Joint Determination of Counterparty and Liquidity Risk in Payment Systems

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Abstract

We propose a methodology to assess how banks jointly manage their funding liquidity and counterparty risk. Our methodology is developed in the context of a centralized payments exchange that uses a deferred net settlement (DNS) system. This setup allows us to simultaneously evaluate critical features of the financial system that are usually analysed in isolation, such as the issuance of secured and unsecured credit obligations and the use of collateral and capital requirements. Throughout the day, banks issue payment orders that represent claims on central bank balances. These claims, or credit obligations, must be settled at the end of the day. A payments operator processes all payment orders and acts as the central counterparty. To remain risk neutral, the operator collects collateral from either the issuer or the recipient of a payment order. Thus, from the point of view of the recipient (i.e., the creditor), orders are secured if they are collateralized with the assets of the issuer (i.e., the debtor) using a defaulter-pay arrangement, and unsecured if they are supported with its own assets using a survivor-pay arrangement. These arrangements closely resemble collateral and capital requirements in the wider banking system. We hypothesize that banks coordinate the issuance of payment orders to jointly manage their liquidity and counterparty exposures. Coordination leads to netting of credit exposures and unencumbering of collateral assets, which increases liquidity. Using intra-day data from the Canadian wholesale payments system, known as the Large Value Transfer System (LVTS), our results show that banks prefer to issue unsecured payments and do not see secured and unsecured payments as substitutes. However, banks coordinate the issuance of both types of payments. For unsecured payments, banks rely on both bilateral and multilateral coordination, whereas for secured payments, they rely almost exclusively on multilateral coordination. The differences in coordination arise because unsecured payments are contingent on the performance of a given counterparty, whereas secured payments only depend on the value of the collateral supporting them. Thus, to the extend that collateral is homogenous, secured payments are fungible regardless of the issuer. Coordination and netting incentives increase with risk exposures and the cost of funding. We conclude that coordination disruptions may increase risk exposures and lead to collateral shortages and funding constraints, particularly among small participants, who tend to net less and require relatively more collateral to issue and to receive payments. In an extreme scenario, coordination disruptions could lead to gridlock and systemic risk. Therefore, coordination is an important risk management tool that should be considered when designing market infrastructures and regulations aimed at enhancing financial stability.

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1. Introduction

For many years, researchers have been trying to understand critical features of the financial system in order to improve its management. These include interlocking obligations across financial institutions, the use of secured and unsecured lending, and the mitigation of credit exposures through the use of central clearing, netting and collateral arrangements. These elements are important because of their implications for financial stability, investment decisions and macroprudential policies, but analysing them in isolation is unlikely to yield a broad understanding of the financial system. Fortunately, many of these features find their analogs in payment systems, which offer an exceptional setting for a holistic analysis.

Payment systems are at the core of the infrastructure supporting the global financial system. They consist of a set of instruments and procedures that allow market participants to transfer the funds needed to settle most transactions in an economy.[1] In sophisticated financial systems, interbank payment transactions take place in a large value payment system (LVPS) that is usually centrally managed by a payments operator.[2] The payments operator interacts with a limited number of direct participants (DPs) who submit their own payment orders, as well as those of their client firms who do not have direct access to the operator.[3] Payment orders are a type of credit obligation. When a DP issues a payment order to pay a counterparty, it effectively creates a credit obligation to that counterparty. The payments operator processes all of these credit obligations and settles them at the end of a predefined period by transferring settlement funds among DPs. Typically, central bank reserves act as settlement funds. Thus, payment systems aggregate transaction throughout the economy and serve as the point of contact between central banks and commercial banks for the implementation of monetary policy.

Depending on how the payments operator clears and settles payments orders, payment systems can be divided into Real Time Gross Settlement (RTGS) systems and Deferred Net Settlement (DNS) systems.[4] In the first case, payment orders are cleared and settled instantly, so no credit risk exposures are absorbed by the payments operator or its DPs. In the second case, the payments operator accepts and clears payment orders, nets them across DPs over a prespecified period of time, and settles them at the end of that prespecified period; usually, one trading day. In general, for a given value and volume of payment orders, the netting of credit obligations allows DNS systems to operate with a lower amount of settlement funds relative to RTGS systems. However, the separation of clearing and settlement in DNS systems creates credit risk exposures that the payments operator must manage through the use of netting, collateral and default resolution arrangements. In practice, most payment systems are a combination of these two configurations and are known as hybrid systems.

In this paper we develop an empirical methodology to characterize netting relationships in payments systems. Our methodology allows us to map the timing and value of payment orders and measure the degree of bilateral and multilateral netting in the system on average and at the margin at different times during the trading day. For RTGS systems, our methodology allows us to assess the average and marginal intraday efficiency in terms of settlement balances. The higher the levels of netting, the lower the amount of settlement

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[1] See CPMI-IOSCO, 2012

[2] Most jurisdictions have two types of payment systems. One for retail transactions and one for interbank transactions.

[3] This process is known as corresponding banking.

balances required to process payments and, as a consequence, the lower the probability of gridlock (see Bech and Soramäki, 2001 and 2002).[5] For DNS systems, our methodology allows us to assess the amount of credit exposures that can be eliminated on average and at the margin through netting. This is important because every unit of credit exposure that can be eliminated through netting does not need to be collateralized. As a result, stable and efficient netting relationships reduce collateral requirements and facilitate the management of the system. This insight combined with the separation of bilateral and multilateral netting relationships in our methodology, allows us to assess the value of multilateral netting arrangements in terms of reductions in credit exposures and collateral requirements.

The distinction between marginal and total netting relationships allows us to shed some light into the mechanism through which operational disruptions affect credit exposures in payment systems and other financial market infrastructures (FMIs) dedicated to the management of credit risk, including central counterparties (CCPs). Partial disruptions, such as the inability of a DP to submit orders to the payments operator due to a failure in communication systems, impair marginal netting relationships and lead to an increase in credit exposures for other DPs. The amount of credit exposure absorbed by each DP increases with the degree of marginal netting typically derived from the affected DP and the duration of the disruption. Similarly, the effects of systemic operational disruptions on credit exposures depend on the level of total netting. When total netting is low, the amount of credit exposures absorbed by each DP increases.

We use intraday data from the Canadian LVPS, known as the Large Value Transfer System (LVTS), to implement our methodology. Our dataset includes every payment order submitted by the DPs in the LVTS from March 1st, 2004 to December 30th, 2016. The LVTS is operated by Payments Canada and is configured as a DNS system that provides equivalence to an RTGS system in terms of the settlement risk faced by DPs. Settlement risk equivalency is achieved through a guarantee provided by the Bank of Canada (Arjani and McVanel, 2006).[6] Unlike most payments operators in other countries, Payments Canada novates each payment order in the LVTS. This means that Payments Canada becomes the sole counterparty to each receiver of funds in the system. Novation increases the concertation of credit risk in the payments operator but it also allows for the multilateral netting of payments obligations. We take advantage of this feature and assess the value of novation in terms of the collateral savings achieved through multilateral netting.

The LVTS also has the peculiar feature of allowing DPs to choose between two alternative risk management arrangements when submitting their payment orders. The first arrangement, known as Tranche 1 (T1), is based on a defaulter-pay provision. In this case, a DP uses its own collateral to support its payment orders to all counterparties. If the DP defaults, its collateral is used to settle its credit obligations. The second arrangement, known as Tranche 2 (T2), is based on a survivor-pay provision. In this case, a DP is granted a bilateral credit line (BCL) by a counterparty; known as the grantor. The grantor collateralizes the BCL and it can only be used to support bilateral payments from the DP to the grantor. If the DP defaults, the collateral of the grantor is used to settle the credit obligations of the defaulting DP.[7] The T1 and T2 arrangements in LVTS resemble secured and unsecured lending provisions in the banking literature. These provisions are typically supported with collateral (i.e., defaulter pay) and capital (i.e., survivor pay) requirements, respectively. Thus, our insights could

[5] At the participant level, evidence suggest that in both RTGS and DNS systems direct participants prefer a continuous and predictable stream of payments from their counterparties because this increases the netting of settlement balances and allows participants to process a larger amount of payment orders (Bech and Soramäki, 2002; Bech and Garratt 2003; McAndrews and Rajan, 2000; and Merrouche and Schanz, 2010).

[7] Arjani and McVanel (2006) provide a comprehensive overview of the LVTS and its design.

be generalized to the broader financial system and shed light into the trade-offs of collateral and capital requirements, which have been used extensively for macroprudential regulation after the Great Financial Crisis of 2008.

This paper also offers a technical contribution. We propose a new approach for conducting econometric analyses of payment systems and other FMIs. Traditionally, studies of FMIs rely on econometric approaches that are subject to severe intraday serial correlation. We mitigate this and other inconvenient data features by partitioning each trading day into short non-overlapping intraday intervals. Then, we analyze each intraday interval individually over all days in our time series. Because variables measured over a specific intraday interval are more likely to be independent across days than over adjacent intervals, our analysis conforms more closely to the assumptions needed for statistical inference.

Netting relationships have received little attention in both academic and in regulatory circles. A significant share of the literature on payment systems focuses on the interconnectedness of DPs and the likelihood of contagion if a shock occurs. Many of these studies rely on network methodologies to determine interconnectedness and credit exposures (e.g., Furfine, 1999; Bech, Chapman and Garratt, 2010; McAndrews and Rajan, 2000; Bech and Soramäki, 2002; Soramäki, et al., 2006; Merrouche and Schanz, 2008; and Bech and Garratt 2012). In contrast, our research focuses on how coordination across market DPs gives rise to netting relationships. In this context, perhaps McAndrews and Potter (2002) is closest to our research. They study how exogenous shocks, such as the events of 9-11, affect bilateral and systemwide netting and coordination in payment systems. In this paper, however, we measure netting relationships during extended periods of time to assess their stability and understand their relation to credit exposures, collateral efficiency, and operational disruptions both on average and at the margin.

In terms of collateral management, previous literature shows that the timing of payment orders can help determine funding requirements (e.g., Bech and Garratt, 2002; Bech, 2003; Ashcraft and Duffie, 2007; Kambhu, Weidman and Krishnan 2007). We complement this literature by proposing a parsimonious framework that illustrates the effect of coordinating the submission of payment orders on credit exposures, collateral and funding requirements. To accomplish this objective, we introduce the concept of *clearing capacity,* a type of funding liquidity with limits and costs that are largely determined by the structure of the payment system. Specifically, clearing capacity is the maximum order value that a payments processor would agree to clear for a DP immediately, without delays or queuing, given a set of risk management conditions. In RTGS systems, clearing capacity is determined by settlement fund balances. In DNS systems, clearing capacity is determined by unencumbered collateral assets, BCLs and netting relationships. By properly defining clearing capacities, we can identify their sources, opportunity costs and frictions. Stable clearing capacities increase the willingness of DPs to coordinate their payments, which leads to a virtuous cycle of higher netting, lower credit exposures, lower collateral and funding requirements, and even more stable clearing capacities. On the other hand, unstable or constrained clearing capacities can have a detrimental effect on coordination, which could lead to a vicious cycle of lower netting, higher credit exposures, higher collateral and funding requirements, and even more constrained clearing capacities. This vicious cycle can lead to systemic gridlock.

Our empirical analysis shows that netting relationships tend to be remarkably stable over time, both on average and at the margin. Most of the coordination of payment orders and netting of credit exposures tends to occur in T2. Netting in T1, on the other hand, tends to be limited and driven by multilateral interactions. This indicates that DPs tend to prefer netting their unsecured credit exposures relative to their secured credit exposure; that is, they prioritize the netting and reduction of credit obligations that might result in a loss if their counterparties default.

We also find that total netting relationships increase almost monotonically throughout the day. Therefore, systemic operational disruptions are more likely to result in large margin calls or shortfalls when they occur early on the trading day. The magnitude of these potential marginal calls or shortfalls is heavily influenced by the netting structure adopted by the payments operator. Our results show that relative to bilateral netting, multilateral netting can reduce credit exposures by an additional 15% at the beginning of the day (from 15% to 30% of the aggregate value of payment orders) and by an additional 55% by the end of the day (from 35% to 90% of the aggregate value of payment orders). These reductions are significant and can be translated to equivalent reductions in collateral requirements. Thus, for the average day in our sample, multilateral netting reduced credit exposures and potential collateral requirements by $24 billion at the beginning of the day and by $87 billion by the end of the day relative to bilateral netting. Our results also show that large DPs, defined as those with daily payment order values above the median, net more of their credit exposures than small DPs, defined as those with daily payment order values below the median. Therefore, relative to the total value of their payments, small DPs tend to require higher amounts of collateral and settlement balances to preserve their clearing capacity, so they would be more exposed to a systemic operational disruption than large DPs.

We find that marginal netting tends to be higher at the beginning and at the end of the trading day. Therefore, partial operational disruptions are more likely to interfere with coordination and lead to gridlock if they occur during these periods. In contrast to systemic operational disruptions, we find that large DPs would be more exposed to partial operational disruptions because, relative to small DPs, they tend to rely more heavily on marginal netting to preserve their clearing capacity.

When we analyze periods of exogenous variation, we find the interesting result that netting relationships only increased slightly during the Great Financial Crisis relative to the period preceding it. However, after the crisis, netting decreased significantly, particularly, for small DPs. Thus, our results tend to indicate that interest rates are major determinants of netting relationships. We hypothesise that the low interest rate environment that followed the financial crisis reduced the opportunity cost of collateral and settlement balances, both of which can be used to increase clearing capacity; thus, reducing the incentive of DPs to preserve clearing capacity through netting of credit exposures.

Consistent with previous studies, we show that DPs in the LVTS prefer to use T2, the survivor-pay provision, to submit most of their payment orders. However, in contrast to previous findings, we show that this result tends to hold for payment orders with relatively small value and has significant cross-sectional variation. Both large and small DPs tend to use T1, the defaulter-pay provision, for large payment orders. Moreover, as a proportion of their daily payment order value, small DPs send more value through T1 than large DPs. A significant amount of this value consists of payments from small DPs to large DPs. However, large DPs tend use T2 to send payment orders to both large and small DPs. This asymmetry in the use of risk management arrangements suggests that DPs prefer to use survivor-pay provisions for managing the bilateral risk arising of relatively small transactions or well-known counterparties. On the other hand, DPs preferer defaulter-pay provisions for managing the risk of relatively large transactions or less known counterparties. There are also systematic intraday variations. Towards the end of the trading day, DPs switch the relative value of their payment orders from T2 to T1, suggesting a relative preference for the survivor-pay provision as the settlement time approaches and the probability of default increases.[8]

The remaining of the paper is organized as follows. Section 2 presents our methodology. Section 3 describes the data and presents summary statistics. Section 4 reports our empirical results and Section 5 summarizes our conclusions and policy implications.

2. Methodology

A LVPS is a centralized exchange of payment orders with a limited number (N) of DPs. Let $P_{t,s}^{ij}$ be the value of a payment order submitted from DP i to DP j on date t at time s. In our notation, i denotes a particular DP ($i = 1, \dots, N$), t denotes a calendar date ($t = 1, .., T$) and s denotes a time during the exchange period ($s = 1, .., S$), where $s = 1$ is when the exchange opens and $s = S$ is when the exchange closes and settlement takes place. When DP i submits a payment order to DP j, it effectively issues a credit obligation to j that must be discharged at the time of settlement ($s = S$).[9]

All payment systems rely on two generic functions (or stages) to transfer settlement funds. First, the clearing function determines whether a payment order is accepted or rejected for further processing and eventual settlement given a set of risk management conditions, which usually include the ability of the sender to fulfill its payment obligations. Second, the settlement function determines the conditions for discharging credit obligations through the transfer of settlement funds (typically central bank reserves) among counterparties.[10]

The payments operator coordinates the exchange and ensures that credit obligations are settled with a high degree of certainty by observing all payment orders in the system (i.e., $P_{t,s}^{ij}\ \forall i, j, t, s$) and establishing the clearing and settlement functions that govern all transactions in the exchange. The clearing function limits the amount of credit obligations that each DP can issue and, as a consequence, determines the aggregate credit risk in the payments system. We call the limit on the amount of credit obligations that can be issued by a DP its clearing capacity and define it as the maximum payment value that the payments processor would agree to clear for a DP immediately, without delays or queuing, given a set of risk management conditions.[11]

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[8] Cruz-Lopez and Ibanez (2018) analyse the change in participants' preferences from survivor-pay to defaulter-pay provisions using a stochastic default model with the option to switch between unsecured and secured credit.

[9] DPs can issue payment orders on their behalf, which arise as a result of their business dealings, or on behalf of their clients, who do not have direct access to the payments exchange.

[10] Formally, clearing is "the process of transmitting, reconciling and, in some cases, confirming payment orders prior to settlement. This process can include netting [of payment orders] and the establishment of final positions for settlement." (Bank of Canada, 2018 – website reference). In a payments system, settlement involves "the release of payment obligations between two or more parties by transferring funds between them" (Bank of Canada, 2016). In general, settlement is "an act that discharges obligations in respect of funds or securities transfers between two or more parties" (Payments Canada, 2018 – website reference).

[11] At this point, it is important to distinguish between clearing capacity and liquidity. Most of the literature in payment systems use the term liquidity to refer to something close to, but not always defined as, clearing capacity. This lack of precision in the use of terms could lead erroneous comparisons or misspecified relationships. We can define two types of liquidity. First, market liquidity refers to the ability of market participants to quickly exchange an asset for cash without significantly decreasing the price of the asset. Second, funding liquidity refers to the ability of market participants to issue new credit obligations without significantly changing their cost of capital. In a payments system, DPs exchange payment

The term clearing is sometimes used erroneously to include settlement (BIS, 2012). However, distinguishing between these two functions is important for uncovering the trade-off faced by the payments operator between ensuring settlement and reducing the amount of funds needed to run the payments exchange. In RTGS systems, where the clearing and settlement of payment orders occur simultaneously, no credit risk accrues to the payments operator or its DPs, but a large amount of funds is required to settle each individual payment order on a gross basis. On the other hand, in DNS systems, where the clearing and settlement functions take place at different times, the payments operator or its DPs are exposed to credit risk from the time that a payment order clears and until it settles. In this case, however, the benefit is that relative to an RTGS system, less settlement funds are required to run the exchange when credit obligations are netted after clearing and prior to settlement. To manage credit risk in DNS systems, the payments operator relies on collateral requirements and loss-sharing provisions.[12]

In RTGS systems, the clearing capacity of a DP is determined by the amount of settlement funds (e.g., central bank reserves) that it has apportioned to the payments exchange and remain unencumbered; that is, the funds that are immediately available to settle a payment order. Therefore, the opportunity cost of clearing capacity in RTGS systems is the cost of settlement funds. In DNS systems that operate with a defaulter-pay provision, the clearing capacity of a DP is determined by the amount of collateral that it apportions to the payments exchange and remains unencumbered; that is, the collateral that is immediately available to secure new credit obligations. Therefore, the opportunity cost of clearing capacity in DNS systems is the cost of the collateral assets accepted by the payments operator from the time of clearing to the time of settlement, as well as the cost of delaying payments. In DNS systems that operate with a survivor-pay provision, as is the case in Canada, the clearing capacity of a DP is determined by the maximum amount of bilateral credit exposure that each counterparty is willing to accept, as well as the maximum amount of multilateral credit exposure that the payments operator allows the DP to impose on the system. Thus, the opportunity cost of clearing capacity is the cost of the collateral assets needed to secure a BCL from the time of clearing to the time of settlement, which is paid by the counterparty granting the BCL, as well as the cost of delaying payments. Delays in payment orders allow a DP to potentially increase its clearing capacity through netting of credit obligations, which unencumbers collateral. In both types of DNS system, the payments operator does not need to clear additional payment orders at the time of settlement, so at that time, the clearing capacity of every DP is zero. Nevertheless, there is still an opportunity cost of funding which corresponds to the overnight cost of settlement balances.

