejected T2 payments to the BoC in 2003-2013 are unlikely to represent an optimal risk management via BCL adjustments.

Combining results in Table 2 and Table 3 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. At the beginning of the crisis, binding credit constraints were the major reason for rejections. Towards the end of the crisis, the collateral constraints started to be more pronounced, especially when banks needed to send payments to the BoC. Second, our results suggest that sometimes credit constraints are binding for non-fundamental reasons. We can see it especially well when looking on the T2 rejected payments to the BoC. These payments are rejected because of the BCL decisions of other banks because the BoC automatically provides BCL to each participant equal to 5% of the aggregate BCLs granted to this participant. The aggregate BCL does reflect the counterparty risk to some degree, but private banks that determine individual BCLs do it without accounting for the counterparty risk faced by the BoC and for the risks caused by rejected payments to the BoC.

Figure 9: **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. The data in table 4 and FRC distributions shown in figures 14-27 in the Appendix suggest to us that for

Table 2: **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
T1	0	15	16	42	13	11	168	8	10	12	28
T2	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
T1	0	1,424	1,366	2,633	6,595	4,440	5,141	876	1,750	5,658	2,406
T2	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. T1 are payments that were rejected due to violations of collateral constraints. T2 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 3: **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
T1	0	12	10	38	4	5	161	6	7	8	14
T2	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
T1	0	1,307	991	1,999	2,091	677	4,032	790	646	3,497	684
T2	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. T1 are payments that were rejected due to violations of collateral constraints. T2 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: **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

some LVTS participants, the extremely high number of FRC is a very rare event. Such one-time extreme events are difficult to predict 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 10 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 2007-2009, however the increase in the measure started in the second half of 2005. Banks provided up to 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 we report the levels of the aggregate BCL at the beginning of the day (standing BCL) and the end of the day (cycle BCL). The standing BCL is higher in the post-crisis period than during the crisis, but the cycle BCL during the crisis during some days reached the post-crisis BCL levels. We argue that banks were reluctant to provide high standing BCL during the crisis because they were concerned about the counterparty and preferred not the take too much risk at the beginning of the day.

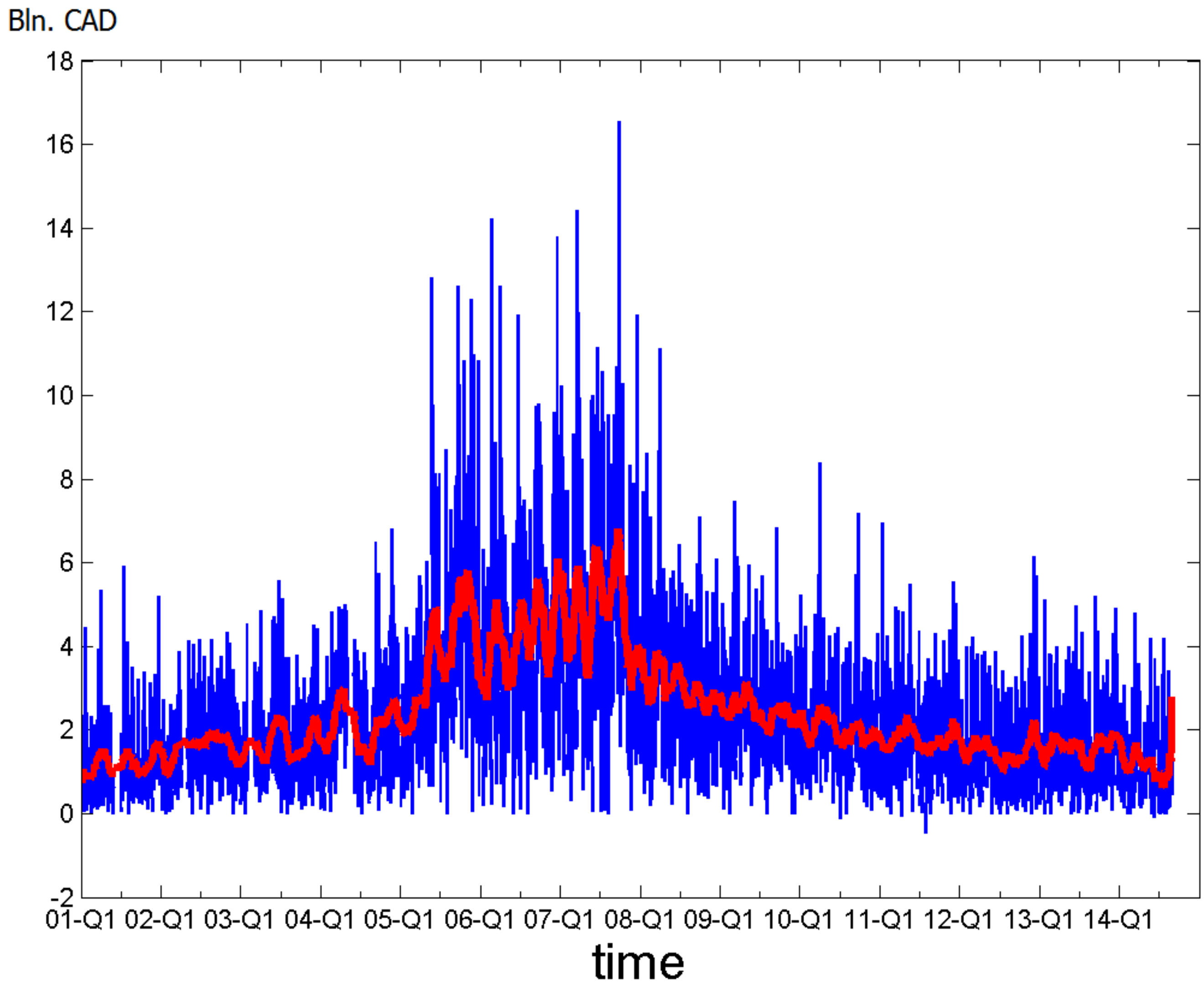
Figure 11 shows the rolling standard deviation of the intraday changes in the BCLs. The highest volatility of ΔBCL is observed during the financial crisis. This measure of risk is going to be low when the difference between the standing BCL and the cycle BCL stays the same over the short-term. It will spike if banks vary the intraday BCL adjustments across days. Such variation signals high uncertainty that requires continuous risk management.

5 Policy Implications

Despite LVTS's designation as a systemically important system, the nature of the systemic risk of LVTS is not well understood. Bank of Canada'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, do not address risks that generate fragility of the LVTS.[24] 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 the abrupt transition of LVTS from T2 to T1 payments. Such transition can be caused by a loss of trust between LVTS participants. Even in normal times, we find a strong reciprocity in provision of credit limits. A reduction in credit limit by one institution results in an almost immediate reciprocal reduction in credit limits. Banks are more likely to cut credit limits after one of the participants fails. Even if there is enough