In the followings section, we present a stylized representation of the LVTS that incorporates the concept of clearing capacity. Then, we present our methodology for characterizing intraday average and marginal netting relationships.

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orders, which are credit obligations. Therefore, clearing capacity is a type of funding liquidity but with limits and costs that are determined by the structure of the payment system.

[12] Under normal circumstances, payment operators manage a matched book of credit risk exposures, where for every DP submitting a payment order there is another DP receiving a payment order. However, all payments operators are subject to operational risk.

2.1. Clearing Capacity in LVTS

The LVTS is a DNS system that guarantees the settlement process through the collateralization and novation of payment orders and the contingent support of the Bank of Canada. Settlement occurs on a net multilateral basis at the end of the payments cycle, but payments orders are processed with finality on a gross basis in real time. Therefore, the LVTS is considered an RTGS-equivalent system.[13]

Unlike an actual RTGS system, however, the LVTS concentrates credit risk because of the temporal separation of clearing and settlement. As a consequence, Payments Canada, which acts as the payments operator, has to manage credit risk through collateralization. Moreover, unlike most payments operators in other jurisdictions, Payments Canada novates each payment order in the LVTS. This means that Payments Canada becomes the sole counterparty to every funds receiver in the system once the corresponding payment orders are cleared. Novation increases the amount of credit risk concentrated in the payments operator, but it also allows the payments operator to net payment orders multilaterally, which reduces collateral requirements. Therefore, the value of novation can be assessed in terms of the collateral savings provided to DPs and contrasted against the risks imposed on them and the payments operator.

The LVTS has another peculiar feature. It has two streams, known as Tranche 1 (T1) and Tranche 2 (T2), which represent alternative collateral arrangements for submitting payment orders. In both cases, DPs have to apportion collateral to Payments Canada, to cover the credit risk associated with their payment orders. However, in the case of T1, senders of payment orders are required to collateralize their submissions, whereas in T2, receivers are required to collateralize their receipts. Thus, the collateral arrangement in T1 is known as defaulter-pay, because if a DP defaults, its apportioned collateral is repossessed by the payments operator and used to cover its T1 obligations. T2 is known as a survivor-pay arrangement. In this case, a DP is granted a BCL by each one of its counterparties. These BCLs can be used exclusively to support bilateral payments to the grantor, which collateralizes the BCL. If the DP defaults, its collateral is repossessed and used to settle its claims, if the liquidation value of the collateral is not enough to satisfy these claims, then the collateral of every BLC grantor is repossessed on a pro-rated basis and used to settle the obligations of the defaulting DP. The T1 and T2 arrangements in LVTS resemble secured and unsecured lending provisions in the banking literature. These provisions are typically supported with collateral (i.e., defaulter pay) and capital (i.e., survivor pay) requirements, respectively. Therefore, some of our analysis can be generalized to this literature.

We classify each payment order into $T1P_{t,s}^{ij}$ and $T2P_{t,s}^{ij}$, depending on whether the order was submitted as a T1 or T2 order, respectively. Let $T1C_{t,s}^{i}$ be the amount of collateral apportioned by DP i in T1 on date t at time s and let $T1H_{t,s}^{i}$ be the T1 haircut applied to that collateral. Payments Canada defines the *T1 Net Debit Cap* $T1NDC_{d,t}^{i}$ of DP i based on these collateral amounts as follows:

$$T1NDC_{t,s}^{i} = T1C_{t,s}^{i} - T1H_{t,s}^{i} \tag{1}$$

Operationally, $T1NDC_{d,t}^{i}$ is defined as the maximum *net* amount that i is allowed to owe to the all other DPs in the system prior to settlement (i.e., when $s = S$). Therefore, at any time during the exchange period, s, the T1 *Multilateral Clearing Capacity* of DP i ($T1MCC_{d,t}^{i}$) is defined as:

[13] Provide BIS definition of finality.

$$T1MCC_{t,s}^{i} = T1NDC_{t,s}^{i} + \sum_{j\neq i}^{N}\left(T1Val_{t,s}^{ji} - T1Val_{t,s}^{ij}\right) \tag{2}$$

Where $T1Val_{t,s}^{ij}$ is the intraday *payment balance* from DP i to j up to time s:

$$T1Val_{t,s}^{ij} = \sum_{d=1}^{s} T1P_{t,d}^{ij} \tag{3}$$

In contrast to T1, where individual DPs support their *net* payment flows with their own collateral, in T2, DPs rely on bilateral credit lines (BCLs); that is, contingent liabilities supported with the collateral of the grantors. Therefore, in T2 each DP i has a *bilateral clearing capacity* ($T2BCC_{t,d}^{i}$) and a *multilateral clearing capacity* ($T2MCC_{t,d}^{i}$) defined as follows:

$$T2BCC_{t,s}^{i} = BCL_{t,s}^{ji} + \left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij}\right) \tag{4}$$

$$T2MCC_{t,s}^{i} = T2NDC_{t,s}^{i} + \sum_{j\neq i}^{N}\left(T2Val_{t,s}^{ji} - T2Val_{t,s}^{ij}\right) \tag{5}$$

Where $T2NDC_{t,s}^{i}$ is the T2 *Net Debit Cap* of DP i, defined as

$$T2NDC_{t,s}^{i} = \sum_{j\neq i}^{N} BCL_{t,s}^{ji}(\theta) \tag{6}$$

The payments operator uses the T2 *Net Debit Cap* to manage the multilateral risk in the system by defining θ, the proportion of the aggregate BCLs extended to DP i. The grantor of the BCL, DP j, has to apportion an amount of collateral $T2C_{t,s}^{j}$ to support the BCLs that it has granted to all of its counterparties, where

$$T2C_{t,s}^{j} = maxASO_{t,s}^{j} = max_{j,s}\left(BCL_{t,s}^{ji}\right)\theta \tag{7}$$

Payments Canada, who acts as a payments operator, stablishes the clearing functions. Let $T1Clearing$ and $T2Clearing$ be binary variables with the value of 1 if a payment message is accepted for clearing and zero otherwise in T1 and T2, respectively.[14] The clearing functions in LVTS are defined as follows:

$$T1Clearing = \begin{cases} 1 & if \;\; T1P_{t,s}^{ij} \leq T1MCC_{t,s}^{i} \\ 0 & otherwise \end{cases} \tag{8}$$

[14] The clearing functions are known as “risk controls” in the rules and documentation of Payments Canada.

$$T2Clearing = \begin{cases} 1 & if\ \ T1P_{t,s}^{ij} \leq T1BCC_{t,s}^{i}\ \ AND\ \ T1P_{t,s}^{ij} \leq T1MCC_{t,s}^{i} \\ 0 & otherwise \end{cases} \tag{9}$$

2.2. Total Netting

Total netting is the proportion of gross credit exposures that can be eliminated at a given time during the exchange period by netting the payment orders that have been cleared from the time that the payment exchange opens.

Total netting can be measured bilaterally and multilaterally. Bilateral netting is defined as follows:

$$\eta_{t,s}^{ij} = \eta_{t,s}^{ji} = min\left(\frac{Val_{t,s}^{ji}}{Val_{t,s}^{ij}}, \frac{Val_{t,s}^{ij}}{Val_{t,s}^{ji}}\right) \tag{10}$$

Multilateral netting is defined as

$$\eta_{t,s}^{i} = min\left(\frac{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}, \frac{\sum_{j\neq i}^{N} Val_{t,s}^{ij}}{\sum_{j\neq i}^{N} Val_{t,s}^{ji}}\right) \tag{11}$$

In the absence of novation, if the payments exchange were to close at a given time s during the day, say because of an operational disruption, the payments operator would have to settle the net bilateral exposures $(1-\eta_{t,s}^{ij})$ of each DP. If the payment operator novates payment orders, then it would have to settle the net multilateral exposure $(1-\eta_{t,s}^{i})$ of each DP.

2.3. Marginal Netting

Marginal netting is defined as the fraction of gross credit exposure that can be eliminated for the next dollar of payment flow through netting.

We propose the following specification to measure marginal netting:

$$\Delta T1Val_{t,s+h}^{ij} = \alpha + \beta_{1,t,s+h}^{ij}\left(\Delta T1Val_{t,s+h}^{ji}\right) + \beta_{2,t,s+h}^{ij}\left(\Delta T2Val_{t,s+h}^{ji}\right) + \varepsilon_{t,s+h}^{ij} \tag{12}$$

Where

$$\Delta T1Val_{t,s+h}^{ij} = T1Val_{t,s+h}^{ij} - T1Val_{t,s}^{ij} \tag{13}$$

The parameters β_1 and β_2 measure the degree of same-tranche netting and cross-tranche netting in T1, respectively. Intuitively, when DP j sends \$1 in T1 payment orders from time s to time $s + h$ on date t, DP i returns β_1 in T1; thus eliminating β_1 of the credit exposure. Similarly, when DP j sends \$1 in T2 payment orders from time s to time $s + h$ on date t, DP i returns β_2 in T1; thus, eliminating β_2 of the cross-tranche exposure. In other words, β_2 shows the degree of substitution from T2 to T1 credit exposures.

The same specification can be used for T2 a follows:

$$\Delta T2Val_{t,s+h}^{ij} = \alpha + \beta_{1,t,s+h}^{ij}\left(\Delta T1Val_{t,s+h}^{ji}\right) + \beta_{2,t,s+h}^{ij}\left(\Delta T2Val_{t,s+h}^{ji}\right) + \varepsilon_{t,s+h}^{ij} \tag{14}$$

Where

$$\Delta T1Val_{t,s+h}^{ij} = T1Val_{t,s+h}^{ij} - T1Val_{t,s}^{ij} \tag{15}$$

In this case, however, the parameters β_1 and β_2 measure the degree of cross-tranche netting and same-tranche netting in T2, respectively.

This specification allows us to test the degree of marginal netting in the system. Under the null hypothesis of no marginal netting, $\beta_1 = \beta_2 = 0$.

$$H_0 : No\ Shadow\ Netting\ (\beta_1 = \beta_2 = 0) \tag{16}$$

Variations can be devised for tranche-specific, cross-tranche and mixed-tranche marginal netting strategies and their perfect-netting subsets as follows:

$$\begin{gathered} H_1 : Tier\ Specific\ Marginal\ Netting\ (\beta_1 > 0\ and\ \beta_2 = 0) \\ H_1^P : Perfect\ Tier\ Specific\ Marginal\ Netting\ (\beta_1 = 1\ and\ \beta_2 = 0) \end{gathered} \tag{17}$$

$$\begin{gathered} H_2 : Cross\ Tier\ Marginal\ Netting\ (\beta_1 = 0\ and\ \beta_2 > 0) \\ H_2^P : Perfect\ Cross\ Tier\ Marginal\ Netting\ (\beta_1 = 0\ and\ \beta_2 = 1) \end{gathered} \tag{18}$$

$$\begin{gathered} H_3 : Mixed\ Tier\ Marginal\ Netting\ (\beta_1 > 0\ OR\ \beta_2 > 0) \\ H_3^P : Perfect\ Mixed\ Tier\ Marginal\ Netting\ (\beta_1 + \beta_2 = 1) \end{gathered} \tag{19}$$

Notice that there is a trade-off between netting and increasing clearing capacity. If a DP nets a credit exposure, it gives up the equivalent amount of clearing capacity. The parameter α tells us the average value of payment orders when there are no incoming payments. Indeed, it is possible for a DP to provide payments even if it has not received any payments from its counterparty; that is, such a DP would be a net clearing capacity supplier.

As is the case with other statistical relationships, our proposed netting measures are linked and provide complementary information. Marginal netting values above total netting values lead to an increase in total netting and vice versa. From an operational risk perspective, these netting relationships have different interpretations. Total netting determines the expected shortfall that a payments processor would incur during total operational disruptions. Specifically, increases in total netting lead to reductions in net credit exposures which reduce the expected shortfall during a total disruption. On the other hand, marginal netting relationships are related to partial operational disruptions. Specifically, partial operational disruptions, such as the inability of a member bank to access or send payments through its terminal, could break marginal netting relationships, resulting in higher net credit exposures per dollar of payment flow, which could lead to other DPs losing clearing capacity and eventually system gridlock.

3. Data

3.1. Data Description

We use historical transaction level data from the Canadian LVTS. Our sample ranges from March 1st, 2004 to December 30th, 2016 and includes all of the payment orders submitted by each DP during the main exchange period of the LVTS, the intraday value of the collateral posted by each DP and the intraday value of the BCLs granted to each DP. Table 1 lists the seventeen DPs currently registered in the LVTS and the number of non-DP partners associated with each DP. Non-DP partners are financial institutions that have a corresponding relationship with DPs to process their payment orders.

A payment order consists of an encrypted electronic message sent by a DP to LVTS through the communications network of the Society for Worldwide Interbank Financial Telecommunication (SWIFT). LVTS processes two types of SWIFT messages, called MT-103 and MT-205, that are generally used for customer and inter-DP (i.e., interbank) transfers, respectively (Payments Canada, 2017 – LVTS Rule 6). Each message includes information identifying the relevant counterparties of the transaction and a set of payment instructions. For our purposes, we use the information contained in the fields stating the sender, receiver, payment value, processing arrangement (T1 or T2), date and time of submission.

Figure 1 presents a timeline of the LVTS operating schedule that illustrates the different phases of the 24-hour payments cycle. For our empirical analysis, we focus on the main exchange period, which takes place between 6:00 and 18:00 and is indicated with a box in the figure. During this time, DPs submit all types of payment orders associated with their regular activities through both T1 and T2, including customer and inter-DP orders. The number of active DPs, as well as the value and volume of payment orders during this period is higher than during any other times in the payments cycle. Therefore, the main exchange period provides the best setting to study the ordinary interactions of DPs.

Payment orders occurring between 00:30 and 06:00 are typically devoted to the settlement of foreign exchange transactions through the Continuous Linked Settlement (CLS) system. (Payments Canada, 2017 – LVTS Rule 6). CLS is a foreign exchange settlement system, operated by the CLS Bank. All Canadian-dollar transactions in CLS are redirected to LVTS, where they ultimately processed for settlement (Bank of Canada, 2018). During this period, DPs with a direct or client interest in foreign exchange transactions dominate the market, which is a small subset of the entire pool of DPs. Prior to Decembe13th, 2010, only CLS related transactions were allowed between 00:30 and 06:00. After that date, non-CLS related payments were allowed but only for cases where the sender and the receiver have a bilateral agreement (Payments Canada, 2017– LVTS Rule 6). Therefore, it is unlikely that this period reflects the ordinary interactions of DPs, so it is excluded from our analysis. To handle this exclusion, we sum the value of all payment orders between 00:30 and 06:00 and use these values to calculate the opening balances of each DP at the start of the main exchange period at 06:00. Under the rules of the LVTS, DPs can use these opening balances to support payment activity during the main exchange period.

Our analysis also excludes the pre-settlement period that runs from 18:00 to 18:30. Most economists and financial professionals would recognize this period as the time when the overnight interbank credit market takes place. During this time, the LVTS only processes bilaterally agreed inter-DP payments that reflect overnight credit arrangements, including access to the lending facilities of the Bank of Canada. Inter-DP orders not associated to overnight lending and client orders cannot be processed during this period. While an analysis of the pre-settlement period could be interesting, it is beyond the scope of this paper. This phase of the payments cycle has the very specific objective of allowing DPs to reduce their net balances prior to settlement. As a consequence, it does not reflect the usual payment activity of direct members and their clients. In addition, there is no distinction between T1 and T2 payment orders during this period. Thus, we cannot assess the trade-offs of alternative collateral arrangements.

Our sample comprises periods of exogenous variation, including the entry and exit of DPs, the Great Financial Crisis, and a change in collateral requirements for BCLs. During our sample, XX DPs became direct members of the LVTS and XX DPs withdrew their direct membership. In accordance with the information provided by the National Bureau of Economic Research (NBER, 2010), we date the Great Financial Crisis from December 1st, 2007 to June 1st, 2009 and consider two additional periods, the pre-crisis period (from March 1st, 2004 to November 30th, 2007) and the post-crisis period (from June 2nd, 2009 to December 30th, 2016). On May 1, 2008, payments Canada increased the system wide percentage from 24% to 30%. This parameter is used to determine the collateral requirements for BCLs as a proportion of their notional value.

3.2. Summary Statistics

Table 2 present the summary statistics of the value and volume of payment orders for the full-sample, pre-crisis, crisis and post crisis periods, respectively. The contains two panels reporting summary statistics for payment orders submitted through T1 and T2, respectively. In addition, to reporting the summary statistics for all of the DPs in the sample (labelled “All”) each table partitions the sample into large and small DPs and reports separate amounts for the Bank of Canada. Large DPs (labelled “Large”), are those that have an average payment order value above the median over the entire sample period. Similarly, small DPs (labelled “Small”), are those that have an average payment value below the median over the entire sample period. Standard deviations are reported in brackets.

We will exclude the Bank of Canada when we report some of our empirical results in the next section. There are a number of reasons for adopting this approach. First, as the central bank of the country, the Bank of Canada plays a role that differs from that of other participants in the LVTS. It acts as the provider and custodian of settlement funds, lender of last resort, and guarantor of the payment system. Second, the Bank of Canada is a relatively passive participant that does not engage in a large number of payment transactions. Moreover, all payment orders addressing the Bank of Canada are restricted to T1 orders, which prevents us from analysing the trade-offs of alternative collateral provisions. Third, and perhaps most importantly, we are interested in understanding the interactions of typical DPs during the course of conducting their day-to-day operations.

Table 2 shows that the average gross daily value of payment orders, excluding the Bank of Canada, is around \$145 billion and the average gross daily volume is around 24,000 for T1 and T2 combined over the full sample period.[15] However, these figures vary significantly during the pre-crisis, crisis and post-crisis periods. Figure 2 complements the summary statistics in Table 2 by plotting the monthly (21 trading day) moving average of the gross daily value (Panel A) and the gross daily volume (Panel B) of payment orders over the entire sample period. The highlighted region in each panel identifies the Great Financial Crisis. The plots show that prior to the crisis, both the gross value and the gross volume of payments consistently increased. Values increased from approximately \$120 billion in mid-2004 to \$200 billion by late 2007. Similarly, volumes increased from approximately 16,000 to 22,000 during the same period. During the crisis, the gross value of payments decreased substantially, from around \$200 billion to \$140 billion, while daily volumes remained relatively constant at around 22,000. After the crisis, the value of payments stagnated at around \$140 billion, but the volume continued to increase from 22,000 to 35,000 payment orders per day.

Taken together, the value and volume data presented in Figure 2 indicates that the value of the average payment order has consistently decreased over time from around \$7.5 million in 2004 to around \$4.5 million by the end of 2016. In addition, the number of payment orders processed per hour during the main exchange has increased on average from 1,300 to 2,900 during the same period. In short, the data shows a trend towards payment orders with lower value that are submitted more frequently. This trend could be the result of the efforts of Payments Canada to distribute the flow of payment orders throughout the day to ensure the smooth operation of the LVTS. These efforts began in the mid-2000s and include the adoption of non-mandatory intraday value and volume targets that DPs are encouraged to follow (Payments Canada, 2017 – LVTS Rule 6). These targets are presented in Table 3. Given the non-mandatory nature of these targets, the trend could also reflect the willingness of DPs to distribute their payment volume more evenly throughout the day to improve netting of exposures and reduce collateral requirements. After all, every unit of collateral that is not encumbered in the payment system, can be used to support other financial transactions, such as swaps, repo and securities lending.

Panel A and B of Table 4 shows collateral statistics for T1 and T2 for each sample period. Notice how the amount of collateral both in T1 and T2 increased during the crisis period, despite the value of payments decreasing (shown in Figure 2). The increase in collateral requirements in T2 were in part the result of a higher collateralization parameter in equation 7, θ, from 0.24 to 0.30. Table 5 shows the average BCL sent and received by each DP over each sub-period. Figure 3 complements this information by showing the cross-sectional average of the intraday level of collateral and BCL. Figure 4 further refines this information by DP size.