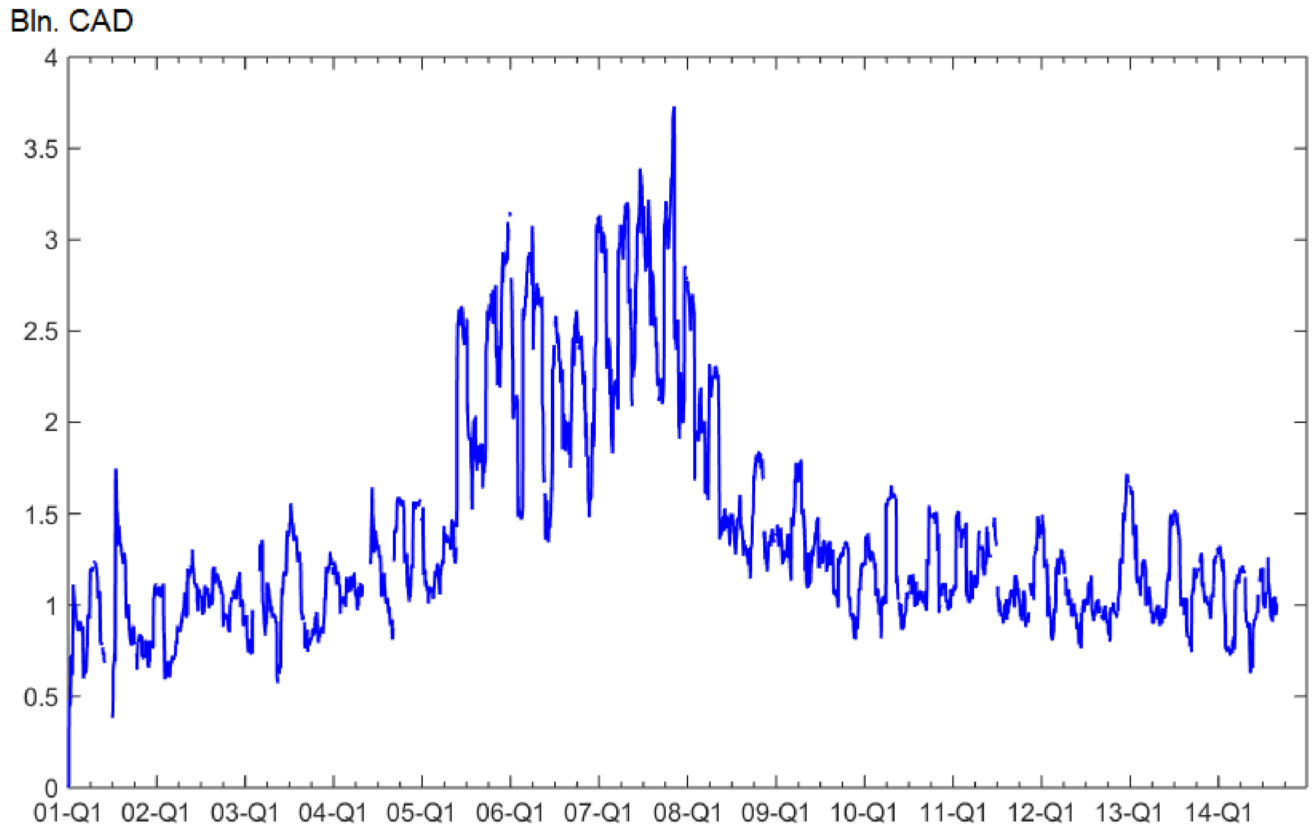
[24] `http://www.osfi-bsif.gc.ca/Eng/Docs/LAR_chpt6.pdf`.

Figure 10: **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.

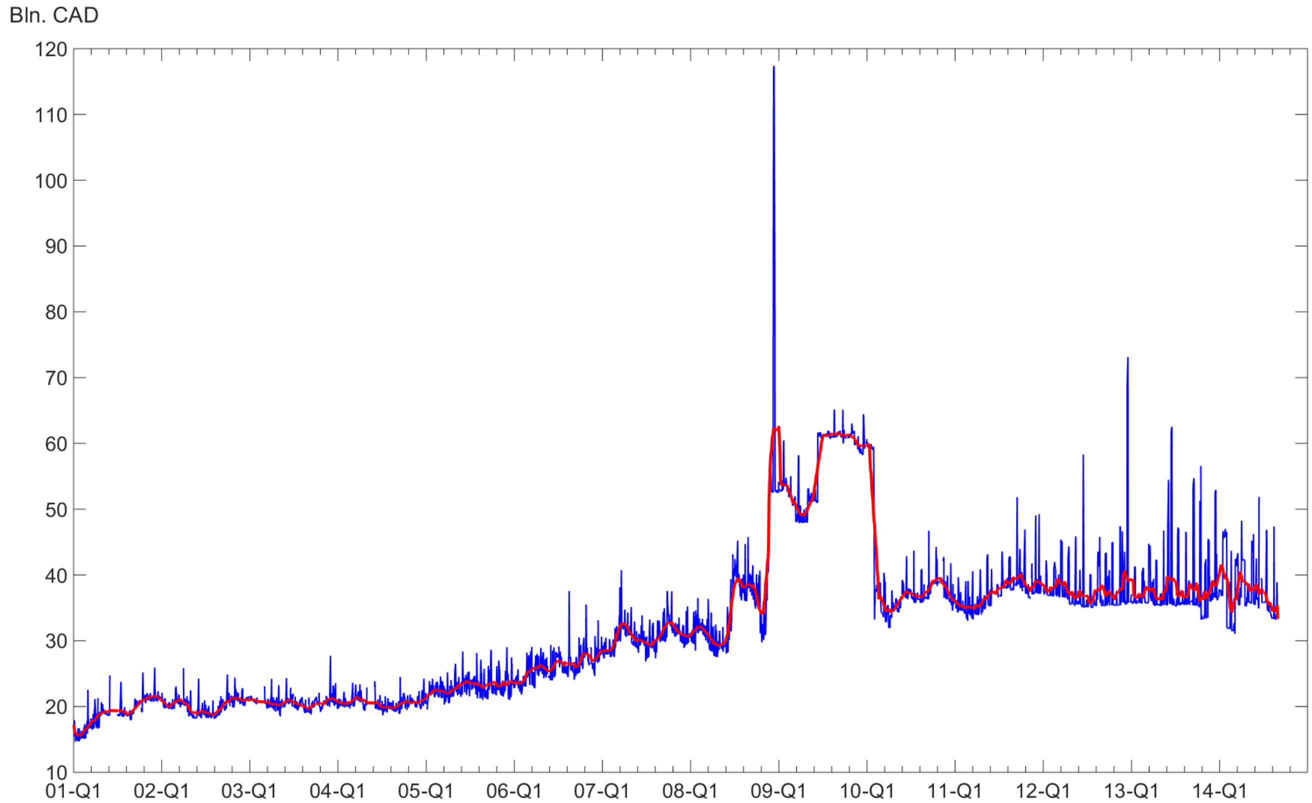
Figure 11: **Volatility of Intraday BCL Adjustments**



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

collateral to cover the losses from this failure, the size of the credit limits after the failure is likely to be smaller, at least in the short run. The risk of transitioning to T1 payments is present if participants in a payment system do not have sufficient amount of excess collateral to send the same volume and value of payments without credit limits. If there is not enough excess collateral, critical payments will be delayed causing stress in the Canadian banking system and potentially in the global financial system.

Figure 12: **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.

During the crisis period, the BoC made several changes in qualification of assets that are accepted for collateral in LVTS. 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. 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. This policy lasted until March 2010. In February 2009, investment-grade corporate bonds entered the list of eligible collateral. In Figure 12, 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.

Our research also 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 don't 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 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.

Our research has also implications for payment systems design. While the benefit of netting is clear, the costs are not well understood. Any future system design should consider the implications of a sudden reduction in BCL levels and propose mechanisms to ensure that participants can withstand this shock. One such mechanism could be to require banks to have sufficient amount of excess collateral. However, this mechanism would reduce the efficiency benefits of a DNS system. A state-contingent approach to collateral management could be another alternative. According to this approach, a central bank would accept additional asset classes as collateral when real-time monitoring suggests a build up of stress in the system. To be able to assess which mechanism is better, one would need to have a model that allows banks to choose whether to use collateral or credit. This theoretical modeling is outside the scope of this paper.

6 Conclusion

Policymakers recognize that payment systems are critical to the functioning of the economy (Greenspan, 1996). We develop systemic risk measures that rely on the data about interbank transfers in large value payment systems. We apply these measures to LVTS and show that they were elevated during the financial crisis. First, we show that day after Lehman's failure, LVTS experienced large number of rejected payments and delays in payments totaling billions of CAD. Second, we show that over a period of two days in May 2008, LVTS faced a significant stress, which was caused by a multi-billion loss by one of the banks in the US sub-prime market. We refer to this episode as a Flash Crash because it lasted a short period of time and could not be picked up by any low-frequency measures. However, a second-by-second analysis shows that during the Flash Crash, the system experienced multiple reductions in bilateral credit limits, a large number of rejected payments, more than $23 billion CAD of payments that settled with delays because of the binding credit and collateral constraints, and abnormal delays in the intraday payment flows. Besides individual days, we also show a significant increase in the annual number of rejected payments in 2007. We argue that interventions by the BoC could explain why the number of rejected payments in 2008 was much smaller. We also report that the volatility of intraday adjustments in the bilateral credit limits has been elevated since the second half of 2005 and picked in 2008. This volatility is a sign of increased uncertainty that forces banks to monitor counterparty risk more closely. We conclude that without monitoring system's risk at high-frequency, it is impossible to know whether a payment system functions well or is at a brink of a collapse.

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7 Appendix

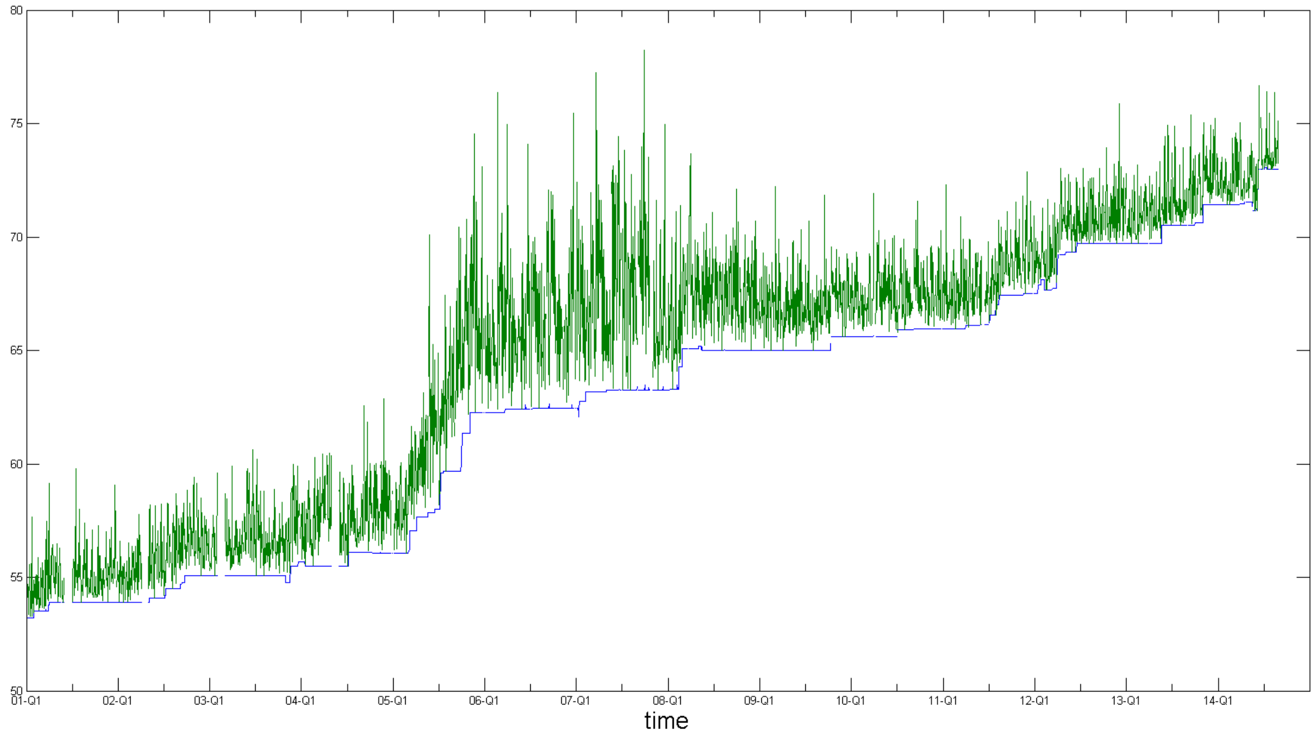
7.1 Additional Tables

Table 5: **Detailed Summary Statistics (Jan. 2013 - Aug. 2014)**

	Volume ('000)	Value (bln.)	Mean ('000)	Median ('000)	SD ('000)
All	11,951	59,002	4,937	18	46,959
T1	150	12,967	86,672	7,499	312,354
T2	11,802	46,036	3,901	17	30,175
T1 (%)	**1.26%**	**21.98%**			
T2 (%)	**98.75%**	**78.02%**			
customer	7,589	13,021	1,716	10	18,962
bank	4,363	45,981	10,540	77	73,252
customer (%)	**63.5%**	**22.1%**			
bank (%)	**36.5%**	**77.9%**			
T1 and customer	27	1,694	62,977	493	166,888
T2 and customer	7,562	11,327	1,498	10	15,761
T1 and bank	123	11,273	91,866	9506	335,699
T2 and bank	4,240	34,708	8,186	70	45,418