[15] These numbers are based on our sample; however, Payments Canada releases similar statistics on an annual basis.

For the intraday charts, the x-axis in all plots reflects the time of the main exchange period, from 06:00 to 18:00.

Figure 5 shows the cross-sectional average of gross payment value at the bilateral ($\bar{P}^{B}_{d+h}$) and multilateral ($\bar{P}^{M}_{d+h}$) level for T1, T2 and T1 and T2 combined. Confidence intervals are shown in dotted lines. Appendix A explains how each variable was constructed from the payment flow, $P^{ij}_{t,s}$. Panel A and B show that the values of T1 orders are lower than those of T2 orders at any time during the main exchange period both at the bilateral and multilateral levels. Panel A shows that the flow of value in T1 remains relatively low throughout the exchange period but peaks towards the end of the day from 16:30 to 18:00. Panel B shows that at around the same time, the value of T2 payment orders, which tends to be high and relatively stable from 08:30 to 16:30, starts decreasing significantly. This would indicate that DPs substitute, on a relative basis, T2 for T1 payment orders as the end of the exchange period, and the time for settlement, approaches. Figure 6 complements this information by showing the average payment order value by DP size.

Figures 6 and 7 show that the payment orders with the highest values tend to be concentrated towards the end of the exchange period both for T1 and T2. This would indicate that DPs coordinate the submissions of at least, their largest payment orders. These orders would normally require, in the case of T1, a large amount of collateral to be posted by the sender or, in the case of T2, using up a significant amount of the BCL granted to the sender and imposing some credit risk on the receiver. Coordination, allows DPs to net a significant amount of the value of these payment orders and reduce the amount of collateral requirements and credit risk.

Figure 7 presents intraday gross volume information. Appendix A also explains the construction of these variables. Intraday gross volume trends are consistent with those of intraday gross payment values. Panels A and B show that the volume of T1 orders is much lower than that of T2 orders. The volume of T1 orders increases from 16:30 to 18:00, while at the same time, the volume of T2 orders starts decreasing. This provides further evidence that indicates that DPs switch their preferences throughout the exchange period and favor, on a relative basis, defaulter-pay agreements as the time to settlement approaches.[16] Figure 8 complements this information by showing the average payment order volume by DP size.

4. Results

4.1. Total Netting

Figure 11 shows the cross-sectional average of total bilateral and multilateral netting for the full sample period. Panel A shows the results for T1 payment orders, Panel B shows the results for T2 payment orders and Panel C shows the results for T1 and T2 payment orders combined. The information provided in Panel C is relevant in LVTS because T1 and T2 payment orders are aggregated before settlement.

The results in Figure 11 have two important implications. First, the increasing pattern of total netting throughout the exchange period implies that, per dollar of payment order, systemic operational disruptions are

[16] Cruz Lopez and Ibanez (2018) show that because T1 orders are collateralized using a defaulter-pay provision, they can be seen as secured credit. On the other hand, T2 orders are collateralized using a survivor-pay provision, so they can be seen as unsecured credit supported with the capital of creditors.

more likely to result in larger margin calls and shortfalls when they occur earlier in the trading day. Recall from our previous discussion that any credit exposures that are not netted out need to be collateralized to ensure their settlement. Therefore, as the day progresses and total netting increases, the payments operator requires less collateral per dollar of payment order to ensure settlement. Panel C shows that by the time that the exchange period concludes, only about 5% of gross multilateral exposures need to be collateralized to ensure settlement.

The second implication of Figure 11 is that the netting structure adopted by the payments operator determines the magnitude of margin calls and shortfalls in case of a systemic operational disruption. Novation allows the payments operator to net credit exposures multilaterally and, as a consequence, reduce collateral requirements, settlement balances, the risk of default and losses given default relative to bilateral netting alone. Panel C of Figure XX shows that compared to the bilateral netting case, the payments operator significantly reduces credit exposures by adopting multilateral netting. At the beginning of the exchange period, credit exposures are reduced by 15% (i.e., total netting increases from 15% to 30% of gross payment order value) and by the end of the exchange period, credit exposures are reduced by 60% (i.e., total netting increases from 35% to 95% of gross payment order value). These reductions imply potential collateral savings of $24 billion at the beginning of the exchange period and $92 billion at the end of the exchange period. Importantly, the fact that multilateral netting is higher than bilateral netting throughout the exchange period implies that on average, DPs interact with more than one counterparty. Other things equal, the larger the counterparty (or netting) set, the greater the difference between bilateral and multilateral netting.

Figure 12 provides additional information on total multilateral netting by dividing the sample into large DPs (black line) and small DPs (magenta line). The chart shows that small DPs net less than large DPs. Therefore, per dollar of payment order, transactions with small DPs tend to contribute more to the risk of the payment system and require more clearing capacity. Figure XX partitions these results for the pre-crisis, crisis and post-crisis periods. We find that total multilateral netting decreased significantly in T2 during the post-crisis period, particularly for small DPs. This result indicates that clearing capacity in T2 was less constrained after the crisis, which is consistent with our findings (not reported in the charts and tables) that DPs contributed more collateral and increased the BCLs that they granted and received after the crisis period. Therefore, our results indicate that the incentive to preserve clearing capacity through netting has decreased, likely as a result of the low interest rate environment prevalent since the financial crisis, which has reduced the opportunity cost of collateral and settlement balances.[17]

Finally, Figure 13 also shows that the difference between multilateral and bilateral netting is lower in T1 than in T2. Relative to T2, the netting dynamics in T1 could be the result of lower aggregate values and volumes of payment orders or less coordination. To separate between these two possibilities, we need to measure the level of coordination at the bilateral and multilateral level in T1 and T2.

4.2. Marginal Netting

[17] Recall that the clearing capacity of a DP in T1 is determined by the amount of collateral that it apportions to the payments operator. In T2, the clearing capacity of a DP is determined by the BLCs grated by its counterparties, who need to collateralize the exposures.

We estimate the specification in equations 12 and 14 and include the control variables listed in Table 6 and Table 7 for T1 and T2, respectively. Figures 14 and 15 show the results of our marginal netting model for T1 and T2, respectively, for the full sample period. Panel A of both figures reports the same-tranche marginal netting coefficients; that is, marginal netting taking place from T1 to T1 and from T2 to T2, respectively. Similarly, Panel B of the figures reports the cross-tranche marginal netting coefficients; that is, marginal netting taking place from T1 to T2 and from T2 to T1, respectively.

In terms of same-tranche netting, Panel A of Figure 14 shows that bilateral netting in T1 is virtually nonexistent. This result indicates that DPs do not coordinate bilaterally to net secured (i.e., defaulter-pay) credit exposures. In contrast, Panel A of Figure 15 shows that for T2, DPs tend to coordinate bilaterally and net out between 20% and 60% of their unsecured (i.e., survivor-pay) exposures within 30 minutes. Thus, this set of results suggests that DPs are willing to coordinate bilaterally and give up some clearing capacity to manage and reduce their unsecured (i.e., T2) but not their secured (i.e., T1) credit exposures.[18]

From an operational risk perspective, our results imply that partial operational disruptions are more likely to have a bilateral impact on T2 than on T1 counterparties. If the typical DP becomes disabled and cannot access the payment system, on average, their counterparties will not experience a direct loss of clearing capacity in T1. However, the counterparties of the disabled DP would experience an additional decrease in T2 bilateral clearing capacity ranging from $0.20 to $0.60 per dollar of T2 payment order within 30 minutes, which is equivalent to the bilateral marginal netting coefficient. This situation occurs because the disabled DP cannot send back a T2 payment order for that amount to net the orders of its counterparties. In other words, the disabled DP becomes a drain on the clearing capacity of its counterparties and the magnitude of such drain increases with its marginal netting coefficient. In an extreme situation, a DP with a large marginal netting coefficient could exhaust the clearing capacity of other DPs and lead to systemic gridlock.

In contrast to our bilateral results, Panel A of Figure 14 shows that DPs net their T1 payment orders at the multilateral level. Multilateral netting in T1 increases throughout the day and peaks in the afternoon at around 40%, when the Bank of Canada is included in the sample, and at around 97%, when it is excluded. The peak in multilateral netting corresponds to the time of the day when T1 gross payment order value reaches a maximum (see Panel A of Figure 5) and, as a consequence, DPs experience tighter clearing capacities that require additional collateral contributions (see Panel A of Figure 3). Thus, these findings confirm that DPs increase their coordination and netting when collateral is scarce. [19]

From an operational risk standpoint, our multilateral marginal netting results for T1 imply that a disabled DP is more likely to cause a drain in multilateral clearing capacity in the afternoon, when netting coefficients are at their highest. If such a disruption occurs, the payments operator would need to collect a up to an additional

[18] It is important to note that DPs tend to use T1 for payment orders to the Bank of Canada and for critical payment orders to other DPs, both of which are difficult to coordinate bilaterally for the purposes of netting by construction. However, the results in Figure 14 show that the bilateral results for T1 are consistent with and without the Bank of Canada in the sample (represented by the blue and red lines, respectively). Moreover, DPs can choose to send payments to other DPs through T1 or T2. The reason they choose T1 for submitting critical payment orders is because the resulting credit exposure is secured, which allows the receiving DP to release the dollar amount to its customers without being exposed to a shortfall at settlement.

[19] Multilateral netting is lower when the Bank of Canada is included because it acts as a lender or borrower with unlimited clearing capacity to facilitate the settlement process. Thus, throughout the exchange period, the Bank of Canada either collects debt repayments or repays deposits that are not matched with corresponding transactions from DPs.

$0.97 in collateral per dollar of T1 order sent to the disabled DP from all of its counterparties in order to cover the risk exposure generated within the next 30 minutes. In an extreme situation, this could lead to collateral shortages and prevent DPs from submitting payment orders; thus, exacerbating the problem.

Taken together, the bilateral and multilateral netting results for T1 show that while DPs do not coordinate bilaterally, they do manage the timing of their payment order submissions and receipts across multiple counterparties to preserve clearing capacity and thus, collateral. This result is consistent with the fact that at the DP level, unencumbered collateral is fungible and can be used to secure credit obligations to any counterparty in a process that resembles collateral rehypothecation (see Singh, 2012).

For T2, multilateral netting is high and persistent during the exchange period. The multilateral netting coefficient ranges from 40% to 95% and tends to remain stable at around 80% for most of the exchange period. This result means that when the typical DP receives $1 of T2 payment orders from any counterparty, it issues on average $0.80 of T2 payment orders within a 30-minute period; thus, eliminating 80% of the multilateral credit exposure. This result also implies that DPs experience an average decrease of only $0.20 in multilateral clearing capacity per dollar issued in T2 payment orders. From an operational risk perspective, this result means that a disabled DP would on average drain $0.80 of clearing capacity from the system for every dollar of T2 payment orders that it receives. Equivalently, this implies that the payments operator would require an additional collateral amount of $0.80 per dollar of T2 orders from all DPs to cover the additional risk exposures generated by the disruption within a 30-minute interval.

The fact that multilateral netting coefficients are greater than bilateral netting coefficients in T2 indicates that DPs try to preserve multilateral clearing capacity more aggressively by managing the timing of their payment orders across different counterparties. This is a sensible strategy for DPs to follow because as explained in Section 3, when a DP exhausts its multilateral clearing capacity in T2, it cannot clear any T2 payment orders, even if it has abundant bilateral clearing capacity.

Panel B of Figures 14 and 15 shows that there is virtually no cross-tranche netting in LVTS. Thus, at the margin, DPs do not substitute secured (i.e., T1 or defaulter-pay) for unsecured (i.e., T2 or survivor-pay) credit exposures and vice versa. There is, however, a small exception to this rule for T1. Panel B of Figure 14 shows that during the period from 16:30 to 18:00 payments sent through T2 are netted out at a rate of between 3%-8% in T1; that is, there is a partial substitution of unsecured for secured credit exposures during the last minutes of the exchange period. During this time, both bilateral and multilateral same-tranche netting in T2 decreases significantly. Thus, these results indicate that at the margin, any substitution of unsecured for secured credit exposures tends to happen as the settlement time approaches and the risk of default increases.[20]

Figure 16 shows the average same-tranche marginal netting coefficients by DP size. The results show that large DPs net more than small DPs. Therefore, operational disruptions affecting large DPs could lead to larger drains of clearing capacity at both the bilateral and multilateral levels, than operational disruptions affecting small DPs. Interestingly, however, large DPs are also the most exposed to partial operational disruptions. Panel B of Figure 16 shows the T2 bilateral netting coefficients for payment orders between large DPs (black line), between small DPs (green line), from large DPs to small DPs (magenta line) and from small DPs to large DPs

[20] Cruz-Lopez and Ibanez (2018) present an option-based model that explains the substitution between secured and unsecured exposures. Market participants have an incentive to convert their unsecured exposures to secured exposures as the time to settlement decrease and the distance to default increases to minimize their loss given default.

(cyan line). These results show that disruptions to large DPs would tend to have a more severe impact on the clearing capacity of other large DPs than on that of small DPs (the black line is above the magenta line). Moreover, if a small DP is disabled, it would tend to have a more severe impact on the clearing capacity of large DPs than on that of other small DPs (the cyan line is above the green line). This is because small DPs do not coordinate and net a significant amount of their transactions among themselves (the green line is at the bottom).

Figure 17 shows the average multilateral marginal netting coefficient for T1 payment orders during the pre-crisis, crisis and post-crisis periods. Figures 18 and 19 show the bilateral and multilateral marginal netting coefficients for T2 during the same periods. Notice that marginal multilateral netting in T1 increased during the post-crisis period, whereas marginal multilateral netting in T2 decreased during the same period, relative to the pre-crisis period. Figure 17 shows that for T1, the increases in multilateral netting were driven by additional coordination between large and small DPs. Large DPs tend to have higher levels of marginal multilateral netting than small DPs for all sub-periods. However, small DPs increased their level of multilateral netting during the crisis and post-crisis periods, so it became more synchronized with that of large DPs. Figure 19 shows that for T2 the decrease in multilateral netting was largely driven by small DPs.

4.3. Summary of Results

Our results show that large DPs tend to have very resilient marginal netting relationships, whereas small DPs have more variation in their netting behaviour. After the financial crisis, small DPs increased their level of netting for secured (i.e., T1 or defaulter pay) credit obligations, and all DPs decreased their level of netting for unsecured (i.e., T2 or survivor-pay) credit obligations. This indicates that small DPs have become relatively more reliant on secured credit after the financial crisis and all DPs tend to carry larger unsecured credit exposures.

In Section 4.1 we mentioned that the higher level of total multilateral netting in T2 relative to T1 could be explained by either lower values and volumes of payment orders or less coordination in T1. By contrasting the results of Figures 14 and 15, we can see that coordination and marginal netting in T2 is significantly higher than in T1. Moreover, Panel B of Figures 5 and 7 show that neither the volumes nor the values in T2 grow monotonically throughout the exchange period. Instead, these variables follow a relatively stable and persistent pattern. Therefore, we can conclude that it is the level of coordination among DPs, and not the level of payment order volumes or values, that leads to higher total netting T2 than in T1.

5. Conclusion and Policy Implications

In this paper, we argue that netting relationships are the main determinant of credit exposures and collateral efficiency. DPs use netting to minimize the amount of collateral that they contribute to the payments operator and to manage their bilateral and multilateral risk exposures. Our results show that unsecured (i.e., survivor-pay) credit obligations tend to be favored when managing the bilateral risk of large and well-known counterparties (i.e., those with low asymmetric information). On the other hand, secured (i.e., defaulter-pay) credit obligations tend to be favored when managing the risk of small or less known counterparties (i.e., those with high asymmetric information). By securing credit exposures with collateral, DPs can manage secured risks multilaterally because collateral is fungible.

We also argue that total netting relationships determine the shortfall of total or systemic operational disruptions and partial netting relationship determine the shortfall or partial operational disruptions. Empirically, we find that large participants net more than small participants. Therefore, per dollar of credit obligation, small participants contribute more to the risk of the system. However, because of their reliance on netting to preserve clearing capacity, large participants are more exposed to both systemic and partial operational disruptions. Importantly, our analysis also shows that by enabling multilateral netting, novation reduces collateral requirements significantly and, as a consequence, it reduces the risk of default, loss given defaults and shortfalls of operational disruptions.

As it would be expected, when risk increases, as it did during the financial crisis, market participants tend to rely more on secured credit and less on unsecured credit. However, intraday, there is little substitution of secured for unsecured credit at the margin during the exchange period. The only exception is as the time of settlement approaches. During the last hour and a half of the exchange period, DPs exchange a small amount of unsecured for secured exposures for their small counterparties. This suggests that there is optionality in unsecured credit exposures and market participants have an incentive to reduce their unsecured exposures as settlement approaches.

Another important result is that small participants are more susceptible to changes in netting and collateralization. Therefore, small participants could be collateral squeezed, particularly during a period of financial distress, when they are required to post more collateral to support their credit obligations and the BCLs that they grant to large participants tend to increase.

Finally, our analysis indicates that when interest rates are low, the incentive to net decreases, because the opportunity cost of collateral is low. When interest rates are high, the opposite happens. This has important implications for monetary policy and its effect on collateral rehypothecation. We should expect and increase in collateral rehypothecation, and its velocity, as we gradually move out of the low interest rate environment.

References

Arjani, N. and McVanel, D. (2006). *A Primer on Canada's LVTS*, Bank of Canada Working Paper, March.

Ashcraft, A. B., and Duffie, D., (2007). *Systemic Illiquidity in the Federal Funds Market*, American Economic Review, Vol. 97 No. 2, pp. 221-225, May.

Bank for International Settlements (2003). *A Glossary of Terms Used in Payments and Settlement Systems*.

Bank for International Settlements (2012). *Principles for Financial Market Infrastructures*

Bank of Canada (2016). *Canada's Major Payments Systems*, http://www.bankofcanada.ca/core-functions/financial-system/canadas-major-payments-systems/

Bech, M. and Soramäki, K. (2001). *Gridlock resolution in interbank payment systems*, Bank of Finland Discussion Papers, No. 9.

Bech, M. and Soramäki, K. (2002). *Liquidity, gridlocks and bank failures in large value payment systems*, E-money and Payment Systems Review, Central Banking Publications, London.

Bech, M. and Garratt, R. (2003). *The intraday liquidity management game*, Journal od Economic Theory, Vol. 109 No. 2, pp. 198-219, April.

Bech, M. Champman, J. T. E., Garratt, R. (2010). *Which Bank is the 'Central' Bank? An Application of Markov Theory to the Canadian Large-Value Transfer System, Journal of Monetary Economics*, Vol. 57, No. 3, pp. 352-363, April.

Bech, M. and Garratt, R., (2012) *Illiquidity in the Interbank Payment System Following Wide-Scale Disruptions*, Journal of Money, Credit, and Banking, Vol. 44, No. 5, August.

Chiu, J., Lai, A. (2007). *Modelling Payment Systems: A Review of the Literature*, Bank of Canada Working Papers, April.

Kahn, C., McAndrews, J., Roberds, W. (2003). *Settlement Risk under Gross and Net Settlement*, Journal of Money, Credit and Banking, Vol. 35, No. 4, pp. 591-608.

Kambhu, Weidman and Krishnan, 2007, The Payments System and the Market for Interbank Funds, Economic Policy Review, Vol. 13, No. 2.

Furfine, C. (1999). *Interbank Exposures: Quantifying the Risk of Contagion*, BIS Working Paper No. 70. June.

Howard, 2005, "A Primer on the Implementation of Monetary Policy in the LVTS Environment", Bank of Canada Working Paper.

Martin, A., McAndrews, J. (2008). *liquidity-saving Mechanisms*, Journal of Monetary Economics 55, 554-567.

McAndrews, J., and Rajan, S. (2000). *The Timing and Funding of Fedwire Funds Transfers*, Economic Policy Review, Vol. 6, No. 2, July.

McAndrews, J. and Potter, S. (2002). *Liquidity Effects of the Events of September 11, 2001*, Economic Policy Review, Vol. 8, No. 2, pp. 59-79, November.