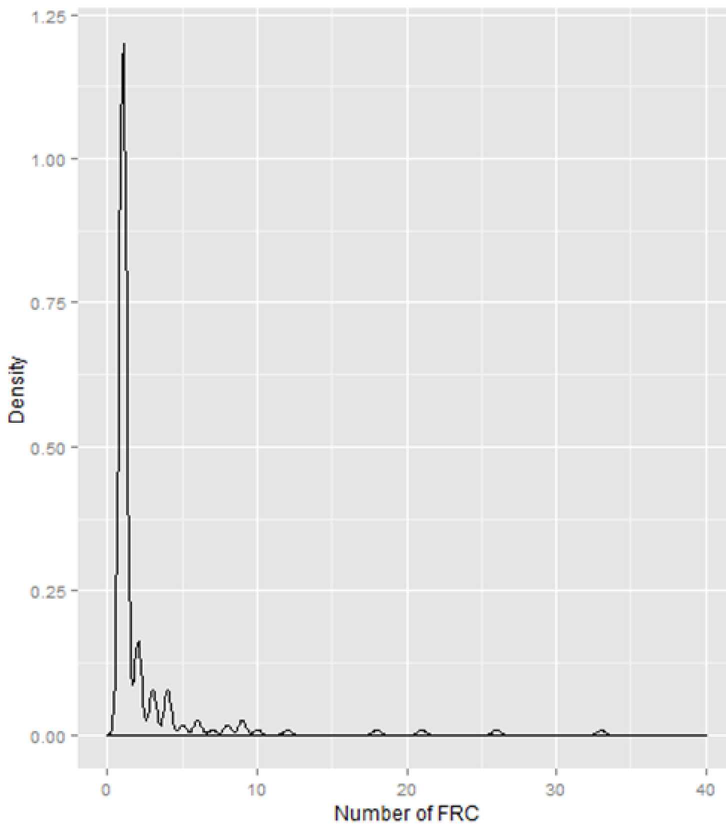
7.2 Additional Figures

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



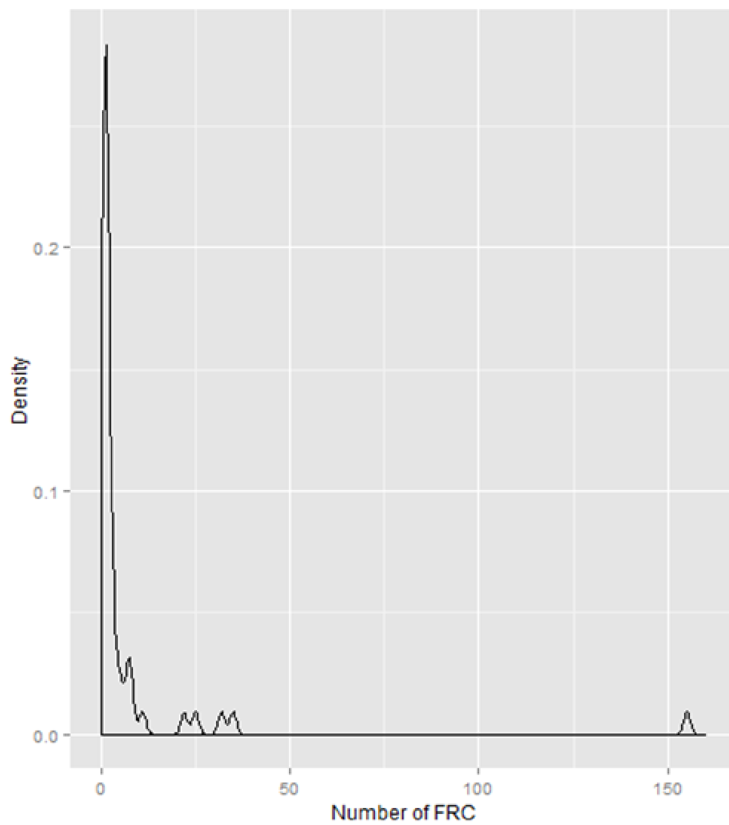
This figure presents aggregate standing BCL at the beginning of the day (blue) and aggregate cycle BCL at the end of the day (green) measured in billions of CAD at daily frequency between January, 2001 and August 2014.

Figure 14: **Rejected payments distribution experienced by Bank A**



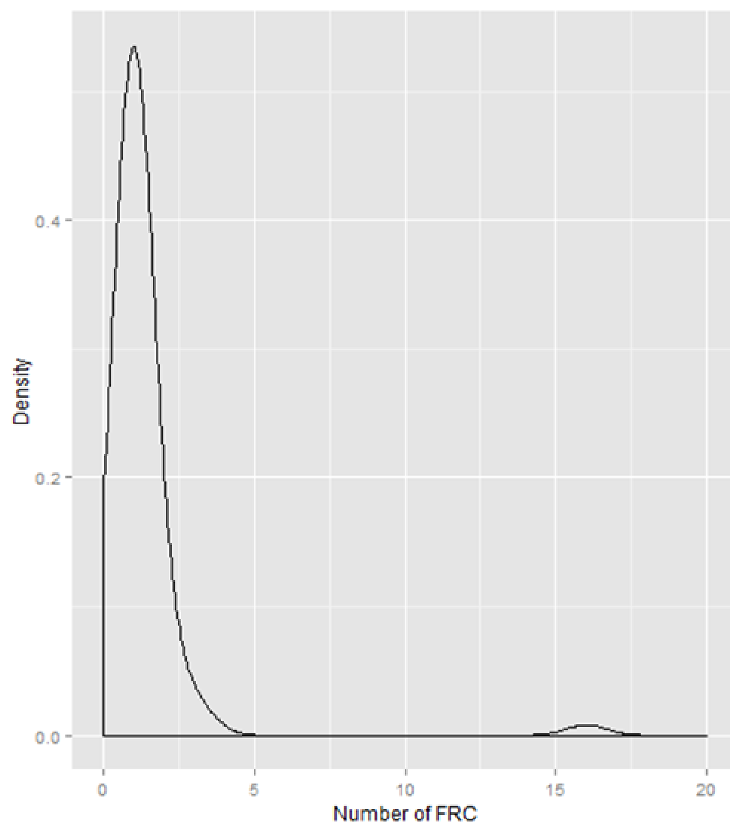
This figure illustrates the distribution of rejected payments experienced by Bank A as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank A experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 33 such rejected payments.

Figure 15: Rejected payments distribution experienced by Bank B



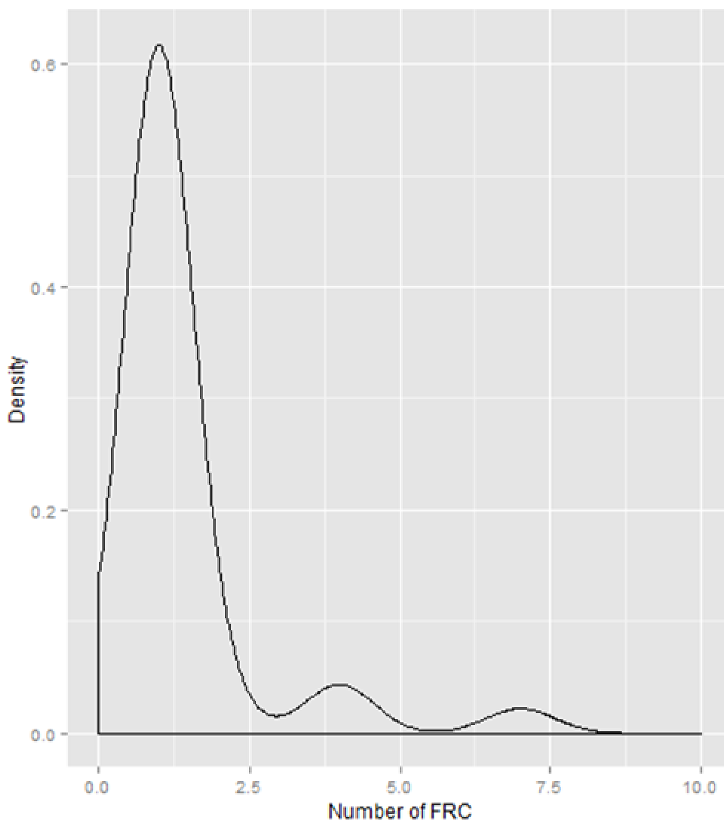
This figure illustrates the distribution of rejected payments experienced by Bank B as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank B experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 155 such rejected payments.

Figure 16: Rejected payments distribution experienced by Bank C



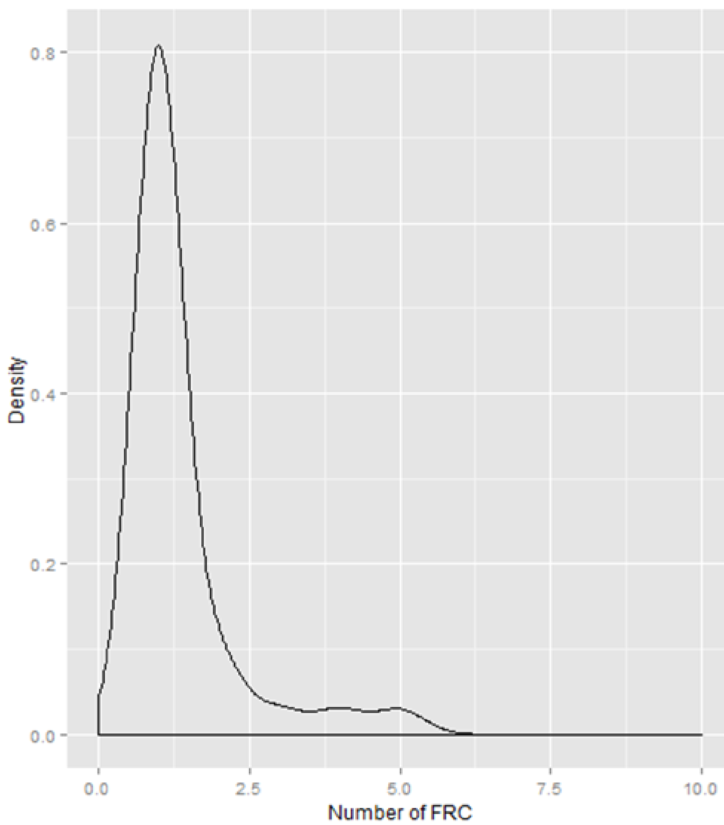
This figure illustrates the distribution of rejected payments experienced by Bank C as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank C experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 16 such rejected payments.