McVanel, D. (2005). *The Impact of Unanticipated Defaults in Canada's Large Value Transfer System*, Bank of Canada Working Paper, September.

Merrouche, O. and Schanz, J. (2010). *Banks' intraday liquidity management during operational outages: Theory and evidence from the UK payment system,* Journal of Banking & Finance, Vol 24, No. 2, pp. 314-323, February.

Payments Canada (2016) *Payments Glossary*, https://www.payments.ca/resources/payments-glossary

Soramaki, et al., (2006). *The Topology of Interbank Payment Flows,* Staff Reports from Federal Reserve Bank of New York, No. 243.

Zhang, N. (2015). *Changes in Payment Timing in Canada's Large Value Transfer System*, Bank of Canada Staff Working Papers.

Zhou, R. (2000). *Understanding intraday credit in large-value payment systems,* Economic Perspectives: Federal Reserve Bank of Chicago, Vol. 24, No. 3, pp. 29-44, August.

Appendix: Construction of Value and Volume Variables

The payments operator observes $P_{t,s}^{ij}$. From this information, we calculate the gross value of payment messages processed on date t as follows

$$P_t = \sum_{s=1}^{S} \sum_{i=1}^{N} \sum_{j \neq i}^{N-1} P_{t,s}^{ij} \tag{A1}$$

The bilateral volume of payment order submissions from DP i to DP j at a particular time (t, s) is

$$Vol_{t,s}^{ij} = I_{\{P_{t,s}^{ij} > 0\}} \tag{A2}$$

Thus, the gross daily volume processed by the operator is

$$Vol_t = \sum_{s=1}^{S} \sum_{i=1}^{N} \sum_{j \neq i}^{N-1} Vol_{t,s}^{ij} \tag{A3}$$

To construct intraday summary statistics plots, we start by aggregating $P_{t,s}^{ij}$ intraday to obtain the bilateral value of payment orders from DP i to DP j over non-overlapping intervals of length $h = 30\ minutes$ as follows

$$P_{t,s+h}^{ij} = \sum_{d=s}^{d=s+h} P_{t,d}^{ij} \tag{A4}$$

We then compute equation 24 to obtain $\bar{P}_{t,s+h}^{i}$, the average payment order value that DP i sends to its active counterparties, $A_{t,s+h}^{i}$, from s to $s + h$ on date t

$$\bar{P}_{t,s+h}^{i} = \left(\frac{1}{A_{t,s+h}^{i}}\right) \sum_{j \neq i}^{A_{t,s+h}^{i}} P_{t,s+h}^{ij} \tag{A5}$$

DP j is an active counterparty of i if it is addressed in at least one payment order of i in the interval s to $s + h$ on date t. We then compute equation 25 to obtain $\bar{P}_{t,s+h}^{B}$, which can be interpreted as the typical value of the payment order submitted by the typical DP to an active counterparty from s to $s + h$ on date t

$$\bar{P}^{B}_{t,s+h} = \left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\left(\frac{1}{A^{i}_{t,s+h}}\right)\sum_{j\neq i}^{A^{i}_{t,s+h}} P^{ij}_{t,s+h} \tag{A6}$$

N_t is the number of active DPs on date t. A DP is considered to be active in the payments system on a given date if it has submitted or received at least one payment order during the main payments exchange.

We average $\bar{P}^{B}_{t,s+h}$ over the entire time series to obtain the expected value of the bilateral payment orders from d to $s+h$.[21]

$$\bar{P}^{B}_{s+h} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\left(\frac{1}{A^{i}_{t,s+h}}\right)\sum_{j\neq i}^{A^{i}_{t,s+h}} P^{ij}_{t,s+h} \tag{A7}$$

The statistic $\bar{P}^{B}_{d+h}$ can be interpreted as the expected value of the payment orders submitted by the typical DP to its active counterparties from s to $s+h$ on a typical day.

We also compute the expected value of multilateral payment orders, $\bar{P}^{M}_{s+h}$, using equation (27). This statistic can be interpreted as the typical value of the payment orders submitted by the typical DP to *all* of its active counterparties from s to $s+h$ on a typical day.

$$\bar{P}^{M}_{s+h} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\sum_{j\neq i}^{A^{i}_{t,s+h}} P^{ij}_{t,s+h} \tag{A8}$$

Finally, the system-wide expected gross value of payment orders, $\bar{P}^{SW}_{d+h}$, can be computed using equation (28) and interpreted as the value of payment orders typically sent for processing to the payments operator from s to $s+h$ on a typical day.

$$\bar{P}^{SW}_{s+h} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\sum_{i}^{N_t}\sum_{j\neq i}^{A^{i}_{t,s+h}} P^{ij}_{t,s+h} \tag{A9}$$

The process for constructing volume variables is similar to that followed for gross payment values, such that

[21] Notice that in the special case where each DP addresses a payment order to all other DPs in the system, $A^{i}_{t} = N_t - 1$, and $\bar{P}^{B}_{d+h} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t\times(N_t-1)}\right)\sum_{i}^{N_t}\sum_{j\neq i}^{N_t-1} P^{ij}_{t,d+h}$.

$$Vol_{t,s+h}^{ij} = \sum_{d=s}^{d=s+h} Vol_{t,d}^{ij} \tag{A10}$$

$$\overline{Vol}_{d+h}^{B} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\left(\frac{1}{A_{t,s+h}^{i}}\right)\sum_{j\neq i}^{A_{t,s+h}^{i}} Vol_{t,s+h}^{ij} \tag{A11}$$

$$\overline{Vol}_{d+h}^{M} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\sum_{j\neq i}^{A_{t,s+h}^{i}} Vol_{t,s+h}^{ij} \tag{A12}$$

$$\overline{Vol}_{s+h}^{SW} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\sum_{i}^{N_t}\sum_{j\neq i}^{A_{t,s+h}^{i}} Vol_{t,s+h}^{ij} \tag{A13}$$

The gross value per payment order at each level is calculated as follows.

$$\overline{VPO}_{s+h}^{B} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\left(\frac{1}{A_{t,s+h}^{i}}\right)\sum_{j\neq i}^{A_{t,s+h}^{i}} \frac{P_{t,s+h}^{ij}}{Vol_{t,s+h}^{ij}} \tag{A14}$$

$$\overline{VPO}_{s+h}^{M} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\left(\frac{1}{N_t}\right)\sum_{i}^{N_t}\sum_{j\neq i}^{A_{t,s+h}^{i}} \frac{P_{t,d+h}^{ij}}{Vol_{t,d+h}^{ij}} \tag{A15}$$

$$\overline{VPO}_{s+h}^{SW} = \left(\frac{1}{T}\right)\sum_{t=1}^{T}\sum_{i}^{N_t}\sum_{j\neq i}^{A_{t,s+h}^{i}} \frac{P_{t,s+h}^{ij}}{Vol_{t,s+h}^{ij}} \tag{A16}$$

Table 1: Canadian LVTS DPs

Number	Direct DP	Non-DP Partners
1	Alberta Treasury Branches	0
2	Bank of America National Association	0
3	Bank of Canada	0
4	Bank of Montreal	14
5	BNP Paribas	0
6	Caisse Centrale Desjardins	4
7	Canadian Imperial Bank of Commerce	9
8	Central 1 Credit Union	13
9	HSBC Bank Canada	0
10	ICICI Bank Canada	0
11	Laurentian Bank of Canada	1
12	Manulife Bank of Canada	0
13	National Bank of Canada	0
14	Royal Bank of Canada	21
15	State Street	0
16	The Bank of Nova Scotia	2
17	Toronto-Dominion Bank	1

Table 2: Aggregate Daily Payment Order Values and Volume

	Full Sample			Pre-Crisis Period			Crisis Period			Post-Crisis Period		
	N	**VAL**	**VOL**	**N**	**VAL**	**VOL**	**N**	**VAL**	**VOL**	**N**	**VAL**	**VOL**
Panel A: T1 Payments												
All	18	29.17	0.24	15	20.61	0.20	15	27.45	0.23	18	33.71	0.26
		(13.09)	(0.05)		(7.68)	(0.03)		(10.14)	(0.04)		(13.53)	(0.05)
Large	8	13.42	0.04	8	9.33	0.03	8	12.84	0.05	8	15.55	0.05
		(7.04)	(0.03)		(4.47)	(0.02)		(6.06)	(0.03)		(7.34)	(0.03)
Small	9	1.54	0.03	6	1.43	0.03	6	1.48	0.03	9	1.60	0.03
		(0.96)	(0.01)		(0.84)	(0.01)		(0.82)	(0.01)		(1.03)	(0.01)
Bank of Canada	1	14.21	0.16	1	9.85	0.14	1	13.13	0.15	1	16.57	0.17
		(5.77)	(0.03)		(2.99)	(0.01)		(4.08)	(0.02)		(5.79)	(0.03)
Panel B: T2 Payments												
All	18	130.25	23.94	15	135.88	18.57	15	150.26	21.96	18	123.54	26.95
		(24.58)	(5.91)		(26.92)	(3.21)		(25.53)	(3.60)		(19.91)	(5.22)
Large	8	121.25	21.71	8	126.43	16.97	8	138.21	19.88	8	115.36	24.40
		(22.61)	(5.37)		(24.80)	(2.96)		(23.53)	(3.30)		(18.64)	(4.84)
Small	9	8.99	2.22	6	9.44	1.60	6	12.05	2.07	9	8.17	2.56
		(2.51)	(0.58)		(2.74)	(0.28)		(2.55)	(0.33)		(1.76)	(0.45)
Bank of Canada	1	0.00	0.00	1	0.01	0.00	1	0.00	0.00	1	0.00	0.00
		(0.01)	(0.00)		0.03	0.00		(0.02)	(0.00)		(0.01)	(0.00)

Note: The table reports the time series average of aggregate payment order values and volumes. VAL is payment order values in billions of Canadian dollars. VOL is payment order volumes in thousands. Numbers in in brackets are standard deviations. The All category includes all Direct DPs in the LVTS. The Large and Small categories group Direct DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. These categories exclude the Bank of Canada.

Table 3: Suggested Guidelines for Payment Transmissions

Time	Daily Payment Order Dollar Value	Daily Payment Order Volume
10:00 (Local)	25%	40%
13:00 (Local)	60%	60%
16:30 (EST)	80%	80%

Note: According to Rule 6 of the LVTS, Direct DPs, excluding the Bank of Canada, are currently encouraged to meet these minimum targets by the specified time on a best efforts basis. However, if Direct DPs do not meet these targets and this situation prevents the smooth operation of the LVTS, the targets could become mandatory or the intraday fee structure could be changed to encourage DPs to meet the targets (Payments Canada, 2017).

Table 4: Aggregate Collateral and Bilateral Credit Lines

	Full Sample		Pre-Crisis Period		Crisis Period		Post-Crisis Period	
	N	**Collateral**	**N**	**Collateral**	**N**	**Collateral**	**N**	**Collateral**
				Panel A: T1 Collateral				
All	17	11.37	14	8.37	14	10.61	17	13.00
		(3.69)		(2.12)		(2.90)		(3.45)
Large	8	8.94	8	6.22	8	7.09	8	10.63
		(3.49)		(1.64)		(2.83)		(3.23)
Small	9	2.44	6	2.15	6	3.51	9	2.36
		(0.91)		(1.06)		(0.58)		(0.72)
				Panel B: T2 Collateral				
All	17	4.63	14	3.63	14	4.64	17	5.11
		(0.74)		(0.49)		(0.53)		(0.19)
Large	8	3.78	8	3.01	8	3.83	8	4.15
		(0.58)		(0.38)		(0.45)		(0.15)
Small	9	0.84	6	0.63	6	0.81	9	0.95
		(0.19)		(0.18)		(0.11)		(0.10)
`	**N**	**BCL**	**N**	**BCL**	**N**	**Collateral**	**N**	**Collateral**
				Panel C: BCL Received				
All	17	75.26	14	75.26	14	81.41	17	92.19
		(7.76)		(7.76)		(2.01)		(4.03)
Large	8	39.35	8	39.35	8	69.10	8	77.19
		(3.22)		(3.22)		(1.71)		(2.76)
Small	9	10.90	6	10.90	6	12.31	9	14.99
		(1.83)		(1.83)		(0.58)		(1.47)
				Panel D: BCL Sent				
All	17	71.68	14	71.68	14	77.53	17	87.80
		(7.39)		(7.39)		(1.91)		(3.84)
Large	8	37.55	8	37.55	8	65.49	8	73.65
		(3.01)		(3.01)		(1.65)		(2.83)
Small	9	10.79	6	10.79	6	12.05	9	14.14
		(1.73)		(1.73)		(0.52)		(1.24)

Note: The table reports the time series average of daily aggregates of collateral in T1 and T2 and BCLS received and sent. Collateral and BCL values are in billions of Canadian dollars. Numbers in in brackets are standard deviations. The All category includes all Direct DPs in the LVTS. The Large and Small categories group Direct DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. All these categories exclude the Bank of Canada because the BoC does not post collateral or extend BCLs.

Table 5: Average Bilateral Credit Line

	Full Sample		Pre-Crisis Period		Crisis Period		Post-Crisis Period	
	N	**Average**	**N**	**Average**	**N**	**Average**	**N**	**Average**
Panel A: BCL Received								
All	17	5.06	14	5.38	14	5.82	17	5.42
		(0.55)		(0.55)		(0.14)		(0.24)
Large	8	9.06	8	8.04	8	8.64	8	9.65
		(0.88)		(0.78)		(0.21)		(0.34)
Small	9	1.50	6	1.82	6	2.05	9	1.67
		(0.27)		(0.30)		(0.10)		(0.16)
Panel B: BCL Sent								
All	17	4.82	14	5.12	14	5.54	17	5.16
		(0.52)		(0.53)		(0.14)		(0.23)
Large	8	8.62	8	7.61	8	8.19	8	9.21
		(0.87)		(0.74)		(0.21)		(0.35)
Small	9	1.44	6	1.80	6	2.01	9	1.57
		(0.23)		(0.29)		(0.09)		(0.14)

Note: The table reports the time series average of cross-sectional average of BCLS received and sent. BCLs are in billions of Canadian dollars. Numbers in in brackets are standard deviations. The All category includes all Direct DPs in the LVTS. The Large and Small categories group Direct DPs above and below the cross-sectional median value of payment orders during the sample period, respectively. All these categories exclude the Bank of Canada because the BoC does not extend BCLs.

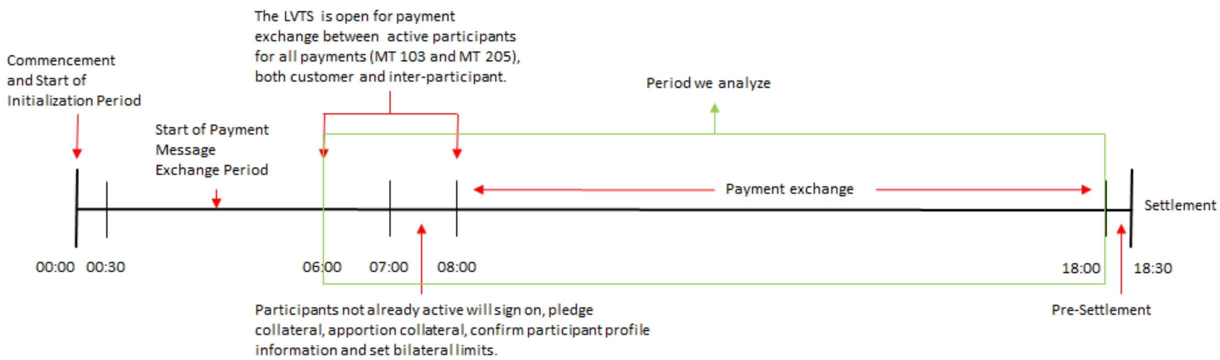
Table 6: Marginal Bilateral Netting Regression Controls

Control Type	**Variables**	**Description**
DP	$T1MCC_{t,s}^{i}$	T1 multilateral clearing capacity for DP i
	$\Delta T1MCC_{t,s+h}^{i}$	Change in $T1MCC$ for DP i over period h
	$T2MCC_{t,s}^{i}$	T2 multilateral clearing capacity for DP i
	$\Delta T2MCC_{t,s+h}^{i}$	Change in $T2MCC$ for DP i over period h
	$T2BCC_{t,s}^{ij}$	T2 bilateral clearing capacity of DP i w.r.t. DP j
	$\Delta T2BCC_{t,s+h}^{ij}$	Change in $T2BCC$ of DP i w.r.t. DP j over period h
	$T1MCC_{t,s}^{j}$	T1 multilateral clearing capacity for DP j
	$\Delta T1MCC_{t,s+h}^{j}$	Change in $T1MCC$ for DP j over period h
	$T2MCC_{t,s}^{j}$	T2 multilateral clearing capacity for DP j
	$\Delta T2MCC_{t,s+h}^{j}$	Change in $T2MCC$ of DP j over period h
	$T2BCC_{t,s}^{ji}$	T2 bilateral clearing capacity of DP j w.r.t. DP i
	$\Delta T2BCC_{t,s+h}^{ji}$	Change in $T2BCC$ of DP j w.r.t. DP i over period h
Others	$\tau_{t,d+h}^{ij}$	Expected arrival time of payment from DP i to DP j from s to $s+h$
	$\tau_{t,d+h}^{ji}$	Expected arrival time of payment from DP j to DP i from s to $s+h$
	$D_{t,d}^{SysWP}$	Indicator variable for change in system-wide percentage from $\theta = 0.24$ to $\theta = 0.3$ on May 1, 2008.
	$Time_{t,d}$	Time trend variable

Table 7 Marginal Multilateral Netting Regression Controls

Control Type	**Variables**	**Description**
DP	$T1MCC_{t,d}^{i}$	T1 multilateral clearing capacity for DP i
	$\Delta T1MCC_{t,d}^{i}$	Change in $T1MCC$ for DP i over period h
	$T2MCC_{t,d}^{i}$	T2 multilateral clearing capacity for DP i
	$\Delta T2MCC_{t,d}^{i}$	Change in $T2MCC$ for DP i over period h
	$\overline{T2BCC}_{t,d}^{i,j}$	Avg. T2 bilateral clearing capacity of DP i
	$\overline{\Delta T2BCC}_{t,d}^{i,j}$	Avg. change in $T2BCC$ of DP i over period h
	$\overline{T1MCC}_{t,d}^{j}$	Avg. T1 multilateral clearing capacity for DP j
	$\overline{\Delta T1MCC}_{t,d}^{j}$	Avg. change in $T1MCC$ for DP j over period h
	$\overline{T2MCC}_{t,d}^{j}$	Avg. T2 multilateral clearing capacity for DP j
	$\overline{\Delta T2MCC}_{t,d}^{j}$	Avg. change in $T2MCC$ for DP j over period h
	$\overline{T2BCC}_{t,d}^{j,i}$	Avg. T2 bilateral clearing capacity of DP j w.r.t. DP i.
	$\overline{\Delta T2BCC}_{t,d}^{j,i}$	Avg. change in $T2BCC$ of DP j w.r.t. DP i over period h
Others	$\tau_{t,d+\mathrm{h}}^{i,N-1}$	Expected arrival time of payment from DP i to any other DP from s to $s+h$
	$\tau_{t,d+\mathrm{h}}^{N-1,i}$	Expected arrival time of payment from any DP to DP i from s to $s+h$
	$D_{t,d}^{SysWP}$	Indicator variable for change in system-wide percentage from $\theta = 0.24$ to $\theta = 0.3$ on May 1, 2008.
	$Time_{t,d}$	Time trend variable

Figure 1: LVTS daily operating schedule

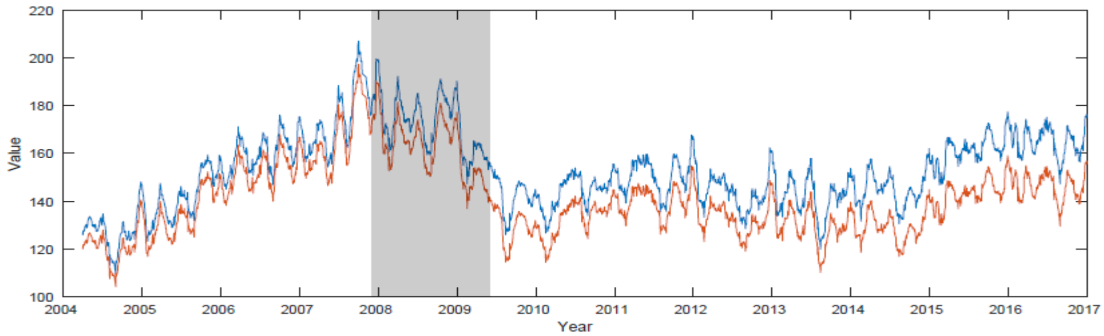


Time	LVTS Cycle
23:00	**Commencement and Start of Initialization Period** DPs wishing to exchange CLS-related or bilaterally agreed upon non-CLS related payments will sign-on, pledge collateral, apportion collateral, confirm DP profile information and set bilateral limits. The Bank of Canada will value DP collateral. CLS-related payments are those payments to/from Bank of Canada for the benefit of the CLS Bank, payments delivered between DPs to fund a DP's position or a client's position for whom a DP is acting as the client's… agent.
00:30 - 18:00	**Start of Payment Message Exchange Period** LVTS is open for exchanging payments.1 There must be bilateral agreement between Sending and Receiving DPs to send non-CLS related payments prior to 06:00 hours.
07:00-08:00	**Sing-on Period** DPs not already active will sign-on, pledge collateral, apportion collateral, confirm DP profile information, and set bilateral limits.
18:00	**End of Payment Message Exchange Period/Start of Pre-Settlement** Start of Inter-DP Payment Message Exchange Period LVTS is open for bilaterally agreed upon inter-DP payments (MT 205 only). This period is to be used by the DPs to bring their Multilateral Net Positions closer to zero.
18:30	**End of Pre-Settlement** No further payment messages may be exchanged through the LVTS.
By 19:30	**Settlement** The Bank of Canada will settle all DPs' Multilateral Net Positions. All DPs' Multilateral Positions are settled simultaneously.

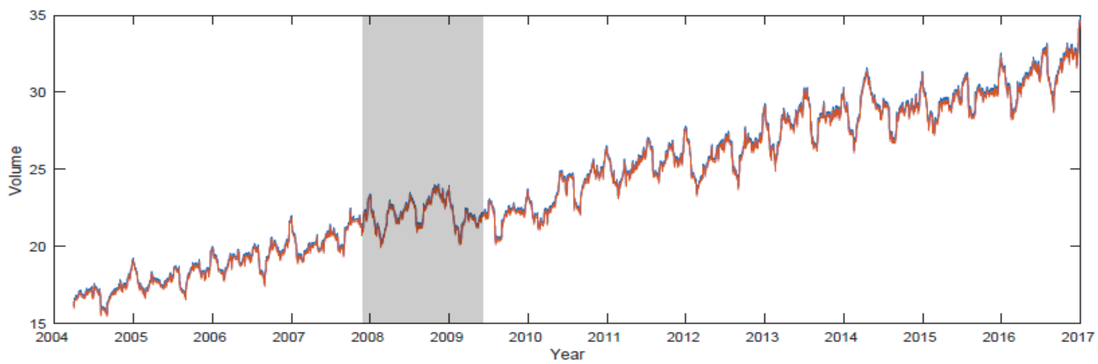
Note: This figure describes the LVTS Cycle as reported in Payments Canada (2017). Bank of Canada will value the collateral of all DPs prior to 00:30 hours regardless of when they become active.

Figure 2: Aggregate System-wide Gross Value and Gross Volume of Payments

Panel A: Gross Value of Payments



Panel B: Gross Volume of Payments

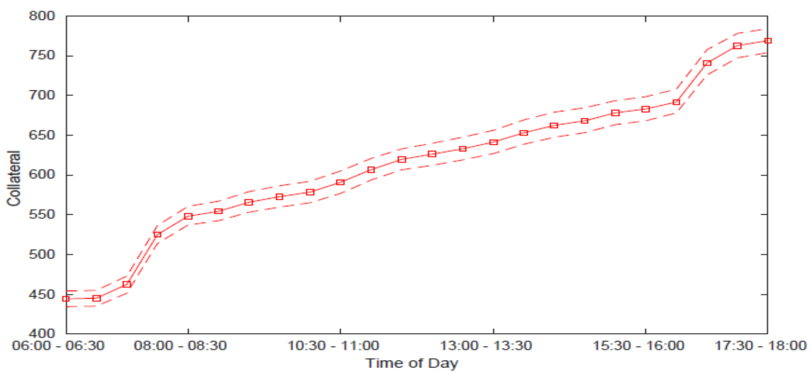


Note: The figure shows rolling monthly (21 trading day) moving averages of the gross value of payment orders (Panel A) and gross volume of payment orders (Panel B) processed in the LVTS for the full sample period from March 1, 2004 to December 30, 2016. The gross value of payment orders is reported in billions of Canadian dollars and calculated using equation eqx. The gross value of payment orders is reported in thousands and calculated using eqx. The shaded area corresponds to the Great Financial Crisis, dated by the National Bureau of Economic Research from December 2, 2007 to June 1, 2009 (NBER, 2010). The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the set of direct DPs.

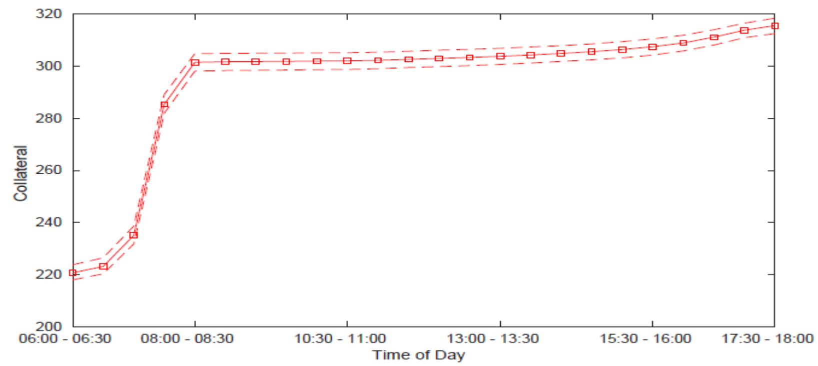
Figure 3: Average BCL and Collateral During the Full Sample Period

Panel A: Collateral

T1

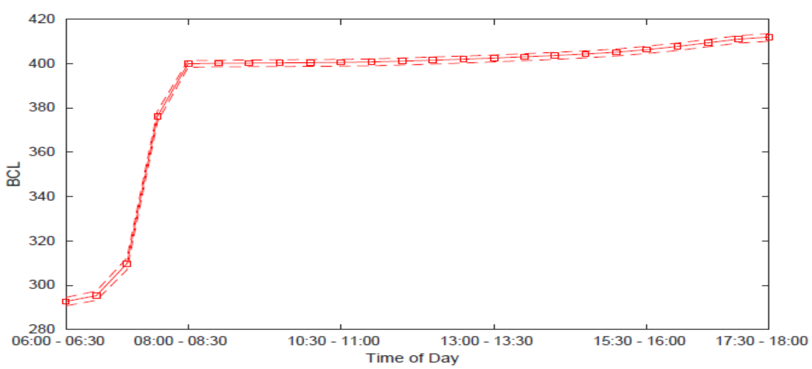


T2

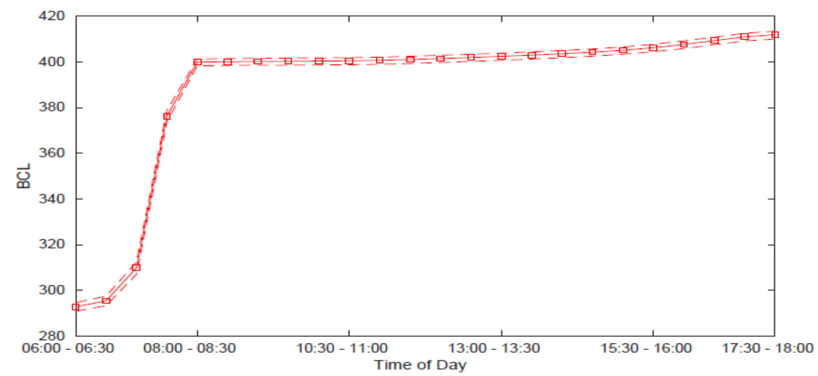


Panel B: Bilateral Credit Line (BCL)

Received



Sent

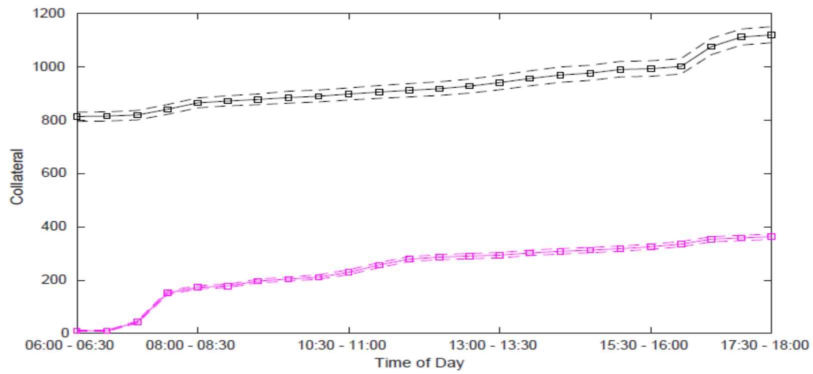


Notes: Values in Millions CAD. The results exclude the Bank of Canada because it does not post BCLs or Collateral.

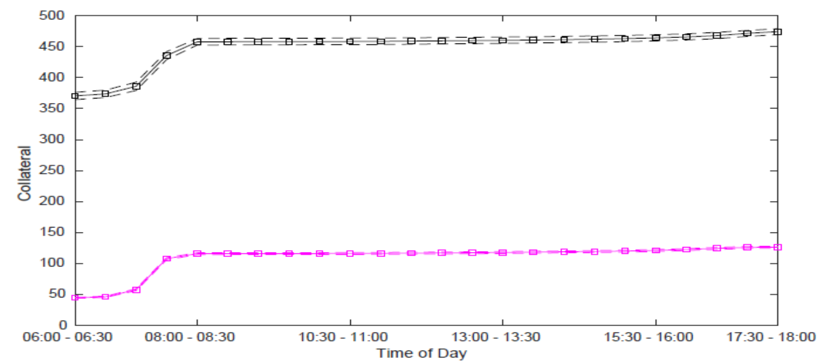
Figure 4: Average BCL and Collateral by DP Size During the Full Sample Period

Panel A: Collateral

T1

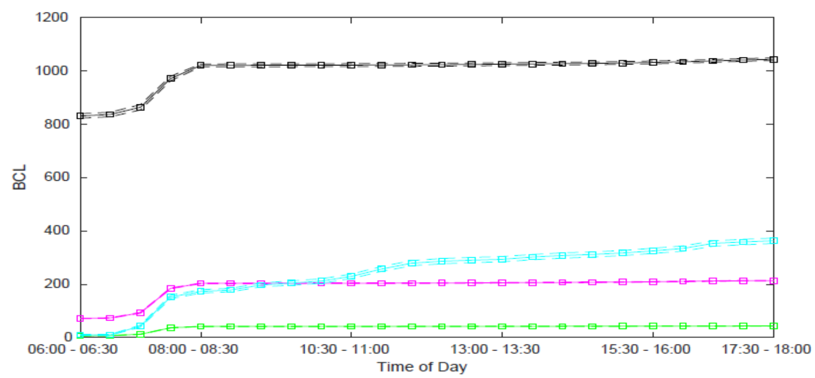


T2

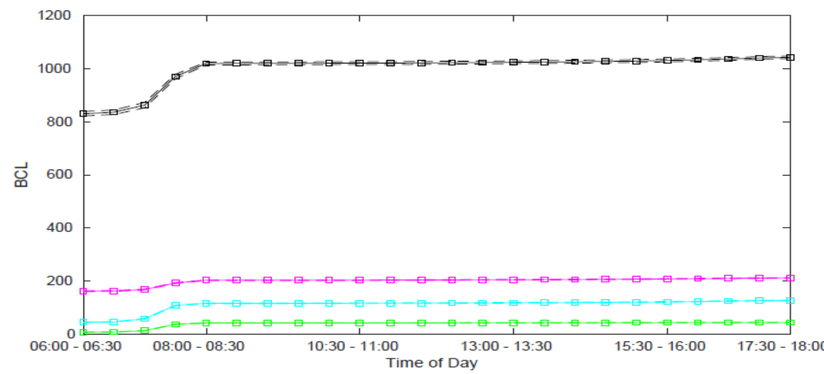


Panel B: Bilateral Credit Line (BCL)

Received



Sent

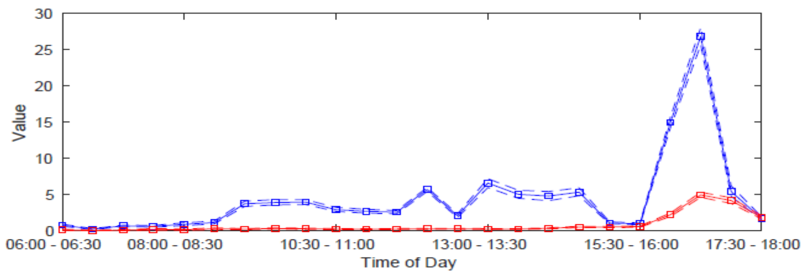


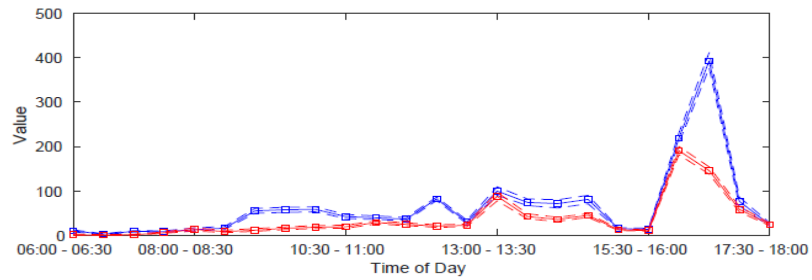
Notes: Values in millions CAD. For BCLs, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the Collateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 5: Average Bilateral ($\bar{P}^{B}_{d+h}$) and Multilateral ($\bar{P}^{M}_{d+h}$) Gross Payment Order Value During the Full Sample Period

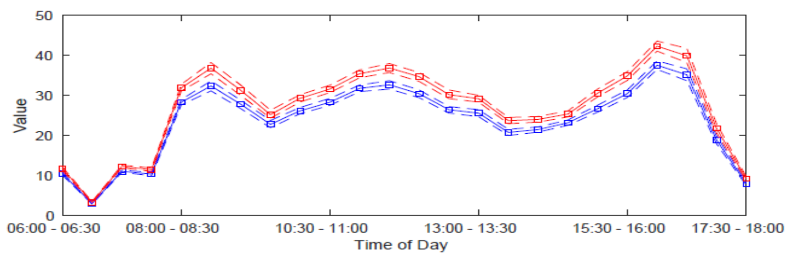
Bilateral ($\bar{P}^{B}_{d+h}$) | **Multilateral ($\bar{P}^{M}_{d+h}$)**

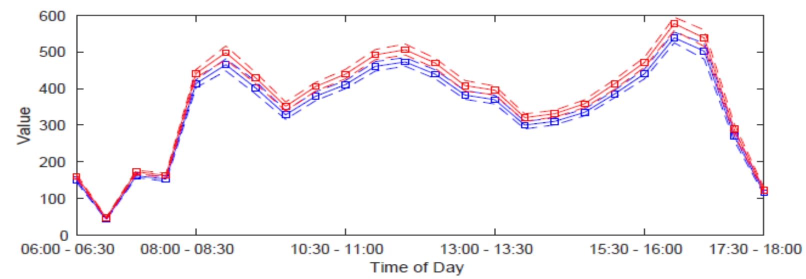
Panel A: T1 Payments



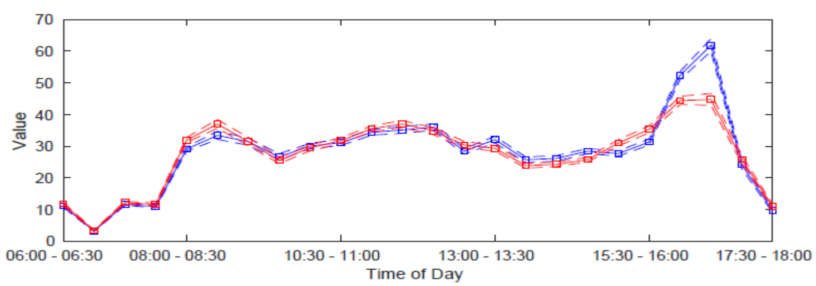


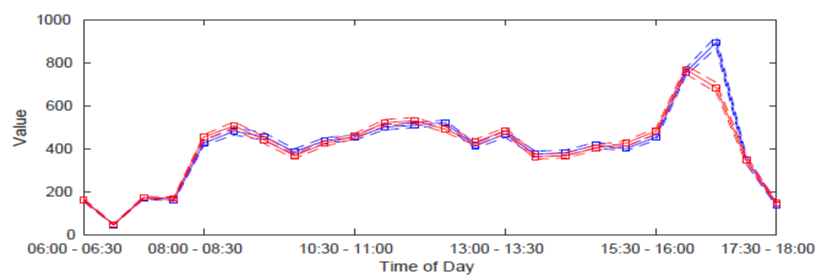
Panel B: T2 Payments





Panel C: T1 and T2 Payments Combined



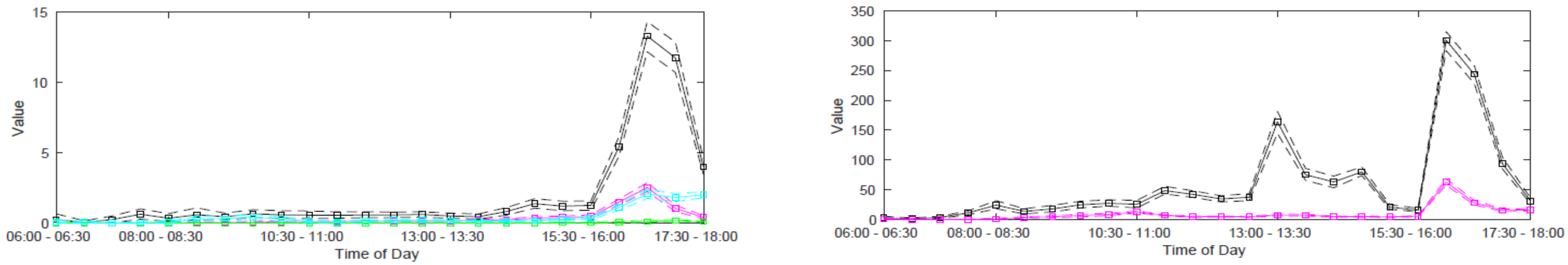


Note: Values in millions. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

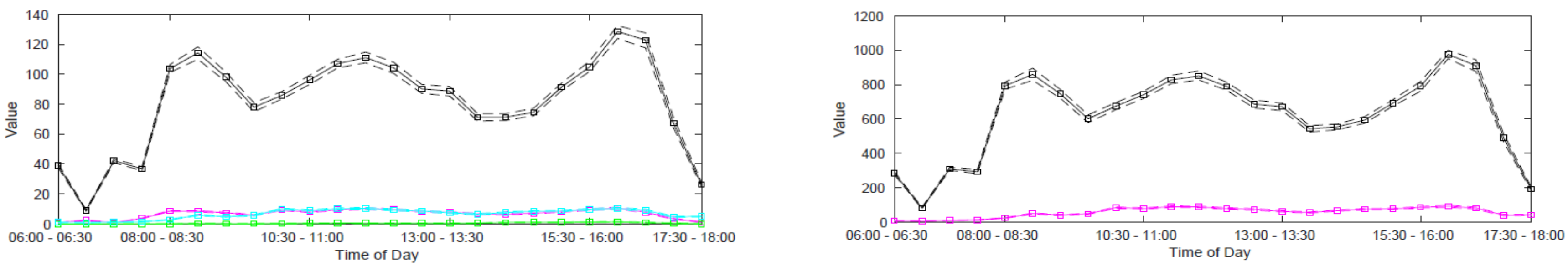
Figure 6: Average Payment Order Value by DP Size During the Full Sample Period