Figure 17: Rejected payments distribution experienced by Bank D



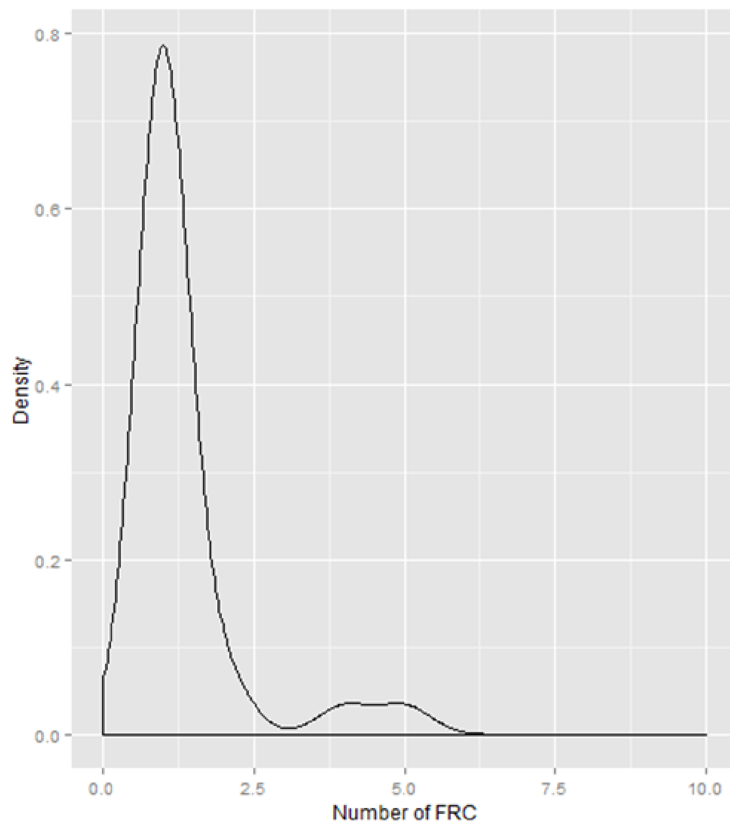
This figure illustrates the distribution of rejected payments experienced by Bank D as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank D experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 7 such rejected payments.

Figure 18: Rejected payments distribution experienced by Bank E



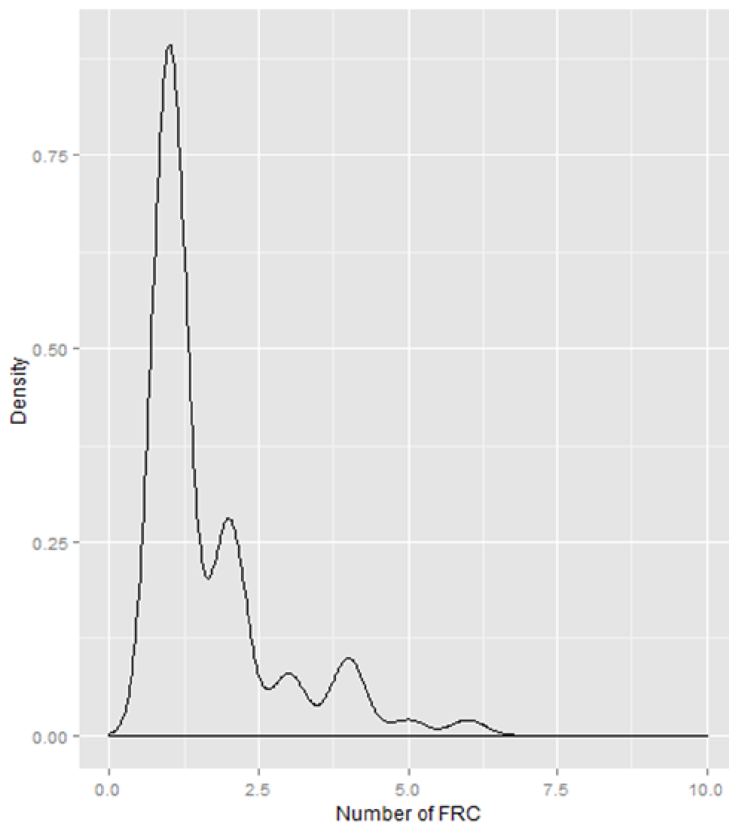
This figure illustrates the distribution of rejected payments experienced by Bank E as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank E experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 5 such rejected payments.

Figure 19: Rejected payments distribution experienced by Bank F



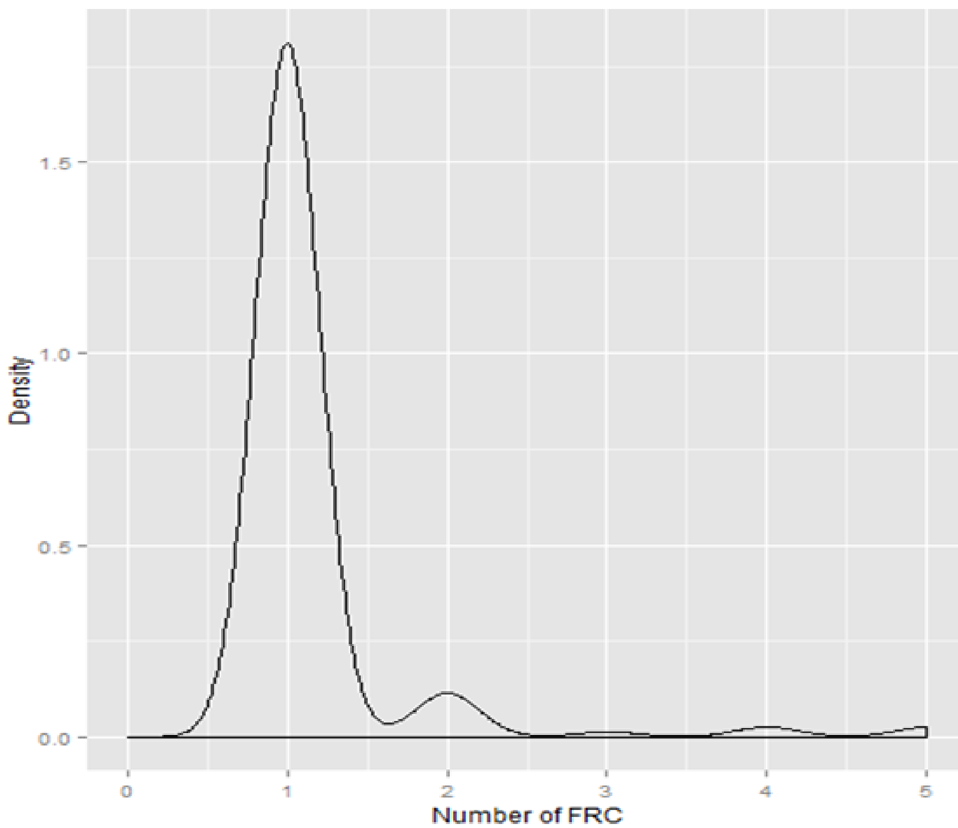
This figure illustrates the distribution of rejected payments experienced by Bank F as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank F experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 5 such rejected payments.