Bilateral **Multilateral**

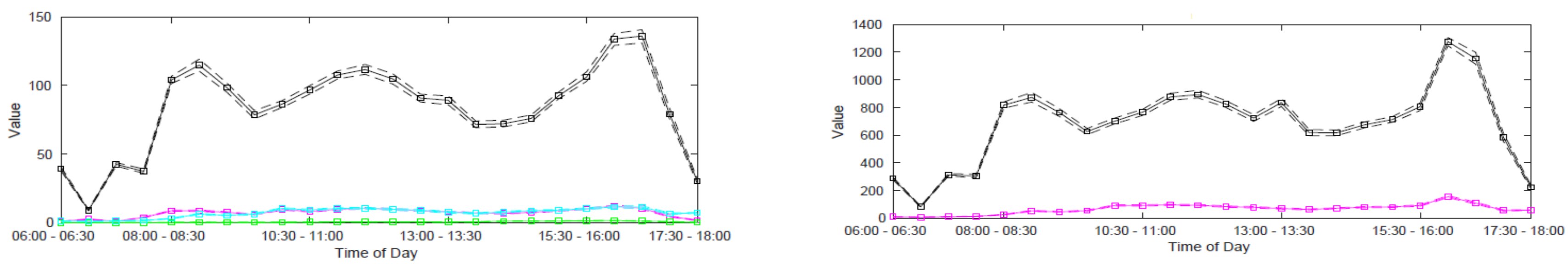
Panel A: T1 Payments



Panel B: T2 Payments



Panel C: T1 and T2 Payments Combined

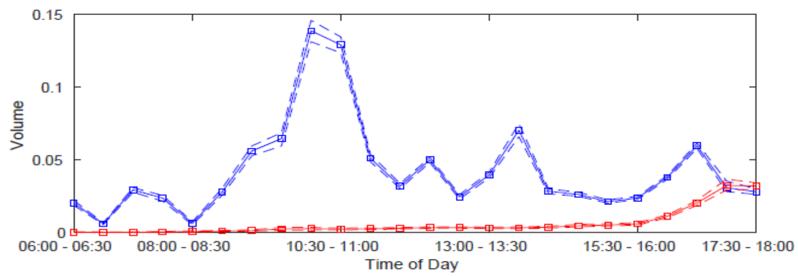


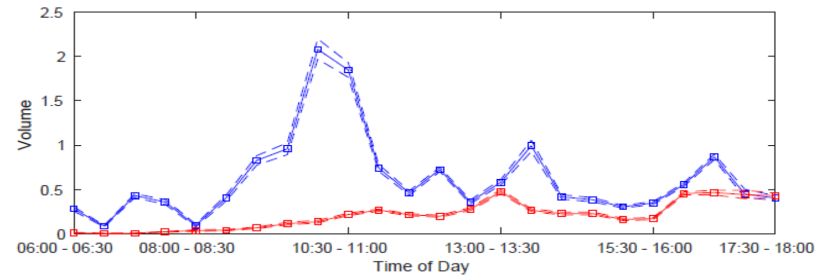
Note: Values in millions. On the bilateral side, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the multilateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 7: Average Bilateral ($\overline{Vol}^{B}_{d+h}$) and Multilateral ($\overline{Vol}^{M}_{d+h}$) Gross Payment Order Volume During the Full Sample Period

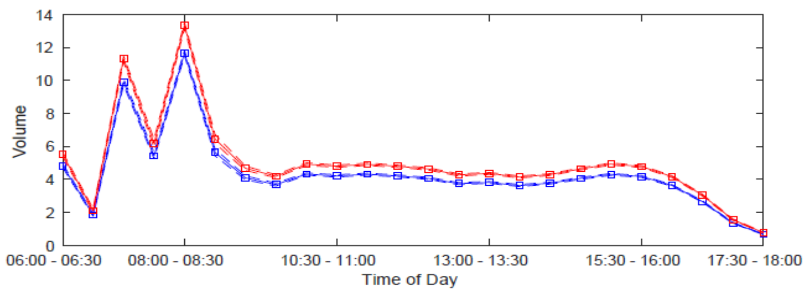
Bilateral ($\overline{Vol}^{B}_{d+h}$) **Multilateral ($\overline{Vol}^{M}_{d+h}$)**

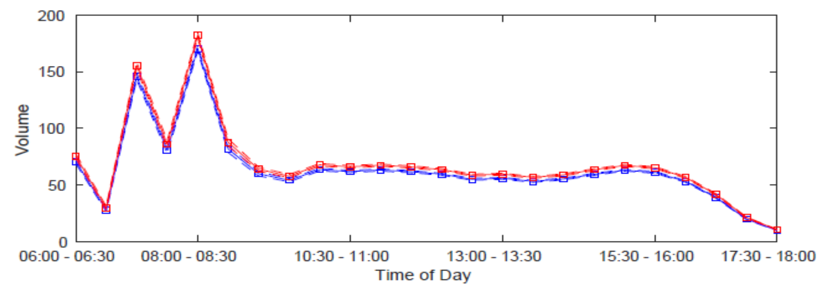
Panel A: T1 Payments



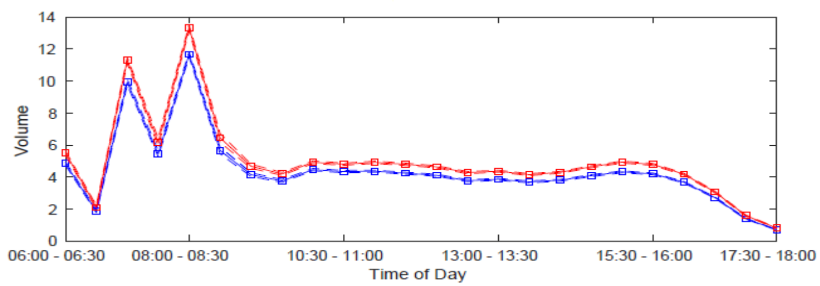


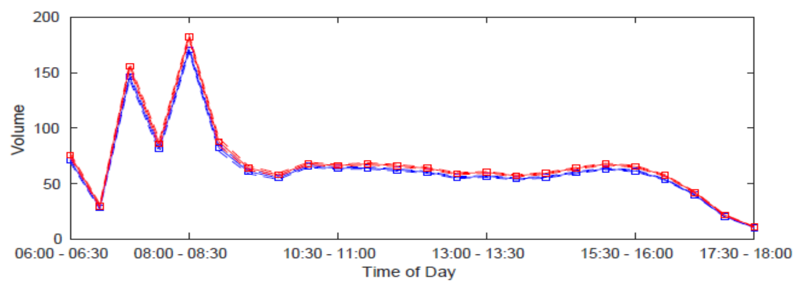
Panel B: T2 Payments





Panel C: T1 and T2 Payments Combined



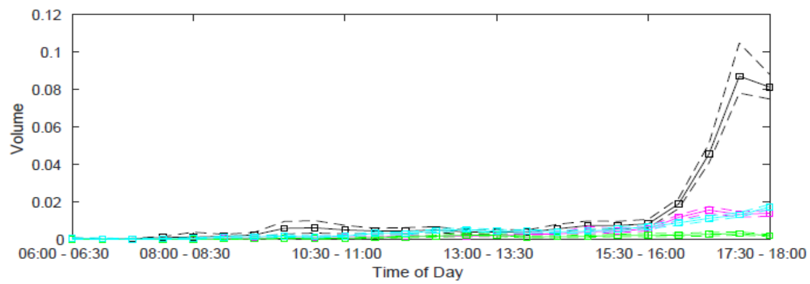


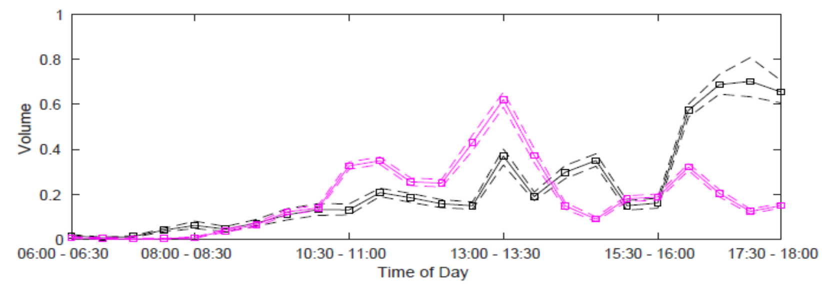
Note: Values in thousands. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

Figure 8: Average Payment Order Volume by DP Size During the Full Sample Period

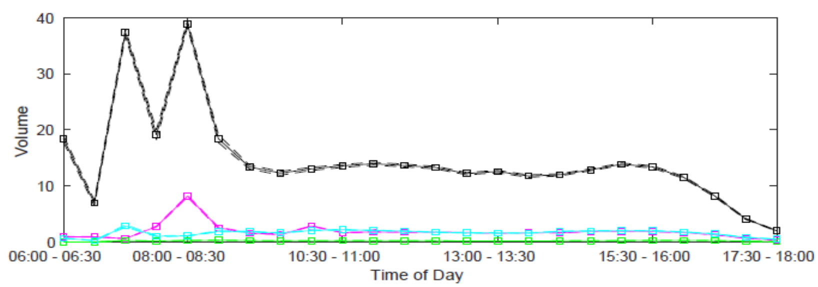
Bilateral | **Multilateral**

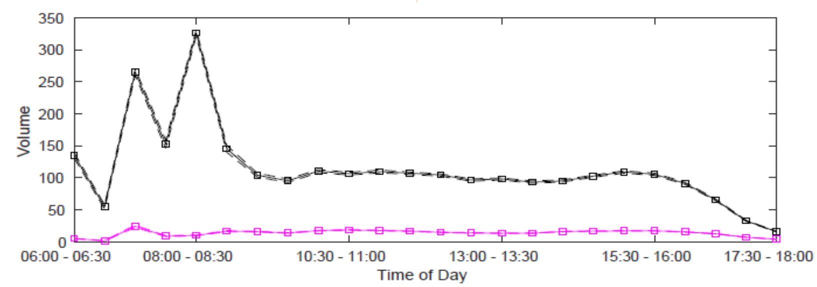
Panel A: T1 Payments



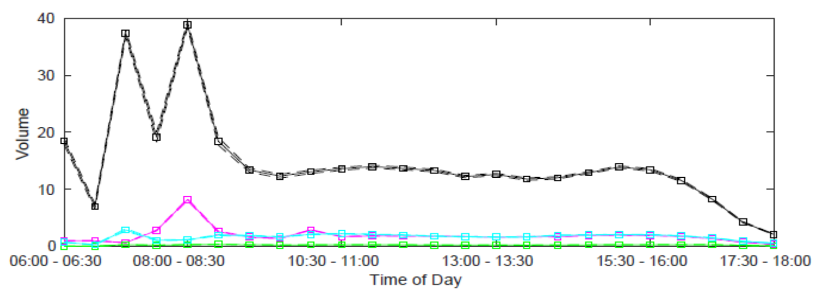


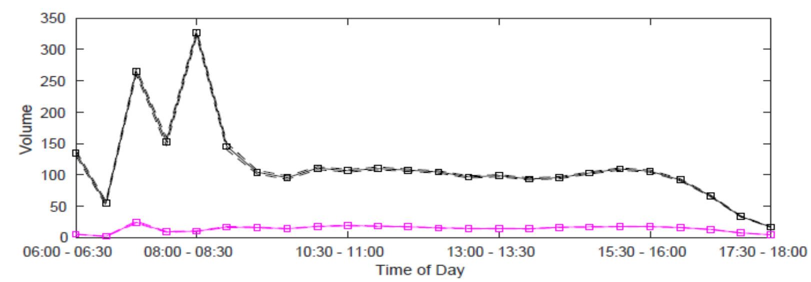
Panel B: T2 Payments





Panel C: T1 and T2 Payments Combined



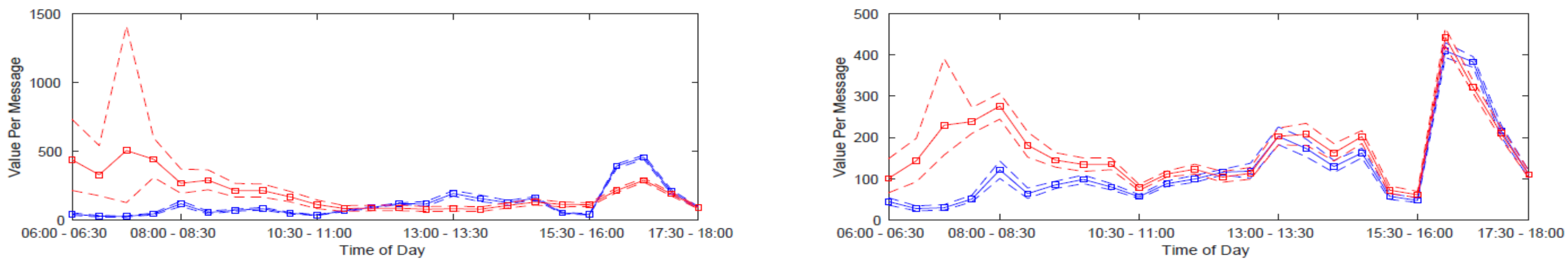


Note: Values in thousands. On the bilateral side, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the multilateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

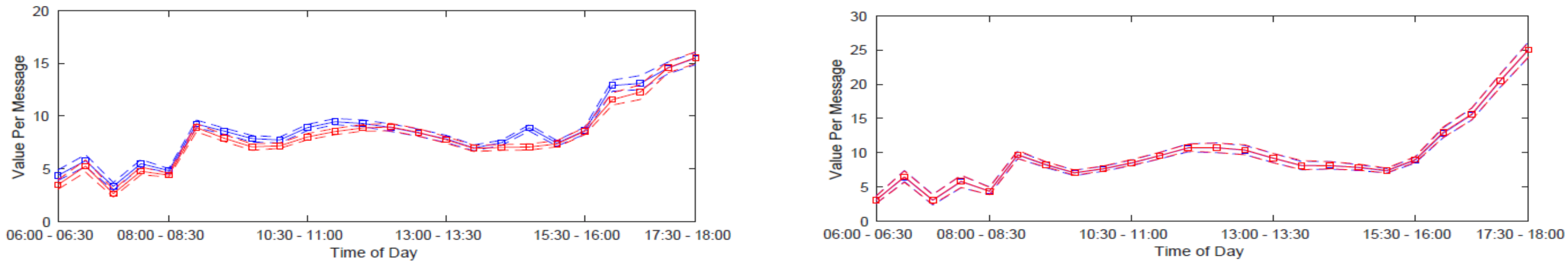
Figure 9: Average Payment Order Value During the Full Sample Period

Bilateral | **Multilateral**

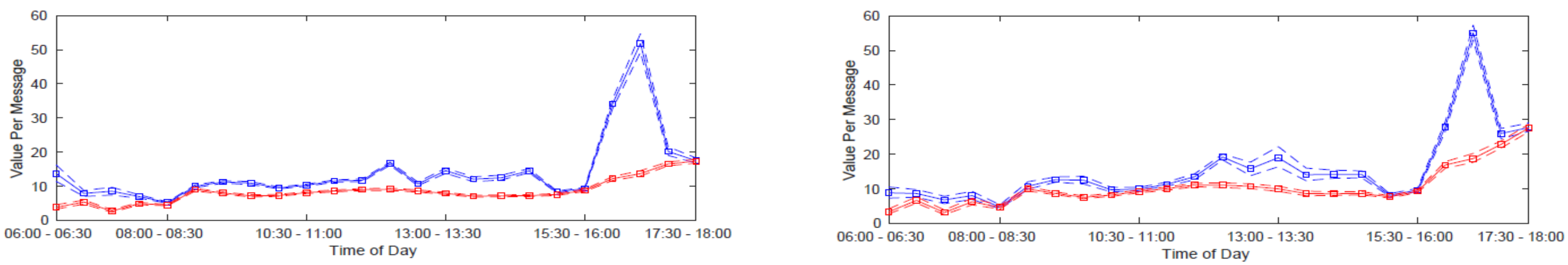
Panel A: T1 Payments



Panel B: T2 Payments



Panel C: T1 and T2 Payments Combined

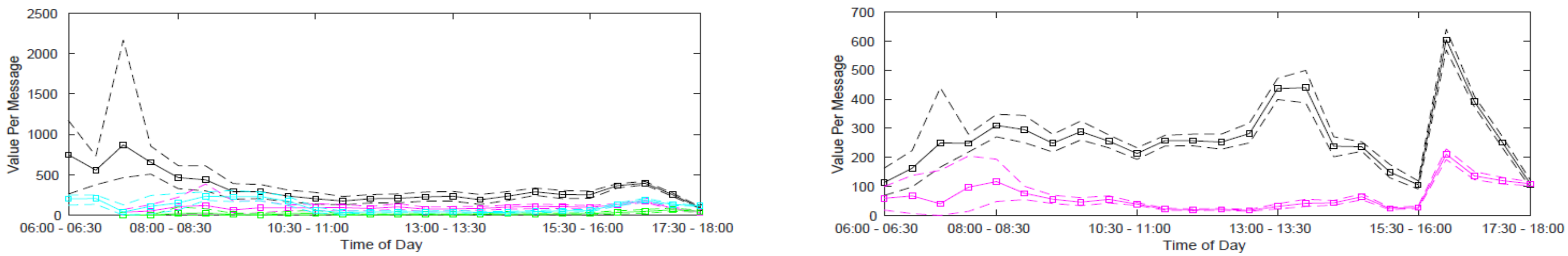


Note: Values in millions. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

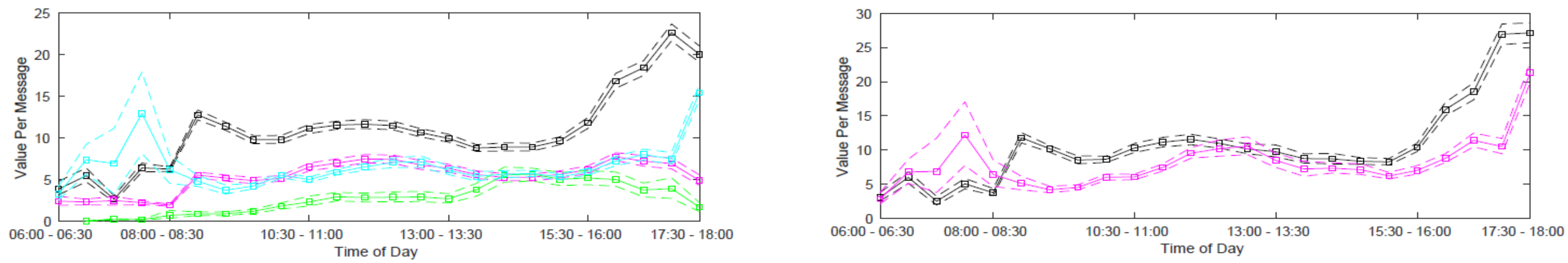
Figure 10: Average Payment Order Value by DP Size During the Full Sample Period

Bilateral | **Multilateral**

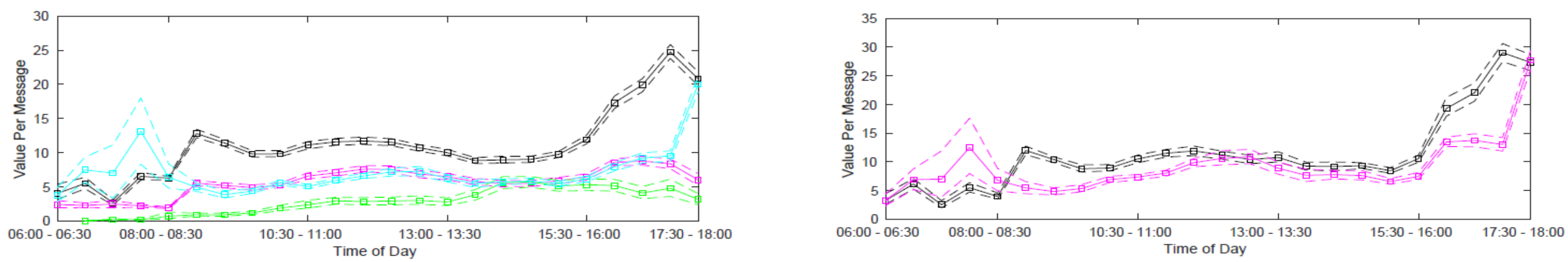
Panel A: T1 Payments



Panel B: T2 Payments



Panel C: T1 and T2 Payments Combined

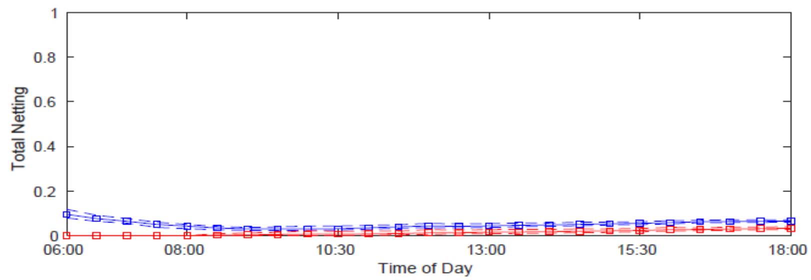


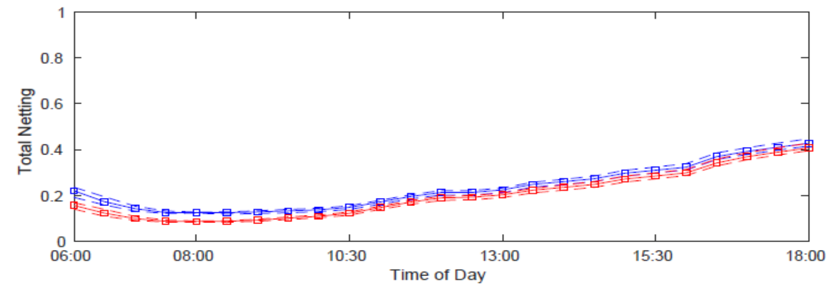
Note: Values in millions. On the bilateral side, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the multilateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 11: Total Netting During the Full Sample Period

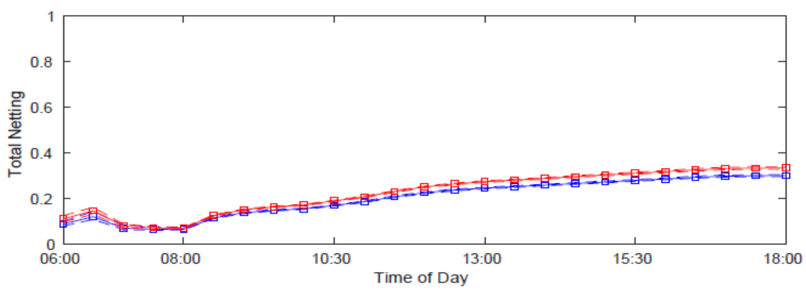
Bilateral | **Multilateral**

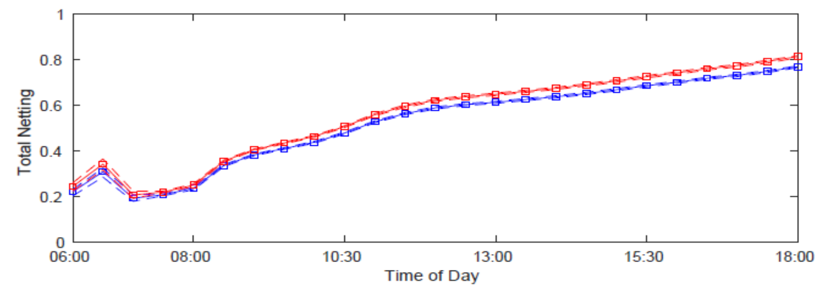
Panel A: T1 Payments



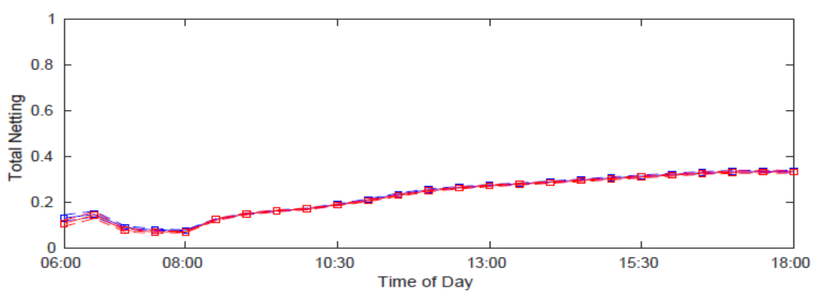


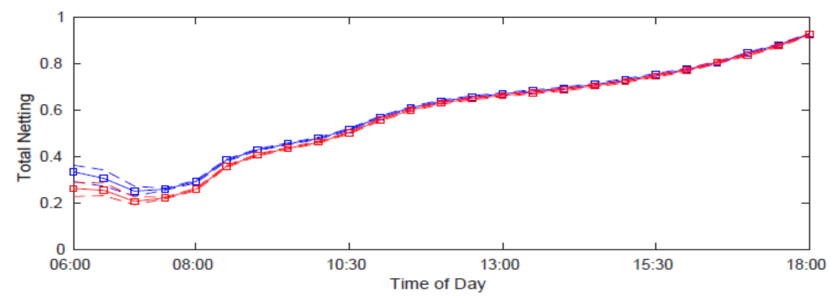
Panel B: T2 Payments





Panel C: T1 and T2 Payments

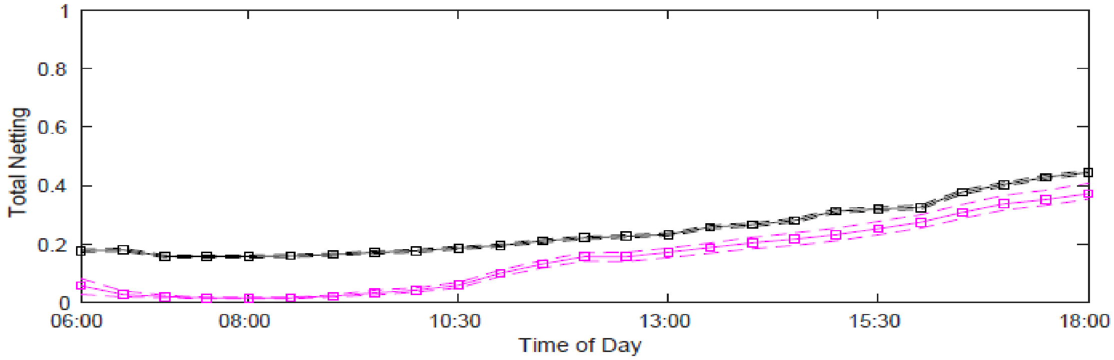




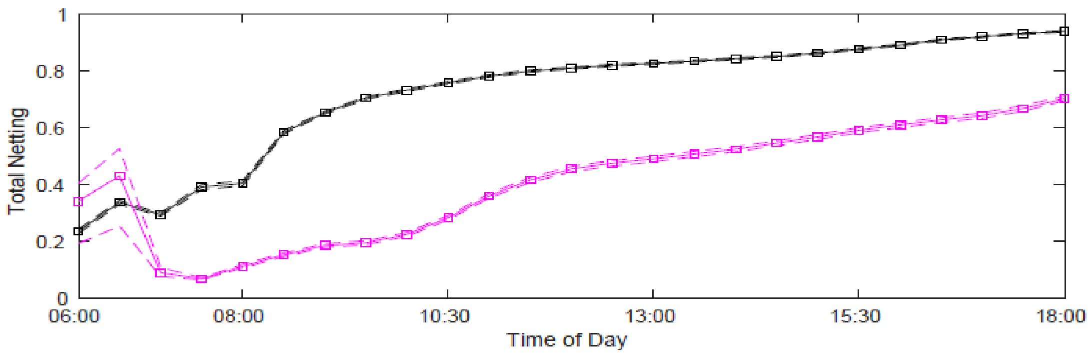
Notes: The charts report the cross-sectional average of total netting per dollar of payment order value. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

Figure 12: Average Multilateral Netting by DP Size During the Full Sample Period

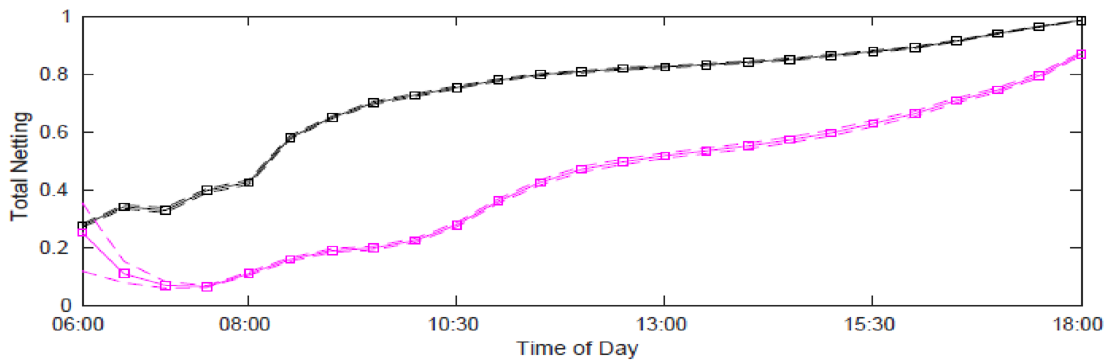
Panel A: T1 Payments



Panel B: T2 Payments



Panel C: T1 and T2 Payments Combined

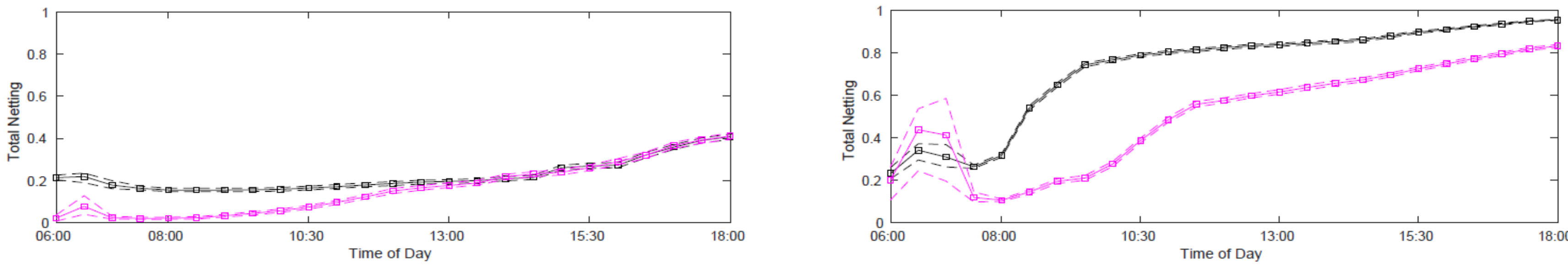


Notes: The charts report the cross-sectional average of total netting per dollar of payment order value by size of DP. The black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

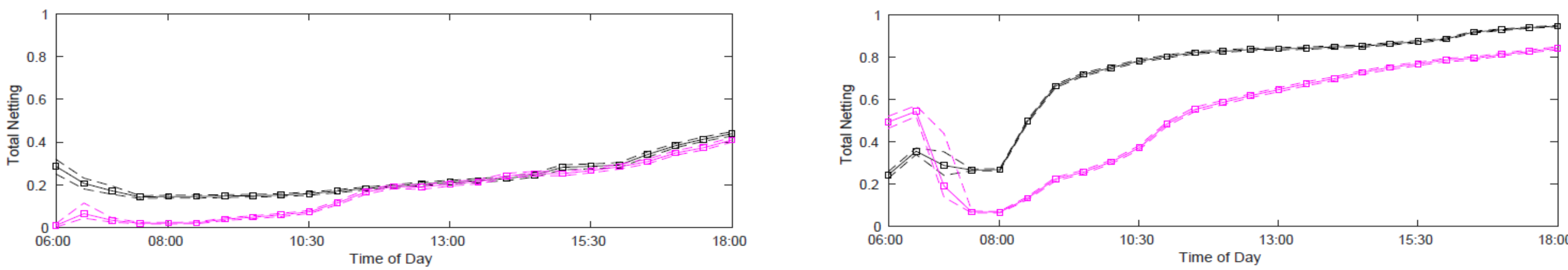
Figure 13: Total netting by DP Size

T1 Payments **T2 Payments**

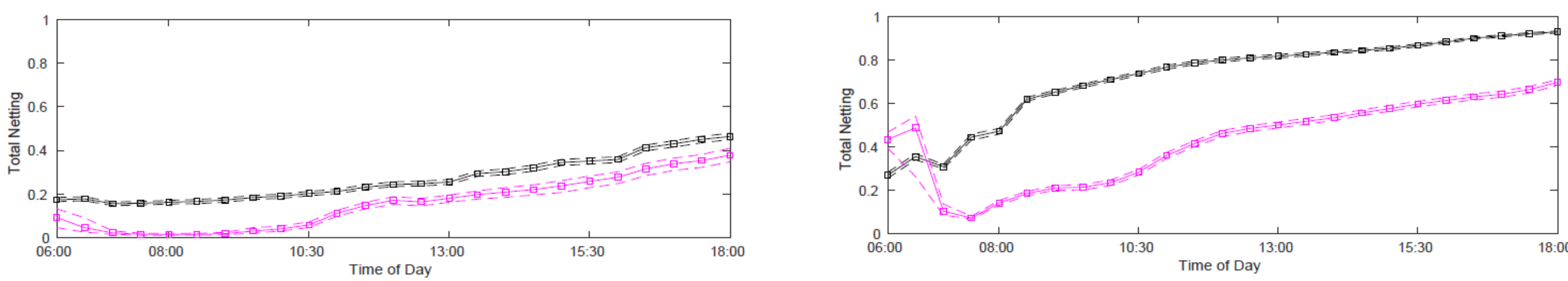
Panel A: Pre-Crisis Period



Panel B: Crisis Period



Panel C: Post-Crisis Period

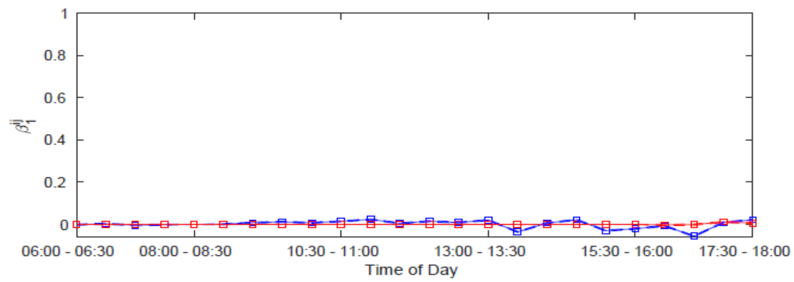


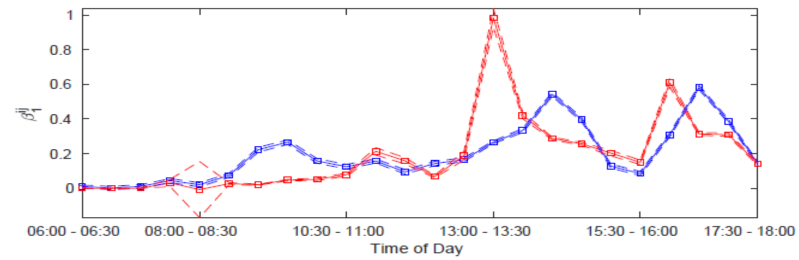
Notes: The charts report the cross-sectional average of total netting per dollar of payment order value by size of DP. The black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 14: Marginal Netting in T1 Payment Orders During the Full Sample Period

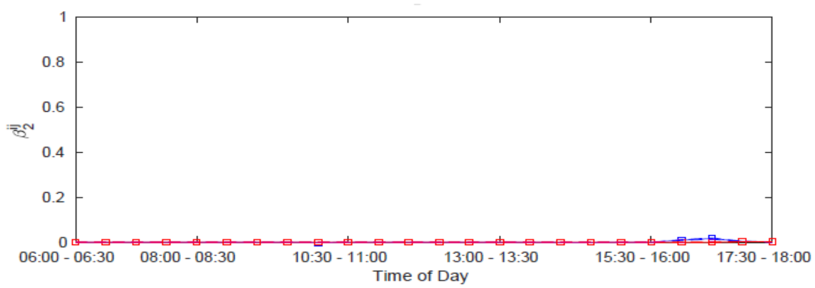
Bilateral | **Multilateral**

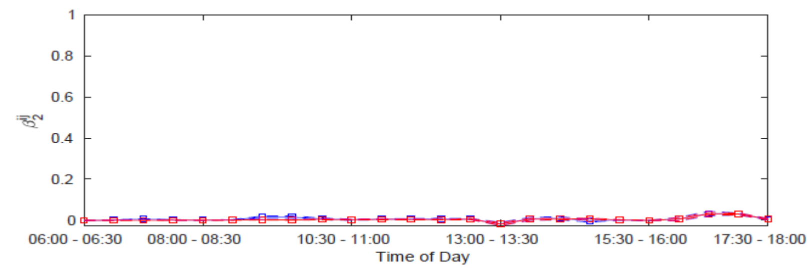
Panel A: Same Tranche Netting (β_1^{ij})





Panel B: Cross Tranche Netting (β_2^{ij})



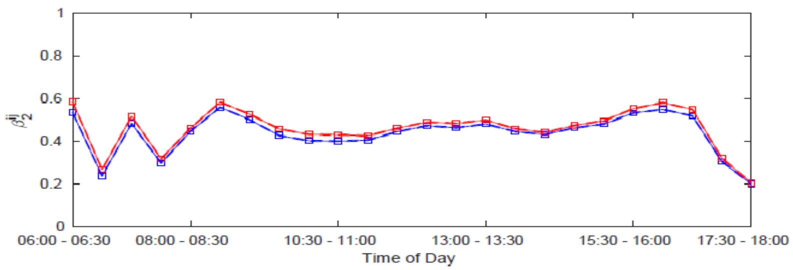


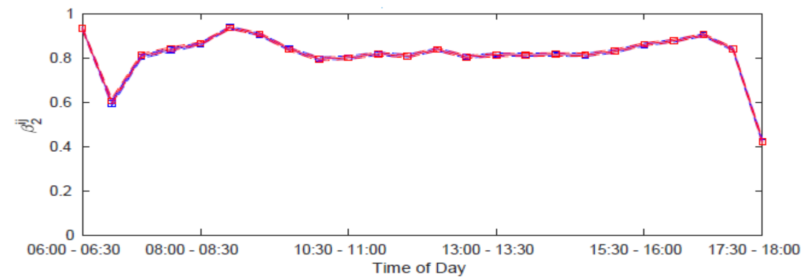
Notes: The charts report the cross-sectional average of marginal netting per dollar of payment order value. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