Figure 20: Rejected payments distribution experienced by Bank G



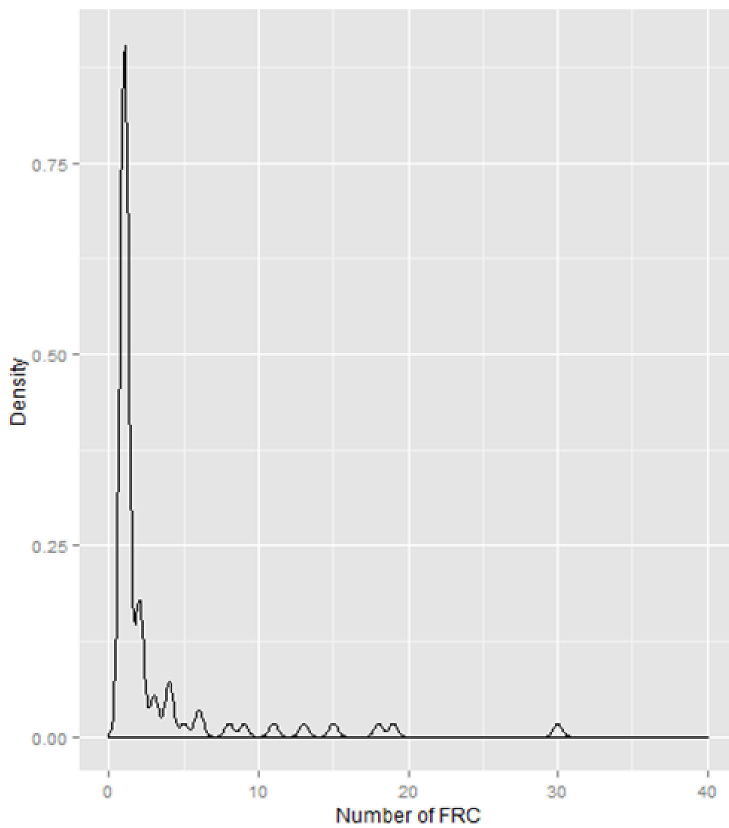
This figure illustrates the distribution of rejected payments experienced by Bank G as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank G experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 6 such rejected payments.

Figure 21: Rejected payments distribution experienced by Bank J



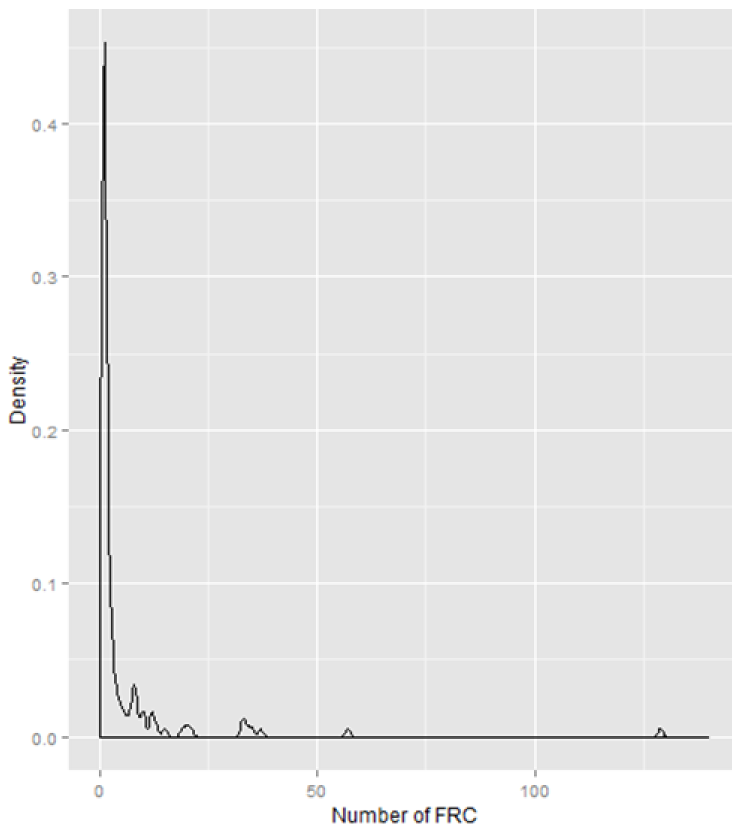
This figure illustrates the distribution of rejected payments experienced by Bank J as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank J experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 5 such rejected payments.

Figure 22: Rejected payments distribution experienced by Bank H



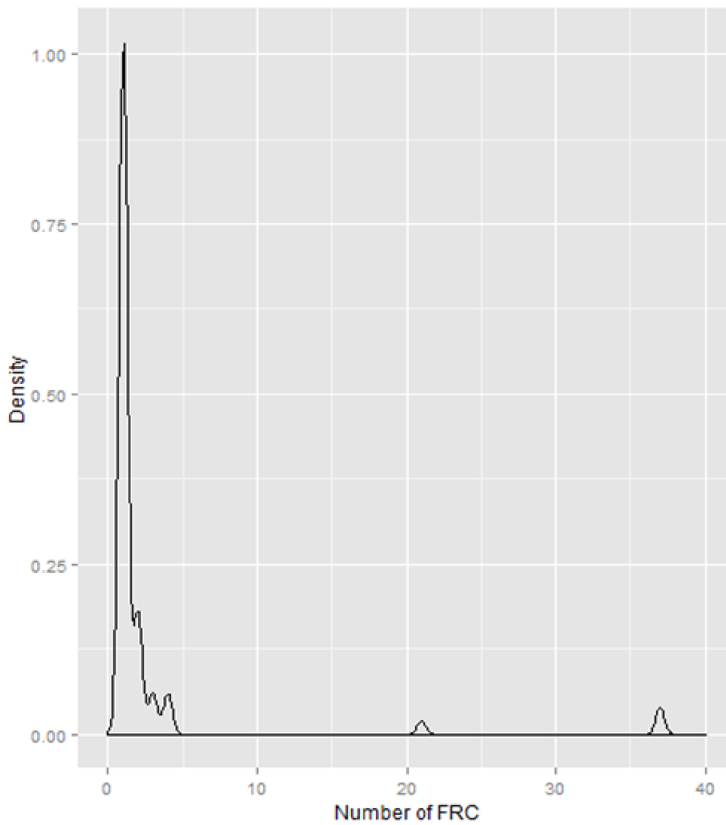
This figure illustrates the distribution of rejected payments experienced by Bank H as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank H experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 30 such rejected payments.

Figure 23: Rejected payments distribution experienced by Bank I



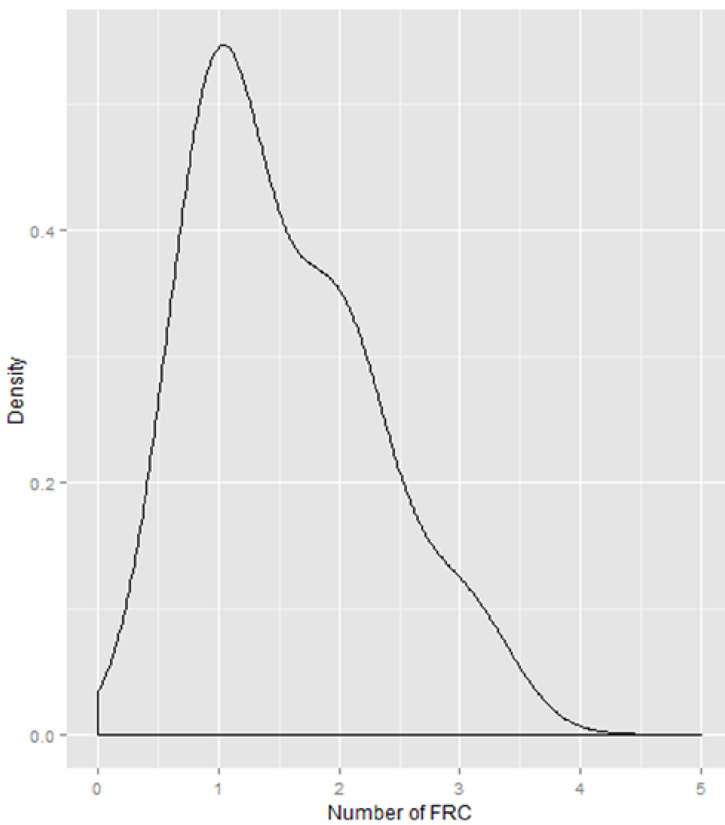
This figure illustrates the distribution of rejected payments experienced by Bank I as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank I experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 129 such rejected payments.

Figure 24: Rejected payments distribution experienced by Bank K



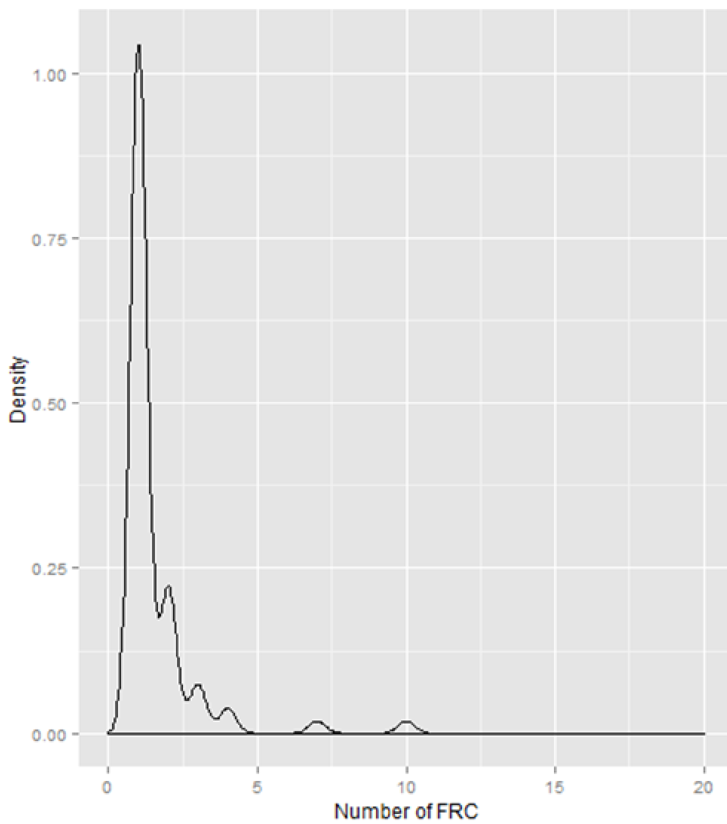
This figure illustrates the distribution of rejected payments experienced by Bank K as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank K experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 37 such rejected payments.

Figure 25: Rejected payments distribution experienced by Bank L



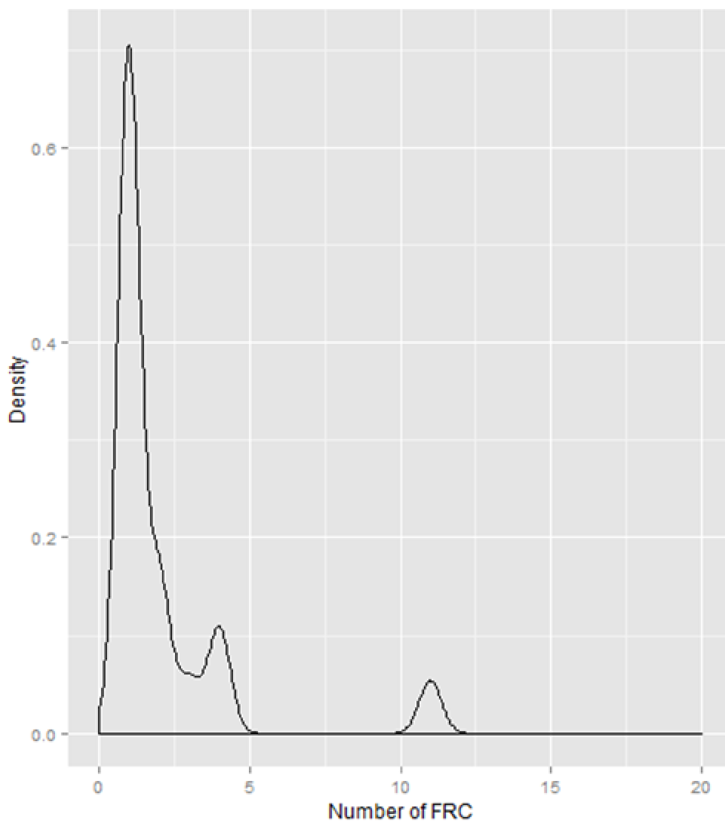
This figure illustrates the distribution of rejected payments experienced by Bank L as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank L experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 3 such rejected payments.

Figure 26: Rejected payments distribution experienced by Bank M



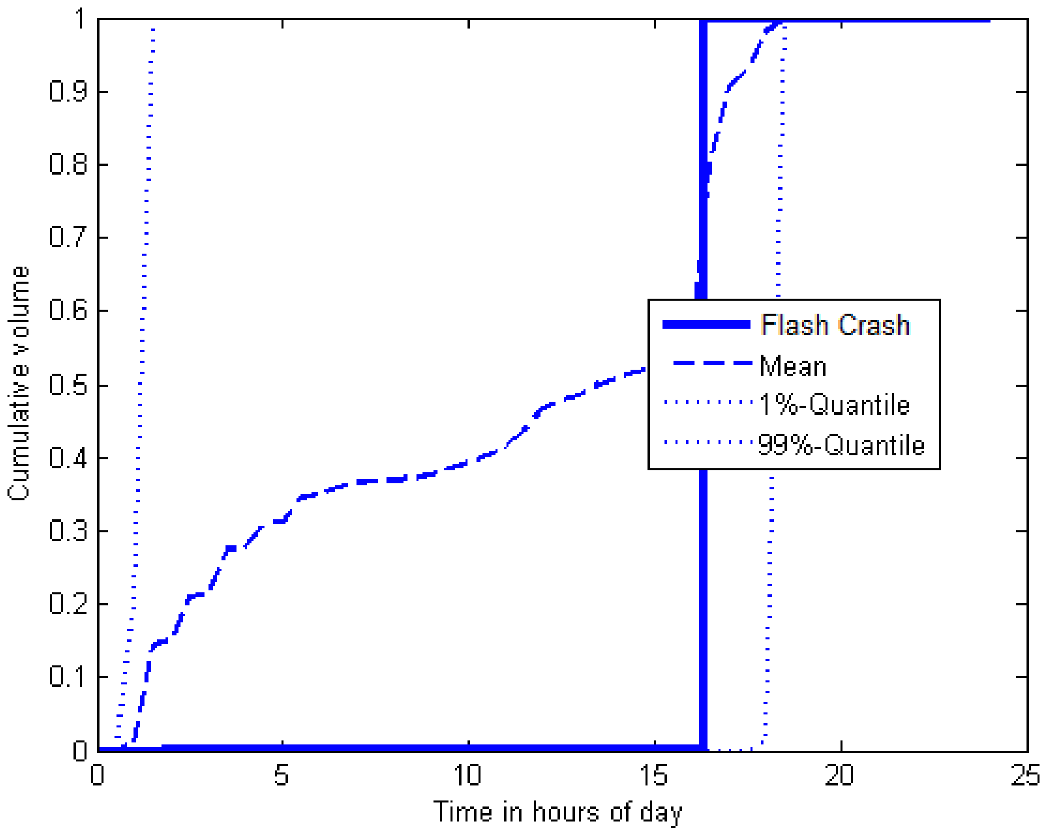
This figure illustrates the distribution of rejected payments experienced by Bank M as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank M experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 10 such rejected payments.