Figure 15: Marginal Netting in T2 Payment Orders During the Full Sample Period

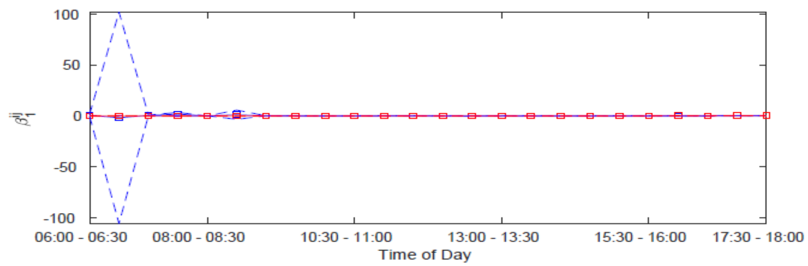
Bilateral **Multilateral**

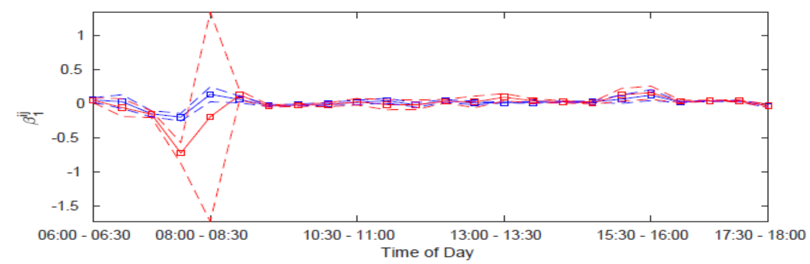
Panel A: Same Tranche Netting (β_2^{ij})





Panel B: Cross Tranche Netting (β_1^{ij})



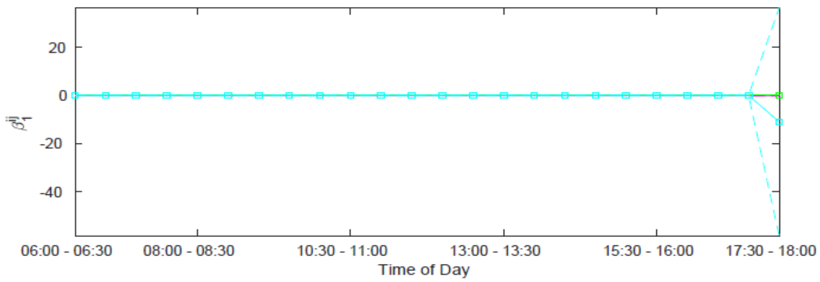


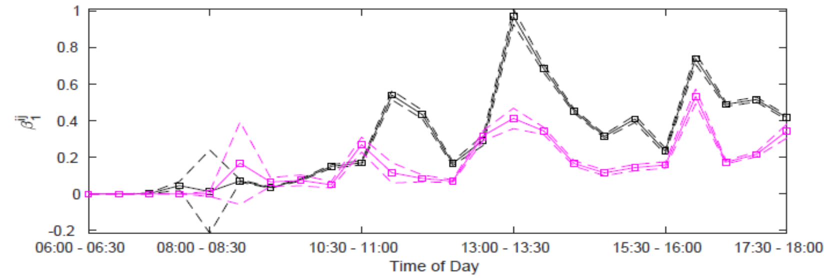
Notes: The charts report the cross-sectional average of marginal netting per dollar of payment order value. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

Figure 16: Same Tranche Marginal Netting by DP Size During the Full Sample Period

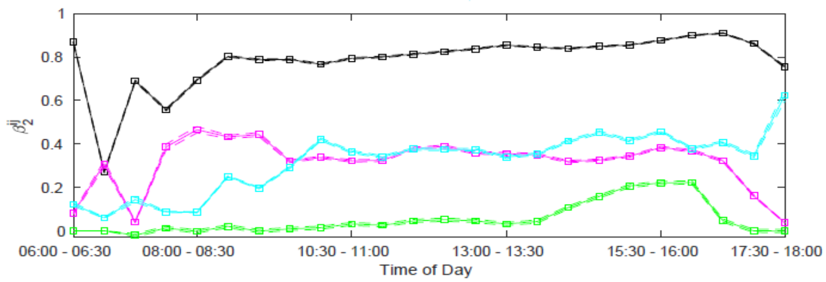
Bilateral | **Multilateral**

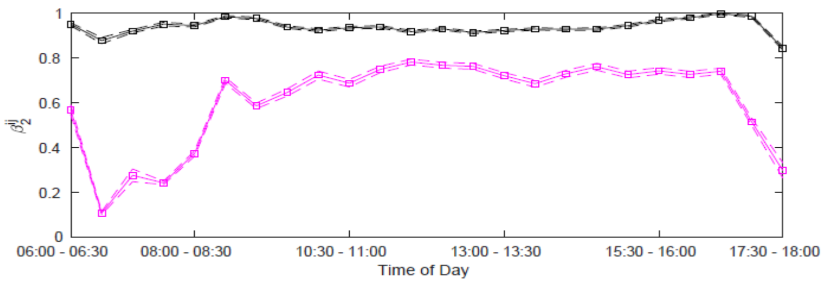
Panel A: T1 Payment Orders (β_1^{ij})





Panel B: T2 Payment Orders (β_2^{ij})



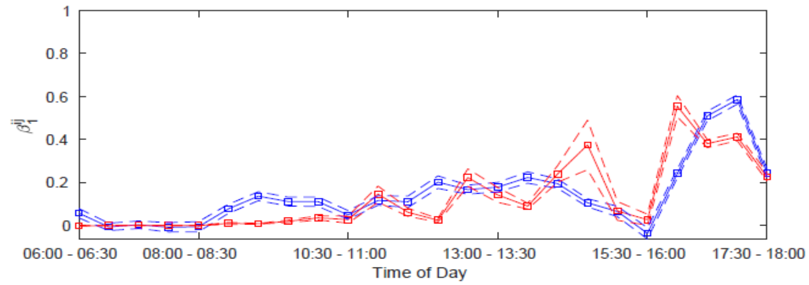


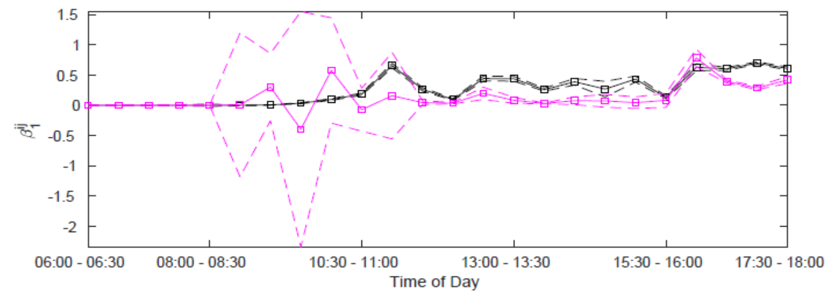
Notes: The charts report the cross-sectional average of marginal netting per dollar of payment order value by size of DP. On the bilateral side, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the multilateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 17: Same Tranche Multilateral Marginal Netting in T1 Payment Orders

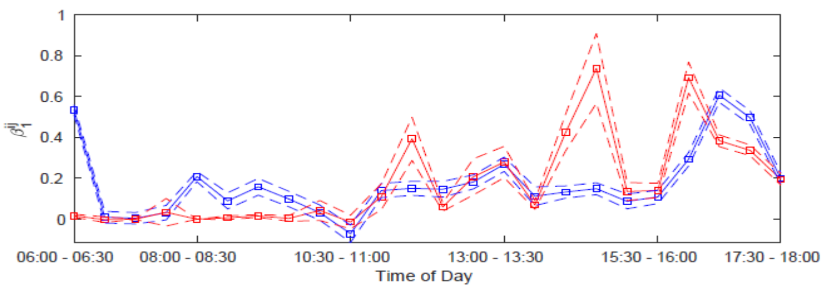
Full Sample | **By DP Size**

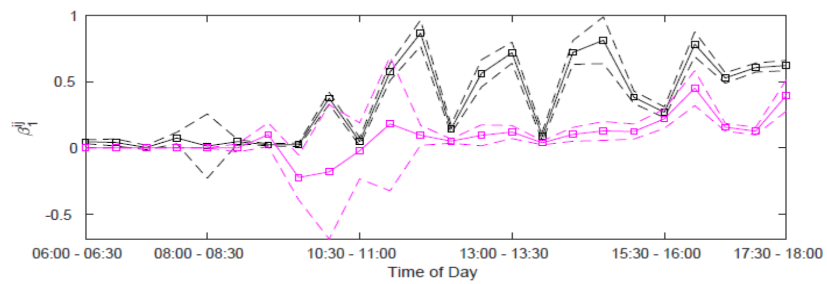
Panel A: Pre-Crisis Period



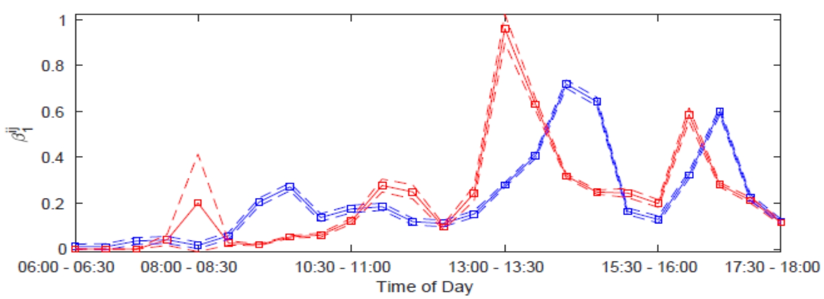


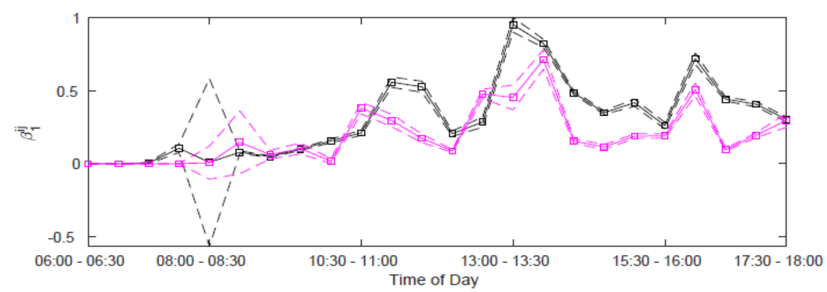
Panel B: Crisis Period





Panel C: Post-Crisis Period



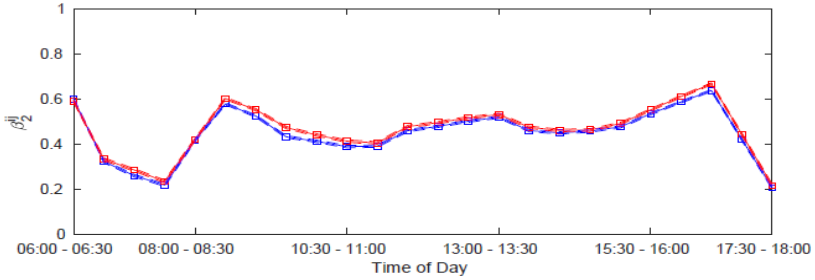


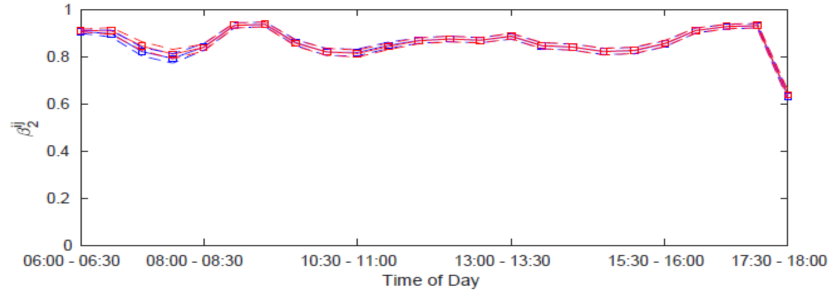
Notes: The black line are payments sent from large DP to all other DPs and the magenta line are payments sent from small DPs to all other DPs.

Figure 18: Same Tranche Marginal Netting in T2 Payment Orders

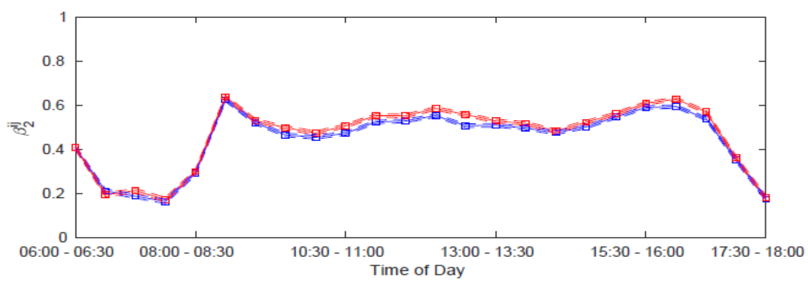
Bilateral | **Multilateral**

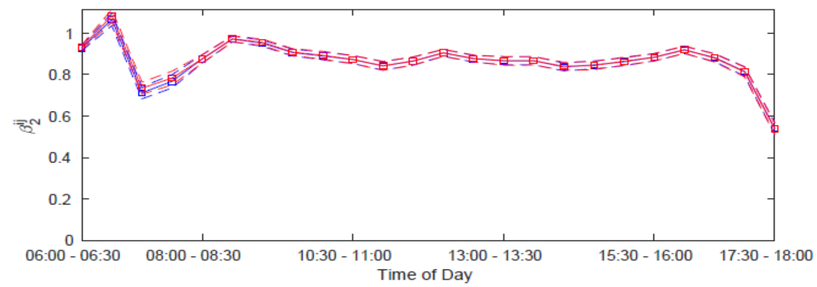
Panel A: Pre-Crisis Period



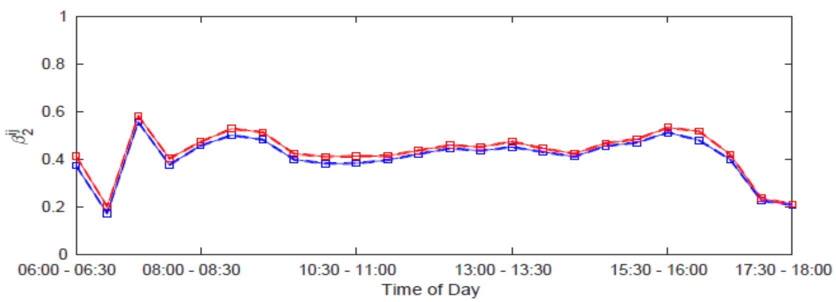


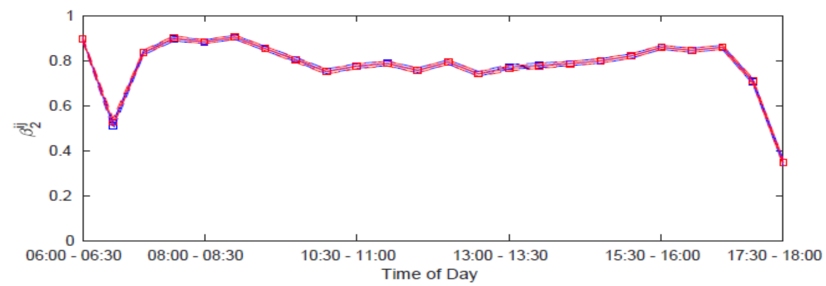
Panel B: Crisis Period





Panel C: Post-Crisis Period



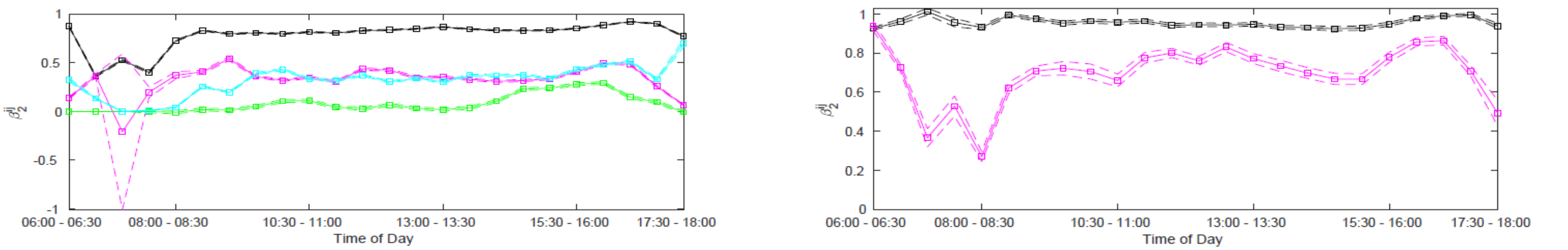


Notes: The charts report the cross-sectional average of marginal netting per dollar of payment order value. The blue line is calculated with the full set of direct DPs in the LVTS. The red line is calculated by excluding the Bank of Canada from the full set of direct DPs.

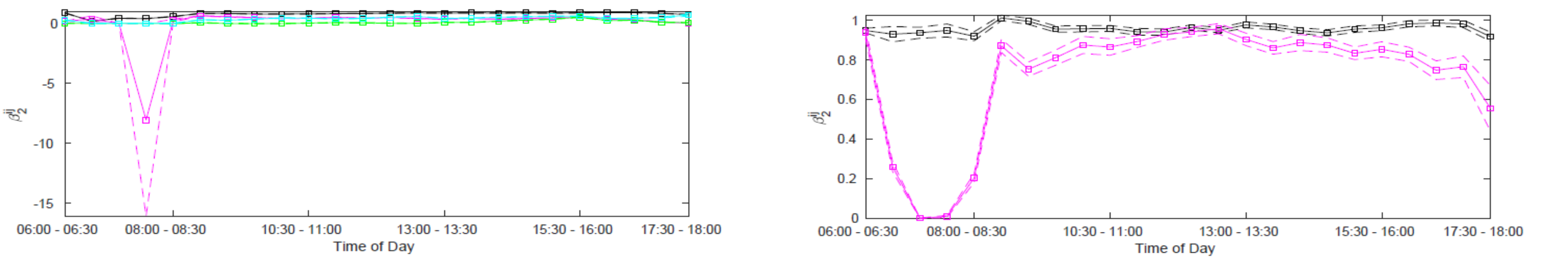
Figure 19: Same Tranche Marginal Netting in T2 Payment Orders by DP Size

Bilateral | **Multilateral**

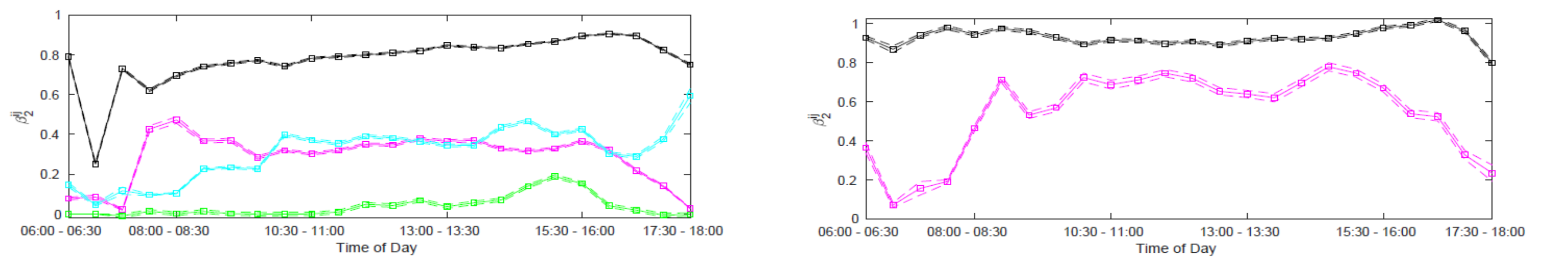
Panel A: Pre-Crisis Period



Panel B: Crisis Period



Panel C: Post-Crisis Period



Notes: The charts report the cross-sectional average of marginal netting per dollar of payment order value. On the bilateral side, the balck line are payments sent from large DPs to large DPs, magenta line are payments sent from large DPs to small DPs, green line are payments sent from small DPs to small DPs and the cyan line are payments from small DPs to large DPs. For the multilateral charts, the black line are payments sent from large DPs to all other DPs and the magenta line are payments sent from small DPs to all other DPs.