Figure 27: Rejected payments distribution experienced by Bank N



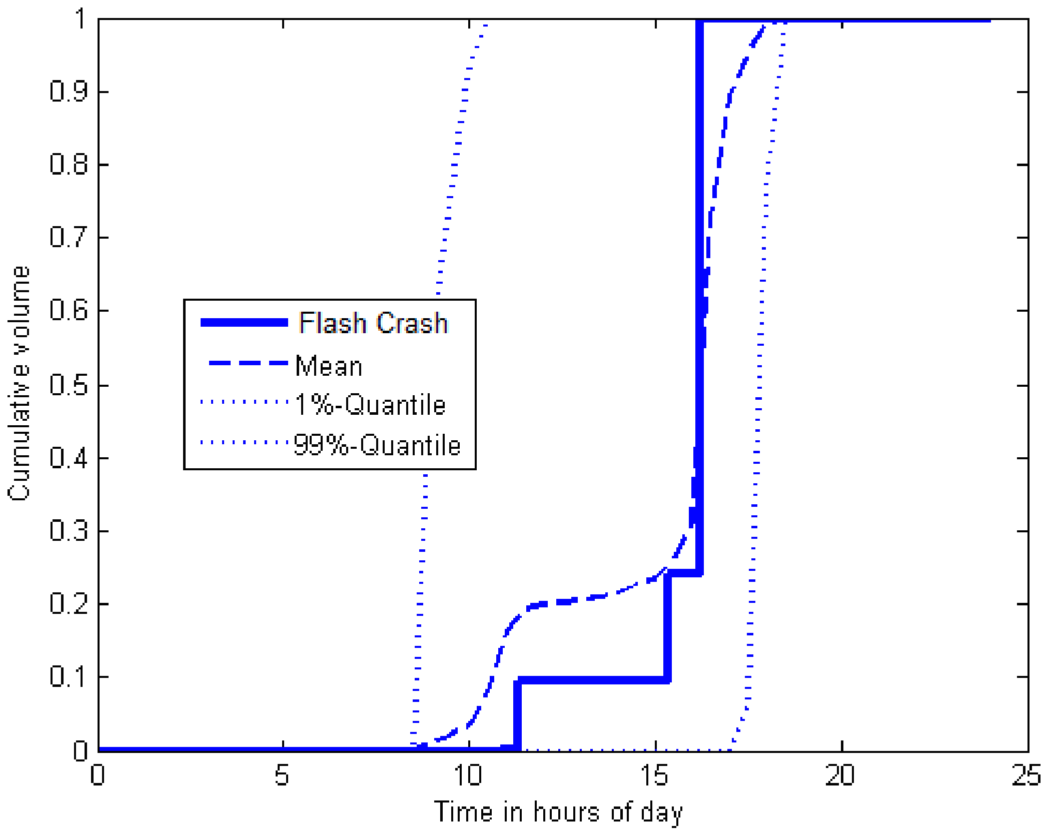
This figure illustrates the distribution of rejected payments experienced by Bank N as a result of a payment failing to meet the LVTS risk control. It shows for instance that on days when Bank N experienced such rejected payments, it typically saw only one rejected payment. However, there was a day during the sample period when it experienced as many as 11 such rejected payments.

Figure 28: Typical daily Tranche 1 payments flow of Bank A compared to its payments flow during the Flash Crash



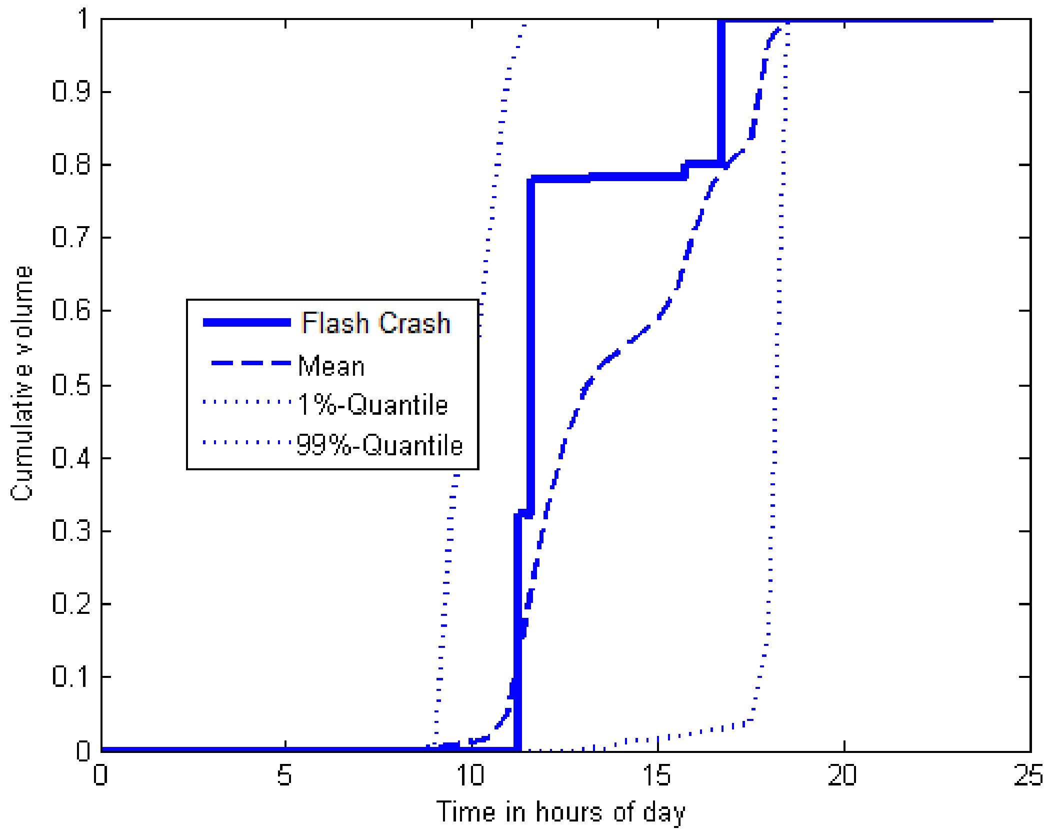
The dotted blue line in the figure provides 1% and 99% percentiles of Tranche 1 cumulative payments flow of Bank A. The dashed line provides the mean and the solid line provides the flow of Tranche 1 payments during the Flash Crash. The figure shows for most part of the day during the Flash Crash, Bank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

Figure 29: 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 30: 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.